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Overview and Comparison of Grid Harmonics and Conducted EMI Standards for LV Converters Connected to the MV Distribution System

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Abstract

Grid harmonics and conducted EMI standards pose fundamental constraints on the design and optimization of commercial and industrial power electronics systems. The aim of this paper is to provide an overview of different such standards which apply to converter modules in non-public low voltage grids connected to the medium voltage distribution system. The examinations cover the IEEE 519, IEEE 1547, and CISPR 11 standards as well as the technical guideline "Generating Plants Connected to the Medium-Voltage Network" from BDEW. In a second step, a comparative analysis is performed which identifies the most stringent limits in the considered frequency range from 100 Hz to 30 MHz. The analysis shows that BDEW generally defines the lowest limits for frequencies below 9 kHz, whereas for frequencies higher than 150 kHz the most difficult standard to comply with is CISPR 11. Additional limits are proposed for frequencies between 9 kHz and 150 kHz for which currently no applicable standards exist.

1 Introduction

A fundamental requirement of commercial and industrial power electronics systems is the compliance with grid harmonics and conducted EMI standards. In medium voltage (MV) distribution systems, typical loads are low voltage (LV) converter systems (e.g. wind farms, factories) comprising a multitude of individual (possibly low power) consuming and/or generating LV converter modules as shown in **Fig. 1(a)**. In contrast to LV grid harmonics standards which are often defined for individual modules (e.g. IEC 61000-3-12 [1]), the MV standards are mostly defined for the point of common coupling (PCC, see [2] for a detailed definition) and hence for the overall converter system. From the design point of view, it is hence of interest what limits the individual modules must comply with in order to guarantee overall system compliance at the PCC. In this paper, an overview of MV grid harmonics standards is given. Based on these standards, limits for the individual modules are derived. Conducted EMI standards, which typically apply to the individual modules and to higher frequencies (**Fig. 1(b)**), are included into the analysis as they are relevant for the proper functioning of the converter system. In a second step, the standards are compared to each other to identify the most stringent limits in the frequency range from 100 Hz to 30 MHz.

Section 2 gives a short summary of the standards considered in this paper. In **Section 3**, the comparative analysis of the investigated standards is performed. Finally, **Section 4** gives a practical example. RMS currents and RMS line-to-line voltages are assumed throughout this paper. If not otherwise stated, SI units are used.

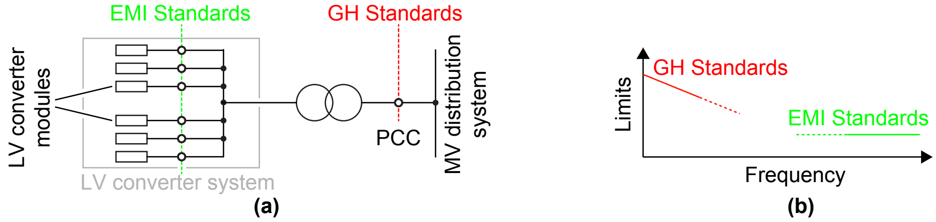

Fig. 1: Power consuming and generating converter modules in a LV converter system connected to the MV distribution system at the PCC **(a)**. Relationship between MV grid harmonics (GH) and EMI standards **(b)**.

Tab. 1: Overview of standards discussed in **Section 2**.

	IEEE 519/1547	BDEW	CISPR 11 A1
Application	Systems of non-linear loads (IEEE 519), power generation equipment (IEEE 1547)	Generating plants	ISM equipment
Grid type	Distribution systems 0.12-161 kV	Distribution systems 1-60 kV	General LV grids
Frequency Range	$\geq$100 Hz	0.1-9 kHz	0.15-30 MHz
Type of limits	Current harmonics limits at integer multiples of the fundamental frequency, IEEE 519: *SCR*-dependent	Integer and non-integer current harmonics limits, linearly dependent from *SCR*	QP and AVG limits of mains terminal disturbance voltages
Measurement	At PCC of consumer/distribution system interface	At PCC of consumer/distribution system interface, geometric summation of harmonics within a band of 200 Hz above 2 kHz	LISN voltage measurement, QP- and AVG-evaluation of harmonics within a frequency band of 9 kHz

2 Overview

This paper analyzes the IEEE 519 [3], IEEE 1547 [4], and CISPR 11 [5] standards as well as the technical guideline “Generating Plants Connected to the Medium-Voltage Network” from BDEW [6] (hereafter referred to as “BDEW”). In this section, these standards are briefly introduced and discussed. A summary of the most important aspects is given in **Tab. 1**.

2.1 IEEE 519 / IEEE 1547

The IEEE 519 standard defines recommended current harmonics limits I_ν at the PCC for converter systems comprising non-linear loads (e.g. static power converters, arc discharge devices and saturated magnetic devices). The limits, which are defined for multiples of the fundamental frequency, are shown in **Tab. 2**. They are lower for even multiples and vary for different distribution system voltage levels U_{MV} and short-circuit ratios (*SCR*). The limits were developed with the objective of limiting the voltage harmonics at the PCC to a constant percentage of the fundamental voltage and under the assumption that the distribution system can be characterized by a purely inductive short-circuit impedance $j\omega L_{\mathrm{SC}}$. In addition to the individual harmonics I_ν, IEEE 519 also defines limits for the total distortion over frequency. The corresponding integral measure is defined as the total demand distortion *TDD*,

Tab. 2: Maximum admissible current harmonics $I_\nu^\star$ (odd and even) and *TDD* in % of I_{L} according to IEEE 519 for distribution system voltages U_{MV} = [0.12, 161] kV. I_{SC} is the short-circuit current at the PCC, $I_{\mathrm{SC}} = \frac{U_{\mathrm{MV}}}{\sqrt{3}\,2\pi 50\,\mathrm{Hz} L_{\mathrm{SC}}}$.

Maximum harmonic current distortion $I_\nu^\star$ and *TDD* in % of I_{L} for distribution systems 0.12-69 kV						
Individual harmonic order ν (odd harmonics) [1)]						
$I_{\mathrm{SC}}/I_{\mathrm{L}}$	< 11	$11 \leq \nu < 17$	$17 \leq \nu < 23$	$23 \leq \nu < 35$	$35 \leq \nu$	*TDD*
≤ 20 [2)]	4.0	2.0	1.5	0.6	0.3	5.0
(20, 50]	7.0	3.5	2.5	1.0	0.5	8.0
(50, 100]	10.0	4.5	4.0	1.5	0.7	12.0
(100, 1000]	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

1) Even harmonics are limited to 25 % of the odd harmonic limits.

2) All power generation equipment is limited to these values of current distortion regardless of $I_{\mathrm{SC}}/I_{\mathrm{L}}$.

For distribution systems in the voltage range 69-161 kV the above limits reduced by 50 % apply.

$$TDD = \frac{\sqrt{\sum_{\nu=2}^{\infty} I^2_{\mathrm{dist},\nu}}}{I_\mathrm{L}} \,, \tag{1}$$

where I_L is the maximum fundamental load current and $I_{\mathrm{dist},\nu}$ the generated current harmonics of the converter system at the PCC.

The IEEE 1547 standard applies to power generation equipment. Its limits are derived from to the IEEE 519 limits for $SCR \leq 20$ (**Tab. 2**) and are independent from SCR.

2.2 BDEW

The BDEW standard was defined by the German association of energy and water industries. It is general guideline for the planning and operation of generating plants connected to the MV distribution system. **Tab. 3** shows the defined current limits applying to the PCC. The admissible harmonic currents $I_{\nu,\mu}$ for module n within a system of N modules can be calculated by multiplication of the values in **Tab. 3** with the short-circuit power S_SC of the MV distribution system at the PCC,

$$I_{\nu,\mu,n} = I^*_{\nu,\mu} \;[\mathrm{A/MVA}] \cdot \frac{S_\mathrm{SC}}{1\,000\,000} \cdot \frac{S_{\mathrm{r},n}}{S_{\mathrm{r},N}} \,, \tag{2}$$

where $S_{\mathrm{r},n}$ is the module rated power and $S_{\mathrm{r},N}$ the system rated power of all N modules.

Lower limits than (2) apply in case of more than one system connected (at different PCCs) to the same MV distribution system. Note that the limits in **Tab. 3** are inverse to the voltage levels and can be interpolated. Furthermore, in contrast to the IEEE standards, BDEW also defines limits for non-integer multiples of the fundamental frequency. For harmonics between 2 kHz and 9 kHz , the distortion levels $I_{\mathrm{dist},\nu,\mu}$ must be measured within a frequency band of 200 Hz, centered around the considered harmonic, according to EN 61000-4-7, Annex B [7],

$$I_{\mathrm{dist},\nu,\mu} = \sqrt{\sum_{n=-19}^{20} I^2_{\mathrm{dist},((\nu,\mu)\cdot 50+n\cdot 5)\mathrm{Hz}}} \,. \tag{3}$$

Tab. 3: Admissible integer current harmonics I^*_ν and non-integer current harmonics I^*_μ related to the short-circuit power S_SC of the MV distribution system according to BDEW.

	Admissible, related harmonic current $I^*_{\nu,\mu}$ in A/MVA		
Ordinal number ν, μ	**10 kV grid**	**20 kV grid**	**30 kV grid**
5	0.058	0.029	0.019
7	0.082	0.041	0.027
11	0.052	0.026	0.017
13	0.038	0.019	0.013
17	0.022	0.011	0.007
19	0.018	0.009	0.006
23	0.012	0.006	0.004
25	0.010	0.005	0.003
$25 < \nu < 40$ [1)]	$0.01 \cdot 25/\nu$	$0.005 \cdot 25/\nu$	$0.003 \cdot 25/\nu$
even-numbered	$0.06/\nu$	$0.03/\nu$	$0.02/\nu$
$\mu < 40$	$0.06/\mu$	$0.03/\mu$	$0.02/\mu$
$40 < \nu, \mu \leq 180$ [2)]	$0.18/\mu$	$0.09/\mu$	$0.06/\mu$

[1)] Odd-numbered
[2)] Integer and non-integer within a range of 200 Hz, measurement according to EN 61000-4-7, Annex B [7]

Tab. 4: CISPR 11 limits U_{CISPR} for class A group 1 (A1) equipment. S_r is the rated module power, I_r the module rated phase currents and "IT grid" refers to isolated neutral or high impedance earthed grids as defined in IEC 60364-1 [13].

Mains terminal disturbance voltage limits U_{CISPR} for A1 equipment in dB(µV)

	$S_r \leq 20\,\mathrm{kVA}$		$S_r > 20\,\mathrm{kVA}$ 2)		$S_r \leq 75\,\mathrm{kVA}$, IT grid 3)	
Frequency (MHz) 1)	**QP**	**AVG**	**QP**	**AVG**	**QP**	**AVG**
0.15-0.5	79	66	100	90	130	120
0.5-5	73	60	86	76	125	115
5-30	73	60	90-73 4)	80-60 4)	115	105

1) At the transition frequency, the more stringent limit shall apply.

2) Limits equivalent to: CISPR 11 A2, $S_r \leq 20\,\mathrm{kVA}$; IEC 61800-3 C3, $I_r \leq 100\,\mathrm{A}$; IEC 62040-2 C3, $I_r = (16, 100]\,\mathrm{A}$
3) Limits equivalent to: CISPR 11 A2, $S_r > 20\,\mathrm{kVA}$; IEC 61800-3 C3, $I_r > 100\,\mathrm{A}$; IEC 62040-2 C3, $I_r > 100\,\mathrm{A}$

4) Decreasing linearly with logarithm of frequency

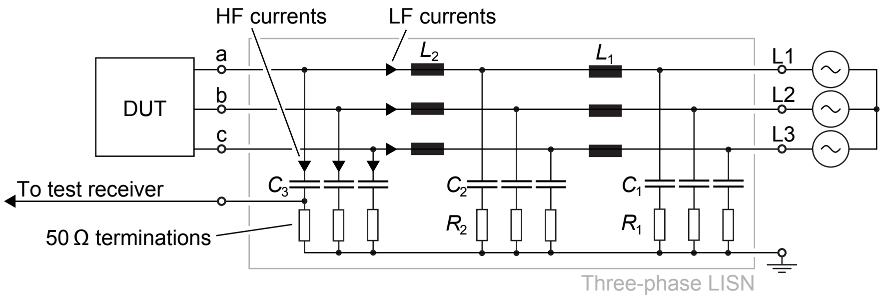

Fig. 2: Typical realization of a three-phase LISN according to CISPR 16 [8]. L_1, L_2, C_1, C_2, R_1 and R_2 form a bidirectional filter. It defines a stable impedance seen from the DUT and filters incoming grid disturbances. High-frequency (HF) emissions from the DUT are coupled to the test receiver, whereas the low-frequency (LF) currents can flow between the grid and DUT.

2.3 CISPR 11

CISPR 11 defines limits for conducted emissions (CE) in the frequency range 0.15-30 MHz for industrial, scientific and medical (ISM) devices. In contrast to the IEEE standards and BDEW, CISPR 11 is a LV standard applying to individual converter modules. The emissions must be measured by means of a line impedance stabilization network (LISN) which is placed between the device under test (DUT) and the LV grid (**Fig. 2**). In the relevant frequency range, the LISN features a defined impedance of $Z_{\mathrm{LISN}} \approx 50\,\Omega$ between phases and ground [8]. A test receiver is used to measure the emissions across that impedance. The associated harmonics inside a moving frequency band of 9 kHz, centered around the analyzed frequency, are then processed either by means of an average (AVG) or quasi-peak (QP) detector, which both show non-linear input-output characteristics. However, both are tuned so as to indicate the RMS value in case of only a single harmonic within the frequency band. The interested reader is referred to [5, 8, 9] for more detailed information.

Tab. 4 shows the emission limits U_{CISPR} of class A group 1 (A1) equipment, which includes amongst others semiconductor power converters in commercial and industrial environments. Note that the generic CISPR 11 class A limits are identical to the device specific limits in IEC 61000-6-4 (industrial equipment) [10] and to those of IEC 62040-2 (UPS systems) [11] and IEC 61800-3 (adjustable speed electrical power drive systems) [12] for category C3 (industrial environment) equipment.

3 Comparison

In this section, based on the investigated standards, limits are derived which can be applied to an individual converter module. The limits should guarantee overall system compliance, provided that all modules comply with these limits. Furthermore, a comparative analysis of the derived limits is performed

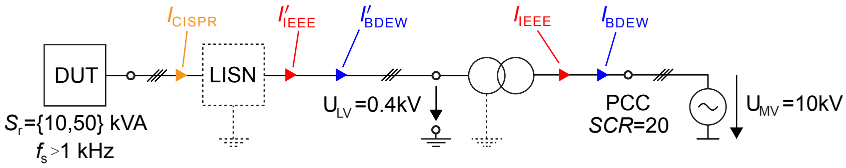

Fig. 3: Setup for comparison of standards and derivation of module-based limits. The converter module (DUT), either in a grounded or isolated IT LV grid, is connected to the MV distribution system by means of a transformer. The depicted currents denote the calculated admissible current harmonics.

in order to identify the most stringent standards in the frequency range from 100 Hz to 30 MHz. Switched converter modules with switching frequencies f_{s} in the kilo-Hertz range are considered.

3.1 Methodology

Although the IEEE and BDEW limits are formulated for the PCC and hence for converter systems that possibly consist of more than one module, equivalent limits can be calculated which can be applied to the individual modules of the system. The translation from PCC-based limits to individual module-based limits requires, however, that the *SCR* at the PCC is given (see (2) and **Tab. 2**). Consequently, for the purpose of this comparison, a worst-case short-circuit ratio of $SCR = 20$ has been assumed. A setup of an individual module in a LV converter system ($U_{\mathrm{LV}} = 0.4\,\mathrm{kV}$) connected to the MV distribution system ($U_{\mathrm{MV}} = 10\,\mathrm{kV}$) has been considered (**Fig. 3**).

3.1.1 Equivalent IEEE 519/1547 Limits

The equivalent IEEE 519/1547 admissible current harmonics I'_{IEEE} for an individual converter module on the LV secondary side of the transformer can be calculated by

$$I'_{\mathrm{IEEE}} = c \cdot I_{\mathrm{IEEE}} = c \cdot I^{\star}_{\nu}\big|_{SCR\,=\,20}\ [\%] \cdot I_{\mathrm{L}} = c \cdot I^{\star}_{\nu}\big|_{SCR\,=\,20}\ [\%] \cdot \frac{I_{\mathrm{r}}}{c} = I^{\star}_{\nu}\big|_{SCR\,=\,20}\ [\%] \cdot I_{\mathrm{r}}\ , \tag{4}$$

where an idealized transformer with turns ratio $c = \frac{U_{\mathrm{MV}}}{U_{\mathrm{LV}}}$ has been assumed and I_{r} is the module rated phase current. The *TDD* limits will not be considered in this comparison.

3.1.2 Equivalent BDEW Limits

The equivalent current limits I'_{BDEW} according to BDEW can be calculated using (2),

$$I'_{\mathrm{BDEW}} = c \cdot I_{\mathrm{BDEW}} = c \cdot I^{*}_{\mu,\nu}\big|_{10\,\mathrm{kV}}\ [\mathrm{A/MVA}] \cdot \frac{S_{\mathrm{SC}}}{1\,000\,000} \cdot \frac{S_{\mathrm{r},n}}{S_{\mathrm{r},N}} = c \cdot I^{*}_{\mu,\nu}\big|_{10\,\mathrm{kV}}\ [\mathrm{A/MVA}] \cdot \frac{SCR}{1\,000\,000} \cdot \sqrt{3}U_{\mathrm{MV}} \cdot \frac{I_{\mathrm{r}}}{c} \tag{5}$$

$$= I^{*}_{\mu,\nu}\big|_{10\,\mathrm{kV}}\ [\mathrm{A/MVA}] \cdot \frac{SCR}{1\,000\,000} \cdot \sqrt{3}U_{\mathrm{MV}} \cdot I_{\mathrm{r}}\ , \tag{6}$$

Equation (6) is valid for single harmonics. However, BDEW considers a measurement band of 200 Hz for frequencies above 2 kHz (3), which may include multiple harmonics. Therefore, for the purpose of a more meaningful comparison, the typical sidebands at multiples of f_{s} of switched converter systems (see **Fig. 6(a)**) will be accounted for by reducing $I^{*}_{\nu,\mu}\big|_{10\,\mathrm{kV}}$ in (6) by a factor $\sqrt{2}$ (3 dB).

3.1.3 Equivalent CISPR 11 Limits

The CISPR 11 equivalent admissible current harmonics I_{CISPR} can be computed by means of the LISN impedance Z_{LISN},

$$I_{\mathrm{CISPR}} = \frac{10^{\frac{U_{\mathrm{CISPR}}\,[\mathrm{dB}(\mu\mathrm{V})]}{20}} \cdot 10^{-6}\,\mathrm{V}}{Z_{\mathrm{LISN}}}. \tag{7}$$

Again, (7) is only meaningful in case of a single harmonic within the corresponding CISPR measurement band of 9 kHz. In case of multiple harmonics, it is not sufficient to guarantee (7) for all individual harmonics as the QP and AVG detectors will indicate higher emission levels [9]. Hence, U_{CISPR} in (7) will be reduced by 15 dB(µV), which is the worst case difference between the individual harmonics and corresponding AVG emission levels observed in simulations of various 2- and 3-level voltage source inverter (VSI) topologies with sinusoidal PWM and $f_{\mathrm{s}} > 1$ kHz. Moreover, only AVG limits will be considered as they are generally more stringent than QP limits. This is due to the similar sensitivity of the QP and AVG detector type for switching frequencies in the kilo-Hertz range ([14], **Fig. 6(c)**)and the lower AVG emission limits (**Tab. 4**). Finally, in contrast to (4) and (6), (7) does not depend on *SCR* but on S_{r} and the grounding conditions of the LV grid. Therefore, a converter with S_{r} =10 kW in a grounded LV grid as well a converter with S_{r} =50 kW in both grounded and isolated IT LV grids have been considered.

3.2 Results

Fig. 4 shows the calculated admissible current harmonics for the considered converter module as shown in **Fig. 3** in percent of I_{r}. Furthermore, reduced BDEW and CISPR limits are depicted as discussed in the last section in order to allow for a more meaningful comparison between limits based on different measurement frequency bands. It can be seen that for frequencies below 150 kHz, the BDEW standard defines more stringent limits than the IEEE standards. This holds true for *SCR*s up to approximately 40, where IEEE 1547 becomes the most stringent standard due to the increasing limits of BDEW and IEEE 519 for growing *SCR*s. For frequencies above 150 kHz, CISPR 11 is clearly more stringent than IEEE, provided that S_{r} is not too low.

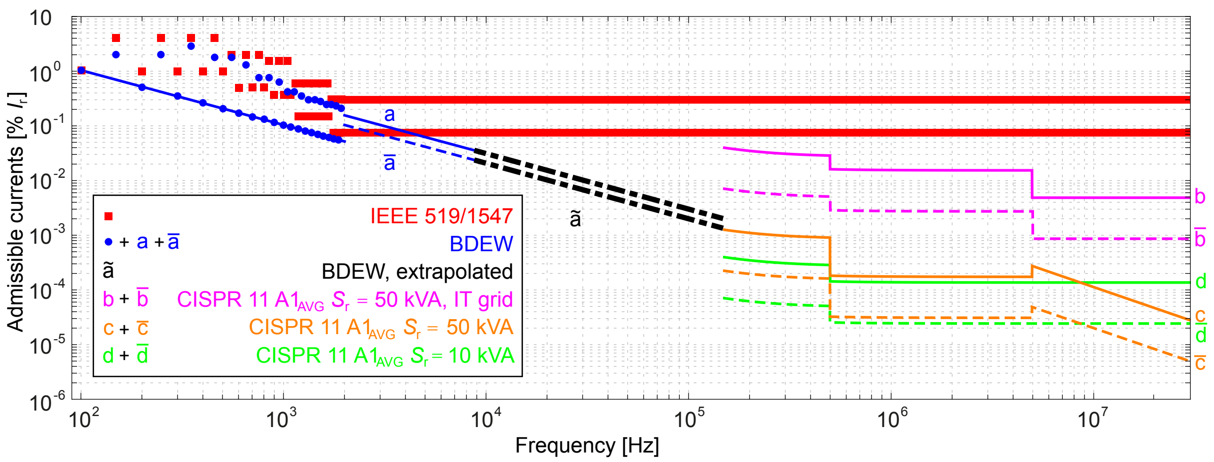

Fig. 4: Comparison of the investigated standards of **Section 2** for *SCR* = 20, $S_{\mathrm{r}} = \{10, 50\}$ kW, based on the setup as shown in **Fig. 3** and (4), (6), (7). Squares and circles correspond to limits for discrete frequencies, the lower IEEE 519/1547 and BDEW limits to even order harmonics. The measurement bands of 200 Hz for BDEW (above 2 kHz) and 9 kHz for CISPR 11 have been accounted for by lowering $I^{*}_{\mu,\nu}\big|_{10\,\mathrm{kV}}$ in (6) by 3 dB (curve $\bar{\mathrm{a}}$) and U_{CISPR} in (7) by 15 dB(µV) (curves $\bar{\mathrm{b}}$, $\bar{\mathrm{c}}$, $\bar{\mathrm{d}}$), respectively. Curve $\tilde{\mathrm{a}}$ represents the extrapolated BDEW limits proposed in **Section 3.3**, which close the currently existing gap of applicable limits from 9 kHz to 150 kHz.

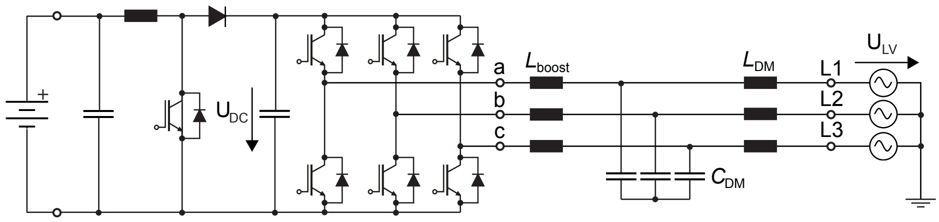

Fig. 5: Fuel cell system with boost converter, 2-level VSI and LCL output filter in a LV grid with grounded MV transformer secondary star point as shown in **Fig. 3**, SCR = 20, S_r = 50 kVA, U_{DC} = 650 V, f_s = 8 kHz, U_{LV} = 400 V.

3.3 Proposed Limits for the Frequency Range 9-150 kHz

To the authors knowledge, there are no other existing standards than IEEE 519 and IEEE 1547 that comprise limits for the frequency range 9-150 kHz. However, the IEEE current harmonics limits are mainly intended for line-commutated and self-commutated thyristor-based converter topologies. As such converters typically generate only LF harmonics at integer multiples of the fundamental frequency, IEEE 519/1547 do not define limits for non-integer harmonics and, moreover, the limits stop decreasing for harmonics with orders $\nu \geq 35$ (**Tab. 3**). On the one hand, this results in a large vertical gap between the admissible currents when compared to CISPR 11 (**Fig. 4**). On the other hand, a further decrease of the admissible currents would be necessary to limit the individual voltage harmonics to a constant value due to ωL_{SC} (see **Section 2.1**). For these reasons, the IEEE limits are not well suited for modern switched converter modules with significant high-frequency input harmonics, possibly located at non-integer harmonics. Due to the increasing penetration of systems comprising such modules, more stringent standards for the frequency range 9-150 kHz must be, however, expected in the future. Consequently, it seems meaningful to apply alternative, more stringent limits than IEEE 519/1547 in the meantime. Based on the existing standards, it is proposed to extrapolate the BDEW limits intended for the frequency range 2-9 kHz up to 150 kHz. As can be seen in **Fig. 4**, this is a simple yet effective approach, which closes the gap between 9 kHz and 150 kHz vertically and horizontally.

4 Example

In this section, the standards investigated in this paper are applied to a practical example. The same setup as shown in **Fig. 3** is considered. The converter module (DUT) with S_r = 50 kVA comprises fuel cell stack with DC/DC boost converter to stabilize the DC-link voltage U_{DC} = 650 V, a 2-level VSI to convert the DC to AC power and an LCL output filter (**Fig. 5**). The VSI operates at a switching frequency f_s = 8 kHz and employs sinusoidal PWM. The impact of BDEW and CISPR 11 to the filter design is now demonstrated. Only differential mode (DM) disturbances are examined and ideal components are assumed.

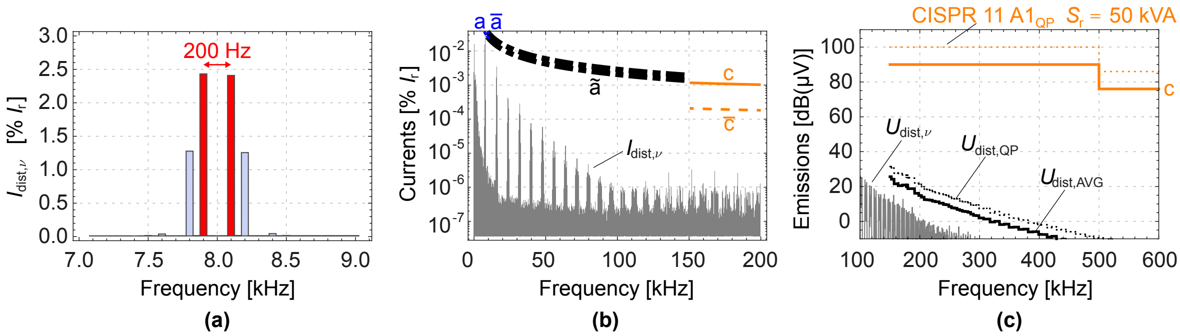

Fig. 6: Disturbance harmonics $I_{dist,\nu}$ without the filter components L_{DM} and C_{DM} **(a)**. $I_{dist,\nu}$ after adding L_{DM} and C_{DM} **(b)**. AVG and QP emission levels $U_{dist,\,AVG}$, $U_{dist,\,QP}$ compared to the applicable limits **(c)**. The labeling of the limits is taken from **Fig. 3**.

In a first, step, the boost inductor is chosen to be L_{boost} = 0.6 mH in order to guarantee a maximum current ripple of approximately ±10 % of I_r. Neglecting L_{DM} and C_{DM}, the output current harmonics $I_{dist,\nu}$, which are dominant over $I_{dist,\mu}$, can be obtained by means of simulations. **Fig. 6(a)** shows the harmonics around f_s, which are the most critical in terms of damping. Applying BDEW (3) gives $I_{dist,\nu,\mu} \approx 3.24\,\%$. Comparison with the admissible magnitude of emission in **Fig. 4** yields an additional required filter attenuation of $a \approx 0.012 = -38\,\mathrm{dB}$ at f_s. In order to enable a clean voltage measurement with low ripples of less than ±1 % of U_{LV}, C_{DM} is chosen to be C_{DM} =60 µF. Hence, the required inductance is

$$L_{DM} = \frac{a+1}{a\left((2\pi f_s)^2 C_{DM}\right)} \approx 0.53\,\mathrm{mH}\,. \tag{8}$$

In **Fig. 6(b)**, the effectiveness of the designed DM filter can be seen. Besides compliance with BDEW, **Fig. 6(b)** also implies compliance with CISPR 11 as the harmonics at frequencies above 150 kHz are largely attenuated. This is confirmed by **Fig. 6(c)** for the considered DM disturbances. Note, however, that for CM disturbances, a more detailed filter design is required, where CISPR 11 becomes relevant. Finally, **Fig. 6(c)** also confirms that the differences in magnitude between the AVG and QP emission levels are only small (see **Section 3.1.3**).

5 Conclusion

In this paper, different MV grid harmonics and conducted EMI standards were investigated. Based on these standards, limits applying to LV converter modules in LV converter systems connected to the MV distribution system were derived. A comparative analysis showed that the most stringent limits for frequencies below 9 kHz and low *SCR*s is BDEW, whereas for frequencies higher than 150 kHz CISPR 11 is the most stringent standard. Furthermore, the investigations found a lack of applicable standards in the frequency range 9-150 kHz. However, standards covering this frequency range can be expected in the near future due to the growing deployment of switched converter systems. Meanwhile, it is thus proposed to apply extrapolated BDEW limits as a guideline for the design of converters and its filters.

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