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Comparison of normative limits for electromagnetic emissions of electric machines and drives to use in different applications

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***Abstract* – Electric machines and power drives of various sizes and ratings are fundamental elements in many applications, such as electric appliances, electric propulsion, medical systems, all with specific limits of electromagnetic emissions, different from those of the original EMC product standards. As compliance should be assessed and guaranteed during design and procurement, this work compares the conducted and radiated emission limits and discusses the variability of results for the respective test setups and measurement methods, including the most relevant source of uncertainty.**

I. INTRODUCTION

Electric machinery ranges from dc to ac motors and generators with a wide range of technologies: asynchronous and synchronous machines, based on induction, salient pole, reluctance, permanent magnet, brushless, etc. Correspondingly, the electromagnetic behaviour is quite varied, especially at low and medium frequency where the intensity and distribution of prevalently magnetic field emissions depend on the machine architecture and its careful design. This part of the spectrum of machine emissions is often used for diagnostic purposes [1] and is less relevant from an electromagnetic compatibility (EMC) point of view.

Electric machinery has its own electromagnetic behaviour and response, from which typical radiated emissions profiles that depend on machine architecture, size, rated values and characteristics. Specific resonances and amplification of some components of emissions have been observed with extensive data for synchronous generators [2]-[4]. It is observed that those reported in [2][3] indicate a significant influence of some machine defects and local failures, fixed after an overall maintenance where specific emissions around 1 MHz disappeared. In [4] the generators were all new and measured during the commissioning phase, excluding any kind of defect and latent failure.

Similarly, dc machines are characterized by peculiar emissions caused by commutation under the brushes, as repeatedly demonstrated experimentally [5]-[8]: the main conducted emissions are due to arcing of motor brushes, modulated by rotational speed (with a spectrum frequency that depend on the number of brushes, their extension and the mechanical speed), although experimental evidence for radiated emissions from large motors lacks of evident resonance peaks and dependency on input current [8].

Different and more complex is the behaviour of a power drive when the motor is excited by the conducted emissions of the driving converter, including resonance effects of the connecting cable [9]. To the aim of radiated emissions and disturbance propagated to external elements the most important is the common-mode component, that has a higher radiation efficiency at long distance, from which the use of shielded cables, common mode ferrites, image planes in particular in the smaller machines [10], as control measures. However, in high-density applications with short coupling distances also differential-mode components become relevant [11][12] and they are usually less easier to filter, due e.g. to the large phase currents of modern high-performance drives.

The first degree of demonstration of compliance of emissions (and most often the only one) consists of the execution of tests in line with the applicable product standards to show that the so assessed emissions are below the stipulated limits. The product standards are the EN 60034-1 [13]-[15] for electrical machinery (sec. 13 of the standard regards EMC) and EN 61800-3 [16][17] for power drives (so covering the wide range of equipment “power drive”, “variable speed drive”, “variable frequency drive”, “electronically controlled motor”, etc.). Since the first issues in the ‘90s when the problem of EMC was concretized and a first set of basic EMC standards was available, these standards have undergone about three revisions in the last twenty years. The limits and measurement methods for emissions are inspired to those of CISPR 11 long ago, with some variations of the limit values for increasing size of the power drive, but without addressing the problem of integration and embedding. If for a large power standalone drive the problem is non-existent (typical installation at industrial sites allows for plenty of space and good cable routing policies), for modern smart products, as well as automotive, avionics and naval applications, the space constraints are significant [18]-[32]. Applications may include additional requirements in terms of type of measurement of emissions and extended frequency range (e.g. E-field measured onboard ships from 150 kHz [33][34], or lower limits [35][36]), and specific limits for co-located apparatus (e.g. radio receivers inside and around vehicles [37][38] and navigation aids onboard ships [34]). Standards for medical applications do not pose critical limits of emissions [39], although for equipment using motors and power regulators reference is to CISPR 14-1 [40] and possibly additional tests (the so called "click emissions"). For smart mobility and automotive sector, and in particular electric vehicles, another concern is the exposure of passengers to electromagnetic fields [41][42], although limits are larger than those for emissions and EMC, and contributing elements are in principle all electrical components including cables, although the rational of common-mode radiation with respect to differential mode still holds to identify the most relevant sources. Similarly possible interference to worn and implantable medical devices (defibrillators, pacemakers, etc) was investigated in the working environment, in connection to heavy work such as welding, electro-erosion and galvanic processes, but also considering proximal motors and power drives [43].

The discussion will focus on the test integration for motors and power drives, starting from their own product standards with the intention of integration in other equipment to which the EMC standards for the final application apply. Besides lower limits and more extended frequency intervals, the other elements affecting the uncertainty of the presumption of conformity are the reduced distance and environmental conditions of modern compact high-density applications, e.g. for automotive.

II. NORMATIVE REQUIREMENTS

The EMC standards previously introduced and that define the framework for acceptance of a motor or power drive product are considered in mode detail. The limit requirements, the degree of agreement between the specific EMC product standards and with the other EMC standards for generic and specific applications, as well as the evolution of the standards through the successive issues of the last twenty years, are discussed in the following. The emission standards for generic and specific applications correspond to the generic light industrial and industrial ones (EN/IEC 61000-6-2 and -4), medical (EN 61010), railway (EN 50121), ship and offshore (EN/IEC 60945, EN 60533) and automotive (CISPR 12, Reg. UNECE 10, CISPR 25) applications.

A. EN/IEC 60034-1

EN 60034-1, sec. 13, focuses on the EMC of electrical machinery, for which in the absence of electronic circuits the immunity is straightforwardly assured, whereas for emissions the limits of CISPR 11 Class B and Class A are assigned to machines without and with brushes, respectively. The limits for radiated emissions are the same for all machines, corresponding to the "usual" 30-37 dBμV/m profile for 30-230-1000 MHz; conducted emissions must comply with 66-56-60 dBμV (Class B) or the 79-73 dBμV (Class A) profiles, defined over 0.15-30 MHz. In the 2004 version there are several inaccuracies in the notes of sec. 13.5.2: the standard prescribes a test at no load stating that machine emissions do not depend on load, not in line with what observed [4][8], both for DC machines (with brushes) and for other types. The DC machine is said not to have conducted emissions because it is not connected directly to the ac supply, that is somewhat misleading looking at the evidence provided in [5][6]: it is acknowledged that such emissions are not injected directly into the ac supply distribution, but may cause as well crosstalk to other cables within the cableway or cable harness.

The EN 60034-1 indicates that no tests are needed for cage induction machines. Curiously the EN 60034-1 standards do not specify limits or tests for synchronous generators although several tests indicate a resonant behaviour and amplification of radiated emissions [4][44], together with a specific excitation coming from the rotating converter connected to the field winding.

Prescriptions have not changed between versions (2004, 2010 and 2020).

B. EN/IEC 61800-3

The IEC 61800-3 is the EMC product standard for Power Drive Systems and reads "The requirements were selected so as to ensure EMC for PDSs at residential, commercial and industrial locations, with *exception of traction applications and electric vehicles*" (applications with compact installation and minimum separation). Emissions for railways and guideway applications are characterized by specific limits and measurement methods [45]: besides fast peak-detected scans in frequency domain, time domain characterization is often advisable for transient emissions, in particular for disturbance to telecom systems [46].

The possible use for medical applications is also not mentioned explicitly. When the drive is part of larger equipment, the EN/IEC 61800-3 gives way to the final equipment product standard with possible non-compliance and inadequacy of emission levels.

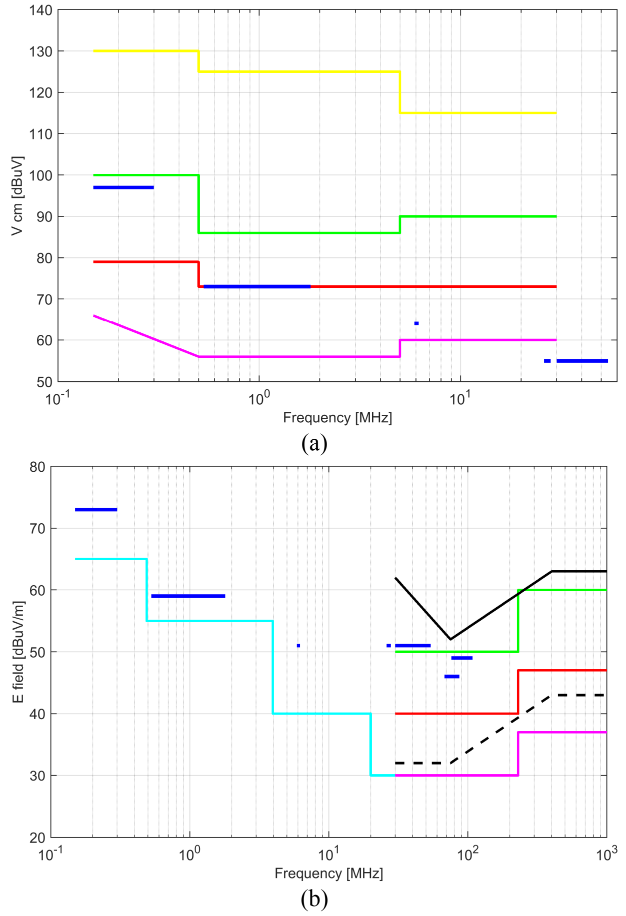
Limits of emissions for PDS are stipulated for four categories: the first two categories (C1 and C2) correspond to the limits of emission for the electric machinery alone (EN/IEC 60034-1), with the exception of the limit for radiated emissions increased by 10 dB (40-47 dBμV/m) with respect to the 30-37 dBμV/m of C1 (see Table 14 and 15 of EN/IEC 61800-3): it is evident that in those 10 dB there is no margin for the emissions of the converter, although emissions from the motor alone are expected to be much lower than limit. A more complex scenario characterizes PDS of cat. C3, whose limits for conducted emissions are shown in Table 17 of the standard: distinction is made for the nominal current below or above 100 A, neglecting the voltage that has a significant impact anyway; the limit for radiated emissions is increased by another 10 dB with respect to cat. C2 (50-60 dBμV/m), but a note says that these limits will be reconsidered in accordance with the results of ongoing activity within CISPR.

The limits are summarized and compared in Figure 1.

C. Emission standards for generic and specific applications

The most likely standards for generic and specific applications (light industrial and industrial, medical, railway, ship and offshore applications) are briefly reviewed, in order to frame the emission requirements for products, possibly including motors and power drives.

The EN 60601-1-2, sec. 7.1.7, refers specifically to CISPR 14-1 for equipment whose main function is performed by motors or regulating devices (such as dental drills, surgical tools, operation tables). The CISPR 14-1 has the additional test of the intermittent emissions (clicks) that is seldom carried out on industrial products.



(a)

(b)

Fig. 1. Limits of emissions (Quasi Peak): (a) conducted, (b) radiated (10 m). Color coding: IEC 60034-1/B & IEC 61800-3/C1 (magenta), IEC 60034-1/B & IEC 61800-3/C2 (red), IEC 61800-3/C3 (≤100A green, >100A yellow), IEC 61800-3 equiv. magn. field (cyan), CISPR25 (blue), UNECE10-esa (black solid), UNECE10-veh (black dotted).

As shown in Figure 1 automotive applications (Reg. UNECE 010) have a complex normative with specific measurements and in some cases quite low limits; in addition, measurement may occur at 3 m distance for which an increase due to reactive field region may be relevant at the lower end near 30 MHz.

Onboard ships there are specific regulations for disturbance to radio and navigation systems (IEC 60945, not included in Figure 1), but also two basic standards are applied common to the automotive sector (absorbed by the Reg. UNECE010): CISPR 12 and CISPR 25 for protection of off-board and on-board radio receivers. It is noteworthy that conducted emissions limits as per CISPR 25 extend significantly and decrease with frequency, partially addressed by cat. C1 and C2 limits, although additional control measures would be required.

III. UNCERTAINTY AND SYSTEMATIC ERRORS

Any statement of compliance to limits and assessment of a quantity brings along the concept of uncertainty. In the present case the measurement of conducted and radiated emissions is disciplined by the set of CISPR 16 standards, and in particular CISPR 16-4-1. However, the focus of CISPR standards is on EMC measurements carried out on equipment of small-medium dimensions that for radiated emissions fit one of the advised facilities, namely open area test site (OATS), semi-anechoic chamber (SAC), fully anechoic chamber (FAC), TEM and GTEM cells. In addition the standards do not account for ancillary equipment with a potentially significant emission contribution (such as lubricating and cooling system, auxiliary converters and machinery to drive or load the machine under test). These factors were extensively discussed in [44], addressing the problem by means of experimental results and analyzing repeatability and Type A uncertainty.

Smaller equipment (that may be a motor or a complete drive) can fit standardized test facilities and may be tested more easily with a better documented uncertainty. However, one more factor comes into play: the purpose of EMC standards is to test the equipment with the minimum ancillary equipment for operation in an environment and with a test setup that maximize reproducibility. More and more often modern motors and drives are used embedded in OEM (Other Equipment Manufacturer) products and in compact applications featuring high power density, such as automotive (and in particular electric vehicles), avionics, medical and laboratory (in particular next to sensors and diagnostic instruments) or within electrical appliances (such as ventilation and conditioning, for which in [24] we see a good exemplification of typical issues of compliance).

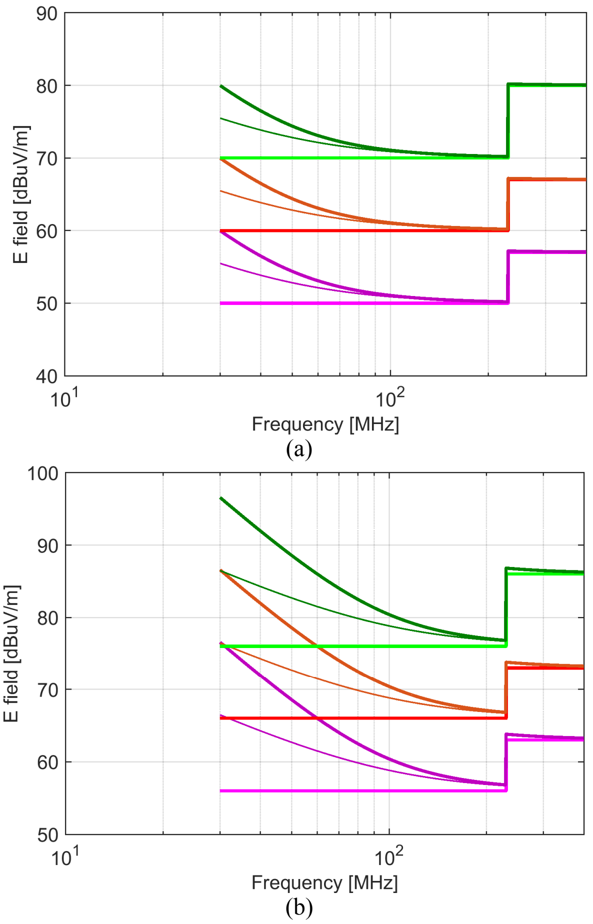
The electromagnetic environment is thus quite different from a nearly open area with far field conditions and absence of scattering and reflections. In addition, the distance at which the possible victims are located is very short, implying that the electromagnetic field components are in the reactive region up to quite a high frequency. The compactness of the setup that reproduces the final application impacts directly on the suitable antennas to adopt that are different from those considered by CISPR and generally accepted for standardized tests: antennas of very small dimensions have a low sensitivity for which the background noise is very close not to say above the limits without using pre-amplification. Second, the reactive behavior of the measured emissions, with a dependency of the square to cubic power of distance, increases the uncertainty due to errors of positioning and measurement of distance, and influences also the expected level of emissions onto nearby victims in the final installation, that is analyzed in the next section.

Among the environmental conditions of the installation temperature and vibration are particularly important for their influence on emissions, taking into account the widespread use of motors and power drives in automotive, avionic, naval and offshore applications, all characterized by a wide range of the two environmental parameters. Environmental factors represent to some extent a source of systematic error, as for the offset with respect to those applied during EMC tests for certification. The variability around the typical operating points is an additional source of uncertainty.

In [48] the influence of vibration on conducted emissions of a DC motor was measured and compared against the limits of conducted emissions for Class 1 of CISPR 25: besides a violation of limits by about 10 dB caused by commutation arcing in normal conditions, the tests carried out when vibration is applied (simulating a realistic condition of use) show an increase of conducted emissions by about another 5 dB on average.

IV. EMISSIONS PREDICTION AND EXPERIMENTAL RESULTS

As anticipated in Section III, the reactive behaviour of the radiated emissions implies that the expected field intensity is much larger, no longer linear with distance (far field assumption), but featuring terms with the square and cubic power of distance. In Fig. 2 the maximum allowed field intensity (emission limits at the standardized measurement distance) is extrapolated to shorter distances *d* characteristic of modern applications. The extrapolation is achieved with the following assumption: the radiating element is a small part of the overall power drive and far-field formulas for dipole antennas are used ($1/\beta=\lambda/2\pi$), rather than those of large antennas. Extrapolation is carried out including second-order terms ($1/(\beta d)^2$) and third-order terms ($1/(\beta d)^3$); terms are rms composed assuming arbitrary time-phase relationship.



(a)

(b)

Fig. 2. Extrapolation of maximum emissions to (a) 1 m and (b) 0.5 m distance; IEC 61800-3 C1 (magenta), C2 (red), C3 (green); darker curves indicate inclusion of second order (thin) and third order (thick) terms.

At distances of 1 m the extrapolated field intensity is significantly larger than the values obtained with a far-field assumption and at the limit of the separation of category of emissions (10 dB). A distance of 0.5 m is evidently a significant issue because all components in the most relevant frequency interval up to 100 MHz are well beyond control. It is underlined also that such components have lower wave impedance than in far field, and the effectiveness of conductive shields is reduced.

V. CONCLUSIONS

This work has introduced and reviewed the normative references for electromagnetic emissions from electric machinery and power drives, considering the problem of embedding such equipment in other applications, with the obligation of applying EMC standards and limits of emissions for the final application. Section II have extensively considered limits of conducted and radiated emissions, showing in particular one final application with particularly restrictive limits: automotive. The power drive needs to comply with the most restrictive limits of its product standard to be usable.

Finally, use of equipment in compact installations may increase problems of internal EMI, as victim circuits are all at very short distance, possibly sharing cable harness and power supply bus. For radiated emissions most of the frequency range is characterized by a reactive region behaviour, that was analyzed in Figure 2. It is underlined that the used extrapolation assumes a point source and that when the distance becomes comparable to the source size larger variability may be expected, although lower on average than with point source assumption.

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