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A magnetic field probe for hostile environments

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Abstract: The measurement of the magnetic field for the evaluation of human exposure is considered, addressing the requisites and specifications of a robust and reliable portable instrument, that outperforms existing products in some aspects related to on-site use, reliability and ruggedness. A rugged open instrument is the response to the exigency of deployment and use in hazardous environments with no risks for the assigned task and operators, as well as best exploitation of performance, interfacing it to a dedicated or a general purpose acquisition system.

Keywords: Electronic circuit design, Guideway Transportation Systems, Magnetic field, Portable instrumentation

I. Introduction

The last two decades have seen a thorough discussion on the subject of human exposure to low frequency magnetic fields and the issue of several standards and regulations, that address short term “established effects”, where a substantial agreement is reached. ICNIRP (International Committee on Non-Ionizing Radiation Protection) guidelines [1][2] date back to 1998 and 2003 respectively, with a new issue in 2010 [3], and have been used as the reference publication for limits by many regulations and standards: the EU Recommendation 519/99 [4] and then the EU Directive 2004/104 [5], that legally extends to workers. When dealing with complex systems and in configurations characterized by the intensity of the sources or by the short distance from the exposed subjects, the assessment of the human exposure needs a valid technical basis to address the operating conditions to apply, the measurement positions and their number, the interpretation of results.
Modern power converters and complex electrical systems are characterized by relevant harmonic distortion and may have more than one fundamental frequency. So, the correct weighting of each spectrum component against its limit is necessary and the overall effect on the human body is evaluated by taking the weighted sum of the components over the prescribed frequency interval. This is the so called “ICNIRP index” that weights the intensity of the components regardless of their phase relationship [1]. In some cases, such as with highly distorted waveforms or with pulsed sources, the phase relationship may have a relevant influence, so that the evaluation of the ICNIRP index is to be performed directly in time domain, by means of a suitable filter transfer function [2].
Another characteristic that must be duly considered is that modern electric systems feature often large and fast dynamics, so that the operating conditions to adopt when testing the system must be chosen adequately and correctly. On one side we must remember that the interaction with the human body shall be repetitive over a considerable time interval to be relevant, while transient conditions, if infrequent, can be neglected. For a complex system, such as an electric vehicle of a modern transportation system, the sources are many and some of them may experiencing a transient while others are in steady state conditions; this means that a certain degree of non-stationarity is always present in the recorded signals and that suitable processing methods shall be adopted [6].
Thus, the measurement instrumentation has evolved from broadband meters giving only an indication of the overall rms value within a given frequency interval, to digital sampling instruments, more flexible and able to record complete waveforms for post-processing. An example of the former characteristic, still required by applicable standards [7]-[9], is the evaluation of the magnetic field around Video-Terminals (VDT), that is condensed in two rms values over two frequency intervals spanning from 5 Hz to 2 kHz and from 2 kHz to 400 kHz respectively. Magnetic field instruments featuring digital sampling are the correct approach to the possible need of post-processing, not only to implement the weighting versus frequency and the calculation of the ICNIRP index, but also to test the stationarity and other spectral properties of the recorded signals [6][10] and to adapt with the least cost to modifications of the applicable standards in terms of limits and required processing.
The solution adopted by the high end instruments is to allow the user to externally sample the magnetic field components along the three orthogonal axes of the sensing probe [11]-[13].

II. Required performances

The requisites and the required characteristics for the instrument depend somehow on the application or product standard, not only on the ICNIRP limits alone. In this work the attention is focused on the assessment of the human exposure to magnetic field for electrical appliances [15], VDT [7]-[9] and railway applications [14]. The former two represent a standard application for the instrument and their requisites are considered the starting point; the latter, on the contrary, is interesting for the demanding environment and application and for the measurement procedure, rather than the limits.

Measurement performances are reviewed first, and then followed by electrical and mechanical performances.

The sensing probe shall be triaxial, with three orthogonal elementary antennas measuring the ac magnetic field components along the said axes. The required isotropy is normally around 1%.

The frequency interval starts from 5 Hz for the three applications; then the upper frequency limit is located at 20 kHz for railway applications and at 400 kHz, as already said, for VDTs and by extension electrical appliances. The EN 50500 requires also the measurement of the dc component, specifying a different type of sensor from the one indicated for the ac field.

The dynamic range is set primarily by the variation of the ICNIRP limits over the considered frequency interval: the limit at 1 Hz for occupational exposure is 200 mT and the minimum limit starting from 810 Hz for residential exposure is 6.25 μT. Commercial instruments rarely extend to as high values as 200 mT and normally saturate at some tens of mT; this is justified by observing that such a field intensity is rarely encountered, except for magnetic resonance magnets at dc, galvanic treatment systems, and very large power industrial systems (such as dc arc furnaces).

In order to account for all the spectrum components over the specified frequency range and accurately calculate the ICNIRP index, a minim sensitivity a hundred times higher is suggested (1% of resolution at the lowest limit value), thus going to a minimum detectable field of 62.5 nT, irrespective of the resolution bandwidth used for the measurement and post-processing. The exigency of reducing even further the minimum detectable field is related to the possible use of the instrument for scientific experiments or laboratory investigations, going down to about one or few nT.

Linearity is generally specified improperly, requiring that it is "better than ±X%", such as 2 or 5%, over the entire dynamic range. Yet, the dynamic range moves along with the ICNIRP limits, e.g. between about 1 μT and 200 mT for the frequency interval that covers power frequency down to 1 Hz, and between about 60 nT and 200 μT for the remaining frequency interval covering harmonics and higher frequency components. In both cases the dynamic ranges we are talking about are in the order of four or five orders of magnitude [11].

The uncertainty is often poorly specified, indicating a value without defining the coverage factor and clarifying which phenomena are to be considered as influencing factors (e.g. if the influence of the operating temperature is to be included in the declared uncertainty).

Additionally, a set of functional requirements may be specified taking into account the environment in which the instrument is required to operate. The use in industrial environments, and in particular in the railway environment, requires a rugged construction that ensures electrical insulation, mechanical robustness and water tightness. These characteristics are necessary to operate in hostile environments and are normally required for electrical equipment in use in the said applications. By extension, users expect similar performances from instrumentation, even if not permanently installed.

III. Instrument characteristics

The design of the measurement instrument is based on a portable acquisition system (PAS) that is used to record the signals fed by the magnetic field probe. The acquisition system is a 3 channel DSP-equipped digital acquisition board, Ethernet connected to an external computer and supplied also by means of Power over Ethernet (PoE). This system is described more extensively in [20]. The Ethernet 100 Mbps rate represents the physical limitation for the continuous data stream of time domain samples: raw 16-bit data from the three axes without compression impose a sampling rate limitation of 2 MSa/s theoretically, reduced to somewhat more than 1 MSa/s taking into account practical limitations (lost packets, latency, packet header overhead, etc.). Data compression is possible with the on-board DSP that can process data in real time, achieving a compression ratio of about 2.5 to 1 (verified experimentally with different magnetic field signal correlation).

The magnetic field probe (MFP) is realized in a sealed housing, connected to the PAS through a proprietary 44-pin connector: analog channels signals (B_{x+}/B_{x-}, B_{y+}/B_{y-}, B_{z+}/B_{z-}), related shields (B_{xs}, B_{ys}, B_{zs}), settings (gain and ac coupling) and power supply run through the same cable. Different probe types (called also "measuring heads") are available, differentiated by the mounted magnetic field sensor and the related performance and characteristics; all the heads are interchangeable, sharing the same 26-pin connector and are recognized by the

PAS by reading the on-board EPROM through the I2C bus. This EPROM not only stores the unique ID of the measuring head, but also calibration data. The sensors may be housed inside the probe enclosure (resulting in a more compact and robust probe) or protrude externally, in case their physical dimensions do not fit the enclosure size (as for the coils) or a miniaturized version of the sensing head is needed (as for measuring the magnetic field in small air-gaps and low clearance). This option is suitable for the measurement of magnetic field in small air gaps, such as around small motors and transformers, magnetic axle counters, etc. The minimum thickness of the miniaturized head is about 6 mm. All these versions are compatible with the same PAS through the 44-pin connector. Supporting both dc and ac measurements there are a dc – 30 kHz Hall effect sensor for intense field levels (up to 50 mT) and a Giant Magneto Resistive (GMR) sensor for weaker field levels (up to 500 µT), but able to operate over a much wider frequency interval (up to some MHz). For compliance with the requirements of some standards [14][15], an ac coil option is also available with 100 cm^2 cross sectional area for each of the three orthogonal coils; a more compact smaller coil is also available with a frequency range extending above several MHz. The ac coil option requires that the sensing element is always mounted outside the probe enclosure because of its physical dimensions. In all cases the entire probe (including its enclosure and the external elements) is sealed to ensure IP 69, to work even immersed in liquids (the connectors are sealed and can withstand liquids and spray); the enclosure is of polyester/PVC to resist to aggressive chemicals and small scratches; shock absorbing material is used to fill the cavity of the external sensing element and the probe enclosure, to resist to vibrations and shocks. To this aim also the mechanical construction has some distinct characteristics, used already for hard drives and computer boards inside laptops: bending moments of the largest and heaviest components have all been evaluated during the design phase, reducing cantilever lengths and using multi-point soldering whenever possible; devices are selected in the smallest package formats compatible with the mounting and soldering procedures; the printed circuit board is fixed to the enclosure by means of dampening stiffeners, with additional dampening offered by shock absorbing foam, that is used also to isolate the internal circuit from moisture and condensation.

A. *Measurement performance*

The PAS exists in two versions, the 200 (200 kS/s sampling rate on each channel, a spurious free dynamic range better than 80 dB, lower power consumption and lower cost) and the 1000 (a five times higher sampling rate, a better spurious free dynamic range by about 10 dB, a nearly doubled power consumption and a 50% higher cost). Both versions are plug-in compatible and interface seamlessly with the software.

As said above, the MFP is at present built around four sensing elements, a Hall effect, a GMR, a small coil and a large coil, the latter compliant with the requirement of 100 cm^2 cross sectional area and derived from the one presented in [7][11][14][15].

The input instrumentation amplifiers [16] on each channel input on the PAS have little influence on the signal-to-noise ratio, because the sensors on the MFP are interfaced to them through a low noise fixed gain instrumentation amplifier built next to each sensor on the MFP itself: the spectral noise density value is 10±2 nV/√Hz from 0.1 Hz to 500 kHz; the current noise spectral density is lower than 10 fA/√Hz to keep this term under control when combined with the input protection and scaling resistive network. An overall equivalent voltage noise spectral density of about 15 nV/√Hz has been estimated over the entire frequency range. For high frequency versions of the MFP (up to about 5 MHz) the used operational amplifiers have similar performances, yet with a five-ten times larger voltage noise spectral density and a correspondingly lower sensitivity up to 20 Hz.

For the external probe heads the noise caused by the coils is negligible (only the resistive part of the winding is responsible for a negligible fraction of the noise voltage); the coil gain is 0.8 µV/µT/Hz for the large one and 0.13 µV/µT/Hz for the small one, that compared to the limiting input noise voltage (for the highest gain) gives for the large coil a sensitivity of 20 nT @ 1 Hz and about 20 pT @ 1000 Hz. For the small coil the sensitivity is proportionally worst by a factor of 0.8/0.13.

The Hall and GMR effect sensors have a flat gain versus frequency, so there is no increase of the signal-to-noise ratio for increasing frequency; the characteristics have been evaluated as outlined in [17]. The Hall-effect sensor [18] has a gain of 31 µV/µT. The manufacturer does not declare any noise value; preliminary measurements give about 2.2 µV/√Hz at 1 Hz and 20-40 nT/√Hz above a hundred Hz, so prevalent with respect to the amplifier terms. This translates into sensitivity of 70 nT @ 1 Hz and about 2 nT at and above a hundred Hz.

The GMR-effect sensor [19] has a gain of 25 µV/µT and an internal noise of 50 nV/√Hz that, added to that of the instrumentation amplifier, gives a 2.1 nT sensitivity over the entire frequency range.

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B. Electrical and mechanical performance

The PAS is dedicated to the direct connection of the MFP and its analog inputs are always used in a configuration that is galvanically isolated from the environment, connected to the three magnetic field axes. These inputs are already protected for residual overvoltages and radiofrequency disturbance by means of an input filter and clamping diodes and do not need any further protection or galvanic isolation. In reality the PAS is derived from a 4 channel unit that is galvanically isolated and suitable for harsh environments [20]. The MFP is conceived for being placed in potentially electrically hazardous areas (such as beneath high voltage lines, inside or close to converters and drives, etc.) and its plastic enclosure ensures the required electrical insulation against direct contact. The insulating sheath of the output cable that goes out of the MFB directly is sized accordingly and extends up to the PAS interface: the cable interface at the MFB is sealed and has no accessible metallic parts; the only connector is located at the PAS, placed in a safe location, so with relaxed requisites with respect to electrical risk, even if a protected connector may be adopted.

IV. Preliminary tests on the prototypes

The tests performed on the first series of engineered prototypes have consisted in functional, metrological and environmental tests. It is underlined that these tests follow in any case the preliminary calibration done while assembling the units and that consists on a general check of the behaviour and the trimming of on-board potentiometers to balance the three *x*, *y* and *z* channels.

A. Functional tests

Functional tests have been executed separately on the MFP and the PAS. For the MFP the absorbed current on the power supply, the noise on the B_x, B_y, B_z signal pairs and the correct output change following a step change in the amplitude of the applied field were considered. For the PAS the connection and the data stream on the Ethernet cable were tested, together with the correct setting of the anti-alias filter and the sampling rate.
Additionally, for the MFP the two commands for dc versions have been checked, that is the dc/ac coupling switch and the degauss signal for the GMR version of the MFP.

B. Metrological tests

Metrological tests have evaluated the linearity, isotropicity and uncertainty by applying a known magnetic field values using a pair of Helmholtz coils [21]; the final verification on the series production will be a combination of certification issued by a recognized calibration centre and a process of monitoring the quality of production by evaluating the repeatability of instrument characteristics (Type A uncertainty).
At the moment a variability of the frequency response amplitude of 1.5% has been observed in the Hall and GMR sensors, while the coils are slightly more constant (less than 1%). Also linearity is within a fraction of % for the Hall and GMR sensors, while it is undisputed for the coils that are inherently linear. The sensitivity has not been tested and its evaluation is based on the estimation done in the previous section.

C. Environmental tests

Environmental tests consist of vibration tests, temperature cycling and water immersion test before repeating the functional tests; temperature influence is also to be evaluated during the metrological tests because of the considerable temperature coefficient of Hall and GMR sensors (about 100-500 ppm/°C the former and 1000-2000 ppm/°C the latter).
To this aim a temperature-stabilized version of the MFP is being designed, that contains a heating element to trim the internal temperature around the sensing element to about 45 °C, so compatible with all most common environmental temperatures. The two Hall and GMR sensing elements are the only devices with a non-negligible temperature coefficient on-board the MFP.

V. Conclusions

This paper presents the main design elements and the results of the functional tests on the first prototype of a high performance instrument for the measurement of magnetic field in demanding and hostile environments, where electrical, mechanical and environmental conditions are quite demanding. The attention is thus focused not only on the metrological characteristics alone, but also on the correct use of the instrument and the available

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sensing heads, based on different physical principles (coil, Hall and GMR). The first pre-series of four MFP devices for each type of sensing head is ready and will undergo extensive characterization and environmental testing and accelerated aging in the next months.

VI. References

[1] "ICNIRP Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)", *Health Physics*, vol. 74, n. 4, pp. 494-522, Apr. 1998.
[2] "ICNIRP Guidance on determining compliance of exposure to pulsed and complex non-sinusoidal waveforms below 100 kHz with ICNIRP guidelines", *Health Physics*, vol. 84, n. 3, pp. 383-387, Mar. 2003.
[3] "ICNIRP Statement — Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz to 100 kHz)", *Health Physics*, vol. 99, n. 6, pp. 818-836, Dec. 2010.
[4] EU Recomm. 519/99, "On the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)", July 12, 1999.
[5] EU Directive 2004/40/CE, April 29, 2004, "On the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)"
[6] D. Bellan et al., "Time domain measurement and Spectral Analysis of Non-Stationary Low Frequency Magnetic Field Emissions on Board Rolling Stock", *IEEE Trans. on Electromagnetic Compatibility*, vol. 46 n. 1, Feb. 2004, pp. 12-23.
[7] IEEE Std. 1140, *IEEE Standard Procedures for the Measurement of Electric and Magnetic Fields from Video Display Terminals (VDTs) from 5 Hz to 400 kHz*, 1994
[8] MPR - I (1987:1)
[9] MPR - II (1990:8)
[10] P. Imbesi and A. Mariscotti, "Design and construction of a measurement system for the evaluation of low frequency magnetic field on-board rolling stock", I2MTC 2012, Graz, Austria, May 13-16, 2012.
[11] A. Mariscotti, "A Magnetic Field Probe with MHz Bandwidth and 7 decades Dynamic Range", *IEEE Trans. on Instrumentation and Measurement*, vol. 58 n. 8, Aug. 2009, pp. 2643-2652.
[12] Narda, ELT 400 manual, undated (ref. NSTS 0107-E0205I-0.0)
[13] Combinova, Magnetic Field Meter 3000 manual, ver. D.
[14] CENELEC Std. EN 50500, *Measurement procedures of magnetic field levels generated by electronic and electrical apparatus in the railway environment with respect to human exposure*, 2008-07.
[15] IEC 61786, *Guide for the measurement and the evaluation of electric and magnetic fields in the frequency range 0 Hz - 10 kHz, with reference to the human exposure*, 1998-08.
[16] Analog Devices, AD 8253 datasheet, Rev. A, 2008.
[17] A. Mariscotti, "Evaluation and Testing of Off-the-shelf Hall Sensors for Compliant Magnetic Field", IMTC 2006, Sorrento, Italy, April 20-23, 2006.
[18] Honeywell, Sensing and control division, SS490 family datasheet, undated.
[19] Honeywell, Three-Axis Magnetic Sensor HMC1043, Rev. G, Aug. 2012.
[20] M. Canepa and A. Mariscotti, "Power Quality Metering Unit with Networking Capability", Proc. of EUROCON 2013, Zagreb, Croatia, July 1-4, 2013.
[21] S. Ciurlo, A. Mariscotti and A. Viacava, "A Helmholtz coil for high frequency high field intensity applications", *Metrology and Measurement Systems*, vol. XVI n. 1, Jan. 2009, pp. 117-125.

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