20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Uncertainty management in the measurements of low frequency magnetic fields

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***Abstract* – The paper deals with low-frequency magnetic field measurements carried out by using a broadband and isotropic instrument. These measurements are characterized by very high uncertainty values, which imply a high risk of wrong decisions when there is the need to establish if a site complies or does not comply with specified emission limits. To reduce this risk, we decided to perform the so called "uncertainty management" that is the discipline of optimizing the cost of a measurement versus the uncertainty target. The task is achieved by using the PUMA method that is an iterative technique originally conceived for geometrical and mechanical measurements. The approach is completely based on the "Guide to the Expression of Uncertainty in Measurement" rules, but provides a more engineering methodology. By using this approach, it is possible to avoid the usage of too expensive instrumentations or, on the contrary, too expensive resources for the uncertainty estimation.**

I. INTRODUCTION

The uncertainty evaluation associated with the electric and magnetic field measurements requires an approach rather different from the approaches used in the traditional metrological areas. The main reason is that in the field measurements, the uncertainty values, that we have to deal with, are very high if compared with the ones usually related to the common electrical measurements.

Particular cases of electric and magnetic field measurements are the ones performed to evaluate the human exposure, when there is the need to establish if the emissions overcame the limits prescribed by laws or standards [1-2]. In these instances, it is necessary to perform an accurate uncertainty evaluation. For this reason, various national and international laws prescribe, beside the emission limits, also the maximum uncertainty values, which the measurements must be performed with.

Besides the legal prescriptions, it is obvious that in any case a reduction of the uncertainty values implies a reduction of the risk to take a wrong decision when there is the need to decide if a site complies or does not comply with the prescribed emission limits [3]. In fact, the reduction of the uncertainty values increases the probability to lie in the Case A or Case D of the figure 1, where an unambiguous decision can be taken.

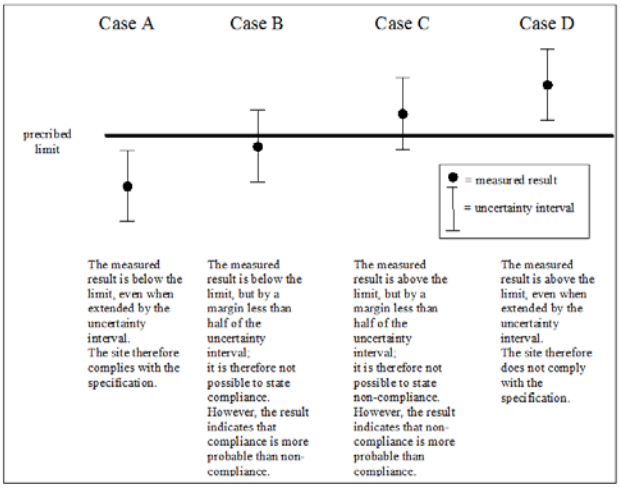

Fig.1. Uncertainty versus prescribed limit

In this paper, we deal with low-frequency magnetic field measurements, with regard to exposure of human beings, carried out by using a broadband and isotropic instrument.

For these measurements, for instance, the Italian laws refers the standard IEC 61786 [4] which prescribes that the measurement must be performed with an expanded uncertainty lower than 10 % with a coverage factor k = 2. However, using the common instrumentation and straightforwardly applying the "Guide to the expression of uncertainty in measurement" (GUM) [5] rules, it is not possible to obtain this uncertainty value.

In the paper we propose an approach which, in particular but very typical cases, allows a reduction of the assessed uncertainty values in the magnetic field measurements.

To achieve the objective, we decided to implement the so called "uncertainty management", which is the discipline of optimizing the uncertainty target and the cost of the measurements. Without a systematic approach

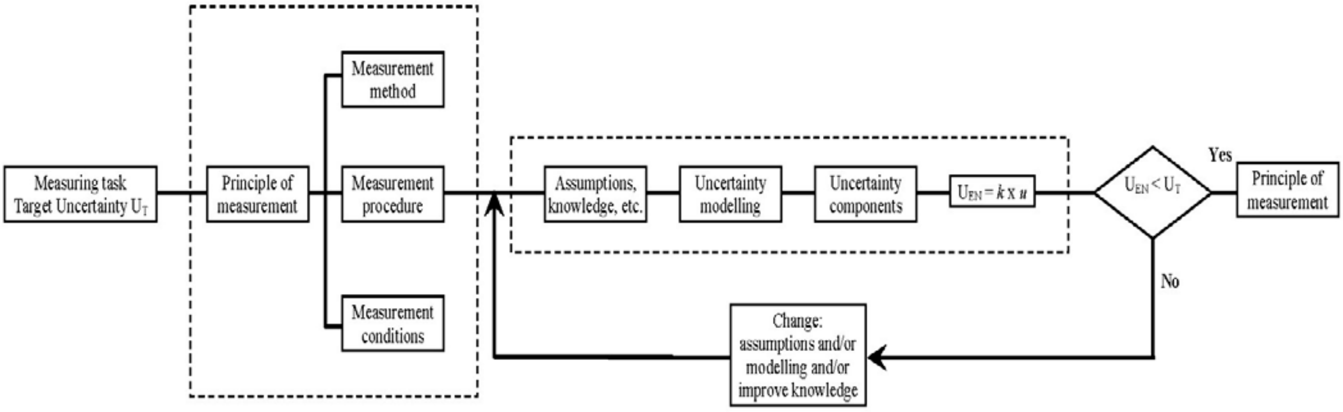

Fig.2. Graphical representation of the PUMA method

to the uncertainty evaluation, the performed measurements could be either not adequate for the target uncertainty or too expensive.

The uncertainty management was implemented by means of the PUMA (Procedure for Uncertainty Management) approach.

This iterative method is completely based on the GUM rules but offers a more engineering methodology. In fact, the basic inspiration is completely different: the GUM prescribes that, in the uncertainty evaluation, it is necessary to avoid overestimations, since an overestimation debases the measurement quality. According to the PUMA approach, on the contrary, when it is necessary to know if an already available instrumentation and an already defined measurement environment are appropriate for a stated target uncertainty, the uncertainty overestimate can be tolerated, especially when an accurate uncertainty estimation involves high expenses and/or long times. By using this approach, it is possible to avoid the usage of too expensive instrumentations or, on the contrary, too expensive resources for the uncertainty estimation.

II. THE PUMA APPROACH

The PUMA approach is defined in the ISO 14253-2 Standard [6], which was developed by the Technical Committee ISO/TC 213. Despite this standard deals with the Geometrical Product Specifications (GPS), and therefore with the geometrical and mechanical measurements, its extension to the other branches of measurements is natural and could result useful [7,8]. The standard is fully dedicated to the uncertainty management performed by using the PUMA approach.

The PUMA method (graphically presented in figure 2) is based on a sequence of uncertainty overestimations, starting from the coarser but quicker ones and carrying on with more accurate but more expensive and more time-consuming techniques. By applying only the first iteration of the method, it is very probable to prove that the uncertainty of the considered measurement process is minor than the target uncertainty and, consequently, that the measurement process is adequate. Just in few practical cases, there is the need of using sophisticated mathematics and statistics.

The uncertainty management is carried out starting from the description of the measurement purpose, the measurement instrumentation, the measurement conditions and from the definition of the uncertainty target value U_T. On this basis, from the first iteration of the PUMA approach, a first estimate U_{E1} of the measurement uncertainty is obtained. If $U_{E1} < U_T$, than the chosen measurement procedure is adequate to the measurement purpose. If $U_{E1} << U_T$, the chosen measurement procedure is obviously still technically adequate, but there is the chance to change the measurement instrumentation and/or conditions to make the measurement less expensive. If $U_{E1} > U_T$, it is necessary to perform another iteration obtaining a more accurate and lower estimate U_{E2} of the uncertainty. By comparing this new value with the uncertainty target, it is possible to verify that the measurement procedure is adequate or that it is necessary to perform another iteration. After having used all the chances to get the more accurate uncertainty estimation, if $U_{EN} > U_T$, than the chosen measurement procedure is actually inadequate to the measurement.

The aim of the paper is the extension of the PUMA method to the low-frequency magnetic field measurements carried out by using a broadband and isotropic instrument, defining various more and more accurate methods for the uncertainty estimation.

III. IDENTIFICATION OF THE ERROR SOURCES

In a generic broadband magnetic field measurements performed by using an isotropic probe, the main error sources, which have to be considered, are: calibration, linearity, anisotropy, frequency flatness, temperature, relative humidity and repeatability [4, 9-11].

In this paper, we refer to a standard magnetic field analyser, with average characteristics and performances among the ones of the magnetic field meters usually used to assess the compliance of a site. In table I, typical values of the uncertainties associated with the aforementioned error sources are reported.

Table I. Uncertainty values

Source	Relative Uncertainty [dB]	Distribution type	Relative Standard Uncertainty [%]
calibration	0,2	uniform	1,34
linearity	0,2	uniform	3,42
anisotropy	1	normal	6,10
frequency flatness	0,5	uniform	1,34
temperature	0,05	uniform	0,33
humidity	0,05	uniform	0,33
repeatability	0,2	normal	1,16

The values of uncertainties associated with linearity, anisotropy, frequency flatness, temperature and humidity were estimated by means of type B evaluation taking into account the specifications of various meters from various manufacturer. The calibration uncertainty value was also estimated by means of type B evaluation taking into account various calibration certificates.

The value of uncertainty associated with the repeatability was assessed by means of type A evaluation performing various measurements of a highly stable magnetic field generated by a square coil (1 m x 1 m). Different series of experiments were performed by using different field meters and varying the field intensity, the field frequency and the probe orientation, considering the presence of operators and ferromagnetic surfaces in the nearness of the probe and taking into account the contemporaneous presence of electric fields.

Starting from the values reported in table I and performing the root-sum-square (RSS) of the relative standard uncertainty, we get an expanded combined uncertainty value (k=2) equal to 14,7 %, that is considerably higher than the 10% value prescribed by the Italian laws. Before considering the usage of more expensive instrumentation, according to the PUMA approach, it is necessary to find a more precise methodology for the uncertainty evaluation.

IV. REDUCTION OF THE ANISOTROPY IMPACT

By analysing the values reported in table I, it is possible to notice that the predominant contribution to the combined uncertainty is given by the anisotropy error. Even not considering the other uncertainty source, the anisotropy would provide an expanded combined uncertainty value (k=2) equal to 12,2 %. Therefore, the first step to perform an incisive implementation of the PUMA approach could be the reduction of this contribution.

In order to reduce the impact of the anisotropy, it could be possible to perform various measurements rotating the probe in different orientations; however, this procedure, besides being quite time consuming, would require a high stability of the measurand; but this condition seldom occurs.

Another way to reduce the contribution of anisotropy is to consider the actual value declared in the calibration certificate, considering that a typical value of anisotropy is 0,2 dB and, therefore, there is a good chance to find a value lower of the worst case (1,0 dB). Actually, during the calibration, the evaluation of the anisotropy is usually performed only for a measurement point (with stated amplitude and frequency), so the obtained value cannot be straightforwardly used in different amplitudes and/or frequencies. However, it is possible to demonstrate that the anisotropy in whatever measurement point cannot exceed a calculable value that is a function of the linearity and frequency flatness uncertainty values.

The IEEE 1309 standard [8] defined the anisotropy (A) as the maximum deviation from the geometric mean of the maximum response (B_{MAX}) and minimum response (B_{min}) when the probe is rotated around the ortho-axis, as shown in the example in figure 3.

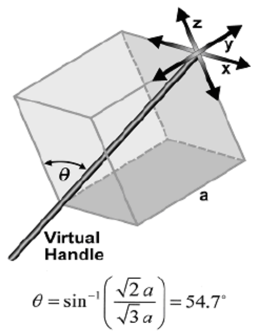

Fig.3. Evaluation of anisotropy

$$A = 20Log\left(\frac{B_{MAX}}{\sqrt{B_{MAX}B_{\min}}}\right) \quad (1)$$

Therefore, at the frequency and at the amplitude where the anisotropy was evaluated:

$$B_{MAX} = B_{\min}10^{\frac{A}{10}} \quad (2)$$

In a different measurement point, because of linearity errors (NL) and/or frequency flatness errors (FF), the B_{MAX}, in the worst case, can become (the variations of

B_{min} are already considered by the overall linearity and errors frequency flatness errors):

$$\overline{B}_{MAX} = B_{MAX} 10^{\frac{NL+FF}{20}} = B_{min} 10^{\left(\frac{A}{10}+\frac{NL+FF}{20}\right)} \qquad (3)$$

if *NL* and *FF* are expressed in decibel.

Then, in a measurement point different from the calibration one, the anisotropy, in the worst case, can reach the value Ā:

$$\overline{A} = 20 Log\left(\frac{\overline{B}_{MAX}}{\sqrt{\overline{B}_{MAX} B_{min}}}\right) = A + \frac{NL+FF}{2} \qquad (4)$$

For instance, if the actual value declared in the calibration certificate is 0,1 dB at a stated amplitude and frequency, in a different measurement point, the anisotropy value to be considered is 0,45 dB (considering the values of linearity and frequency flatness of table II; NL+FF = 0,7 dB).

Using this value of anisotropy, we get an expanded combined uncertainty value (*k*=2) equal to 9,8 %.

V. MAGNETIC FIELD GENERATED BY ELECTRIC POWER SYSTEMS

A very effective reduction of the assessed uncertainty values can be obtained in case of fields generated by electric power systems (50 or 60 Hz). In fact, in this case, if at least one measurement point was calibrated at that frequency, it is obviously possible to neglect the frequency flatness uncertainty. Moreover, this circumstance leads to a further reduction of the anisotropy influence. In fact, the new anisotropy value becomes:

$$\overline{A} = A + \frac{NL}{2} \qquad (5)$$

For instance, if the actual value declared in the calibration certificate is 0,1 dB, the anisotropy value to be considered is 0,2 dB (considering the values of linearity NL = 0,2 dB).

In this case we obtain an expanded combined uncertainty value (*k*=2) equal to 5,1 %.

Often the currents in the electric power system are considerably distorted, therefore, in these cases, the contribution of the frequency flatness uncertainty cannot be ignored. However, it is possible to consider separately the contribution of the fundamental frequency and the harmonic components to the uncertainty.

Let us suppose, for sake of simplicity and without any loss of generality, that the distortion is only caused by a II harmonic component of amplitude x_2; if x_1 is the amplitude of fundamental frequency (50 or 60 Hz), the field is:

$$B = \sqrt{x_1^2 + x_2^2} \qquad (6)$$

applying the uncertainty propagation law of [5] we can evaluate the uncertainty *u(B)*;

$$u(B) = \sqrt{\left(\frac{\partial f}{dx_1}\right)^2 u(x_1)^2 + \left(\frac{\partial f}{dx_2}\right)^2 u(x_2)^2 + 2r(x_1 x_2)\left(\frac{\partial f}{dx_1}\right)\left(\frac{\partial f}{dx_2}\right) u(x_1) u(x_2)} \qquad (7)$$

considering the uncertainty associated with x_1 and x_2 completely correlated (that is considering the worst case) the correlation coefficient $r(x_1 x_2)$ is equal to 1, then:

$$u(B) = \sqrt{\frac{x_1^2}{x_1^2+x_2^2} u(x_1)^2 + \frac{x_2^2}{x_1^2+x_2^2} u(x_2)^2 + \frac{2x_1 x_2}{x_1^2+x_2^2} u(x_1) u(x_2)} \qquad (8)$$

and therefore

$$u(B) = \frac{x_1 u(x_1) + x_2 u(x_2)}{\sqrt{x_1^2 + x_2^2}} \qquad (9)$$

For instance if *THD* = 30% (that is $x_2 = 0{,}3\, x_1$), than:

$$u(B) = \frac{u(x_1) + 0{,}3u(x_2)}{1{,}04} \cong u(x_1) + 0{,}3u(x_2) \qquad (10)$$

$$\dot{u}(B) = \frac{u(B)}{B} \cong \frac{u(x_1)}{B} + \frac{0{,}3u(x_2)}{B} \qquad (11)$$

$$\dot{u}(B) \cong \frac{u(x_1)}{x_1} + \frac{0{,}3u(x_2)}{\frac{x_2}{0{,}3}} \cong \dot{u}(x_1) + 0{,}09\dot{u}(x_2) \qquad (12)$$

For instance, if we consider the above considered cases, $\dot{u}(x_1)$ = 5,1 % and $\dot{u}(x_2)$ = 9,8 %, than $\dot{u}(B)$ = 6,0 %.

In the cases the measurement result lies in the proximity of a calibrated measurement point, it is possible to neglect also the linearity errors and, consequently, the expanded combined uncertainty value (*k*=2) is even lower (equal to 3,9 % in our case). Therefore, if we choose to calibrate the meter at the field intensity equal to a prescribed emission limit, it is possible to further reduce the measurement uncertainty, just in the circumstances when this is more significant.

VI. CONCLUSIONS

In this paper, the problem of the uncertainty estimation of the low-frequency magnetic field measurements carried out by using a broadband and isotropic instrument was considered.

To achieve the objective, we analysed the uncertainty budget compiling a list of the probable sources of error with an estimation of their standard uncertainties.

Given that this kind of measurements entails large values of uncertainties and considering that the uncertainty contributions are not the same for the complete range of measurements, for the uncertainty assessment we proposed three approaches that imply different levels of estimate accuracy, but, at the same time, different amount of required resources. Therefore, these methodologies are perfectly adequate for the implementation of the PUMA method and for a correct management of the uncertainty budget.

Often, in fact, it is not necessary to obtain a very accurate uncertainty evaluation, but it is enough to know if an already available instrumentation and an already defined measurement environment are appropriate for a stated target uncertainty.

In other cases, on the contrary, it is necessary to perform a deep analysis of the measurement process and an accurate evaluation of the uncertainty. In this way, it is possible to avoid the usage of too expensive instrumentation to stay under the maximum values of uncertainty prescribed by various national and international laws.

With this aim, in the paper, we showed that the implementation of the PUMA approach, in particular but very typical cases, allows a reduction of the assessed uncertainty values in the magnetic field measurements.

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