

## CALIBRATION OF MAGNETIC FIELD ANALYZER

*Maja Grbic*<sup>1</sup>, *Dragana Naumovic-Vukovic*<sup>2</sup>, *Aleksandar Pavlovic*<sup>3</sup>

<sup>1</sup>Electrical Engineering Institute Nikola Tesla, Belgrade, Republic of Serbia, [maja@ieent.org](mailto:maja@ieent.org)

<sup>2</sup>Electrical Engineering Institute Nikola Tesla, Belgrade, Republic of Serbia, [dragananv@ieent.org](mailto:dragananv@ieent.org)

<sup>3</sup>Electrical Engineering Institute Nikola Tesla, Belgrade, Republic of Serbia,  
[aleksandar.pavlovic@ieent.org](mailto:aleksandar.pavlovic@ieent.org)

**Abstract** – This paper presents a calibration of a low frequency magnetic field analyzer performed in the Calibration and Testing Laboratory of the Electrical Engineering Institute Nikola Tesla in Belgrade, Serbia. The paper describes the calibration method as well as applied reference standard for magnetic field generation. It also presents the results of the calibration with calculated measurement uncertainty. The calibration results indicate that estimated expanded measurement uncertainty is in accordance with the requirements of IEC 61786:1998.

**Keywords:** magnetic flux density, non-ionizing radiation, calibration, Helmholtz coils.

### 1. INTRODUCTION

Examination of the influence of electric and magnetic fields to people's health becomes more topical within the areas of environmental and occupational safety. There are many countries that already have standards and legislation that prescribe the safety levels of electric and magnetic fields. Research on the influence of magnetic fields involves standard methods and measuring instruments. Magnetic field analyzers, as metrological instruments, are subject to regular calibration with the aim to check their metrological characteristics. Testing laboratories should perform periodic checks and provide full calibration for these instruments. Calibration method must be metrologically verified, and the reference standard should have traceability to the national reference standard.

This paper describes the calibration method and the practical approach to fulfil the requirements of the standards IEC 61786:1998 [1] and IEC 17025:2005 [2]. Calibration of the EFA-300 analyzer (Narda Safety Test Solutions) is done by using a method and reference standard that enables examination of measurement accuracy with an uncertainty 5–10 times lower than the declared error of the calibrated analyzer.

### 2. EQUIPMENT UNDER TEST

EFA-300 magnetic field analyzer is a highly sophisticated device that enables analysis of low frequency alternating magnetic field in wide range from 100 nT to 32 mT, and in frequency range from 5 Hz to 32 kHz. The

instrument consists of a measuring probe and a detector (Fig. 1). The magnetic field measurement is provided by measuring the induced voltage in coils of the probe. The probe is spherical, with the surface area of 100 cm<sup>2</sup>, with three coils positioned orthogonally, in order to enable isotropic measurement of the intensity of the magnetic field vector (simultaneously in all three axes) within the volume of the probe. With such positioning of the coils, it is possible to perform an analysis that is independent of the coil position in relation to the direction of the magnetic field vector. The detector calculates rms value of magnetic field on the basis of the voltage induced in the probe coils.



Fig. 1. Magnetic field analyzer with isotropic probe.

The main goal of the performed calibration was to check if the estimated expanded measurement uncertainty is in accordance with the requirements of [1]. Another goal was to check the measurement error stated by the manufacturer. This error amounts to  $\pm 3\%$  of the measured value when the measured field intensity is greater than 40 nT and the 5 Hz – 2 kHz filter is selected. According to the data stated by the manufacturer, the error of  $\pm 3\%$  is valid in case when the ambient temperature is in the range from 0°C to 50°C and the relative humidity of air is lower than 95%.

### 3. METHODS FOR CALIBRATION OF LOW FREQUENCY MAGNETIC FIELD ANALYZERS

Instruments for low frequency magnetic field measurements are calibrated in accordance with requirements of [1] using one of the following methods:

- introduction of the field meter probe into a magnetic field that can be calculated based on the known coil dimensions and the current flowing through it,
- voltage injection technique, and
- comparison with a reference measurement system.

In this paper the first method was applied.

The standard [1] defines metrological conditions which should be met in order to perform correct calibration. Thus, for a method of generating a reference magnetic field the following conditions should be fulfilled:

- the magnetic flux density should be known with an uncertainty of less than  $\pm 3\%$  (coverage factor 1), and
- homogeneity of magnetic field should be such that the highest deviation of the magnetic flux density on the whole surface of cross section of the measuring probe in relation to the value in the axis of the coils is less than 1%.

### 4. GENERATION OF REFERENCE MAGNETIC FIELD

Magnetic fields are usually generated with the system of coils, i.e. Helmholtz coils [3–6]. The cross section of Helmholtz coils used for calibration is shown in Fig. 2. The marks in Fig. 2 signify:

- $D_1$  – outer diameter of coils,
- $D_2$  – inner diameter of coils,
- $D$  – medium diameter of coils,
- $d$  – distance between coils, and
- $r$  – radius of coils.

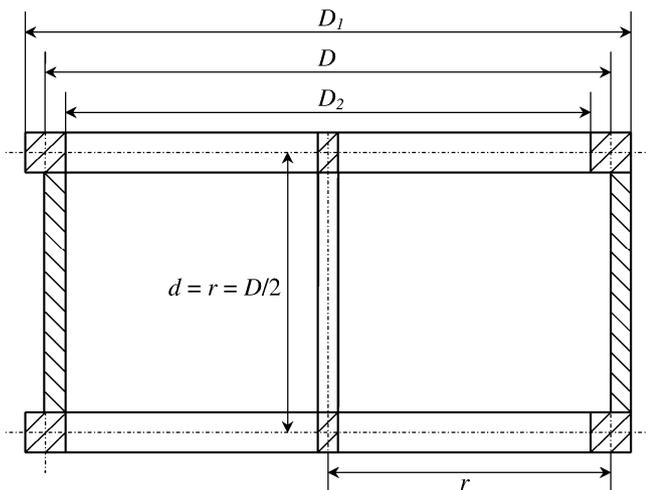


Fig. 2. Cross section of Helmholtz coils.

Intensity of vector  $B_z$  in the axis of Helmholtz coils is a complex function of constructive parameters of the coils and the electric current flowing through them. However, when the coils are positioned at mutual distance,  $d$ , which is equal

to the radius of coils,  $r$ , magnetic flux density can be calculated by the following simplified formula:

$$B_z = \frac{8}{\sqrt{125}} \cdot \frac{\mu_0}{r} \cdot N \cdot I = k \cdot I, \quad (1)$$

where

$\mu_0$  is magnetic permeability of vacuum,

$N$  is number of turns of wire, and

$I$  is intensity of electric current in coils.

Helmholtz coils used in the calibration process have the following constructive parameters:  $N = 126$ ,  $D_1 = 990$  mm and  $D_2 = 935$  mm.

Medium diameter  $D$  can be calculated as:

$$D = \frac{D_1 + D_2}{2} = 0.9625 \text{ m}. \quad (2)$$

Coefficient  $k$  can be calculated as:

$$k = \frac{8}{\sqrt{125}} \cdot \frac{\mu_0}{r} \cdot N = 2.354 \cdot 10^{-4} \frac{\text{T}}{\text{A}}. \quad (3)$$

Finally, the intensity of the vector of magnetic flux density in the axis of Helmholtz coils is:

$$B_z [\mu\text{T}] = 0.2354 \cdot I [\text{mA}]. \quad (4)$$

The above stated formula provides direct relation between the magnetic flux density in the axis of Helmholtz coils and the electric current that flows through the coils. Uncertainty of the generated reference magnetic field stems from the uncertainties of the current measurement and the measurement of Helmholtz coils dimensions. These physical quantities can be determined very precisely, with errors lower than  $\pm 0.1\%$ . Magnetic field homogeneity within Helmholtz coils is very high. The variation of magnetic field within the area of 100 mm in diameter around the axis (area wider than the probe size) is less than  $\pm 0.2\%$  of the value in the axis of the coils.

The Helmholtz coils used for calibration of EFA-300 magnetic field analyzer is shown in Fig. 3.

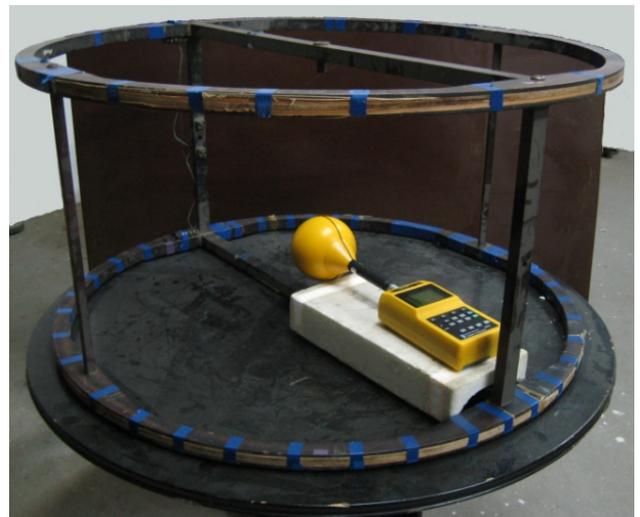


Fig. 3. Helmholtz coils with magnetic field analyzer.

## 5. CALIBRATION PROCEDURE

The calibration was performed in the atomic shelter of the Electrical Engineering Institute Nikola Tesla in Belgrade, Serbia, since this room is situated within a Faraday cage, so it was possible to achieve a very low level of ambient magnetic field.

Electric calibrator 829M (RFL) was used as the source of stable and accurate alternating current of sinus shape. This calibrator provides the required value of alternating current with an error lower than 0.1% of the set value, in the frequency range of 50 Hz – 1 kHz.

Calibration process can be described as follows:

- the measuring probe is placed in the axis of the Helmholtz coils,
- the calibrator is connected and used as a source of electric current,
- with no electric current in Helmholtz coils, measured magnetic field is the consequence of unwanted but present ambient field,
- electric current is passed through Helmholtz coils,
- the probe is positioned in such a way that in one axis magnetic field is at its maximum and in the other two it is equal to zero,
- at least three values of magnetic field are chosen for each measurement range of the analyzer, i.e. appropriate values of currents are chosen on the calibrator,
- for each value of magnetic flux density, the measurement is repeated several times to determine the standard deviation,
- analysis of the deliberately shifted position of the probe is also done in order to verify the homogeneity of magnetic field within Helmholtz coils, and to determine this component of measurement uncertainty,
- flatness of frequency response is tested with an electric current of the same amplitude and different frequencies.

In this paper only the results obtained with power frequency current (50 Hz) are presented.

The same procedure is used for the calibration of the magnetic field analyzer in two other axes of the probe.

## 6. MEASUREMENT UNCERTAINTY AND TRACEABILITY

The calibration of the magnetic field analyzer is done in accordance with [1]. Uncertainty of the calibration process of the magnetic field analyzer is determined by the international guideline on the estimate of measurement uncertainty [7]. In accordance with this guideline, the estimate of measurement uncertainty has covered all relevant uncertainty components with the appropriate type of distribution:

- the presence of ambient magnetic fields (uniform distribution),
- error in the generation of the reference magnetic field (uniform distribution),
- error due to positioning of the probe and inhomogeneity of the reference magnetic field (uniform distribution),
- error in current generation (uniform distribution),
- resolution of the amperimeter (uniform distribution),

- resolution of the measurement system under test (uniform distribution),
- standard deviation of the results (normal distribution).

In estimating the measurement uncertainty, the only influence that was not addressed was the influence of temperature and humidity since there were no technical possibilities to vary their values precisely. Both temperature and humidity of the environment during the calibration were measured and recorded, and their values were within the range stated by the manufacturer of EFA-300.

Presence of the ambient magnetic field in the area where the calibration was performed was registered at the level of 20 nT, which enabled the calibration of the magnetic field analyzer even in the lowest measurement range of 1  $\mu$ T, but with increased uncertainty.

The dimensions of the Helmholtz coils were measured with vernier with uncertainty lower than  $\pm 0.05\%$ . Total uncertainty in generating magnetic flux density is lower than  $\pm 0.2\%$ .

The impact of positioning of the measuring probe and inhomogeneity of magnetic field was verified experimentally during the calibration. Variations of the probe position of  $\pm 20$  mm influenced the measured magnetic flux density in less than  $\pm 0.035\%$ .

Combined uncertainty  $u_c$  is determined by the well known equation:

$$u_c = \sqrt{\sum_{i=1}^n (C_i \cdot u_i)^2}, \quad (5)$$

where

$C_i$  are sensitivity coefficients and

$u_i$  are components of measurement uncertainty.

Expanded measurement uncertainty for a specific confidence level is calculated by multiplying combined measurement uncertainty, determined by the equation (5), with the coverage factor. The coverage factor depends on the prevailing type of the probability distribution of measurement uncertainty components. For normal distribution (type A) for the confidence level of 95%, coverage factor is 2, and for uniform distribution (type B) with the same confidence level, the coverage factor is 1.65. In the described calibration process, the dominant components have uniform probability distribution. These components stem from the presence of ambient magnetic field, and the uncertainty of current measurement. Therefore, in the calculation of the expanded measurement uncertainty, coverage factor of 1.65 is adopted.

Helmholtz coils and a calibrator of alternating current were used for generating the reference magnetic field. Uncertainty in generating reference magnetic field depends on the accuracy of determining the dimensions of Helmholtz coils. For both measurements, of lengths and alternating electric current, there is traceability up to national, and even up to international primary reference standard.

## 7. CALIBRATION RESULTS

The calibration results are shown in Table 1, where the following symbols are used:

$I$  – electric current in Helmholtz coils,  
 $f$  – frequency of magnetic field,  
 $B_M$  – magnetic flux density, value measured by EFA-300,  
 $B_T$  – calculated true value of magnetic flux density,  
 $\delta$  – percent error,  
 $U$  – expanded measurement uncertainty.

Table 1. Calibration results.

Range	$I$ [mA]	$f$ [Hz]	$B_M$ [ $\mu$ T]	$B_T$ [ $\mu$ T]	$\delta$ [%]	$U$ [ $\mu$ T]
1 $\mu$ T	1.000	50	0.2380	0.2354	1.10	0.017
	3.000	50	0.6937	0.7062	-1.77	0.017
	4.000	50	0.9331	0.9416	-0.90	0.017
10 $\mu$ T	5.000	50	1.1613	1.1770	-1.33	0.017
	7.500	50	1.7396	1.7655	-1.47	0.017
	10.00	50	2.3153	2.3540	-1.64	0.017
	15.05	50	3.4940	3.5428	-1.38	0.035
	30.03	50	6.9774	7.0691	-1.29	0.058
100 $\mu$ T	50.02	50	11.632	11.775	-1.21	0.09
	100.20	50	23.157	23.587	-1.82	0.17
	149.90	50	34.754	35.287	-1.51	0.26
	299.30	50	69.775	70.455	-0.96	0.51
	400.00	50	93.037	94.160	-1.19	0.68
1 mT	499.40	50	116.30	117.56	-1.07	0.8
	1003.0	50	233.25	236.11	-1.21	1.7
	1497.0	50	346.98	352.39	-1.54	2.6

## 8. CONCLUSION

The calibration of the magnetic field analyzer was performed in accordance with the international standards [1,2]. The results of the calibration indicate that

measurement uncertainty of the calibrated low frequency magnetic field analyzer is significantly lower than  $\pm 3\%$  of the measured values, as declared by the manufacturer. Overall uncertainty of the calibration process (e.g. estimated expanded measurement uncertainty, with the coverage factor of 1.65) is significantly lower than  $\pm(5\% + 10 \text{ nT})$ , with the coverage factor of 1, as stated in [1].

Calculating measurement uncertainty by using Monte Carlo method would represent an advancement of the procedure described here, which will be the subject of future research.

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