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Performance of low frequency magnetic field meters to sinusoidal and beat-phenomenon magnetic fields

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Abstract

This paper presents the first part of a research work dealing with the performance assessment of commercially available magnetometers. The aim of the article is to make a comparative study on the accuracy of several magnetometers used today by agencies and research institutes to measure magnetic fields produced by power systems in public and work environments. There is still a lack in the knowledge about the measurement accuracy for the complex case of having several harmonic components like those usually present in distribution networks. The frequency behavior of several commercially available magnetometers has been analyzed using a calibrated Helmholtz coil. The accuracy of 41 magnetometers has been investigated during the research by measuring sinusoidal fields in the frequency range from 10 Hz to 10 kHz, including harmonic frequencies of 50 and 60 Hz, interharmonic frequencies and signals having small deviations from the fundamental frequency, and waveforms having beat phenomena. The results of the study show a lack of accuracy of some magnetometers at frequencies above 3 kHz, large errors at the 16.66 Hz frequency used in transportation systems, and increased errors were found in the rms measurement of beat-phenomenon waveforms. The increased error in this non-sinusoidal waveform type demands a deeper research on the accuracy of magnetometers when measuring non-sinusoidal waveforms.

Keywords: Magnetic field measurement; Magnetometer; Helmholtz coils; Harmonics; Interharmonics; Measurement error

1. Introduction

The study of magnetic field measurements has been discussed by the scientific community for some decades. This interest has emerged due to the following facts:

- The physical complexity of magnetic fields [1]: the magnetic field vector in workplaces traces out a complicated shape over time. In the vicinity of different magnetic field sources, the magnetic field varies widely in magnitude, frequency content, form of its path, and other characteristics. The measurement of these fields is difficult

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because of their complexity, broad frequency band, as well as their time and spatial variations as a consequence of multiple sources of different kinds such as power lines, wiring configurations, stray currents, appliances, video display units, RF transmitters, etc. [2].

- The interference caused by magnetic fields on electrical and electronic devices, measuring sets, computers, control systems, etc. [3,4]: the main sources of disturbance could be identified as three-phase lines, unbalanced currents, currents in grounding systems, proximity of power installations, proximity of railway tracks, and presence of harmonics in the neutral conductor [5]. Moreover, magnetic fields are more difficult to reduce than electric fields. A Faraday cage has practically no effect on the magnetic field. Although a shielding made of high magnetic permeability material is an effective way to reduce the intensity of magnetic fields, it is very expensive and it is only used in special cases.
- Some research suggests an association between magnetic fields and biological effects [6,7,23,24]. Several epidemiological studies and research reports have indicated the possibility of direct and indirect association between low frequency EMF and the incidence of childhood leukemia and carcinogenesis. Several experimental studies have also indicated a possible interference from power frequency fields on behavioral, neurological, biochemical, immunological and genetic functions of the living organisms. Nevertheless, other research reports indicate just the opposite.

Owing to the increased use of electronic loads in electric power supply networks, the harmonic content of currents and voltages has increased. This creates a new problem in measuring magnetic fields in power system installations: the currents that produce magnetic fields have not only a fundamental component, but also currents at higher frequencies, and in some cases they are outstandingly higher. Moreover, the harmonic content grows continuously with respect to the fundamental current in every network of the world.

It is important to consider the influence of the magnetic field frequency components, and to identify their sources. A growing number of organizations have been developing standards and guidelines for limiting the exposure to magnetic fields, setting different limits for different frequencies [8–11,25]. Therefore, it is essential to have instruments that correctly measure magnetic fields containing harmonic components.

Additionally, standards for magnetic field meters [12–14] are intended to be applied to instrumentation that measures the rms value of the magnetic field, but they give little information about measuring complex magnetic fields, i.e., having periodic and aperiodic non-sinusoidal waveforms.

2. Magnetic flux density meters

There are many types of magnetometers depending on the application, manufacturing technology, frequency and flux density ranges, magnetic field parameters to be measured, etc. Magnetic field strength is measured using a variety of different technologies. Each technique has unique properties that make it more suitable for particular applications [15]. Magnetic field meters consist of two parts, the probe or field sensing element, and the detector, that processes the signal of the probe and indicates the different parameters of the measured magnetic field according to each type of meter.

The frequency and intensity responses of the probe-detector circuit combination can be made flat. The corrective action provided for the detector is essential to obtain accurate values of the different parameters of the magnetic field [16].

The induction coil and fluxgate sensors are the most widely used vector measuring instruments. They are robust, reliable, and relatively less expensive than the other magnetometers.

2.1. Previous evaluations of magnetic field meters

Existing meters present differences in their frequency response, detector response, sensitivity, type of sensor, ability to record polarized fields, etc. This makes difficult the comparison between magnetic field meters.

Sicree et al. [17] compared different types of induction coil type meters by simulation. Different combinations of the following factors were simulated: (i) scalar magnetic field or maximum magnetic field, (ii) detectors with integrators or with derivative scaling circuits, and (iii) true rms detectors, rectified average detectors, or corrector peak detectors. These simulations show that the best combination is a detector with integrator and true rms value. This study is only valid for the rms value of a waveform.

Olsen et al. [18] presented an evaluation report of the IEEE magnetic fields task force. Fourteen magnetic field meters were evaluated. Tests of intensity linearity, effect of calibration loop size, frequency response, 60 Hz electric field susceptibility, and EMI were made. The evaluation was intended for power frequency magnetic field meters, and the response of each meter was only measured for low order harmonics, i.e., up to 540 Hz. The tests were made using a 28 turn 2 m by 2 m shielded coil located 1 m above the floor.

Ref. [19] is a laboratory testing report for commercially available power frequency magnetic field meters. Fifteen types of meters were tested for 60 Hz accuracy and linearity, frequency response, 60 Hz non-sinusoidal, angular response, 60 Hz *E*-field susceptibility, radio frequency susceptibility, sensitivity, and resolution measurements. The magnetic field tests were made using a circular Helmholtz coil having 1 m diameter, and calibrated by means of a current shunt DC calibration procedure. There is no information about the frequency behavior of the Helmholtz coil. The frequency response test was made for a frequency range of 1 Hz to 10 kHz. The meters were also tested for 60 Hz square and sawtooth waves, but the meters only gave the total rms value. None of the meters had frequency analysis functions.

Isokorpi et al. [20] presented a study of the effect of low-order harmonic frequencies, up to 250 Hz, on magnetic field measurements. Three magnetic field meters were tested for three frequencies, i.e., 50, 150 and 250 Hz, at two magnetic field levels. The magnetic field was generated using a square Helmholtz coil having 1.1 m side. The authors concluded that power frequency harmonics may have a significant effect on magnetic field measurements.

Bowman and Methner [1] presented a comparative study between two magnetic field recorder meters, one of them having a waveform capture function within a frequency range up to 3000 Hz. The analyzed measurements consisted of 59 waveforms at workplaces near sources. The authors state that more research is needed in order to develop a systematic method for calculating accurate FFTs of workplace magnetic fields, because some difficulties exist in the use of Fourier analysis such as leakage error and reduced frequency resolution.

After an exhaustive bibliography research, studies have not been found, besides Ref. [1], dealing with non-sinusoidal magnetic fields, which are fields to be limited according to the guidelines and standards to control the exposure of magnetic fields. It should be noted also that in [1] only 2 meters were tested, and that the accuracy of the meters was unknown. Although some commercially available magnetic field meters currently have frequency analysis tools for magnetic fields up to frequencies of some kHz, there is still a lack of knowledge about the measurement accuracy for the complex case of having several harmonic components like those that usually appear in distribution networks.

2.2. Calibration systems

In order to evaluate the performance of magnetic field meters for broadband sinusoidal and non-sinusoidal fields, it is important to have an accurate wideband magnetic field generator.

The IEEE 1318 standard [12] recommends a rectangular loop of 1 m side. There is no information about the frequency behavior of the coil, but the standard is intended for magnetic fields up to 3000 Hz. The standard also mentions the possibility of using a Helmholtz coil to generate magnetic fields.

IEC [14] also recommends a 1 m-side rectangular loop for induction coil sensors having a cross-sectional area of 100 cm^2. Helmholtz coils are also recommended. Calibrations should be performed at frequencies well below the resonance frequency of the coil system, but no frequency limit or correction is proposed.

Helmholtz coils can be used along with sinusoidal currents to generate AC magnetic fields. The ratio of generated flux density to coil current (coil constant) at DC conditions holds only up to a certain frequency limit [21]. Above this limit the coil constant becomes frequency-dependent and the two most important factors affecting this dependence are: (i) an electric field is generated which also generates a disturbing magnetic field, and (ii) as frequency increases the current distribution becomes progressively non-uniform approaching the first resonance.

Weyand [22] presents different methods which are used at the Physikalisch-Technische Bundesanstalt[1] (PTB) to disseminate the unit of magnetic flux density. The author states that field coils, like Helmholtz coils, have proved to be reliable magnetic

[1] PTB is the national institute of natural and engineering sciences and the highest technical authority for metrology and physical safety engineering of the Federal Republic of Germany.

field generators for industry, if their coil constants are calibrated together with the current measuring instrument, i.e., the coil and the instrument are to be regarded as a combined standard system.

3. Evaluation of magnetometers

The measurements presented in this paper were performed by means of an octagonal Helmholtz coil (see Fig. 1) having a coil constant correction curve in a frequency range from 0 to 10 kHz. The correction factor curve was experimentally obtained by PTB for the octagonal coil using 60 turns. The octagonal Helmholtz coil with centrally directed windings has one axis, the ratio of the inscribed circle of the most inner turn is $R_{in} = 503$ mm, and the 1%-homogeneity region, virtually spherical, has a size of 41.6 dm^3.

3.1. Measurement procedures

After a bibliography study, a measurement program was proposed using a set of waveforms in order to identify the possible errors of all types of magnetometers. The main objective of these tests was to perform a comparative study of the accuracy of several magnetometers used today by agencies and research institutes to measure magnetic fields produced by power systems in public and work environments.

This paper deals with tests using sinusoidal magnetic fields in the frequency range from 10 Hz to 10 kHz, including harmonic frequencies of 50 and 60 Hz, interharmonic frequencies and signals with small deviations from the fundamental frequency.

Fig. 1. Precise-wideband magnetic field generator of NLÖ.

These tests were made at different magnetic field intensities, to verify not only the frequency linearity but also the intensity linearity. Odd harmonics of 50 and 60 Hz were selected for frequencies below 1 kHz, because these harmonics are the most common in power systems. After that, frequency multiples of 1 kHz were used to characterize the meter accuracy in the harmonic frequency test. For the interharmonic frequency tests random frequencies were selected to span the frequency range.

The inclusion of the 16.66 Hz frequency has a practical reason, because it is used in some transportation systems in Europe. Frequencies of 50.05, 60.05, 150.1, and 180.1 Hz were considered in the small deviation from the fundamental frequency test.

Additionally, the response of magnetometers to non-sinusoidal signals having the beat phenomenon is also investigated. When two close frequency components are present, the beat frequency, i.e., the difference of the frequencies, modulates the amplitude of the waveform. The chosen frequencies are the fundamental (50/60 Hz) and some frequencies of CRT computer monitors, i.e., 56 and 72 Hz.

3.2. Set of tested magnetometers

There are several commercially available magnetometers. The study considered 41 magnetometers having different specifications. Some meters are simple instruments having few functions. Others are modern digital magnetometers with several measurement functions. Meters having the ability to change the sensor connected to the detector were analyzed considering each combination as an individual meter. The meters were provided by several research institutes, control agencies, and meter manufacturers. Meters were checked and only the units that proved to be working correctly were considered in the evaluation. Then, a classification of the meters was made for analysis purposes: (a) meters having a frequency range below 10 kHz and no frequency analysis tools (11 meters); (b) meters having a frequency range below 10 kHz and frequency analysis tools (5 meters); (c) meters having a frequency range above 10 kHz and no frequency analysis tools (6 meters); (d) meters having a frequency range above 10 kHz and frequency analysis tools (14 meters); and (e) Gaussmeters, e.g., meters with Hall-effect sensor type (5 meters).

Table 1 shows the list of tested magnetometers along with some important specifications. The table

Table 1
Specifications of the magnetic field meters used in the study

Meter number	Type	Sensor: type	Number of axes	Core	Area cm^2	Frequency response (Hz)	Calibrat. 2 years
2	d	Coil	3	Air	100	5–30 k	No
4	d	Coil	3	N/A	N/A	5–32 k	Yes
4a	d	Coil	3	Air	100	5–32 k	Yes
4b	d	Coil	3	N/A	9.42	5–32 k	Yes
5	e	Hall effect	1	Transverse	N/A	0 and 20–10 k	No
6	c	Coil	3	Air	100	5–30 k	No
7	c	Coil	3	Air	N/A	5–400 k	Yes
8	a	Coil	3	N/A	N/A	16.66–400	No
9	d	Coil	3	Air	100	10–400 k	No
10	c	Coil	3	Air	N/A	5–400 k	Yes
11	d	Coil	3	N/A	N/A	10–30 k	No
11a	e	Coil + Hall	3	Air (coil)	N/A	0–30 k	No
12	a	Coil	3	Air	100	5–2 k	No
15	a	Coil	1	Air	N/A	50–1 k	No
16	d	Coil	3	Air	100	16–45 k	No
17	e	Hall effect	1	Axial	N/A	0 and 20–10 k	No
17a	e	Hall effect	1	Transverse	N/A	0 and 20–10 k	No
18	d	Coil	3	N/A	N/A	16–100 k	No
19	d	Coil	1	N/A	N/A	50–400 k	No
20	a	Coil	3	N/A	N/A	16.66–400	No
21	d	Coil	3	Air	100	16–45 k	Yes
22	d	Coil	3	Air	100	10–400 k	Yes
22a	e	Hall effect	3	N/A	N/A	0–500	Yes
23	c	Coil	3	Air	100	5–30 k	No
24	b	Coil	3	Air	100	10–3.2 k	No
25	a	Coil	3	Air	100	5–2 k	No
26	a	Coil	3	Air	N/A	5–2 k	No
27	a	Coil	3	N/A	N/A	30–2 k	No
30	d	Coil	3	N/A	N/A	5–100 k	Yes
31	c	Coil	1	Air	100	16–30 k	No
32	a	Coil	3	Air	N/A	16–1200	No
33	d	Coil	3	Air	100	5–32 k	Yes
34	d	Coil	3	Air	100	10–30 k	No
35	a	Coil	3	N/A	N/A	40–800	No
36	a	Coil	3	N/A	N/A	40–800	No
37	a	Coil	3	N/A	N/A	16.66–400	No
38	b	Coil	3	Air	100	10–3.2 k	No
39	b	Coil	3	Air	100	10–3.2 k	No
40	c	Coil	3	Air	100	5–30 k	No
41	b	Fluxgate	3	Ferromagnetic	0.1	0–1000	Yes
42	b	Fluxgate	3	Ferromagnetic	0.1	0–1000	Yes

N/A: not available.

shows the meter number for identification purposes, the type of meter according the above classification, the sensor type, number of axes, core type and cross-section area. The frequency response and the calibration information of the meter (calibrated at the most two years before the study or not) are also reported.

The meter specifications confirm that existing meters vary in their frequency response, detector response, sensitivity, type of sensor, etc., and this makes the comparison between magnetic field meters difficult. Consequently, the measurement procedures were applied to all meters, but in some cases the procedure could not be totally applied. For example, meters of type a, intended for measurements in a frequency range smaller than 10 kHz, were only analyzed until their frequency limit.

4. Results

A large amount of data was obtained from the measurements. The results obtained using each magnetometer were compared with the generated magnetic field, which was calculated according to the PTB calibration certificate. The uncertainty associated with the generated magnetic field was calculated considering all components of the magnetic field generation system, obtaining an uncertainty of $u < 3.0\%$ for sinusoidal fields at frequencies from 10 Hz to 2 kHz and $u < 3.5\%$ for sinusoidal fields at frequencies from 2 kHz to 10 kHz. The uncertainties involved in the magnetic field generation process are: uncertainty of the coil as measured by the PTB, uncertainty due to the current measurement, uncertainty due to the inhomogeneity of the field and position of the probes in the center of the coil, uncertainty due to the deviation angle of the probe, and uncertainty due to the environmental magnetic field. The environmental temperature was always in the range of 15–19 °C and the relative humidity between 65% and 75%.

The analysis of the results is divided into four parts. The first part deals with meters having a frequency range smaller than 3.2 kHz (meters of type a and b), the second part deals with meters having a frequency range equal or larger than 10 kHz (meters of type c and d), the third part deals with the Gaussmeters, i.e., meters of type e, and the last part deals with the results of the beat-phenomenon tests.

4.1. Evaluation of meters with frequency ranges below 3.2 kHz

The results for meters with frequency ranges smaller than 3.2 kHz are shown in Table 2. It shows the average relative error according to Eq. (1), the standard deviation of the error, and the χ^2/N test for the measurements using harmonic frequencies, interharmonic frequencies, and frequencies having small deviations from the fundamental frequency.

$$\text{Average error} = \frac{\sum \left(\frac{B_{\text{measured}} - B_{\text{calculated}}}{B_{\text{calculated}}} \cdot 100\% \right)}{N} \tag{1}$$

where B is the measured or calculated magnetic flux density and N is the number of measurements. The χ^2/N test is defined as

$$\frac{\chi^2}{N} = \frac{\sum \frac{(B_{\text{measured}} - B_{\text{calculated}})^2}{B_{\text{calculated}}}}{N} \tag{2}$$

Table 2 also shows the total χ^2/N test. The smaller the value of this test, the more accurate the evaluated magnetometer according to the performed test. Table 2 shows the results for the measurements in the frequency range of each meter, e.g., meter 12 up to 2000 Hz (Table 1). Different behaviors were observed during these tests. Some meters, e.g., meters 20, 32, or 37, presented small average and standard deviation of the relative error. Therefore, these meters have the smaller χ^2/N factors. Other meters had larger errors, but in general, the errors were lower than 10%.

4.2. Evaluation of meters with frequency ranges above 10 kHz

The evaluation results for meters having a frequency range equal or larger than 10 kHz are shown

Table 2
Average error, standard deviation and χ^2/N test for the harmonic, interharmonic and deviation from frequency measurements, for meters of type a and c

Meter	Error at harmonics freq.			Error at deviations freq.			Error at interharmonic freq.			Total
	Average%	SD%	χ^2/N	Average%	SD%	χ^2/N	Average%	SD%	χ^2/N	χ^2/N
8	3.97	1.48	0.0128	4.52	0.56	0.0096	1.13	3.55	0.0056	0.0093
12	−5.11	7.47	0.2058	−1.08	0.20	0.0049	−4.52	3.55	0.1290	0.1132
15	1.29	4.19	1.5656	0.71	2.38	0.4796	1.04	5.93	1.8616	1.3023
20	0.32	2.13	0.0018	0.99	1.42	0.0008	−3.12	4.01	0.0126	0.0050
24	−3.02	3.12	0.0367	−1.96	0.89	0.0221	−2.81	0.80	0.0385	0.0324
25	−5.84	8.48	0.2046	−2.29	0.57	0.0392	−5.33	2.88	0.1722	0.1386
26	−2.56	8.19	0.1037	0.33	0.29	0.0005	−3.03	3.46	0.0860	0.0634
27	0.59	6.93	0.0899	3.34	2.50	0.0956	2.00	3.35	0.0759	0.0872
32	0.59	0.94	0.0004	0.25	0.41	0.0002	−1.84	3.01	0.0101	0.0036
35	−0.18	6.08	0.1880	3.68	3.13	0.0949	−6.68	13.81	0.3290	0.2040
36	−1.33	6.65	0.2415	3.19	2.66	0.0699	−3.43	6.33	0.2489	0.1868
37	0.78	2.14	0.0017	1.50	1.62	0.0008	−0.88	3.14	0.0049	0.0025
38	−2.24	4.76	0.0267	−0.42	0.73	0.0025	−1.28	1.12	0.0129	0.0140
39	−1.31	3.67	0.0131	−0.06	0.60	0.0022	−0.89	1.80	0.0141	0.0098
41	2.48	1.62	0.0169	−3.66	19.91	0.3781	2.90	1.68	0.4485	0.3556
42	0.28	8.24	0.0392	1.12	0.46	0.0094	−5.55	8.69	1.8065	0.7467

SD: standard deviation.

Table 3
Average error, standard deviation (SD) and χ^2/N test for the harmonic, interharmonic and deviation from frequency measurements, for meters of type b and d

Meter	Error at harmonic freq.					Error at deviations freq.			Error at interharmonic freq.			Total
	Err. 50 Hz	Err. 10 kHz	Average%	SD%	χ^2/N	Average%	SD%	χ^2/N	Average %	SD%	χ^2/N	χ^2/N
2	1.34	−1.54	−0.03	1.02	0.0055	0.33	0.91	0.0055	0.85	2.80	0.0435	0.0182
4	−0.56	−1.24	−0.35	1.48	0.0939	0.18	0.63	0.0027	−0.79	1.21	0.0057	0.0341
4a	−5.62	−2.77	−4.65	0.89	0.1408	−5.05	0.35	0.1419	−4.95	1.47	0.1107	0.1311
4b	−4.79	−4.26	−4.24	0.52	0.0737	−4.18	0.33	0.0963	−4.62	1.01	0.0777	0.0826
6	−2.20	0.22	−0.66	5.68	0.0209	−1.22	0.48	0.0085	−1.97	2.03	0.0316	0.0203
7	−1.80	−5.18	−2.88	2.36	0.0165	−1.11	0.76	0.0043	−3.40	2.43	0.0407	0.0205
9	0.05	1.19	−0.29	0.67	0.0007	−0.11	0.13	0.0001	−0.36	0.79	0.0035	0.0014
10	−5.77	−8.75	−9.00	2.91	0.1536	−5.54	0.49	0.1915	−9.58	2.35	0.3148	0.2199
11	1.53	−1.96	0.48	1.66	0.0082	0.63	0.81	0.0065	0.57	2.81	0.0366	0.0171
16	−1.10	−1.04	−1.32	0.40	0.0070	−1.33	0.20	0.0100	−0.82	1.15	0.0073	0.0081
18	−1.85	6.39	0.55	3.38	0.0049	−1.57	1.46	0.0006	−0.87	6.74	0.0075	0.0044
19	−1.32	−73.23	−32.30	30.37	0.1936	−1.47	1.03	0.0003	−28.64	31.50	0.1661	0.1200
21	−0.10	0.65	−0.09	1.26	0.0010	−0.28	0.14	0.0006	0.09	1.05	0.0064	0.0026
22	0.09	1.21	−0.25	0.81	0.0010	0.19	0.10	0.0004	−0.21	0.93	0.0020	0.0011
23	−0.65	1.62	0.12	0.58	0.0008	−0.24	0.41	0.0007	0.22	1.31	0.0023	0.0013
30	2.29	3.61	−0.02	2.63	0.1418	0.34	1.78	0.0155	6.72	14.02	1.2301	0.4625
31	−2.17	−20.44	−4.71	7.95	0.0573	0.30	4.27	0.0805	−5.33	9.72	0.0896	0.0758
33	−3.65	−0.47	−2.36	2.00	0.0714	–	–	–	–	–	–	0.0714
34	−1.82	−5.98	−3.19	1.02	0.0239	−2.18	0.26	0.0049	−2.67	3.70	0.0089	0.0126
40	−0.30	0.83	−0.01	0.48	0.0002	−0.03	0.06	0.0000	0.00	0.75	0.0013	0.0005

–, not measured.

in Table 3 and Figs. 2–4. Forty eight magnetic field measurements were performed, using 24 different harmonic frequencies (see Section 3.1) and two different magnetic densities (approx. 10 μT and 100 μT). During the interharmonic test 12 magnetic field measurements were performed, using six different interharmonic frequencies and two magnetic field densities (approx. 10 μT and 100 μT). The deviation of fundamental frequency test consisted of eight measurements, using four different frequencies (see Section 3.1) and two magnetic field densities (approx. 10 μT and 100 μT). The average error (Eq. (1)) of these measurements, the standard deviation of the errors and the χ^2/N test (Eq. (2)) are presented in Table 3 for each magnetometer. Moreover, Table 3 gives the average error for the 50 Hz (approx. 1 μT, 10 μT, and 100 μT) and 10 kHz harmonic measurements in order to compare the error

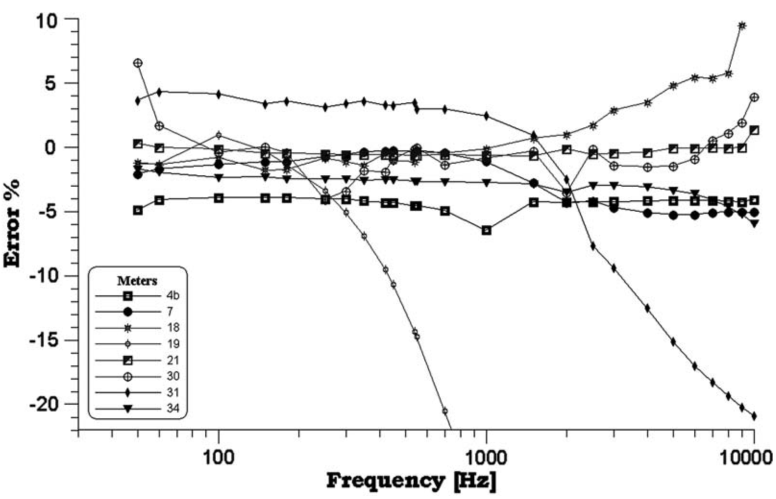

Fig. 2. Error curves for 8 meters at harmonic frequencies (see Section 3.1). Magnetic flux density 10 μT approx.

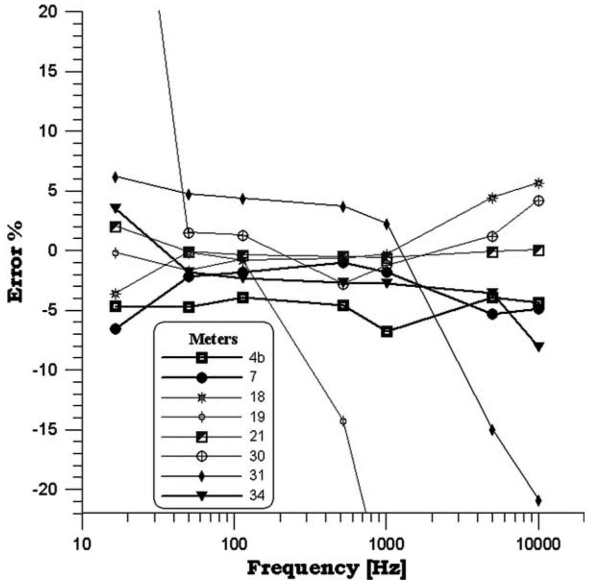

Fig. 3. Error curves for 8 meters at interharmonic frequencies (16.66, 50.05, 113.5, 521.5, 1013.5, 5013.5, and 10013.5 Hz) magnetic flux density 10 μT approx.

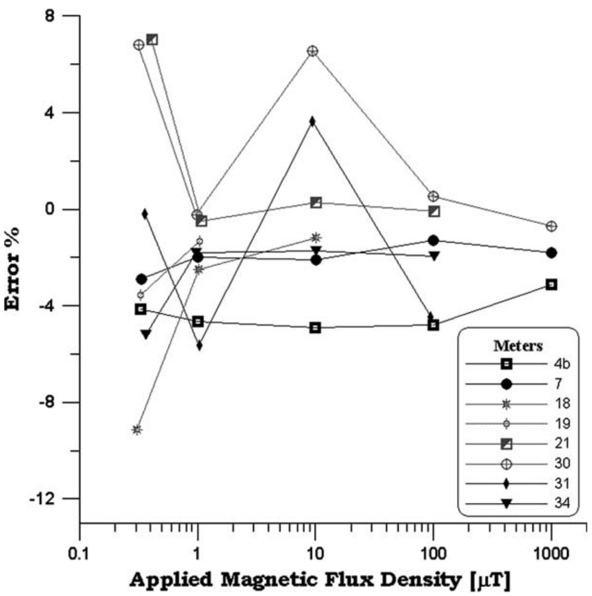

Fig. 4. Accuracy and linearity at 50 Hz for 8 meters.

at these frequencies with the average error of the whole spectrum. In addition, the total χ^2/N test is given, i.e., the test of all measurements using signals containing harmonics, interharmonics, and signals having small deviations from the fundamental. This factor can be used to compare the accuracy of the magnetometers.

Note that the error of meters 2, 4, 7, 9, 18, 22, 23, 31, and 34 at 10 kHz is considerably larger than the average error. Figs. 2–4 depict the relative error of some of the tested magnetometers in different circumstances. Only a sample of meters is shown corresponding to the most representative results. Similar results were found for the other magnetometers. A sample of 8 meters was selected in order to obtain understandable figures. The symbols in the figures for each meter represent the measurement points. These points are joined with lines for visualization purposes, but the lines do not mean error values at intermediate points.

It is desirable in all situations to have flat linear responses with the smallest possible error, or in other words, to have small average and standard deviations of the error in Table 3. Fig. 2 shows the error curves for several meters at harmonic frequencies of 50 and 60 Hz up to 10 kHz (see Section 3.1) keeping the applied magnetic flux density constant (approx. 10 μT). The behavior shown by the curves differs depending on the meter characteristics and its calibration. For example, note that meter 21 has a very good behavior, because its error is always between −1% and 2%. However, the error of meter 19 rises as the frequency increases and the error curve goes beyond the axis limit; Table 3 shows that its average error for the harmonic test is −32%. Table 1 shows that this meter has not been recently calibrated. Although the meter behavior for low frequencies is acceptable, only a frequency evaluation could evidence a malfunction.

Note also that meters 7, 18, and 34 have small errors at low frequencies but the error rises above 4% at frequencies higher than 3 kHz. This is probably produced by an inadequate calibration of these meters at these frequencies. Remember that the coil constant of a calibration coil changes with the frequency of the injected current. Meter 4b shows a good linearity, i.e., the standard deviation of the error is 0.52%, but its average error is −4.24%. Thus, the meter accuracy may be easily improved by calibration. On the contrary, meter 31 presents a nonlinear curve and large errors, which vary from 4% to −21%.

Fig. 3 shows the errors of 8 meters at interharmonic frequencies using an applied field of approx. 10 μT. The errors at these frequencies are similar to the errors at harmonic frequencies, with the exception of the 16.66 Hz frequency test. The error at this frequency is often bigger, due to the cut-off frequency of the high-pass filter of these magnetometers or due to a bad calibration. For example, meter 30 shows an error of 36% that goes beyond the limit of the figure axis. Remember that this frequency is of practical importance in some countries like Germany because it is usually used in transportation systems.

The error curves for the 50 Hz accuracy and linearity test for some magnetometers are shown in Fig. 4. This test shows a different behavior of the magnetometers with respect to the previous tests. Some meters have a good linearity and accuracy, like meter 7. It can be seen that most meters show larger errors at the lowest measured magnetic flux density, i.e., approx. 0.3 μT. This may be produced by sensor noise problems. Nevertheless, these errors are relatively small.

4.3. Evaluation of Gaussmeters

Fig. 5 depicts the relative error of the meters having Hall-effect sensors for the 50 Hz linearity test. In this test, meters of type e present deficient results, showing large errors especially at low magnetic flux densities (type e meters have Hall-effect sensors). Macintyre [15] shows that this type of sensor is not appropriate for low level alternating current (AC) fields owing to their low sensitivity and to saturation problems because of the earth's magnetic field. Only meter 11a had small errors, but this meter has a combination of Hall type sensor with

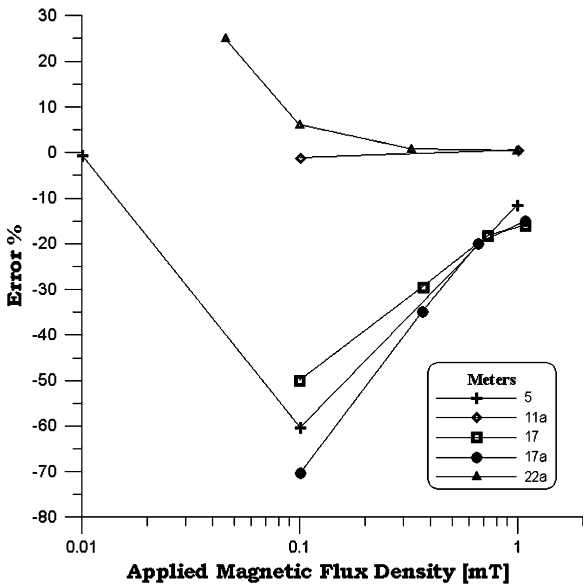

Fig. 5. Accuracy and linearity at 50 Hz for the Gaussmeters.

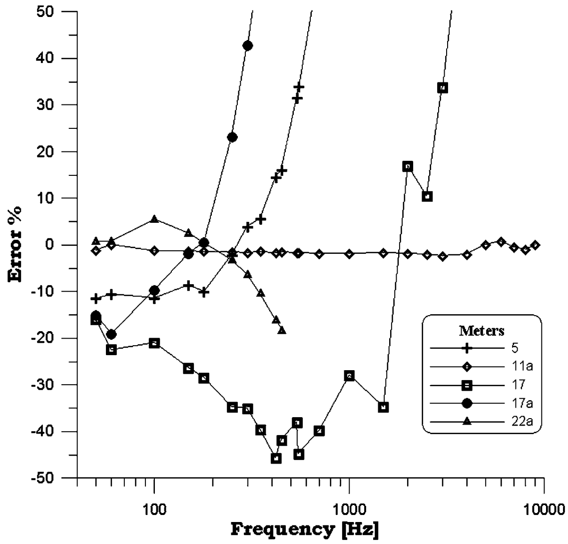

Fig. 6. Error curves for Gaussmeters at harmonic frequencies (see Section 3.1). Variable magnetic flux density.

an induction coil. Fig. 6 shows the error curves at harmonic frequencies of 50 and 60 Hz up to 10 kHz (except for meter 22a which has a frequency limit of 500 Hz) for meters of type e. Only meter 11a had a flat response with a small error. The other meters had in general very large errors. The errors of meters 5, 17, and 17a increase also as the frequency increases because the test could not be made at a constant magnetic flux density, i.e., the maximum flux density of the magnetic generator decreases as the frequency increases. For a proper frequency evaluation of these meters, a more powerful magnetic field generator should be used.

4.4. Beat-phenomenon test results

Table 4 shows the errors of the rms value for each beat case, and the average and standard deviation of the errors for meters of type a and c, respectively. This test shows that most meters of type a and c increase their error when measuring the rms value of this type of waveform, reaching errors up to 35%. The cases that produce the larger errors were the 50–56 Hz and the 60–56 Hz cases, as was to be expected because they have the smallest beat frequency, i.e., 6 and 4 Hz. The 50–72 Hz case, having the largest beat frequency, produces the same errors in each meter as with sinusoidal signals.

Table 5 presents the errors of the rms value for each beat case, and the average and standard deviation of the errors for each meter of type b and d,

Table 4
Type a and c meter errors of the rms value measurement of waveforms having two close frequency components that produce the beat phenomenon

Meter	50–60 Hz	50–56 Hz	50–72 Hz	60–56 Hz	60–72 Hz	Average error	SD error
6	−1.15	−0.26	−1.01	2.96	−0.95	−0.09	1.74
7	−6.77	10.12	−4.47	11.42	−3.89	1.28	8.74
8	12.73	10.59	4.04	−3.65	3.33	5.41	6.50
10	−10.44	8.53	−6.38	–	−5.87	−3.54	8.30
12	−1.04	0.10	−1.40	2.77	−1.42	−0.20	1.77
15	−6.38	−5.79	−3.23	−5.90	−4.85	−5.23	1.25
20	0.50	−5.49	0.54	13.23	0.66	1.89	6.86
23	−0.69	−0.07	−0.87	−1.08	−0.19	−0.58	0.44
25	−4.39	0.56	−1.81	15.39	−3.54	1.24	8.13
26	−0.04	−0.25	−0.45	0.17	−0.23	−0.16	0.24
27	−0.14	−2.90	1.89	6.67	−2.31	0.64	3.86
31	−8.10	−6.66	−6.37	−6.45	−7.18	−6.95	0.71
32	−2.35	5.99	−0.21	35.38	0.91	7.94	15.64
35	−6.73	−20.91	−3.44	−3.67	−5.78	−8.10	7.29
36	−5.48	−7.75	−3.32	4.95	−6.60	−3.64	5.07
37	0.88	−10.25	0.90	16.94	0.10	1.72	9.73
40	−0.02	0.14	−0.37	−0.05	−0.06	−0.07	0.18

SD: standard deviation.

Table 5
Type b and d meter errors of the rms value measurement of waveforms having two close frequency components that produce the beat phenomenon

Meter	50–60 Hz	50–56 Hz	50–72 Hz	60–56 Hz	60–72 Hz	Average error	SD error
2	1.81	0.10	1.09	2.67	0.77	1.29	0.99
4	1.39	−7.61	0.71	19.42	1.29	3.04	9.91
4a	−5.26	−5.84	−5.39	−2.40	−4.81	−4.74	1.36
4b	−3.58	−4.18	−3.82	−0.73	−3.42	−3.15	1.38
9	0.82	2.05	0.30	2.67	–	1.46	1.09
11	1.56	−3.74	−0.32	−2.04	1.98	0.53	1.68
16	−1.18	−3.74	−1.03	10.52	−1.16	0.68	5.61
21	−0.09	−8.53	0.05	22.28	−0.07	2.73	11.53
22	−1.54	−4.61	0.71	−4.26	−0.05	−1.95	2.41
24	7.64	−5.53	0.65	−8.85	−2.00	−1.62	6.30
30	1.62	−0.79	1.92	18.57	0.86	4.44	7.97
38	−10.89	−2.21	1.23	−4.36	−0.75	−3.40	4.66
39	7.71	3.10	1.53	2.76	−2.39	2.54	3.62
42	0.44	−0.04	–	−32.57	−6.26	−9.61	15.61

SD: standard deviation.

respectively. An increase of the error is observed in some meters of type b and d in the rms value measurement of the waveform. Meter 42 has the worst results, because it is designed to capture the waveform and to process it using a fundamental frequency of 60 Hz. Note that the use of frequencies of 50–72 Hz causes no problems in the meters, whereas the other cases using closer frequency components, i.e., smaller beat frequencies, cause larger errors. This is due to the fact that the meters have a fixed integration window to perform the rms value function, and the beat frequencies modulate the signal under analysis.

5. Conclusions

There are many available magnetometers in the market, each one with different specifications and features.

After testing a representative group of magnetometers using sinusoidal fields, a broad spread of responses has been found. In the analysis of sinusoidal signals up to 10 kHz, some meters show suitable results, i.e., the error has a small average and standard deviation. IEC [14] states that the measurement uncertainty of the instrumentation should be less than ±10% in the frequency range from

15 Hz to 9 kHz, and most meters meet this condition.

However, a number of meters was also found to have large errors inside their specified operation range. This fact stresses the importance of proper and regular calibration of magnetometers, which are used in prevention and environmental studies, i.e., the meter response in the frequency range of operation should be well specified.

Some meters show an increase of their errors at frequencies above 3 kHz. It is likely that this could be due to the use of magnetic field generators with no frequency correction in the calibration process. Although the standards [12,14] recommend that calibrations should be performed at frequencies far beyond from the resonance frequency of the coil system, they do not propose a specific frequency limit or correction procedure. Nevertheless, there are standard procedures to find the correction function of each coil system [22] that could improve the frequency performance of the meters.

The tests at interharmonic frequencies and small deviations from the fundamental frequency showed errors similar to those at harmonic frequencies. Only the case of measurements at 16.66 Hz, usual in transportation systems, shows an increase of the error in several meters, because this frequency is near the low frequency limit of the meters.

Additionally, further studies are necessary in order to establish the accuracy of the magnetometers at frequencies higher than 10 kHz.

The beat-phenomenon test showed larger errors in several meters in the waveform rms measurement reaching error values up to 35%. Larger errors were observed for cases corresponding to the waveforms having smaller beat frequencies, i.e., the 50–56 Hz and the 60–56 Hz waveforms. The large errors of some meters in the waveform rms measurement are caused by the short integration window, which leads to an unstable reading in the meters.

The increased error in the rms measurement of beat waveforms (a non-sinusoidal waveform type) demands a deeper research on the accuracy of magnetometers when non-sinusoidal waveforms are measured. The presented research work is to be continued and the next step is to analyze the behavior of magnetometers when measuring non-sinusoidal magnetic fields, where not only the rms value of the waveform is measured but also the frequency components, in order to characterize the errors due to spectral leakage or picket-fence effects in modern magnetometers.

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