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Performance of low frequency magnetometers to non-sinusoidal magnetic fields

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ABSTRACT

This paper presents the second part of a research work dealing with the performance assessment of commercially available magnetometers. The aim of the article is to continue a comparative study of a magnetometer set, but now using non-sinusoidal signals. Nineteen magnetometers were tested using signals with two and more frequency components; some features of the meters were investigated: fft, rms value, peak value and wave capture functions.

1. Introduction

A previous paper [1] showed the importance and pertinence of performing evaluations of commercially available magnetometers. During the research work described in [1], 41 magnetometers were tested using sinusoidal fields, and it was concluded that, in the analysis of sinusoidal signals up to 10 kHz, there exist meters that can measure such fields with small errors, i.e., the meters fulfilled the IEC standard [2] which states that the measurement uncertainty of the instrumentation should be less than ±10% in the frequency range from 15 Hz to 9 kHz. However, in the test using fields with beat phenomena, larger errors were found in several meters in the rms waveform measurement, reaching error values of up to 35%. It was also stated that the increased error in the rms measurement of beat waveforms (a non-sinusoidal waveform type) demanded a deeper research on the accuracy of magnetometers when non-sinusoidal waveforms are measured. Moreover, five previous studies on magnetometers [3–7] have been analyzed in [1], concluding that 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 electrical distribution networks. Thus, this paper shows the results of the second part of the study.

2. Evaluation of magnetometers

The measurements have been performed using the same octagonal Helmholtz coil having a coil constant correction curve in a frequency range from 0 to 10 kHz used in [1]. The octagonal Helmholtz coil with centrally directed

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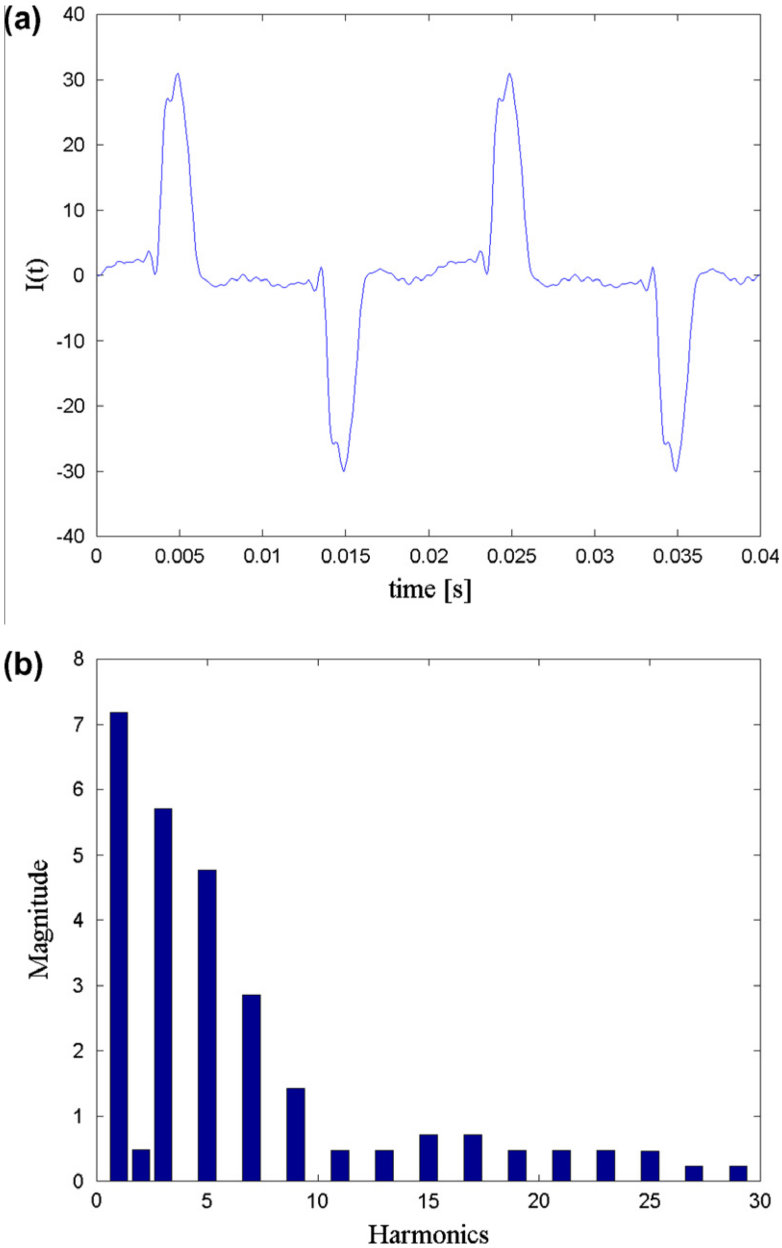

Fig. 1. (a) Current waveform of a computer power supply. (b) Frequency components.

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.

2.1. Measurement procedures

A set of non-sinusoidal periodic signals was used to evaluate the behavior of the meters when more than one component is present. The main objective of these measurements was to test the frequency analysis performed by the magnetometers, i.e., to test the accuracy of the Discrete Fourier Transform (DFT or FFT), or other applied algorithms of frequency analysis. The rms measurement of complex non-sinusoidal signals was also evaluated. The set of used signals was:

- Test using signals having constant phase angle, constant magnitude, and variable frequency: The magnitude and frequency response of filters are, in general, not linear. During this test the phase angle and magnitude were kept constant as frequency varies. The test signal includes a constant first component of 50 Hz and a second component, with amplitude of 10% with respect to the one of the first component, that successively takes the selected harmonic frequency values: 150, 250, 350, 550, 750, 1050, 2000, 5000, and 10,000 Hz.

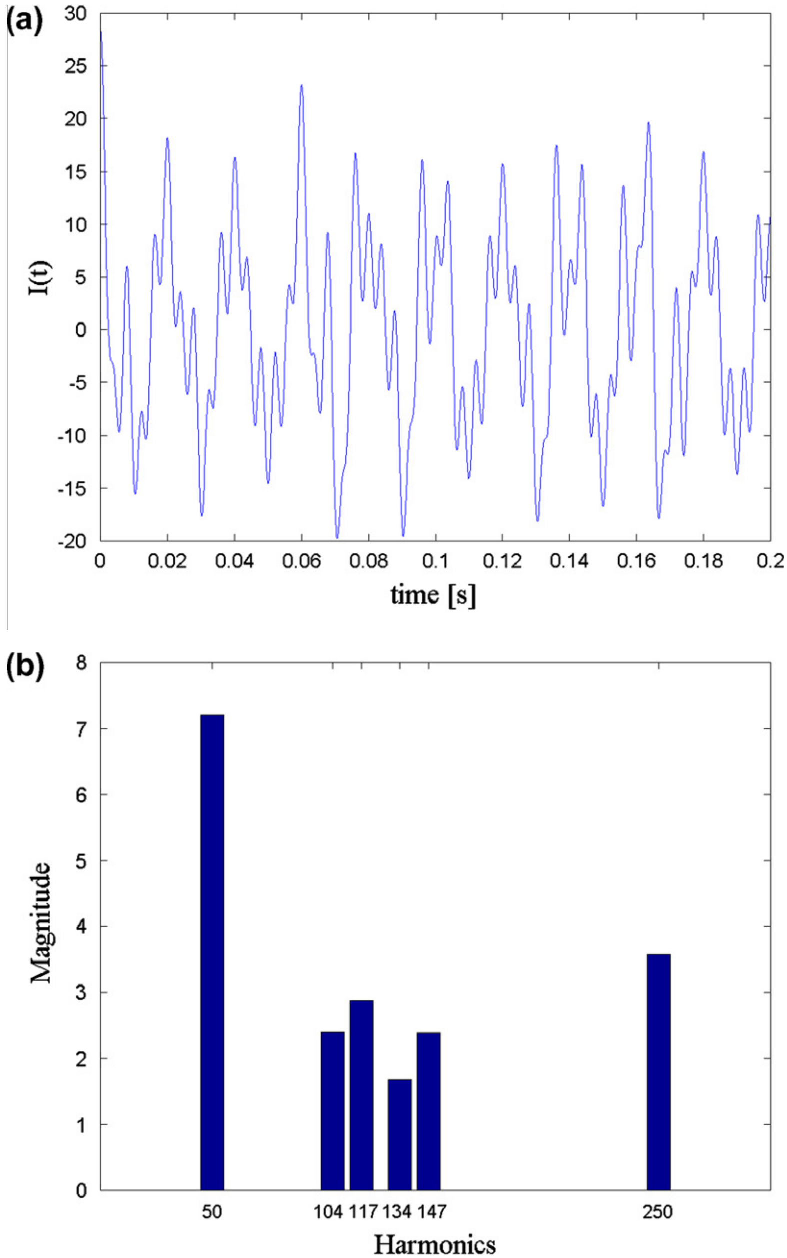

Fig. 2. (a) Current waveform having harmonic and interharmonic frequency components. (b) Frequency components.

- Magnetic fields produced by practical current waveforms: In this part, magnetic fields having several frequency components were generated by known current waveforms obtained from typical signals of some industrial devices. A literature search identified the current waveform of computer, photocopier, and color television power supplies [8], variable speed drives [9], signal with harmonic and interharmonic components [10], DC motor drive, and uninterruptible power supply (UPS) [11]. However, because of the amount of measurements performed, only the current waveform of a computer power supply, having a 50 Hz fundamental frequency (Fig. 1), and a signal having harmonic and interharmonic components (Fig. 2) are reported here.
- Signals related with power phase control: These signals contain a great amount of harmonic components and they are broadly used in the industry, e.g. in the car industry. Moreover, the frequency spectrum of the waveform varies according to the delay angle. The measurements of 50 Hz periodic signals with a phase control of 30% (54°) are reported in this case (see Fig. 3).

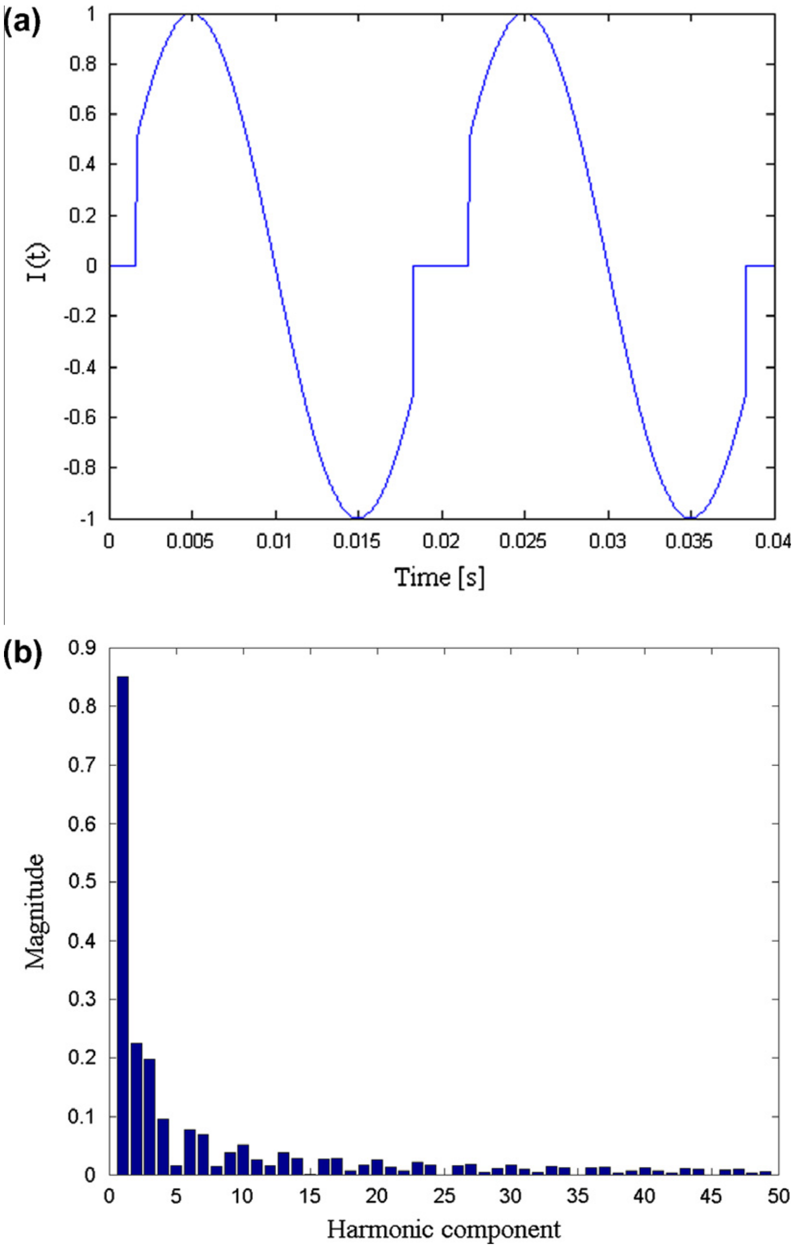

Fig. 3. (a) Current waveform of a 30% phase control signal. (b) Frequency components.

2.2. Set of magnetometers

The non-sinusoidal tests were applied to meters having frequency analysis tools, i.e., meters classified as type b and d in Ref. [1] (both type of meters have frequency analysis tools, but type b meters have a frequency range below 10 kHz and type d meters have a frequency range above 10 kHz). Table 1 shows the list of the tested magnetometers with the following information: magnetometer number for identification purposes, type of meter according the above classification, sensor type, number of axes, core type, cross-section area, and frequency range.

3. Results

The test results are used to characterize the behavior of meters when non-sinusoidal signals are measured. A selection of the more relevant results found in the tests is shown in this section. The reported errors correspond to the average relative error according to the followig equation:

$$Error = \frac{B_{measured} - B_{calculated}}{B_{calculated}} \cdot 100\% \quad (1)$$

where B is the measured or calculated magnetic flux.

Table 1
Specifications of the magnetic field meters used in the study (N/A: not available).

Meter Number	Type	Sensor: Type	Number of Axes	Core	Area cm^2	Frequency range (Hz)
2	d	Coil	3	Air	100	5–30k
4	d	Coil	3	N/A	N/A	5–32k
4a	d	Coil	3	Air	100	5–32k
4b	d	Coil	3	N/A	9.42	5–32k
9	d	Coil	3	Air	100	10–400k
11	d	Coil	3	N/A	N/A	10–30k
16	d	Coil	3	Air	100	16–45k
18	d	Coil	3	N/A	N/A	16–100k
19	d	Coil	1	N/A	N/A	50–400k
21	d	Coil	3	Air	100	16–45k
22	d	Coil	3	Air	100	10–400k
24	b	Coil	3	Air	100	10–3.2k
30	d	Coil	3	N/A	N/A	5–100k
33	d	Coil	3	Air	100	5–32k
34	d	Coil	3	Air	100	10–30k
38	b	Coil	3	Air	100	10–3.2k
39	b	Coil	3	Air	100	10–3.2k
41	b	Fluxgate	3	Ferromagnetic	0.1	0–1000
42	b	Fluxgate	3	Ferromagnetic	0.1	0–1000

3.1. Constant phase angle and magnitude, variable frequency test

Fig. 4a shows the waveform rms value error of meters of type b; these errors were similar to those observed during the measurements of pure sinusoidal signals [1]. Fig. 4b shows the error for the 50 Hz component measurement. Meter 42 shows an increase of the error, a consequence of having an FFT algorithm designed to measure waveforms having a fundamental frequency of 60 Hz.

Similarly, Fig. 5a shows a large error in the variable component measurement of meter 42. For the other meters of type b, Fig. 5b shows that the errors in the variable component measurement are similar to the errors observed for pure sinusoidal signals [1]. However, meters 24, 38, and 39 showed an increase of the error in the 2000 Hz component measurement.

Fig. 6a shows the waveform rms value errors for meters of type d. All meters, except for meter 30, had errors that were similar to those observed during the measurements of sinusoidal signals [1]. Meter 30 showed large errors for the 50–5000 Hz and 50–10,000 Hz tests. For these cases, the meter filter had to be set in a 10 kHz span, but the low cut frequency for this span is 120 Hz. Thus, it is not possible to measure waveforms having so distant frequency components with this meter.

Fig. 6b presents the results for the 50 Hz component measurements. Most meters showed results that were similar to those observed in the previous tests. Meter 30 confirms that the error in the rms value measurement for 50–5000 Hz and 50–10,000 Hz was a product of the filter cut frequency. On the other hand, although meters 2 and 34 showed good results in the waveform rms test, they have problems when measuring signals composed by two components having very distant frequencies. As an example, meter 2 could not measure the components of the 50–10,000 Hz test and meter 34 the components of the 50–5000 Hz and 50–10,000 Hz tests. This is produced by the rigid FFT of the meters.

Fig. 7 shows the variable component measurement error for meters of type d; meters 2 and 34 show the same error of the 50 Hz component in the 50–5000 Hz and 50–10,000 Hz measurements. An error increase of all meters for the 5000 Hz and 10,000 Hz frequency components can also be noticed.

3.2. Practical waveforms

The first case of this type of test is a reconstructed computer power supply current waveform having 16 harmonic components (Fig. 1). For meters of type b, Fig. 8 shows the relative error for each measured harmonic component. In this test, the meters showed different errors for different frequencies and magnetic flux densities. The sudden changes in the error curves, e.g., meter 24 from −3% at 450 Hz to −14% at 550 Hz, are produced by the reduced resolution of the displays for relative low intensities and by the meter intensity linearity. Nevertheless, the relative errors are always smaller than 15%.

Fig. 9 shows the errors of the harmonic components for the computer waveform for meters of type d. The figure presents a diversity of results. Meter 21 measured all harmonic components with small error independent of the magnetic field intensity of each frequency component. Meter 11 had errors smaller than 4%, except for the 100 Hz component, having an error of almost 50%. It must be noted that this harmonic component has a relatively low magnitude. Meters 2, 16, 22, and 30 showed errors smaller than 13% for all harmonic components. Meter 9 showed errors smaller than 4%, except for the last two frequency components that have errors of 27%; however, these harmonic components have the smallest relative magnitude. Meter 34 showed large errors in the relatively small-magnitude harmonic components, e.g., 100, 550, 650, 950, 1050, 1150, and 1250 Hz components had errors larger than 30%, and the last two harmonic components were not detected by its FFT algorithm. Meters 4 and 4a can only measure the nine largest frequency components with their

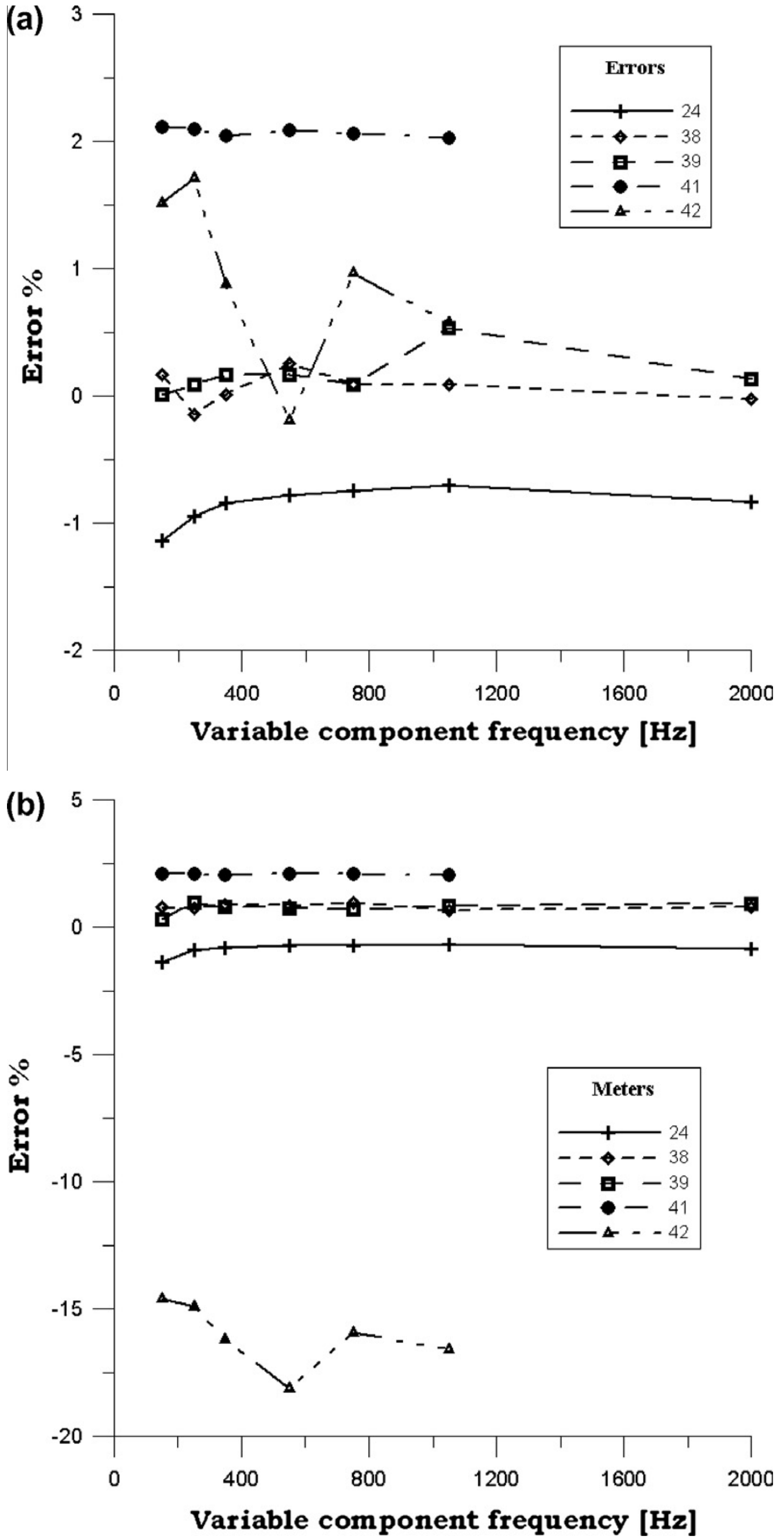

Fig. 4. Type b meter errors for signals having two components, one with 50 Hz and the other with a variable frequency. (a) Waveform rms measurement. (b) Component of 50 Hz.

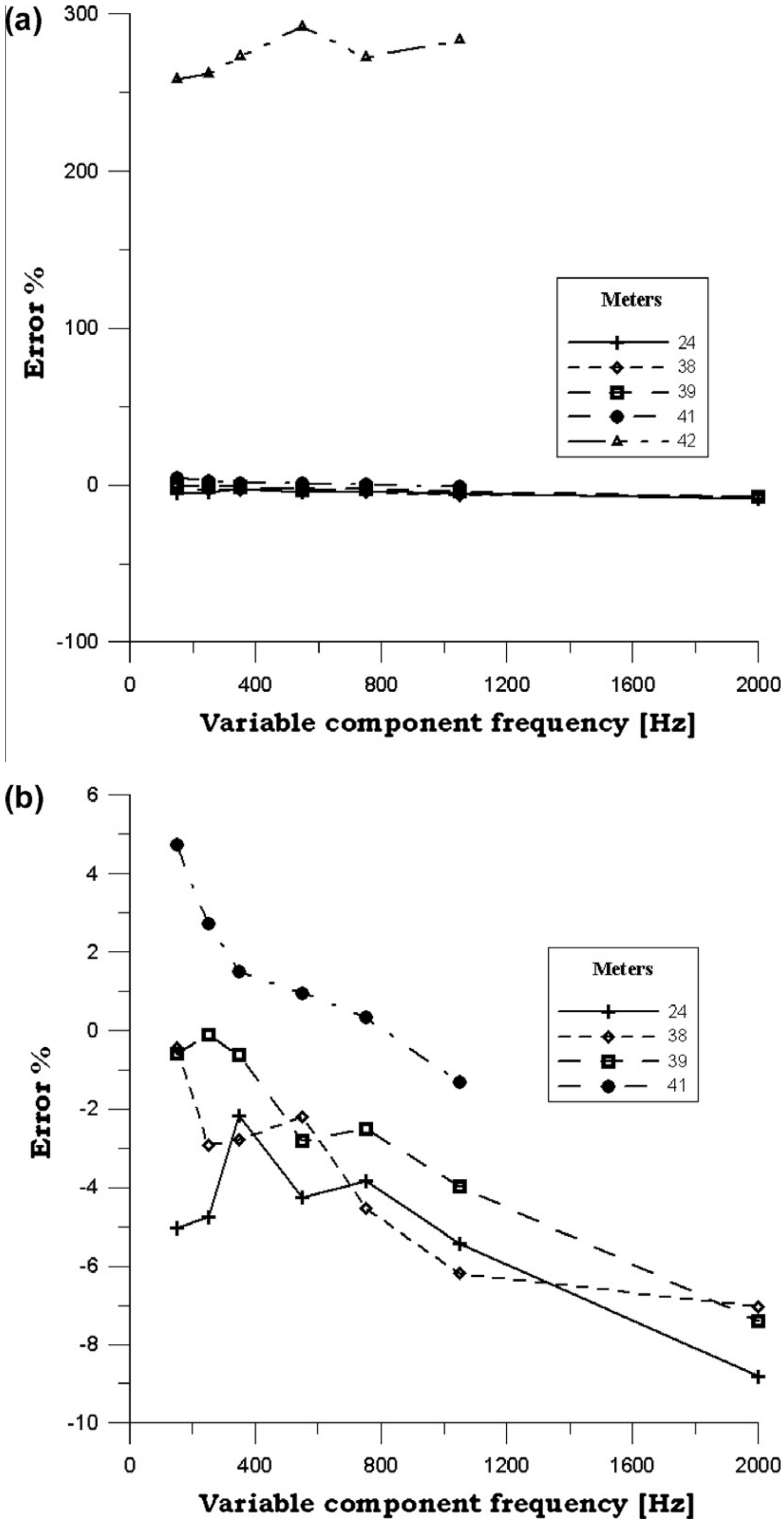

Fig. 5. Type b meter errors for signals having two components, one with 50 Hz and the other with a variable frequency. (a) Variable component. (b) Ignoring meter 42.

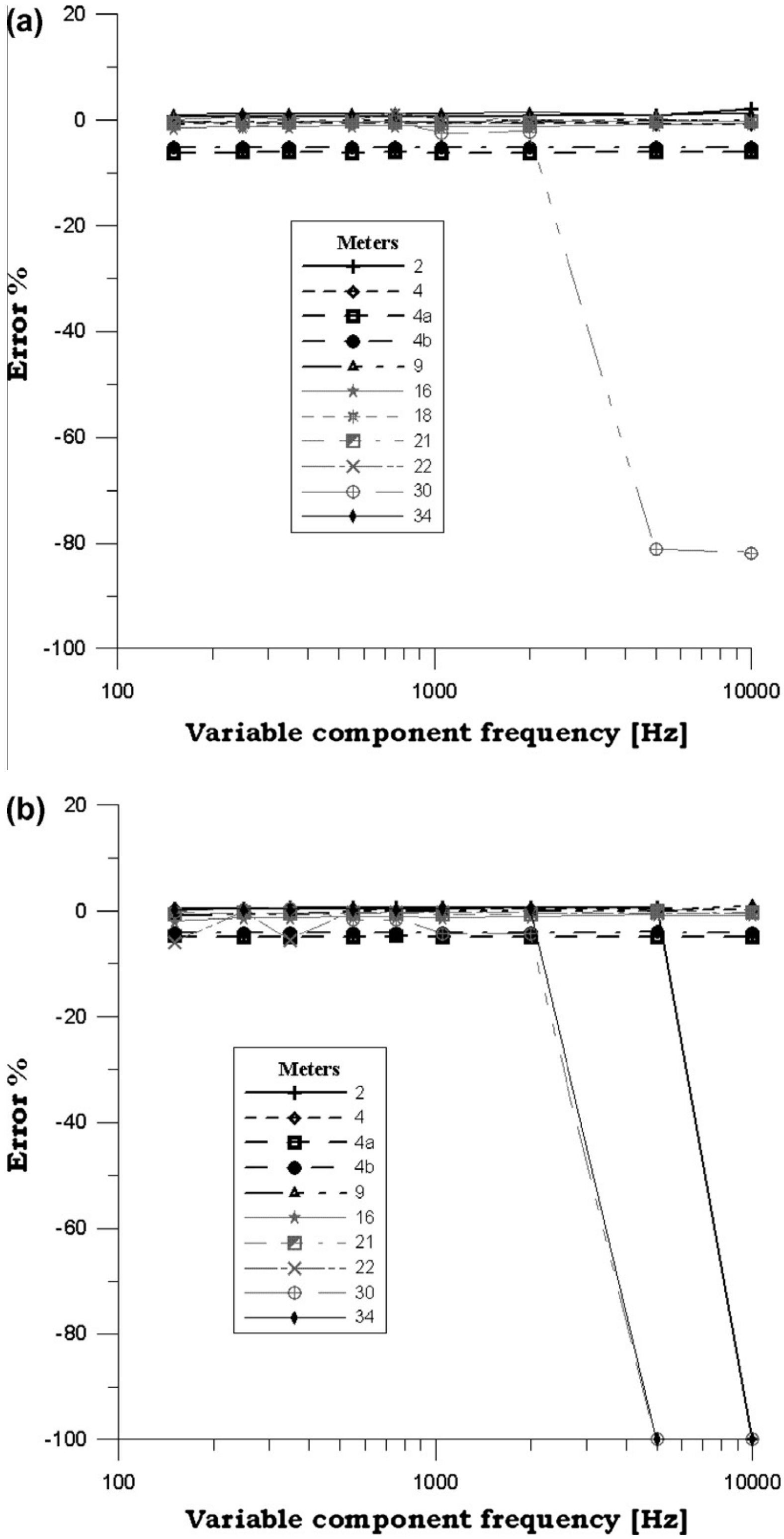

Fig. 6. Type d meter errors for signals having two components, one with 50 Hz and the other with a variable frequency. (a) Waveform rms measurement. (b) Component of 50 Hz.

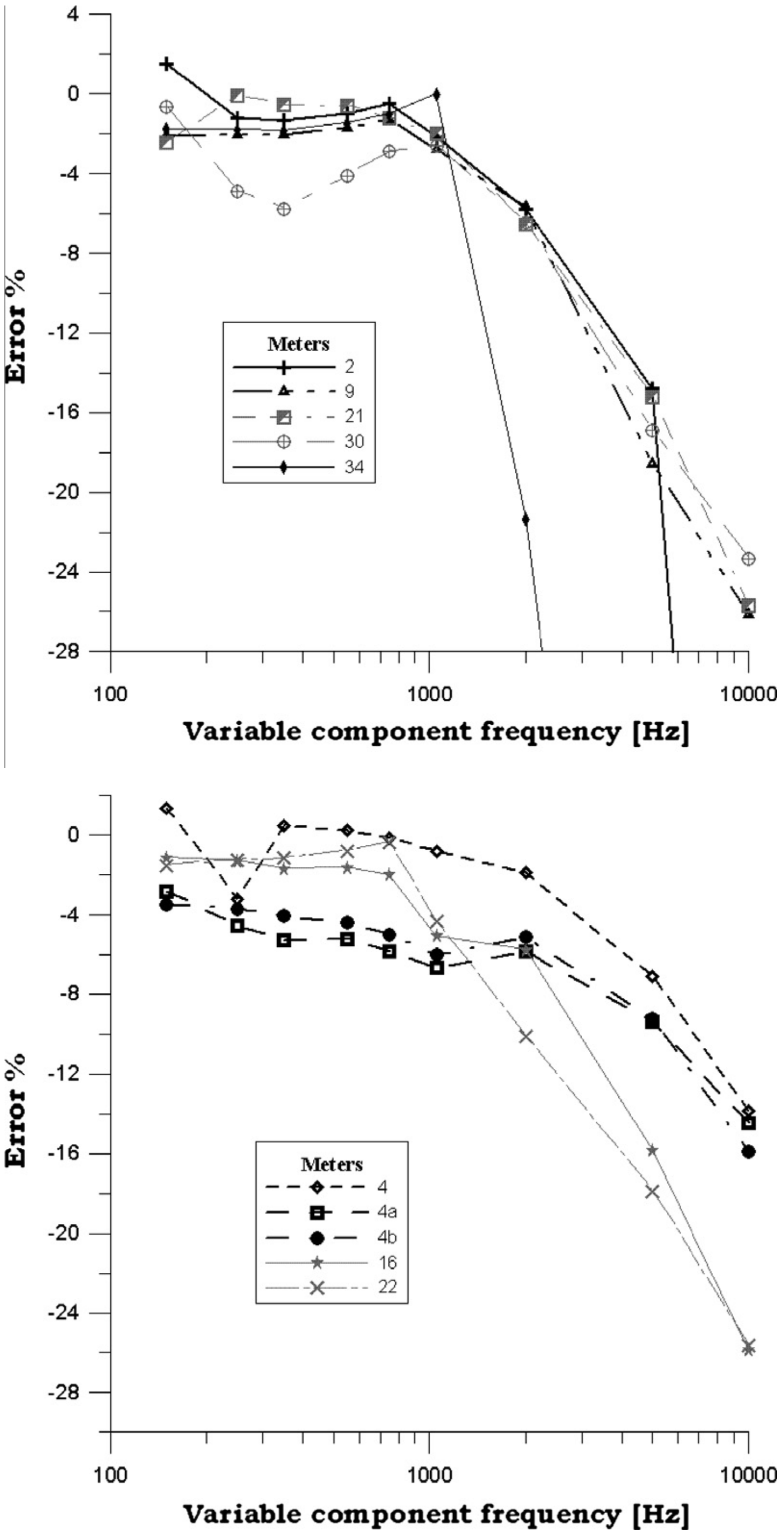

Fig. 7. Variable component errors of type d meters for signals having two components, one with 50 Hz and the other with a variable frequency. Note that errors for meters 2 and 34 exceed the axis limit of 28% (their errors at 10 kHz were −100%, i.e., they failed to detect the second frequency component).

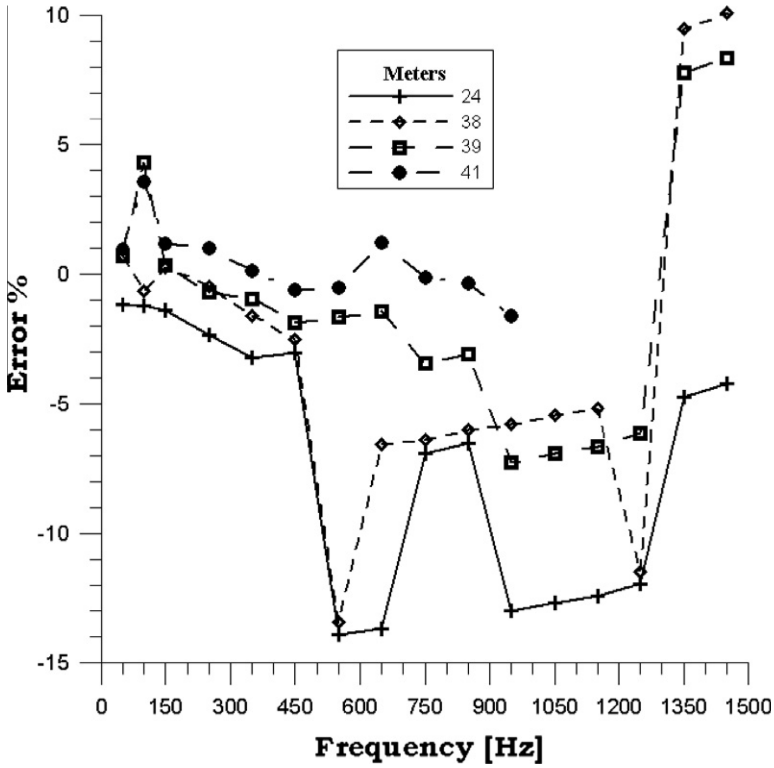

Fig. 8. Type b meter errors in the frequency components of a computer power supply waveform.

FFT function. For these nine components, the errors remained smaller than 8%. However, the meters could not give information about the other frequency components.

The next measurements have been performed using waveforms containing harmonic and interharmonic components (Fig. 2). Fig. 10 shows the errors of the harmonic and interharmonic components for meters of type b. The test was only applied on meters 24, 38 and 39, and they showed small errors for all frequency components, i.e., less than 6%. The three meters can have a frequency resolution of 1 Hz for their FFT functions, which accomplish suitable results for this type of waveform.

Fig. 11 shows the errors of the harmonic and interharmonic components for meters of type d. Fig. 11a shows that meters having a frequency resolution of 1 Hz, had small errors for all components (less than 6%). On the other hand, Fig. 11b shows that meters 2, 11, and 34 had large errors for the interharmonic components, since the minimum frequency resolution of their FFT functions are 16.67, 5.56 and 50 Hz respectively.

3.3. Phase control waveforms

Fig. 3b shows that a 30% phase control signal has several harmonics, and they do not decrease as quickly as other harmonic components of typical waveforms. Fig. 12 shows the errors of the harmonic components of the 30% phase control waveform for meters of type b. The figure only shows the errors of the detected components, e.g., meter 24 did not detect the fifth harmonic (250 Hz) and no symbol is shown in the figure at this frequency for meter 24. Meter 41 only detected 3 components with its FFT algorithm. Meter 24 detected fewer components than meters 38 and 39. Meters 24, 38, and 39 did not detect the smallest harmonic components. For the detected harmonics, the errors were smaller than 25%. Meter 24 did not detect 10 harmonic components up to 1200 Hz. Meter 38 and 39 did not detect 4 and 3 components respectively.

Fig. 13 shows the errors of the harmonic components of the 30% phase control waveform for meters of type d. The non-detected components are not shown in this figure. Meters 2, 4, 4a, 16, 21, and 30 had errors lower than 10% for the detected harmonic components. Meter 22 showed errors lower than 15%, meters 9 and 11 lower than 30%, and meter 34 lower than 35%. Meters 4 and 4a could only measure the nine largest components. Meter 21 did not detect three components up to 1200 Hz, meter 30 one component up to 1000 Hz, meter 2 one component up to 900 Hz, meter 9 one component up to 900 Hz, meter 22 six components up to 1000 Hz, and meter 34 five components up to 900 Hz. Meter 11 detected all harmonic components up to 1100 Hz.

Now, phase control waveforms have several harmonic components of large magnitude. It is interesting to know how accurately the meters can measure the waveform rms value of the phase control waveforms. Table 2 shows the waveform rms measurement error of the 30% phase control waveform for the tested meters. The results of the waveform rms measurement show small errors for all tested meters.

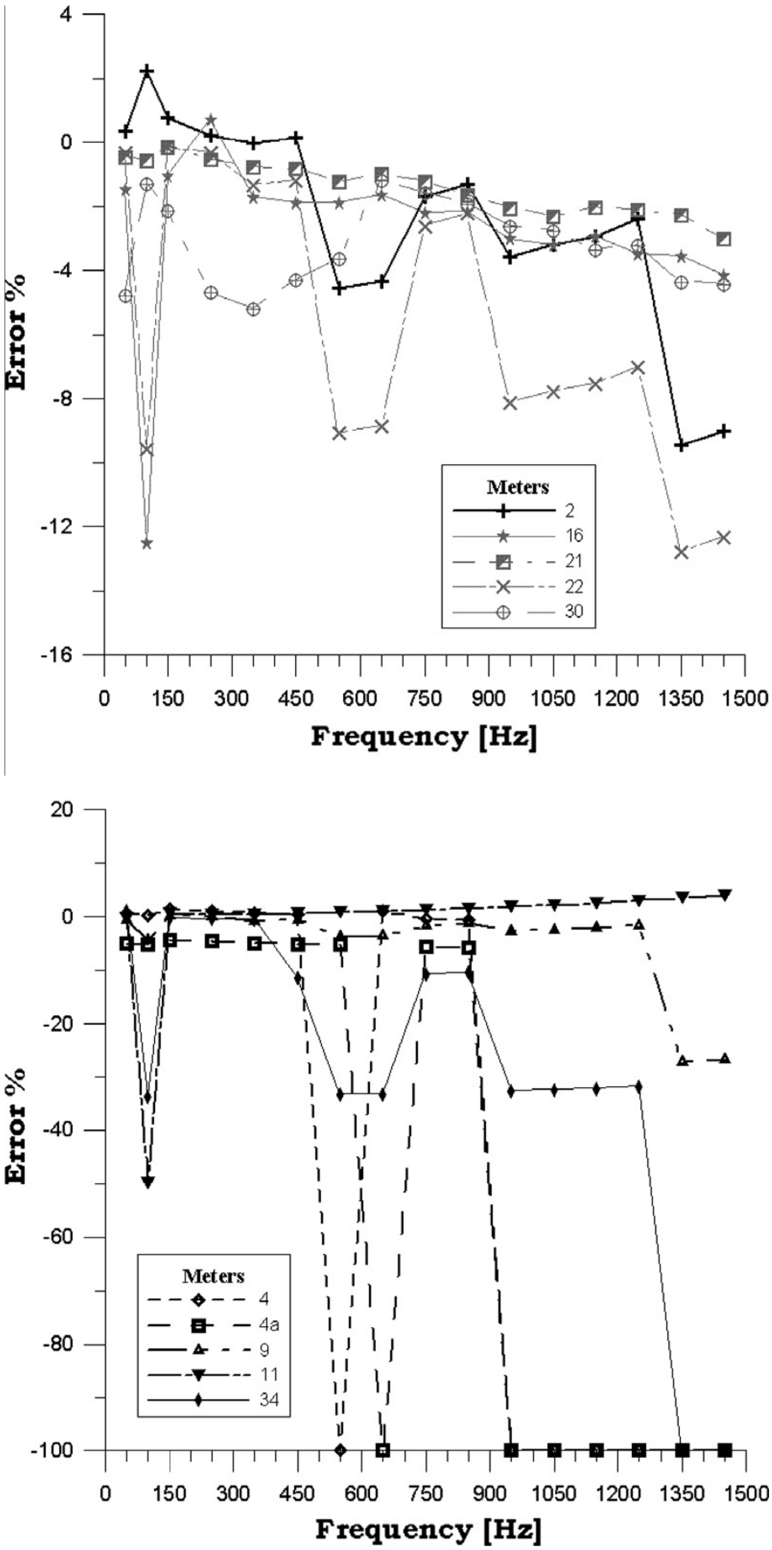

Fig. 9. Type d meter errors in the frequency components of a computer power supply waveform.

Some meters have also a peak measurement function, and it is interesting to investigate the accuracy of this function. Table 2 compares the waveform rms measurement with the waveform peak value measurement errors in the 30% and an additional 50% phase control waveform tests. Although the waveform rms measurement errors

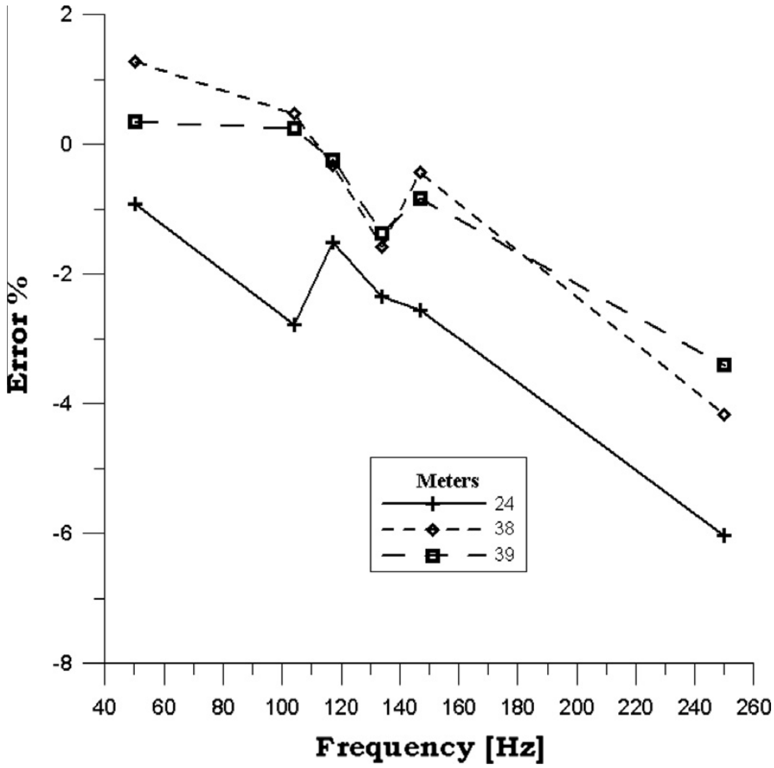

Fig. 10. Type b meter errors in the frequency components of waveform having interharmonic and harmonic frequencies.

were small in all tested meters, the peak measurement errors showed larger errors in several meters. Meters 4, 4a, 23, and 33 had peak value errors for the 30% phase control waveform of 29%, 41%, 47.5% and 44% respectively. However, in the 50% phase control waveform they showed errors of 9.7%, 5%, 9.6% and 7.7% respectively.

3.4. Waveform capture

Some meters also allow the capture of the waveform for further analysis. Fig. 14 shows the 30% phase control waveform capture of meter 11. The figure shows the capture using the three axes of the meter. This figure shows a severe distortion in the waveforms, making the waveform asymmetric.

On the other hand, Fig. 15 shows the 30% phase control waveform capture of meter 21. The figure also showed a three axes capture. This figure shows little distortion of the waveforms, keeping the signals symmetric. The waveform capture shows also oscillations near the firing of the waves, produced surely by the antialiasing low frequency filter of the meter. Fig. 16 shows the 30% phase control waveform capture with meter 42. The figure shows that meter 42 does not produce a distortion of the waveform capture.

Although meter 18 was classified as type d meter, the response of the meter was acquired with a personal computer. The computer had a software package, provided by the meter manufacturer, based on the FFT to identify the frequency components of the magnetic field. However, the response of this software had high spectral leakage, due to an inadequate base frequency. For example, in a test for which two components were used, one of 50 Hz and another of 10 kHz, the base frequency Δf was 2.69 Hz. For the test having two components, one of 50 Hz and other of 150 Hz, the base frequency Δf was 0.49 Hz. The FFT is inappropriately programmed, and the wrong base frequency results in wrong magnitudes and the appearing of non-existent components. Fig. 17 shows an example of spectral analysis of meter 18; it shows that the non-synchronized FFT function introduced frequency components that were not generated by the test set-up.

4. Discussion

In the analysis of non-sinusoidal periodic signals, most meters showed errors larger than 10% in one or more tests. The FFT algorithms of the different magnetometers differ from each other according to their online or offline application, to the frequency resolution that varies in most cases with the possible frequency range, to the number of frequency components that the algorithm reports, etc.

The variable frequency test produced large errors in the frequency component detection for meters 2, 30, and 34 when the two frequency components were very far away, e.g. the 50–10,000 Hz case. The frequency response of the filter (meter 30) and the large frequency resolution and rigid programmed FFT (meters 2 and 34) were the reasons for these errors. For the other meters, errors larger than 10% were found in the 50–5000 Hz and 50–10,000 Hz cases.

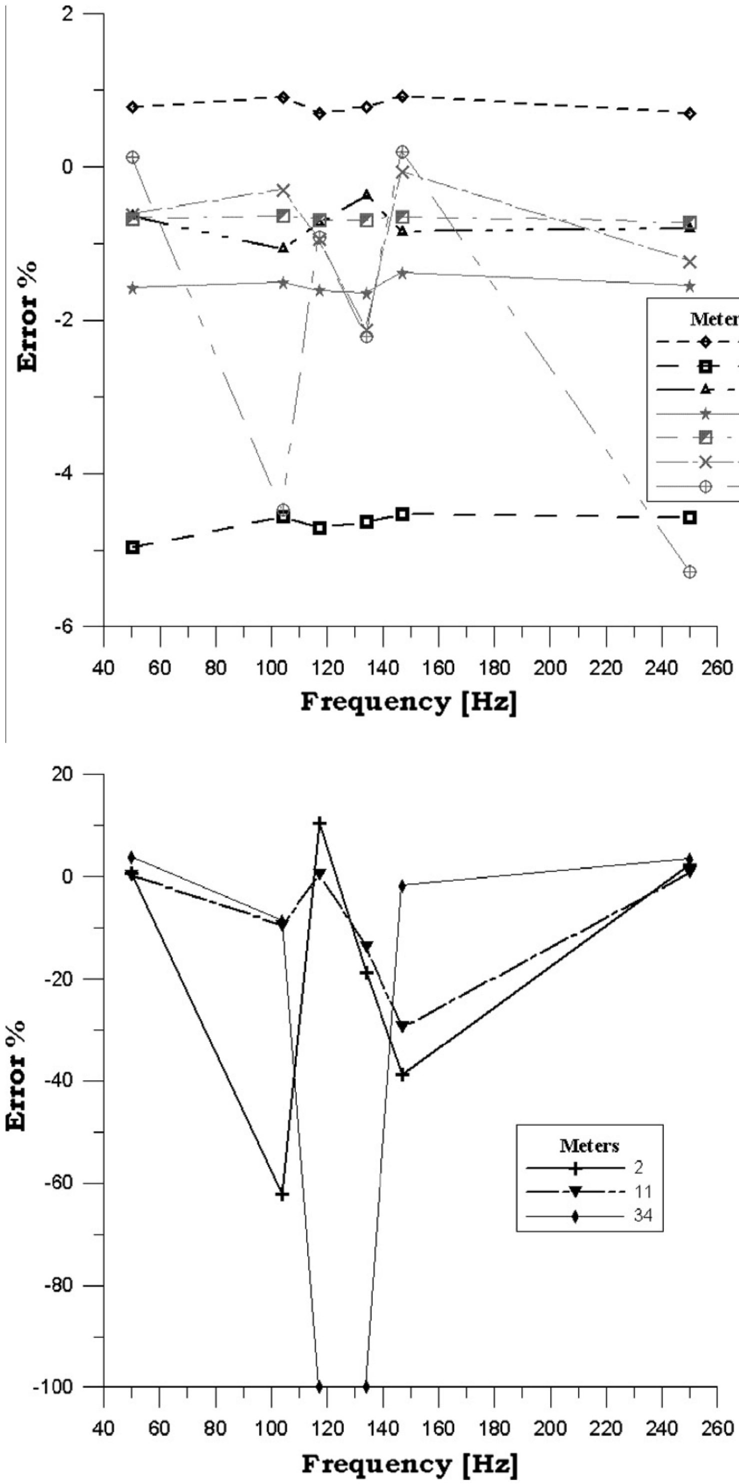

Fig. 11. Type d meter errors in the frequency components of a waveform having interharmonic and harmonic frequencies.

Only meters 16, 21, and 30 had accurate measurements for all frequency components in the practical current waveform tests. The other meters had problems in one or more tests that were caused by reduced frequency resolution and reduced display resolution in the case of measuring frequency components with a large amplitude difference, or by the limited number of frequency components that the meters can report. The errors in the

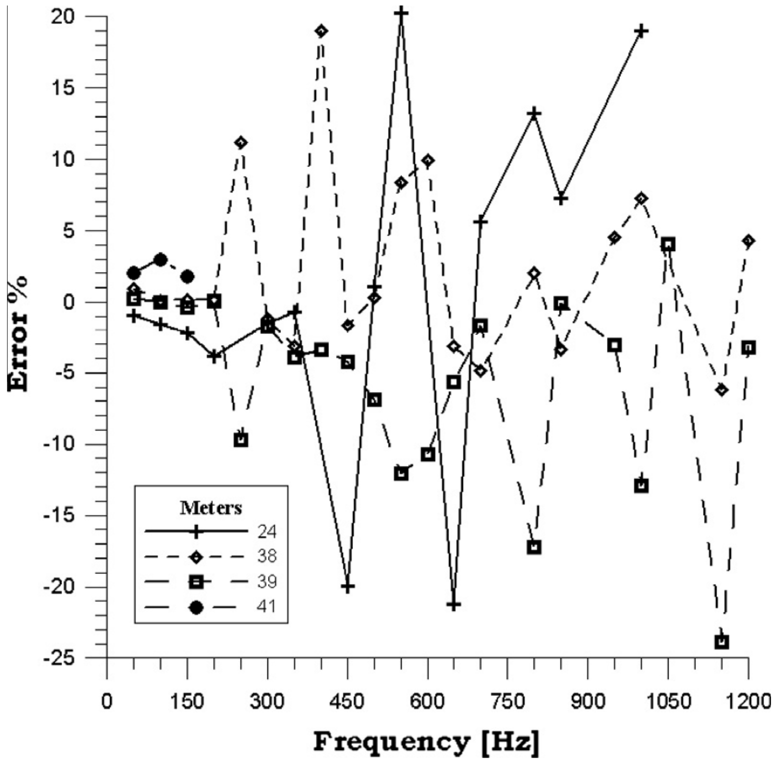

Fig. 12. Type b meter errors in the frequency components of a 30% phase control waveform.

amplitude estimation of the frequency components vary from 10% to 100%, i.e., some meters failed in the detection of some frequency components.

Although the phase control waveforms have the peculiarity of having a great amount of harmonic components of different amplitudes in a broad frequency range, the results with this kind of waveform were similar to those of the practical current waveform tests. Meters 4, 4a, 16, 21, and 30 had errors lower than 10% for the detected harmonic components. However, other meters had errors of up to 35% in the amplitude estimation of the smaller harmonic components.

Large errors were found in the readings of some meters during the peak value measurement of the phase control waveforms. Errors up to 47% in the peak estimation reveal problems for some meters in the accuracy of this function. An examination of this function in the practical waveform tests also shows an error of 19% for meter 22. It is interesting to note that the meters accurately measure the rms value of the non-sinusoidal waveforms, but some of them measure the peak value of some waveforms incorrectly.

The comparison of the wave capture for phase control waveforms with meters 11, 21, and 41 shows that meter 11 distorts the wave of the phase control fields. Further research is necessary to establish the reasons of this distortion, and the behavior of other meters that can capture magnetic field waveforms.

Meters 4, 4a, 4b, 9, and 22 had a function for exposure assessment according to some standards that limit the exposure to magnetic fields, e.g., the ICNIRP guidelines [12], the BGR B11 [13], etc. This type of function is a good alternative to assess the exposure to magnetic fields. However, further research work is necessary in order to test the accuracy of this function for different non-sinusoidal waveforms, including low frequency pulses.

5. Conclusions

The variety of meter designs produced different results depending on the measured waveform. The major drawbacks found for many FFT functions of the meters are:

- reduced frequency resolution or the non-synchronized FFT analysis that produce spectral leakage and picket fence effect errors;
- reduced magnitude resolution when a waveform has simultaneous frequency components with large differences in amplitudes, i.e., some meters have large errors in the magnitude estimation of small-magnitude frequency components because the meter display uses the same display configuration for the large-magnitude and the small-magnitude frequency components;
- failure to detect small-amplitude frequency components when the waveforms have large-amplitude frequency components, produced by signal-to-noise problems or the reduced magnitude resolution of the detector.

It is a challenge to build a magnetometer that successfully succeeds in all proposed tests. The FFT is a rigid tool

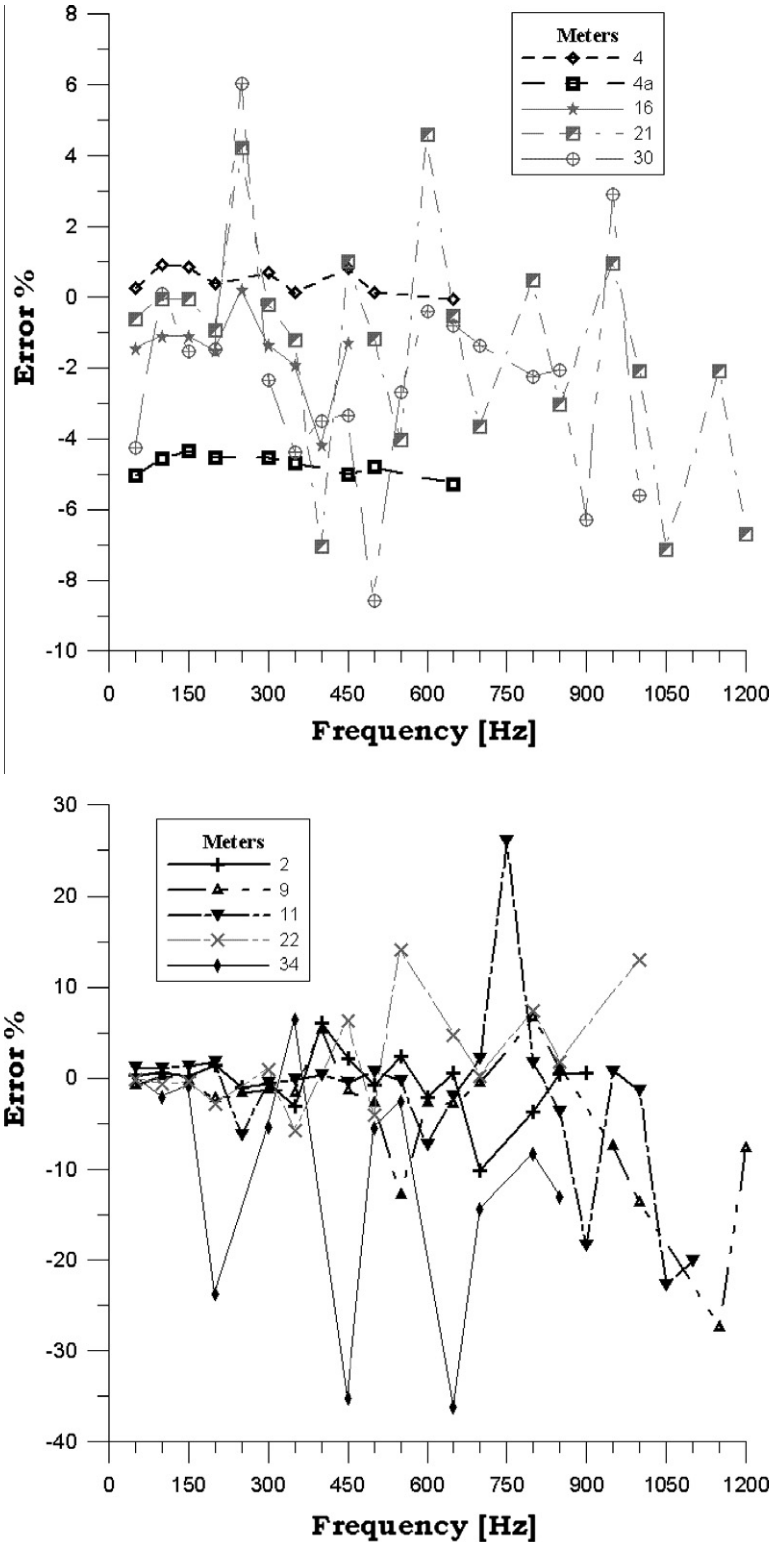

Fig. 13. Type d meter errors of the frequency components of a 30% phase control waveform.

that must be programmed according to the application. However, advances on harmonic and interharmonic detection and estimation are continuously reported [11,14–17].

Table 2
Comparison of the waveform rms value and peak value measurement errors for 30% and 50% phase control waveform tests.

Test meter	Phase control 30%		Phase control 50%	
	Error Brms (%)	Error Bpeak (%)	Error Brms (%)	Error Bpeak (%)
2	0.56	4.40	0.76	6.17
4	−1.86	28.93	−0.50	9.78
4a	−6.08	41.41	−5.60	5.18
9	0.09	6.40	−0.86	6.78
11	0.92	4.71	0.87	6.46
21	−0.63	−0.15	−0.68	4.21
22	0.15	5.91	−0.01	6.32
24	−1.22	47.54	−1.10	9.66
33	−1.22	8.46	−1.37	12.51
34	−4.17	44.34	−3.76	7.78
38	0.78	6.53	0.91	7.99
39	−0.01	9.07	−0.35	13.57

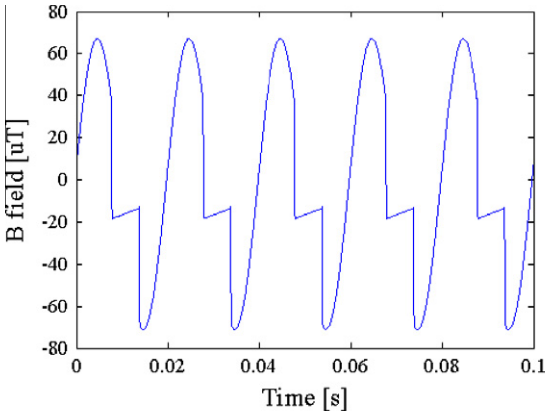

Fig. 14. Meter 11 capture of the of a 30% phase control waveform.

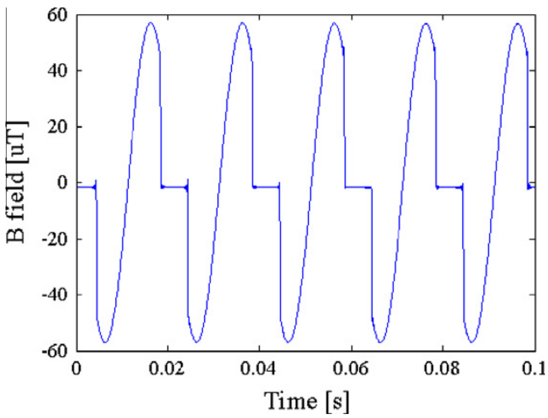

Fig. 15. Meter 16 three axes capture of a 30% phase control waveform.

The failure in the detection of frequency components of small amplitude can result in an erroneous exposure assessment according, for example, to the ICNIRP guideline [12]. If for example a signal has three frequency components of 50 Hz, 100 Hz, and 150 Hz, having amplitudes of

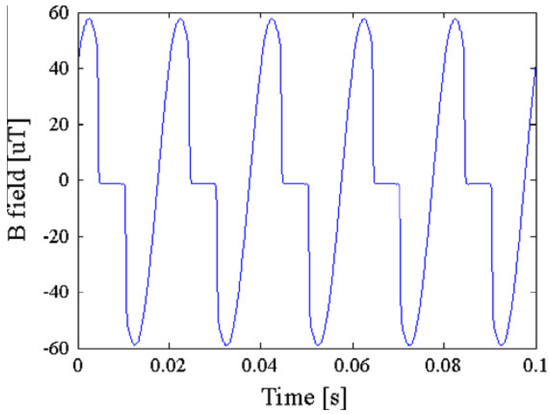

Fig. 16. Meter 42 capture of 30% phase control waveform.

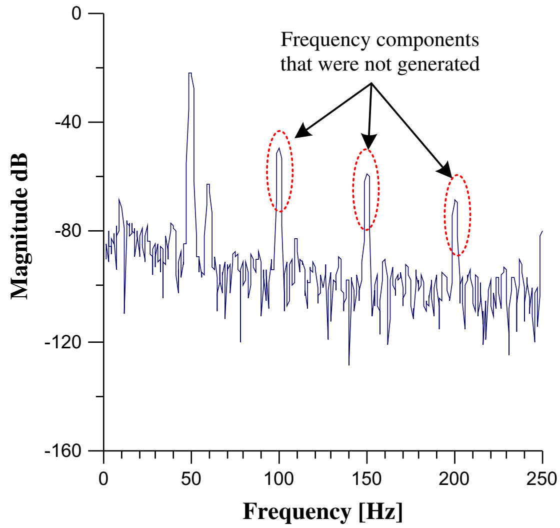

Fig. 17. Evident spectral leakage by the non-synchronized FFT of meter 18 in a test with two frequency components (50 and 60 Hz).

550 μT, 5.5 μT, and 5.5 μT (1% of the fundamental) respectively, the error in the exposure assessment when the meter does not detect the small frequency components is 4%, i.e., the magnitude of the exposure of the three components is 81.6% and for the 50 Hz component is only 77.7%. However, if the two small frequency components have frequencies of 1000 Hz and 1050 Hz, the error in the exposure assessment will be 25%, with the exposure of the three components being 103.1% (reaching the limit). This shows that it is important for a meter also to detect frequency components of small amplitudes.

The problems in detecting and measuring small frequency components observed in several meters were caused by:

- Signal-to-noise problems produced in the signal conditioner integrating amplifier. An alternative for solving this problem is to use a measurement system consisting of a detector without an integrating stage [18]. The

detector can be combined with instrumentation to digitize the signal waveform which is proportional to the derivative of the magnetic field, and using Fourier analysis, the amplitude-enhanced harmonic component amplitudes can be determined using computer software. With this measurement approach for detecting higher order harmonics, the correct harmonic percentages and their phase relations can be determined.
- When the probe and the detector are close, the electrical noise can create a ‘‘noise floor’’ which prevents magnetic field measurements below a certain level [18].
- The use of a reduced magnitude resolution on the display for the small amplitude harmonic components can produce large errors and the non-detection of the small amplitude components.

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