

ERRORS IN MEASUREMENT OF ELECTROMAGNETIC FIELDS

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Abstract – The accurate measurements are essential for an effective control of human exposure to electromagnetic fields. In the paper, some systematic errors that could be introduced in the measurement of ELF electromagnetic fields are identified. The influence of measurement errors on the measurement accuracy is quantified, and the procedures for minimizing and avoiding the errors are stated.

Keywords: electromagnetic fields, measurement, errors.

1. INTRODUCTION

With the development of general consciousness about the possible human health effects of the electromagnetic fields, the questions of electromagnetic pollution is becoming a matter of serious scientific and public health policy concern.

Based upon the results of the large number of epidemiological and laboratory studies of the biological effects of electromagnetic fields, the international guidelines [1] and recommendations [2] for the limitation of the human exposure to electromagnetic fields have been issued.

As a result, more and more countries are including the control of human exposure to electromagnetic fields into their protective legislation.

The legislative control of human exposure to electromagnetic fields is performed mainly by restricting the allowed levels of electromagnetic fields in the human environment. The field levels are controlled by means of the electromagnetic fields measurements.

Therefore, the accurate measurements of electromagnetic fields are of an utmost importance for a trustworthy implementation of the protective legislation.

The term *electromagnetic fields* here denotes a wide frequency spectrum of electromagnetic radiation, from 0 to 300 GHz. It comprises different kinds of fields, from static electric and magnetic fields, over the extremely low frequencies (ELF) fields and radio-frequency (RF) fields, to microwaves.

The electromagnetic fields in the human environment are different not only in frequency. Due to various sources, the electromagnetic fields in the same frequency band may have substantially different wave-forms.

All that makes the measurement of electromagnetic fields a delicate task, requiring a careful selection and use of measurement instrumentation.

The substantial errors could be introduced if the characteristics of measurement instrumentation are not

exactly understood, and if these are not appropriate for the characteristics of the measured fields.

In the paper some typical errors encountered in ELF fields measurements are identified. The influence of these errors on the measurement accuracy is quantified, and the methods to avoid the errors are proposed.

2. ELF FIELDS

The term ELF (extremely low frequencies) denotes the lowest part of the frequency spectrum, comprising some of the major components of electromagnetic pollution, and these are the power-frequency fields and the VDU fields.

Due to the large wavelength (thousands of km) of ELF fields, all the interesting things happen in the near-field region where the magnetic and electric fields are considered and measured independently. For measurement of these fields, various types of probes are used, most of them having similar operation principles, as follows.

2.1. Basic principles of the field-probes operation

The predominant type of probes used for measurement of ELF *magnetic fields* are the inductive coil probes. The general theory of operation of a coil probe is based on Faraday's law, which predicts that a voltage V is produced at the ends of an open loop with N turns of wire placed in a time-varying magnetic field. That voltage (i.e. the probe response) is proportional to the time derivative of the magnetic flux ϕ through the loop, as given by

$$V = -N \frac{d\phi}{dt} = -N \frac{d}{dt} \left[\int_A B_n dA \right] \quad (1)$$

where

B_n is the component of the vector of magnetic flux density perpendicular to the element of the area dA ;

dA is an element of the cross-section area A of the loop.

The major type of probes used for measurement of ELF *electric fields* are the capacitive electrode probes. The general theory of operation of an electrode probe is based on the Gauss' law, which determines the charge Q induced on a pair of uncharged conductive electrodes, each with the surface S , introduced in an electric field, as given (in the air) by

$$Q = \epsilon_0 \int_S E_n dS \quad (2)$$

where

ϵ_0 is the permittivity of the free space;

E_n is the component of the vector of electric field strength perpendicular to the element of the surface dS ;

dS is an element of the electrode surface S .

When the mutually connected electrodes are introduced in a time-varying electric field, the current I through their connection (i.e., the probe response) is equal to the time derivative of the induced charge Q , as given by

$$I = \frac{dQ}{dt} = \epsilon_0 \frac{d}{dt} \left[\int_S E_n dS \right] \quad (3)$$

2.2. Power-frequency fields

The power-frequency fields, as invisible companions of our use of electrical power, oscillate with the power-frequency (60 Hz in USA, or 50 Hz in Europe, etc.), following the sinusoidal waveform of alternating voltages and currents (the waveform marked as $B''(t)$ in Fig. 1).

An important characteristic of a field with a sinusoidal waveform is that its time derivative also has a sinusoidal waveform of the same frequency, and an amplitude proportional to the amplitude of the field. Therefore, the application of the types of field probes stated in section 2.1., which may be named *derivative probes* (as their response is proportional to the time derivative of the measured field), is very convenient for power-frequency fields. Let us illustrate this with a coil probe in the power-frequency magnetic field.

The induced voltage (probe response) in a coil probe with N turns of wire, and a cross-section A , perpendicular to the (in the probe area uniform) magnetic field with the flux density $B(t) = B_m \sin(\omega t)$, oscillating in time t with frequency f , and angular frequency $\omega = 2\pi f$, according to (1) would be

$$V(t) = -NA \frac{dB}{dt} = NA\omega B_m \sin(\omega t - \pi/2) = V_m \sin(\omega t - \pi/2) \quad (4)$$

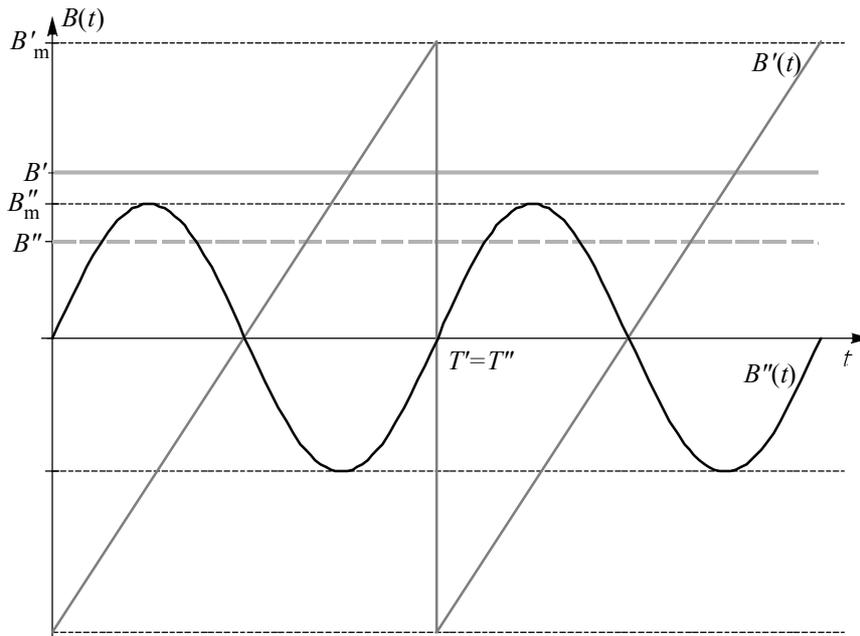


Fig. 1. The sawtooth $B'(t)$ and the sinusoidal $B''(t)$ waveforms of two magnetic fields, which have the same frequency, and induce voltages of the same rms value in a coil probe

where the probe response has the amplitude V_m proportional to the amplitude B_m of the flux density and the rms value V_{rms} proportional to the rms value of the flux density B_{rms}

$$V_m = NA\omega B_m = k B_m \quad \text{and} \quad V_{rms} = k B_{rms} \quad (5)$$

The similar relationship could be shown for the electrode-probe response and the sinusoidal electric field strength E .

Thus, in the sinusoidal field measurements there is apparently no need for integration of the probe response, so that a simple rms indicator can be used as a field-meter detector. A number of commercial field-meters, intended for measurement of power-frequency fields, have been constructed in that manner.

2.3. VDU fields

The video-display units (VDU), in the form of TV sets and computer monitors, are present in our close vicinity at most homes and offices. Therefore, a lot of attention is being paid to the VDU electromagnetic fields, which can be attributed primarily to the cathode-ray tube (CRT) units.

The time-varying VDU fields, that are generated as a consequence of the CRT unit operation, come predominantly from the coil systems for electron beam deflection. The voltages and currents that energize the vertical deflection system are the sources of the ELF electric and magnetic fields which vary in time with the typical frequency of 60-100 Hz (vertical sweep frequency).

Although similar in frequency to the power-frequency fields, VDU fields have a different, *saw-tooth* waveform (marked as $B'(t)$ in Fig. 1).

Due to specific, nonsinusoidal waveform, measurement of VDU fields with derivative probes should include an integrator stage in the field-meter, which should indicate the rms value of the integrated probe response, otherwise a substantial measurement error could be introduced.

3. ERRORS IN FIELDS MEASUREMENTS

3.1. Errors in VDU fields measurement

If, e.g., a field-meter with a derivative probe and without an integrator, intended for 60 Hz power-frequency magnetic field measurement, would be used for measurement of VDU field of the same frequency, then, instead of the real rms value B' , the field-meter would indicate a lower value B'' (as presented in Fig. 1), and the error can be calculated from the probe response $V(t)$, according to (4) and (5), as follows:

$$V(t) = NA \frac{dB'(t)}{dt} = NA \frac{2B'_m}{T} = \text{konst.} = V_{rms} = 2NAf\sqrt{3}B' \quad (6)$$

$$V_{rms} = NA\omega B'' = 2NAf\sqrt{3}B' \quad \text{i.e.,} \quad B'' = \frac{2\sqrt{3}f}{\omega} = 0,55B' \quad (7)$$

We can see that in such a measurement the rms field value B' would be indicated with a significant error of -45%.

The described measurement error would be a bit lower (-34%) if the field-meter were calibrated for 50 Hz power-frequency field measurement. That error decreases with the increase of the VDU vertical sweep frequency up to 90 Hz (where error comes near to zero), and then starts to raise with frequency (e.g., for 100 Hz the error would be +10%).

Generally, the fieldmeters with indication proportional to the derivative of the measured quantity are suited, and should be used, only for measurement of sinusoidal, power-frequency fields

3.2. Errors in power-frequency fields measurement

The field-meters with the indication proportional to the derivative of the measured quantity may generate rroneous indication, not only when applied in measurement of VDU fields, but also in measurement of power-frequency fields. For such an instrument, that has been calibrated for measurement of 60 Hz power-frequency fields (e.g., if purchased in USA), the indication B' is related to the coil probe response V according to (5), as follows

$$V = NA2\pi 60B' \quad (8)$$

If that instrument would be used for measurement of 50 Hz power frequency magnetic field (e.g., in Europe) the coil probe response V , according to (5), would be proportional to the field magnetic flux density B , as follows

$$V = NA2\pi 50B \quad (9)$$

From (8) and (9) comes out the relation between the instrument indication B' and the real field value B as follows

$$B' = \frac{5}{6} B = 0,83B \quad (10)$$

The obtained relation (10) shows that a field-meter with an indication proportional to the derivative of the measured quantity, and calibrated for 60 Hz power frequency, when used for measurement of 50 Hz power-frequency fields,

indicates the field value with an error of -17% (note that in the opposite case, e.g., if such a field-meter was calibrated for 50 Hz, and used for 60 Hz field measurement, the error would be +20%).

Therefore, the field-meters with the indication which is proportional to the derivative of the measured quantity should be used for measurement of fields of the same frequency for which they have been calibrated.

Even in the case when a field-meter with an indication proportional to the derivative of the measured quantity has been calibrated for the frequency of the measured power-frequency field, an error may occur if the field waveform contains higher harmonics. The error in that case depends upon the harmonics content, i.e., the extent of the field sinusoidal waveform distortion. To avoid that kind of error, an integrator stage is built in the field-meter, which integrates the probe response and generates an output proportional to the measured quantity.

Therefore, when a significant harmonic distortion of the field waveform is expected, then the field-meter with an integrator stage should be used, which indicates the *real rms value* of the measured field.

It is important to note that, although the measurement may have been done with a field-meter that indicates the real rms value, an error may occur if the *resultant field value* has not been measured. That may be the case when the one-dimensional probes of the types described in 2.1. are used. The magnitude of such error increases with the angle between the field direction and the perpendicular to the area (surface) of the probe.

To avoid that error and to measure the resultant field value the field-meters with specially constructed three-dimensional probes are used, which simultaneously capture all three spatial components of the field vector, and calculate and indicate the resultant field-value, not depending upon the probe spatial orientation.

However, even a measurement with the field-meter that measures the resultant field value, may yield an error if the measured field is not linearly polarized. That error, due to the *field polarization*, is always positive and may reach a maximum of even +41% (for circular polarization).

Beside the systematic errors described in this section, some additional errors can be introduced in measurement of ELF fields (e.g., electric field measurement error due to proximity of conductive bodies, including the observer himself), as described in more detail in [3] and [4], together with the procedures for avoiding these errors.

4. CONCLUSION

The unfamiliarity with the principal characteristics of the measured field, or the characteristics of the measuring equipment, may cause significant systematic measurement errors, as described in section 3. To avoid the described errors, measuring instrumentation with characteristics appropriate to the characteristics of the measured field should be used.

The major characteristics of the ELF electromagnetic fields that should be considered in measurement preparation are: frequency, waveform (harmonics content), and polarization.

REFERENCES

For the power-frequency fields, simple field-meters with derivative probes, and an indication proportional to the derivative of the field, may be used. It should be checked, however, that the field-meter is calibrated for the frequency of the measured field. If a significant harmonic distortion of the field is expected, or the field has not a sinusoidal waveform (e.g., VDU fields), than the field-meters that measure the real rms value of the field should be used.

For the field-meters that do not measure the resultant field value (those with one-dimensional probe), a procedure for measurement of resultant field value should be defined and applied. In measurement of resultant field value, the field polarization should be considered including the eventual measurement error due to the field polarization.

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