8. The EFA family of instruments for measuring low-frequency electric and magnetic fields

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This family of instruments developed by Wandel & Goltermann represents a complete solution to the problem of measuring electrical and magnetic fields in the frequency range from 5 Hz to 30 kHz. The compact, hand-held instruments in the EFA range (EFA = **E**lectromagnetic **F**ield **A**nalyzer) are characterized by simple operation, measurement conforming to relevant standards and high measurement accuracy, with calibration being traceable to a national standard.
The following describes briefly how these instruments work and the physical principles on which the field sensors are based.

Method used for measuring low-frequency magnetic fields

A sensor based on the induction coil principle is suitable for measuring alternating magnetic fields with frequencies between 5 Hz and 30 kHz. The laws of induction state that a voltage will be induced in a closed conducting loop when the magnetic field passing through the conducting loop changes:

$$\oint_{s} \vec{E} d\vec{s} = -\iint_{(A)} \dot{B}_n dA \qquad (1)$$

Since a voltage is only induced if the field changes, sensors based on the induction principle can only be used for detecting alternating fields. Measurements of constant magnetic fields must be made using a different principle (such as utilizing the so-called Hall effect). Since, however, the type of field usually encountered in engineering is alternating in nature, this article will only discuss the problem of measuring alternating magnetic fields using induction coils.
A magnetic field passing through a coil perpendicularly will induce a voltage U_{ind} in the coil given by:

$$U_{ind} = n2pfBA \qquad (2)$$

where

n	Number of turns in the coil
f	Frequency
B	Magnetic induction
A	Cross-sectional area of the coil

If the coil is terminated with a high impedance, the magnetic field strength can be determined by direct measurement of the induced voltage:

$$B = \frac{U_{ind}}{n2pfA} \qquad (3)$$

As equation (2) shows, the induced voltage depends on both the magnetic induction and the frequency. To render the induced voltage independent of frequency, the frequency response must be compensated for using an appropriate integrator (the better the compensation, the smaller the influence of frequency on measurement accuracy). To isolate the induced voltage from the following amplifier stages as much as possible, the measurement method requires that the induction coil is high-impedance coupled. This makes it more difficult to screen out interference signals.

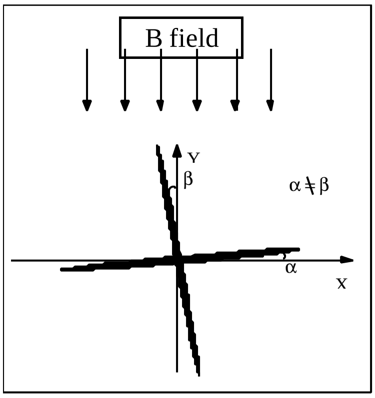
The accuracy of the measurement result very much depends on how accurate the right angle is between the coil and the field. The measurement is only correct if the magnetic field is precisely perpendicular to the coil. In practice, this means that a correct field measurement is obtained by turning the coil in the field until the maximum induction voltage is obtained, at which point the sensor coil is at right angles to the main field vector. This (unidimensional) measurement system thus has potential errors which occur simply on the basis of the way the instrument is held or used. A much better method of field measurement is provided by the so-called isotropic probe which detects the field in three dimensions simultaneously. Electrical and magnetic fields are vector fields, i.e. they have a certain strength and direction at any point in space which, in the case of quasi-stationary fields, may also be time-dependent. To investigate the field at a particular point, it is best if the magnitude and phase (versus time) of all three orthogonal field components can be measured. Field strength measurements for human safety (one application of field strength meters), such precise investigation of the field is unnecessary. It is entirely sufficient to determine a field strength value which can provide sufficient information to serve as a measure for a possible danger to humans. For this reason, the so-called **equivalent field strength** for electrical and magnetic fields has been defined (VDE 0848 part 1):

$$H_e = \sqrt{H_x^2 + H_y^2 + H_z^2} \qquad (4)$$

Ignoring the phase information means that the value obtained for elliptically-polarized fields will be too high ("worst case field strength"); this is, however, acceptable for the purposes of human safety.

An ideal sensor separates the field into its components referred to a Cartesian coordinate system, the orientation of which is determined by the position of the sensor itself. The sensor is then ideally isotropic if it delivers the correct value for equivalent field strength irrespective of its orientation to the field. Such probes used for measuring magnetic fields basically consist of three mutually perpendicular induction coils, each having the same effective area. Compared with the unidimensional field measurement, an isotropic field measurement is not complicated by the precise positioning of the sensor, but accuracy is affected by isotropy error. Isotropy error results in a change in the value of the equivalent field strength when the probe is rotated in the field. The isotropy error is due to mechanical inaccuracies in the relative positions of the three induction coils to each other and cannot be subsequently corrected (see figure).

An important aspect which should not be ignored is the screening of a magnetic field sensor against the influence of electrical fields. If a magnetic field is to be measured in the presence of electrical fields, insufficient screening may lead to such large measurement errors as to make the result unusable.



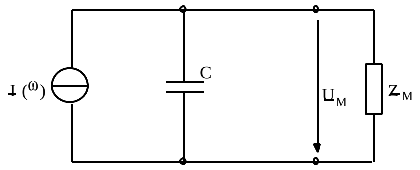
The EFA-series of instruments can be equipped with three different probes for measuring magnetic fields in the frequency range 5 Hz to 30 kHz over a measurement range of 10 nT to 10 mT. Standard measurements can be made using the precision isotropic probe which has an effective area of 100 cm^2 as per VDE 0848. As the relationship in equation (2) shows, the induced voltage is, among other things, proportional to the sensor area. As a result, this precision probe delivers maximum measurement accuracy and is the most sensitive in the range. The probe is screened against electrical fields to the extent that an electrical field strength of the order of 100 kV/m results in an error of around 30 to 60 nT. The overall accuracy of the instrument when equipped with this probe is of the order of 2% to 3% (from 15 Hz to 2 kHz) including the isotropy error of just 0.5%. As well as the precision probe, the basic instrument comes with a built-in isotropic probe which delivers a measurement accuracy of about 5%, despite its small dimensions. Measurements of local fields in small spaces can be made using the small (∅ 3 cm) external isotropic probe which provides a measurement accuracy of between 4% and 5%. All three probes are calibrated against a field which is traceable to a national standard.

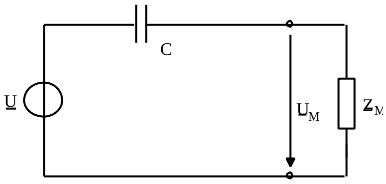
The basic instrument automatically detects which probe is fitted and applies the appropriate set of calibration data for the probe in the calculation of the equivalent field strength.

Measurement methods for detecting low-frequency electrical fields

The capacitance method is most often used for measuring electrical fields. Two electrodes (dipoles or antennas) are placed in the field to be measured and the dielectric current occurring at the electrodes is measured. The shape of the electrodes may differ according to the application. Since in this case only low-frequency electrical fields are being considered, the size of the sensor is practically unimportant. Compared with magnetic fields, the measurement of electrical fields is somewhat more complex. Due to the fact that a body placed in an electrical field will distort the field, special precautions must be taken to ensure correct measurement. The sensor should be equipped with a fiber optics link so that the measurement can be controlled by the basic instrument which is placed outside the field under investigation. This is the only way to ensure that neither the person measuring nor the electrical connections to the sensor affect the field in any way. In the same way as for the magnetic field, an isotropic measurement of the electrical field is advantageous. Together with Dr. Bahmeier of the Munich BW University, Wandel & Goltermann has developed a three-dimensional isotropic sensor which can measure electrical fields with frequencies from 10 Hz to 30 kHz in the measurement range 10V/m to 100 kV/m.
The principle of measurement is as follows:

An AC voltage signal occurs on the plate capacitor when it is placed in an alternating electrical field. It behaves as a capacitive dipole as long as its dimensions are much smaller than the wavelength of the signal under consideration. A capacitive dipole can be represented by the following equivalent circuits comprising current source and parallel capacitance or voltage source and series impedance [1]:





The frequency-dependent current, I, from the current source is the dielectric current which flows in the sensor when it is placed in an electrical field. This dielectric current can be calculated by integrating the electrical field strength over the surface of one of the electrodes:

$$I = j\omega\varepsilon \int_A \vec{E} d\vec{A} \qquad (5)$$

where

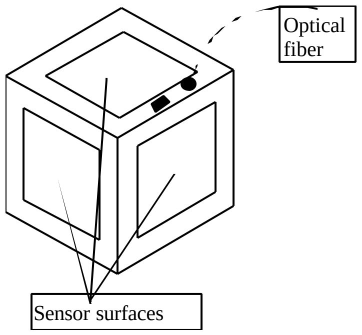
e_0 = 8.854×10^{-12} As/Vm ($e = e_0$ in air)

A = effective area of the electrodes

If the dependency of the measured voltage from the circuit on the dielectric current and the input capacitance C_M of the subsequent measurement circuit is calculated, the following relationship between electrical field strength and measurement voltage is obtained for frequencies above the lower limit frequency specified in [1]:

$$U_M = \frac{\varepsilon \int_A \vec{E} d\vec{A}}{C + C_M} \qquad (6)$$

This principle of measurement was developed into an isotropic sensor in the form of a cube. Basically, it comprises three capacitors placed mutually perpendicular to each other. These separate the field into its orthogonal components.



A digital signal processor built into the probe allows the broad-band field to be measured for the entire range from 10 Hz to 2 kHz or selective measurements to be made. All of the functions available for magnetic field measurements are also available for electrical field measurements from the basic instrument.

Special features of the EFA-series of instruments

The EFA-series of instruments can make broad-band and selective field measurements (up to 2 kHz). If the field under investigation consists of components of different frequencies, the built-in frequency counter will indicate the frequency of the field components which contribute the most (i.e. have the largest amplitude) to the overall field strength when broad-band measurement mode is activated. In selective mode, these components can be more

precisely investigated. The following relevant fixed frequency filters are built-in as standard for this purpose: 16.6 Hz, 50 Hz, 60 Hz, 100 Hz and 400 Hz as well as the 2nd and 3rd harmonics of these frequencies. It is also possible to set any filter frequency with an accuracy of 0.1 Hz within the range 10 Hz to 2 kHz.
The indicated equivalent field strength can be calculated from either the real root-mean square values or from the peak values of the individual field components. In addition to the equivalent field strength value, the percentage proportions of the individual field components referred to the Cartesian axes of the probe are also displayed, making it easier to determine the direction of the main field strength vector. The "MAX HOLD" function simplifies the task of detecting the maximum field strength occurring during a measurement.

Selection between the 6 measurement ranges is automatic or manual. As the instruments are designed with personal safety measurements in mind, an alarm threshold can be defined for monitoring whether a particular field strength is exceeded.

Since the magnetic field strength depends on the current, which in turn can vary considerably with time (e.g. fields beneath high-tension cables), facilities are provided for long term monitoring over a period of up to 24 hours. The instrument is programmed to collect results for this period; these can then be output later to a computer via the built-in optical RS 232 interface for further processing. The long-term monitoring facility is also available for measuring electrical field strength.

The instruments are menu-operated and are very easy to use, even for untrained personnel. A PC Transfer Set for transferring measurement data to a PC via the optical interface rounds off the EFA measurement concept.

Bibliography:

[1] Dissertation by Dipl. Ing. Georg Bahmeier (in German)
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