

12. Measurement of Low Frequency Electrical and Magnetic Fields

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1 Introduction

In the past, the question of whether high-frequency electromagnetic fields affect biological organisms and, if so, how, has gained increasing attention. The focus became sharper as high-frequency generators such as microwave ovens have become popular. In recent times concerns have grown that the increasing number of transmitters (e.g. cellular radio, radar) might have some effect on the health of the populace at large. It is in this context that low-frequency electrical and magnetic fields have been the subject of more intensive discussion. The suspicion that magnetic fields generated by long-distance power lines, for example, might be responsible for various medical symptoms has excited heat discussion among different committees.

This paper will not consider the question of whether such low-frequency fields affect organisms and if so, how.

Instead, test equipment for measuring such fields will be described. Current literature has much to say about the physics of these fields. However, the various approaches come up short when it is time to measure the field parameters with some degree of precision. Accordingly, this paper will examine the possible measurement errors and shortcomings of field sensors based on the underlying theory of electromagnetic fields, thereby allowing a critical choice among the measuring devices currently available commercially.

Wandel & Goltermann is introducing a new line of measuring devices which were developed especially for recording low-frequency electrical and magnetic fields. The concept of these devices will be presented in conjunction with the theoretical considerations.

2 The origin of low-frequency electromagnetic fields

What do low-frequency fields look like, how do they arise and on what order of magnitude is their field strength?

Unlike static fields, alternating electromagnetic fields arise whenever (alternating) current flows through a conductor, i.e. whenever charge is brought into motion. A magnetic field always arises alongside of the electrical field.

Electrical and magnetic fields of equal power also behave according to the relationship between current intensity and voltage:

A high voltage produces a relatively strong electrical field with a relatively weak magnetic field, and vice versa.

During the last century (1873) the English physician James Clerk Maxwell developed a closed system of equations for mathematically describing electromagnetic fields. Reference will be made to these equations later in this paper.

His theories are useful in explaining many relationships in field theory.

2.1 Electrical fields

Electrostatics and electrodynamics are based on the existence of two types of electric charges. They are given the names "positive charge" and "negative charge" since they mutually cancel one another. Between two or more such (fundamental) electrical charges, there acts a force having a magnitude which is inversely proportional to the distance separating the charges. This electrostatic force between two bodies having charges Q_1 and Q_2 can be imagined as a remote effect which somehow bridges the distance between the bodies. However, it is easier to imagine a field: The charge creates an electric potential in the surrounding space which is known as an electrostatic field; at the location of the other charge, it is this field which exerts the observed force upon it. In field theory, fields are graphically represented using lines of force, with the density of the lines of force being a measure of the field strength. A line of force traces at each point the direction of the electrical field strength or the force. In an electrostatic field, where all charges are at rest, the lines of force always connect positive and negative charges; they never end in free space. Nor do closed lines of force occur in electrostatics (unlike fast changing alternating fields). Fig. 2.1 shows the lines of force for a point charge (positive) and for a dipole.

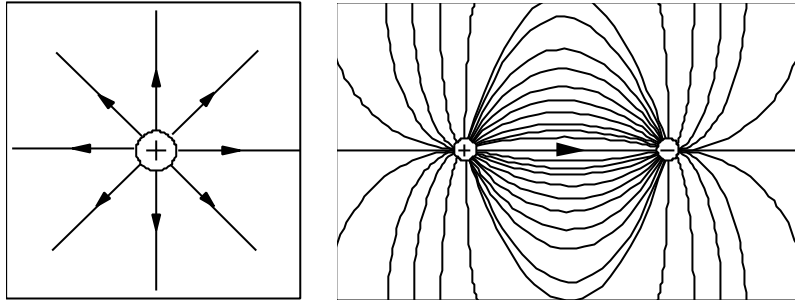


Fig. 2.1: a) Lines of force for a point charge
b) Lines of force for a dipole

The density of the lines of force and thus the field strength decreases at greater distances from the charges. The fields shown here are examples of inhomogeneous fields. On the other hand, the electrical field of a plate capacitor is homogeneous up until the border region (Fig. 2.2).

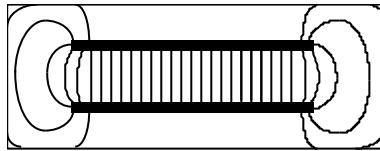


Fig. 2.2: The electrical field of a plate capacitor

To characterize the electrical field, the concept of field strength E with units of [V/m] was introduced:

$$[E] = \left[\frac{V}{m} \right]$$

Between the plates of a capacitor, the electrical field strength is equal to 1 V/m if a voltage of 1 V is applied to the plates and the distance separating them is 1 m.

In the domain of field measurement technology, the electrical field strength is generally specified as an effective (RMS) value.

A distinction is made between electrical source fields which are caused by charges and electrical rotational fields which arise in the vicinity of magnetic fields which are changing over time.

Depending on their frequency, electrical fields are divided into stationary, quasi-stationary and fast-changing fields (wave fields), but the fast-changing fields are of no importance in the frequency range considered here. In the low-frequency range, quasi-stationary fields are of greatest interest. In such fields, the field distribution at any instant is identical to the field distribution of a static field with stationary charges.

2.2 Magnetic fields

As was already mentioned, magnetic fields arise when current flows. A magnetic field is the state of space which arises or changes when electrical charges move. Such magnetic fields can be characterized as follows based on (imaginary) lines of force:

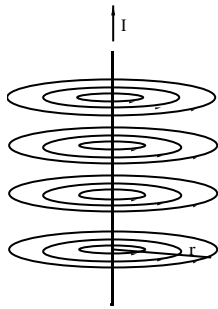


Fig. 2.3: Magnetic lines of force about a current-carrying conductor

The magnetic lines of force form concentric circles about a conductor which carries current. To characterize the magnetic field, the notion of magnetic field strength H was introduced. Quantitative investigation of a current-carrying conductor shows that the magnetic field strength is proportional to the current intensity I and inversely proportional to the distance r from the wire:

$$H \sim I; H \sim 1/r$$

The magnetic field produced by a current always has closed lines of force, i.e. there exist neither sources nor sinks. Magnetic fields are always **rotational fields**.

From the law of magnetic flux, a direct relationship between the magnetic field strength and the conductor current can now be formulated:

$$\oint_K H ds = I \quad (2.1)$$

The line integral of the magnetic field strength over any closed curve K is equal to the total current which passes the curve closed by K . For a straight wire, S is chosen as the circular area of radius r which passes through the wire perpendicularly. For reasons of symmetry, the magnetic field H is constant everywhere on the edge of this circular area. Since its direction is tangential at all points, the line integral over the curve K yields

$$\oint_K H ds = 2\pi r H \quad (2.2)$$

However, this must be equal to the current passing through the circular area S . Thus

$$\oint_K H ds = 2\pi r H = I \quad (2.3)$$

In turn, we obtain the magnetic field strength:

$$H = \frac{I}{2\pi r} \quad (2.4)$$

Magnetic field strength takes on units of [A/m]. At a distance $r = 15.9$ cm from a conductor through which a (constant) current of 1 A flows, the magnetic field strength is equal to 1 A/m. Static fields of this sort are produced

by currents and also by permanent magnets. For example, the earth is surrounded by a more or less constant magnetic field with a field strength of about 32 A/m in Central Europe.

Until now, we have considered only magnetic fields which result from a current which is constant over time. A conductor which carries alternating current also generates (alternating) magnetic fields. Such alternating fields can be characterized using Faraday's law of induction.

If a change occurs in the magnetic field passing through a wire loop, a current is generated in the loop which flows during the change in the magnetic field. It is possible to show by experimental means that the primary result of the change in the magnetic field is an induced potential which causes a current to flow only if the loop is closed. It is also possible to show that it is not just the magnetic field strength which is responsible for the inductive effects.

Instead, a closely related vectorial quantity \mathbf{B} , the magnetic flux density, is also related. This behavior is described mathematically by Faraday's law of induction (one of Maxwell's equations):

$$\oint_K \mathbf{E} ds = - \oint_S \dot{\mathbf{B}} df \quad (2.5)$$

On the left we have the overall potential induced in the wire loop, which is equal to the change in the magnetic flux. As was already mentioned, the induced electrical field has closed lines of force, unlike the static field. Thus we have a rotational field. It should be noted that according to Faraday's law of induction, there exists everywhere in space an induced electrical rotational field even if there is no conductor in which it could induce a current.

It has been shown both experimentally and mathematically that there must be a fixed relationship between the magnetic flux \mathbf{B} which induces fields if it changes over time and the magnetic field strength \mathbf{H} . The proportions are given by the following equation in free space:

$$\mathbf{B} = \mathbf{m}_0 \mathbf{H} \quad (2.6)$$

μ_0 is the permeability of free space or the magnetic field constant. Its magnitude and dimensions are as follows:

$$\mu_0 = 1.256E^{-6} \frac{Vs}{Am}$$

It is common to use the magnetic flux density B instead of the magnetic field strength H as a measure of the strength of a magnetic field. The unit of magnetic flux density is the [T] (Tesla) or Gauss (in the US; 1 G = 100 μ T). The above equation holds only in free space. Otherwise, a material-dependent coefficient must be taken into account:

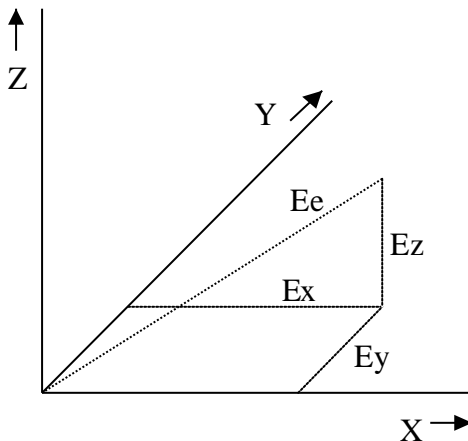
$$B = \mu_r \mu_0 H$$

For air, the relative permeability is about 1. We thus obtain:

$$1 \frac{A}{m} \approx 1.257 mT$$

2.3 Electrical and magnetic equivalent field strength

Until now, we have looked at basic examples illustrating the origin of electromagnetic fields. These were two-dimensional representations of field curves. However, the electrical and magnetic fields are vectorial fields, i.e. they have a specific magnitude and direction at every point in space. These factors are a function of time in quasi-stationary fields. To investigate a field at a certain point, it is useful to measure all three orthogonal components by magnitude and phase (vs. time). In personal safety applications (one usage of field measuring devices), such precise analysis of the fields is unnecessary, however. It suffices to determine a field strength figure which provides enough information to know whether persons are endangered or not. Accordingly, the notion of **equivalent field strength** was defined for electrical and magnetic fields (VDE 0848 Part 1):



$$E_e = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

Fig. 2.4: Vectorial components
of the electrical field strength

$$H_e = \sqrt{H_x^2 + H_y^2 + H_z^2} \quad (2.8)$$

The equivalent field strength consists of the quadratic average of the three field components; the phase differences between the three components do not enter into this parameter.

Neglecting the phase information does have consequences when it comes to a precise characterization of the field. Due to the "near-field" measurement - fields borne by conductors (low-frequency fields) are near fields - the varying phase differences vs. time must be taken into account; the peak of the field vector forms an ellipse in space, whence the term elliptically polarized field. If the field strength vector does not change directions (due to field components of the same phase), the term used is linear polarization. In this special case, the equivalent field strength E_e (or H_e) is equal to the magnitude of the field strength E (or H). In a linearly polarized field, the position of a field probe is of no consequence as long as it correctly breaks down the field into its three orthogonal components. Since in this case the equivalent field strength E_e (or H_e) is equal to the magnitude of the field strength E (or H), this sensor will always measure the correct field strength E (or H). By forming the quadratic average from the three field components, such a sensor has ideal isotropy for linear polarization. The subject of isotropy will be considered later in greater detail in relation to the E-field sensor. When such a sensor is used in an elliptically polarized field, the results it provides are too high (due to the neglected phase relationships). In principle, the worst-case field strength is measured, which is allowable for personal safety applications.

2.4 Field generators and order of magnitude of field strengths

Just where do such fields occur and at what intensity levels? Obvious examples of intense 50 Hz fields are energy transmission systems (such as long-distance power lines and transformers) and devices which consume energy (such as electrical machinery of all sorts).

((Bildtext:))
 400 Hz on-board power supply
 Power plant
 Transformer
 Power grid 220/380 kV
 Heavy industry
 Railways
 Private homes
 Business, industry, offices, stores
 Agriculture
 Small plants

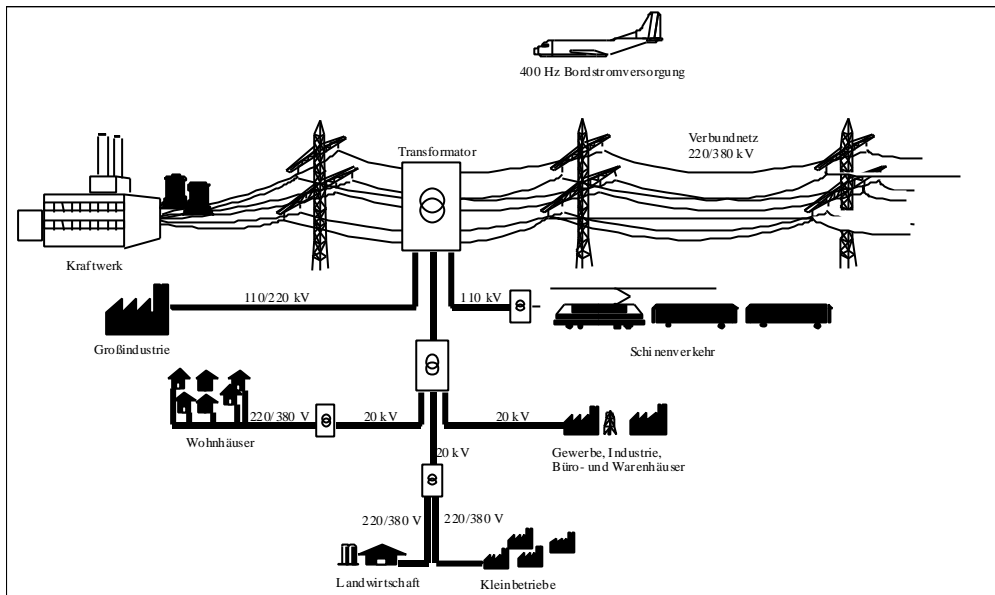


Fig. 2.5 The power supply hierarchy: from power plant to consumer [1]

Fig. 2.6 illustrates the field distribution for a high-voltage line. This figure is found in many publications which have examined the subject of low-frequency electromagnetic fields:

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Voltage

Cable height

Distance from the center in meters

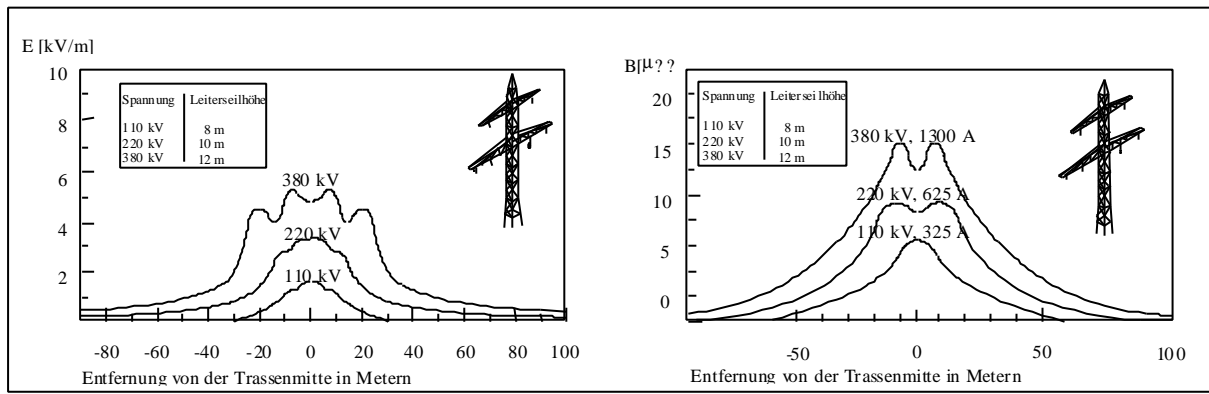


Fig. 2.6: Characteristic cross-section of electrical and magnetic fields in the vicinity of overhead lines [1]

The figure illustrates the characteristic cross-section in the close vicinity of free-hanging lines. The maximum magnetic field strength is on the order of magnitude of 15 μT (for a 380 kV line), which decreases sharply further away from the line. The field strength curve is also highly dependent on the loading of the masts. The magnetic field strength data are for a 380 kV line carrying a current of 1.3 kA per circuit. The maximum value attained by the electrical field strength under equivalent conditions is 5.5 kV/m, which is also dependent on the phase relationship of the lines.

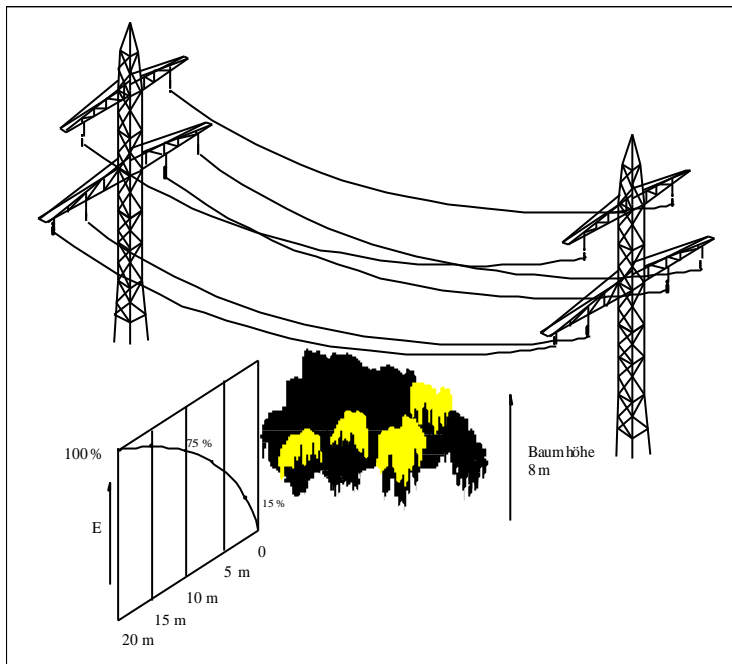
A related topic when considering electrical and magnetic fields is shielding. One might ask what measures should be taken to attain the best possible damping or shielding for these fields. Another question that comes to mind is how the fields are influenced by extraneous objects.

((Bildtext))

Tree height 8 m

Unlike magnetic fields, the electrical field can be easily influenced and shielded using conductive materials.

Fig. 2.7: Influence of a tree on the electrical field in the immediate vicinity of an overhead line [1]



A tree reduces the electrical field of a 380 kV line up to 15% in its immediate vicinity. However, the shielding effect decreases at greater distances. As will be seen later, the shielding effect of objects with respect to the electrical field causes problems when measuring fields since the presence of a person during a measurement will distort the field.

A list of the different field strengths which occur in the LF range is perhaps relevant at this point:

Electrical field in [V/m]	Source	Magnetic field in [μ T]	Source
15000	380 kV station		
10000	380 kV line	2500	Hairdryer
3000	110 kV line	1000	Electric range
500	10 kV line	500	Television
>10000	Human-borne fields	50	380 kV line
5 - 40	Electrical installation	20	110 kV line
300	Fluorescent light	15	Electric space heater
300 - 700	Television	10	Desktop lamp
30	Subway (near ground)	6	10 kV line
		2	220 V installation

Magnetic field strengths range from a few nT (approx. 50 to 70 nT in the home with appliances switched off) to approx. 1 to 2 mT. Electrical field strengths range from a few V/m to several 10 kV/m.

One could easily continue this list. In our case, however, it is intended as an overview of real-world field strengths which are relevant to later observations. The main interest is in the area of "personal safety", which is the subject of much discussion at this time. Unlike high-frequency fields, effects of low-frequency fields on biological mechanisms are either difficult or impossible to verify. The heating which occurs in organic material exposed to high-frequency fields does not occur with (strong) low-frequency fields. Many published studies have recounted extensive experiments involving animals and humans as well as epidemiological investigations (the occurrence of diseases in the human population was studied with the aim of establishing a correlation between a disease and one or more related factors). For example, test persons were subjected to magnetic fields on the order of magnitude of 5 mT at a frequency of 50 Hz. As with many other studies, the results were not clear. It was not possible to establish clear damages or impairments of these test persons in comparison with other groups of persons who were not subjected to any fields. On the other hand, increased incidences of leukemia are being investigated which - as some have maintained - were provoked by high-voltage lines situated in the vicinity of residences. One difficulty of retrospective studies of this sort is the problem of considering a group of disease victims as representative since comparisons with other (endangered) groups of persons are meaningful only if the "environmental parameters" agree.

Given the fact that about 12,000 published articles have not reached a clear consensus, we will restrict ourselves to stating the limits which various committees have proposed in the form of recommendations or legal documents. Such limits are intended to protect persons subjected to continuous exposure from possible negative consequences. The limits are defined with respect to frequency (from 0 Hz to 30 kHz) and differ in their course depending on the committee. The limits for continuous exposure to a 50 Hz magnetic field are as follows:

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Safety limit
380 kV lines
110 kV lines

Limits for pacemakers
 Limits for ventricular fibrillations
 Domestic appliances
 Magnetic flux density

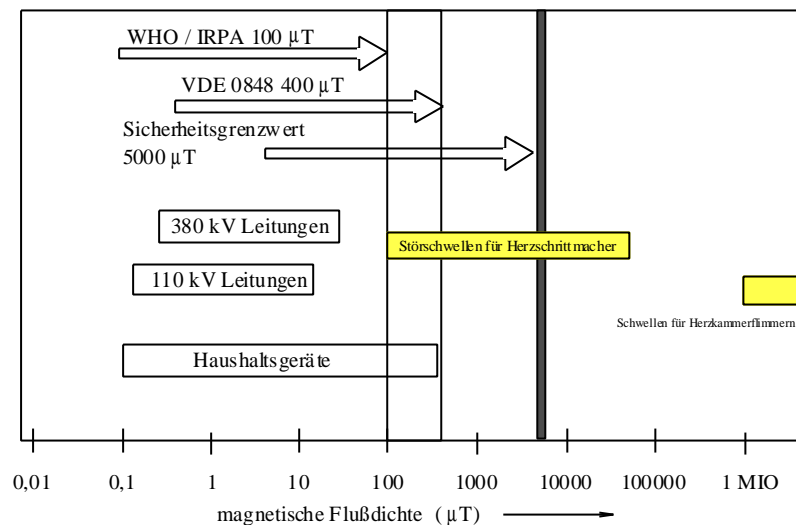


Fig. 2.8 Limits for continuous exposure to a 50 Hz magnetic field [1]

From these figures, one can conclude that test equipment should be able to measure in the range from several 10 nT to 10 mT (magnetic field; 5 mT upper threshold) and several 10 V/m to 20 kV/m (as stipulated by the DKE = German Electrical Engineering Commission). According to the IRPA, the maximum values for continuous exposure of persons are 5 kV/m (electrical field) and 100 μT (magnetic field). The actual limits which become accepted in the future are inconsequential for the test and measurement industry as long as the test equipment covers the related field strengths (ranges) with the specified accuracy and uses the prescribed measurement technique(s).

3 Measurement techniques and errors

Based on knowledge of theoretical physics as it concerns electromagnetic fields, measurement techniques (i.e. sensors) can be developed to handle the field parameters. This section will take a closer look at the measurement techniques which provide the best results given the current state of the art. Various problem areas will also be considered which, either for theoretical reasons or due to incorrect handling of the field measuring devices, can lead to measurement errors.

3.1 Technique for measuring magnetic fields

A commonly used method for measuring magnetic fields involves a practical implementation of Faraday's law of induction. Here, the fact that alternating magnetic fields induce a voltage in a coil which is proportional to the field strength is exploited.

A magnetic field which passes vertically through the coil induces the following voltage in the coil:

$$U_{ind} = n2pfBA \quad \text{Eq. 3.1}$$

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

If the coil has a high-impedance termination, the field strength can be determined directly by measuring the induced voltage:

$$B = \frac{U_{ind}}{n2pfA} \quad \text{Eq. 3.2}$$

As follows from this formula, the induced voltage is dependent on the magnetic induction and also on the frequency. To free the induced voltage from this dependence on the frequency, it is necessary to compensate for the frequency response using an appropriate integrator element (as the frequency response compensation is improved, the influence of the frequency on the measurement accuracy decreases). The accuracy of the result is naturally highly dependent on how precisely the coil is situated at a right angle to the field. The measurement is correct only if the magnetic field passes perfectly vertically through the coil. The induced voltage is dependent on the effective area of the coil, which can be characterized by introducing a "fault angle":

$$U_{ind} \approx \cos \alpha$$

If the coil is positioned perfectly perpendicularly with respect to the field, the fault angle is zero and thus $\cos \alpha = 1$ so that the entire coil area is in effect. The cosinusoidal dependency of the area means that small deviations from the perpendicular cause relatively small errors.

To make correct magnetic field measurements using a single coil, the coil must be turned until the maximum value is displayed, which then corresponds to the field strength for the location.

Isotropic field probes represent an improvement over one-dimensional magnetic field probes; isotropic probes have three coils arranged perpendicularly to one another.

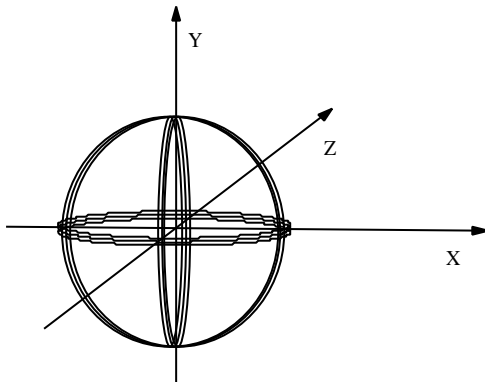


Fig. 3.1 Three-dimensional isotropic coil arrangement

The benefit of such an arrangement is that the sensor always provides the same value for the equivalent field strength no matter what position it is in. If this is the case, one can speak of an ideally isotropic sensor.

The sensor breaks down the field into its components based on a Cartesian coordinate system whose orientation is determined by the position of the sensor itself.

In a three-dimensional arrangement, there is an additional parameter influencing the measurement accuracy, namely, the precision with which the coils are situated with respect to one another.

((Bildtext))
B field

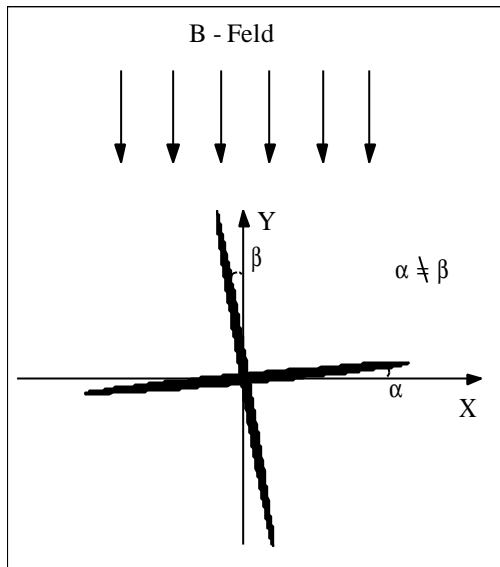


Fig. 3.2: Isotropy error due to an improper configuration of the coils

If these coils are not properly positioned perpendicularly with respect to one another, the measurement result loses precision due to the associated isotropy error. Unlike the case of one-dimensional measurement, influencing the measurement error are a coil with accuracy proportional to $\cos\alpha$ and the perpendicular coil with accuracy proportional to $\sin\beta$ (Note: Let the fault angle α be a result of improper positioning of the sensor. The angle causing the isotropy error is then $\beta - \alpha$.) Even small deviations from the ideal (relative) coil positions can cause measurement errors on the order of magnitude of 1% to 2% and beyond. When comparing measuring devices, it is thus necessary to check the conditions under which the device specifications hold. In error specifications for one-dimensional measuring devices, the isotropy error plays no role in the error calculation.

Another criterion which determines the quality of a magnetic field sensor is the shielding of the sensor (and the device containing it) against electrical fields. Shielding is generally very expensive, and it is tempting to save on production costs by simply omitting it. However, an unshielded measuring device is practically useless in the presence of a (strong) electrical field since the electrical field has a significant influence on the measured value. One possible method for shielding a one-dimensional coil looks as follows [2]:

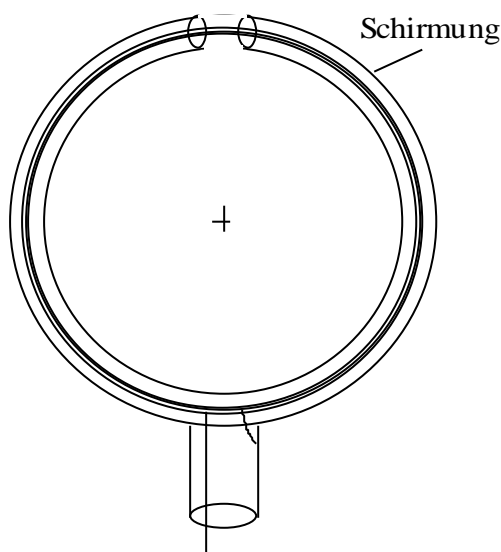


Fig. 3.3: Electrical shielding of a B-field sensor

Note that it is somewhat more expensive to shield a three-dimensional sensor, which in turn effects the price.

((Bildtext))
Shielding

A further difficulty arises with miniature magnetic field sensors which are designed to be integrated directly into the instrument or to allow measurements of spatially local field distributions ("sniffer" probes, used in automotive applications, aircraft power supplies, etc.). If such a sensor is to have the same sensitivity as a larger one, it must have significantly more turns per coil due to the smaller cross-section (see equation 3.1). However, the increased number of turns drastically increases the capacitive effects, i.e. the sensor is more sensitive to electrical fields. If such a sensor is integrated directly into a device, then the ambient effects (i.e. the other components in the device) must be

included in the error calculation. Moreover, perpendicular positioning of the field coils is made more difficult, so that the isotropy error can be significantly larger than that of a large precision probe.

Finally, we should make some comments on the actual test procedure. Since low-frequency magnetic fields penetrate almost all materials, the measurement is not very complicated per se. The ease of the test procedure is highly dependent on the evaluation circuitry which reads the sensor output. The measurement probe determines the range and thus makes a sizable contribution to the sensitivity of the overall arrangement.

Summary:

A good sensor for measuring magnetic field strength should have the following characteristics:

- Large effective area (to avoid effects due to small rotational fields)
- High sensitivity based on many winding turns
- Low capacitance of the windings
- Good shielding with respect to electrical fields
- Low isotropy error through precise positioning of the three coils

- Standard dimensions
- Good mechanical stability
- Flexibility

Of course the sensor cannot be considered in isolation since the input amplifiers which process the induced voltage of the sensor also play a role. In other words, the sensitivity of the test setup can be altered by the number of winding turns used in the sensor and also by the sensitivity of the input circuits.

The design used for the magnetic field sensors in products from Wandel & Goltermann looks as follows: To allow the order of magnitude of a magnetic field to be determined even without an external sensor, a small, three-dimensional isotropic sensor is integrated directly into the basic device. When no external precision probe is connected, the measurement is automatically executed using this internal B-field probe.

The internal sensor coils are positioned relative to one another such that the device itself has the smallest possible effect on the isotropy. Since, for example, the presence of batteries can "bend" the magnetic field, it is not possible to totally eliminate such effects, but they are at least minimized. The additional shielding measures to counter electrical fields allow this arrangement to achieve a measurement accuracy of approx. 5%, which rates as very good. The internal sensor is individually calibrated in production for each device.

For applications requiring standardized (and precise) measurement of magnetic fields, a precision probe conforming to VDE 0848 with an effective cross-section of 100 cm^2 is available. The best possible measurement accuracy is attained with this probe. The isotropy error of this three-dimensional probe ranges from only approx. 0.5% to 1%. The probe has good shielding against electrical fields as well as a very rugged mechanical design. An electrical field of 100 kV/m results in a measurement error of approx. 50 nT to 100 nT. The good reproducibility in production allows us to store a single calibration data set in the device which is representative of all precision probes. Measurement accuracies of 2% to 3% are possible with this probe.

For measuring magnetic fields in hard to access spaces or for recording local fields in a small area, the accessories include a miniature, three-dimensional, isotropic probe. To achieve the greatest degree of precision possible with such probes (given their problematic nature), they are especially calibrated and the calibration data are stored directly in the probe.

These details, combined with suitable shielding against electrical fields, yield measured values with an accuracy of approx. 4% to 5%.

The specifications for the accuracy of the probes always refer to a frequency and field strength range. Upon special request, these devices can also be calibrated at user-specified frequencies for improved accuracy at the frequencies of interest.

3.2 Technique for measuring electrical fields

The most common method for measuring electrical fields is the capacitive method. Two electrodes (dipole, antenna) are brought into the electrical field to be measured and the displacement current is measured. The nature of the electrodes varies depending on the application. Since we are considering only low-frequency electrical fields here, the size of the sensor is of no practical consequence (basically, however, smaller sensors are better suited to measurements at higher frequencies).

Compared to magnetic fields, measurement of electrical fields is somewhat more complicated. Since bodies present in the electrical field distort the field, special precautions must be taken to ensure reliable results.

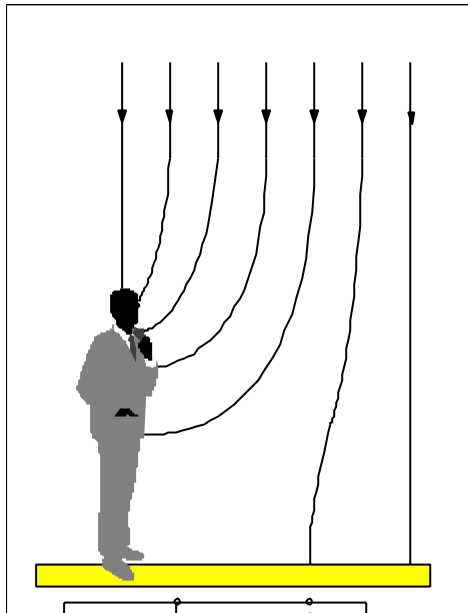


Fig. 3.4: Distortion of an electrical field by the human body

Given the fact that the mere presence of a person in the field distorts the field such that the measured value is practically unrelated to the actual value, it is absolutely necessary to isolate the sensor from the basic device. Experiments have shown that the field is distorted if persons situated at a distance of 7 m from the test site move about.

A circuit diagram of a sensor for measuring electrical fields looks as follows:

As part of dissertation work by Dr. Bahmeier, an intensive study of the measurement of electrical fields was made [2]. In describing the measurement of electrical fields, we will make reference to this work. Usage of any patent rights with regard to the three-dimensional E-field sensor is reserved by the company Wandel & Goltermann.

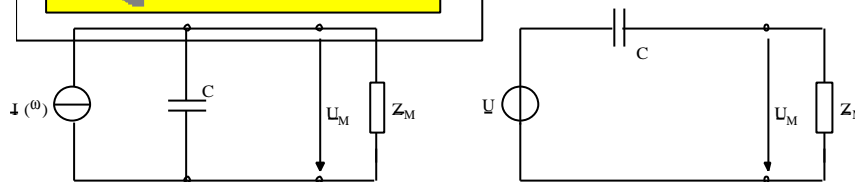
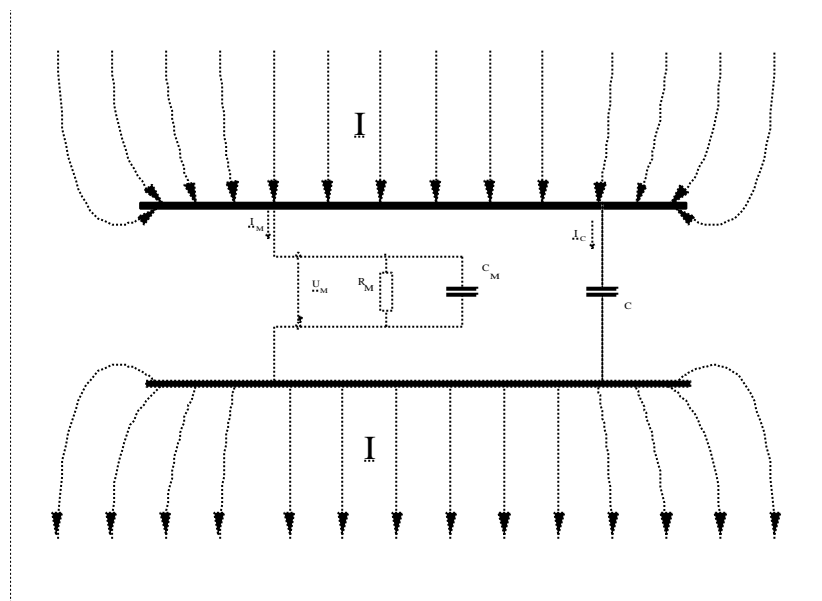


Fig. 3.5: Equivalent circuit diagrams for capacitive dipoles

An alternating voltage signal occurs on the plate capacitor if

it is situated in an alternating field. It behaves like a capacitive dipole as long as its dimensions are much smaller



than the wavelength of the measured signal, which can be assumed for LF fields. To calculate the output voltage of capacitive dipoles loaded with a test impedance Z , the equivalent circuits shown in the figures are basically suitable. In the first equivalent circuit, the dipole is represented as a current source with a parallel capacitance. The frequency-dependent current I of the current source is the displacement current which flows into the sensor in an electrical field (see Fig. 3.6). The second equivalent circuit is based on a voltage source with capacitive series impedance. The voltage U of the voltage source is frequency-dependent and is the

Fig. 3.6: Flow of current through a capacitive sensor [2]

product of the electrical field strength and the effective length of the dipole. The parallel (or series) capacitance C is equal for both equivalent circuits to the capacitance of the dipole, which can be measured with an impedance or capacitance meter at low frequencies. Since the exemplary sensor considered here is very flat, the equivalent circuit with the current source and parallel capacitance is used. The displacement current flowing into the sensor can be computed by integrating the electrical field strength over an electrode surface:

$$I = j\omega \epsilon_0 \int_A \vec{E} d\vec{A} \quad \text{Eq. 3.3}$$

ϵ_0 = $8.854 \cdot 10^{-12}$ As/Vm ($\epsilon = \epsilon_0$ for air)
 A : Effective area of the electrodes

The current I produces a voltage on the electrodes or on the input impedance of the measurement circuitry connected in parallel to the electrodes. The input impedance of the **measurement circuitry** is determined by a high-impedance source follower in order to achieve the greatest possible frequency range with no dependence on frequency. This input capacitance C_M of the source follower is in parallel to the plate capacitance. The voltage \underline{U}_M which occurs on the sensor plates and thus at the input to the measurement circuitry is given by:

$$U_M = I_M Z_M = I Z_{ges} = \frac{j\omega e \int \vec{E} d\vec{A}}{\frac{1}{R_M} + j\omega(C + C_M)} \quad \text{Eq. 3.4}$$

With the assumed test impedance Z_M the sensor represents a 1st order high-pass filter (see the equivalent circuit diagram). Its limit frequency is

$$f_g = \frac{1}{2\pi R_M (C + C_M)} \quad \text{eq. 3.5}$$

At frequencies well above the limit frequency, the input admittance of the measurement circuitry can be neglected with respect to the susceptance of the capacitive elements:

$$1/R_M \ll \omega(C + C_M)$$

Equation 3.4 is thus simplified as follows:

$$U_M = \frac{e \int \vec{E} d\vec{A}}{C + C_M} \quad \text{Eq. 3.6}$$

According to this equation, measurement of the electrical field strength is independent of frequency above the lower limit frequency. To extend the lower limit frequency downwards and produce a sensor that is as broadband as possible, the ohmic resistance of the measurement circuitry must be maximized.

Since we are limiting our scope to low-frequency fields, the theoretical considerations with regard to an upper limit frequency at approx. 180 MHz do not come into play.

Based on these theoretical considerations, we will show how the mechanism of a capacitive sensor is used to measure the electrical field. In the relevant literature and in (current) publications, it is this test setup which is found, if anything.

Theoretical considerations will not be further examined here since the named references cover them in depth.

In the following section, we will consider the practical implementation of this measurement technique in a sensor which rounds out the array of sensors available in our line of field measurement products. As far as we can tell, this sensor is the only one of its type on the market. It has the ability to measure electrical fields three-dimensionally and selectively, i.e. it is fully isotropic. The measurement accuracy which is achieved is superior by far to that of many commercially available one-dimensional sensors. Most noteworthy is its cubical shape.

((Bildtext))

Fiber optical cable

Sensor surfaces

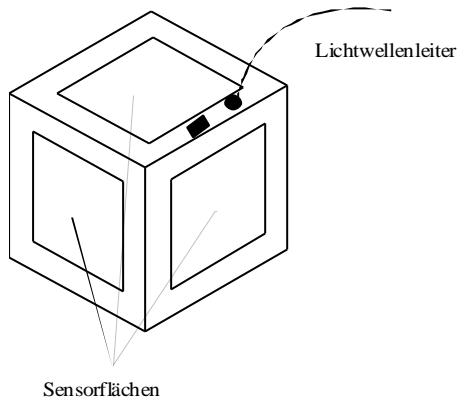


Fig. 3.7: Three-dimensional isotropic sensor for measuring electrical field strength

This technique was examined by Dr. Bahmeier in both its theoretical and practical aspects as part of his dissertation work. In cooperation with Dr. Bahmeier, we carried on with the development of this technique, making it suitable for series production. Interested readers should consult his dissertation for details of the theoretical aspects and the related practical measurement results [2].

The technique described for capacitive measurement is used here for three-dimensional measurement. The sensor has three plates arranged perpendicularly to one another, each of which forms a capacitance with respect to the core of the cube. For reasons of

symmetry, another plate was arranged opposite each of these three "active" plates, but the "inactive" plates do not enter into the measurement. The three field components are determined by measuring the displacement currents of the individual plates. These signals are sampled via three input amplifiers and multiplexer stages and processed by a signal processor. This makes it possible to break down the field components by spectrum and measure the fields selectively. All of the digital signal processing electronics is situated within the actual sensor. Only the computed components are transmitted to the basic device. This minimizes the data stream and thereby increases the lifespan of the rechargeable cell installed in the sensor. To minimize distortion of the electrical field, the data from the sensor are transmitted via fiber optical cables (max. length 20 m). The sensor is thus fully remote-controllable from the basic device.

One very interesting question concerns the isotropy of this structure. An isotropic sensor provides the same value for the equivalent field strength in every position with respect to the field. The theoretical verification being quite complicated, interested readers should consult the above work. A practical proof of the isotropic behavior of the sensor is illustrated hereafter:

- ((Bildtext))
- Sensor
- Styrofoam
- Fiber optics ((LWL))
- Rotary table
- Angle indicator
- Interface

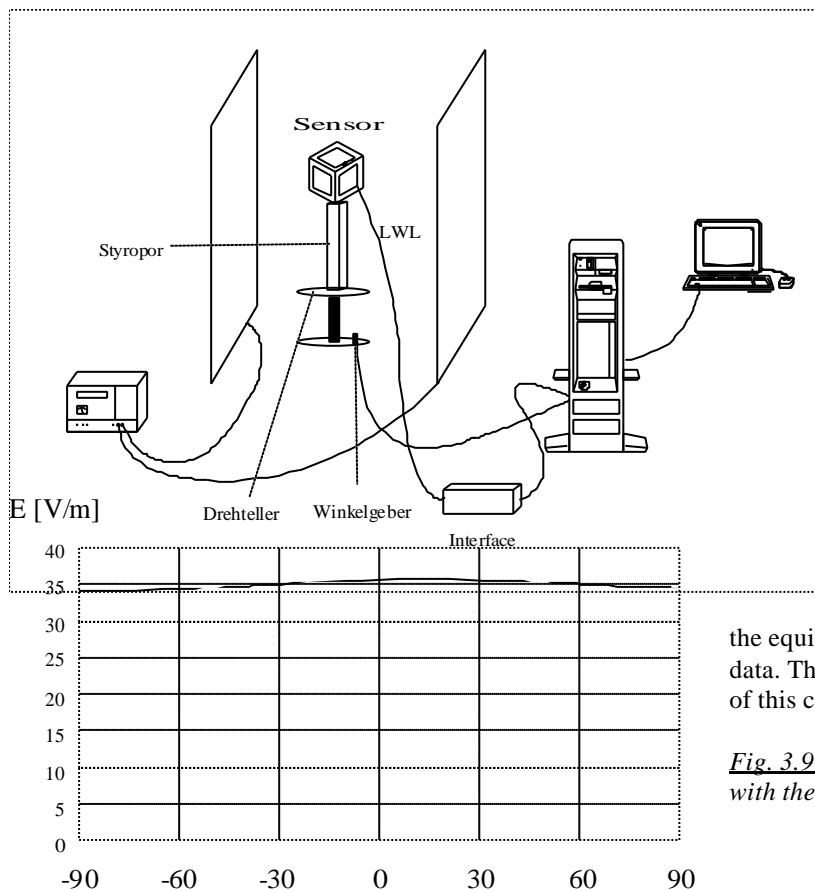


Fig. 3.8: Test setup for measuring isotropy [2]

- ((Bildtext))
- Angle of rotation

The test setup consists of two opposite plates which are used to generate a defined electrical field. A rotary table is situated in the actual field, the table being remote-controlled via a computer. The sensor is first laid on one side and rotated. The evaluation circuitry is located outside of the field and is connected to the sensor via a fiber optical cable. This evaluation circuitry provides the current measured data to the computer, which then computes

the equivalent field strength based on these data. The following figure shows the results of this computation:

Fig. 3.9: Results of the isotropy measurement with the sensor on its side [2]

This chart traces the equivalent field strength for the three cube components; the value hardly changes as the table rotates.

In the next part of our test, the cube is placed on a tip and then rotated again. The results are shown in the chart as before:

((Bildtext))

Angle of rotation

E [V/m]

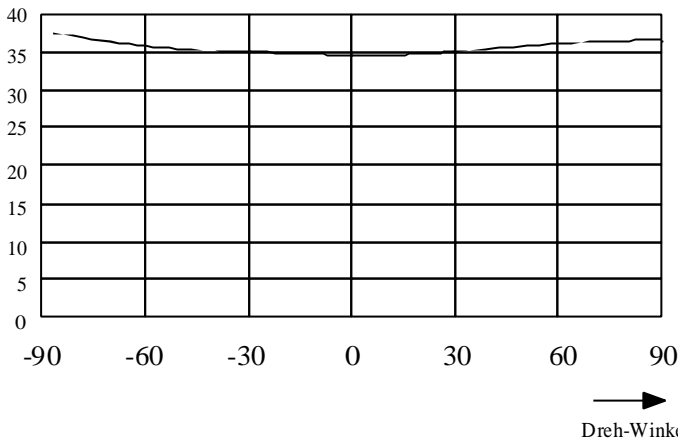


Fig. 3.10: Results of the isotropy measurement with the sensor on a tip [2]

The excellent isotropy behavior of the sensor is evident as before.

The next question concerns the measurement accuracy of this technique. Most critical is precision mechanical production with subsequent calibration of the sensor. It is important that the spacing of the electrodes not be altered after calibration. Very small changes in the spacing of the "test capacitors" result in a

measurement error of several percent. As a result, the sensor is installed with fixed rechargeable cells, which are accessible via a laterally arranged charging jack. For mechanical reasons as described above, the sensor must be recalibrated each time a cell is changed. Wandel & Goltermann provides this service in-house only.

To provide the best possible shielding against low-frequency magnetic fields, extensive MU metal shielding was installed.

Based on the mechanical and electrical measures described above, a measurement accuracy of approx. 5 to 10% is achieved for the electrical field, which rates as extremely good. (Electrical field measurement errors of 30% and more are not uncommon among the commercially available sensors.)

4 W&G's line of equipment for measuring low-frequency electromagnetic fields

4.1 Development criteria

The development criteria for the EFA-1, EFA-2 and EFA-3 line of meters were oriented towards the practical requirements of such devices. The following development aims crystallized during numerous discussions with users of low-frequency meters:

- Development of a complete solution (measurement of E-and B-fields)
- Simple operation (non-technical persons should be able to operate the devices)
- Support for standardized measurements
- Suitable measurement range for real-world field strengths
- Isotropic measurement of fields
- Facilities for selective measurement at relevant frequencies
- Documentation facilities for the measured data
- Alarm function
- Good handling (small and rugged)
- Good price/performance ratio

4.2 Overall concept

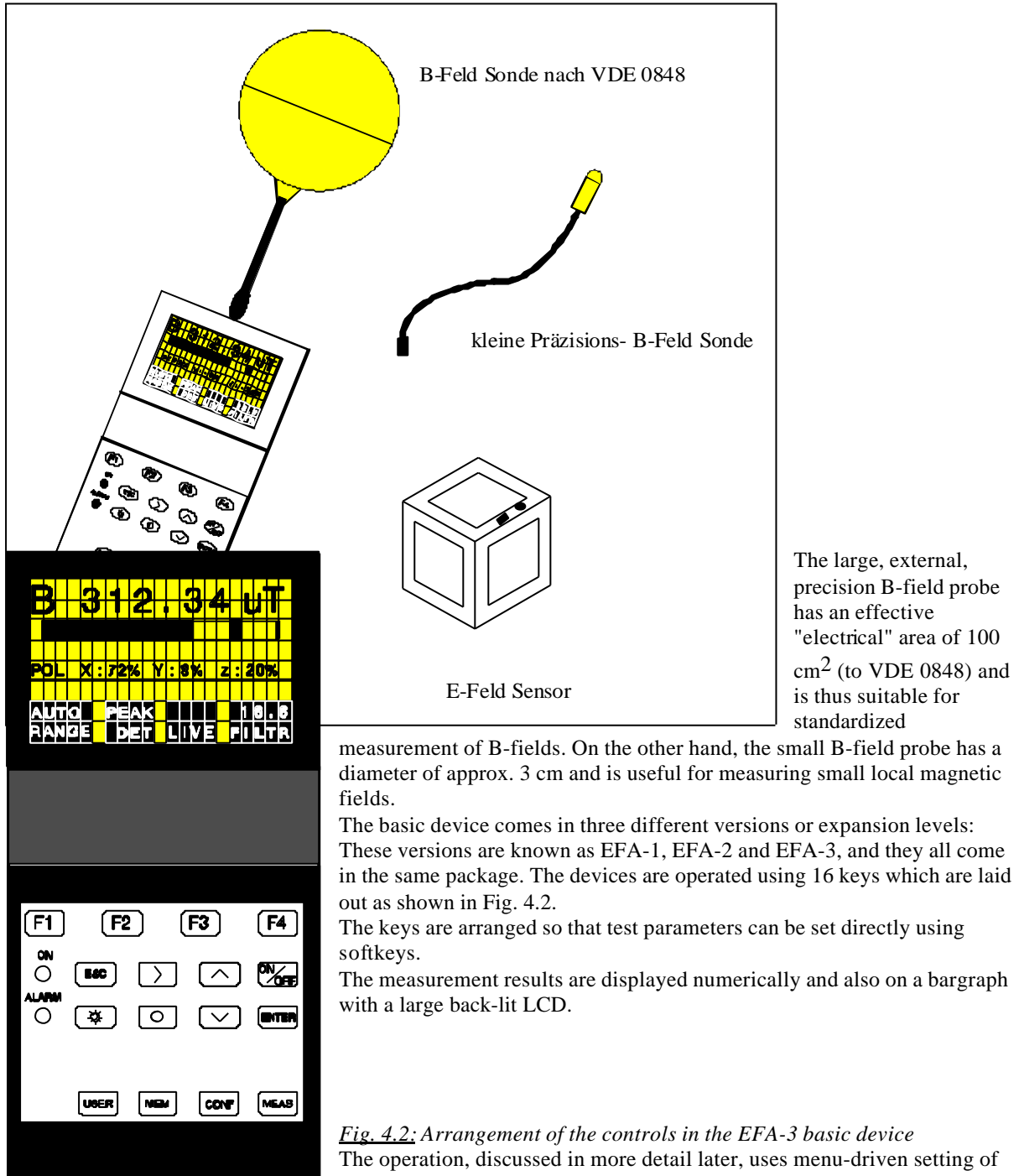
((Bildtext))

B-field probe to VDE 0848

Small, precision B-field probe
 E-field sensor
 EFA-3 basic device

The overall concept entails a basic device, two external, precision probes for measuring the magnetic field strength and the three-dimensional sensor for measuring the electrical field strength as described above.

Fig. 4.1: Field strength meter with accessories



The large, external, precision B-field probe has an effective "electrical" area of 100 cm² (to VDE 0848) and is thus suitable for standardized

measurement of B-fields. On the other hand, the small B-field probe has a diameter of approx. 3 cm and is useful for measuring small local magnetic fields.

The basic device comes in three different versions or expansion levels: These versions are known as EFA-1, EFA-2 and EFA-3, and they all come in the same package. The devices are operated using 16 keys which are laid out as shown in Fig. 4.2.

The keys are arranged so that test parameters can be set directly using softkeys.

The measurement results are displayed numerically and also on a bargraph with a large back-lit LCD.

Fig. 4.2: Arrangement of the controls in the EFA-3 basic device

The operation, discussed in more detail later, uses menu-driven setting of the test parameters based on the softkeys. In labelling the softkeys on the

display, the currently active test parameter is also displayed so that the auxiliary parameters related to the displayed result can be quickly read off. All three device versions are equipped with an internal, three-dimensional B-field probe and automatic probe identification for externally connected sensors. Based on the probe identifier, the correct calibration data set for the current probe is automatically loaded. Unlike the other versions, the EFA-3 device has an optical interface for connecting the E-field probe. The display parameters are automatically updated depending on the field to be measured (display of B- or E-field, units, etc.). Moreover, the

test data can be transferred directly to a printer or computer via an optical RS-232 interface. The devices can be operated from batteries or rechargeable cells; the latter are recharged via a charging jack on the device.

((Bildtext))

E-field probe

B-field probe

Multiplexer + analog amplifier

Digital signal processor

LCD

Microcontroller

Result memory

Keypad

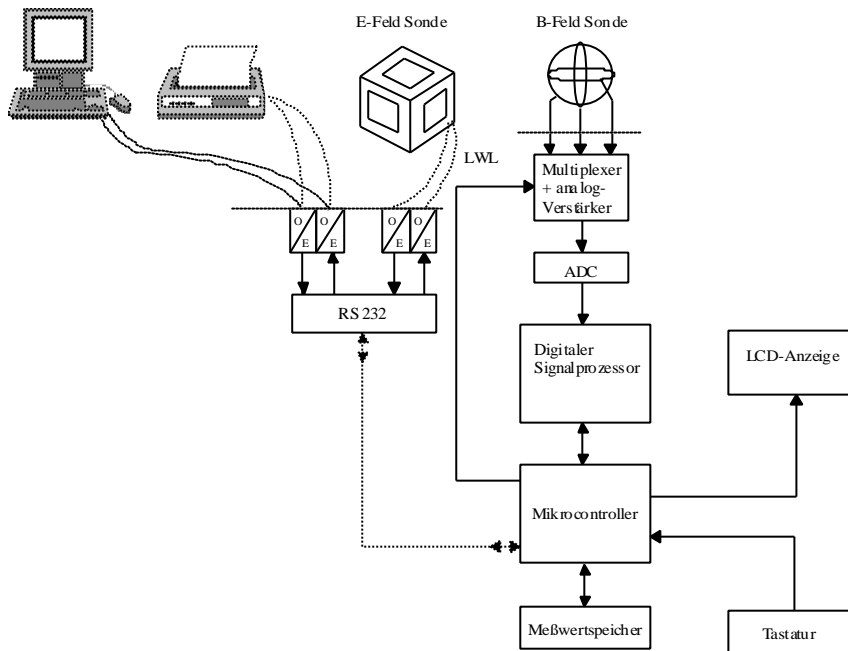


Fig. 4.3: Simplified block diagram of the EFA measuring concept

4.3 Specifications for the basic device

Features of this line of products include:

- * B-field measuring range: 100 nT to 10 mT, divided into six subranges
- * Measurement accuracy 3% 1 nT (with the precision probe)
- * Frequency range 5 Hz to 30 kHz
- * Non-directional (isotropic) measurement
- * True RMS or peak-value measurement
- * Autoranging (EFA-2 and EFA-3)
- * Spectral recording of field components
- * User-definable filter frequency in the range from 15 Hz to 2 kHz (resolution: 0.1 Hz)
- * Adjustable alarm threshold
- * Fully automatic, timed measurement (EFA-2 and EFA-3)
- * User-definable device setups (EFA-2 and EFA-3)
- * Printer interface
- * Built-in frequency counter (1 Hz resolution)
- * Built-in B-field probe

The signal from the probe is sampled by a A/D converter which forwards the digital data to a signal processor. This signal processor handles the data according to the current mode and passes the results to a powerful microcontroller. The controller manages the test sequence, the keypad and the display, and also handles probe identification and parameter settings. Two optical interfaces are used to connect the E-field probe (EFA-3) and a printer or computer. The computer interface can be configured as required.

As was already mentioned, the magnetic field strength is a direct function of the current intensity in the conductor as produced by the magnetic field. To make it easier to measure magnetic fields over longer time

frames, the EFA-2 and EFA-3 device versions include fully automatic, timed measurement capabilities. This capability also exists in the EFA-3 for measuring electrical fields. The measured data recorded over a maximum interval of 24 h can be easily transferred to a computer for further processing.

4.4 Operation and applications of the devices

Operation of these devices is made simple by their menu-driven controls and clear display of test parameters. The following four main menus can be directly accessed from any device setting using four distinct keys:

TEST menu: For displaying measurement results and setting test parameters
 CONFIGURATION menu: For setting device parameters
 MEMORY menu: For programming automatic (timed) measurements
 USER menu: For storing and recalling device setups

Taking the TEST menu as an example (this menu appears when the device is powered up), we'll take a closer look at the basic operation of these devices:

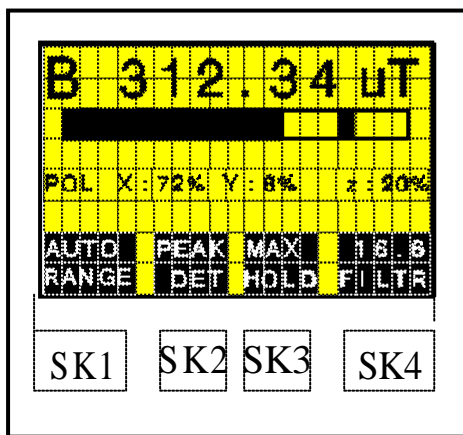


Fig. 4.4: EFA-3 TEST menu

Besides the measured value - displayed in double size - the type of probe connected to the device is also indicated. If no external probe is connected, the internal B-field probe is automatically activated. A bargraph is displayed below the result display. In "AUTO RANGING" mode, the entire measurement range of the device is shown logarithmically and in "MANUAL RANGING" mode, the display is adapted to the current range setting. When the battery charge is nearing its end, the bargraph is replaced by the message "LOW BATTERY".

Besides the equivalent field strength, the field components are also displayed as percentages so that the field component of the highest field strength which has occurred can be determined. At the lower edge of the display, the softkeys (SK1 to SK4) mentioned above are labelled depending on the current parameter settings.

Parameters are normally set using the UP/DOWN keys in the submenu, followed by the ENTER key. To retain the previous setting, the ESC key can be pressed to exit the menu with no changes to the parameter settings. The measurement range is set using SK1.

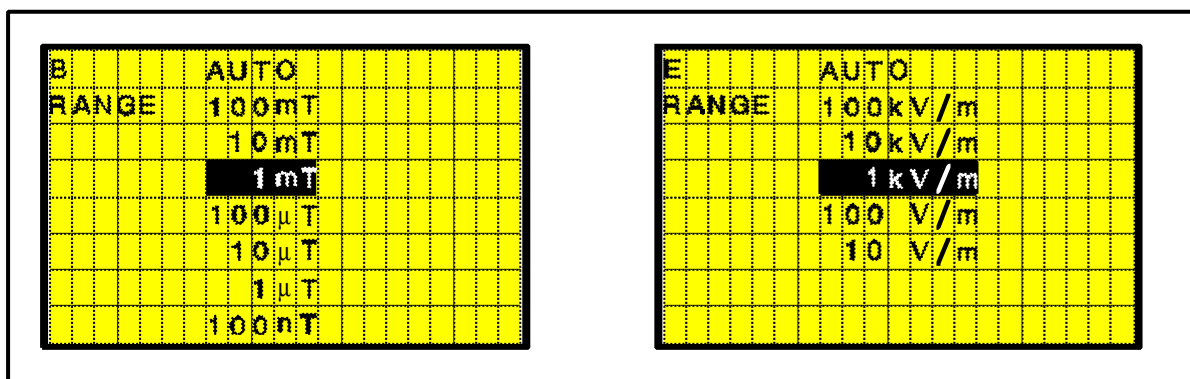


Fig. 4.5: Menu for setting the measurement range

The table of available measurement ranges is automatically adapted to the connected probe in the EFA-3 device version. The two cursor keys are used to select the desired range, and the ENTER key is pressed to confirm the selection.

The submenu accessed via SK2 allows a choice between true RMS detection and PEAK detection. It is also possible to switch off two dimensions of the B-field probes, thereby simplifying the process of determining the direction of maximum field strength.

To make it easy to determine the maximum field strength which has occurred, the display can be switched to MAX HOLD; the data are still updated in the bargraph. The displayed value is then equal to the maximum field strength measured since the display was switched to this mode.

One innovative feature of these devices is the ability to make both selective and broadband field measurements. The following band limits (and filter frequencies) are available:

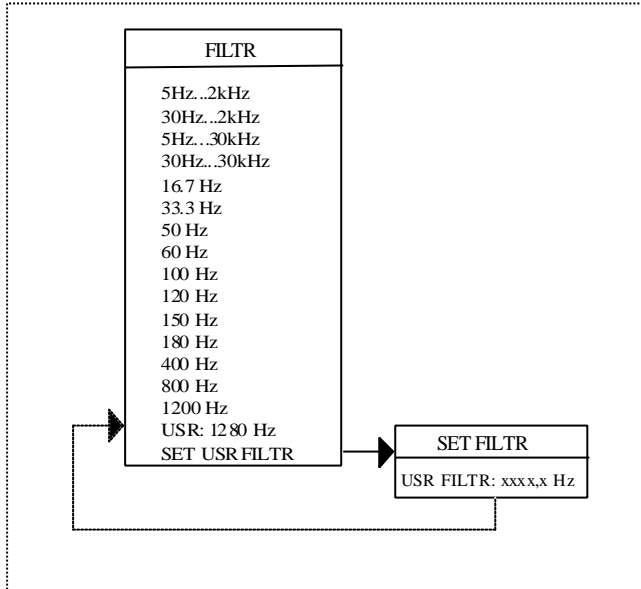


Fig. 4.6: EFA filter functions

To suppress the earth's magnetic field - which becomes noticeable if the test probes are moved - an additional high-pass filter with a limit frequency of 30 Hz is included. This filter can be switched off during certain measurements, e.g. when measuring in the railway frequency range (16.6 Hz). The device has four possible frequency ranges for broadband field measurements. When one of these ranges is activated, the built-in frequency counter is automatically activated as well; it displays the frequency of the maximum field strength which occurs. This is an easy way to determine the source of the strongest fields when multiple field generators are present at different frequencies.

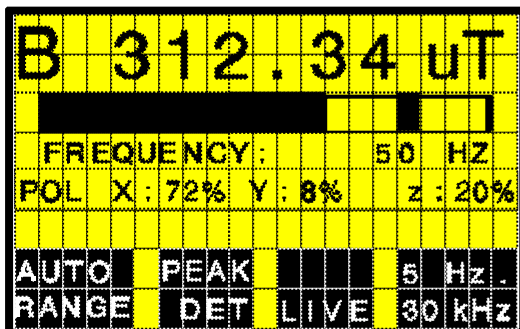


Fig. 4.7: Display of the frequency with maximum level (broadband measurement)

To analyze the field strength at a defined frequency with greater precision, the selective filters listed in the table (Fig. 4.6) were implemented in the devices. The filter frequencies were chosen to allow measurement of the common fundamental frequencies up to their respective 2nd harmonics.

To allow selective analysis of magnetic fields at other frequencies than the ones listed above, a user-definable filter

frequency in the range from 15 Hz to 2 kHz is available as an option.

Finally, we should summarize the parameters which are accessible in the other three main menus:

CONFIGURATION menu:

* Setting the alarm threshold

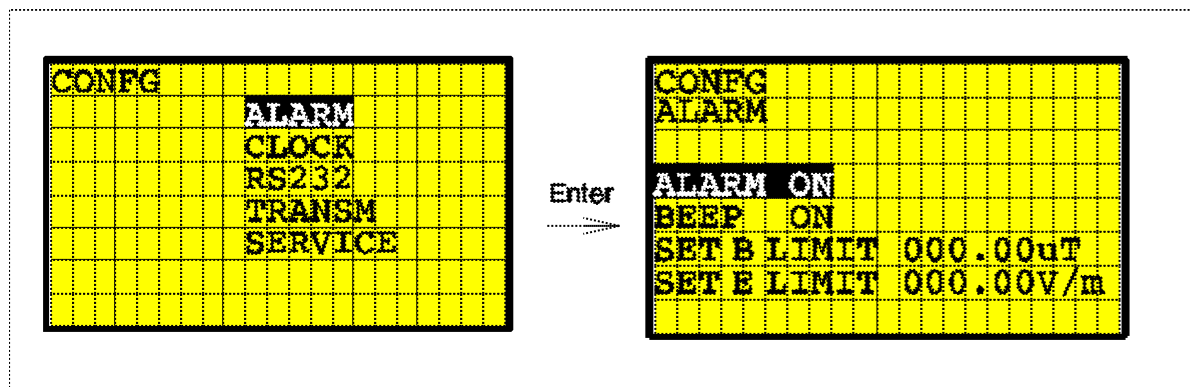


Fig. 4.8: Menu for setting the alarm threshold

The alarm threshold can be set anywhere in the entire measurement range. The alarm is triggered when this threshold is exceeded. Besides a visible alarm, an audible signal can also be output (function can be disabled).

Note: In the EFA-3 device version, the appropriate alarm threshold is activated if the alarm is switched on depending on the probe which is connected.

- * Setting the built-in clock (CLOCK)
- * Configuration of the optical RS-232 interface (RS232)
- * Configuration of the (result) data transfer rate (to the printer) (TRANS)
- * Switching between the units TESLA - GAUSS (SERVICE)

MEMORY menu:

Timed measurements are programmed in the MEMORY menu. Up to 2000 sets of results can be stored; the settings associated with the measured value can be reproduced from a given set of results:

- * Entry of time of day "Start measurement"
- * Entry of time of day "Stop measurement"
- * Entry of step-size for two successive measurements
- * Show function for displaying stored values
- * Print function for outputting the memory content
- * Clear function for erasing the entire memory content or individual locations

USER menu:

- * Recalling the default device setup
- * Function for storing device setups
- * Function for recalling a previously stored setup

Up to four user-definable device setups can be stored.

4.5 Device calibration

Calibration is an important prerequisite for reproducible measurements and standardized verification of field strengths. In the devices in the EFA series, a compensation data set is stored for each sensor used; the data for the current sensor are used in computing results. The data set contains information on the frequency response and level compensation required for the particular probe. The measured data for the probes are selectively recorded and stored for the three dimensions. The production process includes measurement of the isotropy of the built-in probe, thereby making it possible to guarantee the device specifications.

To eliminate the need to pair up the device with a particular external probe, the compensation data set is stored directly in each (external) probe.

The magnetic field probes are calibrated in a "standard magnetic field" which is generated using a Helmholtz frame. Based on a comparison standard calibrated by the Federal German Bureau of Standards (PTB), the required field generation precision can be continually checked and verified.

The sensor for measuring the electrical field is calibrated in a similar manner to the B-field sensor, i.e. using a "standardized field" based on a plate construction which is likewise traceable to a "field standard" of the PTB.

5 *The EFA-1, EFA-2 and EFA-3 device versions*

All device versions have the same measurement accuracy and employ the same probes for measuring low-frequency magnetic fields. The EFA-2 and EFA-2 basic devices are identical up to the capability to connect the sensor for measuring electrical field strength (EFA-3), and have the same features described above.

In the low-cost version (EFA-1), the following features are missing: autoranging, timed measurement and storage of device setups.

6 *Bibliography*

- [1] Elektrische und magnetische Felder
[English translation of title: Electrical and Magnetic Fields]
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Frankfurt (Germany)
- [2] Dissertation, Dipl. Ing. Georg Bahmeier
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