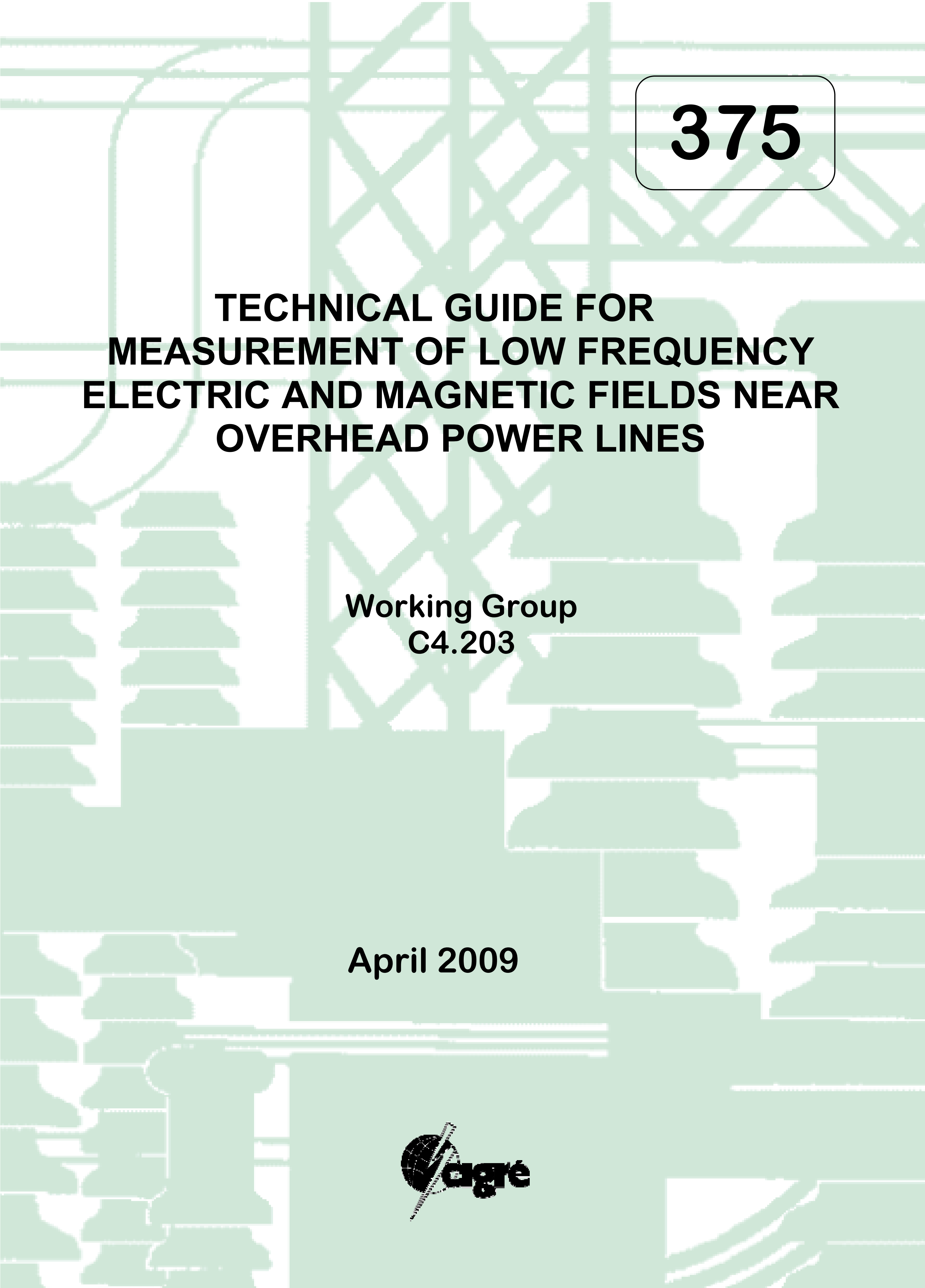

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TECHNICAL GUIDE FOR MEASUREMENT OF LOW FREQUENCY ELECTRIC AND MAGNETIC FIELDS NEAR OVERHEAD POWER LINES

Working Group
C4.203

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Technical guide for measurement of Low Frequency Electric and Magnetic Fields near Overhead Power Lines

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EXECUTIVE SUMMARY

Introduction and scope :

Various regulations, aimed at the protection of human beings against possible adverse effects resulting from exposure to electromagnetic fields, have been issued in many countries, most of them based on safety guidelines published by international expert groups.

These regulations and safety guidelines specify or recommend exposure limits which are expressed in quantities relative to physiological effects (i.e. induced currents or induced ***in situ*** electric field). These quantities are not directly accessible and therefore, measurable limits are also proposed, which derive from the former through conservative assumptions. Therefore, these measurable limits are not absolute ones, nevertheless they are a simple and demonstrative way to check compliance of the exposure of individuals to electromagnetic fields limits.

Regulations and safety guidelines only specify or recommend essential requirements in terms of human safety (i.e. exposure limits) and do not give guidance on the ways to check compliance to these limits. National and international standardisation bodies are working at filling these gaps by issuing standards on measurement procedures, either generic or dedicated to products or equipment. Nevertheless, these procedures may not be sufficient as performing reliable measurements also implies a high level of technical know-how about the possible measurement bias.

With regard to standardisation issues, this document has been developed in view of offering a technical guide of the best practices in performing measurements of low frequency electric and magnetic fields in the vicinity of power transmission equipment. This guide has been drafted with a view to help assessing the human exposure to power frequency fields, but the evaluation of compliance to safety standards or health protection guidelines is outside its scope.

Guide outline :

Referring to previous CIGRE publications (scientific papers and booklets, one of them published in 2007 on EMF characterization), the first section of the present guide only recalls some general information on electric and magnetic fields generated by power lines.

The second section of the guide gives general information on EMF measurements. The first part deals with technical information and requirements for measuring probes, and the second part with measurement procedures. Whereas procedures developed by standardization bodies address to human exposure assessment, this guide focuses on EMF emission of power equipment. Advice is given on the good practices to characterize EMF levels through emission profiles and data to be recorded.

The two following sections are devoted to electric and magnetic field measurements. Major factors influencing the measurements are analysed and best practices are recommended to avoid measurement bias.

Four appendixes are attached to the guide. The first one gives an example of electric and magnetic fields measurement, performed by an accredited laboratory following a protocol consistent with the practices recommended by the present guide. The second one gives an example of data sheet for the measurements, where all influencing parameters are quoted. The third one is a summary of a technical paper on the influence of humidity on electric field measurements (laboratory tests). The last one gives an example of uncertainty calculation for electric and magnetic field measurements.

Target Groups :

The guide is mainly developed for control and standardisation bodies at national and international level. The best practices given are of general use and the guide also helps all technicians and engineers in charge of EMF measurement procedures in electrical utilities and others.

INTRODUCTION

Various regulations, aimed at the protection of human beings against possible adverse effects resulting from exposure to electromagnetic fields (EMF), have been issued in many countries, most of them based on the ICNIRP [1] and IEEE [2] safety guidelines.

Limits on human exposure to extremely low frequency electric and magnetic fields (ELF EMF) are generally given in terms of root-mean-square (rms) values. As an example, the reference levels adopted in the ICNIRP guidelines for exposure of the public to 50 Hz fields, corresponding to the basic restrictions of 2 mA/m², are:

- 5 kV/m rms for the electric field
- 100 µT rms for the magnetic field

Measurements may be necessary to check compliance of the exposure of individuals to EMF generated by distribution and transmission HV installations.

In addition to many scientific papers published in CIGRE technical sessions and conferences, CIGRE has also published booklets on electric and magnetic fields generated by power lines [3] [4] [5]. These documents give detailed information on field characterization, calculation and measurement. Referring to these previous publications, the present document will only recall some general information on electric and magnetic fields, generated by power lines.

The present document gives guidance on how to perform field measurements with the aim of offering these recommendations to the standardisation body, whose task is to set the protocols aiming at checking compliance with recommended limits on human exposure to 50/60 Hz electric and magnetic fields. Measurement protocols are proposed, based on the international standards in force at present as quoted in the bibliography [6] [7] [8], and one should make reference to these standards for items not included in this document.

1. ELECTRIC AND MAGNETIC FIELD GENERATED BY POWER NETWORKS

The electric and magnetic field vectors produced by a three-phase transmission line rotate in space and the vector point describes an ellipse. This is why it is described as ***elliptically polarized field vector*** (for more details, see [5]).

The shape of the ellipse varies between a circle (***circular polarization***) and a straight line (***linear polarization***) depending on the position of the measuring point with regard to the conductors of the line, and also depending on the field character, i.e. electric or magnetic field. The plane of the ellipse is always perpendicular to the direction of the transmission line wires.

Electric fields are always perpendicular to iso-potential surfaces, and are therefore perpendicular to the ground plane. As a consequence, at ground level, the electric field is linearly polarized along a direction perpendicular to the ground surface. In the simple case illustrated in Figure 1, the ground plane is horizontal and at ground level the electric field is vertically orientated, with a negligible horizontal component.

Under the conductors of an overhead line, between 0 and 2 m above ground level, the vertical component of the electric field is predominant and varies only slightly with height. It is therefore considered as uniform. The magnitude of this vertical component however varies along a lateral profile (depending on the horizontal distance to the line) and a longitudinal profile (depending on the height of the conductors). At a height of about 1 m above ground, the influence of the horizontal component on the resultant field is small. This is discussed further in section 3.2.1.

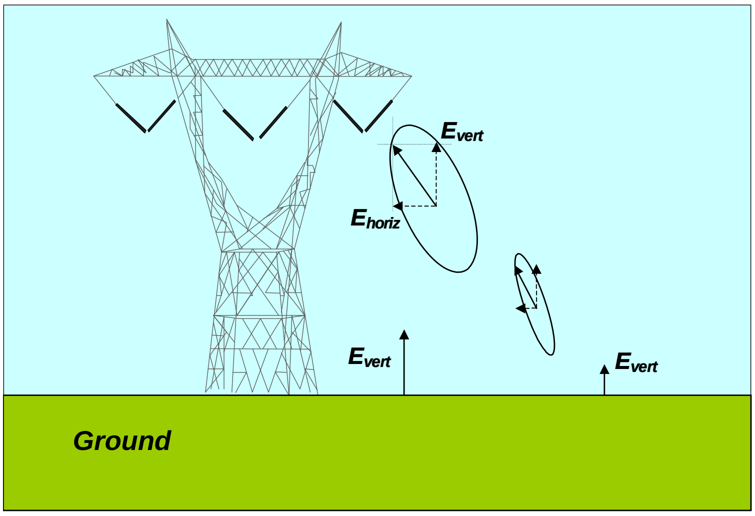

Figure 1: Electrical field polarization at ground level and close to the conductors

At extremely low frequencies, the ground plane does not affect the magnetic field, and its magnitude and the field vector polarization only depend on the distance to the line conductors and on the conductors arrangement in space. Some currents are induced in the ground, the influence of which has only a minor influence on the magnetic field measured in the close vicinity of power circuits. At larger distances, this effect might be proportionally more important.

The currents flowing in the earth wires can reach values in the order of a few percents of the line currents. Therefore they can have a small influence on the magnetic field distribution.

For overhead transmission lines, where the conductors are about ten or more meters high, the magnetic field magnitude increases slightly between ground level and a height of 2 m, with a variation in the order of 20 % [1].

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[1] ***For buried cables, the magnetic field is highly dependent on the height above ground of the measuring point : between ground level and a height of 2 m, it can decrease by a factor of 10.***

2. GENERAL ASPECTS OF MEASUREMENT

High values of electric fields at ground level can only be found in the vicinity of elements of the power transmission networks. Therefore, the interpretation of (high) electric field measurements is generally very simple, as the field sources are very easy to identify.

This is not the case with power frequency magnetic fields, where many sources may contribute to the measured value. Particularly, when measuring low magnetic field levels in an urban environment, the background field due to the presence of other sources operating at power frequency can easily confuse the interpretation of the measurement results.

2.1 Measuring instruments

2.1.1 Probe characteristics

Electric and magnetic field measuring instruments consist of a sensing device (probe) and a unit that determines (and usually displays) the root-mean-square (rms) value of the field. The probe can be of the 3-axis type or the single-axis type.

A 3-axis device performs measurements of the rms field along three orthogonal axes at the same time and determines the resultant field F_R, following :

$$F_R = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2} \qquad \textbf{(1)}$$

F_R is the Resultant Field and is equal to the rms value of the elliptical field at the measuring point,

F_x, F_y, F_z are the rms values of the three orthogonal components of the field at the measuring point.

The resultant field value displayed is thus independent of the orientation of the probe in space[2]. The instrument may also indicate separately the x, y, z components of the electric or magnetic field strength as absolute or percentage values. This can help the understanding and identification of field sources (especially for magnetic field measurements: see section 4). Some measuring devices also give information about the field polarization, which is also helpful for interpretations of measured values.

If a single-axis probe is used, the resultant field F_R can be obtained (using (1)) by taking the square root of the sum of the squares of three meter indications obtained successively when orienting the axis of the probe along three orthogonal directions, without moving the position of its center. It must be noted that such measurements are not simultaneous. This can bias the measured values if the field varies significantly in time, which is often the case for magnetic fields generated by transmission and distribution lines. In addition, it should be noted that it is not an easy task to orient the probe precisely along three orthogonal directions without the assistance of some devices to support and rotate the probe precisely by 90°.

On the other hand, a single-axis probe can be helpful for finding the rms value of the major and minor axis of the ellipse of the polarized field. This can be useful to obtain a complete description of the field in the zone of interest with the minimum and maximum values and also their orientations in the plane

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[2] ***This is not strictly true when measuring strongly non uniform fields. When measuring electric and magnetic fields in the vicinity of power lines at ground level, the effect of the small distance between three separated orthogonal sensors can be neglected.*** **.**

of the ellipse. If the horizontal or vertical components are required for specific needs, the single-axis probe may be used. .

With regard to the general objective of checking compliance with human exposure guidelines, the measurement of individual x, y, z components of electric and magnetic fields is rarely necessary. **For all these reasons, the use of a 3-axis probe is preferred.**

2.1.2 Calibration of the instrument

To ensure accuracy and comparability of measurement results, the instruments should be periodically calibrated, for example according to IEC 61786 [8] or IEEE standard 644-1994 [7]. The calibration should be traceable to national or international standards in conformity with a quality assurance procedure such as specified by ISO 9000. The calibration certificate must be available.

2.1.3 Immunity to disturbances

The instrument should meet the EMC immunity requirements of the industrial environment according to IEC 61000-6-2 [9] or better, the immunity requirements of the environment of power stations and substations according to IEC 61000-6-5 [10].

For specific exposure situations (particularly in some occupational situations), it may be necessary to check the immunity of the measuring instrument with regard to higher levels of disturbances than those specified in the above standards.

Specific immunity requirements for electric field meters :

The IEC immunity specifications for electric field meters [8] requires that the meter should not be affected significantly by ambient power frequency magnetic field as large as 1 mT: the influence of the magnetic field on the meter reading should be less than 1 V/m.

Simultaneous occurrence of a magnetic field higher than 1 mT and a very low electric field will not occur in the vicinity of power lines. To take care of this, an alternative requirement would be that an acceptable measurement error of the measuring device, due to magnetic field interference, should be 1 V/m plus 1% of the reading.

Nevertheless, considering occupational exposure assessment, magnetic field values higher than 1 mT can occur, and for these situations, immunity to these high magnetic fields must be checked.

Attention should also be drawn on possible disturbances of the electronic part of the meter (for example the display) by the electric field or by the related contact currents. If a computer is connected to the meter, its immunity should also be checked.

Specific immunity requirements for magnetic field meters :

Due to the stray capacitance between the turns of the coils [3], the probes for magnetic field measurement might be sensitive to the high electric field under power lines. Therefore, these probes have to be shielded to avoid interferences caused by the electric field.

The magnetic field meter should not be affected significantly by ambient power frequency electric field as large as 20 kV/m: the influence of the electric field on the meter reading should be less than 0.02 µT plus 1 % of the reading.

Due to the Earth static magnetic field, movement and/or vibration of the magnetic field probe may affect the measurement result. Attention should be paid to possible EMC interference from electronic body-worn devices, such as mobile telephones. Some portable magnetic field recorders have been

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[3] ***coils of conductive wires are the most usual type of magnetic field sensors.***

found to be sensitive to mobile phones in contact with them. Nevertheless, if the magnetic field meter fulfills the EMC requirements stated before (see section 2.1.3), such problems should not occur.

2.2 Measurement procedures

Electric fields are very easily perturbed by the presence of conductive objects, even if these objects are poor electrical conductors (trees, fences, vegetation, buildings… etc.) [4]. Such elements have a direct influence on the field magnitude and must be taken into account when a precise exposure assessment is needed.

Depending on whether you characterize the exposure of a person (“***immission***”), or the emission of a power line, the term “***unperturbed field***” may have different understandings :

- The environment of a person includes objects, such as trees, furniture and buildings, which are not movable and which affect the field. The field measurements will incorporate the effects of local field modifications. In these conditions, “***unperturbed field***” should be understood as “***field in the absence of movable objects or persons***”,
- Characterizing the emission of a line implies estimating the field distribution in the absence of any local perturbation. In this case, “***unperturbed fiel***d’ must be understood as “***field in the absence of any object (movable or not) or persons***”,

Whatever the situation (***immission*** or ***emission*** measurements), electric field measurements shall be performed under unperturbed field conditions. This implies, at least, to keep all movable objects and living bodies at sufficient distance from the meter, unless there is a specific requirement for them to be there.

With regard to human exposure to EMF, it is useful to give a visual representation of the field distribution in the vicinity of the power lines. This can be achieved by making spot measurements at particular points of interest. However, it is very useful to produce a profile of fields perpendicular to the line (lateral profile), and sometimes it can also be useful to produce a profile parallel with the line (longitudinal profile). These are described separately in the following.

A schematic plan view of the measurement area shall be drawn, showing the line towers, and all the noticeable elements of the area: main constructions, trees, fences, roads …etc. The nature and height of the vegetation in the measurement area shall also be noted, as it can be of importance when measuring electric fields. See example in Figure 2.

The height of the conductors is of major importance with regard to electric and magnetic field characterisation. Commercial instruments are available for reliable height measurements, such as ultrasonic or laser devices for measuring distances. The range of use of these devices must be suitable for expected conductors height (several instruments have a range of up to about 25 m).

2.2.1 Lateral profile

Lateral profiles are simple and useful ways to describe the main space variation of the electric and magnetic field distribution.

Cases in which the line is symmetrical and the land is flat:

The lateral profile (see Figure 2) of the field should be determined from the centre of the line to a given distance from the outer conductor. The measurements are performed at a specified height above the ground (see sections 3.2.1 and 4.2.1).

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[4] ***even non conductive objects (such as dry rocks) can affect the electric field, due to their relative permittivity higher than 1 (relative permittivity of air).***

Intervals between measurement should be adapted to the desired level of information : under the line, short intervals (e.g. 1 or 2 metres) are useful to characterize local variations, whereas, at longer distances from the centre of the line, larger intervals (e.g. 5 metres) are sufficient.

Measurements are taken from the centreline of the line towards the outer conductors. The axis of the profile will be chosen in a space free of obstacles but representative of the places where the exposure must be assessed.

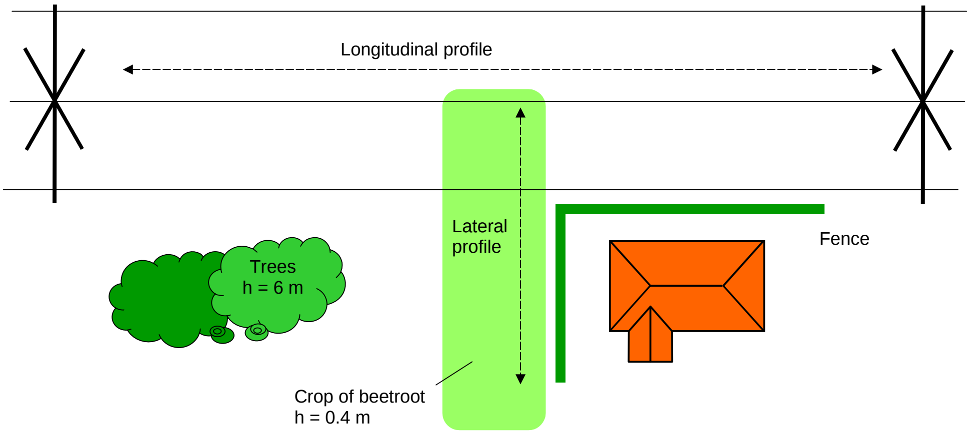

Figure 2 : Plan view of the measurement area

Cases in which the power line is not symmetrical and the terrain is sloping:

If the line is not symmetrical about the centerline on account of the geometry / layout of the phases (phases not arranged symmetrically), of the ground profile, or of the existence of multiple circuits, the lateral profile should be determined completely starting from one side of the line (usually some tens of metres from the outer conductor) and going through to the opposite side. See example in Appendix 1.

To help understanding the results, it is recommended to plot the measurement results into a curve superimposed on the geographical profile of the measurement area. See example in Figure 3. Care should be taken about the fact that distances measured on the sloping ground are not always equivalent to “horizontal distances”.

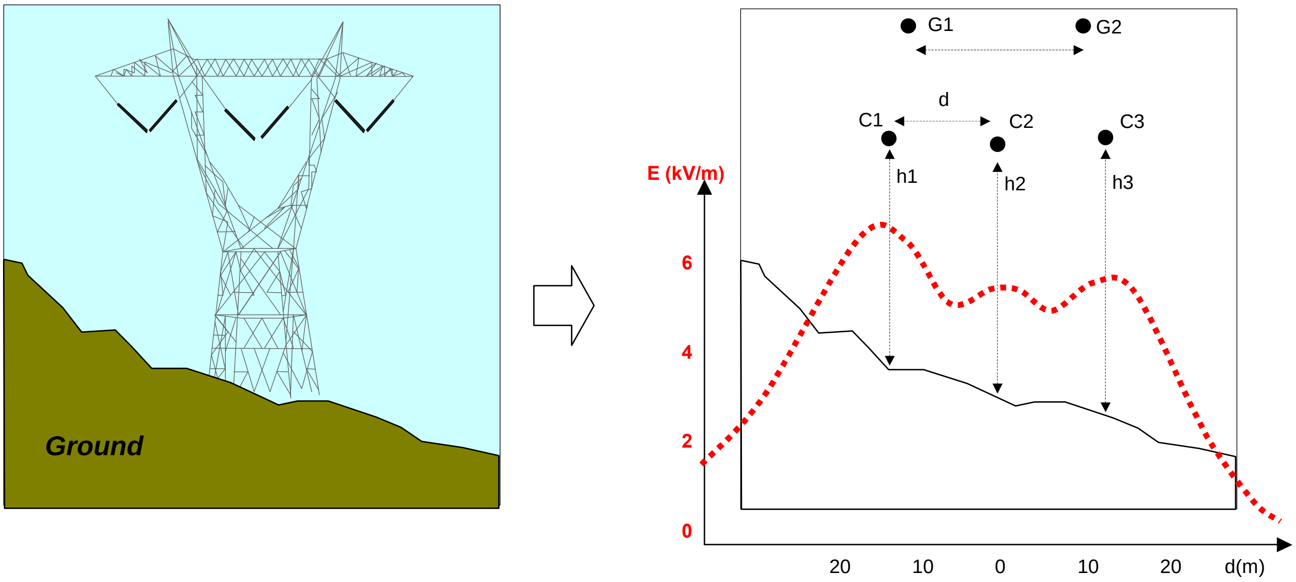

Figure 3: Lateral profile of the electric field strength

2.2.2 Longitudinal profile

The measurement of the longitudinal profile (see Figure 2) can be useful in order to show how the field decreases when moving from the area where the conductor to ground clearance is the smallest towards the extremities of the span. Alternatively it can help finding the cross section where the maximum value can be located.

Care must be taken with the fact that, close to the towers, the electric field is affected (lowered) not only by the increased height of the conductors, but also by the shielding effect of the towers.

2.2.3 Recording of the measurement time

In the given time of a measuring campaign around a HV equipment (typically few minutes to half a day), the electric field does not vary very much, as it only depends on the height of the conductors and the voltage, which will have only very small variations. Therefore, the recording of the precise time of each individual E-field measurement is not needed.

This is obviously not the case when making a set of coordinated measurements of the magnetic field, such as when establishing a lateral or longitudinal profile under a power line. The variations in time of the current flowing in the line can bias the profiles. This is why, in the absence of special precautions (detailed later), the calculation of the magnetic field profile, for a particular load condition, is a good alternative to direct measurements.

2.2.4 Recording of the environmental factors

Air temperature, wind and line load determine the conductor temperature and therefore affects the line sag and ground-conductor clearance. As a consequence the measured electric and magnetic fields at a particular point may differ from one occasion to another, depending on the conductor temperature and height.

This is why it is important to record the weather parameters, particularly when a comparison to computation results is to be performed.

3. ELECTRIC FIELD MEASUREMENTS

3.1 Electric field measuring devices

General information on different types of probes for electric field measurements can be found in the literature [2], [8]. The most usual type of measuring device is the so-called "***free-body***" type that does not need any ground reference. These free-body instruments are easy to use as they are portable and allow measurement above ground level. The free-body instruments can be of the "3-axis" or "single-axis" type.

As stated previously, the use of a 3-axis meter is recommended.

Generally, electric field measuring instruments are made of two main parts : the probe and the unit with a display. The probe and the display are battery-operated and in most cases linked together by an optical fibre. This makes it possible to limit the influence of the operator on the field to be measured.

3.2 Electric field measurement protocol

Limits on human exposure to ELF electric field are generally given in terms of rms value of the unperturbed field (i.e. the E-field which would exist at a given location in the absence of living bodies and of movable objects). Therefore, measurements must be representative of such a quantity.

Power frequency electric fields reach significant values only in the vicinity of HV equipment. As a consequence, this document mainly deals with measurements under overhead power lines. Some additional comments about measurements close to other electrical equipment or facilities are given when needed.

3.2.1 Measurement of the unperturbed field

Type of probe and associated error

As stated before, the electric field close to ground level, and in the absence of conductive[5] objects in the vicinity of the measuring point, is mainly vertical. Nevertheless, the horizontal component can reach values as high as 50% of the vertical component at 1 meter above ground (see Figure 4). In this situation, the vertical field component measured with a single axis probe will be smaller than the resultant field by about 12 % . Similarly, a horizontal component as high as 20 % of the vertical one will generate a difference of 2% between the vertical component and the resultant field. Hence a single-axis measurement can give fair results in most cases when measuring electric fields at ground level.

Moreover, if both the horizontal and vertical components are measured with a single-axis meter, the computed resultant field should be the same as that given by a 3-axis meter.

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[5] ***Attention must be paid that considering ELF electric fields, even objects with a very low conductivity (wood, concrete walls ...) are sufficiently conductive to produce a local perturbation of the electric field.***

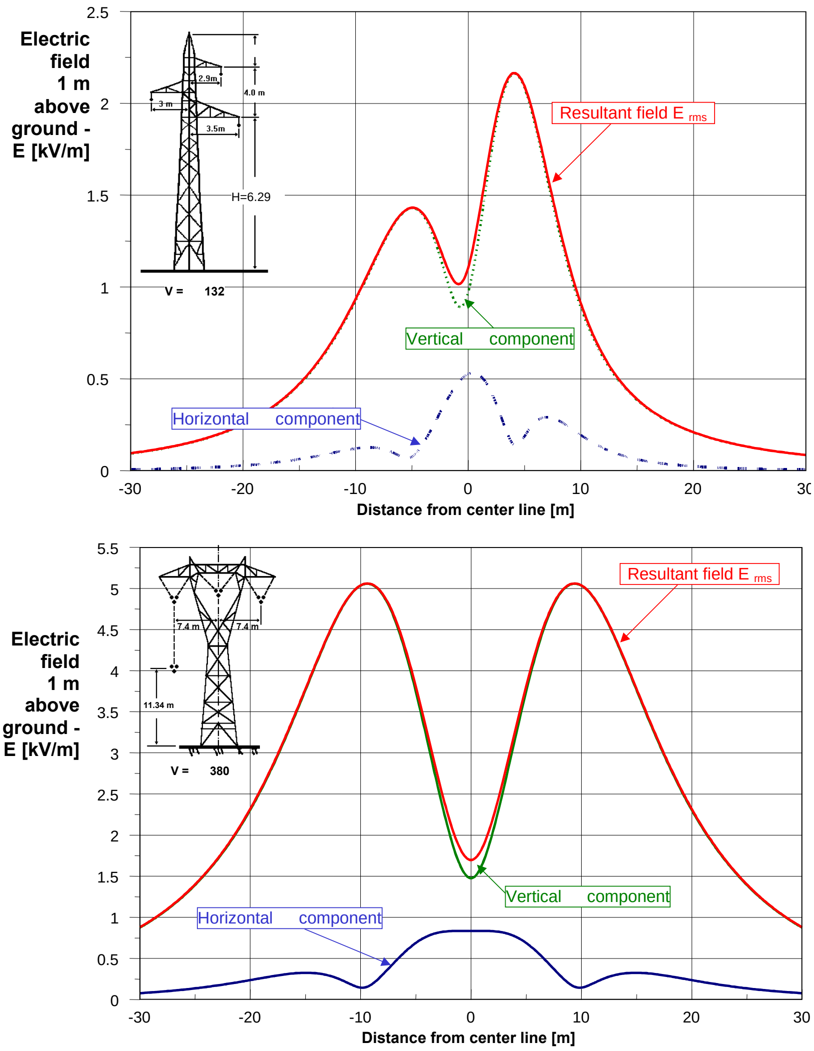

Figure 4 : Vertical and horizontal component of the electric field generated by power lines at ground level (data from *CESI, Italy*)

<u>Position of the probe in space – distance to operator and nearby objects</u>

The measurements need to be performed at a height representative of the human body exposure. Usually, a 1 or 1.5 m height, is chosen as representative of the human body or chest height [6]. However different heights may be specified by local regulations or standards, they shall be respected where applicable. The actual measurement height should be explicitly recorded in the measurement protocol.

The operator should be positioned at some distance from the meter (minimum is 1.5 m and recommended 3 m) to limit the effects of operator proximity on the measurements. Detailed information on the possible measuring error due to proximity effect is given in section 4.2.3.

<u>Note</u> : a practical tip to avoid bias from the operator (easy to use when using a meter with optic fiber) is to move further and further from the probe until the successive measurement results are unaffected.

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[6] ***ICNIRP exposure guidelines [1] specifies that "***reference levels are intented to be spacially averaged values over the entire body of the exposed individual."

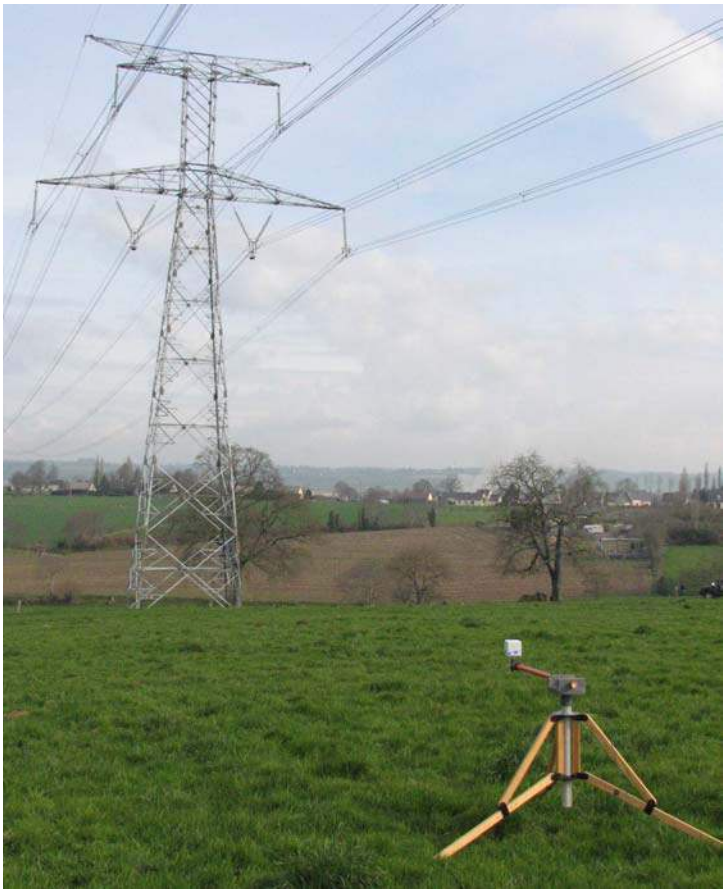

Figure 5 : electric field probe and insulating support (photograph *RTE*)

For line emission assessment, the measurement location should be flat and free from trees, tall grass, fences, buildings and other irregularities. For lateral profiles, the measurements should start from the transmission line to a distance as far as required.

As stated before, all movable objects should be removed whenever possible. If not, then the distance between the probe and the object should be equal to at least three times the height of the object (non-permanent object) or to 1 m (permanent object). Objects that cannot be removed have to be listed, indicating their dimensions and location.

Support of the probe

To have a constant height of the probe above ground, the field meter probe should be held by **an insulating support** that does not affect the measurement (See Figure 5).

Probes installed at the extremity of a hand held non-conductive stick (see Figure 6) can give fair results if the length of the stick is longer than 1.5 m. Nevertheless, attention should be paid on the fact that such measurements are less accurate and less reproducible in terms of probe positioning (height and location).

It is also underlined that the insulating support is one of the major source of measurement errors for electric fields. Special recommendations are given here after (section 3.2.2) to avoid them .

Figure 6 : electric field measurement using a hand-held stick (photograph *RTE*)

Lateral and longitudinal profiles :

To ensure all relevant measurement points are recorded, it is advisable to plot the field profile in real time. The time when the measurements are carried out must be noted in order to correlate them with the values of the line parameters recorded by the dispatching centers of the grid operator.

Nevertheless, as electric fields generated by power lines have slow variation in time, an average value of the current flowing in the line (averaged over the measurement period) is generally sufficient for extrapolation to higher values of current and consequently lower height of conductors.

3.2.2 Measurement conditions

The characteristics of the high voltage line must be recorded in order to compare the measurements with calculations. Some of these data can be recorded on site (height and spacing of conductors, number of conductors per bundle …etc.), and some others have to be collected from the network operator (geometry of line, diameter of conductors … etc.)

In addition, the conditions under which the measurements are performed must be recorded. **Table 1** and **Table 2** in appendix 2 list all the parameters which determine the electric field or influence the measurement conditions.

Measurement of the electric field strength requires a considerable amount of care as the result is influenced by many parameters. Notable among these are:

- accuracy and stability of the measuring instrument
- operator proximity effect,
- influence of the tripod,
- humidity,
- temperature,
- frequency harmonics of the field source,
- non-uniformity of the field,
- corona effect.

Accuracy and stability of the measuring instrument

To improve the measurement accuracy a correction factor can be applied to the measurement result on the basis of the data reported on the calibration certificate, provided that the behavior of the meter does not change with time.

Operator proximity effects

Measurement of the electric field strength at power frequency should be carried out in such a way as to reduce to an acceptable level the interactions caused by the operator and objects located near the probe. Illustration of the electric field perturbation is given in Figure 7, and quantitative results in Figure 8.

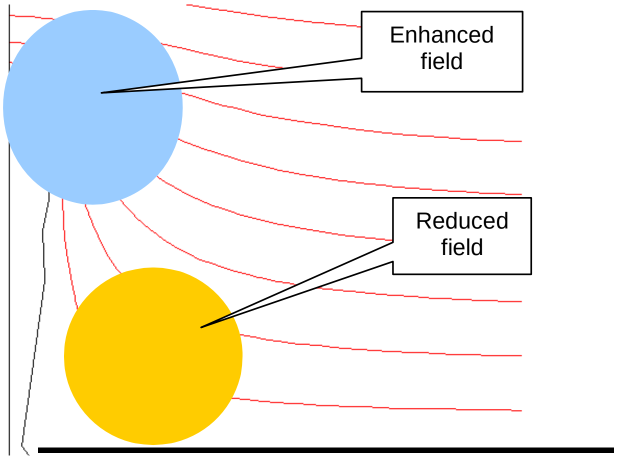

Figure 7 : influence of the operator when measuring electric fields

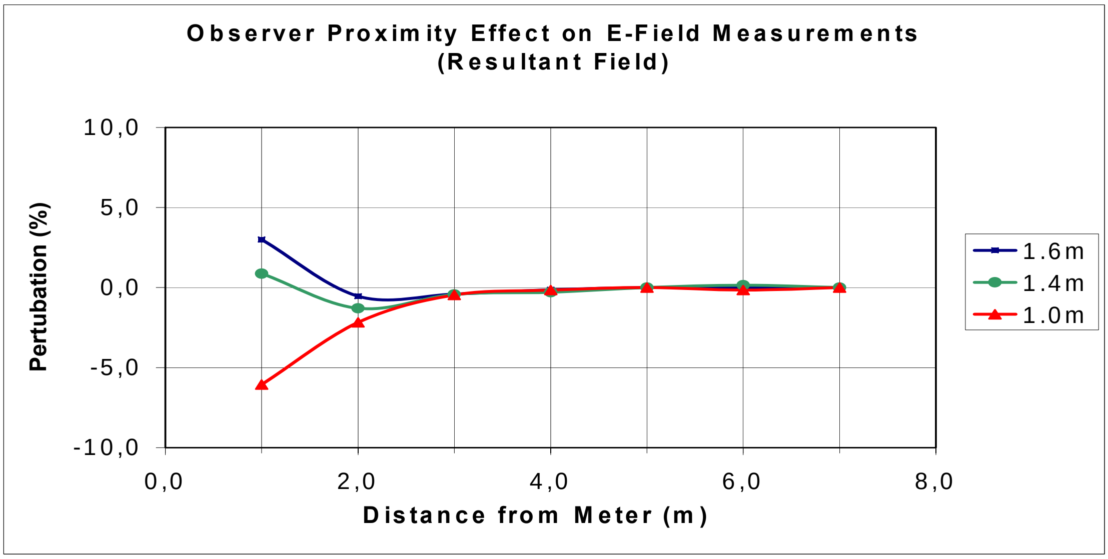

Figure 8 : Perturbation of the E-Field measurement due to the influence of the operator, for different heights of the electric field probe.
(Meter type : 3-axis probe, 10 cm cube supported on a wooden tripod – Operator 1.7 m tall)
(data from *National Grid Transco*)

As it can be seen in Figure 8, a distance of 1.5 m at a measuring height of 1 m leads to some additional inaccuracy less then 5 % , while a distance of 3 m makes the perturbation less than 1 %.

A number of manufacturers provide electric field meters that can be used with short handles (some tens of centimetres). Generally, such instruments lead to rather poor accuracy and reproducibility. Therefore, they can be used for an approximate check/measurement, but not when accurate measurements are required.

Influence of the support

The electric field measured may be perturbed by the presence of the insulating support placed on the ground to hold the meter. To overcome this problem the meter can be moved away from the vertical axis of the support. In this case, it is suggested that the meter be offset from the axis of the support by at least 0.5 m.

Figure 9 : insulating tripod and offset rod for an electric field probe (photograph *RTE*)

Measurements of electric fields can be influenced by the material used in the insulating support: The fact that the support material is electrically insulating is not sufficient to guarantee correct measurements, and care should be taken that the permittivity of this material is close to the permittivity of air[7]. This possible influence may also depend on the geometry of the support : for example, a tripod should normally be less dependant of this factor than other types of support.

This is of particular importance for calibration procedures : for practical reasons the support used during calibration might be different from the one used during measurement (or the support is not used in the same conditions). A correction factor could be applied to take account of this possible effect. Otherwise, an additional measurement uncertainty should be applied.

Humidity and temperature

Humidity is not expected to influence significantly the electric field distribution. Nevertheless, laboratory tests have demonstrated that it can influence the electric field measurement systems, when humidity is sufficient to cause condensation on the sensor and on the supporting structure (tripod). In particular, taking into account the relatively high sensitivity of wood to moisture, wooden supports should be avoided in high humidity conditions.

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[7] ***see tables of dielectric constants for checking the permittivity of insulating material.***
Typical values for relative permittivity : dry wood : 1.4 to 2.9 , Teflon : 2.1 , Bakelite : 5 , polyethylene : 2.5 , Kevlar : 3.5 to 4.5 , rubber : 2 to 4 ; ...

Tests in climatic chambers have established that E-fields readings can be significantly affected when the relative humidity exceeds about 70 % (see appendix 3 for detailed results).

When an additional rod is used to offset the sensor horizontally from the tripod (see Figure 9), the amplitude of the measurement error due to humidity effect is significantly reduced.

It has been found, during these laboratory tests, that E-field measured in high humidity conditions, are always higher than the correct values. As a consequence, such measurements are conservative, and therefore acceptable for checking compliance with limit values. On the other hand, if the measurement exceeds the limit (as specified in EMF exposure guideline and/or legislation), it does not necessarily mean that compliance has not been achieved.

Therefore, when accurate measurement are needed, it is recommended not to carry them out when the humidity exceeds this value. Accurate E-field measurements require a record of the humidity value.

High humidity conditions are usual in some countries. Under these conditions, special care must be taken for measurements and it is possible to demonstrate that this effect can be overcome. The mechanism for this effect is mainly condensation on the insulating tripod, which perturbs the electric field. Therefore, actions to prevent condensation forming help to overcome the phenomenon. As an example, if the meter temperature is higher than the ambient, then there will be no condensation.

It is appropriate to allow the meter temperature to stabilize before starting the measurements. The time required for temperature stabilization will depend on the conditions under which the meter is stored.

Attention has also to be paid when the temperature significantly differs from the ambient temperature at the time of calibration. The manufacturer should indicate the range of temperature and humidity for which the specified accuracy is met.

According to the previous considerations, **accurate electric field measurements cannot be performed under rainy conditions.**

Frequency harmonics of the alternating field source

When it is necessary to assess the harmonic content of the field it becomes necessary to use a meter with capabilities of measuring harmonics. However this is rarely relevant as HV lines in transmission networks are normally operated with a low content of voltage harmonics.

Non-uniformity of the electric field

Since the meter is calibrated in a uniform field, an error can arise when used in a non–uniform field, e.g. when conductive or dielectric objects are close to the measurement point. The relative deviation between the measured field and the actual field at the centre of the meter can be considered negligible, if the distance from the perturbing object is at least 5 times the probe diagonal dimension [8].

Influence of corona

Corona creates a local ionized area in the close vicinity of high voltage conductors. Therefore, the equivalent diameter of the conductors increases and the local electric field decreases. As a consequence, at ground level the electric field slightly increases with intensity of the corona. The phenomenon is likely to be more sensitive for single conductors, than for conductors in bundles, where the equivalent diameter varies as the square root of the diameter of individual conductors [2].

This influence is very difficult to investigate as the most usual conditions for a higher corona activity are high humidity or rain (under which electric field measurements are inaccurate).

3.2.3 Measurement uncertainty

The total uncertainty of the electric field measurement, expressed as the relative “expanded uncertainty” (see appendix 4), should not exceed 15 % of the reading +10 V/m [8].

The measurement uncertainty must be evaluated in accordance with the ISO ***Guide to the evaluation of uncertainty in measurement*** [11]. The quantities which can influence the measurement result, such as those listed in previous section 3.2.2, have to be identified and, when possible, their effect has to be made negligible.

Insofar as the recommendations mentioned in section 3.2.2 are complied with, we may assume that the total uncertainty of measurement is within 10 % of the reading +10 V/m

Measurement uncertainty lower than 10 % + 10 V/m can be obtained by quantifying and controlling the quantities that have influence on the measurement result. An example of such uncertainty evaluation is given in appendix 4.

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[8] ***The inclusion of 10 V/m takes account of the resolution and stability of the meter at the most sensitive scale, when fields in the order of some tens of volts per meter are measured.***

4. MAGNETIC FIELD MEASUREMENTS

4.1 Magnetic field measuring devices

Magnetic field measuring instruments consist of a sensing device and a unit that displays the rms value of the field. There are different types of magnetic field probes :

The most usual probes are made of one coil of conducting wire or a set of three coils. They give fairly accurate results but can only measure AC fields.

The probes using the Hall effect can measure both AC and DC fields. Nevertheless, their sensitivity is low and they require special care (regular reset and/or calibration). Therefore their use is not recommended for AC magnetic field measurements under power lines.

For measuring both AC and DC fields, a possible alternative is the flux gate magnetometer. This type gives accurate results but it is much more expensive and consequently, it is less commonly used.

The ability to measure DC field will only be required for measurements on DC power lines and cables which are uncommon and beyond the scope of this guide.

4.2 Magnetic field measurement protocol

4.2.1 Measurement of magnetic fields near power lines

Position of the probe in space – distance to operator and nearby objects

The measurements need to be performed at a height representative of the human body exposure. Usually, a 1 or 1.5 m height, chosen as representative of the human body or chest height [9]. However different heights may be specified by local regulations or standards, they shall be respected where applicable. The actual measurement height should be explicitly recorded in the measurement protocol.

The presence of the operator does not affect the ELF magnetic field. Consequently, most measuring instruments are hand-held devices. In the same way, most objects, which may perturb the ELF electric field, do not affect the ELF magnetic field.

Metallic objects and more particularly ferromagnetic materials may affect the magnetic field distribution. Therefore mobile metallic objects should be moved away before performing magnetic field measurements.

Support of the probe

The use of a support is not required for ELF magnetic field measurements. Nevertheless, it can help in the precise positioning of the probe in space, and therefore make measurement more reproducible.

The same type of insulated support as for electric field measurements can be used, but all the precautions needed for electric fields (e.g. caution to humidity) are not necessary here.

Lateral and longitudinal profiles

Some commercial devices are specially designed to facilitate the measurement of magnetic field profiles. They comprise a wheel that gives distance information which is recorded by the meter along with the magnetic field information. These particular devices measure the field at a fixed height above ground, which may differ from the usual or specified measurement height.

Due to the instantaneous variations of the current flowing into transmission and distribution facilities, the recording of the measurement time is of major importance, specially when making a set of coordinated measurements, such as when establishing lateral or longitudinal profiles.

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[9] ***ICNIRP exposure guidelines [1] specifies that "***reference levels are intented to be spacially averaged values over the entire body of the exposed individual."

The time when the measurements are carried out must be noted to relate them to the values of the line load recorded by the network operator. Nevertheless, this information on the line load might not be sufficient as its recording time interval is usually longer than that used for making a set of magnetic field measurements.

A useful technique to overcome the problem is to use two synchronized measuring devices, one placed at a fixed position where the field is not affected by other sources (and so measuring the current variation of the transmission lines), and the other one moving along the profile. The comparison of the two simultaneous measurements allows a direct correction of the measurement along the profile versus the current variation.

Attention should be paid to the case of double circuit lines or corridors containing many lines: theoretically, a correlation to the current (magnitude, phase and direction) variations in these different lines or circuits is possible, but practically, the correction is hardly achievable.

Measurement of harmonics

The harmonic content of current in transmission lines is normally low for meeting power quality requirements. However, harmonics in distribution systems may be higher. In order to take account of the possible harmonic content of the associated magnetic field, care should be taken that the bandwidth of the measuring devices allows the measurement of the highest significant harmonics. A bandwidth approaching 1 kHz is suitable in most situations.

Exposure guidelines specify different reference levels (also referred as maximum permissible exposure level) for different frequencies. Measurement of magnetic fields including a high harmonic level and aiming at checking compliance with those guidelines, should take the frequency dependence of the limits into account e.g. by performing a narrow band measurement of each individual harmonic or, better, by applying a broadband weighted filtering.

Note : the arithmetic addition of individual harmonics is a conservative method, because it does not take into account the phase relationship between harmonics, which can partly compensate each other.

When the level of harmonics is low, as it is usually the case for transmission lines, the measurement can be performed using a simple broadband device.

4.2.2 Measurement conditions

The information that needs to be recorded is listed in **Table 1** and **Table 2** of the appendix 1. As explained previously, special attention shall be paid to the time variation of current in the line if the measurement duration is prolonged.

4.2.3 Parameters affecting accuracy

Many of the parameters influencing electric field measurement are not significant when dealing with magnetic field measurement, such as the proximity effects of the operator or the influence of the tripod. However, the influence of other factors cannot be neglected. The main parameters that can affect the accuracy of the measurement are the following:

- movement of the sensor,
- time constant of the meter,
- accuracy and stability of the measuring instrument,
- non uniformity of magnetic field distribution,
- cross talk, non-orthogonality and relative position of the probe coils.

Movement of the sensor

Magnetic field probes are sensitive to quick movements or vibrations in the Earth's static magnetic field. For accurate measurements, it is therefore recommended to keep the meter in a static position for a few seconds.

Time constant of the meter

Sudden variations of the field applied to the meter probe can lead to an incorrect evaluation of the measurement value because of the time constant of the measuring instrument circuitry. Erroneous readings may occur, for example, if the indication of the meter is read immediately after placing the probe in a high field or if the meter indication is recorded right after moving the probe during profile measurements. Reading errors could be also introduced in case of variations of the field due to rapid load fluctuations with respect to the meter response. In any case, the time constant of the meter should always be indicated by the manufacturer.

Accuracy and stability of the measuring instrument

To improve the measurement accuracy a correction factor can be applied to the measurement result on the basis of the data reported on the calibration certificate [10].

Non-uniformity of the magnetic field distribution

When the field is highly non-uniform, such as close to non removable ferromagnetic objects, a measurement "averaging error" can arise due to the dimensions of the probe with regard to the variation to the field in space. If the probe is far enough from the object (at least 1 m), this error can be considered negligible.

Indications of how to estimate the maximum averaging error when a single axis or 3-axis concentric coil probe is used in a highly non-uniform field can be found in [8].

Cross talk, non-orthogonality and relative position of the probe coils

Non-orthogonality of the three-single axis coils, cross-talk and differences in sensitivity between them can lead to an additional inaccuracy, which can be quantified during calibration tests.

To keep this error constant when making a set of measurements, it is recommended to always hold the device in the same orientation with regard to the power line.

Another parameter that can affect the accuracy is when the three orthogonal coils are not concentric. This feature can lead to important measurement errors when the field is highly non-uniform, i.e. when field measurements have to be performed in close vicinity to a magnetic source. This is never the case for measurements of power line magnetic fields.

4.2.4 Measurement uncertainty

The total uncertainty of the magnetic field measurement, expressed as relative "expanded uncertainty", and evaluated according to [11], should not exceed 10% + 20 nT [11]. The quantities which can influence the measurement result, such as those listed in previous section 4.2.2, have to be identified, and, whenever possible, their effect has to be made negligible.

Insofar as the recommendations mentioned in 4.2.3 are complied with and the background field is negligible, it can be assumed that the total uncertainty of the measurement is within 10% + 20 nT.

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[10] ***The calibration periodicity is normally adjusted to take account of possible drift of the meter.***

[11] ***The inclusion of 20 nT takes account of the resolution and stability of the meter at the most sensitive scale, when fields in the order of some tens of nanotesla are measured.***

A measurement uncertainty lower than 10 % + 20 nT can be obtained by quantifying and controlling the quantities that influence the measurement result. An example is given in appendix 4.

5. REFERENCES

[1] **ICNIRP** International Commission on Non-Ionising Radiation Protection. "***Guidelines for Limiting exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz)***" - (**1998**)

[2] **IEEE Standard C95.6** . "***Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0-3 kHz***" - (**2002**)

[3] **CIGRE technical brochure n°21** ***"Electric and magnetic fields produced by transmission systems – Description of phenomena and practical guide for calculation"*** WG 36.01 – (**1980)**

[4] **CIGRE technical brochure n°74** ***"Electric Power Transmission and the Environment – Fields, Noise and Interference"*** WG 36.01 – (**1993**)

[5] **CIGRE technical Brochure n°320** ***"Characterisation of ELF magnetic fields"*** Task Force C4-205 - **(2007)**

[6] **IEC Standard 60833 -** ***Measurement of power frequency electric fields*** -**(1987)**

[7] **ANSI/IEEE Standard 644.** ***IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines –*****(1994)**.

[8] **IEC Standard 61786.** ***Measurement of low frequency magnetic and electric fields with regard to exposure of human beings. - Special requirements for instruments and guidance for measurements*** – **(1998)**

[9] **IEC Standard 61000-6-2.** ***Electromagnetic compatibility (EMC) - Part 6-2: Generic standards - Immunity for industrial environments*** **- (2005)**

[10] **IEC Technical Specification 61000-6-5.** ***Electromagnetic compatibility (EMC) - Part 6-5: Generic standards - Immunity for power station and substation environments***

[11] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OML Guide to the expression of uncertainty in measurements (1993).

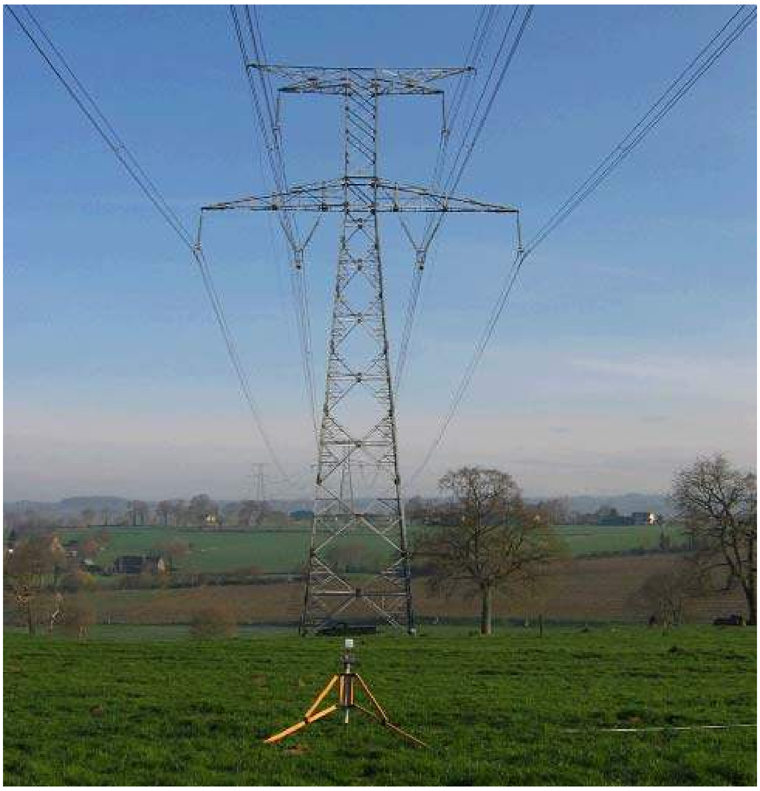
Additional relevant bibliography :

see also **IEEE Draft guide C95-3-1** : ***IEEE Draft Recommended practices for Measurement of Electric, Magnetic and Electromagnetic Fields with Respect to Human Exposure to Such Fields – 0 to 100 kHz***

APPENDIX 1 - EXAMPLE OF MEASUREMENT OF LATERAL PROFILES OF 50 HZ ELECTRIC AND MAGNETIC FIELDS

Measurement Site :

The measurement site is a meadow located under a double 400 kV transmission line. The ground is irregular (grass) with a slight lateral slope which can be seen on the photograph hereunder. Another view of this site is given in figure 5 of this guide.



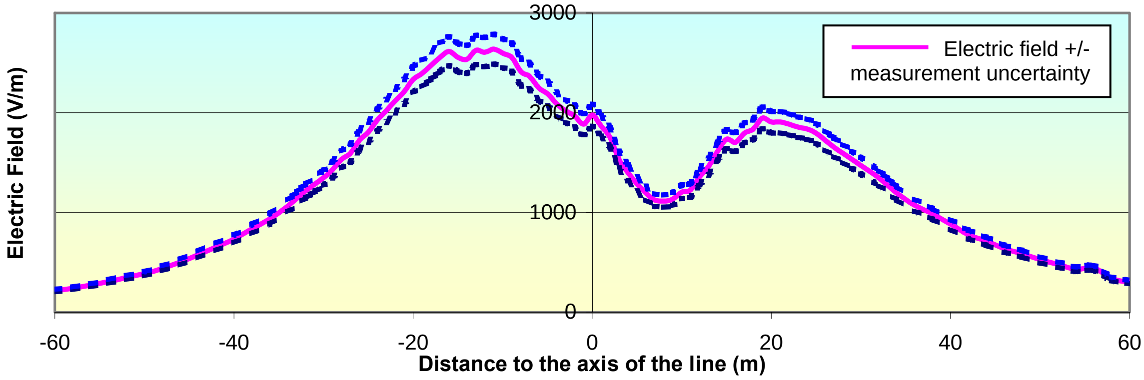
Measurement conditions

The measurement campaign started at 9:00 am and finished at 11:30. The measurement conditions were as follows :

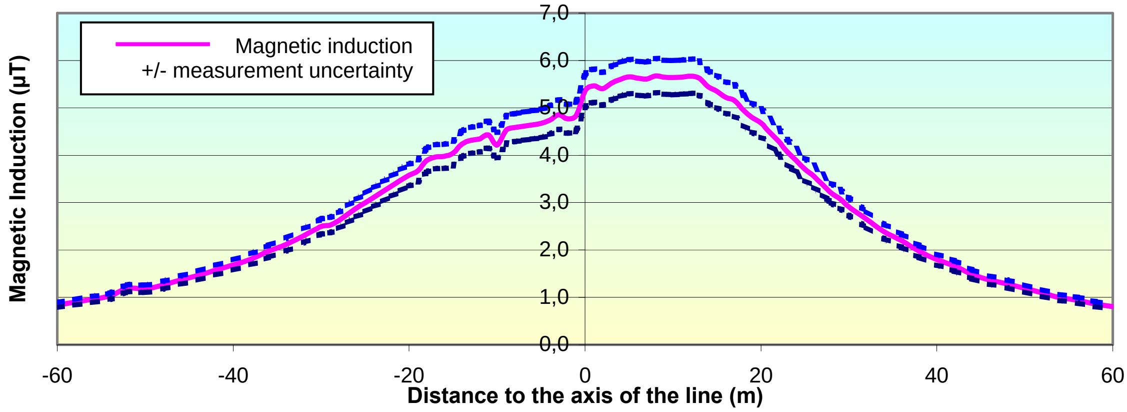
	9 :00	11 :30
Current (identical in the two circuits)	1100 A	900 A
Temperature	3°C	10 °C
Relative humidity	69 %	61 %

Electric and magnetic fields were measured simultaneously. The right side of the lateral profile (following the photograph) was first recorded from 9 :00 to 10:00 am and then the left side from 10:30 to 11:30 am. So, the working conditions of the HV line and the weather conditions were significantly different during these two steps of the campaign.

Electric field profile :



Magnetic field profile :



Qualitative analysis of the measurement data :

The line current variation between 9:00 and 11:30 am was compensated by a temperature increase, so that the height of the line conductors to the ground did not significantly vary during the measurement campaign.

Therefore, the observable dissymmetry on the electric field profile is only due to the ground slope.

The magnetic field profile also shows a dissymmetry, opposite to the previous one, and which is clearly linked to the line current variation between the beginning and the end of the campaign [12].

These measurements were performed by an accredited laboratory and the measurement uncertainties (calculated following a method consistent with those presented in appendix 4 of this guide) are :

- +/- 5,7 % for the 50 Hz electric field,
- +/- 6,4 % for the 50 Hz magnetic field.

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[12] ***A possible way to avoid this bias would be to directly link the magnetic field value to the current in the line and to give the result in µT/kA instead of in µT. Such a presentation allows to easily extrapolate the field values to different load conditions as suggested in [5]. Care must be taken, however, when an extrapolation is done to take into account the variations of the height with the load.***

APPENDIX 2 - RECORDING OF THE PARAMETERS INFLUENCING ELECTRIC AND MAGNETIC FIELDS MEASUREMENTS

Table 1 **: Characteristics of the line**

General characteristics of the line			Electric field	Magnetic field
Rated voltage			R	R
Rated current			I	U
Line conductors and shield wires:	Type		I	I
	Diameter (cm)		U	I
	Bundle	Number of sub conductors	U	I
		Spacing (cm)	U	I
	Sketch of conductors and shield wires (with dimensions)		U	U
	Phasing arrangement (if 2 circuits or more)		U	U
Material of towers (if measurement close to the tower) : Metal / Concrete / Wood / other			U	I
	Sketch of the tower		U	U

R : Required
U : Useful
I : Informative

note : “useful” or “informative” are not necessarily to be understood as “essential for measurements”, but it may be useful if comparing the measurements with calculations or with existing data.

Table 2 : Characteristics the measuring instrument and of the measuring conditions

Line operating conditions (during measurement)			Electric field	Magnetic field
Voltage (including evolution with time)			R	R
	Sampling rate		U	I
Current (including evolution with time)			R	R
	Sampling rate		I	U
	Direction of flow		I	U
Conductor height (m)			U	U
Environmental conditions during measurement				
Atmospheric conditions	Temperature		R	R
	Relative humidity		R	I
	Wind conditions		U	U
	Weather conditions (qualitative)		R	R
Vegetation under the line		Type	R	-
Distance between operator and probe			R	-
Position of the operator with respect to the probe			U	-
Meter characteristics				
Meter	Type - Model	Serial number	R	R
	Sensor Type (1 / 3 axis)		R	R
	Sensor Dimensions		U	U
	Bandwidth		R	R
	Reading characteristics (RMS…)		R	R
	Accuracy and sensitivity		R	R
Probe (if external)	Type - Model	Serial number	R	R
Mounting device	Length of offset		U	-
	Material of tripod		U	-
Calibration	Information, date		R	R
	Correction values		U	U

R: Required

U: Useful

I: Informative

APPENDIX 3 - LABORATORY INVESTIGATIONS ON THE INFLUENCE OF HUMIDITY ON ELECTRIC FIELD MEASUREMENTS

Measurement conditions

The tests were carried out in a climatic chamber on the EDF R&D site “Les Renardières”.

A plate under medium voltage (50 Hz) over the chamber ground produced a roughly uniform vertical electric field of about 10 kV/m.

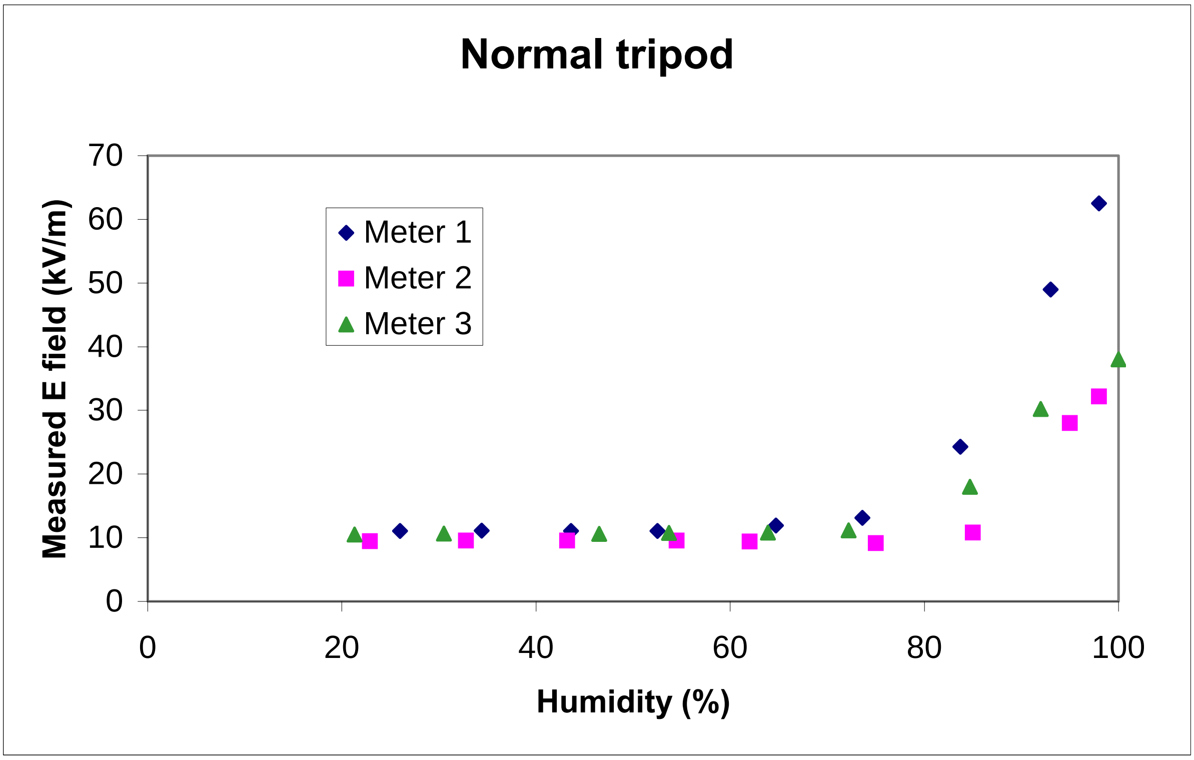
The climatic control was set up to maintain a temperature close to 20 °C while relative humidity was controlled over a wide range of values. During the tests the temperature fluctuated actually between 18 and 21 °C.

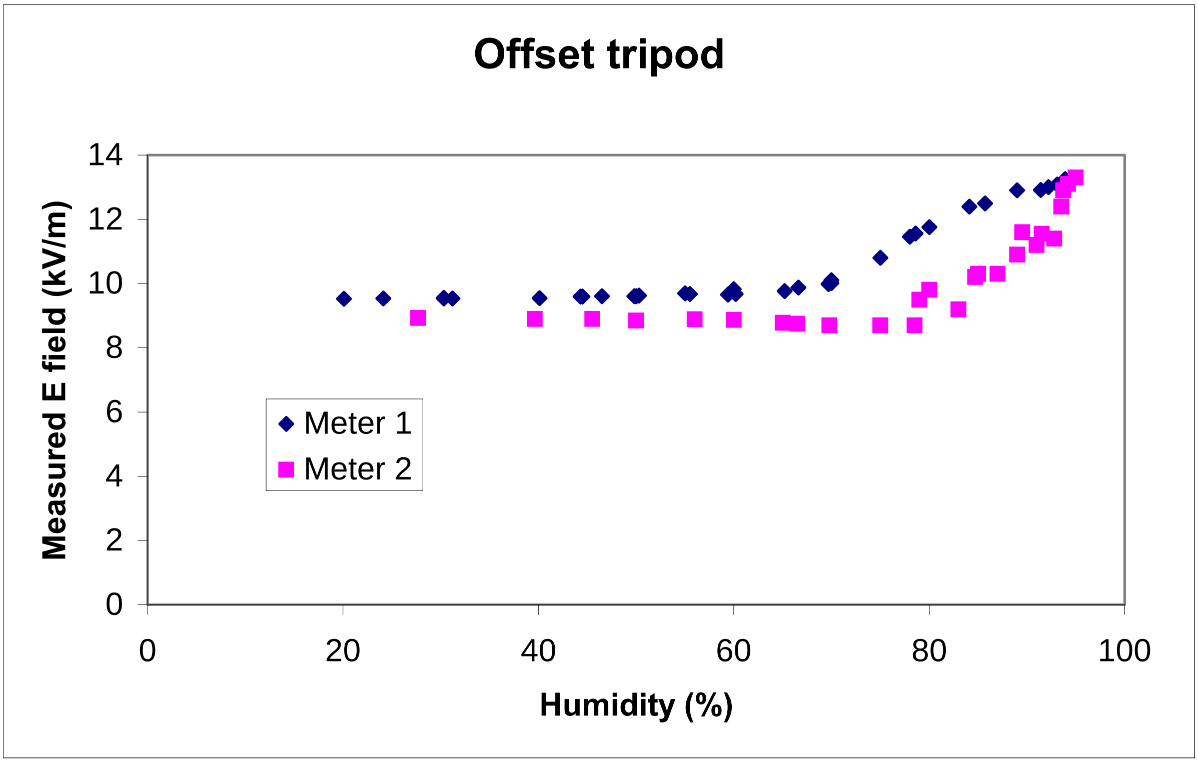
Three free-body type meters were tested, two were “three-axis” and the other “single-axis”.

Two tripods were used with the meters: a “normal” one (insulated tripod) and another with an insulating rod to horizontally offset the sensor (referred to as “offset tripod”).

Main results

The main results of measurements were summarized by the following graphs: measured E field vs. humidity.





The drift of measured field compared to actual field is especially high with a normal tripod when the relative humidity is over about 70% (up to a 7-fold error in reading the applied field). So the offset tripod is recommended because the drift amplitude is much lower (the maximum error is only 40 % of the applied field).

Note : Attempts to reduce the effect of humidity using hydrophobic compounds (silicon grease) to coat the support, have been unsuccessful.

APPENDIX 4 - UNCERTAINTY EVALUATION FOR ELECTRIC AND MAGNETIC FIELD MEASUREMENTS

General considerations :

The measurement uncertainty must be evaluated in accordance with the ISO ***Guide to the evaluation of uncertainty in measurement*** [11].

The quantities, which can influence the measurement result, have to be identified. If the amount of this influence is constant and can be quantified (systematic error) a correction factor, with its associated uncertainty, has to be applied to the measurement result.

Otherwise an associated uncertainty component must be evaluated and introduced in the uncertainty budget. Data from the calibration certificate, tests performed and information given by the manufacturer, technical standard indication and knowledge coming from the operator experience can be used to estimate the uncertainty components.

Once all the components, expressed as standard uncertainty, have been evaluated, the combined uncertainty can be calculated as the square root of their quadratic sum, provided that all the influence quantities are not correlated.

Finally, the expanded (total) uncertainty is obtained by multiplying the combined uncertainty by the coverage factor 2, corresponding to a level of confidence of approximately 95 %, under the assumption of normal distribution of the measurement quantities (see example hereafter).

Example for Electric field :

Measurement carried out by an observer 1.5 m away from the meter secured to the tripod with offset and at an ambient relative humidity of 70 %.
The meter probe is at 1 m height from the ground. No significant perturbation of the field distribution is present.

Technical specifications of the electric field meter stated by the manufacturer :

Type of the probe:	3-axis
Pass band:	5 Hz to 30 kHz (3dB)
Measuring range:	0.5 V/m to 100 kV/m
Accuracy:	± 5 % ± 1 V/m for E > 6 V/m
with:	a) a uniform electric field, b) the vertical insulating rod of the tripod extended as far as possible, c) free from condensation on the whole of the measuring system.

- Accuracy and stability of the measuring instrument
  From the calibration certificate a calibration factor of 99.5 % is obtained. The calibration uncertainty is 1.5% (coverage factor 2): a standard relative uncertainty u_{cr} of 0.75% is then associated to the calibration factor. Comparing the previous calibration certificates, it appears that the meter behaviour is stable.

- Operator proximity effect
  An indication of the perturbation due to the presence of the operator has been obtained in laboratory tests: a relative deviation of 3 % between perturbed and unperturbed meter indication has been obtained for a distance probe-operator of 1.5 m. The standard relative uncertainty u_{pr} is obtained as 3% / $\sqrt{3}$ = 1.7 %, having assumed a rectangular probability distribution and a mean value equal to one for the correction factor due to the proximity effect.

Note : A higher perturbation (9 %) results from the curves reported in Annex B of IEC 61786, which refers to measurement performed with a single-axis probe. With this more conservative limit value of 9 %, u_{pr} increases to 5.2 %.

- Influence of the tripod
  A limit value of 1 % is assumed because of the presence of the tripod. The standard relative uncertainty u_{tr} is then equal to 1 % / √3 = 0.57 %.

- Humidity
  A limit value of 5.3 % as determined by laboratory tests is assumed, leading to a standard uncertainty u_{pr} = 5.3% / √3 = 3.0 %

- Temperature and ambient magnetic field
  The influence of temperature and ambient magnetic field are assumed to be negligible on the basis of laboratory test carried out

- Presence of harmonic components: negligible

- Non uniformity of the electric field: negligible

The measurement value e_m is obtained by multiplying the meter indication by the calibration factor
The relative expanded uncertainty U_r is then calculated from the combined uncertainty u_r according to the relationship :

$$U_r = 2 \cdot u_r = 2 \cdot \sqrt{u_{c_r}^2 + u_{p_r}^2 + u_{t_r}^2 + u_{h_r}^2} = 2 \cdot \sqrt{(0.75\%)^2 + (1.7\%)^2 + (0.57\%)^2 + (3.0\%)^2} = 7.2\%$$

and the measurement result is expressed as $e_m \pm U$
where U is the absolute expanded uncertainty : $U = U_r . e_m$

Example for Magnetic field :

Measurement of magnetic flux density are performed under a HV line, by using a meter with 3-axis coil probe placed at 1 m height from the ground. No conductive or ferromagnetic object is close to the probe.

Technical specifications of the magnetic field meter stated by the manufacturer:

Pass band:	5 Hz at 30 kHz (3 dB)
Measuring range:	100 nT at 10 mT
Accuracy:	± 5 %

with :
- a signal frequency between 50 Hz and 400 Hz
- filter for 5 Hz to 2 kHz
- B > 500 nT

- Accuracy and stability of the measuring instrument
  The results reported on the calibration certificate comply with the meter accuracy specification. The calibration uncertainty u_{cr} is 0.7 % (coverage factor 2). A correction factor equal to one is applied to the indication of the meter and a limit value of ± 5 % is assumed for it, leading to a standard relative uncertainty u_{ar} = 5 % / √3. From the comparison of the previous calibration certificates, the meter behaviour results stable with time.

  The results reported in the calibration certificate comply with the meter accuracy specification, that is the relative deviation between measured and applied field is always < 5 %. The calibration uncertainty U_{cr} is 0.7 % (coverage factor 2). From the comparison of the previous calibration certificates, the meter behaviour results are stable with time. A calibration factor $k_{\text{cal},}$ equal to the mean of the values reported in the calibration certificate for the range of field value to be measured, is assumed and its standard deviation u_{kr} is calculated.

- Temperature and humidity
  The influence of temperature and humidity is assumed to be negligible, since the environmental conditions during the measurement are within the range indicated by the manufacturer
  Since the measurements are performed under temperature and humidity conditions which are far from those occurring during calibration, and no specific information about the meter behaviour is available, a conservative approach of a unity correction factor with an associated standard uncertainty $u_{thr} = 5\ \% / \sqrt{3}$ is assumed.

- Presence of harmonic components: negligible

- Background magnetic field:
  Measurements carried out when no load was present on the line produced a background magnetic field b_f. A correction factor that equals to unity within a limit value of ± b_f / b_m is assumed, where b_m is the magnetic flux density measurement value. Under the assumption of rectangular probability distribution for the correction factor, a relative standard uncertainty of $u_{f\,r} = b_f / (b_l \sqrt{3})$ is obtained.

The measurement value b_m is obtained by multiplying the meter indication b_l by the calibration factor k_{cal}.

The relative expanded uncertainty U_r is then calculated from the combined uncertainty u_r according to the relationship :

$$U_r = 2.u_r = 2 \cdot \sqrt{u_{c_r}^2 + u_{k_r}^2 + u_{th_r}^2 + u_{f_r}^2} = 2 \cdot \sqrt{(0.35\,\%)^2 + (0.9\,\%)^2 + \left(\frac{5\,\%}{\sqrt{3}}\right)^2 + \left(\frac{b_f}{b_l}\frac{1}{\sqrt{3}}\right)^2}$$

and is equal to 7.6 % when a value of 0.9 % is found for u_{kr} and the background field is 4 % of the measured one.

The measurement result is expressed as $b_m \pm U$
where U is the absolute expanded uncertainty : $U = U_r . b_m$