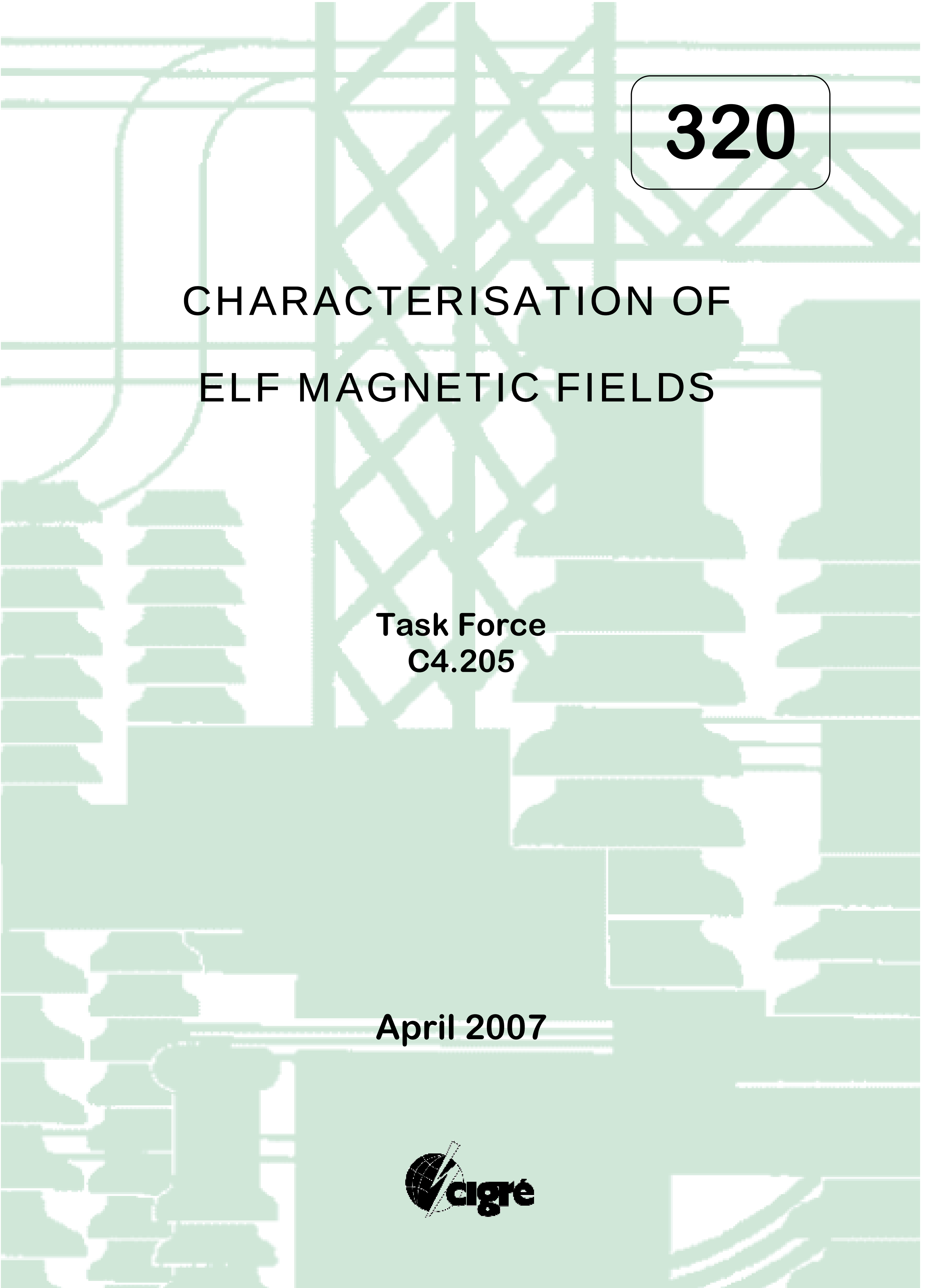

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CHARACTERISATION OF ELF MAGNETIC FIELDS

Task Force C4.205

April 2007

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Task Force
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Executive Summary

Introduction and Scope

Electric and magnetic fields (EMF) at (ELF), and more particularly the power frequency magnetic fields, are an important concern for Power System Operators and for electricity users due to their possible impacts on living organisms.

After more than 30 year of research, the scientific community has not yet reached an agreement on whether prolonged exposure to EMF, at levels lower than the international recommendations, can have an influence on the human health.

Based on known acute effects, reference levels in the range of 100 µT or more have been proposed by international bodies like ICNIRP[1] or IEEE and by international authorities like the Council of the European Union. On the other hand possible long-term health effects have been associated to average fields lower than 1 µT in epidemiological studies. Whether or not this association is causal is not yet evident. As a result, some authorities have adopted, or intend to adopt, a cautionary approach such as through the introduction of limits much lower than the international reference levels.

Notwithstanding the relevance of these decisions or of the real need to set up limits, the fact is that neither the standards nor the existing regulations give clear definitions of the meaning of a given field level or the way to assess conformity with limits.

In the examples above, although the ICNIRP reference level of 100 µT (at 50 Hz) and the epidemiologic cut off points of below 1 µT both refer to the magnitudes of the same ELF magnetic induction fields, they clearly do not address the same characteristics of the fields.

Magnetic fields vary greatly in space and change with time. On the other hand, human activities and movements make exposure assessment very complex.

The low field values mentioned in epidemiological studies refer to estimates of long-term human exposure. Hence, if reference in some regulation is made to values lower than the ICNIRP reference levels, there is a need to define correctly these values, possibly in terms of statistical quantities evaluated over a given space and/or a given period of time (e.g., with respect to time: mean values over 1 day, mean values over 1 year, median values, values not exceeded 95% of the time - as for noise characterization; or with respect to space: choice of measurement location, number of measurement points, distance to the source…).

Space variations not only influence the statistical quantities (e.g., average values) but depend also on the uniformity of the field. The relation between the field levels and the possible induced currents in the body - that are often taken as basic restrictions by the international bodies - is another parameter for consideration.

In addition, since fields can be produced by several sources, there is also a need to be able to assess the contribution of each source individually.

The purpose of this guide is to identify representative characteristics of ELF magnetic fields produced by electrical power system installations and networks and to propose a set of “quantification parameters” to qualify magnetic fields in a way better than that described by a single figure.

In other words the main target of this guide is to try to identify ***Exposure Metrics*** like:

- statistical metrics for long-term exposure
- metrics for instantaneous exposure to non uniform fields
- metrics for multi-source fields and multi-frequency fields

However, due to the importance taken today by the epidemiological data, the guide focuses mainly on statistical metrics.

Guide outline

The guide first discusses some basic concepts like the Biot – Savart and the Ampère’s laws, the relationship between induction field (B) and magnetic field (H) and the field polarization (linear, elliptical…).

Then the main parameters used for characterising magnetic field strengths are described: RMS (root-mean-square) value, Resultant field, Peak value, Root-sum-square, relationship with the magnitude of the semi-major and semi-minor axes of the ellipse described by the field vector, etc. Some comments on the comparison of measurement and calculation data are also given.

The next chapter describes the time and space variations of the fields and more particularly the statistical parameters like the arithmetic and geometric mean, the mean value over a given period, the median and the percentiles. All these quantities are highlighted with practical examples.

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[1] International Commission on Non Ionizing Radiation Protection

Another chapter lists the factors influencing the field levels, like the load conditions, the temperature, and the currents unbalance. In particular, the concepts of rated conditions, normal operating conditions and fault conditions are highlighted. Factors like measurement distances and coupling factors are also discussed, mainly when non-uniform fields have to be assessed.
One of the main chapters of the guide is intended to give some guidance for assessing statistical values in the absence of dedicated data. Based on measurement data coming from different countries, the guide proposes to adopt conservative ratios between magnetic field levels assessed under the three most often specified current conditions:

1) the rated current, i.e. the maximum possible current for which the circuit – most often a line or a cable - has been designed,
2) the annual maximum current
3) the annual mean current or median current.

The idea, here, is to provide to the user the possibility to extrapolate a given field value to different statistically representative load conditions, depending on the type of limit or recommendation that has to be taken into consideration (absolute limits, long-term average levels derived from epidemiologic data…).
Many other parameters could have been discussed in this guide, in particular the field characteristics due to multiple sources (like substations) and multi-frequency sources (like that of harmonics) is just mentioned but not detailed. These topics certainly worth investigations in future studies.

Target groups
This guide is mainly intended for regulatory authorities, standardisation bodies and design engineers.
The existence of well-defined EMF parameters related to a specific installation (e.g., a HV power line) should give the authorities or the regulators the opportunity to follow the change in EMF levels during the evolution of the specific installation with time, to benchmark and to fix objectives or qualify targets in a much more constructive way than by setting up absolute limits. It should also allow Power System Operators to better inform the authorities and to apply voluntary measures appropriately.
Although this guide does not focus on compliance evaluation related to human exposure standards or guidelines, which is the domain of several other documents, the information it brings on field characterisation can provide some assistance in compliance evaluation in many practical cases.

1 Introduction

Electric and magnetic fields (EMF) at extremely low frequencies (ELF), and more particularly the power frequency magnetic fields (MF), are an important concern for operators of electricity systems and for electricity users due to their possible impacts on living organisms.

After more than 30 years of research, the scientific community has not yet reached agreement on whether prolonged exposure to EMF, at levels lower than the international recommendations, can have an influence on human health.

Reference levels based on known acute effects, have been proposed by international bodies[2] such as ICNIRP[3] and by international authorities such as the Council of the European Union. These are in the range of 100 μT and above. On the other hand, possible long-term health effects have been associated with average fields lower than 1 μT in epidemiological studies. Whether or not this association is causal is not yet evident. As result, some authorities have adopted, or intend to adopt, a cautionary approach such as through the introduction of limits at levels much lower than the international limits and reference levels based on known effects.

Notwithstanding the relevance of these decisions or of the need to set up limits, it is important to note that neither the standards nor the existing regulations give clear definitions of the meaning of a given field level or the way to assess conformity with any set of limits.

Magnetic fields vary greatly in space and change with time. The low field values used in epidemiological studies are estimates of long-term average of human exposure magnetic fields. Hence, if reference in some regulation is made to lower values than the ICNIRP reference levels, there is a need to define these values correctly. This can be done in terms of statistical quantities evaluated over a given space and a given period of time. For example, with respect to time, possibilities include the mean values over 1 day, the mean values over 1 year, the median value, or values not exceeded 95% of the time (as for noise characterization), or, with respect to space: choice and number of measurement points, distance to the source, etc).

Space variations not only influence the statistical quantities (e.g., average values) but also the uniformity of the field. The relation between the field levels and the possible induced currents in the body that are often taken as basic restrictions by the international bodies is another parameter for consideration. In addition, since fields can be produced by several sources, there is also a need to be able to assess the contribution of each source.

2 Scope

The purpose of this guide is ***to identify representative characteristics of ELF magnetic fields produced by electrical power system installations and networks and to propose a set of "quantification parameters" which qualify the magnetic fields in a way that is better than a single figure can do***.

In other words the main target of this guide is to try to identify several ***Exposure Metrics*** in the sense[4] defined by WHO in [1] , and, in particular:

- statistical metrics for long term exposure
- metrics for instantaneous exposure to non uniform fields
- metrics for multi-source fields and multi-frequency fields

This guide is mainly intended for regulatory authorities, standardisation bodies and design engineers.

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[2] Or national bodies like IEEE and ACGIH

[3] International Commission on Non Ionizing Radiation Protection (see [2])

[4] A single number that summarises an electric and/or magnetic field exposure over a period of time. An exposure metric is usually determined by a combination of the instrument's signal processing and the data analysis performed after the measurement.

Its purpose is to present well-defined EMF parameters related to a specific installation (e.g., a HV power line) which should enable the authorities to set objectives or quality targets taking account of both the level of the field and its time variation in a much more constructive way than by setting absolute limits. It should also allow operators of electricity systems to better inform the authorities and to apply voluntary measures appropriately.

The purpose of this guide is not to define limit values or the possible impact of limits. However the information it brings on field characterization can provide help for compliance evaluation in many practical cases.

3 Basic concepts

3.1 Definitions[5]

	Definition
Affected area	Location where a measurement has to be performed or where a given limit for the magnetic field level applies
Basic restriction *1	According to the terminology in use in health recommendations relating to exposure to electromagnetic fields, the basic restriction is the exposure limit based on biological effects established by biological and medical studies of the fundamental interaction phenomena. Basic restrictions usually include safety factors to allow for uncertainty in the scientific information defining the threshold for the effect. For power frequencies the basic restrictions are provided on current density or electric field inside a human body to prevent effects on central nervous system functions. Because the basic restriction is a quantity inside the body that cannot be measured, a corresponding reference level is generally derived and used in EMF exposure limits and guidelines.
Coupling factor *K* *1	Factor used to enable exposure assessment for complex exposure situations, such as non-uniform magnetic field or perturbed electric field. The coupling factor *K* has different physical interpretations depending on whether it relates to electric or magnetic field exposure. The value of the coupling factor *K* depends on the model used for the field source and the model used for the human body. When exposure conditions are defined, such as in a product standard, precise values of the coupling factors can be specified directly and can be used such as defined in product standards.
Current density *2 **(*J*)**	A vector whose integral over a given surface is equal to the current flowing through the surface; the mean density in a linear conductor is equal to the current divided by the cross-sectional area of the conductor. The current density is expressed in units of ampere per square meter (A/m^2).
Electromagnetic compatibility *2 **(EMC)**	Ability of systems, equipment, and devices that utilize the electromagnetic spectrum to operate in their intended operational environments without suffering unacceptable degradation or causing unintentional degradation because of electromagnetic radiation.

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[5] Some definitions, that are used only one time, are in the main text and not repeated here (see table of content). Other definitions presented here are sometimes highlighted in a different way in the text.

Emission measurements	Measurements performed in the vicinity of a source irrespectively of its position relative to the affected area; these measurements are generally for assessing whether or not the source complies with some specifications.
Exposure metric [*2]	A single number that summarizes an electric and/or magnetic field exposure over a period of time. An exposure metric is usually determined by a combination of the instrument's signal processing and the data analysis performed after the measurement.
Extremely low frequency [*2] **(ELF)**	Frequencies between 30 Hz and 300 Hz[6].
"Immission" measurements	Measurements performed in the affected area.
Instantaneous value field	Magnitude of the field at a given instant of time.
Magnetic field strength [*1] **(H)**	Magnitude of a field vector H that is related to the magnetic flux density B by the formula: $B = \mu_r \mu_0 H$ where μ_r is the relative permeability of the medium and μ_0 is the permeability of the free space. The magnetic field strength is expressed in units of ampere per meter (A/m).
Magnetic flux density [*1] **(B)**	Magnitude of the field vector B at a point in the space that determines the force F on an electrical charge q moving with velocity v by the formula: $F = qvB$. The magnetic flux density is expressed in units of tesla (T)
Non uniform field [*1]	Field that is not constant in amplitude, direction and phase over the dimensions of the body or part of the body under consideration.
Phasor [*3]	Complex number expressing the magnitude and phase of a time-varying quantity[7].
Polarization [*4]	The shape traced by the tip of an EMF vector over a single cycle[8]. For fields with a single frequency, the polarization is either circular, elliptical or linear.
Power frequency [*2]	Frequency at which alternating current (AC) electricity is generated. For electric utilities, the power frequency is 50 Hz in much of the world and 60 Hz in North America, Brazil, parts of Japan and some other countries. Isolated AC electrical systems may have other power frequencies, e.g. 16 2/3 Hz in some railway systems.
Rated conditions	"Rated" conditions are the conditions for which the circuit parameters have been designed to comply with regulation and territorial constraints, taking into account some environmental conditions (see 4.4.1.1).
Maximum Permissible Permanent Current	Similar to rated current (see 4.4.1.1)

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[6] ELF is sometimes defined as the frequency band between 0 and 30 Hz (ITU) but it is more often considered, as far as safety and health is concerned, as the frequency band between 30 and 300 Hz (cf. Table 1.1 [4]) and more practically as the power frequency band (including the relevant harmonics). The spectrum from 0 to 30 Hz is then called Sub-Extremely Low Frequency (SELF).

[7] Although being different mathematical entities, vectors and phasors look similar; especially when compared with 2D vectors. In fact, a phasor can be visualized as a rotating vector. Impedance and voltage are examples of phasors, while electric or magnetic field are examples of vectors.

[8] Assuming no propagation, which is the case in ELF; otherwise the definition becomes: The shape traced by the tip of an EMF vector in any fixed plane intersecting, and normal to, the direction of propagation. For linear polarization, depending of the field orientation, it is sometimes spoken about horizontal or vertical polarization.

Resultant field [*4] ***(Br)***	Mathematical function used to calculate the vector magnitude B from the vectors components B_x B_y B_z values with Pythagorean theorem. The resultant field is equivalent to the RMS field (see 4.2.2).
Root-mean-square [*2] **(RMS)**	Certain electrical effects are proportional to the square root of the mean of the square of a periodic function (over one period). This value is known as the effective or root-mean-square (RMS) value since it is derived by squaring the function, determining the mean value of the squares obtained, and taking the square root of that mean value.

*1: IEC TC 106
*2: WHO framework for developing EMF standards (2003)
*3: IEEE Std 644 (1994)
*4: NIEHS Working Group report (1998)

3.2 Quantities and constants

Quantity	**Symbol**	**Unit (S.I.)**
Electric charge	Q	coulomb [C]
Electric current	I	ampere [A]
Frequency	f	hertz [Hz]
Angular frequency = 2πf	ω	radian per second [rad/s]
Electric field	E	volt per metre [V/m]
Magnetic field strength	H	ampere per metre [A/m]
Magnetic flux density or magnetic induction	B	tesla [T] volt second per square metre (Vs/m^2) or weber per square metre (Wb/m^2)
Magnetic permeability	μ	henry per metre [H/m]
Electric conductivity	σ	siemens per metre [S/m]
Permittivity	ε	farad per metre [F/m]

Physical Constant	**Symbol**	**Value S.I.**
Permittivity of free space	ε_0	8.854×10^{-12} [F/m]
Magnetic permeability of free space	μ_0	$4\pi \times 10^{-7}$ [H/m]

3.3 Field calculation

The magnetic field produced by an elementary current source can be calculated using the well-known equations for electromagnetic phenomena [6].

A wire with length $d\vec{l}$ and supplied by a current $\boldsymbol{I}$, creates in the air a flux density $d\vec{\boldsymbol{B}}$ and a magnetic field $d\vec{\boldsymbol{H}}$ given by (Biot and Savart law) (Figure 1):

$$d\vec{\boldsymbol{B}}(x,y,z) = \frac{\mu_o}{4\pi}\frac{\boldsymbol{I}\,d\vec{l}\times\vec{r}}{|\vec{r}|^3}$$

$$d\vec{\boldsymbol{H}}(x,y,z) = \frac{d\vec{\boldsymbol{B}}}{\mu_o}$$

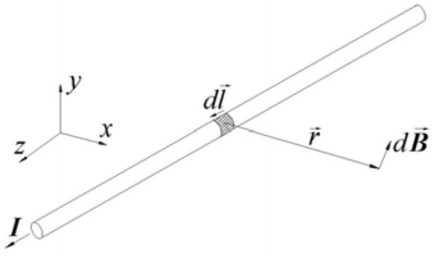

Figure 1: Flux density $d\vec{\boldsymbol{B}}$ generated by a current $\boldsymbol{I}$

where r is the distance between element $d\vec{l}$ and the calculation point of $d\vec{\boldsymbol{B}}$[9]. By integrating along the whole conductor, vectors $\vec{\boldsymbol{B}}(x,y,z)$ and $\vec{\boldsymbol{H}}(x,y,z)$ are obtained.

This basic relationship shows that $\vec{\boldsymbol{B}}$ and $\vec{\boldsymbol{H}}$ are directly proportional to the current, $\boldsymbol{I}$, in air.
Then, the field created by simple sources (such as infinitely long wires, a circular loop, a solenoid, etc.) can be calculated analytically. Depending on the type of source, $\vec{\boldsymbol{B}}$ and $\vec{\boldsymbol{H}}$ decrease more or less rapidly with the distance:

- A single conductor[10] (e.g. railway overhead power supply, earth wire of an overhead power line): the magnetic field decreases as $1/r$, where r is the distance to the energised conductor.
- A system of parallel conductors, energised by a system of balanced currents[11] (e.g. electrical networks): the magnetic field decreases as $1/r^2$, where r is the mean distance to the energized conductors. This feature is valid when r is large compared to the distance between the different conductors.
- A localised source (e.g. electrical domestic appliance, power transformer) can be considered as a magnetic dipole: the magnetic field decreases as $1/r^3$, where r is the distance to the source. Similar to the above point, this approximation only applies when r is large compared to the size of the source itself.

In the most general case, the magnetic field $\vec{\boldsymbol{H}}(x,y,z)$ is a three-dimensional field in space. However, in many high voltage applications such as high voltage lines, the source generating the magnetic field can be considered infinitely long and the magnetic field has only a very small component in the direction of the linear source. When the source is directed in the z-direction H_z is almost zero, leading to a two dimensional field.

The magnetic field generated by an infinite straight wire can be easily computed by applying Ampere's law.
Considering the wire centred in the origin and directed along the z-axis, magnetic field values (H_x and H_y) at a point (x, y) are given by (Figure 2):

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[9] In this document the symbols are marked in bold when they represent a sinusoidal time-varying magnitude (phasor)
[10] with the return path far away, for instance in the ground.
[11] i.e., in which the sum of currents in the system of conductors is zero

$$\boldsymbol{H}_x = \frac{-\boldsymbol{I}}{2\pi}\frac{\boldsymbol{y}}{\left(\boldsymbol{x}^2+\boldsymbol{y}^2\right)}$$

$$\boldsymbol{H}_y = \frac{\boldsymbol{I}}{2\pi}\frac{\boldsymbol{x}}{\left(\boldsymbol{x}^2+\boldsymbol{y}^2\right)}$$

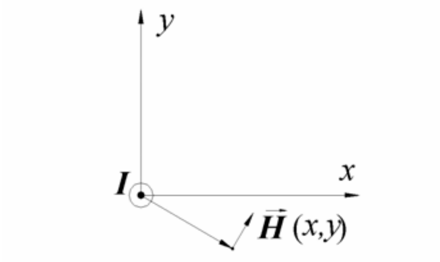

Figure 2: Magnetic field $\vec{\boldsymbol{H}}(x, y)$ generated by current I

where $\boldsymbol{I}$ is the current flowing through the conductor.

In the presence of two infinite parallel wires with the same current flowing in opposite directions (balanced currents), placed a distance d apart and centred with respect to the coordinate system (Figure 3), the magnetic field is expressed by:

$$\boldsymbol{H}_x = \frac{-\boldsymbol{I}}{2\pi}\left[\frac{\boldsymbol{y}-\frac{\boldsymbol{d}}{2}}{\boldsymbol{x}^2+\left(\boldsymbol{y}-\frac{\boldsymbol{d}}{2}\right)^2} - \frac{\boldsymbol{y}+\frac{\boldsymbol{d}}{2}}{\boldsymbol{x}^2+\left(\boldsymbol{y}+\frac{\boldsymbol{d}}{2}\right)^2}\right]$$

$$\boldsymbol{H}_y = \frac{\boldsymbol{I}}{2\pi}\left[\frac{\boldsymbol{x}}{\boldsymbol{x}^2+\left(\boldsymbol{y}-\frac{\boldsymbol{d}}{2}\right)^2} - \frac{\boldsymbol{x}}{\boldsymbol{x}^2+\left(\boldsymbol{y}+\frac{\boldsymbol{d}}{2}\right)^2}\right]$$

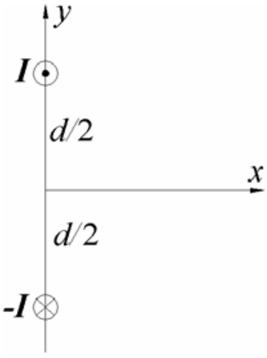

Figure 3: Current dipole

In the case of a system of N straight parallel and infinite wires, the previous expression can be generalized by introducing a summation over all the wires:

$$\boldsymbol{H}_x = \frac{1}{2\pi}\sum_i \boldsymbol{I}_i\left[\frac{y_i - y}{(x-x_i)^2+(y-y_i)^2}\right]$$

$$\boldsymbol{H}_y = \frac{1}{2\pi}\sum_i \boldsymbol{I}_i\left[\frac{x - x_i}{(x-x_i)^2+(y-y_i)^2}\right]$$

where x_i, y_i are the coordinates of the generic wire i, having a current $\boldsymbol{I}_i$.

3.4 H versus B

Although the main parameter characterizing a given source, when dealing with the issue of human exposure, is the magnetic field strength H measured in A/m, it is of common practice to express it in terms of magnetic flux density B (also called magnetic induction, in units of tesla or T or more

practically, in µT or mG)[12] as this quantity is directly related to the electric fields and currents induced in a human body exposed to the magnetic field[13].
It is common to simply refer to both B and H as magnetic field when no distinction is required.

Most often, except for the magnetic materials, the permeability of the medium is equal to that of vacuum or air (μ_0) and the following equivalence applies:

0.8 A/m ⇔ 1 µT = 10 mG

In the remaining part of this document we will use only the B field ignoring the concept of magnetic flux density, with the general assumption that $\mu = \mu_0$ [14].
In other words, as often found in the literature, we will accept the wording "a magnetic field of x µT" knowing that magnetic field here in fact relates to "magnetic flux density".

3.5 Field polarization

In the general case of a periodic time-varying field (harmonic field), the field vector $\vec{B}$ can be represented by three simultaneous Cartesian components:

$$\vec{B}(t) = B_{x'}\cos(\omega t + \alpha_{x'})\vec{u}_{x'} + B_{y'}\cos(\omega t + \alpha_{y'})\vec{u}_{y'} + B_{z'}\cos(\omega t + \alpha_{z'})\vec{u}_{z'} \tag{1}$$

where $\vec{u}_{x'}$, $\vec{u}_{y'}$ and $\vec{u}_{z'}$ are unit vectors along the three axes x', y', z' [15].

This expression indicates that the tip of the vector $\vec{B}$ moves in a single plane which may not be what you would expect.

Indeed, as it is shown in [17], the vector $\vec{B}$ can be broken into two linearly polarised vectors (not necessarily orthogonal in the space) oscillating with a phase lag of $\pi/2$:

$$\vec{B}(t) = \vec{B}_1\cos(\omega t) + \vec{B}_2\cos(\omega t + \pi/2) \tag{2}$$

Where $\vec{B}_1$ and $\vec{B}_2$ are time-invariant vectors with fixed magnitude and direction.
The major and minor axes of the ellipse are not necessarily coincident with the directions of $\vec{B}_1$ and $\vec{B}_2$.
Equation (2) means that it is possible to find in the same plane as $\vec{B}_1$ and $\vec{B}_2$ a set of axes x and y (normally different from x', y', and z') in such a way that:

$$\vec{B}(t) = B_x(t)\vec{u}_x + B_y(t)\vec{u}_y = B_{x,\mathrm{peak}}\cos(\omega t)\vec{u}_x + B_{y,\mathrm{peak}}\cos(\omega t + \varphi)\vec{u}_y \tag{3}$$

where $\vec{u}_x$ and $\vec{u}_y$ are unit vectors along the axes x and y.

For a quasi 2D system like an HV power line or cable, the plane of the ellipse is orthogonal to the direction of the conductors.

Depending of the relative amplitude of B_x and B_y and on their phase relationship φ, the ellipse can collapse into a single segment (***linear polarization***) or become a circle (***circular polarization***)[16].

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[12] tesla (T) is the SI unit, derived from the MKSA system, for the induction field. In North America the CGS unit (gauss) is also used, with the equivalence 1T = 10^4 G

[13] Standards used for electromagnetic compatibility (EMC) express generally the magnetic field in A/m whereas standards used for the protection of people mostly use the magnetic flux density expressed in µT.

[14] This is certainly the case for the human being.

[15] Primes are introduced here because it is not the definitive system of axis.

This is illustrated in Figure 4

As a linearly polarized harmonic field vector has its magnitude varying sinusoidally with time, it is sometimes called a ***sinusoidal field vector***.

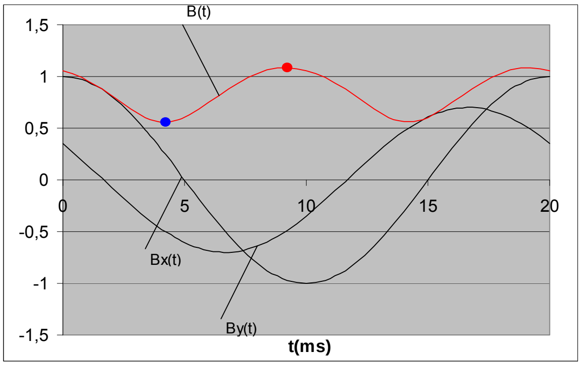
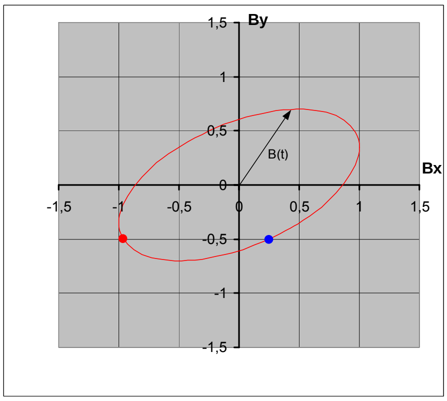
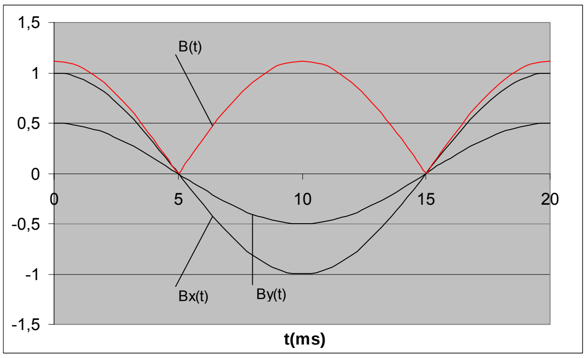
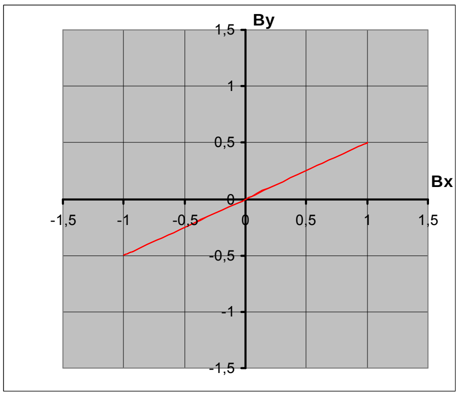
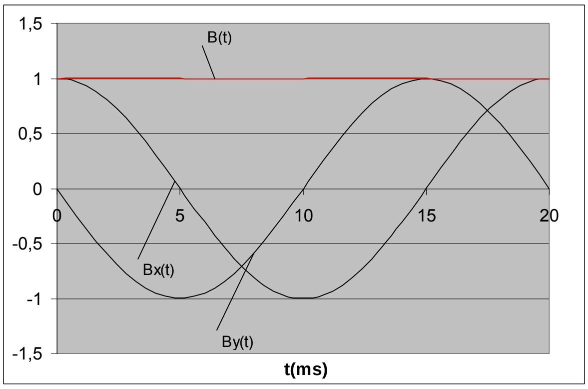
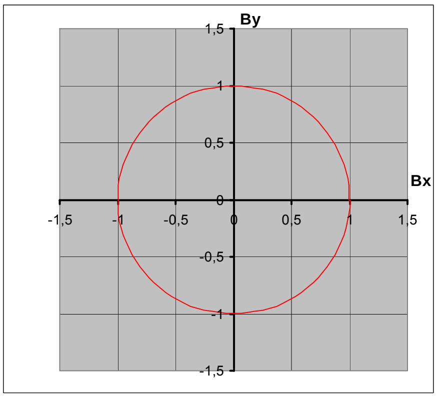
		Variation in time of vectors' amplitude	Variation in space of vectors' amplitude and orientation
Types of polarization	<u>Elliptical</u> ➢ Amplitudes $B_{x,peak} \neq B_{y,peak}$ ➢ Phase angle (φ) $\varphi \neq 0$ and multiples of π	 $B_{x,peak}$ = 1; $B_{y,peak}$ = 0.7; φ = 1/3 π	
	<u>Linear</u> ➢ Amplitudes $B_{x,\text{peak}} \neq B_{y,\text{peak}}$ ➢ Phase angle (φ) $\varphi = 0$ and multiples of π	 $B_{x,peak}$ = 1; $B_{y,peak}$ = 0.5; $\varphi = 0$	
	<u>Circular</u> ➢ Amplitudes $B_{x,\text{peak}} = B_{y,\text{peak}}$ ➢ Phase angle (φ) φ = multiples of $\pi/2$	 $B_{x,peak}$ = 1; $B_{y,peak}$ = 1; $\varphi = \pi/2$	

Figure 4: The three types of field polarizations

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[16] $B_{x,peak}$ and $B_{y,peak}$ are equal to respectively $\sqrt{2}B_{max}$ and $\sqrt{2}B_{min}$ as will be defined in 4.2.2

Example

An example of elliptical field polarization is shown in Figure 5.
It concerns the field calculated at 1 m above ground under a HV vertical double circuit line with transposed conductors (“Low reactance” arrangement). The lowest conductors clearance to ground is 15 m and the vertical distance between conductors about 10 m.
Currents are respectively 1 and 0,5 kA in the circuits.
The small ellipses show the field polarization together with its relative magnitude (the absolute magnitudes of the ellipses are not relevant).

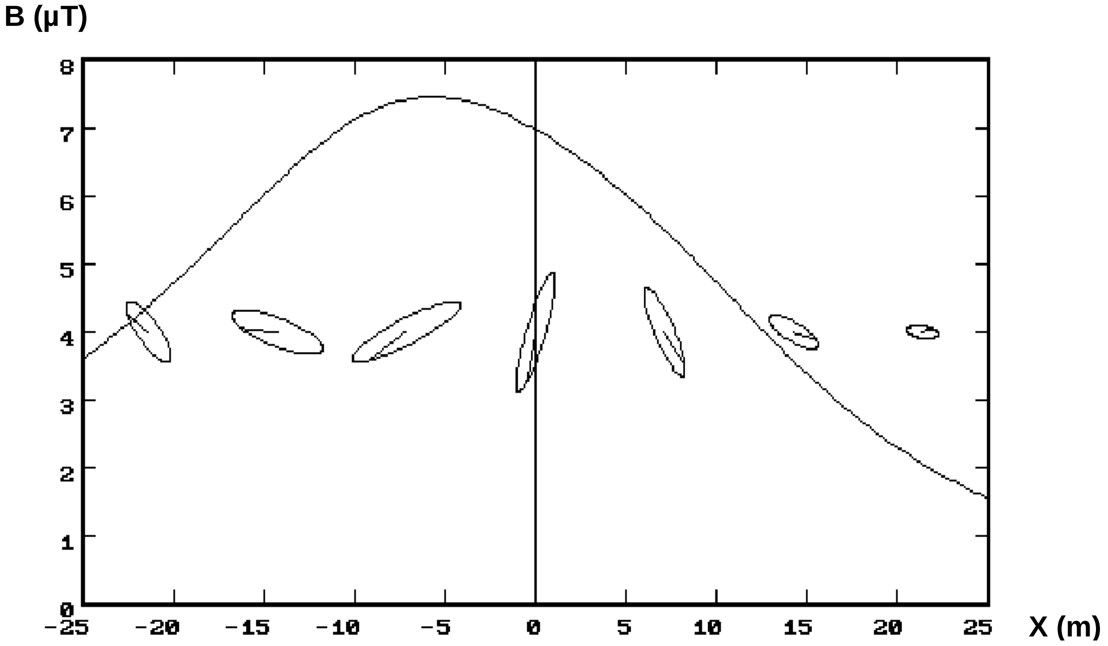


Figure 5: Field level and field polarization under a HV double circuit line

4 Definition and description of the quantification parameters

The quantity that needs to be characterized is the magnetic field $\vec{B}$, which is a function of the current or currents and their location. The currents themselves are functions of time.

The ***magnitude*** of a magnetic field is its main characteristic. However, due to the fact that the field at a given point in space is a vector changing in amplitude and direction, there are different ways of characterising its strength.
These parameters will first be presented and discussed, and then the way in which each variable can influence them will be assessed.

4.1 Field variations

4.1.1 Variations of the field in time (temporal variations)

In the most general case – but not necessarily the most frequent case – the field vector can change very rapidly (transients) and only its instantaneous magnitude is relevant. However, for sources at power frequency under normal operating conditions, the field is ***periodic*** and more or less sinusoidal. Hence, only "slow variations" with respect to the steady state at 50 or 60 Hz have to be taken into account. Even when there are fast and important field variations due to variations of the loads (e.g electrical furnaces or arc welding), the currents and hence, the fields, are supposed to remain stable for long durations with respect to the power frequency period. In that case the concept of "***instantaneous value***" of the field refers to the magnitude of the field at a given time within the duration of observation.

The inclusion of the "slow variations" or the changes from one stable state to another leads to the assessment of ***statistical values*** like "***time averaged values"*** or "***mean values in time***".

4.1.2 Variations of the field in space (spatial variations)

The dependency of the field with the spatial dimensions is an important feature that influences the assessment methodology in at least three different cases:

1) When a given source has to comply with limits. In this case it is important to define correctly the assessment ***distance*** to this source according to requirements laid down by the relevant standard.

2) When the dimensions of the area where the assessment has to be performed are large with respect to the spatial field variations, i.e. when the field is highly ***non-uniform***.

3) When a long time exposure assessment has to be performed on a moving body (animal or human), e.g. when the assessment is made with respect to a statistical value like an epidemiological cut off point.

In the two last cases it will be necessary to perform ***space-averaged*** calculations; i.e. the statistical calculations need to be performed not only in time but also in space.
Moreover in the third case, the field will probably change in both time and in space and the assessment will require both ***space-*** and ***time-averaged*** calculations.

4.2 Instantaneous values of the field strength

Instantaneous values are useful when a field has to be assessed at a specific moment or when looking at its maximum value over a given period (e.g. one year).

Instantaneous values of periodic fields are normally expressed in RMS values (cf. 4.2.1). Giving the peak value of the field strength has little sense as can been seen in section 4.2.3.

4.2.1 RMS value (Root mean square)

The root-mean-square (RMS) value of a variable x, sometimes called the quadratic mean, is the square root of the mean squared value of x:

$$R(x) \equiv \sqrt{\langle x^2 \rangle} \tag{4}$$

$$= \begin{cases} \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}} & \text{for a discrete distribution} \\ \sqrt{\frac{\int P(x) x^2 \, dx}{\int P(x) \, dx}} & \text{for a continuous distribution.} \end{cases}$$

In statistics, the RMS value is a measure of the *magnitude* of a set of numbers. It gives a sense for the typical size of the numbers.

For example, consider the set of numbers: -2, 5, -8, 9, -4.
It is possible to compute the average, but this is meaningless because the negative values cancel the positive values, leading to an average of zero. The easiest way to provide a measure of the size of the numbers without regard for positive or negative is to just erase the signs and compute the average of the new set: for 2, 5, 8, 9, 4 the average is 5.6
For reasons of convenience, statisticians chose a different approach. Instead of wiping out the signs, they square every number (which makes them all positive) and then take the square root of the average.
Hence: To calculate RMS:

- SQUARE all the values,
- Take the average of the squares
- Take the square root of the average

For example, the RMS of -2, 5, -8, 9, -4 is 6.16
The RMS is always slightly greater or equal to the average of the unsigned values.

The root-mean-square of a continuous function becomes particularly useful when the function is periodic [8], such as an electric current at power frequency. In this particular case it assumes the meaning of effective value i.e. the value normally associated with the ***joule heating effects***.
In the case of a periodic function, the RMS value is obtained by taking the square root of the mean of the squared value of the function:

$$F_{rms} = \sqrt{\frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} F(t) \cdot F(t)^* \, dt} \tag{5}$$

where $F(t)^*$ is the complex conjugate of $F(t)$.
If $F(t)$ is a vector, $F(t) \cdot F(t)^*$ is replaced by the module of this vector, i.e. by its inner product.
If $\vec{F}(t)$ is an elliptically polarised field that can be expressed by three orthogonal components, at every instant of time (t) the following relationship applies:

$$\left| \vec{F}(t) \right| = \sqrt{F_x(t)^2 + F_y(t)^2 + F_z(t)^2} \tag{6}$$

Introducing this expression in (5), the following formula can be obtained:

$$F_{rms} = \sqrt{\frac{1}{T} \int_T \left[F_x(t)^2 + F_y(t)^2 + F_z(t)^2 \right] dt} =$$

$$= \sqrt{\left[\frac{1}{T} \int_T F_x^2(t) dt \right] + \left[\frac{1}{T} \int_T F_y^2(t) dt \right] + \left[\frac{1}{T} \int_T F_z^2(t) dt \right]} =$$

$$= \sqrt{F_{x,rms}^2 + F_{y,rms}^2 + F_{z,rms}^2}$$

Hence, for the $\vec{B}$ field: $B_{rms} = \sqrt{B_{x,rms}^2 + B_{y,rms}^2 + B_{z,rms}^2}$, i.e. the RMS value of the $\vec{B}$ field, is the square root of the sum of the squares of the RMS value of each orthogonal component and this is valid for all field polarisations (linear, circular or elliptical).

It is mathematically equivalent to what is called the Resultant Field[17] (see following definition).

In the sections that follow we will therefore consider (contrary to what is said in some IEC and CLC references [8], [6]) that ***there is, indeed, equivalence between RMS field and Resultant field***.

4.2.2 Resultant field: (B_r)

The Resultant [5], [6], [7], [10] or ***Root-sum-square*** [8] field is given by the expression:

$$B_r = \sqrt{B_{x,rms}^2 + B_{y,rms}^2 + B_{z,rms}^2}$$

where $B_{x,rms}$, $B_{y,rms}$, $B_{z,rms}$ are the RMS values of the three orthogonal components.

It has been shown previously that the resultant field was equivalent to the RMS field.

The resultant magnetic field can also be given by the expression:

$$B_r = \sqrt{B_{max}^2 + B_{min}^2}$$

Where B_{max} and B_{min} are respectively the RMS values of the field along the semi-major and semi-minor axes of the magnetic field ellipse[18].

It is important to note that B_r is a computed mathematical term and is not a summation of the semi-major and semi-minor axis field vectors, since these two field vectors do not occur simultaneously in time, but are separated in time by one quarter of a cycle.

If the magnetic field is linearly polarized (e.g. single-phase source), $B_{min} = 0$ and $B_r = B_{max}$.

However if the magnetic field is circularly polarized, $B_{max} = B_{min}$ and $B_r = 1.41\ B_{max}$

For most multi-conductor lines, the magnetic field is elliptical and, hence, $B_{max} < B_r < 1.41\ B_{max}$

---

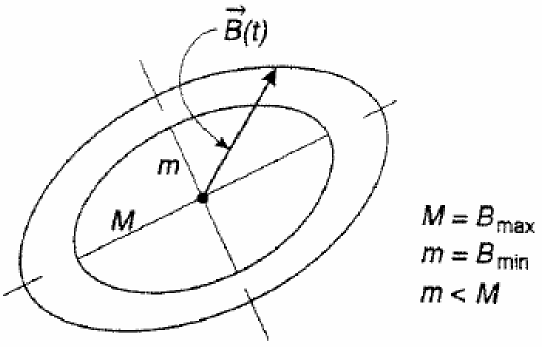
[17] In fact, the term "resultant" is more commonly used to express the sum of vectors in space; it is therefore suitable to describe the field at a given instant in time, as the sum of the fields generated by each current, or the sum of the space components of a field such as those along three orthogonal axes.

[18] It would have been less confusing to use B_{major} and B_{minor} instead of B_{max} and B_{min}, but we have chosen to keep this latter formulation because it is often used in standardization documents.

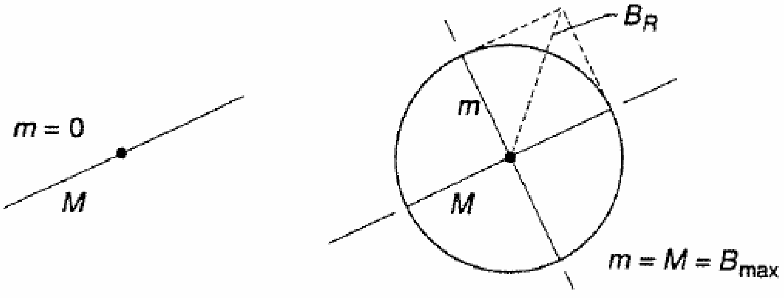
Some publications, such as [6] and [7], conclude from this that, for a circularly polarised field, the resultant field is 1.41 times greater than the "magnitude of the semi-major[19] axis" of the field (cf Figure 6c)[20]. While this is correct some people go on to claim that tri-axial measurement instruments provide an inaccurate measurement in excess of the correct answer by 41 %. Consideration of Figure 6 may provide a better understanding of this. Figure 6a shows two ellipses, where the outer ellipse is the locus of the field vector. M and m are the major and minor axes of the smaller ellipse. M is equal to B_{max} which is the RMS of the field measured along the major axis, and m is equal to B_{min} which is the RMS if the field along the minor axis. Therefore M = B_{max} is not the maximum value of $\vec{B}(t)$ (of which the intensity and direction are strictly related to the instantaneous values of the currents generating the field at a given instant of the time period [see Figure 4]); it is the RMS value of its projection along the semi-major axis of the ellipse.

The misunderstanding may come from the fact that the actual field ellipse is intended for describing the movement of the field vector in space with time, i.e., for describing the instantaneous value of the rotating field vector, but not for representing RMS quantities that, by definition are results from an integration over one full cycle.

In other words, the smaller ellipse drawn in Figure 6 has no physical meaning and is constructed by using the RMS values of the component of field parallel with the semi-major and semi-minor axes.



a) **Quantities for elliptical polarization, $m < M$**



b) **Quantities for linear polarization, $m = 0$**

c) **Quantities for circular polarization, $m = M$**

Figure 6: Presentation of the Major and minor semi-axes of the ellipse using RMS values that could lead to misinterpretation (taken from [7])

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[19] or semi-minor since both axes have the same length for a circularly polarised field.

[20] and between 1 and 1.41 times greater than the magnitude of the semi-major axis in the general case of an elliptically polarised field.

4.2.3 Peak value of field strength: (B_{peak})

The peak value of the field B_{peak} [11] represents the maximum value of the field strength vector $\vec{B}(t)$ that actually occurs in a period. It is made up of three individual components of the field strength, which are instantaneous values in three directions of a rectangular coordinate system (see (6)):

$$B_{peak} = \max\left(\left|\vec{B}(t)\right|\right) = \max\left(\sqrt{B_x^2(t) + B_y^2(t) + B_z^2(t)}\right)$$

By definition, B_{peak} is the magnitude of the semi-major axis of the ellipse and, hence, B_{peak} = 1.41 B_{max} for a linearly polarised field and $B_{peak} = B_r$ for a circularly polarised field.

In other words, for a circularly polarised field only, the magnitude of the field vector remains constant leading to the RMS value equal to the peak value.

It is important to point out, however, that although, for a circularly polarised field, B_{peak} and B_r are numerically equal, they do not represent the same thing.

For the 2D case, according to equation (3) this leads to:

$$B_x(t) = B_{x,peak} \cos(\omega t);\ B_y(t) = B_{y,peak} \cos(\omega t + \varphi);\ \left|\vec{B}(t)\right| = \sqrt{B_x^2(t) + B_y^2(t)}$$

4.2.4 Measured versus calculated values

4.2.4.1 Measured values

A three-axis magnetic field meter simultaneously measures the RMS values of the three orthogonal field components and combines them to indicate the resultant magnetic field B_r, or B_{rms}, not B_{max} nor B_{peak}.

A single axis magnetic field meter measures the RMS value of the field in one direction, i.e. the RMS value of the field projected on a line that is parallel to the axis of the probe (or sensor).

The measurement will also be equivalent to that of a linearly polarised field vector (or so called sinusoidal field vector) oriented along the chosen direction.

If the probe is oriented for maximum reading, the measurement will be equal to the RMS value of the field along the semi-major axis of the ellipse, i.e B_{max}, not B_r.

It can therefore be concluded that single axis field probes are not suitable for measuring the RMS value of elliptical fields, unless they are used to make three measurements of the field that are then combined.. To do this the RMS values of the three orthogonal components of the field are measured and $B_{rms} = \sqrt{B_{x,rms}^2 + B_{y,rms}^2 + B_{z,rms}^2}$ is then derived.

4.2.4.2 Calculated values

When performing calculations it is important to check how the results are expressed.
If the currents generating the field are expressed in terms of RMS or peak values the results will respectively provide RMS or peak field quantities. Therefore, having in mind that measuring instruments are generally designed to provide the RMS value of the measured field, to correctly compare results of measurements with those of calculations, the latter must be performed with reference to the RMS values of the currents. Under this condition, the calculated magnitude of the semi-major axis of the ellipse does not correspond to the peak value of the field (which is usually larger than the measurement values) but is equal to the RMS value of the field along the major axis,

that is B_{max}, and coincides with the measured value obtained by using a single axis magnetic field meter oriented for maximum reading. Similarly, when the resultant field is calculated, the result corresponds to the three-axis meter measurement.

4.2.5 Comments

4.2.5.1 RMS field versus Resultant field

In has been shown in 4.2.1 and 4.2.2 that the RMS field and the Resultant field are mathematically equivalent.
However the term “RMS field” may be misleading because, as already recalled, field meters, whether they are tri-axial or single axis, are generally designed to give a reading expressed in RMS.
On the other hand, contrary to the peak value of the field that represents the magnitude of the field vector in the space, the resultant field is only a mathematical construction that has no physical meaning.
The magnetic field, indeed, does not produce directly a joule heating effect; this effect usually occurs due to the associated induced currents in the human body (or at higher frequencies by the SAR, specific absorption rate).

Hence, RMS values have mainly a meaning for currents (those producing the field and those induced by the field) but generally not for the field itself.

For all these reasons and in order to avoid any confusion, it seems better to use the term Resultant field instead of RMS field.

Nevertheless, as most standards make reference to either the resultant field or the RMS field, it is necessary, in this guide, to make also reference to both concepts.

4.2.5.2 Induced currents

An important question that can be raised when assessing human exposure to magnetic field is what characteristic of the field should be used: the Resultant field B_r or the RMS value of the field along the semi-major axis of the ellipse, B_{max}?

Most standards and recommendations use B_r.

However, if a 2D elliptical disk, perpendicular to the direction of the major axis of the field ellipse, is used to represent a human being, only B_{max} can be used for worst case Joule effect evaluation, and not B_r, since B_{min} results in no induction in this orientation. If a 3D ellipsoid is used to represent a human being, it is not certain that B_r can be used blindly for worst case Joule effect evaluation. It becomes necessary, indeed, to know which ellipsoid surface is perpendicular to B_{max} and which ellipsoid surface is perpendicular to B_{min} before being able to calculate the Joule effect accordingly.
So, using B_r , as suggested in most standards, is may not be absolutely correct for assessing the induced current but is always conservative.

4.2.5.3 Sampling intervals

The sampling intervals of a measuring instrument can have an influence on the result, mainly when looking for maximum values in a given measurement period. Clearly, longer sampling intervals will normally yield lower maximum values as the probability increases that the sampling does not include the maximum instantaneous value. Therefore an instrument recording time series measurements at finite intervals will not necessarily capture the same maximum field over a measurement period as a “peak-hold” instrument will [13][21].

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[21] However, in most digital instruments, peak hold just hangs on to the largest of the time series measurements so it would be the same

4.3 Statistical values (Time and Space variations)

When field measurements or calculations have to be performed for human exposure assessment, it is often necessary to have recourse to statistical magnitudes.

Epidemiologists are indeed more often interested in long-term measures of field exposure than in instantaneous values.

Taking into account that people are moving and that field levels at a given location are changing with time, it becomes necessary to introduce statistical variables that are a function of two parameters: ***space*** and ***time.***

The main metrics that are used for taking the field variability into account are the ***central tendency*** parameters, that is, the arithmetic or geometric mean and the median. These metrics can be assessed in time and/or in space.

4.3.1 Arithmetic mean value in time

The mean or average value of the field $\overline{B}$ over a given period T at a given location can be compared with the equivalent sound level L_{eq} in loudness measurement.

It is given by $\overline{B} = \frac{1}{T}\int \left|\vec{B}(t)\right| dt$, and can be approached, in case of discrete measurement values[22], by

$$\overline{B} = \frac{1}{n}\sum_{1}^{n}\left|\vec{B}(t_i)\right| .$$

4.3.1.1 Mean value over a few minutes

The mean values of fields over a few minutes are only useful when the load is rapidly changing (e.g., arc furnace, rolling-mill, etc.) and they are normally considered as instantaneous values.

In some cases the currents are derived from revenue meters with typical recording intervals of 15 minutes; this can be a reason for calculating field values averaged over 15 minutes.

4.3.1.2 Mean value over 24 hours

Due to the load factor of most power sources, the load pattern - and, hence, the field pattern too - exhibits very often a pseudo-periodicity over one day with, for example, maximum values at about 11 am and 18 pm and minimum values in the early morning (see Figure 7). Therefore, the mean value of the field over one day is a first estimator of the long-term mean and the one day period can be considered as the first "***remarkable time period"*** for long time assessment.

When characterising a field using its mean value over one day, it is necessary to specify which day in the year it is.

In the absence of any information about the period of the year, when the 24 h mean has to be assessed it seems reasonable to use a conservative approach and to choose one day in the winter (or in the summer in case of intensive use of air conditioning), when the load is close to the annual maximum.

This is sometimes called the ***seasonal maximum 24-hour average***.

In addition, depending on the place to be characterized by the statistical values of magnetic field, it could be useful to distinguish daytime from night, working day from weekend, etc.

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[22] In fact, measurements of magnetic field are given in the form of magnitudes like B_r, B_{max}, B_{min} or B_{peak}. Therefore, this last definition of $\overline{B}$ can be changed by $\overline{B} = \frac{1}{n}\sum_{1}^{n} B_i$, being B_i any of the magnitudes mentioned: $B_{r,i}$, $B_{max,i}$, $B_{min,i}$ or $B_{peak,i}$. This notation will be followed in the rest of the document.

Some studies make use indeed of the arithmetic mean of daytime exposure and/or of the arithmetic mean of nocturnal exposure.

Figure 7: Typical hourly load variation over one day for a 150 kV line

4.3.1.3 Mean value over 1 week

The mean value over 1 week is a better estimator than the mean value over 24 h, as it takes into account the weekend variations with respect to the working days. Figure 8 shows for the same line as in Figure 7 the typical weekly variations from Monday to Sunday (Figure 7 corresponds to Dec 16 in Figure 8). The pseudo periodicity of the load curve is generally more pronounced and regular when it is for a line or a substation feeding a public distribution network than when it is for a link that is part of an interconnecting transmission network. This is highlighted in Figure 9, which shows a typically urban load variation.

The same comment as for the daily mean applies for the choice of the week in the year: Depending on the seasonal variations of the load, the week shall be chosen in the winter or in the summer period.

Figure 8: Typical daily load variation over one week for a 150 kV line

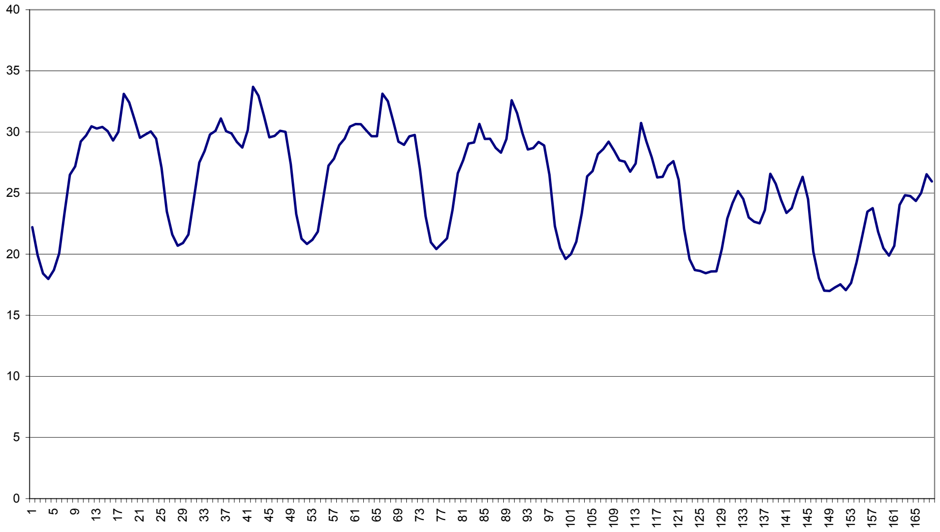

Figure 9: Typical daily load variation over one week for a 70/10 kV transformer in an urban area

4.3.1.4 Mean value over 1 year

The mean value over 1 year is probably the best estimator of the long-term mean, as it takes into account the seasonal variations. It is difficult to apply for direct measurement but, at least in transmission networks, it can easily be assessed by calculation for a single source knowing the instantaneous current during a field measurement and the annual load flow of the source. Where there are other sources present, as is the case for double-circuit lines or for two or more independent single-circuit lines, the relationship between field and currents may be not linear.

Figure 10 shows the yearly load variations for the same line as in Figure 8. However, for each day, only the maximum and the minimum have been registered and the graph shows two curves: the daily maxima and minima. The actual load curve is even more perturbed than the curves shown, knowing that, for each day, it fluctuates between both curves!

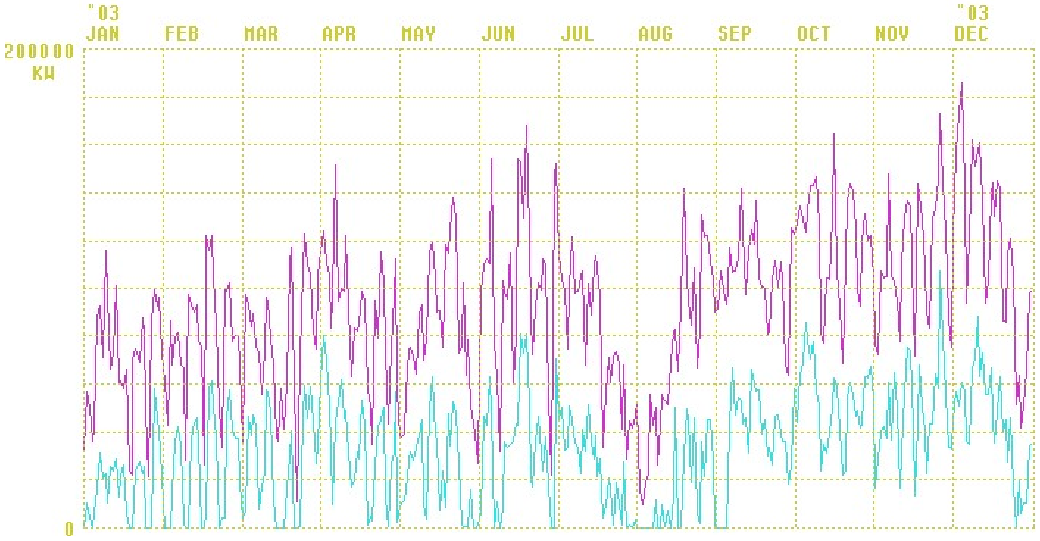

Figure 10: Typical max. and min. load variation over one year for a 150 kV line

Figure 11 shows the annual load variations of the same transformer as in Figure 9.

In this example the weekly variations including a reduction of the load during the weekends are clearly visible. However, the weekly variations are less important in the summer period (holiday) than in the other periods of the year.

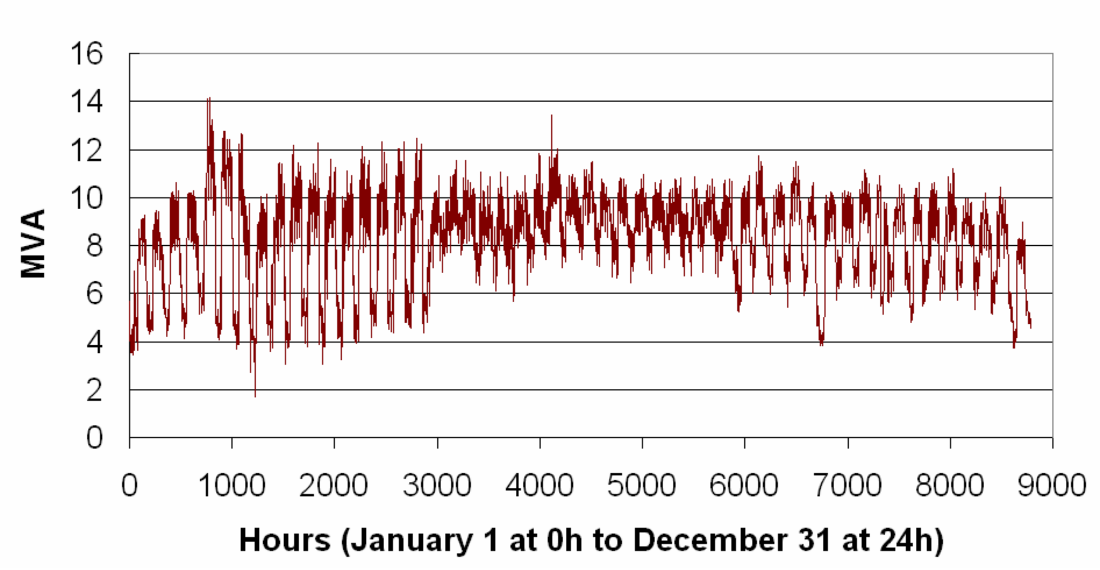

Figure 11: Hourly load variation over one year for a 70/10 kV distribution transformer

4.3.2 Median

The median is the middle value in a set of *n* data points sorted by increasing or decreasing order[23]. It is quite easy to calculate and is not influenced by extreme values (ie outlying values).

If the data are measurement samples of the field taken at regular intervals at a given location, the median can be used as an estimator of the long-term field exposure.

As for the mean, the median value can be calculated over one day, one week or one year or any other interval of choice.

In order to illustrate this, Figure 12 presents an example of median calculation for a double circuit 132 kV line in Italy.

In this example, the day-to-day variations are highlighted by the daily median values that are compared with the yearly average value. The actual intraday variations are not represented; they are of course, much more extensive than the variations of the daily median values.

This example shows that the daily average or median, although much better than any single measurement sample, is still not a good estimator for assessing long-term exposure.

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[23] When n is odd, the median is the middle value of the set of ordered data; when n is even, the median is usually taken as the mean of the two middle values of the set of ordered date.

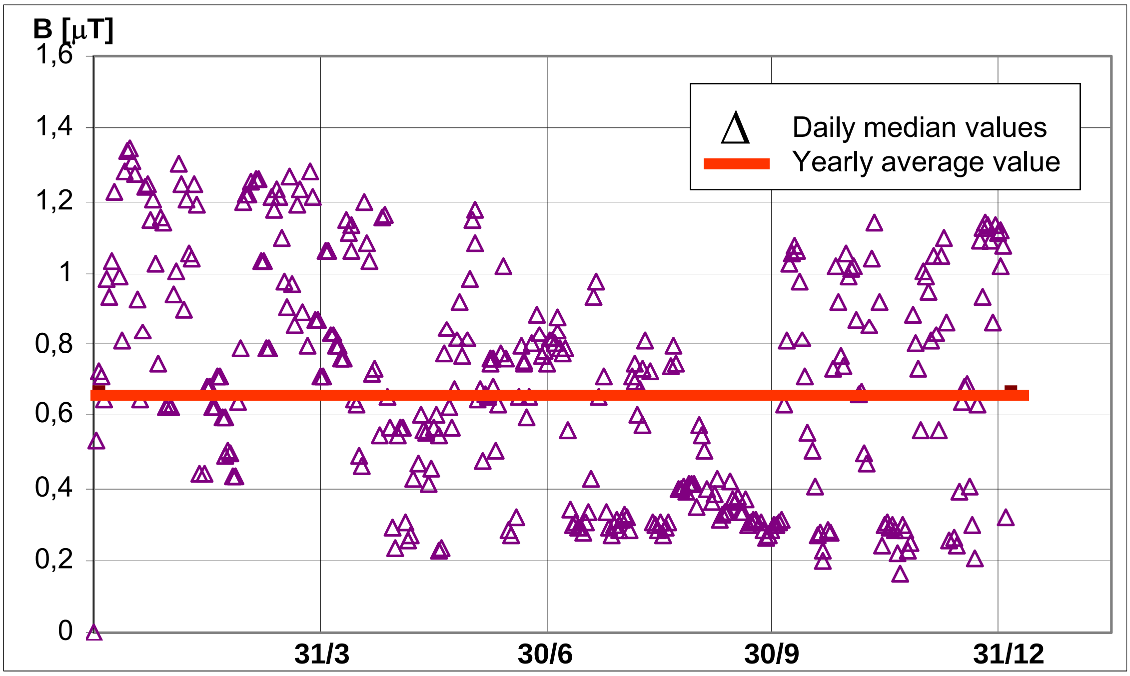

Figure 12: Daily variation of the magnetic flux density over one year, at 1 m above ground at the centreline of an Italian double circuit 132 kV line (2 independent circuits)

4.3.3 Value not exceeded during a given percentage of time

This is simply a given ***percentile*** of the integral distribution of the field during a given time period. If the samples are arranged in an ascending order of magnitude, the j^{th} percentile P_j (j = 1,2,…99) is given by the $j(n+1)/100$ th value, with n the number of samples. It may be necessary to interpolate between successive values [22].

The most interesting values are probably the 90 or 95th percentiles (value of the field not exceeded during respectively 90 or 95 % of the time) which are representative of the ***annual maximum value*** [24]. This kind of parameter can be compared with the classical Percentile Sound Levels used in acoustics (L_{10}, L_{95}…). The use of the 90 or 95th percentiles (P_{90}, P_{95}) leads normally to more realistic estimators of the worst-case long-term exposure value than the maximum value (see 4.3.4) that includes exceptional values.

The 50th percentile (P_{50}) is nothing other than what is also called the ***Median***.

Instead of the percentiles, the ***quartiles*** are sometimes used. They simply correspond to the 25, 50 and 75th percentiles of the set of data.

In order to highlight the percentile concept, typical monthly load curves of two 380 kV lines (rated reference current: 1500 A) [16] are presented in Figure 13. One set of curves corresponds to a heavily loaded line and the other set to a lightly loaded line. All of the curves, however, show an S shape, which is typical for this kind of curves. The 50th and the 95th percentiles are superimposed on the graph. For the heavily loaded line, P_{50} is higher than half of P_{95} whereas for the lightly loaded curve P_{50} is lower than half of P_{95}. This is a typical behaviour of most line load statistics (see also 4.5).

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[24] This value is sometimes called “annual peak value” and should not be confounded with the “peak value of the field strength” that refers to the maximum amplitude of the B vector within one cycle of the power frequency (cf section 4.2.3)

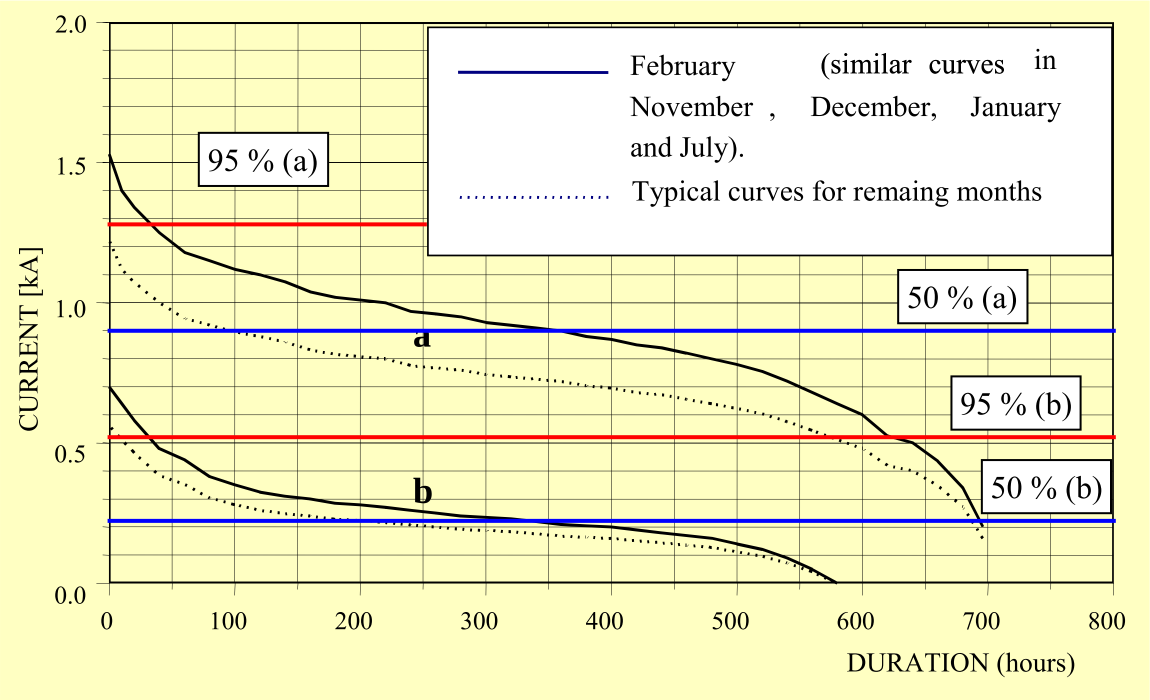

Figure 13: Load curves of two 380 kV lines of the Italian grid which, in 1990, were characterised by a) heavily loaded line; b) lightly load line (including no load periods)

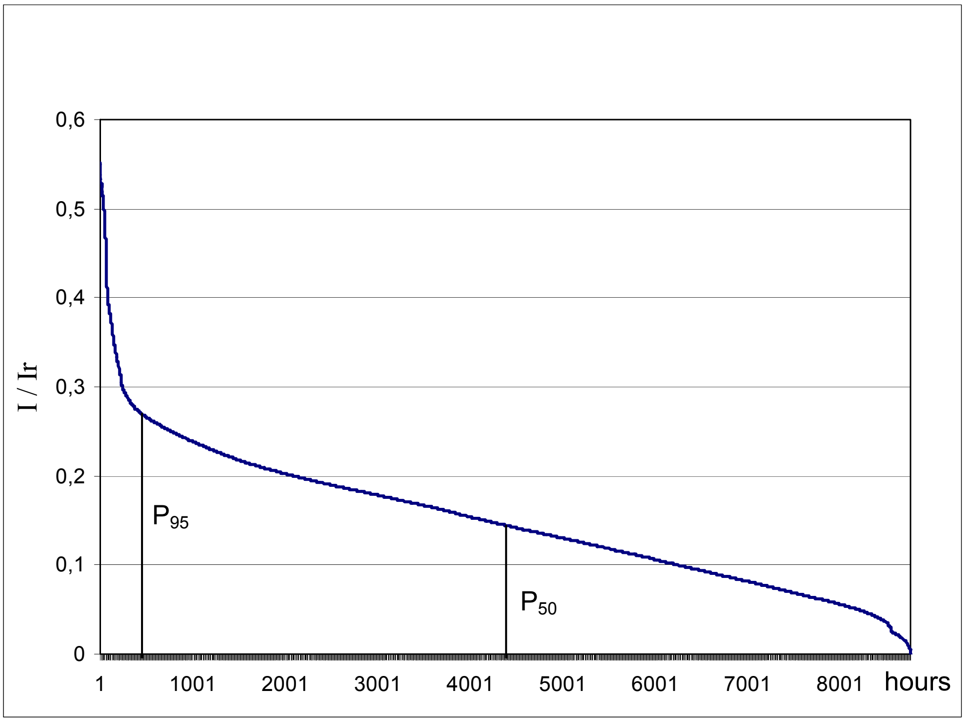

Figure 14: Cumulative load distribution curve of 25 HV lines of the Helsinki Energy 110 kV network with percentiles P_{50} and P_{95} represented (I_r is the rated current)

Another example is given in Figure 14. It concerns the global statistic of 25 separate 110 kV overhead lines of the Helsinki Energy network calculated for 2005. The vertical axis is the ratio of the current to the rated current. It is worth noting that in this sampling (which can be considered as representative for the 110 kV network), the median (i.e. P_{50}) is only about half the 95th percentile and 14 % of the rated current. These figures are compared with other similar examples in 4.5.1.

4.3.4 Arithmetic mean value in space

If it becomes necessary to assess the field variation in space, for instance in a given dwelling when the field is non-uniform, it may be of interest to assess the arithmetic mean in the space of interest (at a given time t_0)[25]:

$$\overline{B} = \frac{1}{V}\int B(x, y, z, t_0)\, dV$$

Where V is the volume in which the assessment needs to be performed (for most of the time, this will be a simple area S (x, y) where the vertical dimension is ignored because the measurements are typically done at a fixed height above ground, e.g., 1 m above ground).
A typical example of such a situation is given in Figure 15, where a 150 kV cable (1 kA rated current) is installed in the street, under the pavement, near a dwelling.

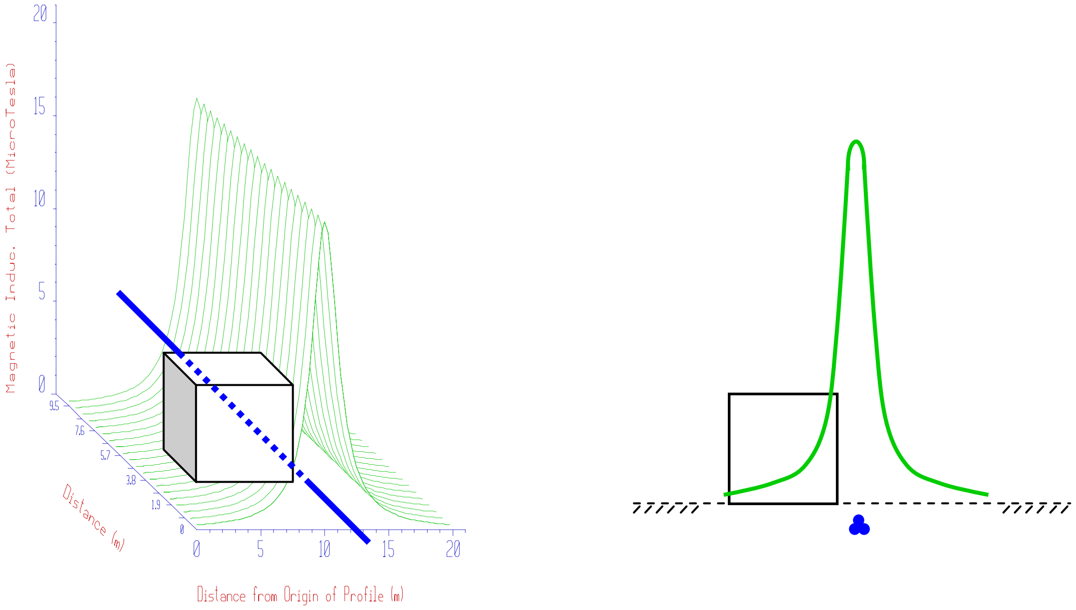

Figure 15: Field non-uniformity in a dwelling[26] located near a HV power cable
(left: 3 D, right: 2 D, ground level and horizontal axis confounded)

4.3.5 Arithmetic mean value in space and time

In the most general case where exposure assessments have to be done, the mean value needs to be calculated in both space and time:

$$\overline{B} = \frac{1}{VT}\iint \left|\vec{B}(x, y, z, t)\right| dt\, dV$$

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[25] Depending on the case, $B(x,y,z,t_0)$ represents any of the calculated or measured magnetic fields: $\left|\vec{B}(t)\right|$, B_r, B_{max}, etc.

[26] The dwelling is represented by a simple parallelepiped where the integration has to be done.

Practically, when such an assessment has to be done several (at least two) measuring instruments are often used.

Among them, one is maintained in a fixed position for recording the time variations and the other is moved within the volume for synchronously recording the space variations. After the measurement, the space results are corrected taking into account the data recorded by the first instrument. This allows getting a synchronous picture of the field in the space. Knowing the space variations and the time variations of all the data, it is then possible to proceed to average calculations.
This procedure can easily be applied for assessing fields in the vicinity of transmission power lines. For distribution lines, and more particularly for LV lines, it is not usually appropriate due to the presence of zero sequence currents and net currents. Indeed, zero sequence currents mean earth return (or earth wire return). Hence the decay law of the magnetic fields produced by zero sequence currents is generally 1/r instead of $1/r^2$ (r being the distance to the source – see also 4.4.3). Taking into account that the time variation of the zero sequence currents generally doesn't follow the same law in time as the phase currents, there is no independence of the time and space recording values and the procedure cannot be applied.

4.3.6 Geometric mean value in the space and in the time

The geometric mean of n samples of B field measurements is given by

$$\overline{B} = \sqrt[n]{B_1 B_2 \ldots B_n}$$

The geometric mean is often used in epidemiology instead of the arithmetic mean.

It is always smaller or equal to the arithmetic mean and has the advantage, like the median, of reducing the weight of the extreme values (i.e. outlying values)[27].

For the same reason, the use of the geometric mean can be recommended when performing space average measurement, as it reduces the influence of the very high values present near the source of EMF (cf Figure 15).

4.3.7 Relative Exposure Index (REI)

Most epidemiological studies are based on 24 or 48-hour stationary home measurements or calculations. Since a person may spend a great deal of time in different magnetic field environments, the question arises if stationary exposures are representative for personal ones [26].

In order to get a clear understanding of this relationship a relative exposure index (REI) has been proposed [27] for estimating the ratio between the actual personal exposure that can be assessed by a recording equipment individually worn that follows the daily displacements of the people and the stationary home (residential) exposure.

The relative exposure index (REI) is the ratio between the personal exposure (PE) and the home exposure (HE): REI = PE/HE.

If REI < 1, then the personal exposure is smaller than the stationary home exposure and vice versa[28].
The REI can be calculated for the arithmetic, the geometric mean or the exposure integral (cf. 4.3.8)
The use of the REI can be considered as leading to a "dynamic" exposure assessment contrary to the classical residential exposure assessment, which can be considered as being "stationary".

Whatever the metric used (REI or another), it is always important to emphasise the great difference that may exist between the average field level measured at a given point of a given place and the actual exposure level of people living or working in that place.

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[27] Any zero values should be discarded before calculating the geometric mean

[28] In most of the cases where the REI has been calculated up to now it was significantly lower than 1

4.3.8 Other metrics

The central tendency characteristics don't give any information about other parameters like the maximum values, the temporal stability of the exposure, the time spent above a given threshold, or the cumulative dose [21].
With that respect, dispersion parameters like the classical ***standard deviation*** is, of course, often used for assessing the variability of the field.

However, in the absence of any plausible biological mechanism for explaining a possible effect of ELF magnetic fields on health it is very difficult to know which characteristic is relevant and, hence, which metric or index should be used.

In any case, it is important to mention that other metrics have been proposed such as the ***rate-of-change metric (RCM)*** and the ***standardized RCM (RCMS)*** [20]. The RCM expressed the variability of exposure, while the RCMS reflects its temporal stability.

In order to assess a possible dose-response it has also been proposed to calculate the area under the curve representing the field-time variation – this is the ***exposure integral***.

4.4 Factors influencing the assessment of the field level

The magnetic field in the vicinity of a given source depends directly, and most of the time linearly (see 4.4.2), on the load conditions of this source.

Two kinds of sources can be considered: Power lines and Substations.

4.4.1 Maximum load conditions for power lines

For a line or a cable the load condition is simply the current flowing in the circuit[29]. In this case, there is a linear relationship between the magnetic field and the current and all that has been discussed for assessing the field can be equally said for assessing the corresponding current (mean, percentile, maximum, etc.).

The main problem concerns the definition of the maximum possible value for the current.

Depending upon the criterion used for defining the maximum current, different corresponding maximum field levels will be obtained.

4.4.1.1 Rated conditions

The "rated" conditions, sometimes called "pre-fault conditions" or steady state ratings are the conditions for which the circuit parameters have been designed to comply with the maximum expected load flow, taking into account regulations, territory constraints and environmental conditions like wind speed, outside temperature, maximum temperature of conductors etc. These conditions define normally what we could call the Maximum Permissible Permanent Current (MPPC) and are usually standardised at national level. However, as they can vary from country to country, they should always be mentioned in an assessment report.

Typical examples of standardised [12] environment conditions for an overhead line are the following:

- Maximum temperature of conductors: 75 °C
- Air temperature: 25 °C
- Wind speed: 0.55 m/s
- Solar power radiation: 1000 W/m^2
- Solar energy absorption factor of the conductors: $\alpha_s = 1$
- Radiation factor of conductors: $\varepsilon = 1$

---

[29] Supposed to be balanced

A distinction has to be made also between the rated conditions for the ***line*** (overhead or underground) and the rated conditions for the ***circuit***. The latter can be lower than for the line as the circuit involves other plants like transformers, switching devices etc.

When an assessment has to be made under rated conditions, it seems logical to take the circuit rating into account. However, the network may evolve and an upgrading (or uprating) can occur later. In that case, it becomes necessary to make the assessment for the rated conditions of the line or to take into account the foreseen upgrading.

4.4.1.2 Normal operating conditions

The maximum load in normal operating conditions means the maximum load that can last for a long time in the absence of any degradation of the network (unavailability of another circuit in case of fault or maintenance).

For most of the time (cf P_{95} and rated curves in Figure 21) the maximum load in normal operation is close to half the rated conditions because it has to take into account the so-called n-1 criterion, i.e, the ability to take over the load of any link of the network that has accidentally tripped.

The assessment of the maximum load in normal operation can be made by load flow calculations or by measurement at the winter peak (or summer peak in case of large use of air conditioning loads).

4.4.1.3 Exceptional conditions disregarding the n-1 criterion

When a network is degraded, for example by the loss of one circuit (ie link) this is known as an n-1 condition. When this happens the load on the other circuits is likely to increase, taking up the load from the lost circuit. Under these circumstances a higher rating is used for a limited period of time and is referred to as the “post-fault” rating.

The time limit can be the consequence of a thermal limit or just a safety measure for avoiding an n-2 condition.

These abnormal load condition should not be taken into account when assessing long-term field exposition. Instead, the use of the 95th percentile (cf. 4.3.3) is recommended when maximum load conditions are required.

Contrary to the 95th percentile, the exceptional load conditions are normally very close to (or even higher than) the rated conditions.

4.4.1.4 Fault condition

During fault conditions, currents that are much higher than the rating can flow in a circuit for a brief period of time. These are the highest currents that can flow in a circuit and occur when there is a phase to phase short circuit or a phase to ground short circuit due to unavoidable failure of some equipment. To protect the equipment connected to the circuit, devices are used to disconnect the short circuit within less than a second of it occurring.

Because faults are very brief, very rare and not completely avoidable they not taken into account when assessing long term exposure to field or compliance with field limits. They may be taken into account when assessing EMC or safety conditions (influence on telecom line or on pipelines).

4.4.2 Temperature dependency of the sag

It is usually assumed that a linear relationship exists between current and magnetic field in the vicinity of power lines.

There is indeed a linear relationship for underground cables but not in the immediate vicinity of overhead lines where the sag of the conductors depends on their temperature and, hence on the current in the line and on the environmental conditions. The variations of this sag easily exceed some meters at mid-span. Therefore the field at ground level in the direct vicinity of the line does not only depend on the current.

To illustrate this, the typical sag variation of a 380 kV line has been plotted in Figure 16 as a function of the current in the line for the constant environment conditions presented in section 4.4.1.1. These conditions are quite extreme (sunny with little wind) and result in a conductor temperature of 40 °C[30] with zero current and a temperature of 75 °C at full load.

With these conditions, it can be seen in the figure that the maximum sag variation at mid-span is about 2 m. In reality, taking into account also the winter conditions with temperatures close to 0° C, the total sag variation can easily be twice that shown in Figure 16, i.e. about 4 m[31].

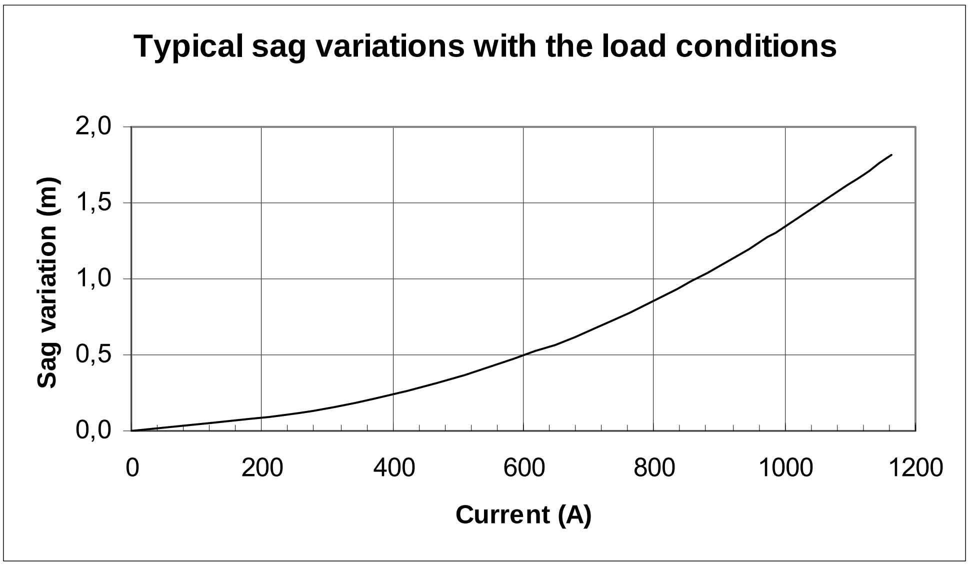

Figure 16: Sag – current relationship for a typical 380 kV overhead line
(conductor 707 AMS-2Z – span = 450 m, initial temperature: 40° C)

Knowing that the minimum conductor-ground clearance of a 400 kV line is for example 10 m, it is possible to assess the effect of neglecting the sag variation when calculating the magnetic field for different load conditions by simple linear extrapolation.[32] The effect is largest under the line.

Therefore, when an assessment has to be done by extrapolation, a conservative approach is to calculate the fields by assuming the sag is always a maximum (i.e. for rated conditions) regardless of the actual load conditions.

4.4.3 Unbalanced currents and effects of currents in shielding wires

Currents in a power line are not always well balanced, especially in the case of distribution lines where even small amounts of unbalances[33] (typically 1 or 2 %) can cause large differences in the magnetic fields, particularly at distances far from the line axis.

Even when the phase currents are well balanced for HV lines and underground cables, the presence of a shielding wire (or sky-wire), used to prevent the power line from being struck by lightning, or of the

---

[30] Due to the solar radiation

[31] For the example shown here the mid span sag temperature dependency is of about 5 cm / °C

[32] Up to 40 % in this worst case example but typically up to 20 % according to [24]

[33] Actually this applies to zero sequence currents. Negative sequence currents have the same distance relationship as positive sequence

metallic screen of the cable can result in a zero-sequence current that can influence the field at a sufficiently large distance.

This effect can be explained by applying a power series expansion to the Biot-Savart law, and expressing the magnetic field at any point in space as the sum of terms which are proportional to $1/r$, $1/r^2$, $1/r^3$, … where r is the distance from the field point and the centre of the assembly of conductors [7] (see subsection 3.2). It can easily be shown that the first term, proportional to $1/r$, is proportional to the net current (i.e. the zero sequence component) and, having the slowest rate of decay, will dominate at larger distances.

With balanced currents the first term disappears and the far field will be dominated by the $1/r^2$ term, which is proportional to current magnitude and conductor spacing. From the power series expansion other interesting properties may be drawn. For instance, with double circuit low-reactance lines the $1/r^2$ term also disappears, when the two circuits carry balanced and identical currents, and the far field quickly decays at $1/r^3$ rate.

Because of this, the magnetic field at far distance becomes more susceptible to current unbalance and to zero sequence-currents.

Practically speaking, for overhead lines the presence of a current in the earth wire leads normally to an increase of the field at large distance from the line. Ignoring this current usually leads to an underestimated field value at large distance from the line.

For underground cables with screens earthed at both ends, the current flowing in the screens are mainly reverse components (and not zero-sequence) because the layout of the screen(s) is (are) symmetrical with respect to the phase conductors. Hence the resultant field is usually smaller than when the screens are earthed at only one end or when cross bonding is applied. It results from this that ignoring the currents in cable screens normally leads to a conservative field level (higher than in the reality).

4.4.4 Maximum load conditions for substations

The case of substations is much more complex than that of lines or cables because the load conditions are more difficult to assess. Indeed they depend upon the load conditions of the transformer(s), busbars and different lines and cables connected to the substation.

In addition, the layout of the substation, the location of the individual bays that are used to connect the lines and transformers and the substation type (e.g. single busbar, double busbar, “breaker-and-a-half” scheme) strongly affect the load currents in the individual components. As an example, the single line diagram of a 380 kV substation is given in Figure 17.

The problem becomes even more complex when it concerns part of the substation (e.g. a cell) that has to meet a given product standard or a given specification. This is not only a technical problem but also a problem of share of responsibilities[34].

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[34] For instance, in a HV/MV substation, some feeders or cells can be under the responsibility of the Transmission System Operator and other under the responsibility of the Distribution System Operator

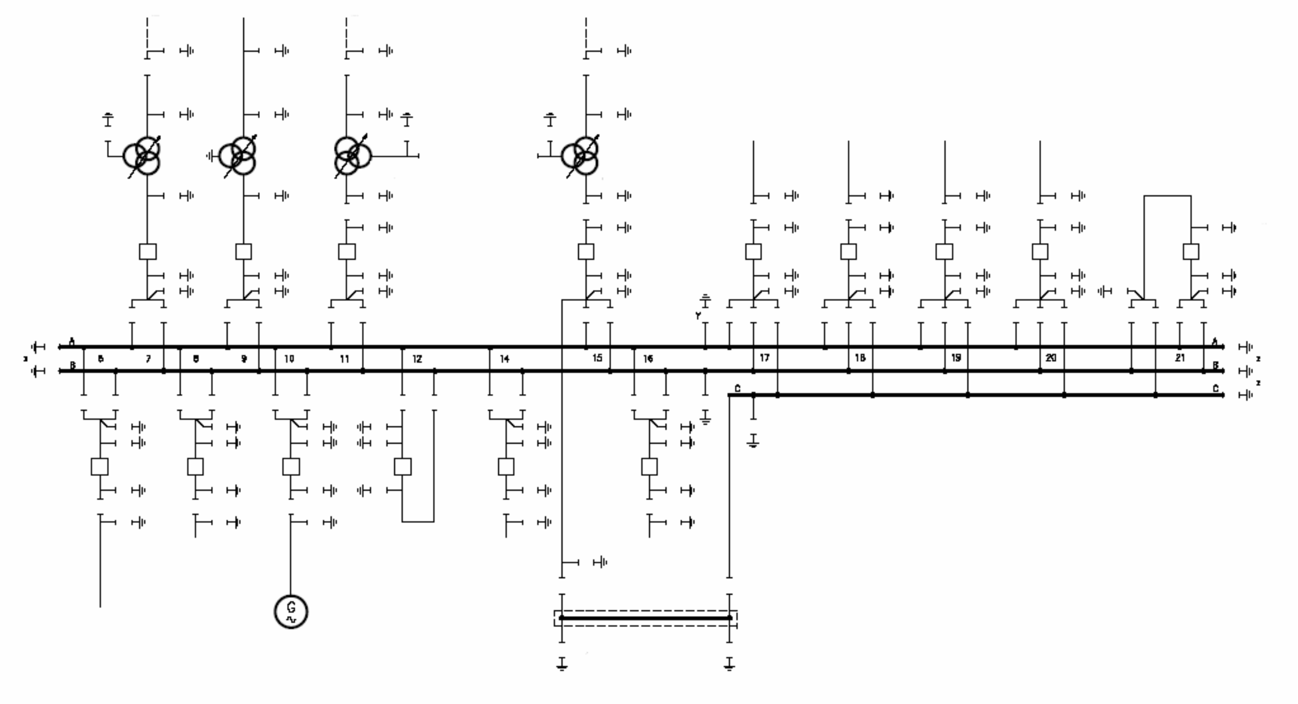

Figure 17: Typical single line diagram of a 380 kV substation

4.4.4.1 Rated and exceptional conditions

The same definition as for power lines applies for the rated conditions of substations.
In small substations, when only one transformer is present, the rated conditions are those of the transformer, which is normally the limiting element.

When there is more than one transformer, it is not necessarily appropriate to use the sum of their rated powers as one transformer is often used as back up for the other. Indeed, the sum of all the individual rated power should preferably be regarded as a condition closer to the exceptional conditions described in 4.4.1.3 than to the rated condition of the substation.

4.4.4.2 Normal operating conditions

The normal operating conditions can differ significantly from the rated conditions mainly in new substations where the transformer, which is the most expensive part (mainly if used alone), has to take into account possible extensions or load increase. When more than one transformer is present, it seems logical to apply the n-1 criterion and to consider the maximum normal load conditions as those resulting from the n-1 transformer rated condition. As an example, in a substation with two transformers operating in parallel, the rated conditions will be that of one single transformer, whereas, if three transformers are operating in parallel, it will normally be the global rated power of two transformers.

If a substation is mainly used to connect different lines and cables and if the transformer load is low compared to the normal operating conditions of the lines, then the conditions for the assessment can be based on the transmission lines only. As an example, the calculated magnetic field for a 380 kV substation in The Netherlands is given in Figure 18. This figure shows that the magnetic field generated by the substation is mainly determined by the magnetic field generated by the individual lines connected to the substation.

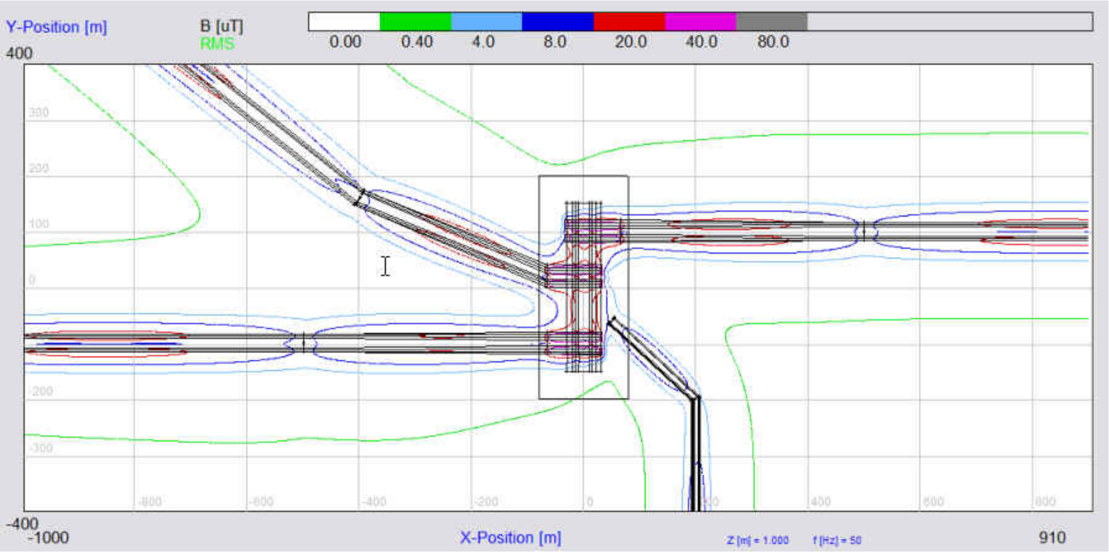

Figure 18: typical magnetic field calculated near a 380 kV station

It is useful to note that, when a magnetic field assessment has to be done outside a HV substation, the main field sources that have to be considered are usually the feeders and the lines and not the transformers which are generally located at some distance from the boundary of the substation.
For MV or HV substations located in urban area or when the field assessment has to be performed inside the substation the most important field sources are usually the cable terminals at the bushing on the lower-voltage side of the transformers, where the currents and the separation between phases are the largest[35]. These fields are highly non-uniform (see 4.4.5) but decrease rapidly.

As regards Gas Insulated Substations (GIS), the main difference compared with Air Insulated Substations (AIS) is the fact that it is possible to approach much closer to the busbars. This has only an influence for assessments inside the substation. Cables terminals again are usually the main field sources.

4.4.5 Measurement distances and assessment of non-uniform fields

4.4.5.1 Measurement height above ground

It is usual, when measurements have to be done in the vicinity of overhead lines, to perform them at a height of either 1 m or 1.5 m[36] corresponding roughly to the mean height of the chest of a person. However in the absence of any accepted standard specifying this height there is no general agreement over which height is the correct value to use.

The absence of a commonly accepted standard is not so important for overhead lines because the field near ground level is rather uniform. It is however more relevant for underground cables which are laid in the ground at a depth of the same order of magnitude as the measurement height. In this case it can be useful to perform the assessment at more than one height above ground.

Other measurement heights can sometimes be specified (e.g. the field at 1 m above floor level of a building in the vicinity of an overhead line, or the field at floor level near an underground cable). In some cases it could also be the minimum clearance distance to the source that is relevant (cf. distance to the source).

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[35] Although the phase separation is greater on the HV bushings, the current ratio makes that the field level is usually larger at the LV side of the transformers.

[36] In [18] an additional measuring height of 0.5 m is also considered

4.4.5.2 Measurement distance to the source

The measurement distance to the source depends, of course, on the applicable specification or regulation. The distances can become very important mainly when the measurements deal with high exposure levels and when assessment of conformity to limits expressed in term of induced current in the body ("basic restrictions").

For "immission" measurement[37], the measurement distance is usually not very relevant as it simply depends on the relative position of the "source" with respect to the "affected area".

On the contrary, for "emission" measurement this distance becomes very important.

Sometimes the distance used is determined by the minimum safety distance (clearance distance) to the source (HV line, busbar, etc.) or by the burial depth of the cable in the ground.

However, when the source is simply insulated, like a power cable or a MV/LV kiosk, and can be touched without harm, there is no safety distance and the field can become very significant at short distance from the source[38]. In this particular case, which is characterised by a high degree of non-uniformity of the field, it can be necessary to define a minimum distance for making the assessments.

This distance could be set conventionally at 30 cm as proposed in some IEC standards [9].

For horizontal distances, it could also be a typical "passing clearance" i.e the distance between the centre line of the body and surface of the equipment (e.g. 30 cm) that takes into account the arm-to-arm width of a human body [18].

When it is not possible to fix a conventional distance to the source that is large enough to achieve field uniformity, it becomes necessary to assess directly, either the average field or the induced currents in the body, by the use of suitable models.

Different approaches have been proposed for taking the field non-uniformity into account:

4.4.5.3 Three heights method

A first approach assumes a standing human body that can be represented by a uniform spheroid. The proposal is based on the identification of 3 equivalent measurement heights (e.g. 0.5 – 1 – 1.5 m) giving 3 field values of which the mean value is a good estimator of the equivalent uniform field that would produce the same value as the actual field averaged inside the body [18].

This rather simple method is mainly intended for the assessment of the public exposure to fields produced by power installations.

4.4.5.4 Normalised or coupling factor methods

Another approach [19], that seems more suitable for high field exposure assessment (live line work..) is based on the computation of two ***induction factors*** making the link between field level and induced current density (or induced electrical field): The first one, the "***uniform field induction factor***" (UIF) is computed for a uniform field and expressed in (mA/m^2)/mT (or in (mV/m)/mT). The second one, the "***non-uniform field induction factor***" (NIF) is referenced to the maximum field incident at the surface of the body. It depends on the distance (r) to the source and on the orientation of the incident field relative to the body. It is expressed in the same units as the uniform field induction factor. By dividing the NIF by the UIF a ***normalised induction factor*** $L(r)$ is obtained which is valid for a given model of

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[37] "Immission" is a new word than can be found in some publications for indicating that the measurement is made in the vicinity of the affected area.

[38] For a single conductor, the maximum magnetic field exposure is estimated from the inverse dependence on distance ($1/r$). For a multiple-phase source the field will decrease more rapidly. Any acceptable solution for a single conductor will thus lead to conservative estimates for a dipole or three-phase source.

the body and a given field orientation. An example of normalised induction factor taken from [19] is given in Figure 19 for three line sources.

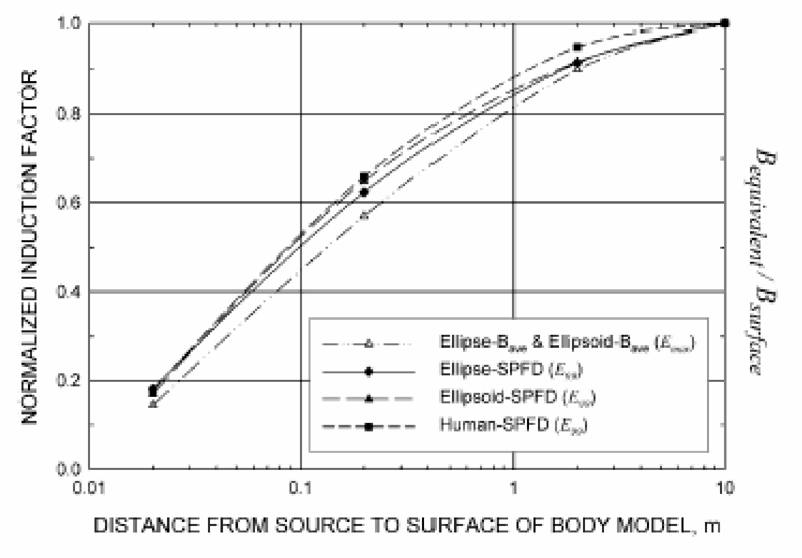

Figure 19: Normalized non-uniform induction factors referenced to maximum surface field and calculated for different body models

Multiplying the maximum field exposure at a known distance from the source by the normalised induction factor at the same distance yields the equivalent uniform magnetic field exposure that can directly be compared with the corresponding guideline limit for compliance with the basic restriction.

A similar approach is found in [5], where the current density induced in a model representing the human body (in this case a homogeneous disk with a given conductivity) by a specific source generating a non-uniform field is calculated and compared with the current that would be induced by a uniform magnetic field whose magnitude is equal to the (maximum) magnitude of the non-uniform field at the edge of the model closest to the localised source.

The current density for the non-uniform field being always lower than for the equivalent uniform field, the result can be quantified using a coupling factor for non-uniform field K, which is physically defined as:

$$K = \frac{J_{nonuniform}}{J_{uniform}}$$

where:

$J_{nonuniform}$ is the maximum induced current density in the disk exposed to the non-uniform magnetic field from the localised source.

$J_{uniform}$ is the maximum induced current density in the disk exposed to a uniform magnetic field from the localised source.

An example with a disk of radius 100 mm and conductivity 0.2 S/m is given in Figure 20.

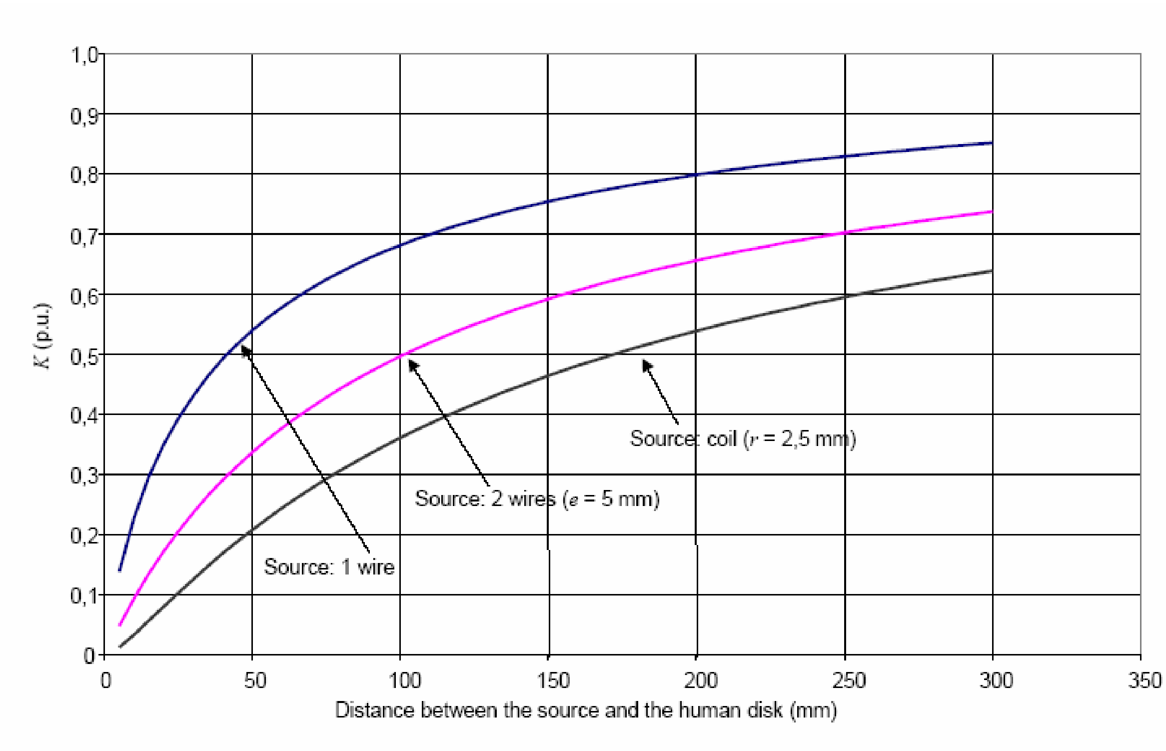

Figure 20: Variation with distance to the source of the coupling factor *K* for non-uniform magnetic field produced by three different sources

Knowing the coupling factor *K*, the equivalent field magnitude that has to be used for performing the conformity assessment is simply the product of the field magnitude measured or calculated at the edge of the human body and *K*.

4.4.6 Multiple sources and multi-frequency sources

4.4.6.1 Multi-circuit lines

Commonly, ac double-circuit overhead transmission lines originate from the duplication of a single three-phase line, mainly because of the large amount of power that has to be carried by the line (present or in the future). In this case, under the assumption that the three phase currents of each circuit are balanced, the corresponding phase currents flowing in the two circuits can be described by two phasors that exhibit no displacement between them, i.e. no phase shift between the two current terms.

A different situation occurs when the double-circuit line is made up of two independent single-circuits (i.e. linking different nodes of the transmission network), placed on the same towers for a portion of their length. In this case, in addition to difference in the magnitudes of the currents, phase shifts between current phasors of the two circuits may exist.

This current phase-shift affects significantly the magnetic field generated by the double-circuit line. Neglecting current phase-shift effects can involve severe errors in magnetic field calculation (even larger than 45%, as shown in [23]), leading sometimes to underestimate the field, sometimes to overestimate it.

In the absence of any information about this phase shift it seems logical to assume the worst-case situation.

This worst-case situation depends on the phase arrangement in both circuits and on the respective current flow direction.
For the so-called “untransposed” or “super bundle” arrangement, that is, when the phase order from top to bottom is the same on both circuits and the currents flow is in the same direction, the worst-case assumption is simply no phase shift.

However, if the currents in both circuits are flowing in opposite directions (what is seldom the case[39]), a 180° phase shift should be assumed.

The opposite assumption should be made for the so-called “transposed” or “low reactance” arrangement[40]; that is a 180° phase shift if the currents flow in the same direction and no phase shift if they flow in opposite directions.

It is however worth mentioning that the assumption of the worst-case conditions will lead to a significant, and often unnecessary, over-estimate of the exposure levels.

Indeed, it would make no sense to apply the low reactance configuration as a field mitigation technique if the assumption is also made that the currents are flowing in opposite direction.

4.4.6.2 Independent lines

In other cases, different types of lines (transmission/distribution, overhead/underground, etc) run parallel with each other or cross each other. In a similar way to the previous case, in the absence of information about the phase shift between the currents flowing in the independent circuits, assuming the worst-case situation often involves an over-estimate of the exposure levels. If some measurements are available, they may be helpful in evaluating the phase shifts and performing a more realistic field assessment [19].

4.4.6.3 Multi-frequency sources

Multi-frequency sources can have, at least, three different origins:

1) Independent sources emitting fields at several frequencies that are not correlated with each other.
2) Non-sinusoidal (or distorted sinusoidal) periodic sources producing harmonics.
3) Non-periodic (transient) sources.

In the first case, i.e. when the source(s) generate(s) fields at ***independent frequencies***, the resulting field is rather complex and the only characteristic that can usually be assessed is an upper bound of the instantaneous magnitude applying formulas like that proposed by ICNIRP (formula 8 of [2.]) Long-term metrics like annual mean or median are very difficult to assess unless one of the frequencies largely dominates the other. As far as emission assessment is concerned, it is usually accepted to consider each source individually, whereas for immission assessment, additional safety factors are sometimes required.

In the case of ***harmonics***, there is a strong correlation between all the frequency components and considering them individually assuming the worst possible phase relationship as in the ICNIRP formula, would lead to an overestimation of the result.

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[39] This could be the case when a single power links feeds different loads (or power sources like windmills) located at different places and makes the go and return in the same trench or on the same poles.

[40] Two combinations of phase order are assumed here. In practice every circuit can have six different phase orders, and for a double circuit line there are many combinations. “Super bundle” and “low reactance” are most common, but in general any combination can (and does) occur. This is because, in many systems, the phase orders are not selected just for optimising the field levels but in a way that minimises the circulation of induced negative sequence currents in the network because when they get too high they can cause overheating of generator rotors.

Hence, the best way to assess periodic fields with harmonics is to use broadband measuring equipment that automatically takes into account the actual phase relationship of each frequency component.

If an assessment has to be made against limits that are frequency dependent (like the ICNIRP reference levels), it becomes necessary to use either a broadband measurement equipment that includes a dedicated frequency weighting function filter or to analyse each frequency component individually (Fourier analysis) and to make a post measurement processing on the individual complex data (amplitude and phase). More details on possible ways to proceed can be found in [3] and [9].

The case of non-periodic transient (or pulsed) fields is beyond the scope of this document.

4.5 Guidelines for assessing statistical values

As stated previously, long-term exposure assessments need the use of statistical values like percentiles or means over long periods (week, year). These values are always very different from the rated values for which the installation (power line, substation, etc.) has been designed.

However, long-term statistical values are not always available, mainly when the assessment concerns a new project.

In such cases there is a need to assess the statistical values based on the data that are available, such as the rated current of the line concerned or the annual maximum current of a representative similar line.

4.5.1 Practical examples

a) Belgium

In order to illustrate the important differences that exist between mean and maximum values, measurements have been made at mid span under overhead lines in a representative part of the Belgian 380 kV overhead network [14].

These measurements have allowed drawing three of the four curves in Figure 21, showing respectively:

- The maximum possible field under rated[41] current (at the minimum clearance and for the worse case line configuration) – (**max**)
- The maximum field under rated current (averaged over the whole network and all the spans) – (**rated**)
- The mean field (in time and in space) not exceeded in 95 % of the cases – (**95%**).
- The mean field over 1 year (averaged over the whole network and all the spans) – (**yearly mean**)

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[41] See 4.4.1.1 for the definition of the “rated” conditions

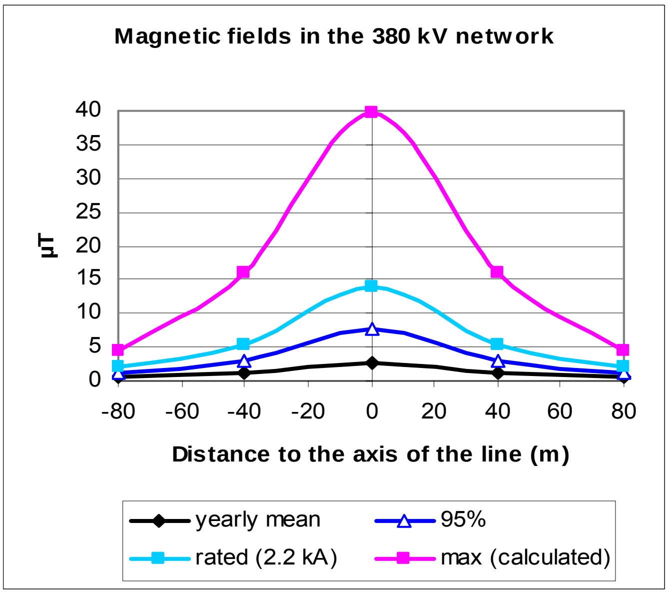

Figure 21: Magnetic field profiles averaged over all the Belgian 380 kV overhead lines (taken from [14])

This figure highlights the enormous differences between mean and maximum values[42].
In particular, it shows that practically a ***factor 2*** exists between:

- Worst case span (max) *and* average over all the spans of the network (rated)
- Rated conditions (rated) *and* maximum normal load conditions (95 %)
- Maximum normal load conditions (95 %) *and* mean values calculated over 1 year (yearly mean)

More details about these ratios for the entire network can be found in Table 1 (overhead network) and in Table 2 (underground network).

These tables show that all the ratios between the 95 percentiles (values close to the annual maximum) and the rated currents or between the annual mean currents (values close to the annual median) and the 95 percentiles are in the vicinity of 0.5 or even lower.

Current ratio (averaged over the entire network)	Overhead network		
	380 kV	150 kV	70 kV
95 % / rated	0.57	0.48	0.31
Yearly mean / 95 %	0.34	0.38	0.32

Table 1: Ratio of the statistical parameters for the Belgian overhead transmission network

Current ratio (averaged over the entire network)	Underground network	
	150 kV	70 kV
95 % / rated	0.35	0.35
Yearly mean / 95 %	0.49	0.46

Table 2: Ratio of the statistical parameters for the Belgian underground transmission network

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[42] It should be noted that all the measurements have been made at mid span were the magnetic field is the highest

As result from these tables, ***the annual maximum values (95 % percentile) are typically 2 to 3 times the long time average values (yearly mean).***

In the same way, ***the maximum <u>possible</u> values (rated) are typically 2 to 3 times the <u>annual</u> maximum values (95 % percentiles).***

b) <u>Canada</u>

Calculations have been performed by Hydro-Québec in order assess the magnetic levels in the vicinity of the overhead network and of the 25 kV underground network.

The results of these assessments are given in Table 3

Voltage (kV)	**Corridor width (m)**	**Magnetic field [2] and corresponding current µT (A)**					
		Under the conductors			**At the edge of the corridor [3]**		
		99.9 % [4]	95%	50%	99.9%	95%	50%
25 [5]	5	4.1 (700)	1.8 (300)	1.2 (200)	1.7 (700)	0.7 (300)	0.5 (200)
25 [6]	5	1.7 (200)	0.7 (85)	0.5 (55)	1.4 (200)	0.6 (85)	0.4 (55)
25 [7]	1.5	6.3 (700)	2.7 (300)	1.8 (200)	1.3 (700)	0.6 (300)	0.4 (200)
25 [8]	1.5	13.9 (700)	5.5 (300)	3.6 (200)	1.6 (700)	0.7 (300)	0.5 (200)
69	20	24 (750)	8 (250)	3.2 (100)	6.6 (750)	2.2 (250)	0.9 (100)
120	30	45 (1500)	15 (500)	6.0 (200)	6.2 (1500)	2.1 (500)	0.8 (200)
161	30	40 (1500)	13 (500)	5.4 (200)	6.1 (1500)	2.0 (500)	0.8 (200)
230	30	58 (2000)	15 (500)	5.8 (200)	15.6 (2000)	3.9 (500)	1.6 (200)
315	40	97 (3500)	21 (750)	8,1 (300)	20 (3500)	4.3 (750)	1.7 (300)
735	80	80 (5250)	30 (2000)	15 (1000)	14 (5250)	5.5 (2000)	2.7 (1000)

Table 3: Maximum magnetic fields in the vicinity of the power lines of the Hydro-Québec network

<u>Notes</u>:

1 The fields are calculated assuming the minimum conductor clearance to ground
2 The corresponding currents in amperes are indicated between brackets
3 For the 25 kV lines the field are indicated at 10 m from the axis of the line instead as at the edge of the corridor
4 For the 25 kV lines (distribution lines), the percentiles are calculated for one year because the lines are assumed to be fully loaded directly after they are put into service. For the other lines (transmission lines), the percentiles are estimated for the full lifetime of the lines (assumed generally to be 50 years) taking into account an annual increase of 3% per year[43].
The 99.9% percentile corresponds mostly to emergency situations where the lines are operated close to their thermal rating (cf rated conditions in 4.4.1.1)
5 Three-phase overhead line
6 Single-phase overhead line
7 Three-phase underground cable
8 Underground link with 7 circuits

<u>Comments</u>

The results of Table 3 have been synthesised in Table 4, in a similar way as for the Belgian network. With the exception of the 50/95 ratio of the 25 kV distribution network, all the ratios are again less than 0.5 and the same inferences as for the Belgian network can be drawn

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[43] only during the first 30 years of the lifetime for the 735 kV lines

Current ratio	735 kV	230-315 kV	69-161 kV	25 kV
95 % / 99.9	0.38	≤ 0.25	0.33	≈ 0.42
50 % / 95 %	0.5	0.4	0.4	≈ 0.66

Table 4: Ratio of the statistical parameters for the Hydro Québec network

c) The Netherlands
An analysis of the currents during 2003 for all 380 kV and 220 kV circuits performed by the National Institute for Public Health and the Environment [15] has shown that the choice of an annually averaged current equal to 30% of the rated capacity[44] of a line was a good future-oriented estimate. For lower voltage lines (150, 110, 50 kV) insufficient data were available. Therefore, a conservative approach is to adopt for new circuits an annual average current equal to 50 % of the capacity.
This can be summarised as follows:

Current ratio	380 kV	220 kV	50-150 kV
Yearly mean / rated	0.30	0.30	0.50

Table 5: Ratio of the statistical parameters for the Netherlands

d) Finland
The results presented in Figure 14 for the 110 kV network of Helsinki Energy are summarized in Table 6.

Current ratio	110 kV
95 % / rated	0.26
50 % / 95 %	0.51

Table 6: Ratio of the statistical parameters for part of the Helsinki Energy network

Similar results have been found in other countries (France, UK, and USA).

4.5.2 Proposal for conservative ratios

Taking into account the examples given in 4.5.1 it is proposed, ***in the absence of any accurate information***, to adopt the following conservative ratios for performing long-term exposure assessments in the vicinity of HV power lines or cables:

Yearly current ratio (or field ratio)	Conservative	Very conservative
95 % / rated	0.5	0.7
50 % / 95 % or mean / 95%	0.5	0.7
50 % / rated or mean / rated	0.5 x 0.5 = 0.25	0.7 x 0.7 ≈ 0.5

Table 7: Conservative ratios for long-term exposure assessments

In other words in can be accepted that for practically all HV transmission power links, ***the maximum possible field level at a given location is at least twice the annual maximum level and often larger than four times the average level.***

The choice between conservative or very conservative will depend on each particular case and on the requirements. It should be noted that, in particular, circuits feeding large industrial loads (24 hour operation) connected directly to the transmission network are usually operated closer to their nominal

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[44] based on the 2005-2012 Capacity Plan

rating than circuits feeding distribution networks. Hence, the very conservative approach is probably more appropriate for the first type of circuit.

For MV distribution networks, despite the absence of sufficient data and the higher variability from country to country, the conservative ratios proposed in Table 7 should also be applicable. Indeed, if the n -1 rule is generally not applied in distribution networks, the lines are usually designed for loads not exceeding 50 % of the rated current. As an example, a long term assessment in the vicinity of a 13 kV overhead network presented in [28] shows that the annual maximum field levels (with duration longer than 15 minutes) were about 3 times higher than the mean levels (or medians).

5 Conclusions

Due to their possible link with health effects, extremely low frequency (ELF) magnetic fields are very often mentioned in publications, standards, regulatory documents or newspapers in which the magnetic field is just characterised by a single number which is intended to represent its magnitude. However to fully characterised the field it is necessary to provide more information.

In contrast with what is done for other environmental factors such as noise or chemical agents, very few publications are devoted to the way magnetic fields should be characterised, assessed and measured.

This guide is an attempt to fill this gap, showing the complexity of the topic, listing most of the field characteristics, highlighting the influencing factors and proposing some metrics and practical assessment criteria.

In particular, it has shown that for a given field, depending on the way the assessment is done, the amplitude values can vary by up to an order of magnitude. This is because the concept of “field magnitude” itself can have different meanings or interpretations and needs clear definitions. Therefore additional characterising parameters have to be introduced.

Taking into account the fact that numerous publications address long term field exposures, this guide proposes a conservative way to assess the exposure to time varying fields produced by HV lines (or cables) when no or limited data is available concerning their long term variation.

This guide can in no way be considered as an exhaustive document. Its purpose is to alert the reader and the decision maker in particular, to the necessity to correctly **characterise** magnetic fields.

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