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Basic standard for the evaluation of workers' exposure to electric and magnetic fields from equipment and installations for the production, transmission and distribution of electricity

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National foreword

This British Standard is the UK implementation of EN 50647:2017.

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English Version

Basic standard for the evaluation of workers' exposure to electric and magnetic fields from equipment and installations for the production, transmission and distribution of electricity

Norme fondamentale pour l'évaluation de l'exposition des travailleurs aux champs électriques et magnétiques produits par les équipements et installations de production, transport et distribution d'électricité

Basisnorm für die Evaluierung der beruflichen Exposition gegenüber elektrischen und magnetischen Feldern ausgehend von Komponenten und Anlagen zur Erzeugung, Übertragung und Verteilung elektrischer Energie

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European Committee for Electrotechnical Standardization
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European foreword

This document [EN 50647:2017] has been prepared by CLC/TC 106X “Electromagnetic fields in the human environment”.

The following dates are fixed:

• latest date by which this document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2018-04-10
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1 Scope

This European Standard provides a general procedure to assess workers' exposure to electric and magnetic fields (EMF) in work places associated with the production, transmission and distribution of electric energy, and to demonstrate compliance with exposure limit values and action levels as stated in the Council and European Parliament "EMF" Directive 2013/35/EU [11].

NOTE 1 The Council and European Parliament Directive 2013/35/EU will be transposed into national legislation in all the EU member countries. It is important that users of this standard consult the national legislation related to this transposition in order to identify the national regulations and requirements. These national regulations and requirements may have additional requirements that are not covered by this standard

It has the role of a specific workplace standard. It takes into account the non-binding application guide for implementing the EMF Directive [10] and it defines the assessment procedures and compliance criteria applicable to the electric industry.

The frequency range of this standard covers from DC to 20 kHz, which is sufficient to include the power frequency used for electric power supply systems throughout Europe (50 Hz) and the various harmonics and inter-harmonics occurring in the supply system. In this extremely low frequency range, electric and magnetic fields are independent and, therefore, they both have to be addressed in the exposure assessment.

NOTE 2 Electrical companies also use radio frequency transmissions to operate and maintain their networks and power plants. Similarly, other exposures to EMF may occur during maintenance operations, for instance, due to the use of hand-held electrical tools. All these EMF sources are outside the scope of this standard.

NOTE 3 Regarding EMF in the low frequency range, the scientific basis of the EMF directive is the ICNIRP health guidelines published in 2010 [13]. Reference is made to this scientific basis when necessary for justifying or clarifying some of the technical statements of the present document.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 61786-1, *Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 1: Requirements for measuring instruments (IEC 61786-1)*

EN 50527-1, *Procedure for the assessment of the exposure to electromagnetic fields of workers bearing active implantable medical devices - Part 1: General*

EN 50527-2-1, *Procedure for the assessment of the exposure to electromagnetic fields of workers bearing active implantable medical devices - Part 2-1: Specific assessment for workers with cardiac pacemakers*

IEC 61786-2, *Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 2: Basic standard for measurements*

3 Terms, definitions, physical quantities, units and abbreviations

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1
action level
AL
operational level established for the purpose of simplifying the process of demonstrating compliance with the relevant exposure limit value or, where appropriate, to take relevant protection or prevention measures

Note 1 to entry: "Reference levels" as defined in the European Recommendation 1999/519/EC [3] for limiting the exposure of the public and in ICNIRP Health Guidelines [13] are based on the same approach as Action Levels and the two terms are defined to achieve the same objective.

Note 2 to entry: For electric fields, "Low ALs" and "High ALs" are levels which relate to the specific protection or prevention measures specified in the EMF Directive [11].

Note 3 to entry: The Low AL for external electric field is based both on limiting the internal electric field below ELVs and on limiting spark discharges in the working environment. Below the High AL, the internal electric field does not exceed ELVs and annoying spark discharges are prevented, provided that the relevant protection measures are taken.

Note 4 to entry: For magnetic fields, "Low ALs" are levels which relate to the sensory effects ELVs and "High ALs" to the health effects ELVs.

Note 5 to entry: Compliance with the ALs will ensure compliance with the relevant ELVs. If the assessed exposure values are higher than the ALs, it does not necessarily follow that the ELVs have been exceeded, but a more detailed analysis is necessary to demonstrate compliance with the ELVs.

Note 6 to entry: ALs may not provide adequate protection to workers at particular risks, for whom a particular risk assessment shall be performed.

3.1.2
compliance distance
distance from a source of field that ensures respect of the relevant exposure limit values or action levels

Note 1 to entry: Working at distances smaller than compliance distances requires a specific assessment.

3.1.3
contact current
current between a person in established contact with a conductive object, resulting from the inductive or capacitive coupling between the field and the person and/or object, and expressed in amperes (A)

Note 1 to entry: The EMF directive [11] specifies limits for the steady-state value of the contact current.

3.1.4
electric field
constituent of an electromagnetic field which is characterized by the electric field strength ***E*** together with the electric flux density ***D***

Note 1 to entry: In French, the term "champ électrique " is also used for the quantity electric field strength.

[SOURCE: IEV, ref 121-11-67]

3.1.5
exposure index
EI
assessed exposure divided by the relevant action level or exposure limit value

3.1.6
exposure-limit-equivalent field
LEF
magnitude of uniform external electric or magnetic field that exposes the person to the sensory or health effects ELV

Note 1 to entry: The numerical values of LEFs are derived from dosimetry.

3.1.7
exposure limit value
ELV
limit which is based directly on established health effects and biological considerations

Note 1 to entry: In the frequency range covered by the present standard, ELVs are expressed in terms of induced electric fields except between 0 Hz and 1 Hz where the ELV is given in terms of external magnetic field.

Note 2 to entry: “Basic restrictions” as defined in the European Recommendation 1999/519/EC [3] for limiting the exposure of the public and in ICNIRP Health Guidelines [13] are based on the same approach as Exposure Limit Values and the two terms are defined to achieve the same objective.

3.1.8
exposure limit values for sensory effects (sensory effects ELVs)
ELVs above which workers might be subject to transiently disturbed sensory perceptions, i.e. retinal phosphenes and minor changes in brain functions

Note 1 to entry: The sensory effects relate only to the central nervous system of the head. Exceeding sensory effects ELVs is allowed under controlled conditions for informed workers.

3.1.9
exposure limit values for health effects (health effects ELVs)
ELVs above which workers might be might be subject to adverse health effects, such as stimulation of nerve and muscle tissue

Note 1 to entry: Compliance with health effects ELVs will ensure that workers exposed to electric and magnetic fields are protected against all established adverse health effects.

Note 2 to entry: The threshold for muscle excitation is far higher than for nerve excitation, and therefore the directive [11], consistently with its scientific basis [13], considers limits to prevent only nerve excitation, as they are conservative with regard to muscle excitation. As a result, the health effects relate to the peripheral nervous system, i.e. the whole body.

3.1.10
induced electric field
electric field inside a human body resulting directly from an exposure to an external source of electric or magnetic field

3.1.11
magnetic field
constituent of an electromagnetic field which is characterized by the magnetic field strength $\boldsymbol{H}$ together with the magnetic flux density $\boldsymbol{B}$

Note 1 to entry: In French, the term “champ magnétique” is also used for the quantity magnetic field strength.

Note 2 to entry: In this document, the term magnetic field is used for magnetic flux density.

[SOURCE: IEV ref 121-11-69]

3.1.12
total exposure index
TEI
sum of all exposure indexes (e.g. at different frequencies, or from different sources) of either electric or magnetic field

Note 1 to entry: If the total exposure index is less than one, the exposure is compliant.

Note 2 to entry: Using the arithmetic sum makes the TEI a conservative assessment of exposure.

3.1.13
unperturbed field
field at a point that would exist in the absence of persons or in the absence of movable objects which are not necessary for the work progress

Note 1 to entry: All limits expressed in terms of fields external to the human body refer to the unperturbed field.

[SOURCE: EN 61786-1:2014, 3.3.1]

3.2 Physical quantities and units

For the purposes of this document, the physical quantities and units given in Table 1 apply.

Table 1 — Physical quantities and units

Quantity	Symbol	Unit	Comments
Electric field strength	E	V/m	
Magnetic flux density	B	T	µT is more usually used at 50 Hz
Contact current	I_c	A	

3.3 Abbreviations

AL	action level
CNS	central nervous system
DC	direct current
EI	exposure index
ELV	exposure limit value
GIS	gas insulated substation
HV	high voltage
LEF	exposure limit equivalent field
PNS	peripheral nervous system
TEI	total exposure index
WPR	worker at particular risk
rms	root mean square

4 Assessment procedure

According to Article 4 of EU Directive 2013/35/EU [11] "...the employer shall assess all risks for workers arising from electromagnetic fields at the workplace and, if necessary, measure or calculate the levels of electromagnetic fields to which workers are exposed......In workplaces open to the public it is not necessary for the exposure assessment to be carried out if an evaluation has already been undertaken in accordance with the provisions on the limitation of exposure of the general public to electromagnetic fields, if the restrictions specified in those provisions are respected for workers and if the health and safety risks are excluded. Where equipment intended for the public use is used as intended and complies with Union law on products that establishes stricter safety levels than those provided for by this Directive, and no other equipment is used, these conditions are deemed to be met."

Electrical equipment for the production, transmission and distribution of electricity is highly standardized and a few general assessments may cover many sites which have similar equipment and work positions. Therefore, a systematic and thorough assessment of every site containing electrical equipment is not necessary. For a given site, the risk assessment should be limited to any specific equipment or work positions not covered by the general assessments.

The exposure assessment shall be updated if any modification to the installation, the working environment or the work practice significantly affects the EMF exposure conditions.

In electrical companies, many workplaces are exposed simultaneously to electric and magnetic fields. The internal electric fields induced simultaneously by external electric and magnetic fields are vectors, which most often are neither collinear in space nor coincident in phase. ICNIRP's position [13] is that situations where these field vectors are collinear and in phase "*are judged to be very infrequent taking into account the great difference in the distribution of the electrically and magnetically induced electric fields*".

Therefore, when assessing compliance with the Directive according to the present standard, exposure to low frequency electric and magnetic fields shall be considered separately and not additively.

This clause gives a general procedure for the exposure assessment of a work place, which is presented in Figure 1 as a flowchart. It shows all the possible methods to demonstrate compliance with the EMF directive [11]. The different steps of this flowchart are developed in Clauses 5, 7, 8, 9, 10 and 13.

Compliance can be demonstrated using any of the possible methods. For example, in some cases it might be more simple and efficient to demonstrate compliance using measurements (e.g. subclause 8.3) rather than identifying all the electrical equipment and checking whether it meets the criteria for simplified assessment (e.g. subclause 8.2).

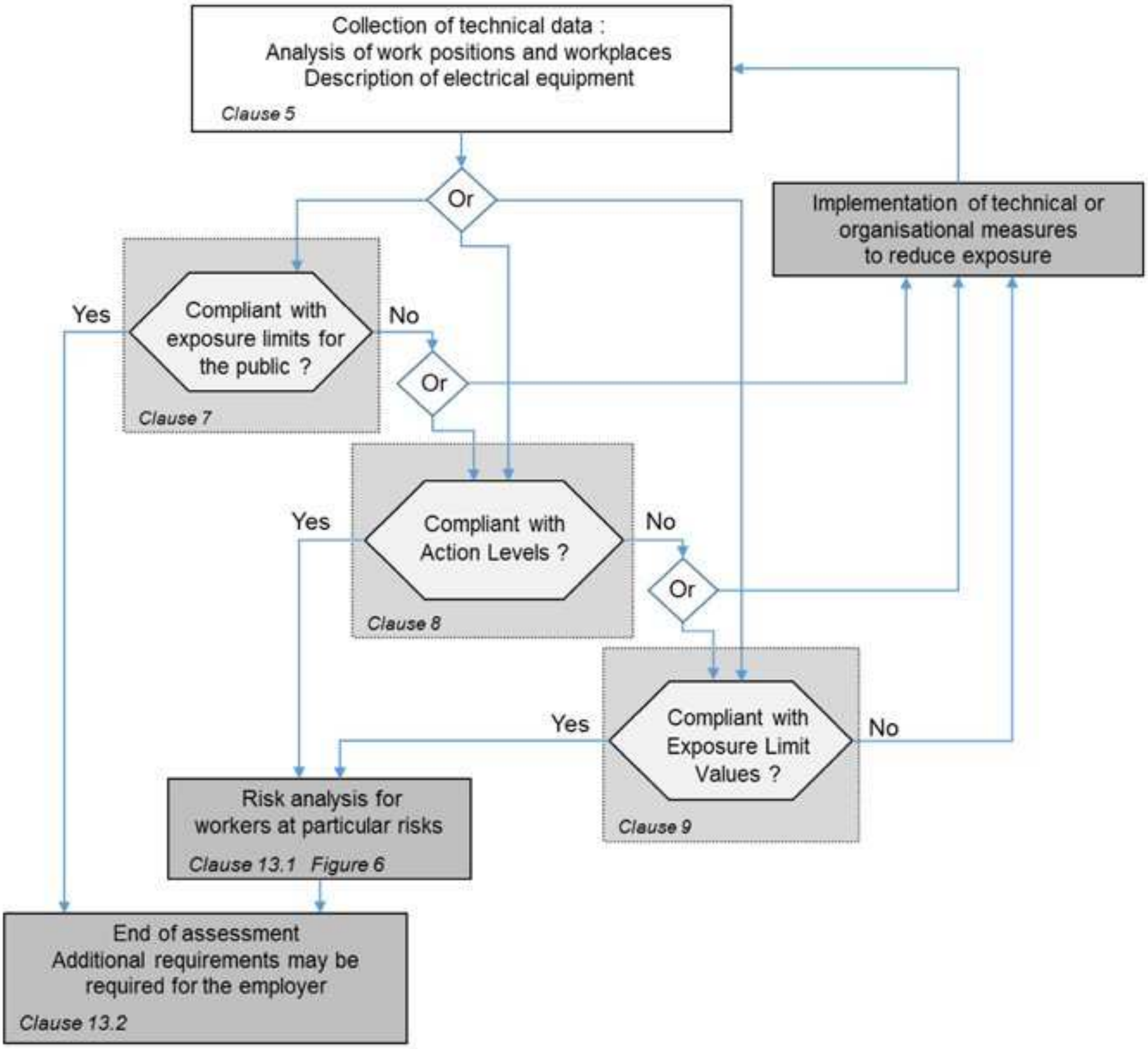


Figure 1 — General flowchart of the compliance assessment procedure

5 Collection of technical data

For assessing compliance, it is necessary to characterize the workplace in terms of EMF sources and of work positions in relation to them, and of the work practices involved. In terms of the scope of this standard, relevant field sources are energized electrical conductors and electrical equipment for producing and distributing electricity.

A simple identification is sufficient for the equipment covered by simplified procedures and general assessments (see Clause 7 and 8.2).

For the specific electrical equipment which may need a particular assessment, the following technical data may be useful to characterize the workplaces being assessed:

— type of equipment;

— rated characteristics (e.g. voltage, current);

— whether the equipment is insulated or not;

— whether any screens or shields are present;

— extent of any harmonics;

— distance of the energized parts of the equipment to workers;

— etc.

6 Methods for assessing exposure of workers

6.1 General

When assessing exposure in a particular area, it is normally sufficient to identify only the main EMF sources that affect that area. If the workers are very close to - or in contact with - one EMF source, any other sources located further away can generally be neglected (examples: HV live-line working, GIS inspection, etc.).

For working environments where different sources are at comparable distances to the workers (examples: low voltage environments, where the three phases are close to each other), the simultaneous contribution of all such sources should be considered.

The worst case exposure of workers shall be determined. As the exposure may vary as a function of the operating conditions, it may be necessary to extrapolate the exposure to worst case exposure conditions. Magnetic fields are generated by currents in electric equipment, such as lines, cables, coils and windings. The current may vary significantly over time and thus so will the magnetic field. This means that extrapolations of measured or calculated values will often be relevant when considering magnetic fields. Electric fields are generated by non-shielded electric equipment, such as overhead lines or busbars in substations. The voltage does not vary significantly over time and neither does the electric field at a given point, provided it remains unperturbed i.e. not affected by any moving object. Therefore, extrapolations of measured or calculated values are not normally relevant when considering power frequency electric fields, except under special circumstances such as a change in maximum operating voltage.

Waveforms of electric and magnetic fields at 50 Hz are not always purely sinusoidal but may contain significant harmonic components, which have to be taken into account in the exposure assessment when relevant. See 6.2.2 and 6.2.3.

6.2 Exposure assessment regarding external fields

6.2.1 General

External fields may be assessed by measurements and/or calculations.

Field meters shall be compliant with EN 61786-1.

This standard does not specify any specific measurement protocol, because of the diversity of the exposure situations experienced by workers. The measurement protocol shall be compliant with IEC 61786-2.

For small distances to a magnetic field source, where the magnetic field is highly non uniform, the size of the measuring probe may introduce an averaging bias and therefore may underestimate the actual field. Therefore the size of the probe shall be appropriate to the spatial variation of the field. Guidance is given in the measurement standard IEC 61786-2.

Magnetic field measurements should not be performed for assessing compliance for distances to field sources smaller than the measuring probe.

Measurements and calculations of electric fields are much more complex than for magnetic fields, as the electric field is perturbed by all conducting objects, even poorly conducting objects, and particularly by metallic structures. This is known as the “peak effect” and it results in strong local enhancements of the electric field. The strongly non-uniform field resulting from the peak effect is not representative of the exposure of a worker. That is why, in order to measure the unperturbed field, IEC 61786-2 recommends:

— a minimum distance of 2 m between the operator and the E field probe;

— to remove movable objects if possible;

— a minimum distance of 1 m to permanent objects if possible.

To overcome this effect, it is recommended to remove any movable object not necessary for the work in progress that might disturb the measurements during electric fields measurements.

Similarly, the peak effect also affects E-fields measurements close to fixed metallic structures, and a minimum distance to such structures should be respected in order to perform reliable and reproducible measurements. IEC 61786-2 recommends a minimum distance of 1 m when possible. However, a measuring distance of 1 m is not applicable to many work situations which involve contact to metallic structures, such as workers climbing in lattice steel electrical towers. In this case, a minimum distance of 20 cm shall be maintained between conducting objects and the measurement probe to reduce the peak effect measurement bias.

6.2.2 Harmonics of magnetic field

For transmission and distribution systems it is acceptable to perform a simplified assessment of harmonics, except around supplies for industry operating high power converters and rectifiers. Annex A proposes different approaches for assessing harmonics.

For simplified assessment of harmonics, the total exposure index is allocated partly to the exposure index for 50 Hz and partly to the sum of exposure indexes of harmonics. A total exposure index, including the fundamental and all harmonics, below 1 demonstrates compliance. Criteria for the 50 Hz exposure index, depending on the nominal voltage, are given in order to demonstrate that the total exposure index remains lower than 1. Alternative values may be used if based on specific assessment of harmonics.

— ***Criterion for voltage range ≥ 60 kV***

Based on available field measurements and current measurements, the harmonics of magnetic field at voltage levels higher than 60 kV can be neglected because the maximum harmonic content of currents in transmission and distribution systems is limited during normal operations.

NOTE Circumstances where significant harmonics can occur, such as resulting from saturation of transformers during energizing or during geomagnetic storms, are too rare to need considering further.

— ***Criterion for voltage range 1 kV to 60 kV***

Based on available field measurements and current measurements from medium voltage distribution and transmission systems, the harmonics up to the 50th might be relevant, but the exposure is compliant if the exposure index for 50 Hz is below 0,8 (see Annex A). The same criterion can be applied for broadband measurements.

— ***Criterion for low voltages (<1kV)***

Based on available field measurements and current measurements from low voltage distribution systems, the harmonics up to the 50th might be relevant, but the exposure is compliant if the exposure index for 50 Hz is below 0,7 (see Annex A). The same criterion can be applied for broadband measurements.

For power plants, assessment of harmonics may be limited to the excitation unit.

6.2.3 Harmonics of electric field

The harmonics of electric field at any voltage level can be neglected because the maximum harmonic content of voltage in transmission and distribution systems, which is limited by voltage quality requirements, usually increases the total exposure index only within the range of the expected uncertainty of assessment.

6.3 Numerical calculation of induced electric fields inside the human body

Numerical computations of induced electric fields inside the human body can be performed using different numerical methods, such as Finite Elements Method, Finite Integration Technique, Finite Difference Time Domain, and Scalar Potential Finite Difference. (See [7] and [8]).

Sophisticated models for calculating induced currents in the body have been used and are the subject of a number of scientific publications. These models use numerical 3D electromagnetic field computation codes and detailed models of the internal structure with specific electrical characteristics of each tissue within the body. Such scientific models can be used to assess compliance to ELVs.

7 Assessment against exposure limits for the public

At many workplaces, EMF levels will remain below the reference levels or basic restrictions for the public, such as those established in the Council Recommendation 1999/519/EC [3]. For such workplaces, when compliance to these values has already been demonstrated, no further assessment is needed.

The Application Guide [10] of the EMF Directive [11] gives a non-exhaustive list of workplaces where it should not be necessary to carry out a specific assessment as there is expected to be no risk from EMFs. The corresponding sources (Table 2) are not expected to give rise to exposures in excess of the reference levels of the Council Recommendation [3] under any conditions of normal operations.

Table 2 — Equipment or work places deemed to comply with reference levels for public exposure, i.e. 100 µT or 5 kV/m at 50 Hz (from Table 3.2 of the application guide [10])

Type of equipment or workplace	Type of exposure
Overhead bare conductors of any voltage	Magnetic fields
Electrical installations or electrical circuits within an installation, with a phase current rating of 100 A or less for the individual circuit (includes wiring, switchgear, transformers, etc.)	Magnetic fields
Any underground or insulated cable circuit, rated at any voltage	Electric fields
Any overhead bare circuit in substations above the work place rated at a voltage up to 110 kV	Electric fields
Any overhead bare circuit in substations with a grounded shield, rated at any voltage	Electric fields
Any overhead line above the work place rated at a voltage up to 150 kV	Electric fields
Any overhead lines at any voltage over-sailing the workplace building where the workplace is indoors	Electric fields

8 Assessment against Action Levels

8.1 General

Action Levels may not provide sufficient protection for workers at particular risk, as defined in the EMF directive [11], and a separate assessment is required for those categories of workers (see 13.1).

The rms values for Low and High ALs are given in Figure 2 (magnetic field) and Figure 3 (electric field). At 50 Hz the corresponding values are given in Table 3.

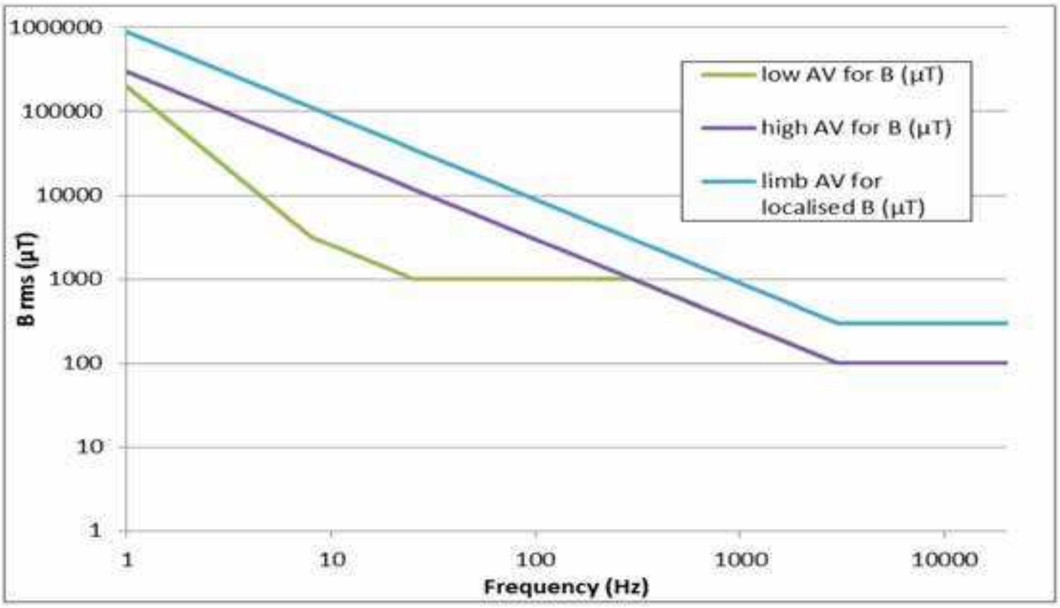


Figure 2 — Low and High Action Levels for magnetic fields in the frequency range from 1 to 20 kHz

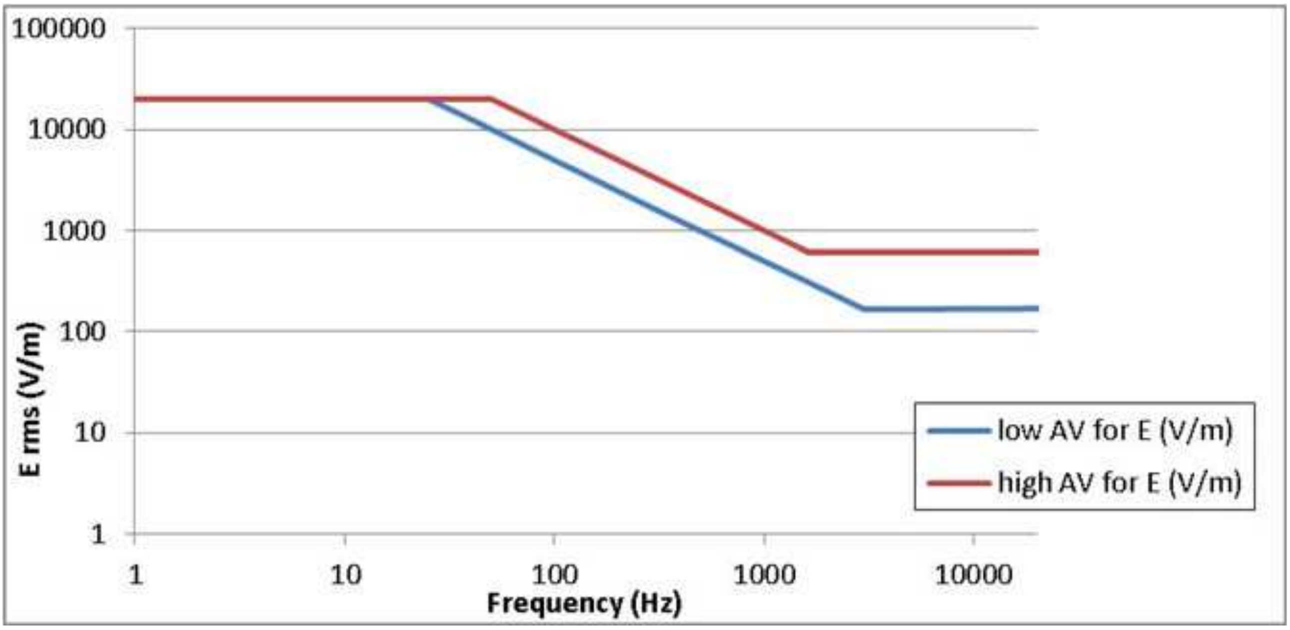


Figure 3 — Low and High Action Levels for electric fields in the frequency range from 1 to 20 kHz

Table 3 — Action Levels at 50 Hz

	Low AL	High AL	AL for limbs exposure to a localized field
Electric field	10 kV/m	20 kV/m	-
Magnetic field	1 000 µT	6 000 µT	18 000 µT
Contact current	1 mA		

For magnetic fields up to 400 Hz, the Low and High ALs refer to different biophysical effects and different organs of the human body. In practice, the Low ALs are related to sensory effects on the central nervous system and are only applicable to the head. The High ALs are related to health effects on the peripheral nervous system and therefore apply to the whole body.

Therefore, when the magnetic field is non uniform over the body, compliance with the Low ALs at the position of the head may not necessarily imply compliance with the High ALs over the remainder of the body. On the other hand, when the magnetic field can be considered as uniform over the body, compliance with the Low AL always ensures compliance with the High AL.

Regarding electric fields, the Low and High AL are based upon the same biophysical effects, and therefore compliance with the Low AL for electric fields always ensures compliance with the High AL.

8.2 Simplified criteria for compliance with action levels

8.2.1 General

This section gives non-exhaustive lists of electrical equipment and operating conditions under which the equipment is deemed to be compliant with the ALs. For other equipment or different operating conditions further assessment is needed (see 8.3).

Some electrical equipment is compliant with the ALs provided that a compliance distance to the magnetic field source is respected. A workplace containing only this kind of equipment is deemed to be compliant with the EMF Directive [11] regardless the number of instances of such equipment. Such workplaces will require no further assessment. There may be additional requirements for the employer (see Clause 13).

8.2.2 Magnetic fields

For electrical circuits, this compliance distance depends directly on the current flowing in the circuit. A rationale for the compliance distance applicable to electrical circuits is given in Annex B (Table B.1).

The list of equipment given in Table 4 is compliant with the Low AL for 50 Hz magnetic fields without further assessment.

Table 4 — Equipment or work places deemed to comply with the Low AL for 50 Hz magnetic field *(live-line situations not considered)*

Type of electrical equipment	Remark
Overhead bare conductors of any voltage	Provided that electrical safety distances are respected
Any electricity installation or circuit in the workplace with a phase-current rating of 250 A or less (includes wiring, switchgear, transformers, etc.)	Justification for 250 A is given in Annex B For currents exceeding 250 A, a compliance distance can be calculated using Formula (2) or Table B.1 of Annex B Exceptions listed below in Table 5
Any iron-cored transformer (with metallic enclosure) or motor or generator	Excluding the connections to these equipment and the end-windings of high-power turbogenerators
IPB (Isolated Phase Busbars) and GIS/GIC/GIL (Gas Insulated Substations/Cables/Lines) of any rating	Excluding parts outside the regions where the metal enclosures of the different phases are bonded together

Other situations may exceed the ALs for magnetic field and require further assessment for demonstrating compliance with the ELVs of the EMF Directive [11]. Based either on measurements or computation, a possible method is to determine the distance which guarantees that the magnetic field strength falls below the ALs (subclause 8.3 assessment) or below the exposure-limit-equivalent-field (subclause 9.2 assessment). Some examples are given in Table 5:

Table 5 — Examples of equipment or workplace requiring further assessment with regard to 50 Hz magnetic field

Type of electrical equipment	Remark
Air-cored reactors	Manufacturers are able to provide information (calculated or measured values) on the magnetic fields levels in the vicinity of the reactors. This can be used to define the distance from the reactors at which ALs are met, and to determine whether safety measures are necessary to protect workers. A simplified method for calculating the maximum magnetic field produced by a single air-core reactor is given in C.1. This maximum calculated value is conservative with regard to a 3-phase system of reactors. Such a calculation can be used to check the need for limiting access to the reactors (e.g. using fences) or to determine a conservative safe distance to the reactors.
Connections to transformers, motors and generators, where the current rating exceeds 250 A.	
In the vicinity of the busbars of power generators	

8.2.3 Electric fields

Electric fields are generated by non-shielded electrical equipment, such as overhead lines or busbars in substations. Non-shielded equipment is not directly accessible and electrical security requires respecting a minimum safety clearance, depending on the voltage level.

The list of equipment given in Table 6 is compliant with the Low AL for 50 Hz electric fields without further assessment.

Table 6 — Equipment or work places deemed to comply with the Low Action Level for 50 Hz electric field (10 kV/m)

Type of electrical equipment	Remark
Any low voltage (up to 1 kV) wiring and associated components	
Any cabling with a conducting sheath at any voltage	Conducting sheaths are normal on insulated cables for use at 1 kV or more
Any underground cable	
Any overhead line up to 400 kV, for a person standing at ground level	See note
In substations, any overhead unshielded conductor up to 200 kV, for a person standing at ground level	
In substations outside HV compounds	Where clearance to ground is higher to allow circulation of vehicles
Inside any building, with energised conductors of any voltage located outside the building	

NOTE Some designs of 400 kV lines can theoretically produce fields above 10 kV/m (up to 12 kV/m) when operating at minimum clearance. Such instances are deemed to be rare in practice and only temporary and it is not necessary to include them in assessments.

8.3 Assessment using measurements or calculations

8.3.1 General

For electrical equipment and workplaces not covered by the simple criteria assessment (subclause 8.2), workers' exposure may be assessed by measurements or calculations of field levels.

8.3.2 Magnetic fields

As the Low and High ALs are applicable to different parts of the body, measurements and calculations of magnetic fields should cover all the worker's body. Nevertheless, as magnetic fields decrease when the distance to the field source increases, in most cases it will be sufficient to measure or calculate the magnetic field at the part of the body closest to the source (to check compliance to the High AL) and at the part of the head closest to the source (to check compliance to the Low AL).

The process is illustrated under the form of a flowchart in Figure 4.

Assessment against Low Action Levels

If all the assessment results (measured, calculated or extrapolated values) are lower than the Low ALs, then the exposure is compliant. If not, further assessment is needed (see below) or, alternatively, the employer has to state the working conditions under which the workplace is compliant with the Low ALs.

Further assessment against Low and High Action Levels

If some of the spot measurements or calculations or extrapolated values exceed the Low AL for magnetic fields, the parts of the worker's body that may be exposed to fields higher than the Low AL need to be determined. If the head is not exposed in excess of the Low AL, and no other part of the body is exposed in excess of the High AL, then the workplaces and work positions are compliant. Otherwise, further assessment is needed to check compliance to the exposure limit values (Clause 9 assessment) or organizational measures must be taken to reduce the exposure of workers.

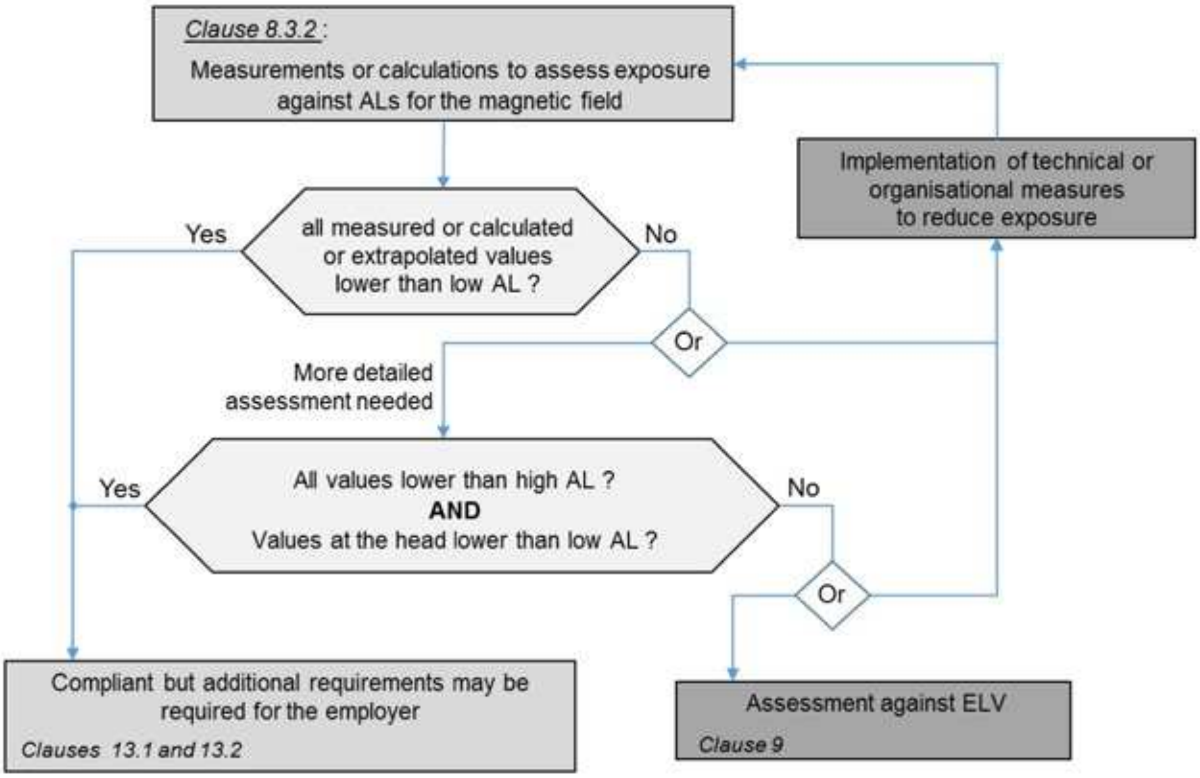


Figure 4 — Assessment against ALs for magnetic fields

8.3.3 Electric fields

The process is illustrated in the form of a flowchart in Figure 5.

When assessing compliance to Low and High ALs, the measurements or calculation results may be spatially averaged over the body in order to compare the averaged value to the reference uniform field, i.e. the action levels for electric fields..

NOTE Guidance for averaging can be found in the non-binding guide for implementing the EMF directive section D.2.2.2 [10]. Other methods for averaging that are based upon sound scientific principles are acceptable.

If the maximum measured or calculated values over the position of the worker are lower than the Low ALs, then the exposure, under the working conditions for which it was assessed, is compliant with the ALs without the need for this averaging. If the maximum measured or calculated values exceed the Low AL, compliance can be assessed after averaging the measured or calculated values over the body.

If the spatially averaged values exceed the Low AL, then compliance can be checked to the High AL provided that contact currents remain lower than the relevant AL and that excessive spark discharges are prevented with relevant measures, such as grounding of metallic objects and structures and equipotential bonding of workers.

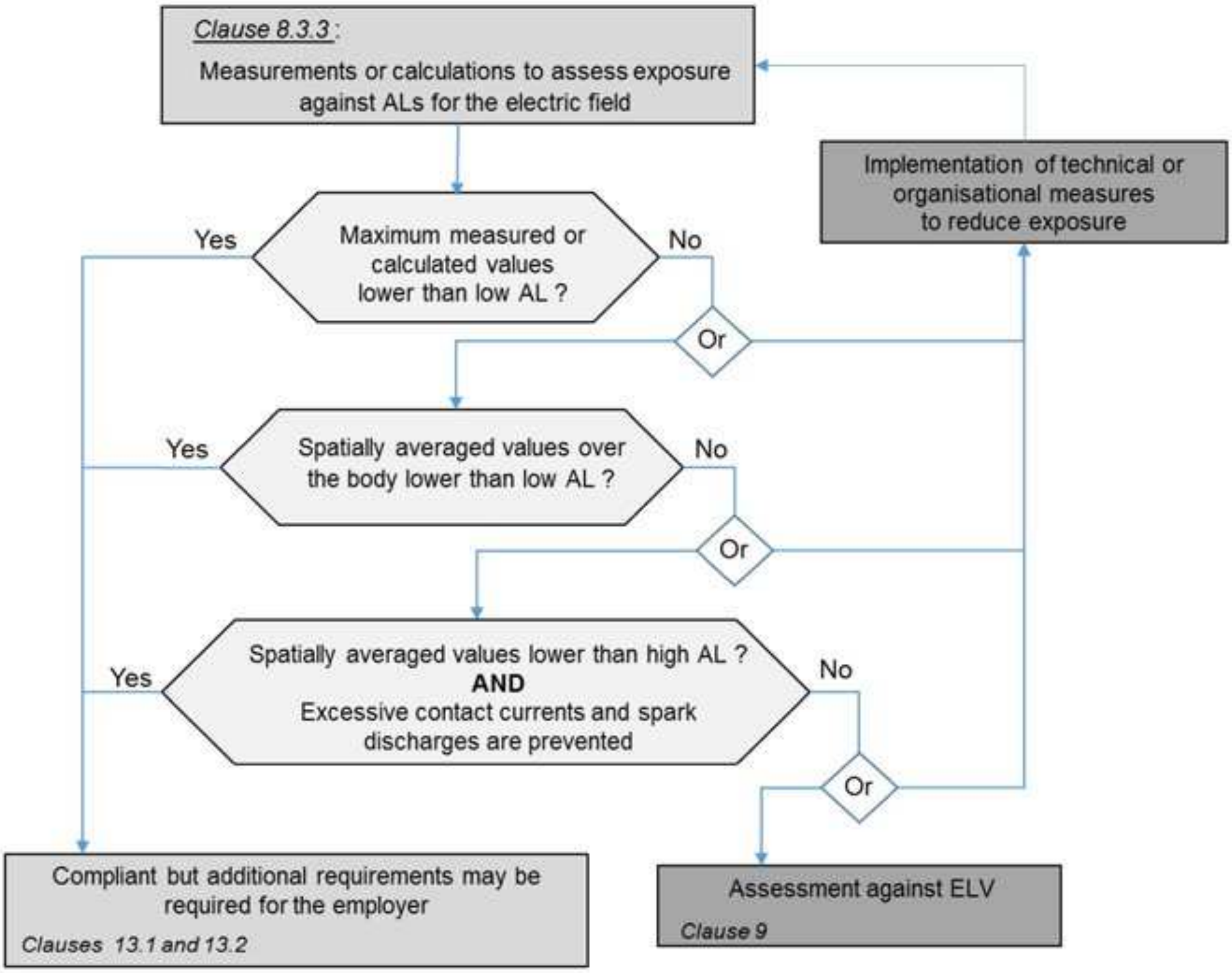


Figure 5 — Assessment against ALs for electric fields

9 Assessment against Exposure Limit Values

9.1 General

When exposures exceed the Action Levels, it is necessary to assess exposure against the Exposure Limit Values (ELVs). It is important to remember that ELVs may not provide sufficient protection for workers at particular risk, as defined in the EMF Directive [11], and a separate assessment is required for those categories of workers (see 13.1).

The ELVs, in the frequency range 1 Hz to 20 000 Hz, are expressed in terms of induced electric fields in the head and the body. They aim at preventing sensory effects i.e. transiently disturbed sensory perceptions and minor changes in brain functions, or health effects i.e. unintended excitation of muscles and nerves. Therefore, the EMF Directive [11] states that the sensory effects relate only to the central nervous system of the head, whereas the health effects relate to the peripheral nervous system, i.e. the whole body.

NOTE 1 The threshold for muscle excitation is far higher than for nerve excitation, and therefore the directive [11], consistently with its scientific basis [13], considers limits to prevent only nerve excitation, as they are conservative with regard to muscle excitation.

In either case, induced electric fields in the body cannot be directly measured; in other words, compliance to ELVs cannot be directly assessed.

Assessment against ELVs requires a dosimetric calculation of the external field that corresponds to the ELV. Such computations use detailed representative anatomical body models. For a given external field, the calculated induced electric field is different in each of the organs of the body, depending on its shape, size, location in the body and electrical characteristics (mainly conductivity).

The most simple computation configuration is for exposure to uniform magnetic and electric fields (unperturbed field for electric field), with the field in the direction relative to the body that corresponds to the maximum coupling situation. Such calculations are conservative with regard to exposure to non-uniform fields.

NOTE 2 For electric fields, the maximum coupling situation occurs when the field is orientated parallel to the main axis of the body. A typical example (the reference exposure situation) is a man standing on the ground and exposed to a vertical electric field.

9.2 Simplified criteria for compliance with exposure limit values

9.2.1 General

A simplified approach is provided by the use of exposure-limit-equivalent fields (LEFs). This approach simplifies the assessment against ELVs by allowing comparison to measurable external quantities.

Exposure-limit-equivalent fields (LEFs) are the lowest values of uniform external fields corresponding to the ELVs. These values are conservative with regard to exposure to non-uniform fields.

In order to calculate LEFs, numerous choices have to be made, e.g. of size and shape of the body model; tissue conductivity; relevant organs; model resolution; averaging procedures; how to take account of uncertainties; etc. Annex D presents a justified set of choices for these parameters, and gives numerical values for the LEF based on these choices. It is acceptable to assess compliance with the Directive using the LEFs derived in Annex D, and examples are given in the following sections and in Annex B. However, it is also acceptable to assess compliance using alternative values of LEFs, obtained by making different choices for the various parameters, provided these are clearly set out and have a sound scientific basis.

When the exposure of workers is below the values of the LEFs, the work positions and workplaces are compliant with the ELVs and require no further assessment. There may be additional requirements for the employer (see Clause 13).

If measured, calculated or extrapolated values of the external fields exceed the LEFs, more evaluation will be necessary, using in necessary specific models for describing the working procedure and specific choices of the various parameters (subclause 9.3).

9.2.2 Magnetic fields

On the basis of the LEFs and of the compliance distance approach, this section gives a list of electrical equipment and operating conditions under which the equipment is deemed to be compliant with the ELVs.

For other equipment or different operating conditions, further evaluation is needed, as well as for the case of exposure above the LEFs. Such evaluations should be clearly set out and have a sound scientfic basis (subclause 9.3).

Some electrical equipment is compliant with the LEF for sensory effects provided that a compliance distance to the magnetic field sources is respected. For electrical circuits, this compliance distance depends directly on the current flowing into the circuit. A rationale for the compliance distance applicable to electrical circuits is given in Annex B (Table B.1). A workplace containing only this kind of equipment is deemed to be compliant regardless of the number of instances of such equipment. Such workplaces will require no further assessment. There may be additional requirements for the employer (see Clause 13).

Based on the particular example of the calculation of the LEF given in Annex D, Table 7 gives a list of equipment compliant with the ELV for sensory effects, provided that specified compliance distances, if relevant, are respected.

Table 7 — Equipment or work places deemed to comply with 50 Hz magnetic field exposure limit value for sensory effects *(following the simplified criteria of compliance to the example of LEF given in Annex D)*

Type of electrical equipment	**Remark**
Overhead bare conductors of any voltage	Provided that electrical safety distances are respected
Any electricity installation or circuit in the workplace with a phase-current rating of 500 A or less (includes wiring, switchgear, transformers, etc.)	Justification for 500 A is given in Annex B For currents exceeding 500 A, a compliance distance can be calculated using the Formula (2) of the Annex B, or Table B.1 of the Annex B. Exceptions listed in Table 8
Any iron-cored transformer (with metallic enclosure) or motors or generator	Excluding the connections to these equipment
IPB (Isolated Phase Busbars) and GIS/GIC/GIL (Gas Insulated Substations/Cables/Lines), of any rating	Excluding parts outside the regions where the metal enclosures of the different phases are bonded together

Other situations may exceed the LEF for magnetic field and require further assessment for demonstrating compliance with the EMF Directive [11]. Some examples are given in Table 8 for the specific example of the LEF given in Annex D. Based either on measurements or on calculations, a possible method is to determine the distance at which the magnetic field strength falls below the LEF.

Table 8 — Equipment requiring further assessment with regard to 50 Hz magnetic field ELV for sensory effects *(following the simplified criteria of compliance to the specific example of the LEF given in Annex D)*

Type of electrical equipment	**Remark**
Air-cored reactors	Manufacturers are able to provide information (calculated or measured values) on the magnetic fields levels in the vicinity of the reactors. This can be used to define the distance from the reactors at which LEFs are met, and to determine whether safety measures are necessary to protect workers. Additional information on magnetic fields generated by air-cored reactors can be found in C.1.
Connections to transformers and generators, where the current rating exceeds 500 A	
Vicinity of the busbars of power generators, Isolated Phase Busbars excluded	

9.2.3 Electric fields

On the basis of the LEFs, this section gives a list of electrical equipment and operating conditions under which the equipment is deemed to be compliant with the ELVs.

Based on the particular example of the calculation of the LEF given in Annex D, Table 9 gives a list of equipment compliant with the ELV for sensory effects, provided that specified compliance distances, if relevant, are respected.

For other equipment or different operating conditions, further evaluation is needed, as well as for the case of exposure above LEFs. Such evaluations should be clearly set out and have a sound scientific basis (subclause 9.3).

Table 9 — Equipment or work places deemed to comply with 50 Hz electric field ELV *(following the simplified criteria of compliance to the specific example of the LEF given in Annex D)*

Type of electrical equipment	Remark
Any low voltage (up to 1 kV) wiring and associated components	
Any cabling with a conducting sheath, at any voltage	Conducting sheaths are normal on insulated cables for use at 1 kV or more
Any underground cable	
Any overhead line for a person standing at ground level	
In substations, any overhead unshielded conductor, for a person standing at ground level	
In substations outside HV compounds	Where clearance to ground is higher to allow circulation of vehicles
Inside any building, with energised conductors, of any voltage, located outside the building	

Assessment for exposure to electric field for working in towers with live conductors is described in C.3. However, it should be noted that such work practices may differ between companies, ranging from access restrictions to some parts of the tower to access forbidden to the whole tower.

Working above ground in substations may result in complex exposure situations. Methods using indirect assessment, such as contact current measurement, may be used, consistent with the approach proposed in C.3.

9.3 Assessment using dosimetry and considerations for non-uniform fields

Apart from the simplified approach suggested in 9.2, other evaluations are acceptable, provided they are based upon sound scientific principles.

Separate values for external electric and magnetic field can be derived for the different organs of the body corresponding to the different ELVs that are applicable to the central and peripheral nervous system.

For non-uniform fields, and taking account of the particular coupling between the body and the electric field, spot measured or calculated values of the external unperturbed electric fields might overestimate the actual interaction between the field and the body. Averaging the external electric field results in a better assessment of the exposure. Therefore, for assessing compliance for non-uniform electric fields, the calculated or measured exposure should be averaged over the volume occupied by the worker’s body, and the resulting fields should be compared to the LEF as previously defined.

For magnetic field exposures to non-uniform fields, for example working very close to an insulated cable or working close to a live overhead conductor (during live-line working), it is possible to demonstrate compliance with the ELVs, even for field values locally higher than the LEFs as defined in 9.2. For example, when it can be demonstrated that field values in the head remain smaller than the LEF for sensory effects, higher field values can be accepted in other parts of the body, provided that the health effects ELVs are not exceeded.

Other methods are possible for demonstrating compliance, such as the use of sophisticated dosimetric methods to calculate the induced electric field in realistic human models, and directly comparing these induced fields to the ELVs. Annex D gives a summary of published computation results, under the conservative assumption of an exposure to a homogeneous field. The same computation methods can be used to evaluate more accurately realistic exposure situations, e.g. taking into account the non-homogeneous field.

10 Exposure to DC fields

No limits are given in the Directive for DC electric fields.

The exposure limits for DC magnetic fields are given directly in terms of field magnitude, as induction effects happen only when a conducting object is moving in a static field. No working situation has been identified close to DC power transmission or generation systems that could exceed the exposure limits, as stated in Table 10.

Some particular equipment may locally generate static magnetic fields in excess of the AL for workers at particular risk (i.e. 0,5 mT). See Annex E for examples.

Table 10 — A priori compliant equipment or workplace with regard to the DC magnetic field

Type of electrical equipment	Remark
Any equipment for production, transmission and distribution of direct current is compliant with the exposure limit value for static magnetic field, for any current	A few types of equipment may require assessment against AL of 0,5 mT applicable to workers at particular risk.

11 Exposure to contact currents

Contact currents are indirect effects of electric and magnetic fields that occur when a person comes into contact with a conductive object (usually a metallic structure) where the person and/or the object are under the influence of the field. Different situations have to be considered depending on the type of field (electric or magnetic) and the isolation level of the person and/or the object with respect to the earth.

Contact currents are to be understood as the permanent currents existing once contact has been established with conductive objects. Whether due to an electric or a magnetic field, the object with which the contact is made shall be earthed if there is a risk of exceeding 1 mA.

NOTE This earthing is relevant only for large objects. See Annex F.

Where the contact current is produced by an electric field, the location and the quality of the earthing are not critical. Where the contact current is produced by a magnetic field, the earthing has to be applied in the immediate vicinity (tens of meters) of the point of contact and needs to be of good quality.

When the person first comes into contact with the conductive object, a spark discharge (transient current) may occur. Spark discharges can be an annoyance to workers and, where necessary, appropriate mitigation measures are required to prevent them occurring..

Additional information describing these phenomena and giving examples of mitigation measures is given in Annex F.

12 Exposure during transients and fault conditions

Normal operation of transmission and distribution systems involves various ways in which voltages or currents higher than normal can be produced, but lasting only very short periods, typically only a few cycles of the 50 Hz waveform.

These temporary exposures are of too short a duration to constitute over-exposure, and no further action need be taken. For further details and explanation see Annex G.

Where controlled faults are applied intentionally, for example for testing or for fault location, then planned protective measures should nonetheless be taken to ensure exposures remain lower than the ELVs.

13 Additional requirements for the employer

13.1 Workers at particular risk

Following the general assessment procedure given in Clause 4, protection of workers at particular risk needs to be evaluated, nevertheless, when public limits are not exceeded, this assessment is not required. In line with the EMF Directive, two categories of workers at particular risk (WPR) shall be considered: pregnant women and workers with implanted or body worn medical devices. Figure 6 describes the process for a risk assessment for these WPRs.

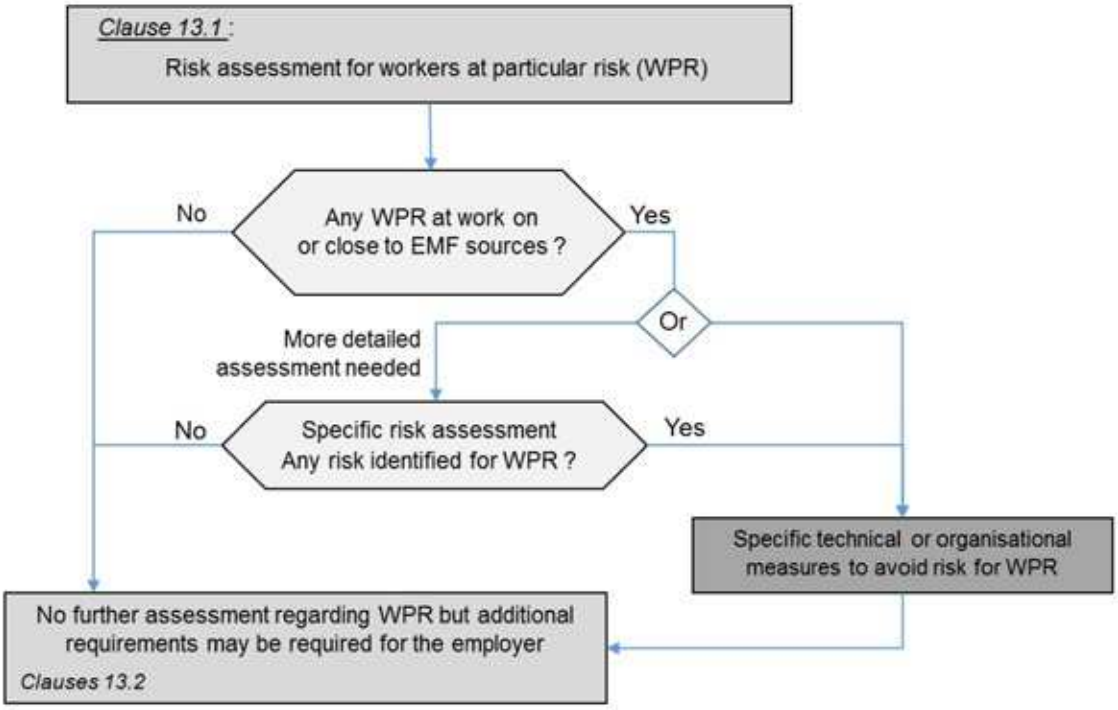


Figure 6 — Risk assessment for Workers at Particular Risk

The pregnant workers referred to in the EMF Directive [11] are the pregnant workers “who have informed their employer of their condition” (Article 5.4).

NOTE 1 The requirement for giving this information may differ in accordance with national legislation.

The workers with implanted or body worn medical devices referred to in the EMF Directive [11] are those who have declared the use of such medical devices (Article 5.4). Appendix E of the application guide [10] gives a list of medical devices worth to be considered.

The risk assessment for workers with implanted devices shall be done following EN 50527 standards.

NOTE 2 Medical implants are continuously developing and therefore the EN 50527 standards do not cover all body worn devices or passive implants in present day use, but the methods proposed can still be applied.

13.2 Other requirements

The results of the risks assessments shall be recorded in a traceable way.

The employer shall refer to the national legislation in relation to the EMF Directive to look for additional requirements, such as signalling of zones with significant EMF sources, information and/or training of workers, etc.

Annex A
(informative)

Assessment of harmonics in magnetic fields

A.1 Introduction

Nonlinear loads connected to the grid cause periodic, non-sinusoidal currents. Mathematically these non-sinusoidal currents are expressed as a set of components at frequencies that are multiples of the network frequency. Depending on the type of equipment, different current spectra (amplitudes and phase angles) are produced. Depending on the phase shift, superposing currents can cancel out (−180°) or add linearly (0°).

The assessment of non-sinusoidal magnetic field exposure when harmonics are present either by calculating and summing all exposure indexes for harmonics or by the weighted peak analysis requires acquisition of much data and complex calculations or measurements. The number of instruments providing harmonic assessment in a proper way is still very limited.

Three methods of assessment for magnetic fields containing harmonics are presented here. The simplified assessment method for transmission and distribution systems (defined in 6.2.2) is explained in A.4. When the given exposure is not in the scope of the simplified assessment method, it is recommended to apply the method using TEI (A.2), and if this fails to demonstrate compliance, the more detailed assessment using the weighted peak method (A.3) should be applied.

According to the Directive, “In the case of non-sinusoidal fields, the exposure evaluation carried out in accordance with Article 4 shall be based on the weighted peak method (filtering in time domain), explained in the practical guides referred to in Article 14, but other scientifically proven and validated exposure evaluation procedures can be applied, provided that they lead to approximately equivalent and comparable results”.

A.2 Assessment Method using TEI

When considering harmonics, the total exposure index is the sum of all the exposure indexes for the different frequencies as the following formula demonstrates for the Low AL.

$$TEI_{B\ low\ AV} = \sum_{1\,Hz}^{20\,kHz} \frac{B_i\left[\mu T\right]}{B_{low\ AV}\left[\mu T\right]} = \sum_{1\,Hz}^{8\,Hz} \frac{B_i \cdot f_i^{\,2}\left[Hz\right]}{200.000} + \sum_{8\,Hz}^{25\,Hz} \frac{B_i \cdot f_i\left[Hz\right]}{25\,000} + \sum_{25\,Hz}^{300\,Hz} \frac{B_i}{1\,000} + \sum_{300\,Hz}^{3\,kHz} \frac{B_i \cdot f_i\left[kHz\right]}{300} + \sum_{3\,kHz}^{20\,kHz} \frac{B_i}{100}$$

The method of assessment by calculation of exposure indexes for each relevant harmonic is demonstrated below with two examples:

freq. Hz	B(t) RMS µT	Low AV µT	EI
50	100,0	1000	10%
100	1,8	1000	0,2%
150	13,0	1000	1,3%
200	0,8	1000	0,1%
250	6,5	1000	0,7%
300	0,8	1000	0,1%
350	4,3	857	0,5%
400	0,8	750	0,1%
450	3,0	667	0,5%
500	0,8	600	0,1%
		TEI	13%

Figure A.1 — TEI method applied to a magnetic field generated by a low voltage feeder

The first example (Figure A.1) is that of a low voltage feeder in a small scale industrial site presenting a 100 µT magnetic field (at fundamental frequency, 50 Hz) with representative harmonics. It can be easily assessed by applying the TEI-equation on the spectral components listed in the table on the right of the graph. The total exposure index is 0,13 (13 %) and therefore is compliant.

The second example (Figure A.2) concerns a non-sinusoidal magnetic field exposure measured close to the excitation unit of a 400 MW generator.

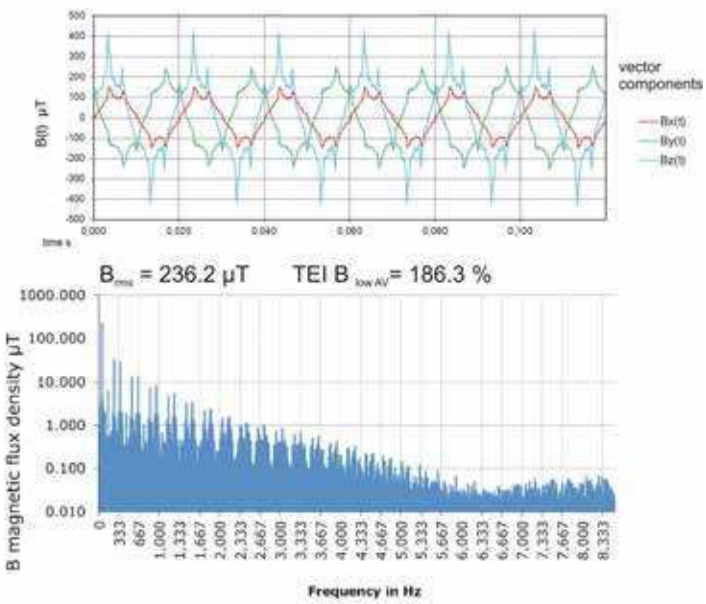


Figure A.2 — 3-axis magnetic field non-sinusoidal exposure close to the supply of a 400-MW-gas-generator's excitation

The total Low AL exposure index for all spectral components of this magnetic field calculated by FFT (Fast Fourier Transform) is 186 %. In this example, only one harmonic component exceeds 5 % of the fundamental. The fifth harmonic is around 12 %. Eight spectral components exceed 1 % of the fundamental. The total exposure index calculated from the fundamental and only these eight harmonics is 42 %. This example demonstrates the significant impact of noise when data from measurement instruments are used. To avoid this overestimation the Directive recommends applying the weighted peak assessment. This method is based on the actual phase angle of the spectral components instead of the worst case phase angle. As it is more complex than TEI assessment it should be applied when the TEI-method fails to demonstrate compliance with the relevant limit.

A.3 Assessment using the weighted peak function

The principle of weighted peak (WP) assessment is to apply the inverse Low Action Level curve as a filter (Figure A.3). The exposure is compliant when the absolute values at the output of this filter do not exceed 1. The example above of the excitation unit results in 0,28 (28 %).

NOTE Some commercial field meters have implemented this method, providing easy assessment..

The ideal filter changes its phase shift exactly at the cut off frequencies in a stepwise manner, while a real filter's transfer function (G) provides a continuous function (the dotted line in the transfer function diagram). The assessment can be performed by applying a proper analogue or digital filter, or can be calculated from sample values using Fourier-transform (FFT), filter functions, or the convolution integral.

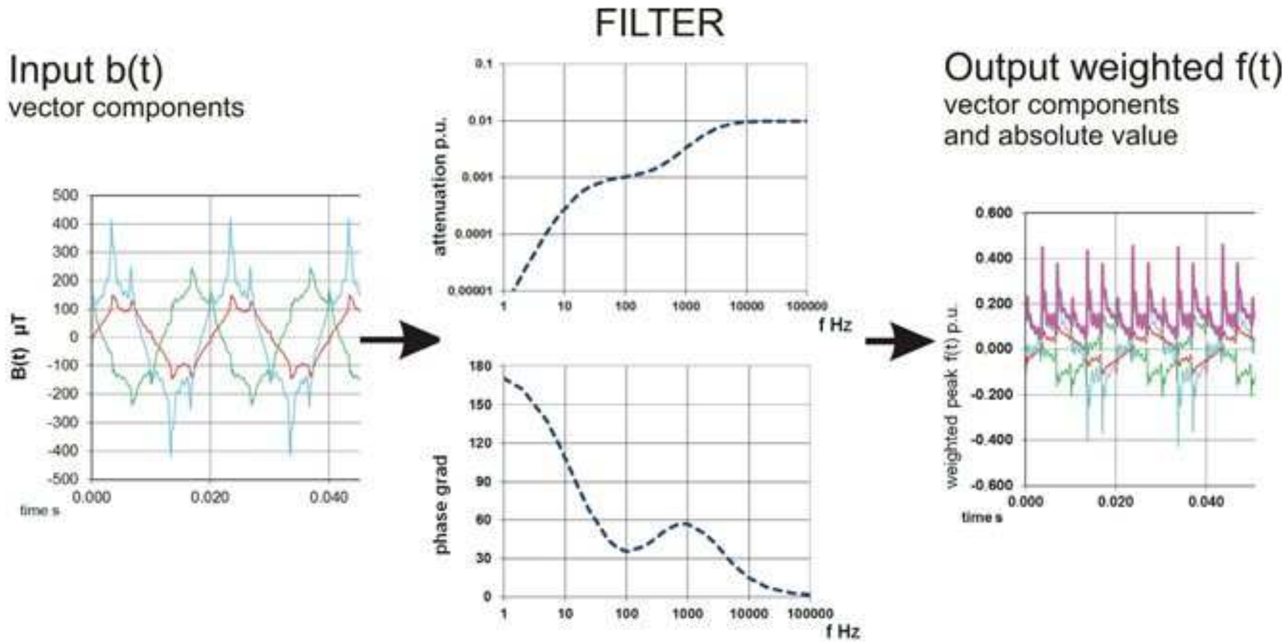


Figure A.3 — Filtering method used for applying the weighted peak assessment

The following equations demonstrate the application for assessment of low action levels. Using other filters with appropriate parameters the weighted peak assessment can be applied for any other action levels or exposure limits.

$$WP = MAXIMUM\left\{\left|\sum_{fi=f_{min}}^{f_{max}}\left(b_i/\sqrt{2}\right)\cdot\left|\underline{G}\right|\left(f_i\right)\cdot\cos\left(2\pi f_i t+\theta_i+\varphi\left(f_i\right)\right)\right|\right\}$$

NOTE ICNIRP gives two options piece wise linear and RC filter. However, the un-physical step wise change of phase leads to numerical problems and unpredictable results.

The transfer function for RC-filters is a set of six transfer functions expressing a chain of filters.

$$\underline{G} = 5\,10^{-14}\prod_{k=1}^{6}\underline{G}_k$$

k = 1,2,5:

$$\underline{G}_k = \left(1 + \mathrm{j}\frac{f}{f_{gk}}\right)$$

k = 3,4,6:

$$\underline{G}_k = \left(\frac{1}{1 + \mathrm{j}\frac{f}{f_{gk}}}\right)$$

Where f_{gk} is defined in Table A.1.

Table A.1 — Filter parameters for various frequencies

k	f_g (Hz)
1	0,000 1
2	0,000 1
3	8
4	25
5	300
6	3 000

k = 1,2,5:

$$\left|\underline{G}_k\right| = \left|1 + \mathrm{j}\frac{f}{f_{gk}}\right| = \sqrt{1 + \left(\frac{f}{f_{gk}}\right)^2}$$

$$\varphi_k = \arctan\left(\frac{f}{f_{gk}}\right)$$

k = 3,4,6:

$$\left|\underline{G}_k\right| = \left|\frac{1}{1 + \mathrm{j}\frac{f}{f_{gk}}}\right| = \frac{1}{\sqrt{1 + \left(\frac{f}{f_g}\right)^2}}$$

$$\varphi_k = \arctan\left(-\frac{f}{f_{gk}}\right)$$

$$\left|\underline{G}\right| = 5\,10^{-14}\prod_{k=1}^{6}\left|\underline{G}_k\right|$$

$$\varphi = \sum_{k=1}^{6}\varphi_k$$

The example of a 400-MW-generator’s excitation at first (Figure A.2) assessed by simply adding all EI (Exposure Indices) all over the spectrum and further assessed by applying the weighted peak method demonstrates clearly the difference of results. The sum of all spectral components in Figure A.2 divided by the action values at their frequencies does not take the phase into account and results in a total exposure index of 186 %. This worst case assumption is also applied to any frequency component at the noise level typically caused by the measurement instrument.

The weighted peak method ensures the assessment is based on real phase angles where the contribution of noise levels to the total exposure index is very limited and all other components are assessed regarding the given differences of phase angles. For the given example of the 400-MW-generator excitation the peak of the filtered signal (Figure A.3) is 0,45 (TEI = 45 %). For this example, the TEI without taking account of phase angles does not demonstrate compliance but the weighted peak method does.

A.4 Simplified assessment procedure for public grids

One major difference between equipment used in industry or the excitation units of power plants and public grids is that the resulting harmonic currents in the latter depend on a large number of customers and the totality of the equipment used by them. As consumer electronics is often replaced by new equipment with different harmonic emissions, in the long term it is not possible to define realistic specific exposure characteristics regarding harmonics.

Harmonic currents cause harmonic distortion of voltages. The typical maximum distortion of voltage occurring at supply terminals (low voltage level and medium voltage level) is specified by power quality standard EN 50160 [5]. To ensure compliance with voltage quality requirements, the emission of harmonic currents by each customer to the public grid is limited by regulations and specific standards.

At a given node of the grid, harmonic voltage levels result from the harmonic levels occurring in the feeder system and the harmonic levels caused by local emitted currents at the given network impedance. The network impedance basically increases linearly with frequency, but due to local resonances, higher impedance levels have to be expected. Thus absolute levels of harmonic currents are very limited in comparison to rated currents.

Harmonic currents were investigated in a study related to exposure assessment considering harmonics in public grids for representative transmission and distribution in Austria [12]. To easily achieve results that are comparable to those from detailed analysis, this study suggests, instead of calculating the total exposure index from spectral components, only to multiply the fundamental by factors derived from representative harmonic content. These factors are dependent on the voltage level and are 1,25 for medium voltage and 1,4 for low voltage grids. The demonstration of compliance then requires a reduced limit for the exposure index of the fundamental (1/1.25 = 0,8 for MV and 1/1,4 = 0,7 LV). In practice this means that the compliance margin (100 %) is shared between the exposure index for fundamental (80 % for medium voltage and 70 % for low voltage) and the sum of exposure indexes for harmonics (20 % for medium voltage and 30 % for low voltage)

If the level of fundamental exposure is not available, but the RMS from a broadband measurement is, it can be used instead. Typically the difference between the level at fundamental frequency and the RMS is around 1 % or 2 % due to limited harmonics.

Annex B
(normative)

50 Hz magnetic field sources in the environment of equipment and installations for production, transmission and distribution of electricity

B.1 General

There are many sources of power frequency magnetic field in the industrial environment. However for the field to be large enough to exceed either the Action Levels (ALs) or the Exposure Limit Values (ELVs), it is necessary to be very close to conductors which are carrying large currents.

NOTE Instead of ELVs, which are not defined as external field values, the simplified criteria of Exposure-Limit-Equivalent-Fields (LEFs), as defined in 9.2 of this standard and calculated in Annex D will be used in this annex.

B.2 Currents in single conductors

Compliance with ALs and LEFs can be demonstrated by showing that workers are always at a distance larger than a given compliance distance from conductors which carry high currents. For a current I (in amperes) flowing in a single straight conductor, the magnetic field magnitude B (in μT) is proportional to the current I (in A) and inversely proportional to the distance D (in m) to the centre of the conductor (Ampere's law):

$$B\ (\mu T) = 0.2\frac{I}{D} \qquad \text{(B.1)}$$

This is valid where the person is close to the conductor relative to its length, in other words when it can be considered that the conductor is an infinite straight wire. Practically, this simplified assumption is conservative as it overestimates the real field.

From (B.1), a compliance distance D_{lim} (in m) can easily be calculated corresponding to the magnetic field exposure limit being used, B_{lim} (in μT), which in practice is the AL or the LEF, and depending on the current flowing in the conductor.

$$D_{\text{lim}}\ (m) = 0.2\frac{I}{B_{\text{lim}}} \qquad \text{(B.2)}$$

In practice, considering (i) the cross section of an insulated cable able to withstand current flows of a few hundreds of amperes, (ii) the thickness of the cranium, and (iii) the wearing of a protective helmet by workers, it is considered that the brain is always at a distance not less than 5 cm from the centre of the conductor, even in the situation of contact with the cable.

Therefore, when applying the Formula (B.2), it follows that the current must exceed 250 A before the Low AL at 50 Hz (1 mT) is likely to be exceeded, and 500 A before the example of LEF for sensory effects at 50 Hz calculated in Annex D (2 mT) is likely to be exceeded.

Similarly, considering (i) the cross section of a conductor able to withstand current flows of a few hundreds of amperes, and (ii) the thickness of clothes, it is considered that the skin is always at a distance not less than 2 cm from the centre of the conductor, even in the situation of contact with the cable. Therefore, the current must exceed 500 A before the high AL (6 mT) and the example of LEF for health effects (7 mT) calculated in Annex D are likely to be exceeded.

For conductors carrying currents of different phases in bundles it is the, much lower, net current in the conductor bundle that is applicable.

Table B.1 gives the distance to the centre of an individual conductor carrying a given current at which the Low AL (1 mT at 50 Hz) and the example of LEF for sensory effects calculated in Annex D (2 mT at 50 Hz) are met for a particular value of current (between 20 A to 2 000 A). Reciprocally, this distance can also be considered as the compliance distance to the centre of the conductor for respecting the relevant AL or example of LEF.

Calculations for real insulated cables (i.e. taking into account the radius of the conducting core and the thickness of the insulation) are given in Table B.3 and in C.2.

Table B.1 — Compliance distance in metres (rounded values), to the centre of an individual conductor for meeting Low AL or the example of LEF for sensory effects calculated in Annex D

Current in conductor (A)	**distance D_{lim} (m) from the centre of a conductor corresponding to:**	
	Low Action Level (Central nervous system of the head) 1 mT at 50 Hz	**Exposure Limit Equivalent Field** (for sensory effects) as calculated in Annex D 2 mT at 50 Hz
20	0	0
50	0,01	0
100	0,02	0,01
150	0,03	0,01
200	0,04	0,02
300	0,06	0,03
500	0,10	0,05
1 000	0,20	0,10
1 500	0,30	0,14
2 000	0,40	0,19

Table B.2 gives the distance to the centre of an individual conductor at which the high AL and the example of LEF for health effects calculated in Annex D, both applicable to the whole body, are met for a particular value of current (between 20 A and 2 000 A).

Table B.2 — Compliance distance in metres (rounded values), to the centre of an individual conductor for meeting high AL or the example of LEF for health effects calculated in Annex D

Current in conductor (A)	**distance D_{lim} (m) from the centre of an insulated conductor corresponding to:**	
	High Action Level (applicable to the body) 6 mT at 50 Hz	**LEF for health effects** (applicable to the body) as calculated in Annex D 7 mT at 50 Hz
100	0	0
150	0	0
200	0,01	0
300	0,01	0,01
500	0,02	0,01
1 000	0,03	0,03
1 500	0,05	0,04
2 000	0,07	0,06

B.3 Currents in circuits

The conductors carrying electric current from their source to their destination and back again are referred to as an electrical circuit. Electrical circuits always use two or more conductors.

For an idealised single phase circuit, two parallel conductors carry equal currents flowing in opposite directions. Because the currents are equal and opposite and the conductors are close together, the fields largely cancel out, where the degree of cancellation depends on how close together the conductors are. When the two conductors carrying current I (in A) are at distance S (in m) apart and where S < < D, the magnetic field B (in μT) is given by:

$$B(\mu T) = 0.2 \frac{I}{D} \frac{S}{D} = 0.2 \frac{IS}{D^2} \qquad \text{(B.3)}$$

Similarly an idealized three-phase circuit comprises three currents phased approximately 120° apart. Either these three currents are balanced so that they sum to zero or there is a fourth conductor (the neutral) and the four currents sum to zero. In either case, if the conductors are close together the fields largely cancel.

In the real situations there may be some leakage of currents from the circuit (e.g. into water pipes, other metallic services or the ground itself) so that the currents are not exactly balanced, or the conductors of the circuit may not be close together (e.g. if the neutral takes a different route, creating a large loop).

The current leakage will occur where there are alternative return paths for the currents such as when the neutral of a circuit is grounded in more than one place or where there are parallel circuits supplying a particular load.

The conductors of a circuit, when they are insulated, will usually be bundled together as part of the same cable. In these situations very low magnetic fields are produced even very close to the cable. Situations where the separate conductors are not close together include overhead lines, where the conductor separation increases with the voltage of the circuit. There are also more particular situations where phases and/or neutral conductors of a circuit follow different routes. This is most likely to occur only within a substation containing transformers and/or distribution switching equipment.

The information described above is applied using the method presented in B.2 for assessing exposures from electrical circuits. These are very conservative and cover most situations that arise in practice.

B.4 Assessing magnetic fields exposures

The methodology for assessing exposures from three types of magnetic field source, insulated conductors, bare conductors and other sources, is considered here and a check list for applying it is given in B.5.

<u>Insulated cables</u>

For insulated conductors, the simplest assessment is to use the current rating of the circuit and to assess the compliance distance using Table B.1. The current rating of a circuit can be found from the steady-state rating of the fuses or circuit breaker protecting the circuit. This is a highly conservative approach because it considers the field produced by the current from only one phase of the circuit, and it does not take account of the often almost complete cancellation of this field by the fields created by the other phases.

For single conductors, and considering (i) a minimum radius of 1 cm for an insulated conductor able to withstand current flows of hundreds of amperes, (ii) a thickness of 1 cm between the skin and the brain, and (iii) an additional 3 cm spacing from the protective helmet, it follows that in practice the brain is always at a distance not less than 5 cm from the centre of the conductor. When considering Table B.1, the Low AL is met at 5 cm when the current is 250 A and the example of the LEF for sensory effects calculated in Annex D is met at 5 cm when the current is 500 A.

In addition, considering Table B.2, it is demonstrated that the high AL is not exceeded when the current is 500 A or less.

As a consequence, all circuits rated at less than 500 A (per phase) can be regarded as being compliant without any further consideration.

From the nominal characteristics (current rating and cross section) of high voltage insulated cables, it is possible to calculate the maximum magnetic field at contact. Typical examples are given in the following table:

Table B.3 — Maximum magnetic field value in the body of a worker in contact with typical high voltage cables

Cable	Current rating	Radius of the cable	Magnetic field at the surface of cable with rated current	Magnetic field at 1 cm from surface of cable with rated current *	Magnetic field at 4cm from surface of cable with rated current **
90 kV	1000 A	4,2 cm	4,8 mT	3,8 mT	2,4 mT
220 kV	1500 A	6,0 cm	5,0 mT	4,3 mT	3,0 mT
400 kV	1800 A	7,5 cm	4,8 mT	4,2 mT	3,1 mT

* this represents the maximum field in the brain for a worker whose head is directly in contact with the surface of the cable, assuming a thickness of 1 cm for the cranium bone and tissues
** this represents the maximum field in the brain for a worker whose helmet is directly in contact with the surface of the cable, assuming a thickness of 1 cm for the cranium bone and tissues with an additional thickness of 3 cm to take into account the protective helmet

Additional data about a set of representative cables and corresponding rated currents are given in C.2.

From Table B.3, it can be concluded that the High AL for magnetic fields (6 mT at 50 Hz) is never exceeded with insulated HV cables.

The Low AL (1 mT) and the example of LEF for sensory effects calculated in Annex D (2 mT) can be exceeded in the brain when the head (specifically, the protective helmet) is in contact with the cable and under maximum load conditions.

This assessment does not require consideration of whether or not the conductors of a circuit are bundled or follow different routes and because this approach is conservative it is not necessary to make additional provision for multiple circuits running close together.

Similarly any workplace where the rating of the electricity intake supplying the workplace is less than 500 A will be compliant with regard to sensory effects. Where there are more than one electricity intakes, each one may be considered separately. Where the supplies are taken from a step down transformer within the workplace, each circuit on low voltage side of the transformer may be considered separately.

Exceptionally, where a circuit is rated at more than 500 A and where the separation of the conductors is small, an assessment of the maximum possible net current in the cable may be made and this value compared with 500 A.

Where a circuit is rated at more than 500 A and the spacing between conductors is large compared with the distance to where people may be, then the compliance distance to each conductor shall be assessed separately for each conductor for the rated phase current of the conductor.

<u>Overhead bare conductors</u>

For overhead bare conductors minimum safety clearances are specified ([7], [6]) to prevent flashover to objects or people. These distances are all greater than the compliance distances derived using Table B.1, so all overhead circuits with bare conductors are compliant with magnetic field exposure limits without further consideration.

<u>Other magnetic field sources</u>

While certain items of equipment are capable of producing fields greater than the Low AL at their surface, there are very few where the field can exceed the Low AL at a distance of 0.2 m or more from their surface (see Table B.1). Items where this is likely to happen will need to be subject to further investigation involving the determining the magnetic fields values in the vicinity of the equipment, by either calculation or measurement, and comparing them with the High AL or the LEF.

The types of equipment requiring such further investigation are those with high currents (hundreds of amperes) flowing in multiple adjacent turns of a winding, such as those of air-cored reactors, and the end windings of high-power generators.

By contrast, iron-cored devices are designed, for reasons of efficiency, to minimize leakage fields. The fields associated with motors and transformers, particularly where they are enclosed in a ferromagnetic or conducting case will not normally be large enough to exceed the Low AL.

However, whether iron- or air-cored, where the current rating is high, consideration need to be given to the currents in the connections to generators, motors and transformers at both the phase and neutral end of the windings.

Where there is doubt about whether or not the fields surrounding a particular item of equipment in places where workers have access are below the ALs then further investigation is required.

B.5 Check list for assessing compliance for magnetic fields

The following list of equipment is compliant with the Low AL or the example of LEF for sensory effects calculated in Annex D for magnetic field:

— overhead bare conductors of any voltage;

— any electricity installation in the workplace with a phase-current rating of 500 A or less;

— any individual circuit with a phase-current rating of 500 A or less;

— any circuit where the spacing of the conductors is small compared with the distance to places where workers have access, and where the net current is 500 A or less;

— any conductor rated at 500 A or more where the compliance distance between the centre of the conductor to where workers have access is more than the distances given in Table B.1 for the Low AL field. (Alternatively, the larger distances given in Table B.1 for the example of LEF for sensory effects calculated in Annex D may be used as part of a subclause 9.2 assessment.);

— any iron-cored transformer or motors or generator, excluding the connections to them which shall be assessed separately (as above), and the end-windings of high-power turbogenerators;

— switchgear and any other circuit components associated with the above circuits apart from the exceptions listed below.

The following situations may exceed the Low AL or the example of LEF for sensory effects calculated in Annex D for magnetic field and require further investigation of the distance at which the field falls below the ALs (subclause 8.2 assessment) or the example of LEF (subclause 9.2 assessment), based on either measurements or computation for:

— air-cored reactors;

— the vicinity of busbars of generators;

— the end-windings of high-power turbogenerators

Annex C
(informative)

Examples of application of the different assessment criteria

C.1 Assessment for air-cored reactors: Simplified calculation of the magnetic field under a vertical air-cored self-inductance

Air-cored self-inductances can be used in different HV applications. The main ones are:

1. Compensation of capacitive power of transmission lines under light load conditions.
2. Current limitation in networks fed by a transformer of very low short circuit current.
3. Harmonic limitation for capacitor banks.
4. Notch filter for power line carriers.
5. Filtering for HVDC converter stations
6. Current limitation in the grounding of power transformers.

Except in the last case (6), where the inductance is only energised by a fault current, all the other inductances are fed by a steady-state current and can produce a significant magnetic field in normal operating conditions.

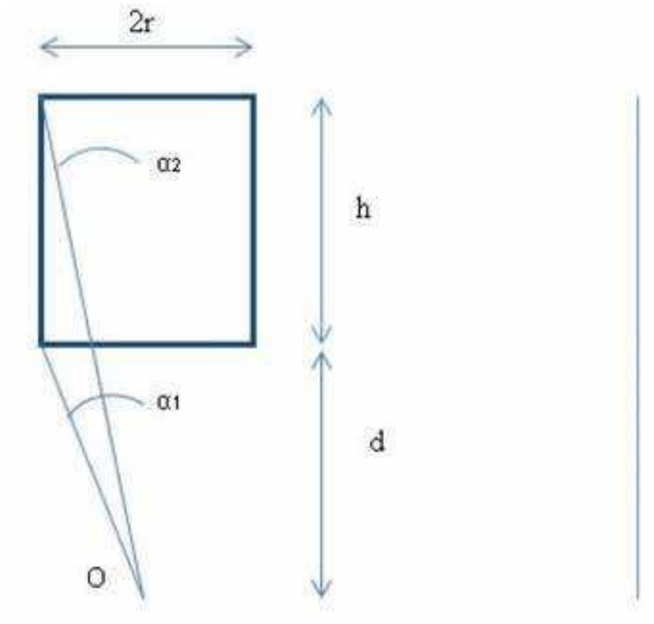
In the most general case, these inductances have the shape of a vertical cylinder installed on insulators at some distance above the ground and it is possible to walk around or even under their base.

The magnetic field produced is the highest on the axis inside the coil or near its base and top. It decreases rapidly with the distance outside the coil (roughly the inverse of the third power of the distance).

In order to know the distance at which the magnetic field falls under a given exposure limit, calculations or measurement have to be performed. This will normally be needed for case 1 (compensation of capacitive power) because these inductances always have a quite high value.

However, for cases 2, 3, 4 and 5, knowing the main characteristics of the inductance (value, shape, current, etc.), it is possible to make an initial assessment by calculation of the field level along the axis of the inductance. If the field calculated on this axis, for the highest possible current and at a distance corresponding to the highest possible position of the head of a human being, remains under the relevant exposure limit, then the inductance will automatically comply with the Directive and there will be no need to limit the access by a fence or by other means.

The calculation of the field on the axis of the coil at a distance d from its basis is given by the following Formula (C.1):



$$B_0 = \mu_0 \frac{N}{2h} I (\cos \alpha 2 - \cos \alpha 1) \quad \text{(C.1)}$$

$$\cos \alpha 2 = \frac{h+d}{\sqrt{(h+d)^2 + r^2}} \quad \text{(C.2)}$$

$$\cos \alpha 1 = \frac{d}{\sqrt{d^2 + r^2}} \quad \text{(C.3)}$$

$$N = \frac{1}{r} \sqrt{\frac{hL}{\mu_0 \pi}} \quad \text{(C.4)}$$

where

- I is the current in the coil (A);
- L is the inductance of the coil (H);
- N is the number of turns of the winding (possibly with several layers);
- H is the height of the coil (m);
- r is the radius of the coil (m).

NOTE In the case of a coil used as harmonic limitation for a capacitor bank, the current in the coil is generally not known but the reactive power is known. In that case, a first approximation of the current is given by:

$$I = \frac{Q}{U\sqrt{3}} \quad \text{(C.5)}$$

A better assessment that takes the impedance of the coil into account is given by:

$$I = \frac{U}{(\frac{U^2}{Q} - Z_L)\sqrt{3}} \quad \text{(C.6)}$$

where

- U is the voltage in V;
- Q is the reactive power in VAr;
- Z is the coil impedance in Ω.

Very often however, the rated current I_n of the coil is known. If the magnetic field calculated with I_n using (C.1) gives acceptable values, then it will be also the case for the actual value of the current, since $I_n > I$.

EXAMPLE

Figure C.1 — Air coils used for harmonic limitation of a capacitor bank

The air coils of Figure C.1 have the following characteristics:

L = 38.5 mH

H = 0.99 m

r = 1.16 m

I_n = 263 A

I calculated using (C.6): 195 A

B calculated at the base of the insulators (d = 1 m): 2.2 mT

B measured at the base of the insulators (d = 1 m): 2 mT

B calculated at 2 m above ground (d = 1.6 m) with I = In: 1.45 mT

B calculated at 2 m above ground (d = 1.6 m) with I = 195 A: 1.1 mT

The field level calculated at 2 m above ground exceeds the Low AL of 1 mT (even using the actual current I); hence this coil does not comply automatically and a more accurate assessment will be needed.

C.2 Assessment for insulated cables: Calculation of compliance distances for typical XLPE cables

The compliance distances (Dlim) with respect to the Low Action Level (Low AL) and the High Action Level (High AL) are firstly calculated from the centre of the single phase cable using Ampère's law (see Formula (B.1) and for the rated current of the cable under the specific conditions (Ir). They are then compared to the radius of the cable (R). If they are smaller than this radius and if the current does not exceed the rated current, no additional distance needs to be added for complying with the relevant AL.

This single phase calculation is conservative with regard to three-phase systems. Therefore, the compliance distance as calculated in Table C.1 can also be applied to three-phase systems using the distance to the centre of the cable closest to the worker.

The rated current depends on the layout and on the operating conditions of the cables. Here, theratings assume permanent conditions (not cyclic) and cables installed in trefoil formation at a depth of 120 cm (U > 36 kV) or 80 cm (U ≤ 36 kV) in a ground having a thermal resistivity of 1 Km/W (typical for controlled backfill). For cable laid in tubes, the rated current will be higher and conversely, for cables laid deeper in the ground or without controlled backfill, the rated current will be lower.

Table C.1 gives examples for actual cables in use. For all the cables presented in this table (sorted by decreasing order of rated current), no additional distance needs to be added for complying with the high AL although some compliance distances (calculated from the centre of the cable) slightly exceed the cable radius (by less than 1 cm).

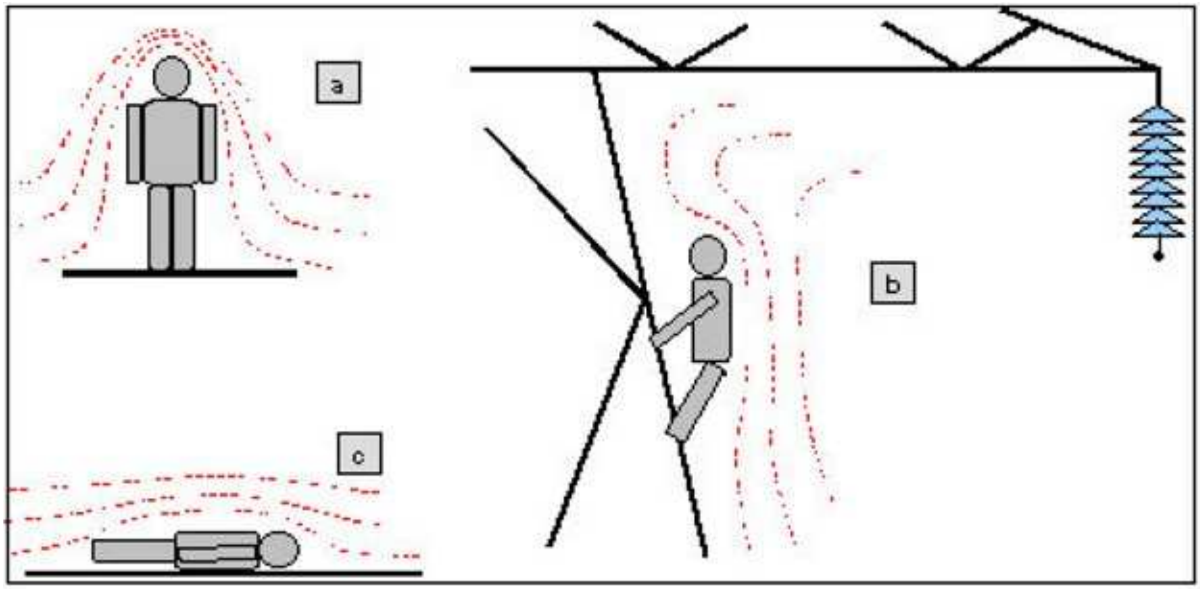
Table C.1 — Minimum compliance distance (D_{lim}) for a set of representative cables

U	**section**	**material**	**diameter 2R**	**I_r**	**D_{lim} for Low AL 1 000 µT (*)**	**D_{lim} for Low AL - R (**)**	**D_{lim} for high AL 6 000 µT (*)**	**D_{lim} for high AL - R (**)**
kV	mm²		cm	A	cm	cm	cm	cm
380	2 500	cu	14,4	1 790	35,8	28,6	6,0	−1,23
380	2 000	cu	13,2	1 640	32,8	26,2	5,5	−1,13
150	2 500	alu	11,8	1 540	30,8	24,9	5,1	−0,77
220	2 500	alu	12,7	1 485	29,7	23,4	5,0	−1,40
150	2 000	alu	10,8	1 375	27,5	22,1	4,6	−0,82
110	1 600	alu	9,9	1 230	24,6	19,7	4,1	−0,85
20	1 000	cu	6,6	1 170	23,4	20,1	3,9	0,60
380	1 600	alu	12,9	1 160	23,2	16,8	3,9	−2,58
36	1 000	cu	6,5	1 110	22,2	19,0	3,7	0,45
36	1 000	alu	6,4	936	18,7	15,5	3,1	−0,08
70	1 000	alu	8,2	895	17,9	13,8	3,0	−1,12
150	800	alu	9,1	800	16,0	11,5	2,7	−1,88
36	630	alu	5,5	754	15,1	12,3	2,5	−0,24
150	500	alu	8,6	640	12,8	8,5	2,1	−2,17
36	400	alu	5,0	585	11,7	9,2	2,0	−0,55
70	400	alu	6,5	560	11,2	8,0	1,9	−1,38
15	630	alu	5,0	580	11,6	9,1	1,9	−0,57
15	400	alu	4,7	460	9,2	6,9	1,5	−0,82
15	240	alu	4,1	360	7,2	5,2	1,2	−0,85
15	150	cu	3,7	310	6,2	4,4	1,0	−0,82
* Compliance distance calculated from the centre of the cable ** Compliance distance calculated from the outer surface of the cable. A negative value means that the radius of the cable is higher than Blim, and therefore means that the cable is compliant even with the rated current flowing.								

C.3 Assessment for exposure to electric fields considering different coupling conditions

The coupling between the electric field and the body is of major importance with regard to the induction of electrical quantities in the body. The maximum coupling situation occurs when the electric field is orientated parallel to the main axis of the body (see Figure C.2 a). This is typically the case for a man standing at ground level under energised overhead conductors or busbars, which is usually considered as the reference situation for exposure to electric field.

The minimum coupling situation is when the field is orientated perpendicular to the main axis. A typical situation is a man lying on the ground (see Figure C.2 c). Many working situation correspond to moderate coupling i.e. when the body in neither perpendicular nor parallel to the equipotential ground plane. A typical example is given in Figure C.2 b representing a worker climbing in a tower.



a reference exposure situation (maximum coupling)

b human body with an angle to the ground plane (intermediate coupling)

c body perpendicular to the electric field (minimum coupling)

Figure C.2 — Different situations of an electric field coupling to the human body (dotted red lines show approximate equipotentials)

No published dosimetric study considers coupling situations other than the reference one, i.e. the maximum coupling situation. A possible way to assess the real coupling is to consider the contact current between the body and the ground (or the grounded structure to which the worker is connected). From a physical point of view, the human body exposed to an electric field can be considered as an electric charge collector and the contact current is the sum of all collected charges, and is therefore a representative proxy of the overall exposure to the electric field. This is well described in WHO [18] and CIGRE [1] publications.

Following published references, for a human body in perfect contact to the ground and exposed to uniform vertical electric field (the reference exposure situation), the order of magnitude for the contact current is 15 μA per kV/m. In other words, when exposed to a 10 kV/m vertical uniform electric field, the contact current is about 150 μA.

An EPRI publication [10] gives a formula to assess the contact current flowing through a standing human body exposed to an electric field

$$I = \alpha l^2 f$$

where

l is the length of the body;

f is the frequency of the electric field;

α is a parameter depending on the orientation of the field with regard to the body.

For the reference exposure situation (a human body standing at ground level and exposed to a vertical E field), EPRI gives $\alpha = 9 \cdot 10^{-11}$ for a 60 Hz field. When applied to a human body 1.75 m tall and exposed to a 50 Hz 10 kV/m field, the formula gives $I = 140\ \mu A$, fairly consistent with the 150 µA previously given.

The EPRI study has also investigated the exposure situation of a worker climbing a tower, using a standing conducting mannequin supported by a harness and connected to the tower by the feet (see Figure C.3):

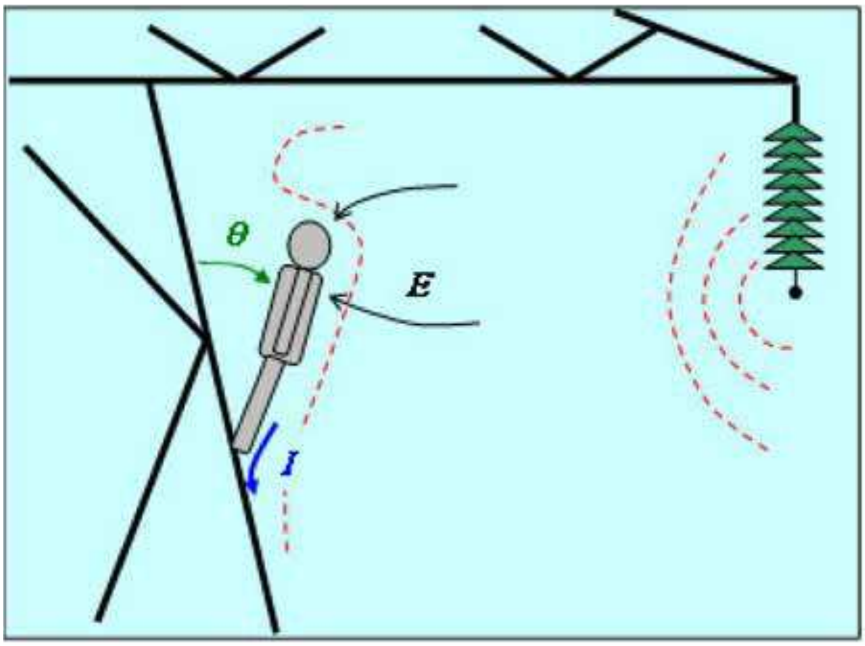


Figure C.3 — Worker climbing a tower with a contact current flowing through the feet

For an angle $\theta = 30$ *degrees*, the EPRI study gives $\alpha = 5.7 \cdot 10^{-11}$. When applying the above formula to a man 1.75 m tall, and exposed to a 10 kV/m E-field, it results in an induced current $I = 87$ µA, therefore 38 % lower than the value calculated in the reference exposure situation.

In other words, a worker climbing a tower and exposed to a 10 kV/m E-field (averaged exposure) has an actual exposure equivalent to a man standing at ground level in a 6.2 kV/m vertical field. In this situation, a 30 kV/m averaged exposure in a tower would be equivalent to 19 kV/m at ground level, therefore lower than the high AL.

Expressed alternatively, the High AL of 20 kV/m for the reference exposure situation is equivalent to an average exposure on the tower in this situation of 32 kV/m. The example value of the Limit Equivalent Field derived in Annex D, 35 kV/m, is then equivalent to 56 kV/m.

This approach of using the contact current to scale the electric field to different coupling scenarios is only approximate, because the contact current is only an approximation to the quantity of ultimate interest, the induced electric field in the relevant organs. The distribution of a given contact current through the body will, in principle, change with the orientation of the external field. However, EPRI record that the fraction of the total contact current induced in the head is 0.29 for the 30-degree-from-tower situation compared to 0.30 for the vertical situation, suggesting the difference may not be large in practice. The values of α are for the feet well grounded, and would be lower for practical situations where the feet are not perfectly grounded, but this is expected to have a similar effect on both exposure situations and therefore not to alter the ratio between the two situations.

Although experimental data are available only for the one angle of lean out from the tower, 30°, the contact current is expected to depend strongly on this angle. At θ = 30 degrees out from the tower, the person has attained roughly 50 % (sinθ) of the distance from the ground plane of the reference situation, and therefore roughly (for a uniform field) 50 % of the space potential, but is still presenting 87 % (cosθ) of the perpendicular area to the field as when they are flat against the tower. It is expected that the ratio of $\alpha_{reference}/\alpha_{angled}$ will increase as the angle reduces below 30° and simple modelling could be used to identify appropriate values of the ratio for smaller angles.

For the ELVs related to health, the limiting region of the body is likely to be the ankles, where the greatest current is channelled through the smallest area, producing the highest induced electric field. Making contact with the tower with a hand would reduce the current through the ankle, but the worst case scenario remains the worker grounded through the feet but not the arms or hands. There are exposure scenarios where the limiting regions is elsewhere, but this discussion considers the common situation where the limiting region is the ankles.

As stated above, there are no published dosimetric calculations dealing with fields oriented other than vertically along the body. However, one set of unpublished data are available (Findlay 2015 personal communication). These modelled a person standing against a vertical ground plane in a uniform horizontal electric field, with the person either vertical or leaning out 30° and modelled either grounded through the feet only, or through the feet and hands. The results for the maximum induced field in the whole body broadly confirm the EPRI experimental results, giving $\alpha_{reference}/\alpha_{angled}$ = 1.4 compared to EPRI's 1.6. This gives further confidence in the validity of the approach for assessing compliance in these exposure scenarios presented here.

Annex D
(informative)

Method for deriving Exposure-Limit-Equivalent-Fields (LEFs)

D.1 Introduction

Health guidelines for electric and magnetic fields in the low frequency range define exposure limits for electric and magnetic fields in terms of induced electric field in the human body, which is not directly measurable, requiring use of dosimetry, i.e. sophisticated modelling of induced phenomena in the human body. However, many parameters, such as the human models, calculation codes and post-processing methods, etc. influence the calculation results.

This annex is based upon a survey of published dosimetric data dealing with uniform exposure and relevant for considering ELVs [15]. It is based upon many published papers between them covering a wide range of the influence parameters. It proposes a method for conservatively deriving measurable levels of electric and magnetic fields equivalent to ICNIRP's basic restrictions, which are equivalent to the ELV of the Directive [13].

When using dosimetric studies for assessing compliance with exposure limits, the level of confidence given to these studies is of critical importance when addressing health and safety issues. This confidence can be assessed, for example by using safety/reduction factors to take into account dosimetric uncertainties, or by evaluating dosimetric uncertainties.

In practice many ways are possible to quantify the computation and modelling uncertainties. For example, a possible way is to consider a number of published results and select the most conservative of them. Nevertheless, all published results cannot be easily compared as they do not give exhaustive results covering all the organs of the human body. In addition, some of these publications give detailed results in terms of induced currents in the body, whereas this quantity is no longer relevant in the Directive and its scientific basis. The method described hereunder is based upon a comparative analysis of published data in order to make a statistical quantitative assessment of each of the various dosimetric uncertainties.

D.2 Method

1. Identify all the human body models with published data on induced electric fields in the human body and uniform exposure conditions.

2. Select a reference model (and, ipso facto, reference computation data), and reference organs with regard to the ELVs, going back to the scientific basis (i.e. the effects to be avoided, as explained in the basic restrictions of ICNIRP).

3. Analyse the different parameters which may influence the calculation result, using all the other available computation data. When possible, i.e. when there is sufficient data, calculate standard deviations. If not, calculate maximal differences from the mean data when relevant.

4. Calculate the combined standard uncertainty.

5. Calculate the Exposure-Limit-Equivalent-Field (LEF) by adding the uncertainties to the results for the reference model.

D.3 Selection of the reference model:

The different models considered in the review are given in Table D.1 (the names of the models are explained in [15]). The closest model to the ICRP reference man is Maxwell. Only models with results relevant for comparison with ELVs, i.e. expressed in terms of induced electric field, are considered here.

Table D.1 — Comparison of representative male human body models

mass (g)	adult male ICRP	UVIC (calculated from volume)	NORMAN	MAXWEL	DUKE
Adipose tissues	18 200		17 221	17 737	11 800
Blood	5 600	1 029		2 039	
Bone, total	5 500	10 031		6 118	7 900
Brain	1 450	1 484	1 532	1 471	1 370
Heart tissue only	330		355	340	
Heart with blood	840				750
Kidneys	310	377	332	348	360
Liver	1 800		1 877	1 952	1 240
Lung with blood	1 200		1 029	1 044	4 180
Marrow, bone	3 650	1 440			
Muscle, skeletal	29 000	38 055	30 427	28 602	34 100
Skin	3 300	6 532	5 106	5 310	5 500
Total height (in m)	1,76	1,77	1,76	1,76	1,74
Total mass (in kg)	73	76	73	73	70

D.4 Reference organs and data

The sensory effects ELV aims at protecting the CNS tissue of the head. Relevant organs are thus the brain (separated into white and grey matter in some body models), the retina and the optical nerve. The spinal cord is mostly not in the head, so is therefore not included in considerations of the sensory effects ELV.

The health effects ELV aims at protecting the CNS and PNS of the whole body. IC NIRP 2010 specifies that the skin should be taken into account: "*There is no conversion factor for peripheral nerve tissue available at present. Therefore, the skin, which contains peripheral nerve endings, was chosen as a worst-case target tissue*." Hence, the following organs were considered for the PNS ELVs: the brain, the retina, the optical nerve, the spinal cord and the skin. It should be noted that taking all organs into account would raise a problem of coherence between models because the most critical organ depends on the model or because the results are not available for all organs. Table D.2 gives the induced electric field in different organs of the body and for different field orientations of the magnetic field. For the electric field, only the vertical orientation for a human body connected to the ground is presented as it is the worst case exposure situation.

In order to avoid numerical singularities, the criteria used to express the maximum induced field is the 99th percentile of the distribution in each organ, as recommended by ICNIRP. In the Table D.2, the highest value is highlighted, also defining the most critical organ with regard to sensory effect (in practice: the brain) and health effects (in practice: the skin).

Table D.2 — Induced electric field (mV/m; 99th criterion) for the reference model (Maxwel)

	1 mT LAT *	1mT AP **	1 mT TOP***	1 kV/m TOP***
blood	17,2	25,6	13,8	5,7
brain grey matter	34,5	26,3	26,3	1,9
brain white matter	33,9	27,2	19,1	1,0
csf	17,5	14,3	13,7	1,0
eye retina	17,7	8,7	6,9	0,6
fat	53,3	100,0	52,9	14,4
heart	33,9	53,8	43,2	2,4
muscle	27,9	43,8	22,7	7,3
skin	42,2	78,9	41,9	14,8
spinal cord	48,2	29,7	23,0	3,5
*LAT: horizontal field, lateral exposure (i.e. side to side) **AP: horizontal field with an orientation antero-posterior (i.e. face to back) ***TOP: vertical field (i.e. top to bottom)				

D.5 Uncertainty assessment

Various parameters potentially influencing the computation results have been considered (the detailed justification is given in [15]):

— computation method;

— meshing of the human body;

— conductivity of tissues;

— post-processing;

— morphology of the model.

The calculated uncertainty for the brain exposed to a magnetic field is 37 %. The detailed calculation is given in Table D.3:

Table D.3 — Calculation uncertainty for magnetic field regarding central nervous system

Uncertainty sources	Value of the uncertainty uv_i	Probability distribution	Division factor k_i	Sensitivity coefficient c_i	Standard uncertainty $u_i = uv_i / k_i$
Morphology (for the brain)	±2,5·10⁻¹	Rectangular	√3	1	1,44·10⁻¹
Conductivity	±3,0·10⁻¹	Rectangular	√3	1	1,73·10⁻¹
Calculation method	negligible	Rectangular	√3	1	0
Resolution size	±5,0·10⁻²	Rectangular	√3	1	288·10⁻²
Post processing	±5,0·10⁻¹	Rectangular	√3	1	2,88·10⁻¹
Combined standard uncertainty		$u_c = \sqrt{\sum_1^m c_i^2 . u_i^2}$			3,67·10⁻¹

A similar calculation results in a combined uncertainty of 38 % for the skin which is the relevant organ for considering effects on the peripheral nervous system.

For exposure to electric fields the calculated uncertainty is 50 % for the brain, and 44 % for the skin.

D.6 Deriving the Exposure-Limit-Equivalent-Field (LEF)

Regarding exposure to magnetic fields, the highest induced electric field is 34,5 mV/m in the brain for a 1 mT LAT exposure (see Table D.2). The corresponding calculated uncertainty is 37 % (formally 36,7 % see Table D.3). Adding this uncertainty to the calculated values finally results in a conservative estimate of the highest induced field in the brain: 47,2 mV/m for a 1 mT uniform field exposure.

The 50 Hz magnetic field equivalent to the exposure limit for sensory effects (100 mV/m in the central nervous system) is therefore 2,12 mT, conservatively rounded to 2 mT.

Following the same approach, the highest induced field in the skin is 109 mV/m. The resulting LEF for health effects (800 mV/m in the peripheral nervous system) is thus 7,34 mT, conservatively rounded to 7 mT.

For electric fields both the two effects, on central and peripheral nervous systems, result in the same rounded value: 35 kV/m.

Table D.4 — Exposure-limit-equivalent-fields LEFs (lowest value of uniform field corresponding to exposure limit values)

	Lowest value of uniform field corresponding to the exposure limit values	
	Sensory effects	Health effects
50 Hz magnetic field	2 mT	7 mT
50 Hz electric field	35 kV/m	35 kV/m

Annex E
(informative)

Considerations about DC magnetic fields in electrical companies

E.1 Introduction

Directive 2013/35/EU defines two ALs for exposure to static magnetic field:

— For the hazard of interference with Active Implanted Medical Devices (AIMD): 0,5 mT;

— For the hazard of attraction and projection of metallic objects in the fringe field close to high field (>100 mT) sources: 3 mT. This is the case close to MRI installations, where the magnetic field inside the coil is more than 1 T.

The ELVs for static magnetic field are still much higher: 2 T (normal working conditions) and 8 T (localized limbs exposure).

E.2 Exposure of workers to DC magnetic field in electrical companies

Most of electric current transmission and distribution is AC at 50 Hz in Europe, but some power lines are DC and their number is growing (for example with subsea cables). Such lines generate a static magnetic field. Maximum exposure situations are found in the close vicinity of lines and cables, and inside AC/DC conversion substations.

When analysing exposure to DC magnetic field, it should be considered that there exists a background exposure due to the Earth's magnetic field (between 30 µT and 70 µT depending on the proximity to the magnetic poles). With regard to exposure of workers close to cables, the formulas given in Annex B are applicable. They show than in any case, the ELVs are never exceeded.

A number of particular sources have been found in electricity generation, such as:

— Generator excitation: the DC magnetic field measured close to the exciter of a turbogenerator (eg inside the cabinet) has been found to be of order of 5 mT.

— Overhead conveyor belt for the transportation of coal: the static magnetic field can be created by a permanent magnet or by an electromagnet for separation of ferromagnetic impurities. The measured static magnetic field is in the order of 100 mT just under the magnet and in the order of 10 mT at 20 cm. Such power magnets are sometimes signalled with warning « forbidden for cardiac implant ».

E.3 Attention points

The exposure to static magnetic field is always lower than the ELVs, but some situations have been identified where the exposure can, very locally, be higher than the ALs:

— close to generator exciters;

— close to overhead conveyor belt magnets;

— close to HVDC cables.

Annex F
(informative)

contact currents

F.1 Introduction

Contact currents are indirect effects of electric and magnetic fields that occur when a person comes in contact with a conductive object (usually a metallic structure) when the person and/or the object are under the influence of the field.

Different cases have to be considered depending on the type of field (electric or magnetic) and the isolation level of the person and/or the object with respect to the earth.

The cases considered hereunder assume that the minimum electrical safety clearances as specified by IEC / CEN [6] [7] are complied with. The safety rules adopted by electrical companies are designed to ensure that these minimum clearances are maintained.

F.2 Influence of electric fields

F.2.1 General

An electric field induces, by capacitive coupling, a voltage on people and objects that are isolated from earth, i.e. at floating potential. When contact is made between a person and an object, a current appears that tries to cancel the difference of potential. Depending on the respective level of insulation of person and object, different cases have to be considered.

F.2.2 Person isolated (at floating potential), capacitive coupling to ground

This exposure situation can be simply modelled (Figure F.1). In practice the isolation is never perfect and a leakage current to ground always reduces the floating potential of the person. Nevertheless under dry conditions, this leakage can be neglected.

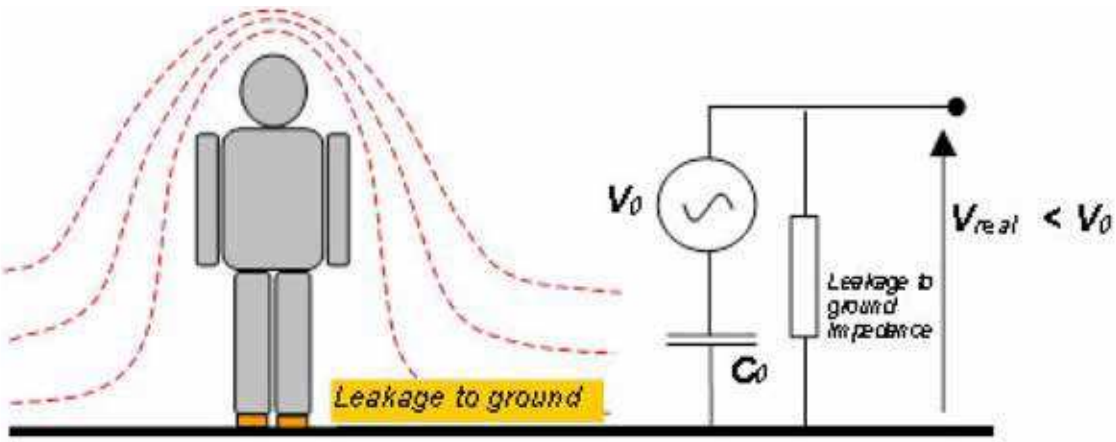


Figure F.1 — Capacitive coupling for an isolated person exposed to an electric field

The capacitive current flowing in a person standing in a vertical uniform field is about 15 µA per kV/m [1; 10].

If the person comes into contact with an earthed object, the contact current will be of the same order of magnitude.

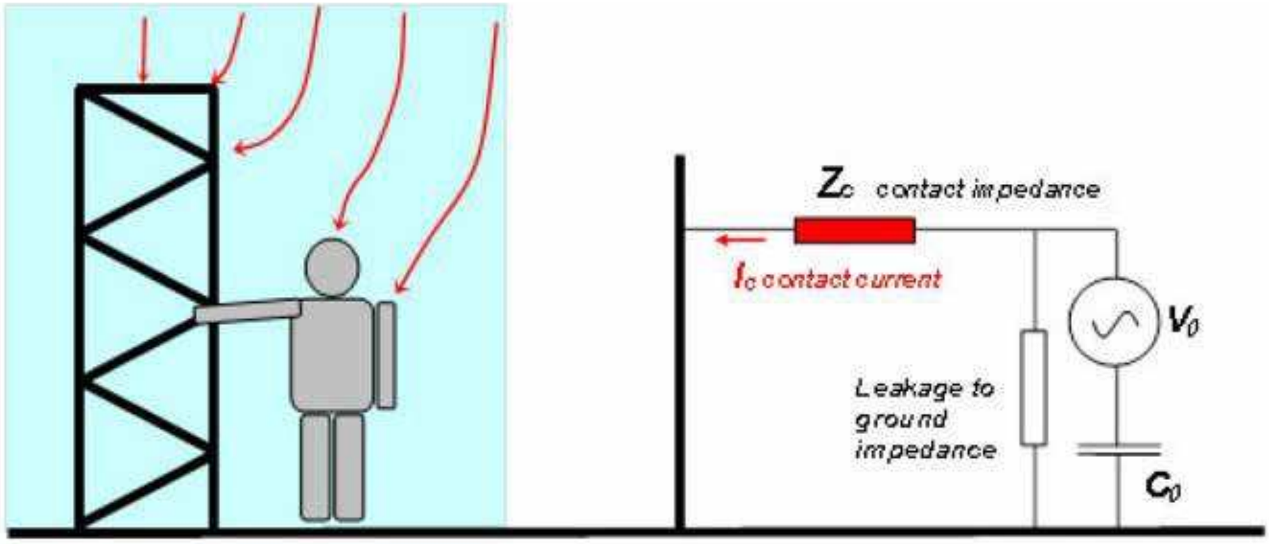


Figure F.2 — Contact with a grounded structure and equivalent electric circuit

The contact current Ic is independent from the contact impedance Z_c as long as this impedance is negligible compared to the capacitance of the body to the ground C_o, i.e. $Z_c << (2\pi.f.C_0)^{-1}$. In practice, the capacitance C_o is about (150-200) pF, and the practical condition for neglecting the contact impedance is Z_c < 10 MΩ, which will always be the case for established contacts.

Work positions above ground in substations have been investigated [4]. The contact currents (hand to grounded structure) were measured and the exposure to electric fields was assessed using different sets of measurements (legs, trunk, head, and averaged). A consistent correlation was observed with a ratio of 18 µA per kV/m of electric field averaged over the body. Under this correlation, the 1 mA limit for contact current would be reached for an averaged exposure of 55 kV/m, what never happens in practice. Hence the contact current between a person and a grounded structure will always be much lower than 1 mA.

For a worker climbing on a tower the field can become highly non uniform. Nevertheless, for most work positions the coupling between the field and body is reduced (see C.3) and for a given level of exposure to electric fields, the contact current is lower than in the reference exposure situation, i.e. a man standing at ground level exposed to a vertical electric field.

F.2.3 Person at earth potential, isolated object

According to several studies [10], [16], [1] the contact current between a grounded person and a vehicle isolated from ground ranges from 0,05 mA per kV/m (small car) up to 0,5 mA per kV/m (truck, bus…). This means a contact current up to 5 mA in a field of 10 kV/m.

NOTE The situation of a grounded worker is somewhat theoretical as security shoes are normally not conducting. The use of conducting shoes is usual for live line working and also for workers climbing towers with energized circuits.

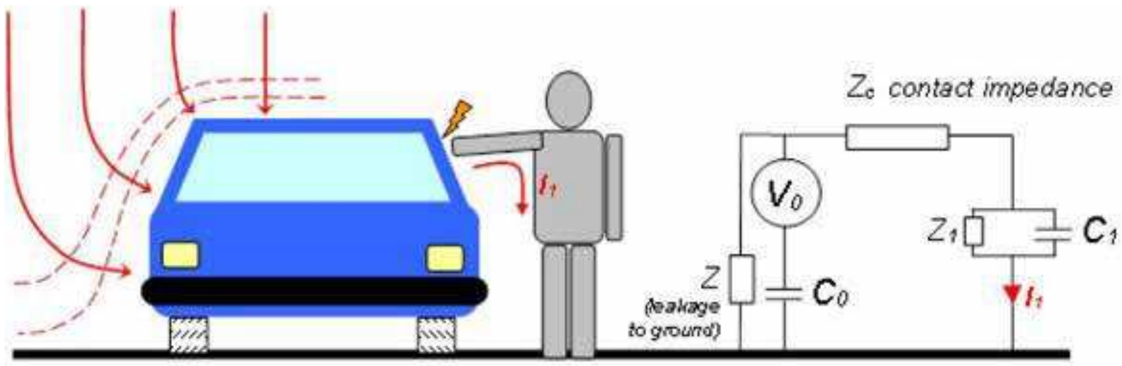


Figure F.3 — Contact current for a grounded person touching an isolated vehicle

For an isolated conductor in the vicinity of the earth (e.g. a fence), the magnitude of the contact current is worth about 0,2 to 0,3 mA per kV/m for 100 m of influence. This means about 3 mA for a 100 m long conductor parallel to a power line.

This contact current is even higher for an isolated conductor in the vicinity of the power line (e.g. a de-energised circuit in a double circuit line). Hence, the only way to ensure that the contact current remains lower than 1 mA is to earth it in order to bring it at the same potential as the person. The quality of the earthing is not critical (e.g. a single rod is sufficient). Care should also be taken in relation to the induction effect of the magnetic field, which might require additional precautions (see F.3).

If the person wears isolated gloves, the risk of contact currents is highly reduced. If the person simply wears shoes with isolated soles, a capacitive current can still flow. This current is normally smaller than 1 mA.

F.2.4 Spark discharges

Whatever insulation level of the person or object with respect to the earth, a transient discharge (capacitive spark discharge, also called “microshock”) usually occurs before the contact is established. Such a spark discharge has orders of magnitude higher peak amplitude than the steady-state current that follows but is very short in duration (from less than 1 µs to about 100 µs). Although not harmful, this kind of transient current is readily perceivable and can sometimes be experienced as unpleasant [17] [2] . It can also, to some extent, be compared to the well-known electrostatic discharge that has higher peak amplitude but shorter time duration.

The Directive does not give quantitative limits on spark discharges but recommends that excessive spark discharges are prevented. As no safety threshold is given, workers in electrical transmission companies should be taught to manage this unpleasant phenomenon: it is well known that the annoyance can be reduced if the contact is established on a large surface (e.g. the palm of the hand) rather than a small one (e.g. the top of a finger). The possible pain can also be reduced if the grasping contact is established promptly or if the first contact is made through a metallic item (for example a tool) that the worker grasps with their hand, or if it is made by contacting a less sensitive part of the body (for example, the forearm is much less sensitive than the fingers). Using an equipotential bonding is also a possible solution to avoid spark discharges.

F.3 Influence of magnetic fields

F.3.1 General

As for electric fields, magnetic fields can induce voltages in conductive objects. However, contrary to what happens with the capacitive coupling due to the electric field, the magnetic coupling occurs only when a significant parallelism exists between an object (e.g. a conductor or a pipe) and the source of magnetic field (e.g. an overhead line). Contrary also to the capacitive coupling, earthing the conductive object at a large distance from the point of contact will actually increase the amplitude of the contact current. A parallelism of about 100 m can result in contact currents exceeding 1 mA in normal operating conditions.

F.3.2 Working adjacent to live circuits

A situation where significant currents can be induced by magnetic fields is when a circuit is earthed down so that work can be done on it, and where another circuit runs parallel with the first circuit and is carrying currents. Under this situation, electrical companies apply appropriate safety procedures and rules to prevent the associated risk of electrical shock.

In any event, for safety reasons in case of an earth fault occurring on the power line, it is mandatory either to avoid the electrical contact by wearing gloves and isolated shoes or to ensure that the object is correctly earthed in the immediate vicinity of the point of contact (e.g. less than 10 m).

F.4 Summary

Whether due to an electric or a magnetic field, contact currents can always be kept under the level of 1 mA if the object with which the contact is made is earthed. For the influence of an electric field, the place and the quality of the earthing are not relevant. For the influence of a magnetic field, the earthing has to be done in the immediate vicinity (a tens of meters) of the point of contact and needs to be of good quality.

Annex G
(informative)

Exposure during transient and fault conditions

G.1 Introduction

Normal operation of transmission and distribution systems involves various ways in which voltages or currents higher than normal are produced, but lasting only very short periods, typically only a few cycles of the 50 Hz waveform. Examples are faults; switching transients; lightning strikes; and inrush currents.

This annex first gives further factual information about these events and the exposures they produce, then considers how the Directive applies to them.

G.2 Faults

G.2.1 Overview

Faults are unwanted events that occur on the electricity system from time to time. They are rare because of the many preventative measures that are taken, but they are inherent in the operation of an electricity system and cannot be avoided altogether. Faults have a variety of causes, including plant failure at power stations or on the transmission system, and weather-related events. Lightning is the most common cause.

All faults occurring on an electrical transmission system are recorded and their causes are investigated as appropriate. An order of magnitude is that there are approximately 10 faults per year for 1 000 km of transmission system.

G.2.2 Short-circuit currents during faults

The main characteristic of a fault is a short-duration increase in the current in one or more of the phases. The voltage can also be affected but to a much lesser extent. The current that flows depends on the circumstances surrounding the fault. The highest current at any given point on the system is expressed as the “fault level”, which varies throughout the system and depends on the system impedances between the location of the fault and the sources of the power. The highest fault level found on present-day transmission systems is typically around 60 kA (taking into account all the possible network system voltages), corresponding to the rating of the switchgear, which has to be able to break the highest fault current.

G.2.3 Prevention and protection against faults

Faults are undesirable from an operational point of view because they disrupt the electricity supply and can cause damage to connected equipment. Considerable efforts are devoted towards preventing faults from occurring. Maintenance and replacement strategies, and the provision of earth wires on overhead lines, are designed to prevent them occurring in the first place, and protection systems are in place throughout the network to ensure faults are detected and isolated as soon as is technologically feasible after they have occurred.

The target fault clearance time (for the main in-feeding circuit) is about 100 ms for systems at 66 kV to 400 kV, i.e. at most a few cycles of a 50 Hz wave. Slightly longer values may apply when the fault is also being fed from a remote end, but in that instance, the fault current is also lower. Once the fault has been cleared, the circuit can be switched back on, and the current, and the resulting exposures, will revert to normal levels. On the low-voltage distribution systems where fuses are used, low-level faults may be sustained for longer than a second, but the current and therefore exposures would be correspondingly lower as well.

G.2.4 Magnetic field exposures during faults

In practice, faults do not in fact normally result in exposures exceeding the ELV.

The highest fault level anywhere on a high-voltage transmission system is around 60 kA. Fault levels on lower-voltage systems tend to be lower than this. The highest magnetic-field exposure to someone standing on the ground close to an overhead line will result if a fault current flows in the bottom conductor. The lowest permissible ground clearance for 400 kV circuits varies from country to country and with other factors such as the use of the land being crossed, but is typically no less than 8 m. In practice the ground clearance is usually greater than this. At 1 m above the ground, i.e. 7 m from a minimum-height conductor carrying 60 kA, the field would be 1 700 μT, less than the High Action Level. In other words this worst-case fault situation would still be compliant with the Directive. Furthermore, normally the line will be at a greater height, the fault may not be on the bottom phase, the current may be lower than the fault level, and the probability of someone being in that location when the fault occurs (usually during a thunder storm) is minimal.

The possibility of problems would therefore arise only for situations where workers are closer to the conductor than on the ground beneath an overhead line, such as when working on transmission towers, in substations, in cable tunnels or in the vicinity of underground three-phase cables. The probability of a worker being in one of these locations at the instant of a fault is low.

In some circumstances, it is permissible to operate a circuit permanently under fault conditions, but this occurs only when the fault current is within the rating of the circuit, and therefore does not give rise to any higher exposures than normal operations.

G.3 Switching transients

When switching the voltage on to an overhead-line circuit, the complex electrical parameters of the overhead line give rise to transient voltages. For transmission circuits, these comprise a waveform at a higher frequency, typically of order 1 kHz, superimposed on the 50 Hz waveform, and lasting typically no more than one cycle of the 50 Hz, 20 ms. The initial amplitude of the higher frequency can be comparable to the amplitude of the 50 Hz, meaning that the peak voltage can be roughly doubled. If, at the instant it is re-energised, the line still has charge on it from a previous energisation, higher peak voltages, up to typically three times the steady-state peak voltage, can be produced. This transient voltage would give rise to a transient electric-field exposure to a worker located on a tower at the relevant place at the instant the voltage was applied.

G.4 Lightning strikes

As already stated, lightning strikes are one of the more common causes of faults on transmission systems, and therefore are the indirect cause of the high currents that flow during a fault. However, the lightning strike also increases the voltage of the circuit for the short duration it lasts for. The maximum voltage is determined by the insulation properties of the circuit (when the voltage produced by the lightning strike exceeds the insulation withstand voltage, the voltage flashes over, which is the cause of the fault). This limits the peak voltage to, typically, three or four times the peak voltage under steady-state conditions. The duration of this transient voltage is usually taken as less than 1 ms.

G.5 Inrush currents

Some loads that are connected to distribution systems, such as motors, produce an inrush current when first energised. This can be larger than the steady-state current by a factor up to 32 but lasts typically half a cycle, 10 ms.

G.6 Compliance of short-duration events with the Directive

In all these cases, the duration of any high exposures is strictly limited. In the case of faults, this is ensured by the protection systems that disconnect a faulted circuit. In the case of switching transients and inrush currents, it is ensured by the intrinsic characteristics of electrical circuits. This therefore fulfils one of the requirements of Article 5 (8): that immediate action should be taken to remove exposure in excess of the limits.

The probability of over-exposure actually occurring is extremely small, because it necessitates a worker to be present in a specific location (on the body of a tower with live circuits level with the conductors; close to the path of the fault current) at the instant that an already rare event (switching or fault) occurs.

If, however, this extremely low-probability exposure event does take place, the duration of the exposure is at most a few cycles of the 50 Hz waveform. Such short exposures are unlikely to have significant biological effects. In the absence of pragmatic guidance from ICNIRP, it is legitimate to draw on the corresponding IEEE C95.6 standard [14] which states that the averaging time for assessing exposures, based on time constant of nerve stimulation, should be 200 ms. The temporary exposures discussed here are of less duration that this. Faults that are of longer duration are generally of lower level, e.g. some faults on low-voltage distribution systems or, on transmission systems, faults that take longer to clear because they are remote from the protection.

Therefore, these transient exposures are extremely unlikely to constitute over-exposure, and no further action need be taken.

Where controlled fault currents are applied intentionally, for example for testing or for fault location, then planned protective measures may nonetheless need to be taken to ensure exposures remain lower than the ELVs.

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