PD CLC/TR 62271-208:2010

BSI Standards Publication

High-voltage switchgear and controlgear

Part 208: Methods to quantify the steady state, power-frequency electromagnetic fields generated by HV switchgear assemblies and HV/LV prefabricated substations

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National foreword

This Published Document is the UK implementation of CLC/TR 62271-208:2010. It is identical to IEC/TR 62271-208:2009.

The UK participation in its preparation was entrusted by Technical Committee PEL/17, Switchgear, controlgear, and HV-LV co-ordination, to Subcommittee PEL/17/1, High-voltage switchgear and controlgear.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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High-voltage switchgear and controlgear - Part 208: Methods to quantify the steady state, power-frequency electromagnetic fields generated by HV switchgear assemblies and HV/LV prefabricated substations

(IEC/TR 62271-208:2009)

Appareillage à haute tension -
Partie 208: Méthodes de quantification des champs électromagnétiques à fréquence industrielle en régime établi générés par les ensembles d'appareillages HT et les postes préfabriqués HT/BT

(CEI/TR 62271-208:2009)

Hochspannungs-Schaltgeräte und -Schaltanlagen -
Teil 208: Bestimmung der stationären, betriebsfrequenten elektromagnetischen Felder von HS-Schaltanlagen und fabrikfertigen HS-/NS-Stationen

(IEC/TR 62271-208:2009)

This Technical Report was approved by CENELEC on 2010-03-05.

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CENELEC

European Committee for Electrotechnical Standardization

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Europäisches Komitee für Elektrotechnische Normung

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Foreword

This Technical Report consists of the text of the International Technical Report IEC/TR 62271-208:2009 prepared by SC 17C, High-voltage switchgear and controlgear assemblies, of IEC TC 17, Switchgear and controlgear.

It was circulated for voting in accordance with the Internal Regulations, Part 2, Subclause 11.4.3.3 (simple majority) for acceptance as a CENELEC Technical Report.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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

NOTE Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 61000-6-2	- 1)	Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity for industrial environments	EN 61000-6-2	- 2)
IEC 61786	- 1)	Measurement of low-frequency magnetic and electric fields with regard to exposure of human beings – Special requirements for instruments and guidance for measurement	-	-
IEC 62271-200	- 1)	High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV	EN 62271-200	- 2)
IEC 62271-201	- 1)	High-voltage switchgear and controlgear – Part 201: AC insulation-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV	EN 62271-201	- 2)
IEC 62271-202	- 1)	High-voltage switchgear and controlgear – Part 202: High voltage/low voltage prefabricated substation	EN 62271-202	- 2)

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1) Undated reference.

2) Valid edition at date of issue.

CONTENTS

INTRODUCTION

Manufacturers of electricity supply equipment may be asked to provide information about the electromagnetic field characteristics to enable the user to

- assess the electromagnetic field conditions to assist with planning, installation, operating instructions and service,
- take measures to meet requirements or regulations on electromagnetic fields,
- compare different products as far as their level of electromagnetic fields is concerned.

The purpose of this technical report is to describe a methodology for the evaluation (measurement or calculation) of generated electromagnetic fields.

The electromagnetic field characteristic of the equipment comprises the values of the electric and the magnetic fields around its accessible surfaces.

The electromagnetic field characteristic defined in this technical report refers to a single product as defined in the scope. In real installations, several field sources can superimpose, so the resulting electromagnetic fields on site may differ significantly from the single product characteristics.

This technical report does not define a mandatory test for the products mentioned in the scope.

Neither the establishment of limits for the electromagnetic fields generated by equipment, nor the establishment of assessment methods for the human exposure to electromagnetic fields is within the content or intent of this technical report.

HIGH-VOLTAGE SWITCHGEAR AND CONTROLGEAR –

Part 208: Methods to quantify the steady state, power-frequency electromagnetic fields generated by HV switchgear assemblies and HV/LV prefabricated substations

1 Scope

This part of IEC 62271 gives practical guidance for the evaluation and documentation of the external electromagnetic fields which are generated by HV switchgear assemblies and HV/LV prefabricated substations. Basic requirements to measure or calculate the electric and magnetic fields are summarised for switchgear assemblies covered by IEC 62271-200 and IEC 62271-201, and for prefabricated substations covered by IEC 62271-202.

NOTE 1 The methods described in this technical report refer to three-phase equipment. However, the methodology may be used correspondingly for any single- or multi-phase equipment covered by this technical report.

This technical report applies to equipment rated for voltages up to and including 52 kV and power-frequencies from 15 Hz to 60 Hz. The electromagnetic fields which are generated by harmonics or transients are not considered in this technical report. However, the methods described are equally applicable to the harmonic fields of the power-frequency.

Detailed generic information on requirements and measurements of low-frequency electromagnetic fields is given in IEC 61786.

This technical report covers evaluation under factory or laboratory conditions before installation. The electric and the magnetic fields can be evaluated either by measurements or by calculations.

NOTE 2 Where practicable, the methods described in this technical report may also be used for installations on site.

It is not within the scope of this technical report to specify limit values of electromagnetic fields or methods for the assessment of human exposure.

2 Normative references

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

IEC 61000-6-2, *Electromagnetic compatibility (EMC) – Part 6-2: Generic standards - Immunity for industrial environments*

IEC 61786, *Measurement of low-frequency magnetic and electric fields with regard to exposure of human beings – Special requirements for instruments and guidance for measurements*

IEC 62271-200, *High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV*

IEC 62271-201, *High-voltage switchgear and controlgear – Part 201: AC insulation-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV*

IEC 62271-202, *High-voltage switchgear and controlgear – Part 202: High-voltage/low-voltage prefabricated substation*

3 Terms and definitions

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

3.1
EMF
abbreviation for the term “electromagnetic field(s)”

3.2
electric field characteristic
values (r.m.s.) and spatial distribution of the electric field strength at rated voltage and frequency around all accessible surfaces of the equipment. The electric field characteristic is the resultant of the r.m.s. values of the three orthogonal vector components

3.3
magnetic field characteristic
values (r.m.s.) and spatial distribution of the magnetic flux density at rated normal current and frequency around all accessible surfaces of the equipment. The magnetic field characteristic is the resultant of the r.m.s. values of the three orthogonal vector components

NOTE The terms “resultant electric field” and “resultant magnetic field” are defined in IEC 61786.

3.4
accessible surfaces
those parts of the walls and roof of prefabricated substations or HV switchgear assemblies that can be touched with all covers and doors in closed position in normal service conditions

3.5
reference surface
RS
virtual envelope containing the equipment for evaluation purposes

3.6
measurement surface
MS
defined outside the reference surface at 20 cm distance

NOTE This surface is used for measuring the hot spots and the variation of the EMF.

3.7
hot spot
centre of an area of a local maximum of the electric or the magnetic field

3.8
EMF characteristic
spatial distribution of the resultant (modulus) of the r.m.s. electric field strength (E) and the magnetic flux density (B). The spatial distribution is derived from a measurement or calculation grid

3.9
measurement volume
MV
virtual space in which the electromagnetic background field must not exceed an appropriate level to permit the uninfluenced measurement of the electric and magnetic fields generated by the equipment

4 Evaluation requirements

4.1 General

The EMF characteristic of HV switchgear assemblies or HV/LV prefabricated substations is the measured or calculated electric field strength and magnetic flux density around all accessible surfaces under the conditions for evaluation described below. These conditions represent the service, where the loading of the switchgear assemblies and, in a substation, of the transformer is at defined values.

As the electric and magnetic fields are dependent on the physical arrangement of incoming and outgoing cables and their loadings, these parameters have to be recorded. The presence of other field sources and shielding or other metallic structures shall be recorded.

The EMF characteristic shall be evaluated for the conditions that would result in the highest levels of electric and magnetic fields in normal, undisturbed service. These conditions include the highest currents and largest loops realistically possible through the assembly working at maximum capacity. EMF caused by switching operations, including interruption of fault currents, or other transient phenomena is deemed to be incidental and shall not be considered.

The highest current on the HV side is the rated normal current given on the nameplate of the switchgear assembly, and on the LV side the rated normal current of the transformer with the highest rating. In a calculation both currents have to be simulated. During a measurement it is preferable to have both currents present.

Electric field strength and magnetic flux density shall be recorded as the resultant of the r.m.s. values of the three orthogonal components.

The evaluation shall be carried out at the rated frequency of the equipment.

However, in the frequency range up to and including 60 Hz the actual value of frequency does not significantly affect the levels of generated E fields for any given values of voltage. Therefore evaluation at any frequency up to and including 60 Hz is considered valid.

Similarly, the difference in attenuation of B fields by metallic enclosures at 50 Hz and 60 Hz can be ignored for the purpose of this technical report. Therefore evaluation at 50 Hz is considered applicable also for 60 Hz and vice versa.

In the power-frequency range covered by this technical report the electric and magnetic fields may be treated separately. When selecting the conditions to obtain the highest level of electric and magnetic fields as realistically as possible in undisturbed service, the following subclauses shall be considered.

4.2 Methods of evaluation

The manufacturer may evaluate the EMF characteristic by measurement or by calculation.

4.3 Evaluation of electric fields

4.3.1 HV switchgear assemblies

The equipment shall be evaluated at the rated voltage of the HV switchgear assembly.

Only if the evaluation cannot be carried out at rated voltage, the results shall be extrapolated to the rated value. Since the electric field strength is a linear function of the voltage, the field strengths for different high voltages may be extrapolated linearly.

4.3.2 HV/LV prefabricated substations

The equipment shall be evaluated at the rated high voltage of the HV/LV transformer(s).

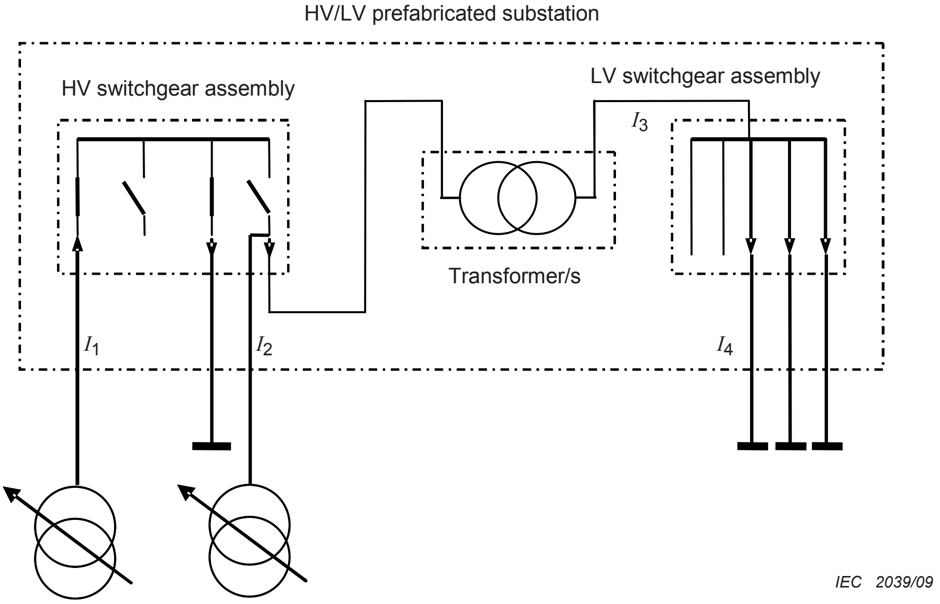
Only if the evaluation cannot be carried out at rated voltage, the results shall be extrapolated to the rated value. Since the electric field strength is a linear function of the voltage, the field strengths for different high voltages may be extrapolated linearly.

4.4 Evaluation of magnetic fields

4.4.1 HV switchgear assemblies

The HV switchgear assembly is loaded with its highest permissible current determined by the rated normal current given on the nameplate. The HV circuit must be selected to form the widest possible current loop between the incoming and outgoing functional units (panels) of the switchgear assembly to obtain the maximum magnetic field by using the smallest number of circuits, taking into account their rated normal current. An example is shown in Figure 1.

If the evaluation cannot be carried out at the rated normal current the results shall be extrapolated to the rated value. Any saturation effect will be less pronounced at lower currents, therefore extrapolation from lower to higher values of current is allowed since it can only result in an overestimate of the B field.



Key

I_1 = HV switchgear highest loop current
I_2 = HV/LV loop (HV side) current
I_3 = HV/LV loop (LV side) highest current
I_4 = HV/LV (LV outgoing) highest current

Figure 1 – Example of test circuits configuration to obtain the maximum external magnetic field of a switchgear assembly and/or a prefabricated substation

4.4.2 HV/LV prefabricated substations

For the HV switchgear assembly, 4.4.1 applies.

The LV switchgear assembly and the transformer shall be loaded with the highest normal current derived from the maximum rated power of the prefabricated substation for a given LV level. The circuit shall be configured to form the highest concentration of currents to obtain the maximum magnetic field. This can be achieved by using the smallest number of circuits, choosing those located closest to the enclosure of the prefabricated substation and taking into account their rated normal current. An example is shown in Figure 1.

If the design of the HV/LV prefabricated substation admits transformers of different rated power, the manufacturer shall at least provide an evaluation for the transformer with the highest rated power for a given LV level.

NOTE The rated power of the transformer should correspond to the cooling by natural ventilation. EMF evaluation with other means of cooling (for example forced cooling) should be subject to agreement between manufacturer and user.

If the evaluation cannot be carried out at the rated power for a given LV level, the results shall be extrapolated to the rated value. Any saturation effect will be less pronounced at lower currents, therefore extrapolation from lower to higher values of current is allowed since it can only result in an overestimate of the B field.

The extrapolation of magnetic field values is not permitted if the currents on the HV and LV sides of the prefabricated substation vary independently.

5 Measurements

5.1 General

At power-frequency the electric and magnetic field are independent from each other. Hence, magnetic flux density and electric field strength characteristic need not be recorded simultaneously.

The electric field characteristic of the equipment is independent of the load current.

The magnetic field characteristic of the equipment is independent of the voltage.

NOTE General guidance on measurement procedures for electric and magnetic fields can also be found in IEC 62110 and IEC 61786.

5.2 Measuring instruments

Instruments for measuring electric and magnetic fields shall meet the requirements of specification and calibration given by IEC 61786. The calibration report shall be traceable to national or International Standards. These instruments should be used in appropriate conditions, in particular with regard to

- electromagnetic immunity according to IEC 61000-6-2,
- immunity of power-frequency electric field on magnetic field measurement,
- temperature and humidity ranges as recommended by the instrument manufacturer.

A three-axis instrument measures r.m.s. values of resultant field F_r. A single-axis instrument may be used to obtain F_r by measuring F_x, F_y, and F_z, using Equation (1), where F_x, F_y and F_z are r.m.s. values of the orthogonal three-axis components of electric or magnetic field.

$$F_r = \sqrt{F_x{}^2 + F_y{}^2 + F_z{}^2} \quad (1)$$

The use of a three-axis instrument with three concentric sensors is preferred. However, if a single-axis instrument is used, special attention should be paid to the orientation of the sensor along three orthogonal directions. The orientation of the sensor shall be changed without moving the position of its centre.

In the case of non-concentric sensors, the locations and orientations of the sensors that are contained within the housings of field meters shall be clearly indicated on the instrument or in the instruction manual.

During the evaluation of the magnetic field generated by HV switchgear assemblies and HV/LV prefabricated substations, the distance between the field source and the measuring instrument is relatively short (in comparison to other AC power equipment like overhead lines). In general, the measurements will be carried out in non-uniform fields. In case of the magnetic field measurement, it is necessary to consider the ratio of distance (d_{sc}) from the field source and sensor radius (a). For measurements with a three-axis instrument, a minimum ratio of 4 is considered suitable.

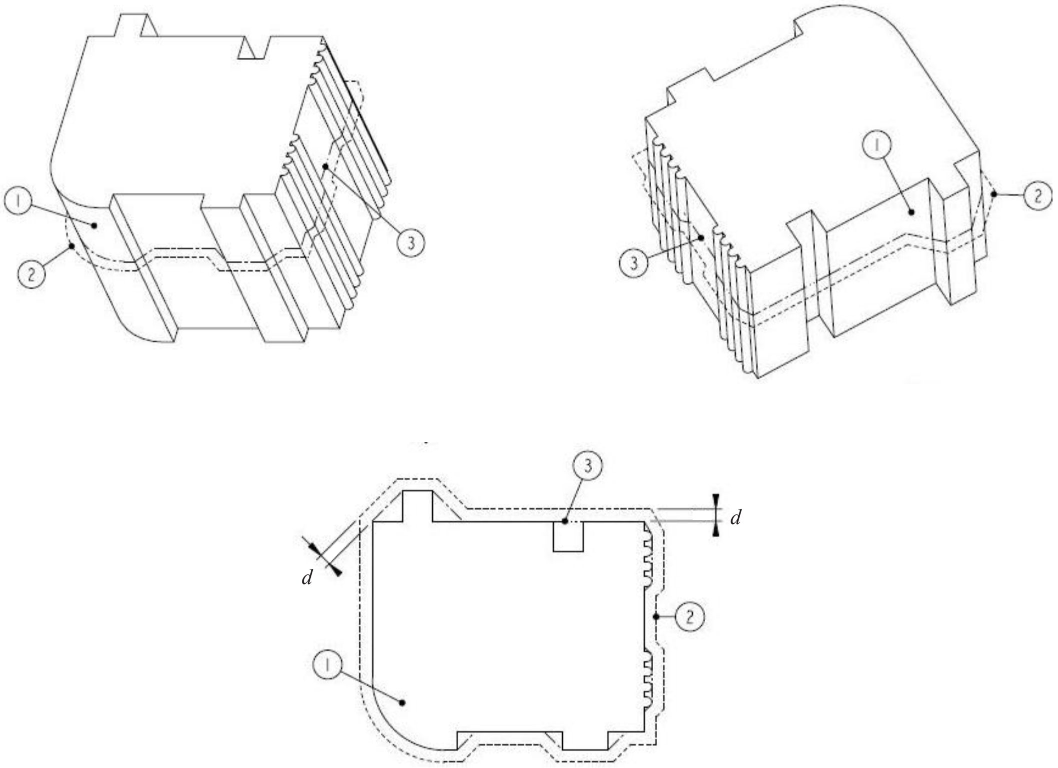
NOTE When using a probe with radius 5 cm the minimum distance to the field source should be at least 20 cm considering a ratio of 4. More information about this topic can be found in IEC 61786.

5.3 Measurement procedures

5.3.1 General

To consider equipment of all kinds of shape, a virtual envelope containing the equipment is defined as the reference surface (RS); see Figure 2. The purpose of the RS is to integrate irregularities and to eliminate abrupt changes in the measurement surface (MS). The MS is defined outside the RS at 20 cm distance.

Protruding elements (for example handles) shall be disregarded.



IEC 2040/09

Key

1 Equipment surface

2 Measurement surface

3 Reference surface

d Distance between equipment and measurement surface (20 cm)

Figure 2 – Reference surface (RS) for equipment of irregular shape

5.3.2 Electric field

The maximum value(s) of the electric field over the accessible measurement surface shall be found by first scanning on a coarse grid to find the regions of maximum field and then refining the grid for the hot spot locations. See also Figure 3.

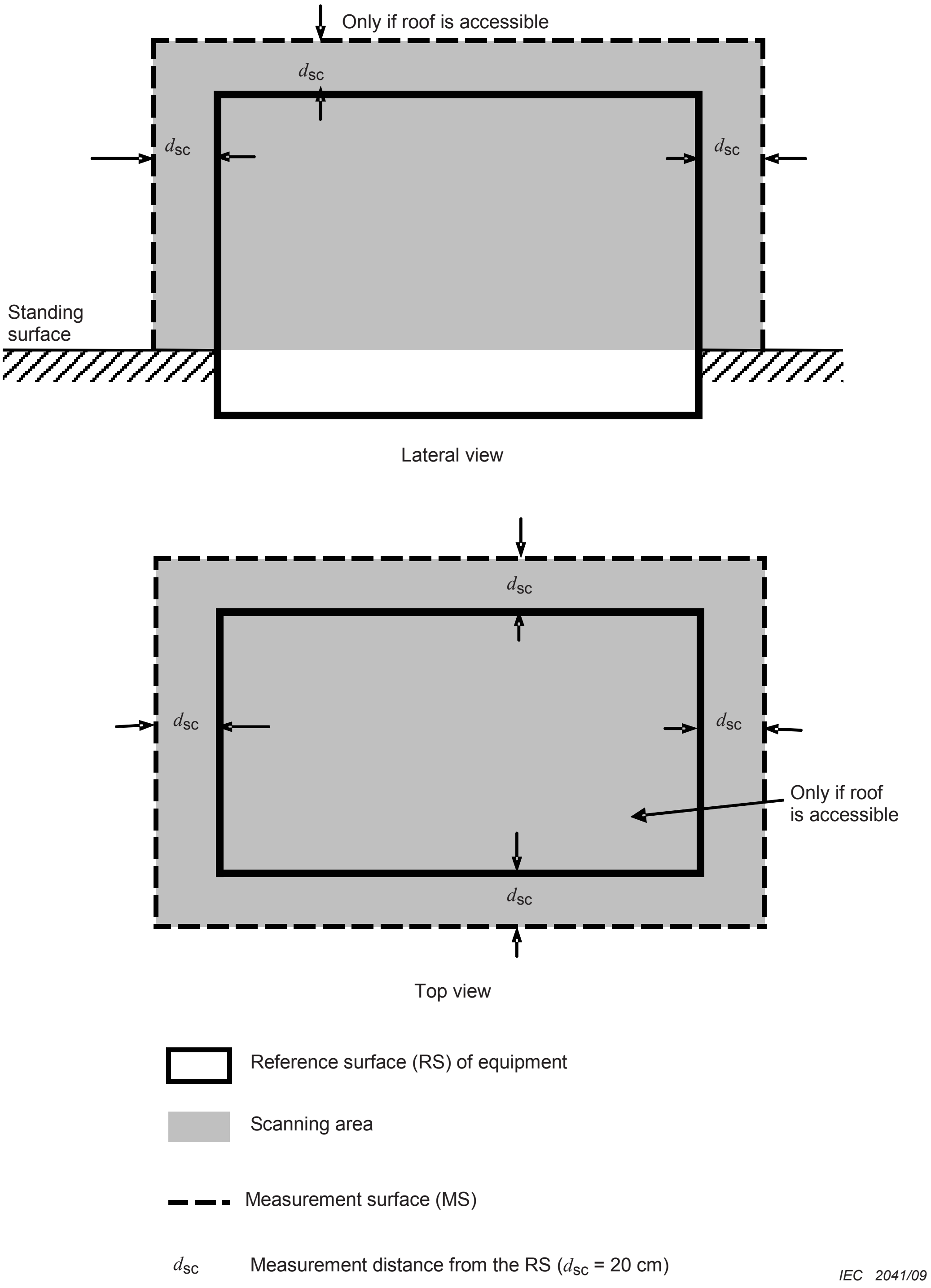
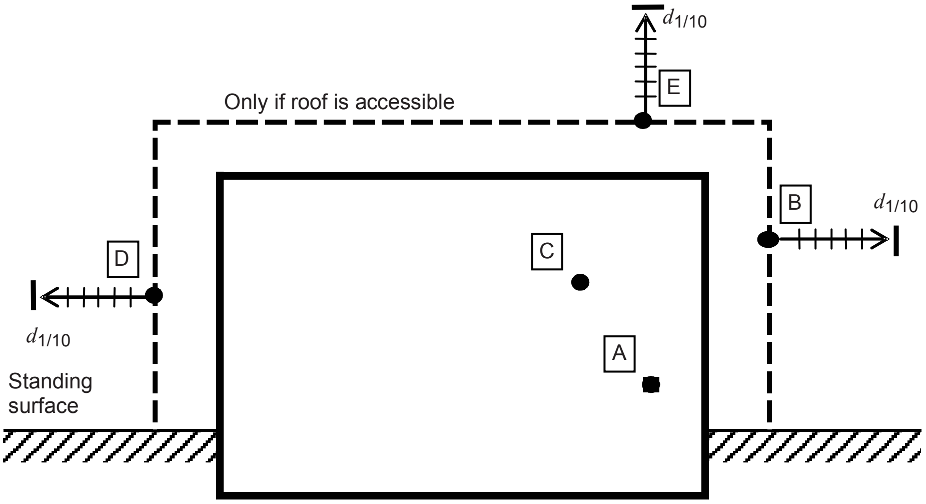


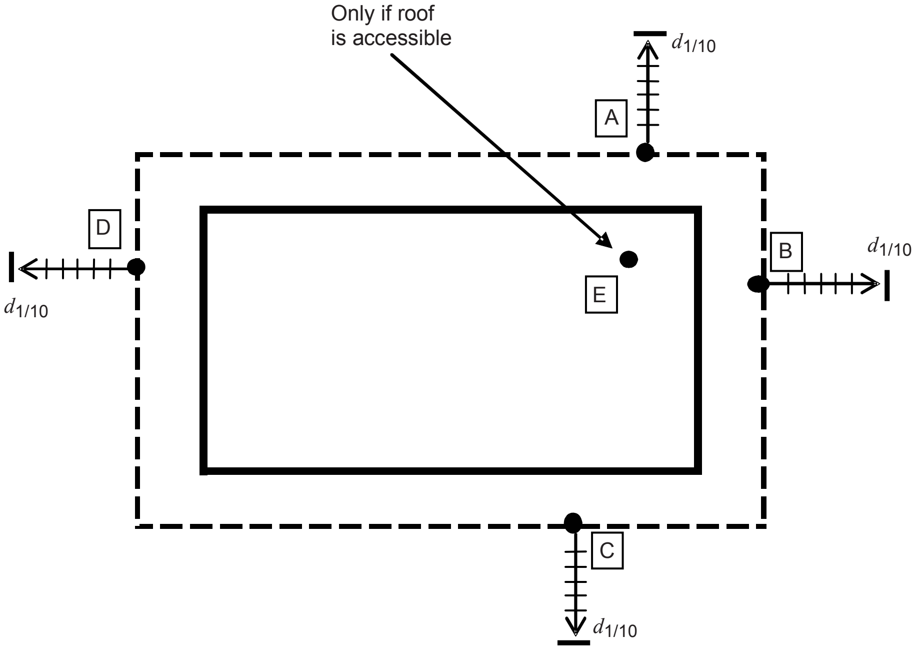
Figure 3 – Scanning areas to find the hot spots

The variation of the electric field shall be determined as a function of the distance from the MS. Starting at each hot spot, the field values shall be measured along a line perpendicular to the MS until the measured value is lower than 1/10 (–20 dB) of the hot spot value; see Figure 4. Additional measurements may be carried out to fulfil specific requirements (e.g. for a client or country).

NOTE Significant electric fields are not expected for the equipment in the scope of this technical report. However, it is the intention of this technical report to give guidance for the measurement of these fields where manufacturers and users require them.



Lateral view



Top view

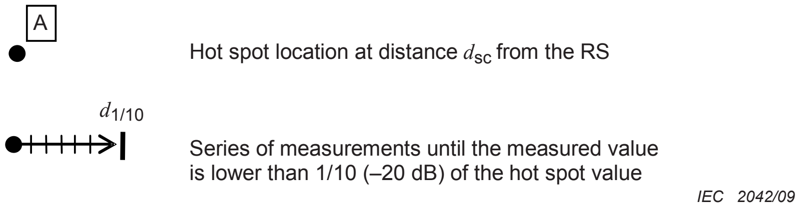


Figure 4 – Determination of the field variation as a function of the distance from the hot spot locations (perpendicular to the reference surface)

5.3.3 Magnetic field

The maximum value(s) of the magnetic field over the MS shall be found by first scanning on a coarse grid to find the regions of maximum field and then refining the grid for the hot spot locations. See also Figure 3.

The variation of the magnetic field shall be determined as a function of the distance from the MS. Starting at each hot spot, the field values shall be measured along a line perpendicular to the MS until the measured value is lower than 1/10 (–20 dB) of the hot spot value; see Figure 4. Additional measurements may be carried out to fulfil specific requirements (e.g. for a client or country).

5.3.4 Background fields

Immediately after the measurements, the equipment shall be switched off and the background field level shall be measured and recorded.

By coarsely scanning the electric or magnetic field within the MV when voltage or current is switched off, it shall be verified that the background field level is below 1/10 (–20 dB) of the lowest value measured at any of the hot spots found during the live measurement.

Guidance on reducing the interfering background fields, caused by the external cables connected to the test specimen, to a minimum, is given in 5.4.1.

5.3.5 Environmental factors

5.3.5.1 Electric field measurement

Environmental factors (e.g. humidity, temperature etc.) have no significant influence on the electric field. However, the electric field measuring instrument can be influenced significantly when the humidity is sufficient to cause condensation on the sensor and the supporting structure. Thus the environmental factors shall be measured to ensure that the measuring instruments are used within their specified environmental limits. Special attention should be paid to humidity.

Acceptable humidity limits for proper measurements are deemed to be

- 60 % relative humidity when using a normal tripod,
- 70 % relative humidity when using an offset tripod
  (measuring instrument shifted by 0,50 m form the vertical axis of the tripod).

If those limits are exceeded, the measurements shall be considered as conservative, due to the fact that the values measured in high humidity are higher than those in lower humidity for the same equipment excited with the same voltages.

Likewise, electric field measurements in rain conditions are inappropriate.

5.3.5.2 Magnetic field measurement

Environmental factors (e.g. humidity, temperature etc.) have no significant influence on the magnetic field. However, the environmental factors shall be measured to ensure that the measuring instruments are being used within their specified environmental limits.

5.3.5.3 Other conditions

During electric field measurements, objects or persons shall be kept outside the influence zone of the measuring device.

Only objects containing or consisting of high permeability materials can cause significant distortions of the magnetic field. Persons do not influence the magnetic field, thus measuring instruments may be directly held by persons when making measurements.

The presence of high permeability materials, which are not part of the equipment, in the vicinity of the field source and/or the measuring instruments, shall be stated in the measurement report.

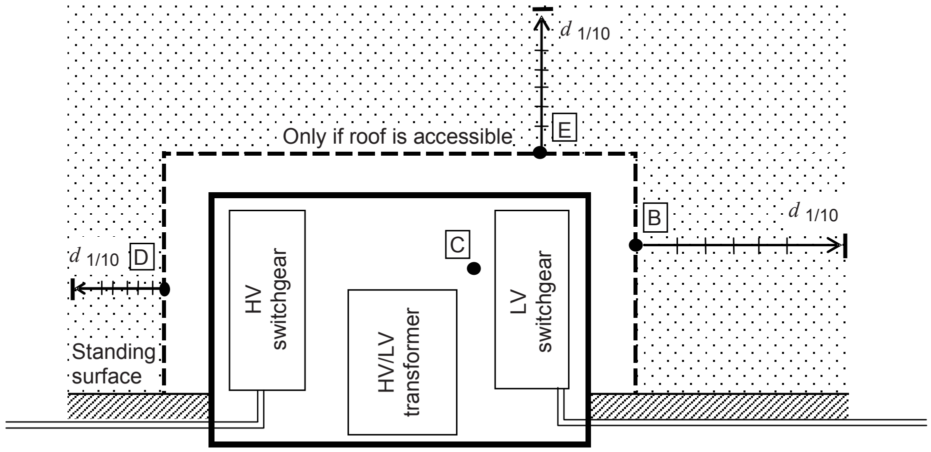
All parts of the equipment intended to be earthed shall be earthed according to the manufacturer's instructions.

5.4 Measurement set-up

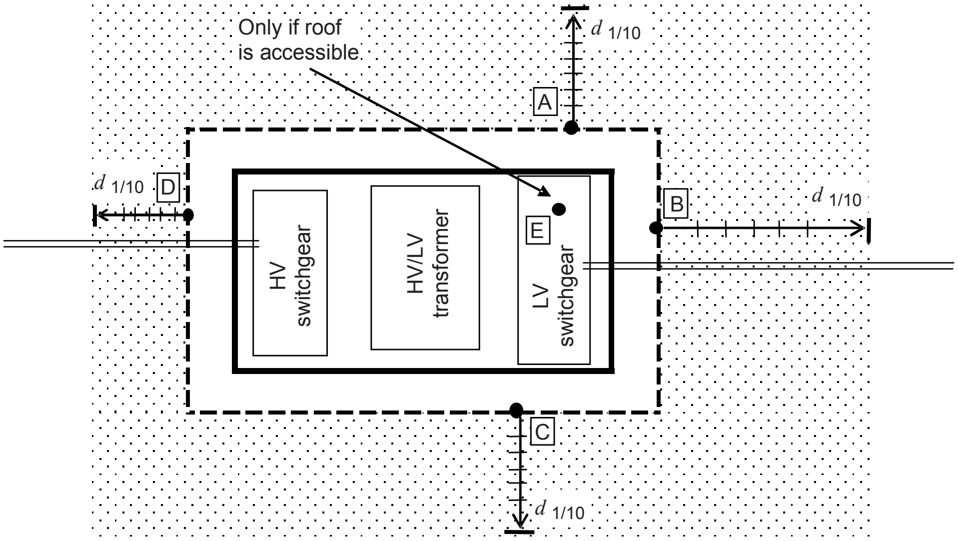
5.4.1 General

All measurements shall be carried out with a three-phase voltage or current supply. The test set-up shall meet the following requirements; see also Figure 6.

The equipment under test shall be surrounded by a virtual measurement volume (MV) large enough to allow the decay of the field perpendicular to the reference surface at each hot spot to 1/10 (–20 dB) of its value; see Figure 5.



Lateral view



Top view

● A Hot spot location at distance d_{sc} from the RS

═ HV and LV cables (external connections)

⁚ MV: background field level is below 1/10 (–20 dB) the lowest value measured at any of the hot spots

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Figure 5 – Test set-up of main components, external cables, hot spot locations and measurement volume

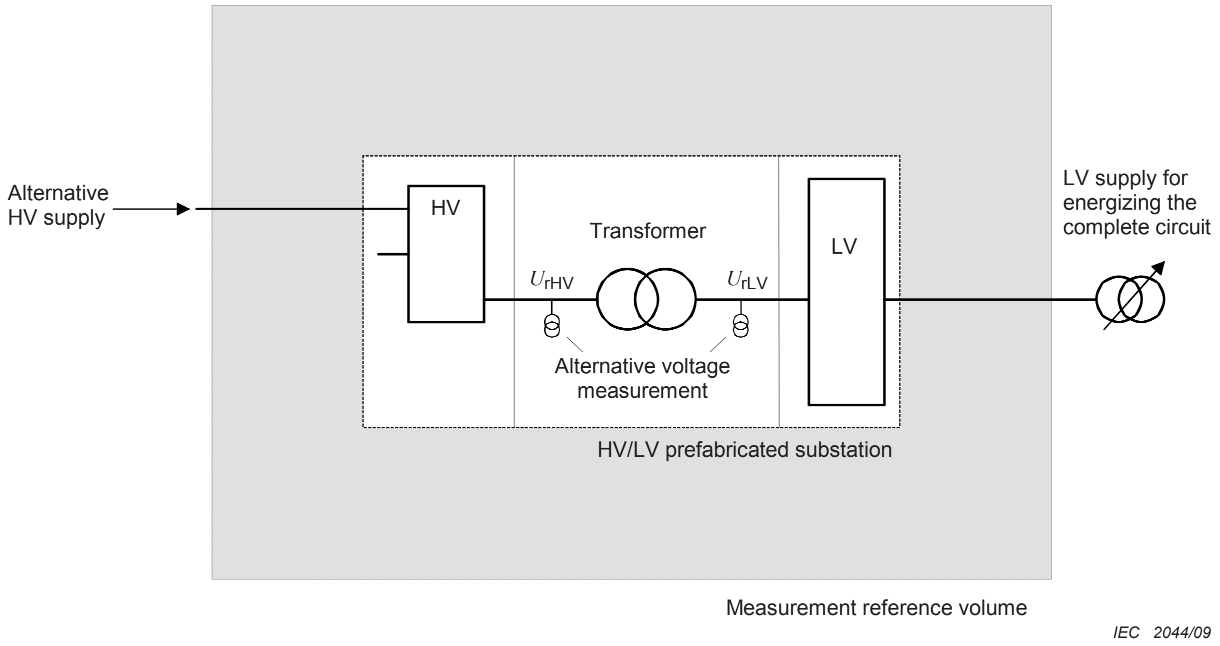
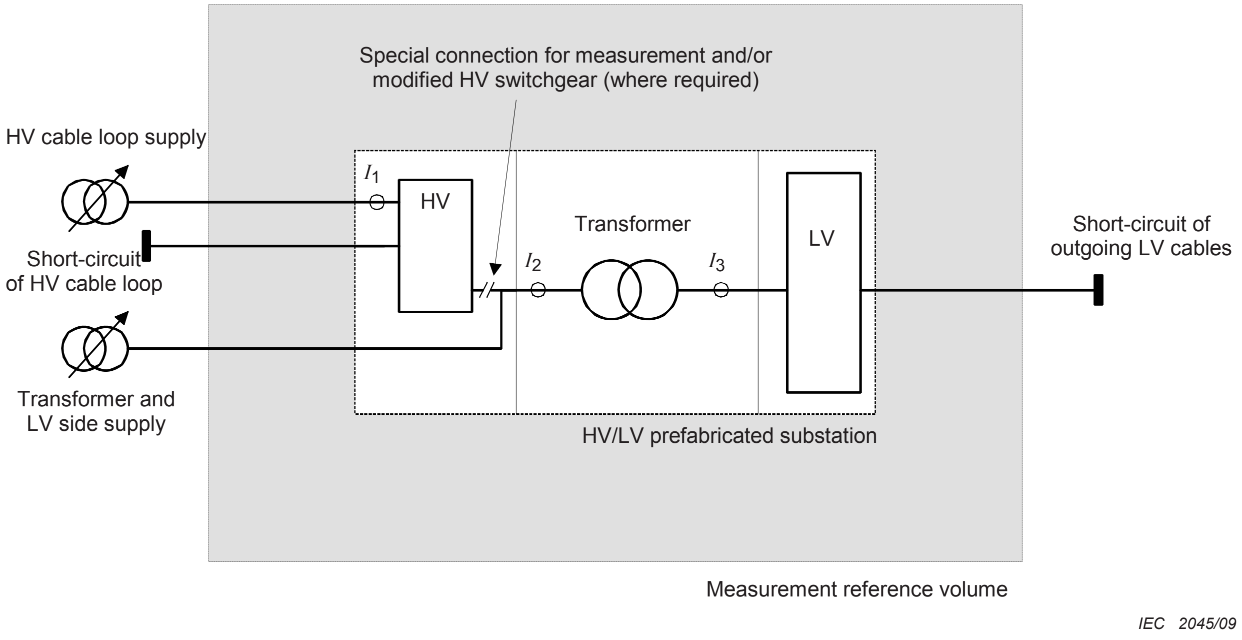


Figure 6a – Test circuit for electric field measurement



Key

I_1 Rated normal current of HV cable loop
I_2 Rated HV normal current of transformer
I_3 Rated LV normal current of transformer

Figure 6b – Test circuit for magnetic field measurement

Figure 6 – Test circuit for electric and magnetic field measurement

The objective during the test is to reduce external influence, in order to characterize the equipment rather than the test circuit. To minimize the interfering background fields inside the MV, some provisions are made for the external connections to the test specimen. Preferably three-phase shielded cables on the HV side and 4-core cables on the LV side shall be used. If other cables are used they shall be arranged so that their near field is minimized. This cable arrangement shall be maintained to a sufficient distance outside the MV boundaries so that the background field level inside the MV is not affected.

Where the contribution of the field generated by the external connections is deemed to have significant influence on the measurement results (for example in a single phase system), it is allowed to subtract the field values due to the external connections from the actual measurement results. The method used shall be stated in the test report.

NOTE When no correction is made for the field generated by the external connections, the measured results will be an overestimate.

The type of cables and connections should represent those used in normal service conditions.

The HV cables shall leave the equipment perpendicular to the sides until they reach the boundary of the measurement reference volume.

The field generated by the short-circuit connection of the HV cable loop and the LV (outgoing) cable circuits shall not alter the field level at the boundary of the measurement reference volume. Therefore an appropriate distance shall be kept from the point of short-circuit to the MV boundary.

In the case of HV/LV prefabricated substations, the LV cables shall leave the equipment perpendicular to the sides until they reach the boundary of the measurement reference volume. The field generated by the short-circuit connection of the LV cables shall not alter the field level at the boundary of the measurement reference volume (MRV). Therefore an appropriate distance shall be kept from the point of short-circuit to the MRV boundary.

5.4.2 Additional provisions for HV/LV prefabricated substations

5.4.2.1 Electric field

The test voltage may be supplied from the LV side, as shown in Figure 6a, or alternatively, from the HV side.

5.4.2.2 Magnetic field

The current in the HV cable loop I_1 and the current in the transformer(s) circuit I_2 shall be synchronized; see Figure 6b.

A special arrangement or modified HV switchgear assembly may be required for the connections to perform the test.

6 Calculations

6.1 General

At power frequencies, the electric and magnetic fields are independent of each other. The magnetic flux density and electric field strength characteristics may therefore be calculated in separate studies.

This technical report is intended to give general guidance on the modelling of this equipment for the purpose of comparing one equipment with another. Detailed recommendations on how to execute the calculations are, however, beyond its scope, given the wide variety of equipment and layouts, solution methods, software, practitioners and computing resources available.

Guidance on these matters is available from software manufacturers, in text books, papers and on-line, although detailed advice on how to model the specific equipment in the scope of this technical report is mainly limited to suppliers of specialist software.

For the purposes of this technical report, calculation is acceptable as an alternative to measurement – it is the responsibility of the customers to satisfy themselves that the calculations have been carried out to an acceptable accuracy (see 6.5).

Validation of calculations against the measurements described in Clause 5 is particularly recommended. Once a calculation has been validated against one equipment, it is generally acceptable to characterize similar equipment by calculation, without the need for measurements.

6.2 Software

Any software that solves the Biot-Savart relationship or Maxwell’s equations is potentially suitable for the calculations of the electromagnetic fields for the equipment in the scope of this technical report.

Some software is specialized for this type of equipment, while some is general software for electromagnetic field calculation. It is not the purpose of this technical report to judge whether one software is better (in any sense – accuracy, ease of use, computational economy etc.) than another.

6.3 Calculation procedures

Calculations should be carried out for the evaluation requirements set out in Clause 4. If it is intended to perform measurements as well as calculations, the calculations should include significant components of the test set-up such as supply cables, to allow accurate comparisons.

The equipment in this scope is necessarily three-dimensional and it is recommended that only 3-dimensional models are used for the calculations. The equipment is also complex in layout and it is anticipated that accurate models will require considerable computing resources (memory and speed).

The equipment should be modelled as explicitly and comprehensively as possible, within the constraints of the solution method. In particular all field sources and large components should be included, and more detail will generally (although not always) lead to more accurate models.

In electric field calculations, metallic structures may be modelled as surfaces at a single voltage (zero if earthed), rather than having explicit material properties ascribed to them. By this token, a model of an equipment completely surrounded by a metallic enclosure will necessarily yield a zero external electric field. The cables leading to the equipment will be a source of electric field only if they are not screened and earthed.

6.4 Results

As a minimum, the documented results of the calculations should be those specified for the measurements in 5.3.2 and 5.3.3. Numerical calculations usually yield the field values everywhere in the model, so the calculation provider may agree with the customer to supply additional information such as field contour maps around the equipment.

Since the results described in Clause 5 include the locations of field maxima (hot spots) as well as magnitudes of the fields, the accuracy of the calculation results (see 6.5) should be judged on both these criteria.

In comparison with measurements, the calculated field values should agree to within ±10 %. Each calculated hot spot should be specified for an area of dimensions 10 % height x 10 % length of the measurement surface on which a measured hot spot is located (see Figure 3, Figure 4 and Figure A.1).

6.5 Validation

There is no accepted method of quantifying calculation error or uncertainty, since it has many components including inherent inaccuracy in the method, approximations in material and structural representations, meshing density and boundary conditions.

It is recommended that providers of calculations be required by the customer to demonstrate their capabilities in the applications covered by this technical report by reproducing benchmark calculations or test measurements.

Benchmark calculations with analytical solutions are particularly useful, because they have no numerical or other approximations, even though they are necessarily simpler than many practical problems. Examples of suitable problems with analytical solutions are given in Annex B.

As stated in 6.4, 90 % accuracy is acceptable. It should be borne in mind that comparisons of calculations with measurements necessarily incorporate the measurement uncertainty.

7 Documentation

The following information shall be given in the EMF evaluation.

7.1 Characteristics of the HV switchgear assembly or prefabricated substation

Type designation and ratings of the main components of prefabricated equipment, i.e.

- transformer/s,
- HV switchgear,
- LV switchgear,
- HV and LV interconnections.

7.2 Evaluation method

The chosen evaluation method shall be stated.

7.3 Presentation of the measurement results

The following information should be provided when measurement results are presented:

- identification of evaluation report;
- date and time of measurements;
- organization and persons who performed the measurement(s) ;
- identification of each measuring instrument: brand name, model (and serial number), calibration date, due date and certificate reference;
- product identification and rated values, including rated power of the substation and transformer connection symbol (vector group) ;

- operating conditions, including configuration of various switching devices and other equipment that may have different settings, earthing of the equipment;
- settings of the measurement equipment (e.g. measurement range, pass band, sampling frequency) ;
- environmental conditions (e.g. temperature or humidity);
- positions and currents of incoming and outgoing HV and LV cables;
- currents, voltages and frequency at each circuit on the product, and spatial disposition,
- background fields;
- location of hot spots, e.g. as shown in Annex A;
- the electric and magnetic field measurements shall be presented separately in the form of tables and graphs of field variation perpendicular to the hot spots;
- drawings or photographs which describe the area and locations where measurements are performed.

7.4 Presentation of the calculation results

The following information should be provided when calculation results are presented:

- identification of evaluation report;
- name, version and manufacturer of calculation software used;
- product identification and rated values, including rated power of the substation and transformer connection symbol (vector group) ;
- operating conditions including configuration of various switching devices and other equipment that may have different settings;
- description of assumptions and boundary conditions including earthing of the equipment;
- sufficient details to enable reproducibility of the calculation results;
- positions and currents of incoming and outgoing HV and LV cables if included in the study;
- description of magnitude, phase and location of all excitation voltages and currents; directions should be included for currents;
- location of hot spots, e.g. as shown in Annex A;
- the electric and magnetic field values shall be presented separately in the form of tables and graphs based on the field variation perpendicular to the hot spots.

Annex A
(informative)

Presentation of E or B field measurement data – Example for a typical HV/LV pre-fabricated substation

A.1 General

The presentation method described in this annex may be used likewise for HV switchgear assemblies and HV/LV prefabricated substations.

A.2 Hot spot locations (see Figure A.1)

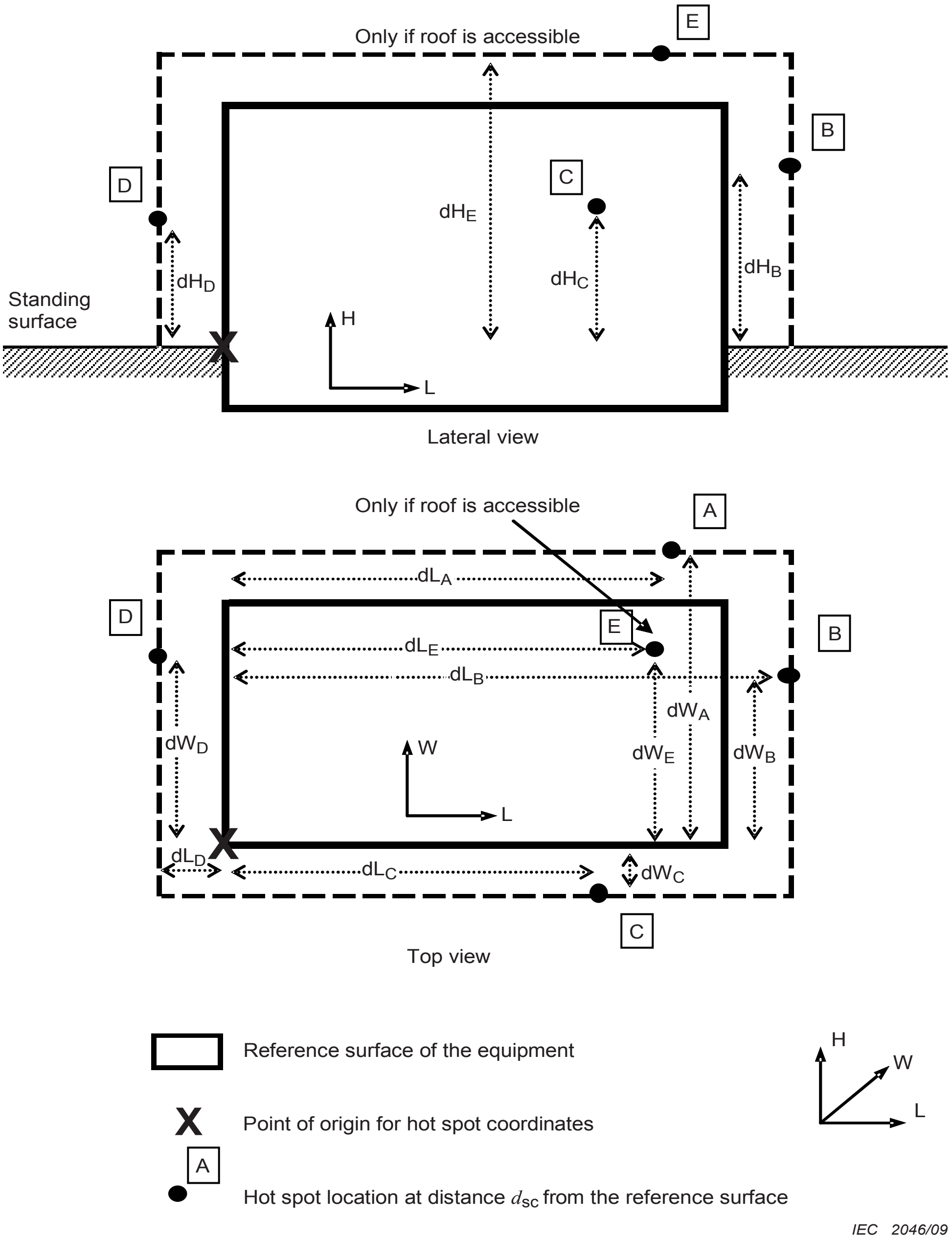


Figure A.1 – Hot spot locations representing the field maxima

A.3 Hot spot locations with its E or B field values

Distance to surface d_{sc} = 0,2 m

Table A.1 – Listing of the hot spot coordinates

Hot spot location	**Distance to reference point**			**Field value** V/m or µT
	Direction L m	**Direction W** m	**Direction H** m	
A	dL_A	dW_A	dH_A	A_{max}
B	dL_B	dW_B	dH_B	B_{max}
C	dL_C	dW_C	dH_C	C_{max}
D	dL_D	dW_D	dH_D	D_{max}
E	dL_E	dW_E	dH_E	E_{max}

A.4 Variation of the E or B field as a function of the distance

Table A.2 lists the field variation perpendicular to the accessible reference surface. The procedure for the other hot spot locations is identical. For graphical presentation, see Figure A.2.

Table A.2 – Variation of field values for one hot spot

Hot spot location	**A**
Distance to surface m	**Field value** V/m or µT
d_{sc}	A_{max}
dA2	A2
dA3	A3
dA4	A4
dA5	A5
dA6	A6
$dA_{1/10}$	$A_{max/10}$

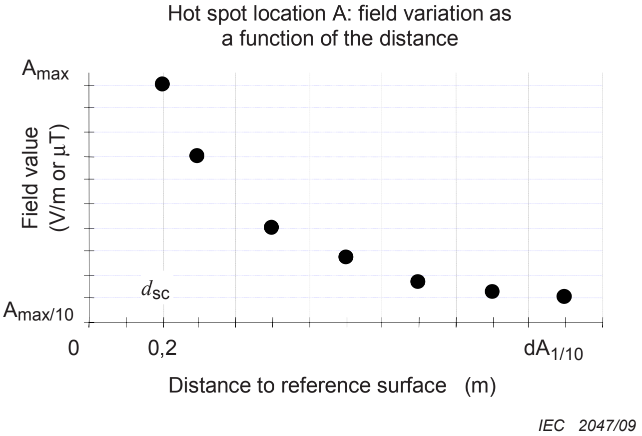


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Figure A.2 – Graphical presentation of the field variation

A.5 Field variation around substation at hot spot locations (see Figure A.3)

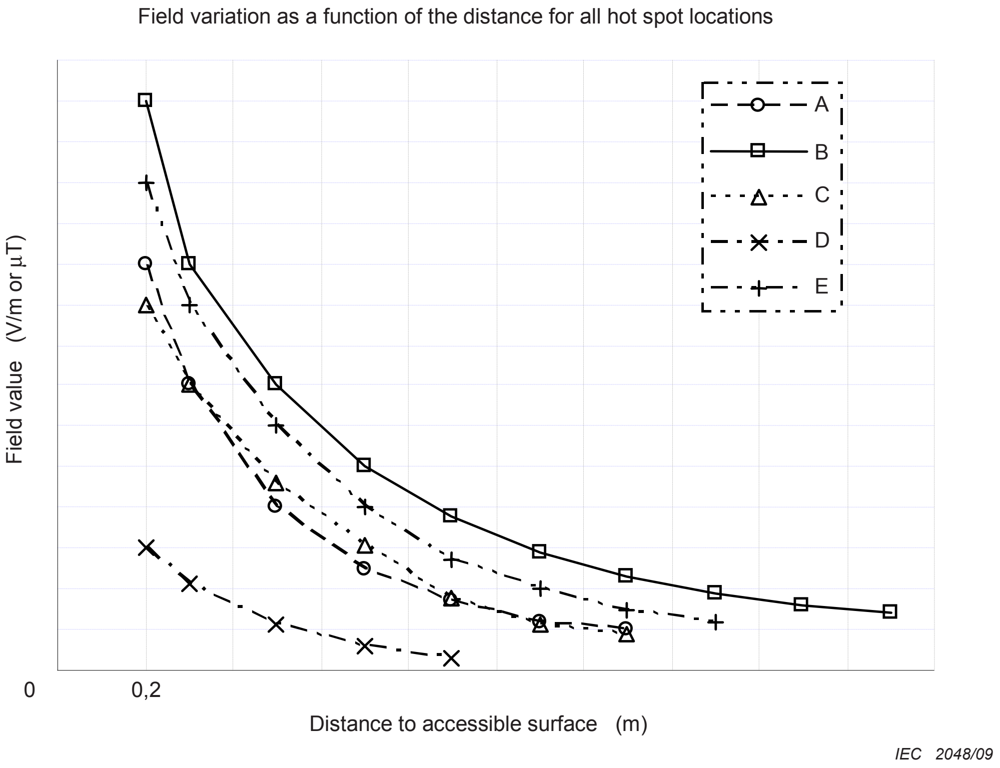


Figure A.3 – Example diagram for the field variation at hot spots

A.6 Background fields

The equipment is completely switched off.

Table A.3 – Background fields

	Field value V/m or µT	**Remark**
Allowable background field level	–	The maximum allowable background field level = 1/10 the lowest field value measured at the hot spot locations (see Figure A.1)
Measured background field level	–	

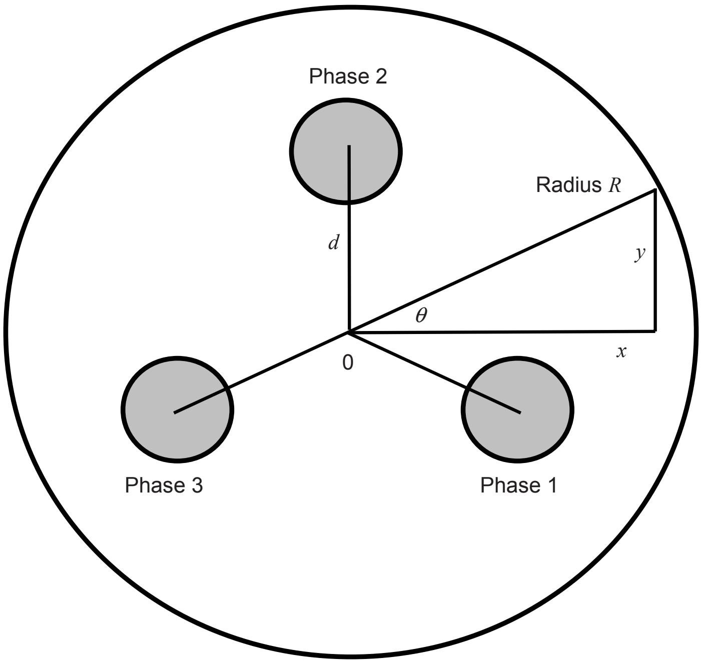
Annex B
(informative)

Examples of analytical solutions to benchmark EMF calculations

B.1 Magnetic field

This annex presents the analytical solution of the magnetic field of a set of 3-phase currents in infinitely long lines. This solution is presented as an example of a calculation amenable to both analytical and numerical solution. It can therefore be used to benchmark software used for the calculations described in Clause 6.

The lines carrying the 3-phase currents are arranged symmetrically at a distance d from an origin at (0,0) in the x-y plane as shown in Figure B.1. The currents are flowing in the z-direction (perpendicularly to the plane of the diagram).



IEC 2049/09

Figure B.1 – Schematic for 3-phase magnetic field calculation

The centres of the 3 lines are therefore at $\left(\frac{d\sqrt{3}}{2}, \frac{-d}{2}\right)$, (0,d) and $\left(\frac{-d\sqrt{3}}{2}, \frac{-d}{2}\right)$.

The magnetic field resulting from the 3 currents is calculated outside the cable, that is, at distances greater than (d + line radius) from the origin. In this simple analysis, the lines are considered to be of insignificant radius compared to the distance between them and the distance from the calculation point. In other words, the currents are considered to be flowing at a point at the centre of each line.

Ampère's law gives the magnetic field H at a distance R from a line carrying current I as

$$H = \frac{I}{2\pi R} \tag{B.1}$$

Therefore a line at the origin (0,0) carrying a current $I_{\mathrm{pk}}\cos(\omega t)$ would produce a magnetic field $H = \underline{i}H_{\mathrm{x}} + \underline{j}H_{\mathrm{y}}$ such that

$$H_x = \frac{-yI_{\mathrm{pk}}\cos(\omega t)}{2\pi\left(x^2 + y^2\right)} \tag{B.2a}$$

$$H_y = \frac{xI_{\mathrm{pk}}\cos(\omega t)}{2\pi\left(x^2 + y^2\right)} \tag{B.2b}$$

for $R = \sqrt{\left(x^2 + y^2\right)} > 0$ and $x = R\cos\theta$ and $y = R\sin\theta$.

The lines shown in Figure B.1 are all displaced by a radius d from the origin, so the following derivations are for $R > d$.

The field components for a line I displaced from the origin to coordinates (x_{dis}, y_{dis}) and carrying a current I_{phase} are derived from Equations (B.2a) and (B.2b) as

$$H_{x\mathrm{i}} = \frac{-y_{\mathrm{local}}\ I_{\mathrm{phase}}}{2\pi\left(\left(x_{\mathrm{local}}\right)^2 + \left(y_{\mathrm{local}}\right)^2\right)} \tag{B.3a}$$

$$H_{y1} = \frac{x_{\mathrm{local}}\ I_{\mathrm{phase}}}{2\pi\left(\left(x_{\mathrm{local}}\right)^2 + \left(y_{\mathrm{local}}\right)^2\right)} \tag{B.3b}$$

where $x_{\mathrm{local}} = x - x_{\mathrm{dis}}$ and $y_{\mathrm{local}} = y - y_{\mathrm{dis}}$.

In this example, phase 1 is at $\left(\frac{d\sqrt{3}}{2}, \frac{-d}{2}\right)$ carrying a current $I_{\mathrm{pk}}\cos(\omega t)$. Substituting these coordinates into Equations (B.3a) and (B.3b) gives

$$H_{x1} = \frac{-\left(y + \frac{d}{2}\right) I_{\mathrm{pk}}\cos(\omega t)}{2\pi\left(\left(x - \frac{d\sqrt{3}}{2}\right)^2 + \left(y + \frac{d}{2}\right)^2\right)} \tag{B.4a}$$

$$H_{y1} = \frac{\left(x - \frac{d\sqrt{3}}{2}\right) I_{pk}\cos(\omega t)}{2\pi\left(\left(x - \frac{d\sqrt{3}}{2}\right)^2 + \left(y + \frac{d}{2}\right)^2\right)} \tag{B.4b}$$

Similarly, the field components for phase 2 at (0,d) carrying a current $I_{\mathrm{pk}}\cos(\omega t\text{-}120°)$ are

$$H_{x2} = \frac{-\left(y-d\right) I_{\mathrm{pk}} \cos(\omega t - 120^\circ)}{2\pi\left(\left(x\right)^2 + \left(y-d\right)^2\right)} \qquad \text{(B.5a)}$$

$$H_{y2} = \frac{\left(x\right) I_{\mathrm{pk}} \cos(\omega t - 120^\circ)}{2\pi\left(\left(x\right)^2 + \left(y-d\right)^2\right)} \qquad \text{(B.5b)}$$

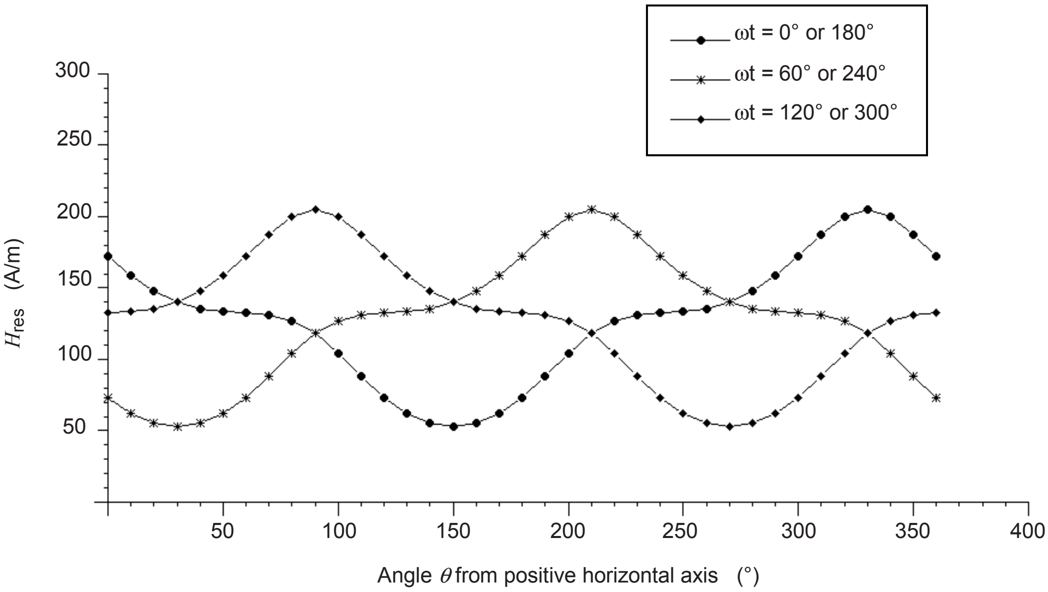
Finally the field components for phase 3 at $\left(\frac{-d\sqrt{3}}{2}, \frac{-d}{2}\right)$ carrying a current $I_{\mathrm{pk}}\cos(\omega t+120^\circ)$ are

$$H_{x3} = \frac{-\left(y+\frac{d}{2}\right) I_{\mathrm{pk}} \cos(\omega t + 120^\circ)}{2\pi\left(\left(x+\frac{d\sqrt{3}}{2}\right)^2 + \left(y+\frac{d}{2}\right)^2\right)} \qquad \text{(B.6a)}$$

$$H_{y3} = \frac{\left(x+\frac{d\sqrt{3}}{2}\right) I_{\mathrm{pk}} \cos(\omega t + 120^\circ)}{2\pi\left(\left(x+\frac{d\sqrt{3}}{2}\right)^2 + \left(y+\frac{d}{2}\right)^2\right)} \qquad \text{(B.6b)}$$

Thus the x- and y-components of magnetic field strength for this 3-phase system of currents at any value of time angle ωt are the sums of the individual 3-phase components. The resultant field strength is given by

$$H_{\mathrm{res}} = \sqrt{\left[\left(\sum_{i=1}^{3} H_{\mathrm{x}i}\right)^2 + \left(\sum_{i=1}^{3} H_{\mathrm{y}i}\right)^2\right]} \qquad \text{(B.7)}$$



IEC 2050/09

Figure B.2 – Variation of resultant magnetic field around 3-phase cable

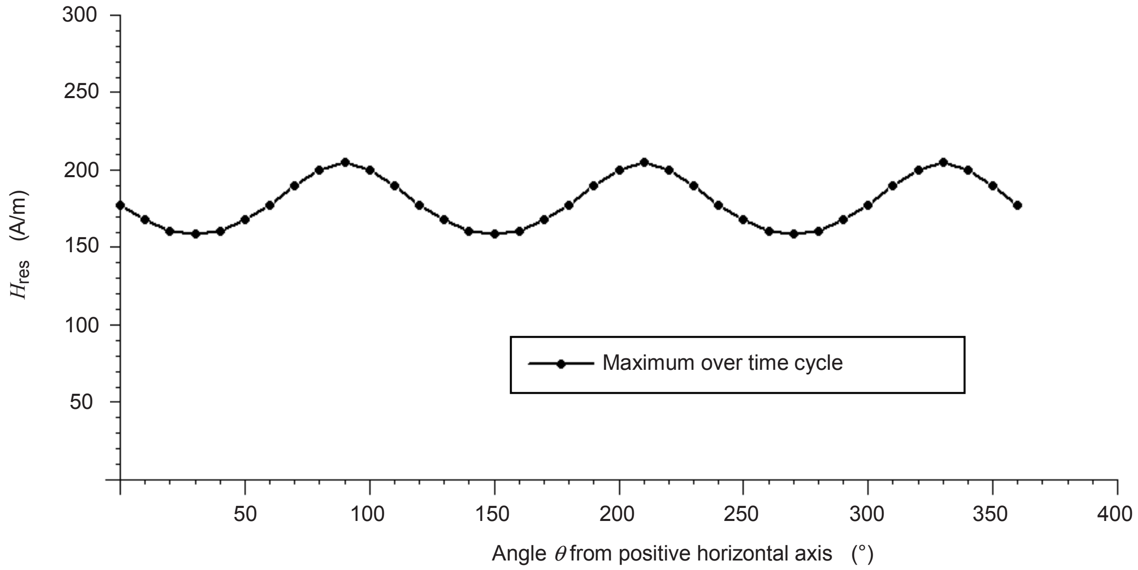
Figure B.2 shows the variation of the resultant magnetic field around the cable shown in Figure B.1 at a radius R of 1 m from the cable centre for various values of ωt, for a distance (d) of 0,5 m of each phase from the cable centre and a balanced 3-phase current with a peak value of 1 000 A. Table B.1 shows the values of the points shown in Figure B.2.

Table B.1 – Values of H_{res} for spatial angles θ and time angles ωt

Angle θ from y = 0	ωt 0° or 180°	ωt 60° or 240°	ωt 120° or 300°
0	172,296	73,394 91	132,424 9
10	158,693 8	62,259 55	133,355 6
20	147,946 2	55,377 49	135,683 5
30	140,361 5	53,051 65	140,361 5
40	135,6835	55,377 49	147,946 2
50	133,355 6	62,259 55	158,693 8
60	132,424 9	73,394 91	172,296
70	131,223 3	87,990 68	187,165 4
80	127,237 1	104,051	199,616 2
90	118,141 9	118,141 9	204,627 8
100	104,051	127,237 1	199,616 2
110	87,990 68	131,223 3	187,165 4
120	73,394 91	132,424 9	172,296
130	62,259 55	133,355 6	158,693 8
140	55,377 49	135,683 5	147,946 2
150	53,051 65	140,361 5	140,361 5
160	55,377 49	147,946 2	135,683 5
170	62,259 55	158,693 8	133,355 6
180	73,394 91	172,296	132,424 9

Angle θ from y = 0	ωt 0° or 180°	ωt 60° or 240°	ωt 120° or 300°
190	87,990 68	187,165 4	131,223 3
200	104,051	199,616 2	127,237 1
210	118,141 9	204,627 8	118,141 9
220	127,23 1	199,616 2	104,051
230	131,223 3	187,165 4	87,990 68
240	132,424 9	172,296	73,394 91
250	133,355 6	158,693 8	62,259 55
260	135,683 5	147,946 2	55,377 49
270	140,361 5	140,361 5	53,051 65
280	147,946 2	135,683 5	55,377 49
290	158,693 8	133,355 6	62,259 55
300	172,296	132,424 9	73,394 91
310	187,165 4	131,223 3	87,990 68
320	199,616 2	127,237 1	104,051
330	204,627 8	118,141 9	118,141 9
340	199,616 2	104,051	127,237 1
350	187,165 4	87,990 68	131,223 3
360	172,296	73,394 91	132,424 9

The maximum field strength over a time cycle at a given angular position (H_{max}) can be found from the maximum value at that angular position of the family of curves of which Figure B.2 and Table B.1 show a subset. The variation of this maximum with angle θ around the cable is shown in Figure B.3.



IEC 2051/09

Figure B.3 – Maximum resultant magnetic field around 3-phase cable

The values of the points shown in Figure B.3 are given in Table B.2.

Table B.2 – Values of maximum H_{res} for spatial angles θ

Angle θ from y = 0	Maximum H_{res}
0	177,666 7
10	167,6491
20	161,303 6
30	159,154 9
40	161,303 6
50	167,649 1
60	177,666 7
70	189,725 3
80	200,293 6
90	204,627 8
100	200,293 6
110	189,725 3
120	177,666 7
130	167,649 1
140	161,303 6
150	159,154 9
160	161,303 6
170	167,649 1
180	177,666 7
190	189,725 3
200	200,293 6
210	204,627 8
220	200,293 6
230	189,725 3
240	177,666 7
250	167,649 1
260	161,303 6
270	159,154 9
280	161,303 6
290	167,649 1
300	177,666 7
310	189,725 3
320	200,293 6
330	204,627 8
340	200,293 6
350	189,725 3
360	177,666 7

The values of the maximum resultant field given in Table B.2 can be calculated directly from Equations (B.4) to (B.7) as shown below.

For phase 1, Equations (B.4a) and (B.4b) can be rewritten:

$$H_{x1} = A\cos(\omega t) \tag{B.8a}$$

where

$$A = \frac{-\left(y + \frac{d}{2}\right) I_{pk}}{2\pi\left(\left(x - \frac{d\sqrt{3}}{2}\right)^2 + \left(y + \frac{d}{2}\right)^2\right)}$$

and

$$H_{y1} = C\cos(\omega t) \tag{B.8b}$$

where

$$C = \frac{\left(x - \frac{d\sqrt{3}}{2}\right) I_{pk}}{2\pi\left(\left(x - \frac{d\sqrt{3}}{2}\right)^2 + \left(y + \frac{d}{2}\right)^2\right)}$$

or

phase 2:

$$H_{x2} = E\cos(\omega t) + F\sin(\omega t) \tag{B.9a}$$

where

$$E = \frac{-(y-d)\, I_{\text{pk}} \cos(120°)}{2\pi\left((x)^2 + (y-d)^2\right)} \quad \text{and} \quad F = \frac{-(y-d)\, I_{\text{pk}} \sin(120°)}{2\pi\left((x)^2 + (y-d)^2\right)}$$

and

$$H_{y2} = G\cos(\omega t) + H\sin(\omega t) \tag{B.9b}$$

where

$$G = \frac{(x)\, I_{\text{pk}} \cos(120°)}{2\pi\left((x)^2 + (y-d)^2\right)} \quad \text{and} \quad H = \frac{(x)\, I_{\text{pk}} \sin(120°)}{2\pi\left((x)^2 + (y-d)^2\right)}$$

phase 3:

$$H_{x3} = K\cos(\omega t) + L\sin(\omega t) \tag{B.10a}$$

where

$$K = \frac{-\left(y+\frac{d}{2}\right) I_{\text{pk}} \cos(120°)}{2\pi\left(\left(x+\frac{d\sqrt{3}}{2}\right)^2+\left(y+\frac{d}{2}\right)^2\right)} \quad \text{and} \quad L = \frac{\left(y+\frac{d}{2}\right) I_{\text{pk}} \sin(120°)}{2\pi\left(\left(x+\frac{d\sqrt{3}}{2}\right)^2+\left(y+\frac{d}{2}\right)^2\right)}$$

and

$$H_{y3} = M\cos(\omega t) + N\sin(\omega t) \tag{B.10b}$$

where

$$M = \frac{\left(x+\frac{d\sqrt{3}}{2}\right) I_{\text{pk}} \cos(120°)}{2\pi\left(\left(x+\frac{d\sqrt{3}}{2}\right)^2+\left(y+\frac{d}{2}\right)^2\right)} \quad \text{and} \quad N = \frac{-\left(x+\frac{d\sqrt{3}}{2}\right) I_{\text{pk}} \sin(120°)}{2\pi\left(\left(x+\frac{d\sqrt{3}}{2}\right)^2+\left(y+\frac{d}{2}\right)^2\right)}$$

The resultant x-component of H is therefore

$H_{\text{x}} \quad = H_{\text{x1}} + H_{\text{x2}} + H_{\text{x3}}$

= (A + E + K)cos(ωt) + (F + L)sin(ωt)

= Pcos(ωt) + Qsin(ωt)

where P = A + E +K

and Q = F + L

while the resultant y-component of H is

$H_{\text{y}} \quad = H_{\text{y1}} + H_{\text{y2}} + H_{\text{y3}}$

= (C + G + M) cos(ωt) + (H + N) sin(ωt)

= Rcos(ωt) + Ssin(ωt)

where R = C + G +M

and S = H + N

The resultant is H_{res} as in Equation (B.7), so

$$H_{\text{res}}^2 = (P\cos(\omega t) + Q\sin(\omega t))^2 + (R\cos(\omega t) + S\sin(\omega t))^2 \tag{B.11}$$

which expands to

$$H_{\text{res}}^2 = \left(P^2+R^2\right)\cos^2(\omega t) + \left(Q^2+S^2\right)\sin^2(\omega t) + 2(PQ+RS)\sin(\omega t)\cos(\omega t) \tag{B.12}$$

and thence to

$$H_{res}^2 = \left(\frac{P^2+R^2+Q^2+S^2}{2}\right) + \left(\frac{P^2+R^2-Q^2-S^2}{2}\right)\cos 2(\omega t) + (PQ+RS)\sin 2(\omega t) \quad \text{(B.13)}$$

The maximum value of H_{res}^2 is therefore given by

$$\left(H_{\text{res}}^2\right)_{\text{max}} = \left(\frac{P^2+R^2+Q^2+S^2}{2}\right) + \sqrt{\left(\frac{P^2+R^2-Q^2-S^2}{2}\right)^2 + (PQ+RS)^2} \quad \text{(B.14)}$$

and the maximum value of H_{res} itself is therefore the square root of Equation B.14. The graph of $(H_{\text{res}})_{\text{max}}$ is Figure B.3 and the corresponding values are given in Table B.2.

B.2 Electric field

This annex presents the analytical solution of the electric field of a set of 3-phase voltages on infinitely long lines. This solution is presented as an example of a calculation amenable to both analytical and numerical solution. It can therefore be used to benchmark software used for the calculations described in Clause 6.

The lines carrying the 3-phase voltages are arranged symmetrically at a distance d from an origin at (0,0) in the x-y plane as shown in Figure B.4. The equivalent charge on each line is distributed in the z-direction (perpendicularly to the plane of the diagram).

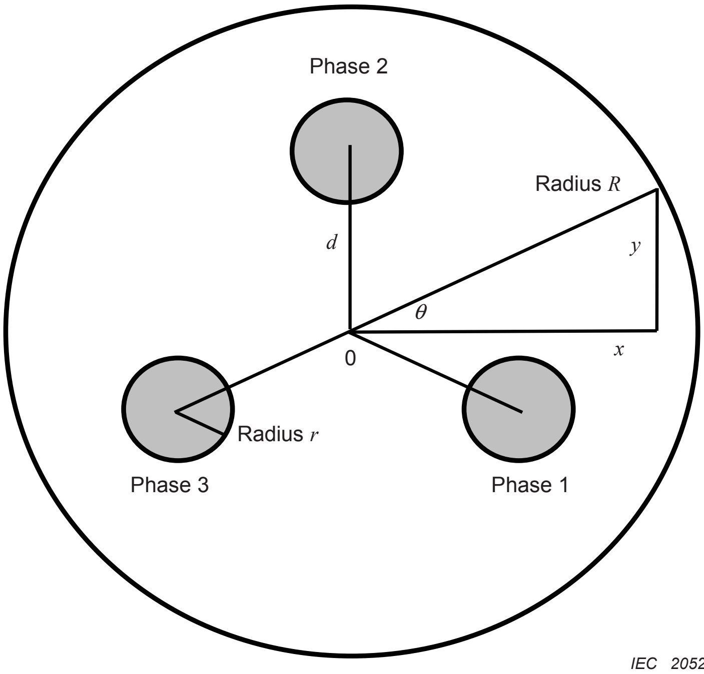


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Figure B.4 – Schematic for 3-phase electric field calculation

The centres of the 3 lines are therefore at $\left(\frac{d\sqrt{3}}{2}, \frac{-d}{2}\right)$, (0,d) and $\left(\frac{-d\sqrt{3}}{2}, \frac{-d}{2}\right)$.

The electric field resulting from the 3 voltages is calculated outside the cable, that is, at distances R greater than (d + r) from the origin, where r is the line (conductor) radius.

The separation (s) between each pair of lines is given by

$$s=\sqrt{\left(\frac{d\sqrt{3}}{2}\right)^2+\left(\frac{3d}{2}\right)^2}=\sqrt{3}\,d \tag{B.15}$$

From Gauss' Law, the electric field E at a distance R from a line carrying charge λ(C/m) is

$$E=\frac{\lambda}{2\pi\varepsilon_o R} \tag{B.16}$$

where ε_o is the permittivity of free space ≈ 8,854 3 × 10^{-12} F/m.

Therefore a line at the origin (0,0) carrying a charge $\lambda_{pk}\cos(\omega t)$ would produce an electric field $E = \underline{i}E_x + \underline{j}E_y$ such that

$$E_x=\frac{x\lambda_{pk}\cos(\omega t)}{2\pi\varepsilon_o R^2} \tag{B.17a}$$

$$E_y=\frac{y\lambda_{pk}\cos(\omega t)}{2\pi\varepsilon_o R^2} \tag{B.17b}$$

R is the distance from the centre of the line, so

$$R^2=x^2+y^2$$

In most electric field calculations, it is the voltage that is known, not the charge. It can be shown that the relationship between charge and voltage for line i of a balanced 3-phase system can be expressed as

$$\frac{\lambda_i}{2\pi\varepsilon_o}=\frac{V_i}{\ln\left(\frac{s}{r}\right)} \tag{B.18}$$

where

r is the line radius:

s is the line separation = $\sqrt{3}d$;

V_i is the voltage of line i to ground.

$V_i + V_j + V_k = 0$

{i j k} = {1 2 3} then {2 3 1} then {3 1 2} as usual [1].

The lines shown in Figure B.4 are all displaced by a radius d from the origin, so the following derivations are for $R > (d + r)$.

The field components for a line displaced from the origin to coordinates (x_{dis}, y_{dis}) and carrying a charge λ_{phase} are derived from Equations (B.17a) and (B.17b) as

$$E_{\text{xi}} = \frac{x_{l\,\text{ocal}}\lambda_{\text{phase}}}{2\pi\varepsilon_o R_{\text{local}}^2} \tag{B.19a}$$

$$E_{\text{yi}} = \frac{y_{\text{local}}\lambda_{\text{phase}}}{2\pi\varepsilon_o R_{\text{local}}^2} \tag{B.19b}$$

where

i = 1, 2, 3;

$x_{\text{local}} = x - x_{\text{dis}}$ and $y_{\text{local}} = y - y_{\text{dis}}$;

$R_{\text{local}}^2 = x_{\text{local}}^2 + y_{\text{local}}^2$.

Substituting Equation (B.18) into Equations (B.19a) and (B.19b) yields expressions for electric field strength in terms of voltage to ground:

$$E_{\text{xi}} = \frac{x_{\text{local}}V_{\text{i}}}{\ln\left(\frac{s}{r}\right)R_{\text{local}}^2} \tag{B.20a}$$

$$E_{\text{yi}} = \frac{y_{\text{local}}V_{\text{i}}}{\ln\left(\frac{s}{r}\right)R_{\text{local}}^2} \tag{B.20b}$$

In this example, phase 1 is at $x_{\text{dis}} = \left(\frac{d\sqrt{3}}{2}\right)$ $y_{\text{dis}} = \left(\frac{-d}{2}\right)$ at a voltage $V_1 = V_{\text{pk}}\cos(\omega t)$, so

$$x_{\text{local}} = x - \frac{d\sqrt{3}}{2}$$
$$y_{\text{local}} = y + \frac{d}{2}$$

$$R_{\text{local}}^2 = \left(x - \frac{d\sqrt{3}}{2}\right)^2 + \left(y + \frac{d}{2}\right)^2$$

Similarly, phase 2 is at $x_{\text{dis}} = 0$ $y_{\text{dis}} = d$ at a voltage $V_2 = V_{\text{pk}}\cos(\omega t\text{-}120°)$, so

$$x_{\text{local}} = x$$
$$y_{l\,\text{ocal}} = y - d$$

$$R_{\text{local}}^2 = (x)^2 + (y-d)^2$$

Finally, phase 3 is at $x_{\text{dis}}=\left(\frac{-d\sqrt{3}}{2}\right)$ $y_{\text{dis}}=\left(\frac{-d}{2}\right)$at a voltage $V_3 = V_{\text{pk}}\cos(\omega t+120°)$, so

$$x_{\text{local}} = x + \frac{d\sqrt{3}}{2}$$
$$y_{\text{local}} = y + \frac{d}{2}$$

$$R^2_{\text{local}} = \left(x + \frac{d\sqrt{3}}{2}\right)^2 + \left(y + \frac{d}{2}\right)^2$$

Thus the x- and y-components of electric field strength for this 3-phase system of voltages at any value of time angle ωt are the sums of the individual 3-phase components. The resultant field strength is given by

$$E_{\text{res}} = \sqrt{\left[\left(\sum_{i=1}^{3} E_{\text{xi}}\right)^2 + \left(\sum_{i=1}^{3} E_{\text{yi}}\right)^2\right]} \tag{B.21}$$

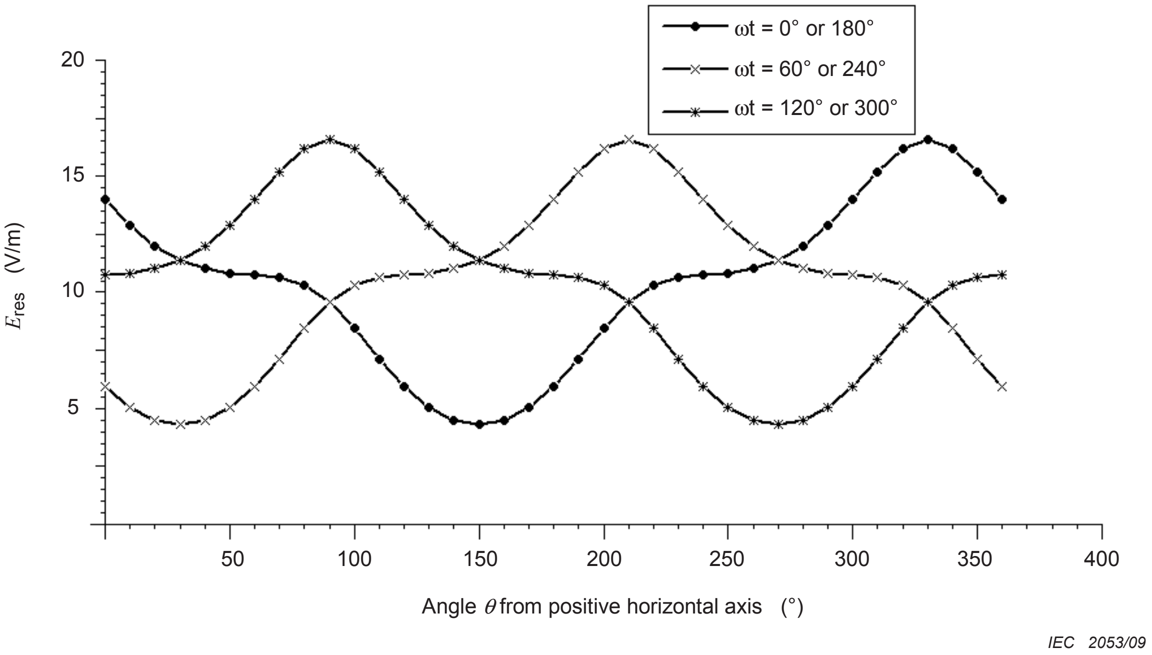

Figure B.5 – Variation of resultant electric field around 3-phase cable

Figure B.5 shows the variation of the resultant electric field around the cable shown in Figure B.4 for various values of ωt. In this case, the parameters are as follows:

R = 0,04 m = calculation radius from the cable centre;

d = 0,02 m = distance of each phase from the cable centre;

s = 0,0346 m = separation of 2 lines;

r = 0,005 m = line radius;

V_{pk} = 1 V.

Table B.3 gives the values of the points shown in Figure B.5.

Table B.3 – Values of E_{res} for spatial angles θ and time angles ωt

Angle θ from y = 0	ωt 0° or 180°	ωt 60° or 240°	ωt 120° or 300°
0	13,982 3	5,956 2	10,746 7
10	12,878 5	5,052 5	10,822 2
20	12,006 3	4,494 0	11,011 1
30	11,390 7	4,305 3	11,390 7
40	11,011 1	4,494 0	12,006 3
50	10,822 2	5,052 5	12,878 5
60	10,746 7	5,956 2	13,982 3
70	10,649 2	7,140 7	15,189 0
80	10,325 7	8,444 0	16,199 4
90	9,587 6	9,587 6	16,606 1
100	8,444 0	10,325 7	16,199 4
110	7,140 7	10,649 2	15,189 0
120	5,956 2	10,746 7	13,982 3
130	5,052 5	10,822 2	12,878 5
140	4,494 0	11,011 1	12,006 3
150	4,305 3	11,390 7	11,390 7
160	4,494 0	12,006 3	11,011 1
170	5,052 5	12,878 5	10,822 2
180	5,956 2	13,982 3	10,746 7
190	7,140 7	15,189 0	10,649 2
200	8,444 0	16,199 4	10,325 7
210	9,587 6	16,606 1	9,587 6
220	10,325 7	16,199 4	8,444 0
230	10,649 2	15,189 0	7,140 7
240	10,746 7	13,982 3	5,956 2
250	10,822 2	12,878 5	5,052 5
260	11,011 1	12,006 3	4,494 0
270	11,390 7	11,390 7	4,305 3
280	12,006 3	11,011 1	4,494 0
290	12,878 5	10,822 2	5,052 5
300	13,982 3	10,746 7	5,956 2
310	15,189 0	10,649 2	7,140 7
320	16,199 4	10,325 7	8,444 0
330	16,606 1	9,587 6	9,587 6
340	16,199 4	8,444 0	10,325 7
350	15,189 0	7,140 7	10,649 2
360	13,982 3	5,956 2	10,746 7

The maximum field strength over a time cycle at a given angular position (E_{max}) can be found from the maximum value at that angular position of the family of curves of which Figure B.6 and Table B.3 show a subset. The variation of this maximum with angle θ around the cable is shown in Figure B.6.

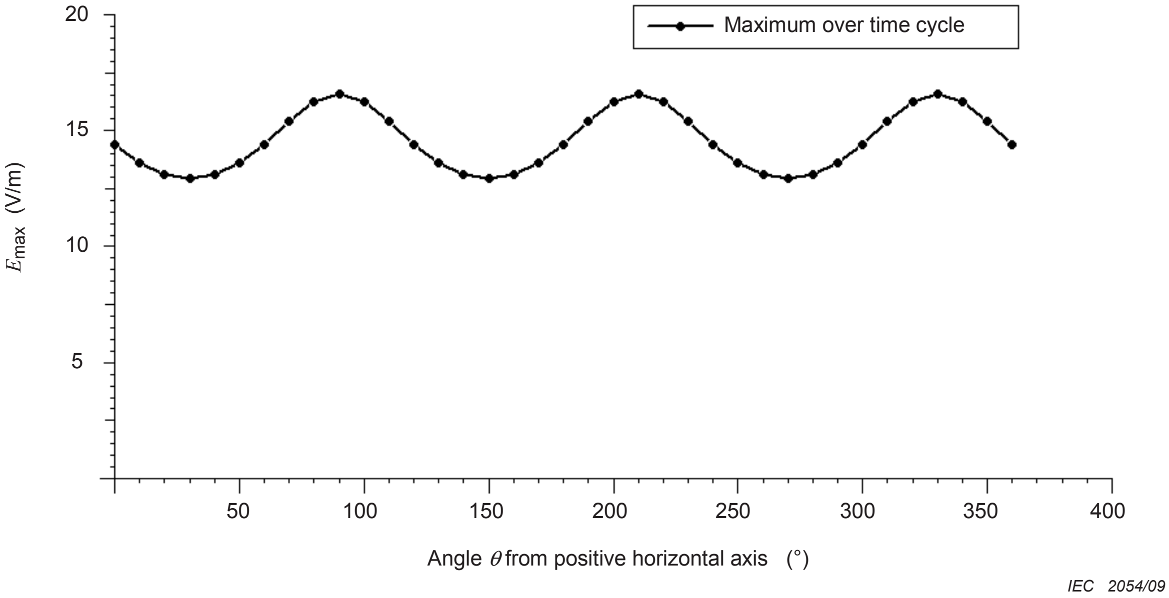

Figure B.6 – Maximum resultant electric field around 3-phase cable

The values of the points shown in Figure B.6 are given in Table B.4.

Table B.4 – Values of maximum E for spatial angles θ

Angle θ from y = 0	Maximum E V/m
0	14,418 2
10	13,605 2
20	13,090 3
30	12,915 9
40	13,090 3
50	13,605 2
60	14,418 2
70	15,396 8
80	16,254 4
90	16,606 1
100	16,254 4
110	15,396 8
120	14,418 2
130	13,605 2
140	13,090 3
150	12,915 9
160	13,090 3
170	13,605 2

Angle θ from y = 0	Maximum E V/m
180	14,418 2
190	15,396 8
200	16,254 4
210	16,606 1
220	16,254 4
230	15,396 8
240	14,418 2
250	13,605 2
260	13,090 3
270	12,915 9
280	13,090 3
290	13,605 2
300	14,418 2
310	15,396 8
320	16,254 4
330	16,606 1
340	16,254 4
350	15,396 8
360	14,418 2

The values of maximum resultant field given in Table B.4 can be calculated directly from Equations B.20a, B.20b and B.21 as shown below.

For phase 1, Equations (B.20a) and (B.20b) can be rewritten:

$$E_{\mathrm{x1}} = A\cos(\omega \mathrm{t}) + B\sin(\omega \mathrm{t}) \tag{B.22a}$$

where

$$A = \frac{x_{\mathrm{local}} V_{\mathrm{pk}}}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^{2}}$$

B=0

and

$$E_{\mathrm{y1}} = C\cos(\omega \mathrm{t}) + D\sin(\omega \mathrm{t}) \tag{B.22b}$$

where

$$C = \frac{y_{\mathrm{local}} V_{\mathrm{pk}}}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^{2}}$$

D = 0

For phase 2, Equations (B.20a) and (B.20b) can be rewritten:

$$E_{\mathrm{x}2} = E\cos(\omega t) + F\sin(\omega t) \tag{B.23a}$$

where

$$E = \frac{x_{\mathrm{local}} V_{\mathrm{pk}} \cos(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^2}$$

$$F = \frac{x_{\mathrm{local}} V_{\mathrm{pk}} \sin(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^2}$$

and

$$E_{\mathrm{y}2} = G\cos(\omega t) + H\sin(\omega t) \tag{B.23b}$$

where

$$G = \frac{y_{\mathrm{local}} V_{\mathrm{pk}} \cos(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^2}$$

$$H = \frac{y_{local} V_{\mathrm{pk}} \sin(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^2}$$

For phase 3, Equations (B.20a) and (B.20b) can be rewritten:

$$E_{\mathrm{x}3} = K\cos(\omega t) + L\sin(\omega t) \tag{B.24a}$$

where

$$K = \frac{x_{\mathrm{local}} V_{\mathrm{pk}} \cos(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^2}$$

$$L = -\frac{x_{local} V_{\mathrm{pk}} \sin(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\mathrm{local}}^2}$$

and

$$E_{\mathrm{y}3} = M\cos(\omega t) + N\sin(\omega t) \tag{B.24b}$$

where

$$M = \frac{y_{\text{local}} V_{\text{pk}} \cos(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\text{local}}^2}$$

$$N = -\frac{y_{\text{local}} V_{\text{pk}} \sin(120^\circ)}{\ln\left(\frac{s}{r}\right) R_{\text{local}}^2}$$

The resultant x-component of E is therefore

$E_{\text{x}} \quad = E_{\text{x1}} + E_{\text{x2}} + E_{\text{x3}}$

$= (\text{A} + \text{E} + \text{K})\cos(\omega t) + (\text{B} + \text{F} + \text{L})\sin(\omega t)$

$= P\cos(\omega t) + \text{Q}\sin(\omega t)$

where $P = \text{A} + \text{E} + \text{K}$

and $\quad \text{Q} = \text{B} + \text{F} + \text{L}$

while the resultant y-component of E is

$E_{\text{y}} \quad = E_{\text{y1}} + E_{\text{y2}} + E_{\text{y3}}$

$= (\text{C} + \text{G} + \text{M}) \cos(\omega t) + (\text{D} + \text{H} + \text{N}) \sin(\omega t)$

$= \text{R}\cos(\omega t) + \text{S}\sin(\omega t)$

where $\text{R} = \text{C} + \text{G} + \text{M}$

and $\quad \text{S} = \text{D} + \text{H} + \text{N}$

The resultant is E_{res} as in Equation (B.21), so

$$E_{\text{res}}^2 = (P\cos(\omega t) + Q\sin(\omega t))^2 + (R\cos(\omega t) + S\sin(\omega t))^2 \tag{B.25}$$

which expands to

$$E_{\text{res}}^2 = \left(P^2 + R^2\right)\cos^2(\omega t) + \left(Q^2 + S^2\right)\sin^2(\omega t) + 2(PQ + RS)\sin(\omega t)\cos(\omega t) \tag{B.26}$$

and thence to

$$E_{\text{res}}^2 = \left(\frac{P^2 + R^2 + Q^2 + S^2}{2}\right) + \left(\frac{P^2 + R^2 - Q^2 - S^2}{2}\right)\cos 2(\omega t) + (PQ + RS)\sin 2(\omega t) \tag{B.27}$$

The maximum value of $E_{\text{res}}{}^2$ is therefore given by

$$\left(E_{\text{res}}^2\right)_{\max} = \left(\frac{P^2 + R^2 + Q^2 + S^2}{2}\right) + \sqrt{\left(\frac{P^2 + R^2 - Q^2 - S^2}{2}\right)^2 + (PQ + RS)^2} \tag{B.28}$$

and the E_{max} is therefore the square root of Equation (B.28). The graph of E_{max} is Figure B.6 and the corresponding values are given in Table B.4.

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