

Exposure to electric or magnetic fields in the low and intermediate frequency range — Methods for calculating the current density and internal electric field induced in the human body —

Part 2-1: Exposure to magnetic fields — 2D models

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National foreword

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**Exposure to electric or magnetic fields
in the low and intermediate frequency range –
Methods for calculating the current density
and internal electric field induced in the human body
Part 2-1: Exposure to magnetic fields –
2D models
(IEC 62226-2-1:2004)**

Exposition aux champs électriques
ou magnétiques à basse
et moyenne fréquence –
Méthodes de calcul des densités
de courant induit et des champs
électriques induits dans le corps humain
Partie 2-1: Exposition à des champs
magnétiques –
Modèles 2D
(CEI 62226-2-1:2004)

Sicherheit in elektrischen oder
magnetischen Feldern im niedrigen und
mittleren Frequenzbereich –
Verfahren zur Berechnung der induzierten
Körperstromdichte und des im
menschlichen Körper induzierten
elektrischen Feldes
Teil 2-1: Exposition gegenüber
magnetischen Feldern –
2D-Modelle
(IEC 62226-2-1:2004)

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European Committee for Electrotechnical Standardization
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Foreword

The text of document 106/79/FDIS, future edition 1 of IEC 62226-2-1, prepared by IEC TC 106, Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 62226-2-1 on 2004-12-01.

This Part 2-1 is to be used in conjunction with EN 62226-1¹⁾.

The following dates were fixed:

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¹⁾ To be published.

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INTRODUCTION

Public interest concerning human exposure to electric and magnetic fields has led international and national organisations to propose limits based on recognised adverse effects.

This standard applies to the frequency range for which the exposure limits are based on the induction of voltages or currents in the human body, when exposed to electric and magnetic fields. This frequency range covers the low and intermediate frequencies, up to 100 kHz. Some methods described in this standard can be used at higher frequencies under specific conditions.

The exposure limits based on biological and medical experimentation about these fundamental induction phenomena are usually called “basic restrictions”. They include safety factors.

The induced electrical quantities are not directly measurable, so simplified derived limits are also proposed. These limits, called “reference levels”, are given in terms of external electric and magnetic fields. They are based on very simple models of coupling between external fields and the body. These derived limits are conservative.

Sophisticated models for calculating induced currents in the body have been used and are the subject of a number of scientific publications. These use numerical 3D electromagnetic field computation codes and detailed models of the internal structure with specific electrical characteristics of each tissue within the body. However such models are still developing; the electrical conductivity data available at present has considerable shortcomings; and the spatial resolution of models is still advancing. Such models are therefore still considered to be in the field of scientific research and at present it is not considered that the results obtained from such models should be fixed indefinitely within standards. However it is recognised that such models can and do make a useful contribution to the standardisation process, specially for product standards where particular cases of exposure are considered. When results from such models are used in standards, the results should be reviewed from time to time to ensure they continue to reflect the current status of the science.

EXPOSURE TO ELECTRIC OR MAGNETIC FIELDS IN THE LOW AND INTERMEDIATE FREQUENCY RANGE – METHODS FOR CALCULATING THE CURRENT DENSITY AND INTERNAL ELECTRIC FIELD INDUCED IN THE HUMAN BODY –

Part 2-1: Exposure to magnetic fields – 2D models

1 Scope

This part of IEC 62226 introduces the coupling factor K , to enable exposure assessment for complex exposure situations, such as non-uniform magnetic field or perturbed electric field. The coupling factor K has different physical interpretations depending on whether it relates to electric or magnetic field exposure.

The aim of this part is to define in more detail this coupling factor K , for the case of simple models of the human body, exposed to non-uniform magnetic fields. It is thus called “coupling factor for non-uniform magnetic field”.

All the calculations developed in this document use the low frequency approximation in which displacement currents are neglected. This approximation has been validated in the low frequency range in the human body where parameter $\varepsilon\omega \ll \sigma$.

For frequencies up to a few kHz, the ratio of conductivity and permittivity should be calculated to validate this hypothesis.

2 Analytical models

2.1 General

Basic restrictions in guidelines on human exposure to magnetic fields up to about 100 kHz are generally expressed in terms of induced current density or internal electric field. These electrical quantities cannot be measured directly and the purpose of this document is to give methods and tools on how to assess these quantities from the external magnetic field.

The induced current density J and the internal electric field E_i are closely linked by the simple relation:

$$J = \sigma E_i \quad (1)$$

where σ is the conductivity of living tissues.

For simplicity, the content of this standard is presented in terms of induced current densities J , from which values of the internal electric field can be easily derived using the previous formula.

Analytical models have been used in EMF health guidelines to quantify the relationship between induced currents or internal electric field and the external fields. These involve assumptions of highly simplified body geometry, with homogeneous conductivity and uniform applied magnetic field. Such models have serious limitations. The human body is a much more complicated non-homogeneous structure, and the applied field is generally non-uniform because it arises from currents flowing through complex sets of conductors and coils.

For example, in an induction heating system, the magnetic field is in fact the superposition of an excitation field (created by the coils), and a reaction field (created by the induced currents in the piece). In the body, this reaction field is negligible and can be ignored.

Annex E and F presents the analytical calculation of magnetic field H created by simple sources and Annex G presents the analytical method for calculating the induced current in a conductive disk.

2.2 Basic analytical models for uniform fields

The simplest analytical models used in EMF health guidelines are based on the hypothesis of coupling between a uniform external magnetic field at a single frequency, and a homogeneous disk of given conductivity, used to represent the part of the body under consideration, as illustrated in Figure 1. Such models are used for example in the ICNIRP ¹⁾ and NRPB ²⁾ guidelines.

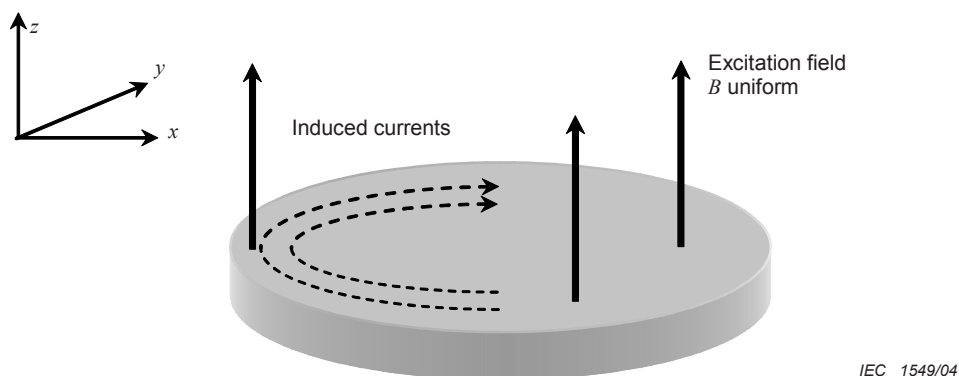


Figure 1 – Conducting disk in a uniform magnetic flux density

The objective of such a modelling is to provide a simple method to assess induced currents and internal fields. This very first approach is simple and gives conservative values of the electrical quantities calculated.

For alternating magnetic fields, the calculation assumes that the body or the part of the body exposed is a circular section of radius r , with conductivity σ . The calculation is made under maximum coupling conditions i.e. with a uniform magnetic field perpendicular to this disk. In this case, the induced current density at radius r is given by:

$$J(r) = \frac{r\sigma}{2} \frac{dB}{dt} \quad (2)$$

where B is the magnetic flux density.

¹⁾ Health Physics (vol. 74, n° 4, April 1998, pp 496-522).

²⁾ NRPB, 1993, Board Statement on Restrictions on Human Exposure to Static and Time-varying Electromagnetic Fields and Radiation, Volume 4, No 5, 1.

For a single frequency f , this becomes:

$$J(r) = \sigma \pi r f B \quad (3)$$

As illustrated in Figure 1 (see also Annex A), induced currents are distributed inside the disk, following a rotation symmetry around the central axis of the disk. The value of induced currents is minimum (zero) at the centre and maximum at the edge of the disk.

3 Numerical models

3.1 General information about numerical models

Simple models, which take into consideration field characteristics, are more realistic than those, which consider only uniform fields, such as analytical ones.

Electromagnetic fields are governed by Maxwell's equations. These equations can be accurately solved in 2- or 3-dimensional structures (2D or 3D computations) using various numerical methods, such as:

- finite elements method (FEM);
- boundary integral equations method (BIE or BEM), or moment method;
- finite differences method (FD);
- impedance method (IM).

Others methods derive from these. For example, the following derive from the finite differences method:

- finite difference time domain (FDTD);
- frequency dependent finite difference time domain ((FD)²TD);
- scalar potential finite difference (SPFD).

Hybrid methods have been also developed in order to improve modelling (example: FE + BIE).

Commercially available software can accurately solve Maxwell's equations by taking into account real geometrical structures and physical characteristics of materials, as well as in steady state or transient current source conditions.

The choice of the numerical method is guided by a compromise between accuracy, computational efficiency, memory requirements, and depends on many parameters, such as:

- simulated field exposure;
- size and shape of human object to be modelled;
- description level of the human object (size of voxel), or fineness of the meshing;
- frequency range, in order to neglect some parts of Maxwell's relations (example: displacement current term for low frequency);
- electrical supply signal (sinusoidal, periodic or transient);

- type of resolution (2D or 3D);
- mathematical formulation;
- linear or non linear physical parameters (conductivity, ...);
- performances of the numerical method;
- etc.

Computation times can therefore vary significantly.

Computed electromagnetic values can be presented in different ways, including:

- distributions of magnetic field H , flux density B , electric field E , current density J . These distributions can be presented in the form of coloured iso-value lines and/or curves, allowing a visual assessment of the phenomena and the possible "hot" points;
- local or spatial averaged integral values of H , B , E , J , etc.;
- global magnitude values: active power.

These methods are very helpful for solving specific problems; however they cannot be conveniently used to study general problems.

3.2 2D models – General approach

In order to gain quickly an understanding of induced currents in the human body, 2D simulations can be performed using a simple representation of the body (a conductive disk: example of modelling given in Figure 2) in a non-uniform magnetic field, as illustrated in Figure 3.

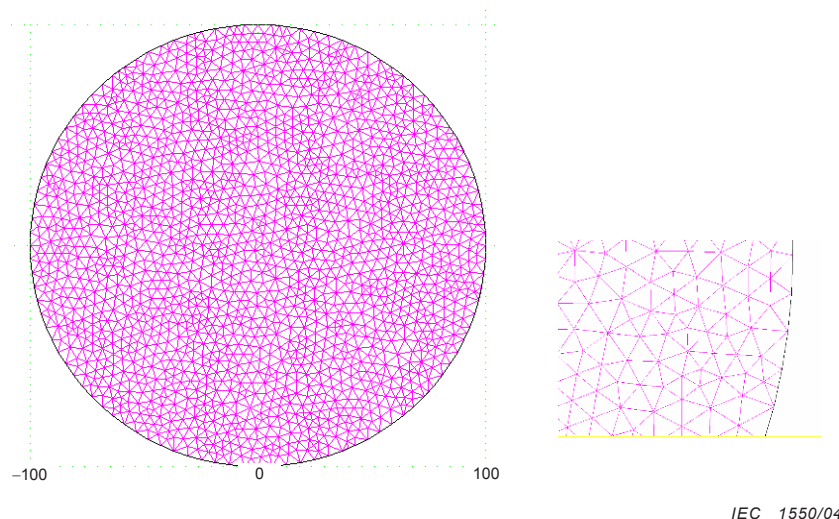


Figure 2 – Finite elements meshing (2nd order triangles) of a disk, and detail

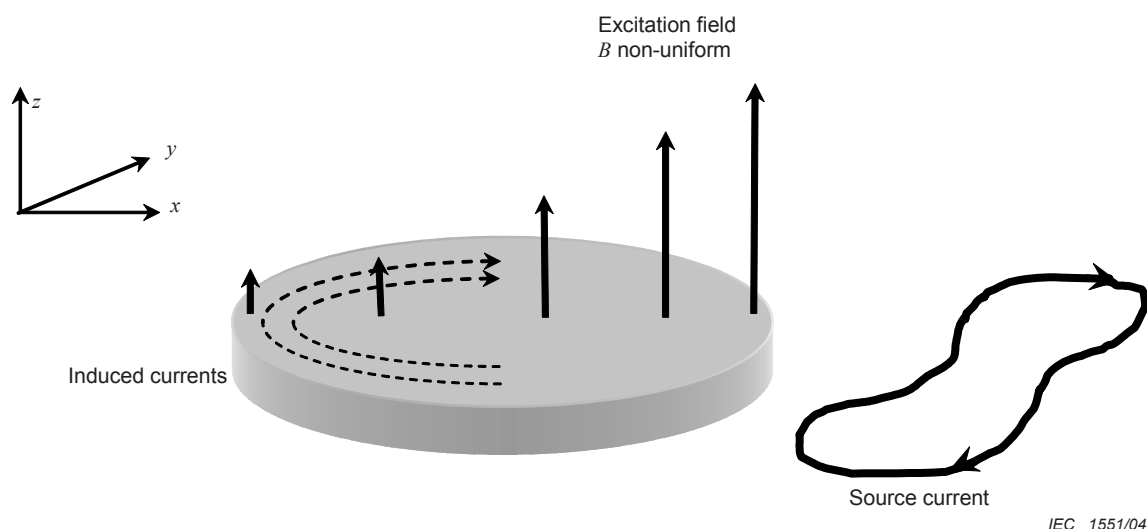


Figure 3 – Conducting disk in a non-uniform magnetic flux density

Starting from Maxwell's relations (low frequency approximation), a single equation can be obtained with a specific mathematical formulation (see Annex G):

$$\frac{1}{\sigma} \nabla^2 \vec{H}_r - \mu_0 \frac{\partial \vec{H}_r}{\partial t} = \mu_0 \frac{\partial \vec{H}_{ex}}{\partial t} \quad (4)$$

where

H_{ex} is the excitation field created by the source currents,

H_r is the reaction field created by the induced currents:

$$\vec{J} = \text{Curl}(\vec{H}_r) \quad (5)$$

Equation (4) is solved for a 2D geometry using the finite element method applied to the meshing illustrated in Figure 2.

The excitation field H_{ex} is calculated for three non-uniform field sources using the analytical expressions given in Annex F. The three sources modelled are: a current flowing through an infinitely long wire, two parallel wires with balanced currents and a current loop.

X , Y , Z co-ordinates are used. XY -plane is the study plane of the disk in which induced currents are generated. Except for the particular case where H_{ex} is uniform, source currents are in the same plane. Only the one component of H_{ex} along the Z -axis is taken into account. The induced currents in the disk have two components J_x , J_y .

Examples of numerical results are presented in Annexes A to D.

3.3 Conductivity of living tissues

The computation of induced currents in the body from the external magnetic field is strongly affected by the conductivity of the different tissues in the body and their anisotropic properties. The results presented in this document assume that the conductivity is homogeneous and isotropic with a value of 0,2 S/m. This value is consistent with the average value assumed in EMF health guidelines.

The most recent assessment of the available data indicates the average conductivity to be slightly higher: 0,22 S/m. More experimental work is in progress to provide more reliable conductivity information. The preferred average conductivity could be changed in the future as improved information becomes available. In that situation the values of induced current presented in this report should be revised in proportion to the conductivity. Nevertheless, the coupling factor for non-uniform magnetic field K , defined previously, is independent of the conductivity.

3.4 2D Models – Computation conditions

2D computation codes were used to simulate the current induced in a conductive disk by an alternating magnetic field of frequency f , produced by four different field sources:

- uniform and unidirectional field in all considered space (Annex A);
- current flowing through one infinitely long wire (Annex B);
- 2 parallel wires with balanced currents (Annex C);
- current flowing through one circular coil. (Annex D).

In order to facilitate comparisons with analytical models, all numerical values of computation parameters are fixed throughout this standard:

- radius of disk: $R = 100$ mm, and $R = 200$ mm;
- conductivity of disk: $\sigma = 0,2$ S/m;
- field sources at 50 Hz frequency.

With the exception of the first of the four field sources, the magnetic field from the source is non-uniform, decreasing with increasing distance from the source. In these cases the field value quoted is the value at the edge of the disk closest to the source.

The reaction field created by the induced current in the disk is negligible (due to the very low conductivity of the disk) and is ignored.

3.5 Coupling factor for non-uniform magnetic field

The current density induced in the disk by a localised source of magnetic field (therefore generating a non-uniform field), is always lower than the current density that would be induced by a uniform magnetic field whose magnitude is equal to the magnitude of the non-uniform field at the edge of the disk closest to the localised source. This reduction of induced current for non-uniform field sources is quantified using the coupling factor for non-uniform magnetic field K , which is physically defined as:

$$K = \frac{J_{\text{nonuniform}}}{J_{\text{uniform}}} \quad (6)$$

where

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

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

J_{uniform} is derived from equation (3):

$$J_{\text{uniform}} = J(r = R) = \sigma \pi R f B \quad (7)$$

It shall be noted that $K = 1$ when the field is uniform. Annex A illustrates the current distribution in a disk of radius $R = 100$ mm for an applied uniform field $B = 1,25$ μ T. The coupling factor for non-uniform magnetic field K is calculated numerically for the three non-uniform sources of field, in Annex B, C and D respectively.

NOTE 1 Calculated spot values of induced current densities have been averaged in this document (see Annexes A to D). So the values of J_{uniform} and $J_{\text{nonuniform}}$ given here above are averaged values, integrated over a cross section of 1 cm^2 , perpendicular to the current direction.

NOTE 2 Values of K are calculated at a frequency of 50 Hz. Nevertheless, due to the low frequency approximation, these values are also valid for the whole frequency range covered by this standard i.e. up to 100 kHz. Also, due to the low frequency approximation, K is independent of the conductivity.

For real cases, the spatial arrangement of field cannot easily be described in equations, and the coupling factor K can only be estimated (for example using the table values given in annexes of this document).

3.6 2D Models – Computation results

This subclause is a summary of the detailed numerical results given in Annexes B, C and D, which deal with the three types of sources. Whatever the source, the model of human body is treated as a homogeneous disk:

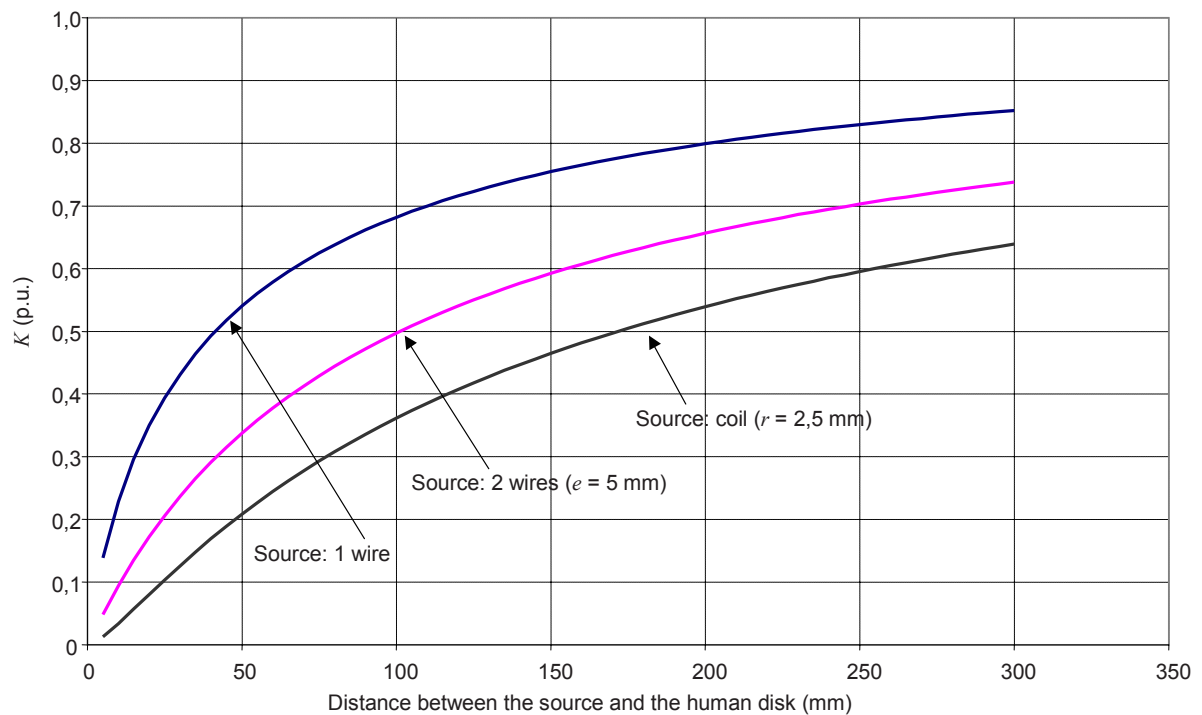
- radius of disk: $R = 100$ mm and $R = 200$ mm;
- conductivity of disk: $\sigma = 0,2$ S/m .

For comparison between the different types of sources (i.e. coupling models), the value of the local maximum magnetic field is normalised. Whatever the source, the magnetic field magnitude at the edge of the disk closest to the source is equal to the uniform field magnitude (i.e. $B = 1,25$ μ T, see annex A).

Table 1 presents a selection from Annexes B, C and D of the numerical values of the factor K for the three different sources and for a disk radius $R = 100$ mm. These results are also presented in a graphic form in Figure 4.

All the values in Table 1 are less than 1, and sometimes much less than 1, by a factor up to about 100. This demonstrates that, for a specified maximum current density in the disk, the corresponding magnetic field at the edge of the disk can have a wide range of values depending on the characteristics of the field source and on the distance between the disk and source.

The uniform field approximation (for which $K = 1$) is appropriate only when the distance between the source and the “human disk” becomes large relative to the size of the disk (typically 10 times the disk radius). At more usual distance of exposure from, for example, domestic appliances, the non-uniformity of the magnetic field with the distance has to be taken into account in the way presented in this standard.



IEC 1552/04

NOTE Values for distances up to 1 900 mm, and for other wire separations and coil sizes are given in Annexes B, C and D.

Figure 4 – Variation with distance to the source of the coupling factor for non-uniform magnetic field, K , for the three magnetic field sources (disk radius $R = 100$ mm)

Table 1 – Numerical values of the coupling factor for non-uniform magnetic field K for different types of magnetic field sources, and different distances between sources and conductive disk ($R = 100$ mm)

K factor for different sources			
Distance between the source and the disk mm	1 infinite wire	2 parallel wires with balanced currents, 5 mm spaced	1 circular coil 2,5 mm radius
10	0,229	0,094	0,034
20	0,350	0,172	0,080
30	0,432	0,237	0,126
40	0,492	0,291	0,169
50	0,540	0,337	0,208
60	0,579	0,378	0,244
70	0,611	0,413	0,277
80	0,638	0,444	0,308
90	0,661	0,472	0,336
100	0,682	0,497	0,361
110	0,700	0,520	0,385
120	0,716	0,540	0,407
130	0,730	0,559	0,428
140	0,743	0,576	0,447
150	0,754	0,592	0,465
160	0,765	0,607	0,482
170	0,775	0,621	0,497
180	0,783	0,634	0,512
190	0,792	0,645	0,526
200	0,799	0,657	0,539
210	0,806	0,667	0,552
220	0,813	0,677	0,563
230	0,819	0,686	0,575
240	0,824	0,695	0,585
250	0,830	0,703	0,595
260	0,835	0,711	0,605
270	0,839	0,718	0,614
280	0,844	0,725	0,623
290	0,848	0,732	0,631
300	0,852	0,738	0,639

NOTE Values for distances up to 1 900 mm, and for other wire separations and coil sizes are given in Annexes B, C and D.

4 Validation of models

The validation of the numerical tools used for computation of induced current densities shall be made by comparison with the results given in the annexes of this standard, which have been validated by comparison with scientific literature.

Additional information concerning the software used for the validation of numerical computation can be found in the bibliographic references of IEC 62226-1.

Annex A (normative)

Disk in a uniform field

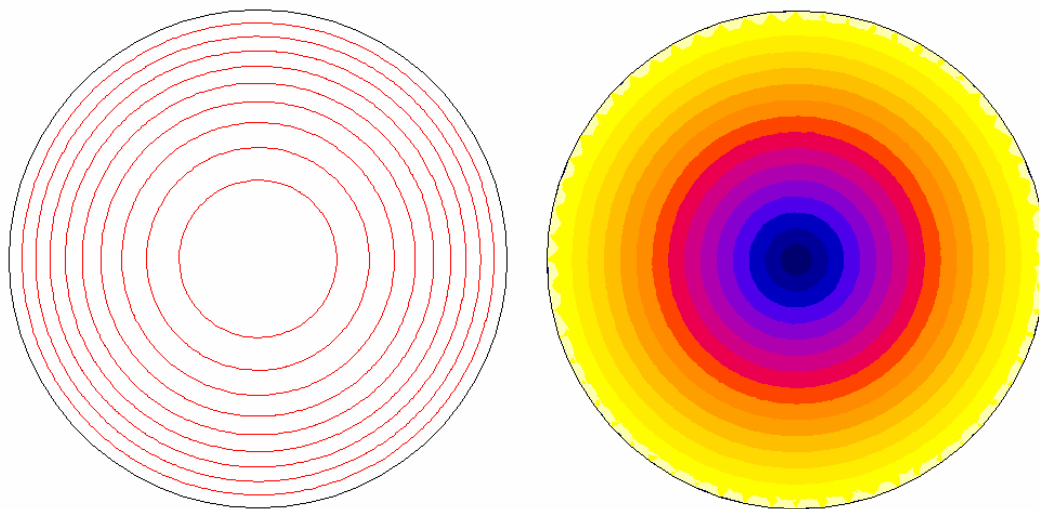
The induced currents are calculated in a disk of homogeneous conductivity. In order to allow comparison between different field sources configurations (depending on geometry of the source and distance to the disk, see Annex B to D) the following standard values have been chosen:

- f , frequency = 50 Hz (see note 2 in 3.5);
- B , uniform magnetic flux density = 1,25 μT ;
- R , radius of the conductive disk = 100 mm;
- σ , conductivity (homogeneous) = 0,2 S/m.

Using these values in equation (3) gives, at the edge of the disk:

$$J_{\max} = 0,393 \times 10^{-5} \text{ A/m}^2 \text{ (analytical calculation)}$$

Results of a numerical computation using finite element methods are presented hereafter in the form of graphs giving the shape of the distribution of induced currents in the disk (Figure A.1) and curve giving numerical values of local induced currents (Figure A.2):



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Figure A.1 – Current density lines J and distribution of J in the disk

This computation gives, at the edge of the disk a value of:

$$J_{\max} = 0,390 \times 10^{-5} \text{ A/m}^2$$

Considering the meshing effect of numerical models, this numerical value of $J_{\max}$ can be considered as equal to the analytical one. So, analytical and numerical approaches give very similar results in this simple case.