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COMBINED ANALYTICAL AND NUMERICAL METHOD FOR MAGNETIC COMPONENT DESIGN

by

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Summary

High frequency magnetic components have significant advantages related to cost and physical size compared to their low frequency counterparts. The advent of high frequency power switch technology made the transformer frequency a variable and recent advances in this field have been ever pushing the switching frequency of higher power converters. Although high frequency inductors and transformers have been used and applied extensively to an increasingly broad range of applications over recent decades, analysis and design of these devices involves certain difficulties, related to extra losses due to eddy currents as well as smaller cooling surfaces, to the developer and designer. Numerical simulations of eddy currents in windings are slow, if not impossible in many cases, due to the large mesh impositions required in order to converge. Eddy currents and thermal constraints impose limitations on flux- and current densities, complicating the design. As yet, a convenient means of design, analysis and optimization of the physical magnetic topology does not exist.

In this study, a method for analysing eddy currents in windings, using a combined analytical and numerical approach, is presented and implemented in a CAD tool. The one dimensional solutions for eddy currents in strip conductors are written in a more flexible form.

A new approach to magnetic component design, called scant modelling, is presented and applied to two practical examples. The scant model comprises a minimum number of functional and form parameters in analysing and optimizing a design, but considers eddy current effects, thermal constraints and the effects of physical size and shape of core and windings at high frequencies.
Opsomming

Hoë frekwensie magnetiese komponente hou belangrike voordele betreffende koste en fisiese grootte in vergeleke met konvensionele lae frekwensie magnetiese komponente. Die ontwikkeling van hoë frekwensie drywing-skakelaars het die frekwensie 'n versterbare veranderlike gemaak en daar word steeds gestreef na nog hoër frekwensies. Al is hoë frekwensie transformators en induktore al in gebruik vir meer as 'n dekade, word hul ontwerp en analise steeds gecompliseer deur die effek van werwelstrome en die termiese beperkings as gevolg van kleiner verkoelingsoppervlakke. Numeriese metodes om werwelstrome in geleiers te ondersoek, is beperk en dikwels selfs onmoontlik, as gevolg van die groot maas wat benodig word vir konvergensie. Die vloedekskursie in kerne en die stroomdigtheid in geleiers word beperk deur werwelstrome en termiese eienskappe en bemoeilik dus ook die ontwerp- en analiseproses. Daar bestaan vandag nog geen aanvaarbare ontwerpsmetode vir hoë frekwensie magnetiese komponente, wat hierdie probleme aanspreek nie.

In hierdie studie, word 'n nuwe metode vir die analise van werwelstrome in geleiers aangebied, wat gebruik maak van 'n kombinasie van numeriese en analitiese tegnieke. Die metode is geïmplementeer in 'n rekenaaralgoritme en word m.b.v. 'n praktiese voorbeeld getoënsstreer. Verder word 'n meer buigsame vorm van die eendimensionele vergelykings vir die analise van werwelstrome in geleiers ontwikkel en hul akkuraatheid word teen EEM geëvalueer.

'N Nuwe benadering tot die ontwerp, analise en optimering van hoë frekwensie magnetiese komponente word ook hierin aangebied en geïlustreer m.b.v. twee praktiese voorbeelde. Die sg. 'scant'-model maak gebruik van slegs die nodige aantal vorm- en funksionele parameters, maar hoë frekwensie werwelstrome, termiese eienskappe en die fisiese struktuur en grootte word in ag geneem.
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List of Symbols

A  Magnetic vector potential (MVP)  [weber/meter]
A_w  Winding Aspect Ratio
A_c  Core Aspect Ratio
A_{ps}  Primary to Secondary Area Ratio
A_g  Winding to Window Height Ratio
B  Magnetic flux density  [tesla]
B_{max}  Maximum Flux Density  [tesla]
d  Diameter of Round Conductor  [meter]
D  Electric flux density  [coulomb/meter]
D  Derating Factor
E  Electric field intensity  [volt/meter]
F_w  Winding Packing Factor
F_r  ac to dc Resistance Ratio
H  Magnetic field intensity  [ampere/meter]
g  Air Gap Length  [meter]
h  Strip Conductor Thickness  [meter]
I  Current  [ampere]
J  Current density  [ampere/meter^2]
m  Foil Conductor or Layer Position from Zero MMF-Line
P  Power  [watt]
R  Resistance  [ohm]
S  Surface Area  [meter^2]
t  Thickness of Square Conductor  [meter]
  Time  [second]
V  Electric Potential  [volt]
w  Strip Conductor Width  [meter]
\[ Z \quad \text{Impedance} \quad \text{[ohm]} \]
\[ \varepsilon \quad \text{Permittivity} \quad \text{[farad/meter]} \]
\[ \mu \quad \text{Permeability} \quad \text{[henry/meter]} \]
\[ \rho \quad \text{Electric charge density} \quad \text{[coulomb/meter\(^2\)]} \]
\[ \sigma \quad \text{Conductivity} \quad \text{[mho/meter or siemens]} \]
\[ \omega \quad \text{Radial frequency} \quad \text{[radians/second]} \]
\[ f \quad \text{Sinusoidal frequency} \quad \text{[cycles/second]} \]
\[ \delta \quad \text{Skin Depth} \quad \text{[meter]} \]
\[ \alpha \quad \text{Complex Inverse of Skin Depth} \]
\[ \theta \quad \text{Phase Angle} \quad \text{[degrees]} \]
\[ \phi \quad \text{Electric Potential} \quad \text{[volt]} \]
\[ H_s \quad \text{Surface Magnetic Field Intensity} \quad \text{[ampere/meter]} \]
\[ H_{av} \quad \text{Average Magnetic Field Intensity} \quad \text{[ampere/meter]} \]
\[ K_T \quad \text{Ratio of Exposed to Total Surface Area} \]
\[ P_p \quad \text{Proximity Effect Loss} \quad \text{[watt]} \]
\[ P_S \quad \text{Skin Effect Loss} \quad \text{[watt]} \]
\[ J_p \quad \text{Proximity Effect Current Density} \quad \text{[ampere/meter\(^2\)]} \]
\[ J_S \quad \text{Skin Effect Current Density} \quad \text{[ampere/meter\(^2\)]} \]
\[ F \quad \text{Skin Effect Geometrical Factor} \]
\[ G \quad \text{Proximity Effect Geometrical Factor} \]
\[ \eta \quad \text{Packing Factor} \]
\[ \xi \quad \sqrt{2} \text{ times inverse of Skin Depth} \]
\[ \upsilon \quad \text{Ratio of Height to Skin Depth} \]
Design of magnetic devices for electrical equipment is an art which spans a century. The first large-scale manufacturing installation for power transformers appeared in 1886, fifty five years after Michael Faraday's portentous experiments in which he demonstrated the basic principles of the transformer, inductor, motor and generator.

Today, manufacturing of power transformers is a major industry and designs are mostly driven by material and running costs while every effort is being made to reduce weight by taking full advantage of the materials at hand. The chief limitation on the core size is the maximum flux density of the core material, while close attention is given to heat removal in the windings of larger transformers. A general approach is to design for equal copper and iron losses and to use equal volume material.

The availability of semiconductor switching devices has made the transformer frequency a variable. Due to the fact that the size of reactive components and transformers decreases, almost in inverse proportion, with frequency, the switching frequency is, as a rule, chosen to be as high as possible. A turning
point was the development of the power MOSFET, almost twenty years ago, making it possible to construct switchmode power supplies operating in excess of 100 kHz. More recently advances in IGBT's, MCT's and SIT's have been ever pushing the switching frequency of higher power converters. At the higher frequencies ferrite becomes the preferred core material and eddy currents in the windings become a serious consideration.

Faraday's law states that a voltage will be induced in a conductor loop if it is subjected to a time-varying magnetic flux that links with it. The induced voltage, or electromotive force (emf), will produce a current in the closed conductive path. This is the basic principle that governs eddy currents in all electric frequency devices. The manifestation of eddy currents in magnetic devices, including electric machines, must be accounted for by the designer and investor. They produce heating due to ohmic losses which may result in degeneration or even total breakdown due to local overheating. Another manifestation of eddy currents is the forces arising from the interaction of the inducing and induced magnetic fields, which also may be detrimental to the device. Manufacturers of electric machines and transformers remedied this undesirable effect by laminating iron cores in devices, thus reducing the losses considerably. Eddy currents can also be beneficial in certain applications such as induction motors, electromagnetic brakes, induction heating, melting furnaces and metallurgical treatment, to name but a few.

I. Eddy Currents in Transformer and Inductor Windings

Concerning transformers and inductors, the generation of eddy currents in conductors is definitely undesirable due to the higher ohmic losses and the reduced cost effectiveness of the design owing to under utilization of materials.

Two approaches exist for the analysis and design of windings in high frequency transformers and inductors; namely by using numerical methods, usually a finite
Figure 2. The current distribution in an isolated foil conductor at 40kHz. The white and bright yellow regions indicate highest current densities and the cooler green to blue to purple regions indicate high to intermediate to low values. Note that the current concentrates near the edges of the conductor due to the skin effect.

Figure 4. The current density distribution in a strip conductor inside an airgapped core. The photograph uses the same colourcode as in Figure 2. Note that the current concentrates near the air gaps, where the surface magnetic field intensity is at its highest.
element method (FEM), or analytical by solving one dimensional closed form equations.

Consider an isolated foil conductor, as shown in Figure 1, which is infinitely long in space and carries a sinusoidal current $i(t)$. The penetration of the current in the foil is determined by the skin depth and the current decays exponentially as a function of penetration depth. The current distribution along the circumference of the foil is a complicated function and a general analytical equation has, as yet, not been derived.

The photograph in Figure 2 shows the current distribution of a foil conductor of dimensions $1 \times 20\text{mm}$ at $50\text{kHz}$ as obtained with a finite element program. The light yellow regions indicate areas where the highest current density occur, the cooler green to light blue to deep blue regions indicate high to intermediate to low values and the darker purple regions are for lowest current densities. Note that the current tends to concentrate near the edges of the foil conductor.

When a foil conductor is placed inside a gapped core, the major current concentration moves from
the corners to the middle of the conductor, close to the air gap, where a concentration of magnetic fringing flux exists. Figure 3 shows the configuration of an infinitely long foil conductor placed inside an infinitely long gapped core and the photograph in Figure 4 shows the cross sectional current distribution of this foil conductor at 50kHz.

A. Analytical Methods

Early important contributions in this field were done by Snelling [2] and Dowell [1]. Two dimensional eddy current solutions are generally intractable, limiting the scope of analytical methods. At the beginning of the boom in switching power supplies, papers were written by Jongsma [16] in which Dowell's equations are used in a practical high frequency winding design aid.

Contributions by Ferreira in references [3,4,5] generalized the application of the one dimensional solution by recognizing the orthogonality that exists between the skin- and proximity effect in symmetrical conductors [3,4] and extended the one dimensional solution to round conductors. He presented a generalized method to analyze litz wire [5]. This method develops a map of the magnetic field distribution inside the winding window, giving a solution method that permits fast results with flexible CAD programs [3]. These methods have all been successfully applied to design problems within their scope of accuracy. However, a flexible analytical method does not yet exist to analyze lateral current distributions of windings consisting of foil conductors. Mullineux [6] presented a rigorous approach, but its application is limited and numerical methods are required to solve the elliptic integrals.

The one dimensional techniques are investigated in chapter one. In addition, new and more flexible versions of the equations are derived for the current distribution and the losses in foil conductors.
B. Numerical Methods

Despite their ever-increasing sophistication, analytically based methods lack generality and are applicable to only a limited class of problems with simple geometric configurations. Other problems involving inhomogeneous media, nonlinearities or problems with complicated geometries are beyond the scope of analytical methods. For these problems, exact analytical solutions are not available and approximate methods are sought to overcome the drawbacks of analytical methods. Several numerical techniques exist and can be applied to more complicated problems, such as the finite difference method (FDM), weighed residual method (Galerkin's method), Rayleigh-Ritz method, finite element method (FEM) and boundary element method (BEM). All of the numerical methods involve discretizing of the problem field region into a number of subregions or elements and solving the governing equations for each in the system iteratively.

Analysing eddy current problems in windings using pure numerical methods is very time consuming and requires relatively powerful computers, because of the fine mesh required in each conductor. In the case of foil conductors, the current distribution along the height of the conductor is determined by the penetration ability of the electromagnetic fields into the conductor, which is very frequency dependent. The required number of elements is related to the skin depth and usually necessitates at least two or three elements within the least of one skin depth or the thickness of the foil. Therefore the numerical algorithms require a large number of elements over the cross section of all the conductors in order to compute an accurate solution, or for the solution to converge at all. Taking into account the fact that the thickness of the conductor is usually much smaller than its width and the other physical dimension of the construction, the numerical analysis of low voltage magnetic components is virtually impossible at sufficiently high frequencies. Further complications result when solutions are required for a number of different frequencies, as a new mesh must be generated
Nevertheless, numerical techniques, especially FEM, are considered to be the most versatile for analysing eddy current problems in conductors. In chapter two the finite difference method and the finite element method are considered for analysing these problems.

C. Combined Analytical and Numerical Method

In chapter three a new method is described to circumvent the fine mesh requirements by using a hybrid method employing a combination of numerical and closed form analytical solutions. The chapter also describes a CAD tool for inductors and transformers, called EddySim, that applies the hybrid method to solving eddy currents and the losses in windings consisting of wire, foils or litz wire.

II. High Frequency Transformer Design

At high frequencies, the occurrence of eddy currents in windings has far reaching implications with respect to transformer design as a whole, and specifically where a choice of different core types plays a role. A conventional approach to design is inadequate for high frequency power transformers and so far, a general design strategy does not exist for these applications.

A. Conventional Transformer Design

The most commonly used method for transformer design uses area products and has been in use since the 1920's. An improved version, the so-called "Kg approach", was proposed by McLyman [7,31]. Jansson [8] wrote a paper on the power capacity of transformers in which he introduced the formula for the
power capacity of the transformer:

\[ P_0 = X Y Z \]  

where \( X \) is the winding loss factor, \( Y \) is the core volts per turn, and \( Z \) is a type factor. The winding loss factor \( X \) includes the effects of ac resistance, and copper packing, and \( Y \) may include derating of the flux density at a higher frequency.

B. High Frequency Transformer Design

More recently the area products method has been applied to high frequency transformers by Coonrod [9]. This paper allows for the derating of the core flux excursion at higher frequencies, but does not include the effect of eddy currents in the windings. The design aid carries assumptions which comes from the old school of transformer design, which includes equal copper and core losses, as well as equal primary and secondary losses.

These approaches did not take cognizance of the following factors relating to high frequency transformers:

- \textit{At higher frequencies the relative cost of the transformer, as well as its contribution to the system losses decreases. It is not so important any more to have minimum losses or equal copper and core losses for that matter.}

- \textit{Reduction of transformer size at higher frequencies, (but for the same power capacity), also reduces the exposed surface area. The total exposed surface area for cooling becomes more important than copper and core cross sectional area.}

- \textit{Eddy currents, arising from the proximity effect between layers and}
conductors within windings, restrict the height of the winding window, giving rise to flatter transformers thereby moving away from the old boxy transformers.

- Transformers have always been one of the most expensive components in power converters. Manufacturability of transformers has become an important issue as is evident from the number of papers on this topic being presented at conferences.

The factors mentioned above have led to a substantial number of "unconventional" transformer designs, some of which are described in references [10-15]. It can in general be said that the classic design approaches are inadequate for the new generation of transformers.

C. Scant Modelling

Chapter four introduces a new approach to transformer design, called SCANT modelling, which is suitable for optimizing the new generation of transformers using interactive CAD software (see Figure 5). The scant model uses the one dimensional techniques described in chapter one to calculate winding losses, but is not tied by the normal difficulties involved with the physical construction of windings. This modelling technique allows interactive optimization of the shape and size of the transformer, while taking into account thermal effects accountable to eddy current losses in windings and core losses in relation to exposed cooling surfaces. The general model is described and applied to square core transformers.
Figure 5. The SCANT design method allows interactive optimization.
Analytical Techniques

The complexity of field problems for an exact solution of electromagnetic field quantities has lead to numerous analytical simplifications. Generally, the geometrical configuration is reduced to a two dimensional one with linear properties. A differential formulation of Maxwell's equations is then solved analytically to obtain closed form solutions.

The one dimensional method, introduced by Dowell [1], for calculating the current distribution in foil conductors, will be investigated in this section. This technique uses closed form solutions to determine skin- and proximity effect losses in winding sections. A new, more flexible version of the one dimensional equations, for both the losses and the current distributions, is also presented.
I. **Eddy Currents in terms of Maxwell's equations.**

The analytical solutions investigated in this section are derived from the differential formulation of Maxwell's equations. The field equations are manipulated into second order differential equations that are then solved to yield the analytically based solutions.

For time-varying fields the point forms of Maxwell's equations are:

\[ \nabla \times H = J + \frac{\partial D}{\partial t} \]  \(2\)

where

\[ J = \sigma E \]  \(3\)

\[ \nabla \times E = -\frac{\partial B}{\partial t} \]  \(4\)

\[ \nabla \cdot B = 0 \]  \(5\)

with

\[ B = \mu H \]  \(6\)

and

\[ \nabla \cdot D = \rho \]  \(7\)

with

\[ D = \varepsilon E \]  \(8\)

The material under consideration is assumed to be linear and homogeneous, and a frequency domain analysis is performed by assuming sinusoidal waveforms in the form \( K = K_m \cos(\omega t + \theta) \), where \( K_m \) is the peak value and \( \theta \) is the phase.
angle, and setting $\frac{\partial}{\partial t} = j\omega$.

Maxwell's equations then become:

$$\nabla \cdot E = \rho/\varepsilon$$  \hspace{1cm} (9)

$$\nabla \times E = -j\omega B$$  \hspace{1cm} (10)

$$\nabla \cdot B = 0$$  \hspace{1cm} (11)

$$\nabla \times B = j\omega \mu E + \mu J$$  \hspace{1cm} (12)

Substituting equation (3) into (12), it becomes:

$$\nabla \times B = (\sigma + j\omega \varepsilon)\mu E$$  \hspace{1cm} (13)

and substituting (10) into (13):

$$\nabla \times \nabla \times E = \nabla (\nabla \cdot E) - \nabla^2 E = -(\sigma + j\omega \varepsilon)j\omega \mu E$$  \hspace{1cm} (14)

Substituting (9) into (14), the following diffusion equation is obtained:

$$\nabla^2 E = \frac{1}{\varepsilon} \nabla \rho + (\sigma + j\omega \varepsilon)j\omega \mu E$$  \hspace{1cm} (15)

Similarly, an equation for $B$ can be obtained from (12) and (10) and recognizing that $\nabla \cdot B = 0$:

$$\nabla^2 B = j\omega \mu (\sigma + j\omega \varepsilon)B$$  \hspace{1cm} (16)
In equation (15) $\nabla \rho / \varepsilon$ refers to a static charge distribution in conductors that will generally be negligible. For frequencies in the kilohertz region, the term $-\omega^2 \varepsilon \mu$ in equations (14) and (15) that describes displacement current in conductors, is also ignored. The remaining term, $j \omega \sigma \mu$ is related to moving charges and therefore includes any eddy current effects.

With these simplifications, the following diffusion equations are obtained from equations (15) and (16):

$$\nabla^2 E - j \omega \sigma \mu E$$

and

$$\nabla^2 B = j \sigma \omega \mu B$$

II. One Dimensional Methods

The solutions described in this section apply to nonmagnetic conducting material acting as windings, or part thereof, in magnetic components. The one dimensional solution for the isolated foil conductor, (see references [1,3,4,17,18]), gives good insight into the principle of the one dimensional method and is therefore considered first. Insofar as the dimensions of the foil conductor are concerned, it is assumed that its thickness is much smaller than its width. (See Figure 6.)

Figure 6 Isolated foil conductor
A. Isolated Foil Conductor

An isolated strip conductor of thickness, $h$, width $w$, and carrying a peak current $I$, is shown in Figure 7. We seek a solution for the current distribution along the thickness of the foil and assume that it is part of an infinite loop so that its curvature is negligible and end-effects can be ignored. This implies that the magnetic fields are always perpendicular to current flow and parallel to the flat surface of the conductor.

For nonmagnetic conductive materials, $B = \mu_0 H$ inside the conductor and equation (18) is rewritten as:

$$\nabla^2 H = \alpha^2 H$$

where

$$\alpha = \frac{1 + j}{\delta}$$

and the skin depth is defined as follows:

$$\delta = \text{skin depth} = \frac{1}{\sqrt{\pi \sigma \mu_0}}$$
Equation (19) has a solution of the form:

\[
H_z = A_1 e^{ax} + A_2 e^{-ax}
\]  

(22)

Applying Ampere's circuital law and using the coordinate system indicated in Figure 7, yields the following boundary values:

\[
H_{sl} = -H_{s2} = \frac{I}{2w}
\]

(23)

Solving equation (22) for \( H \), the following solution is obtained:

\[
H_z = \frac{I \sinh ax}{2w \sinh \frac{ah}{2}}
\]

(24)

and recognizing that \( \frac{\partial}{\partial y} (H_z) = J_x \), a solution for the peak current density is given by: (See Figure 8)

\[
J_x = \frac{aI \cosh ax}{2w \sinh \frac{ah}{2}}
\]

(25)

The skin effect loss per unit length is given by:

\[
P_s = \frac{w}{2\sigma} \int_0^h |J_x|^2 \, dy
\]

(26)

\[
= \frac{I^2}{4w\sigma \delta} \frac{\sinh u + \sin u}{\cosh u - \cos u}
\]

where the subscript \( s \) is used to indicate the skin effect and

\[
u = \frac{h}{\delta}
\]

(27)
Figure 8. Current distribution across thickness of isolated foil.

Figure 9. Current distribution across thickness of foil subject to uniform magnetic field.

Suppose that a uniform magnetic field, $H_z \cos(\omega t)$, is applied to the surfaces of the strip conductor. The average magnetic field intensity across the cross section of the conductor is also equal to the applied field. Equation (24) then becomes:

$$H_z = H_z \frac{\cosh \alpha y}{\cosh \alpha \frac{h}{2}}$$

and the current density, given by equation (29), is shown in Figure 9. Note that
the observed step in the phase angle actually indicates a smooth transition across 180° from a positive- to a negative flowing current.

\[
J_x = J \frac{\sinh \alpha y}{\cosh \alpha \frac{h}{2}}
\]  

(29)

By applying the magnetic field at the foil surface, the skin effect is not present and the proximity effect loss per unit length is given by:

\[
P_p = \frac{w}{2\sigma} \int_0^h |J_x^2| \, dy
\]

(30)

\[
= \frac{wH_s}{\sigma \delta} \frac{\sinh \nu - \sin \nu}{\cosh \nu + \cos \nu}
\]

where the subscript \( p \) indicates proximity effect.

---

**B. Isolated Foil Conductor with Arbitrary Field at the Surfaces**

This section deals with the method followed by Dowell [1], where the current distribution inside the strip conductor (Figure 10), is derived without limitations on the value of the magnetic field on the conductor surface. This solution will then be manipulated in order to decouple the skin- and proximity effect current distributions from each other. Finally, the orthogonality principle [3,4] is used.
to distinguish between skin- and proximity effect losses to obtain a solution that will be an important stepping-stone to the hybrid method discussed in later chapters.

Using the fact that $J = \sigma E$, equation (17) reduces to:

$$\frac{\partial^2}{\partial x^2} (J_x) = \alpha^2 J_x$$

with $\alpha$ given by (20).

Equation (31) has a solution of the form:

$$J_x = A_1 \cosh \alpha y + A_2 \sinh \alpha y$$

Applying Ampere's circuital law yields:

$$H_{s2} - H_{sl} = \frac{I}{w}$$

Let

$$H_{sl} = \frac{(k-1)I}{w}$$

so that

$$H_{s2} = \frac{kI}{w}$$

Note that (33) and (34) do not impose any restrictions on the isolated foil, (k=½), but rather extends the scope of the analysis to include foils within winding sections. In this case $H_{s2} - H_{sl}$ may be seen as this particular foil's contribution to the total MMF of the winding section.
The magnetic field intensity inside the conductor along its thickness is given by:

\[
H_z(y) = \frac{1}{w} \left[ \frac{l(k-1)}{w} + \int_0^y J_x \, dy \right] 
\]  
(36)

and the magnetic flux density is:

\[
B_z(y) = \mu_0 \left[ \frac{l(k-1)}{w} + \int_0^y J_x \, dy \right] 
\]  
(37)

From equation (10) and substituting \( J = \sigma E \), we get:

\[
\frac{\partial J_x}{\partial y} = -j\omega \sigma B_z 
\]  
(38)

and substituting (37) into (38):

\[
\frac{\partial J_x}{\partial y} = j\omega \mu_0 \sigma \left[ \frac{l(k-1)}{w} \int_0^y J_x \, dy \right] 
\]  
(39)

Setting \( y=0 \):

\[
A_s = \frac{\alpha l(k-1)}{w} 
\]  
(40)

The total current is the integral along the plate thickness:

\[
I = w \int_0^h J_x \, dy = \int_0^h \left[ wA_1 \cosh \alpha y + \alpha l(k-1) \sinh \alpha y \right] \, dy 
\]  
(41)

Solving for \( A_1 \) yields:

\[
A_1 = \frac{\alpha l}{w} \left[ \frac{1}{\sinh \alpha h} - (k-1) \tanh \frac{\alpha h}{2} \right] 
\]  
(42)

Equation (32) then becomes:

\[
J_x(y) = \frac{\alpha l}{w} \left[ \frac{\cosh \alpha y}{\sinh \alpha h} - (k-1) \tanh \frac{\alpha h}{2} \cosh \alpha y + (k-1) \sinh \alpha y \right] 
\]  
(43)
C. The Orthogonality Principle

The built-in orthogonality that exists between the skin- and proximity effect losses in the well known one dimensional solution for the ac resistance of multi-layer windings, was first recognized by J.A. Ferreira and published in 1990. This solution, found in references [3] and [4], has certainly been the most significant result for the purpose of this work and deserves the following quote from the latter reference:

"It seems over a period of almost 50 years, since one dimensional analysis has been applied to multi-layer windings, many publications have appeared and the inherent orthogonality between skin effect and proximity has not been recognized. The orthogonality opens the way to new possibilities concerning analytical solution of eddy currents in magnetic components."

This section is a brief description of this result, that decouples the skin- and proximity effect losses. As part of this work, it will be shown in the following section that the orthogonality principle can be extended to also decouple the current density distribution due to the skin effect and proximity effects.

1. Decoupling the Skin- and Proximity Effect Losses

For sinusoidal waveforms, the conducting losses per unit length in a conductive lead are given by:

\[
P = \frac{1}{2\sigma} \int_A J J^* \, dA
\]

\[
eq \frac{1}{2\sigma} \int_A (J_s + J_p) (J_s^* + J_p^*) \, dA
\]

(44)

where \( J_s \) and \( J_p \) denote the skin- and proximity effect current densities respectively.

20
For the one dimensional analysis of a plate conductor having a plane of symmetry and an external magnetic field perpendicular to this plane, $J_s$ and $J_p$ display reciprocal symmetry to one another. Under these conditions $J_s$ is an even function and $J_p$ is odd, so that equation (44) becomes:

$$P = \frac{1}{2\sigma} \int_A (J_s J_s' + J_p J_p') \, dA$$

$$= P_s + P_p$$

$$= F I^2 + G H^2$$

where:

$$F = R_{DC} \frac{u}{4} \frac{\sinh u + \sin u}{\cosh u - \cos u}$$

and

$$G = w^2 R_{DC} \frac{u}{4} \frac{\sinh u - \sin u}{\cosh u + \cos u}$$

and the dc-resistance per unit length is given by:

$$R_{DC} = \frac{1}{\alpha hw}$$

Equation (45) holds for any conducting strip carrying a current peak $I$ and with known values of uniform magnetic field intensity on its surfaces.

2. Decoupling the Skin- and Proximity Effect Currents

Replacing $y$ with $y+h/2$ in equation (43) and after some manipulation (refer to Appendix D), it becomes:

$$J_s = \frac{\alpha I}{2w} \left[ \frac{\cosh \alpha y}{\sinh \frac{\alpha h}{2}} + (2k-1) \frac{\sinh \alpha y}{\cosh \frac{\alpha h}{2}} \right]$$
or:

\[ J_x = \frac{aI}{2w} \frac{\cosh ay}{\sinh \frac{h}{2}} + \alpha H_s \frac{\sinh ay}{\cosh \frac{h}{2}} \]  

(50)

where the average magnetic field across the foil thickness is given by:

\[ H_s = \frac{H_{s1} + H_{s2}}{2} = \frac{(2k-1)I}{2w} \]  

(51)

It is important to note that equation (45) is divided into the two components given respectively by equation (25) for skin effect and equation (29) for the proximity effect contributions to the current density. It is therefore the addition of two independent solutions of the current distribution - one for an isolated foil and the other for a single foil subjected to a uniform magnetic field.

Recognizing that the skin-effect coefficient, \( I/2w \), is simply the integral of the magnetic field intensities on the foil surface, we may also write equation (50) in terms of \( H \) only:

\[ J_x = \frac{H_{s2} - H_{s1}}{2} \frac{\cosh ay}{\sinh \frac{h}{2}} + \frac{H_{s1} + H_{s2}}{2} \frac{\sinh ay}{\cosh \frac{h}{2}} \]  

(52)

See Appendix A (I) to (III) for practical results obtained with this equation.

It should now be evident, that equation (45) may be written in similar form as equation (52):

\[ P = \frac{w^2 R_{dc}}{4} \left[ \frac{\sinh u + \sin u}{\cosh u - \cos u} \left[ H_{u1} - H_{u1} \right]^2 + \frac{\sinh u - \sin u}{\cosh u + \cos u} \left[ H_{u1} + H_{u2} \right]^2 \right] \]  

(53)

These last two results offer more alternatives in determining the two-dimensional current density distribution, magnetic field intensity distribution and the loss distribution in foils with non-uniform lateral current distributions such as those found in gapped core inductors. Numerical algorithms, especially finite elements,
combined with interpolation techniques, could produce sufficient solutions to these quantities without the fine mesh currently required within the conductor skin depth.

D. Multiple Layer Windings

![Position of zero MMF](image)

Figure 11 The analysis is performed on the \( m \)th foil from the zero MMF position.

If the foil conductor, with current \( I \), is part of a winding section as depicted in Figure 11, then the magnetic field distribution inside the winding window may be calculated using a linear MMF mapping as shown in Figure 12. Here it is assumed that the winding fills the entire width, \( w \), of the window, and that all

![One dimensional MMF diagram](image)

Figure 12 One dimensional MMF diagram.
magnetic fields are parallel to the surface of the conductors. For these assumptions, the MMF diagram in Figure 12 is obtained by calculating the ampere-turns product, or the per unit width magnetic field intensity along the height of the winding.

Using the MMF-distribution diagram, the average magnetic field across the \( m \)th foil is given by:

\[
H_m = \frac{(2m-1)I}{2w}
\]  

(54)

Using equation (45) to calculate the losses in the \( m \)th foil, we get:

\[
P_m = FI^2 + GH_m^2
\]  

(55)

i.e:

\[
P_m = R_{DC} \frac{u}{4} \left( \frac{\sinh u + \sin u}{\cosh u - \cos u} \right) I^2
\]  

\[
+ w^2 R_{DC} \frac{u}{\cosh u + \cos u} \left[ \left( \frac{m - \frac{1}{2}}{w} \right) I \right]^2
\]  

(56)

The dc resistances of all the foils in the winding are equal, so that the subscript, \( m \), can be omitted from \( R_{DC} \), but the ac resistance per unit length of the \( m \)th foil is obtained by dividing by \( I/2 \):

\[
R_{ACm} = R_{DC} \frac{u}{2} \left[ \frac{\sinh u + \sin u}{\cosh u - \cos u} + (2m-1)^2 \frac{\sinh u - \sin u}{\cosh u + \cos u} \right]
\]  

(57)

For inductor windings and windings where the zero-MMF line is in the centre of the winding section, the first foil is also specified as the one nearest or on the zero-MMF line with \( m = s, s+1, \ldots, n-1, n \) where:

\[
s = \begin{cases} 
0 : N \text{ is uneven} \\
1 : N \text{ is even} 
\end{cases}
\]  

(58)
It is possible to obtain the same result for $R_{ac}$ via a simple form of the Poynting theorem:

$$-\frac{1}{2} \int_{S} (E \times H^*) \cdot dS = -\frac{w}{2} \left[ (EH^*)_{y=\xi_2} - (EH^*)_{y=\xi_3} \right]$$

$$= -\frac{w}{2a} \left[ J_x(-\xi/2) H_{s_1}^* - J_x(\xi/2) H_{s_2}^* \right]$$

$$= \frac{1}{2} Z_i I^2$$

Where $S$ represents the surface of the conductor and $H_{s_1}$ and $H_{s_2}$ are the magnetic fields on the left- and right-hand conductor surfaces respectively. The ac resistance is then obtained by taking the real part of $Z_i$. The surface impedance obtained above is also known as the internal impedance of the conductor and includes its contribution to the winding leakage inductance associated with the flux cutting the conductors. Note that all the flux in the winding window must be accounted for to calculate the total leakage inductance of the transformer.

### E. Round Wire Windings

![Figure 13 Representation of round conductors by replacing them with square conductors.](image)
To facilitate round wire windings, Dowell replaced each round conductor with a square one having the same cross sectional area. The gaps between adjacent square conductors are accounted for by defining a packing factor, $\eta$, as shown in Figure 13, thus keeping the current density constant. With these modifications, each layer of round conductors in a winding section is treated as a foil conductor (having the same current density as the original round conductor) so that

$$I_{sq} = \frac{w}{t} I$$

(61)

where $I_{sq}$ denotes the current in the original round conductor, and $I$ is the current in the foil consisting of equally spaced square conductors.

The average magnetic field across the $m$th layer, using Figures 11 and 12, is then:

$$H_m = \eta (m - \frac{1}{2}) I$$

(62)

and using the orthogonality principle, the ac resistance value for the $m$th layer is found to be:

$$R_{AC_m} = R_{DC} \frac{\xi}{2} \left[ \frac{\sinh \xi + \sin \xi}{\cosh \xi - \cos \xi} + \eta^2 (2m - 1)^2 \frac{\sinh \xi - \sin \xi}{\cosh \xi + \cos \xi} \right]$$

(63)

where

$$\xi = \frac{\sqrt{\pi} d}{2 \delta}$$

(64)

(See references [1,4])
The Geometrical Skin Depth

The packing factor, $\eta$, involves a second dimension in the one dimensional solution. The conductivity is effectively decreased by the factor $\eta$ and Dowell accommodated this feature by introducing a geometrical skin depth, $\delta(\eta)$, to facilitate the change in the total voltage drop over the cross section of the conductor:

$$\delta(\eta) = \frac{1}{\sqrt{\eta \sigma \pi / \mu}} \quad (65)$$

Dowell obtained the surface impedance, $Z_s$, of the $m$th layer using a procedure identical to the one involving the Poynting theorem, by calculating the sum of the resistive- and induced voltage drops on the conductor edges which are furthest from the zero-MMF line, and dividing by the current $I$. Using this approach, Dowell obtained the ac resistance, or $\Re(Z_s)$, of the $m$th round wire layer follows:

$$R_{ac} = \Re \left[ \alpha h R_{dc} \left( \coth(\alpha h) + 2m(m-1) \tanh(\alpha h/2) \right) \right] \quad (66)$$

or:

$$R_{ac} = R_{dc} \frac{\xi(\eta)}{2} \frac{\sinh \xi(\eta)+\sin \xi(\eta)}{\cosh \xi(\eta)-\cos \xi(\eta)} + (2m-1)^2 \frac{\sinh \xi(\eta)-\sin \xi(\eta)}{\cosh \xi(\eta)+\cos \xi(\eta)} \quad (67)$$

where

$$\xi(\eta) = \frac{\sqrt{\pi} \cdot d}{2 \cdot \delta(\eta)} \quad (68)$$

Strictly speaking, the modification built into the geometrical skin depth deviates from the one dimensional frame, for it was previously shown that the current distributes itself across the height of the foil as a function of the magnetic field intensity only, without any adjustment to $\alpha$ and $\nu$. In some instances however,
the geometrical skin depth offer a more accurate approximation in practical terms, increasing the surface impedance of individual leads and thus compensating to a certain degree for the proximity effect losses between these leads within a layer.

*In Appendix A paragraph IV, the geometrical skin depth is further investigated by means of two examples.*
The availability of faster and more powerful computer processors over recent years has paved the way towards accurate modelling and simulation of increasingly complex problems. Advances in the field of numerical methods, especially Finite Elements, have made it possible to obtain sufficiently accurate answers to sophisticated problems and these methods are now recognized as convenient means to simulate and analyze two- and three-dimensional electromagnetic problems.

This section gives a brief description of two dimensional numerical techniques, particularly finite differences and finite elements, as methods to analyze eddy currents in conductors of inductors and transformers.
I. Maxwell's Equations in terms of Potentials

In eddy current problems, potentials are easily calculated using numerical algorithms and are therefore frequently used as auxiliary functions in the computational process. (See references [17,18,21]). Neglecting displacement currents in problems where the frequency is sufficiently low, it can be shown that the relation \( \nabla \times \mathbf{B} = 0 \), is satisfied automatically by using the magnetic vector potential, \( \mathbf{A} \) (or MVP), determined as:

\[
\mathbf{B} = \nabla \times \mathbf{A}
\]  

(69)

In accordance with equation (4), the scalar potential, \( \phi \), is defined as follows:

\[
\mathbf{E} = -\nabla \phi - \frac{\partial \mathbf{A}}{\partial t}
\]  

(70)

Substituting (6) and (2) one obtains:

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{J}
\]  

(71)

and substituting (3) and (70) into (71):

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{A} \right) = -\sigma \left( \nabla \phi + \frac{\partial \mathbf{A}}{\partial t} \right)
\]  

(72)

Consider a linear medium with constant permeability:

\[
\nabla \times \nabla \times \mathbf{A} = -\sigma \mu \left( \nabla \phi + \frac{\partial \mathbf{A}}{\partial t} \right)
\]  

(73)

The current density, \( \mathbf{J} \), is composed of two components, namely an externally impressed source current density and an eddy current component:

\[
\mathbf{J} = \mathbf{J}_s + \mathbf{J}_i
\]  

(74)

where

\[
\mathbf{J}_s = -\sigma \nabla \phi
\]  

(75)
is the source current density representing the electrostatic effects of surface charges and

$$J_s = -\sigma \frac{\partial A}{\partial t}$$  \hspace{1cm} (76)$$

is the internally generated induction component. (See Figure 14)

![Figure 14](image)

**Figure 14.** The source current density, $J_s$, and induced eddy current density, $J_i$, for a round conductor carrying a total current $I$.

For a source-free region, equation (73) reduces to the diffusion equation:

$$\nabla^2 A = \mu \sigma \frac{\partial A}{\partial t}$$  \hspace{1cm} (77)$$

For two dimensional problems the assumption is made that transverse electric fields do not exist so that no $z$-components are imminent in $A$ or $J$. The potential gradient is also a constant over the cross-section of a conducting region and equation (72) becomes:

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = \sigma \mu \left( \frac{\partial \phi}{\partial z} + \frac{\partial A}{\partial t} \right) = -\mu \left( J_s + J_i \right)$$  \hspace{1cm} (78)$$

Adopting phasor notation for sinusoidal waveforms in equation (78), it becomes:

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = \sigma \mu \left( \frac{\partial \phi}{\partial z} + j\omega A \right) = j\omega \sigma A - \mu J_s$$  \hspace{1cm} (79)$$
II. The Finite Difference Method (FDM)

One of the older and well-known numerical methods, is the FDM [18,21,23]. In essence, the FDM consists of superimposing a grid on the space-time domain of the problem, usually confined within specific boundary conditions, and assigning discrete values of the unknown field quantities at the nodes of the grid. The governing equation is replaced by a set of finite difference equations relating the value of the field variable at the node to the value at the neighbouring nodes. These equations are then iteratively applied to every node in the mesh until a solution for every node is obtained, that satisfy the governing equation.

For eddy current solutions in inductor and transformer windings, the FDM is used to simultaneously solve for the magnetic vector potential, $A$, and the electric scalar potential gradient, $\nabla \phi$, while keeping the integral of current density, across every isolated current carrying cross-sectional region, constant. Note that all field quantities in the following section are represented using phasor notation and are therefore complex values.
Figure 15 shows part of a non-uniform grid with a node \((i,j)\) and its associated point-area indicated by the shaded region. Node \((i,j)\) has a magnetic vector potential, \(A_{ij}\), and writing first and second order derivatives for \(A\) at node \((i,j)\) with respect to \(x\) and \(y\), they are:

\[
\frac{\partial A}{\partial x} = \frac{A_R - A_L}{\Delta x + \Delta x_L} \quad \frac{\partial A}{\partial y} = \frac{A_B - A_T}{\Delta y + \Delta y_T} \tag{80}
\]

and

\[
\frac{\partial^2 A}{\partial x^2} = \frac{A_R - A - A_L}{\Delta x + \Delta x_L} \quad \frac{\partial^2 A}{\partial y^2} = \frac{A_B - A - A_T}{\Delta y + \Delta y_T} \tag{81}
\]

Substituting equation (81) into equation (79) and rearranging, we obtain the finite difference solution for \(A_{ij}\):

\[
A_{ij} = \frac{A_R}{\Delta x (\Delta x + \Delta x_L)} + \frac{A_L}{\Delta x (\Delta x + \Delta x_L)} - \frac{A_B}{\Delta y (\Delta y + \Delta y_T)} - \frac{A_T}{\Delta y (\Delta y + \Delta y_T)} \frac{P J_s}{2} \tag{82}
\]

A. Current Restrictions

In order to apply equation (82), it is necessary to obtain a solution for \(V\phi\) in terms of \(J_s\) at every node in the mesh. As previously noted, the electric scalar potential that exists in conducting regions only, is a constant for every insulated (and non-parallel) conductor cross-section. Therefore, the value of \(J_s\) is also constant for all the nodes representative of such a region.

To calculate \(J_s\) in an insulated conductive region, current restraints are imposed in order to keep the total current flowing in that region constant so that:

\[
I_{\text{total}} = \int_S (J_l + J_s) \, dS \tag{83}
\]
B. Boundary Conditions

For high permeability core material, and with the understanding that we are only interested in the magnetic field distribution inside the winding window, it is not necessary to include the core as part of the mesh. Instead, boundary conditions are imposed along the core-window interface and along the lengths of any air gaps that may be present. They are, respectively:

- \textit{Neumann} boundaries and
- \textit{Dirichlet} boundaries.

In order to implement these conditions for the FDM, the permeability of the core is assumed to be infinite. It is assumed that fringing in the air gaps occur in the winding window alone and not into the space surrounding the structure, so that magnetic fields follow a straight line across an air gap linking the outer surfaces along the gapped side-leg of, for instance, an E-core. The cross section under consideration is a symmetrical one, so that it is only necessary to consider one of the windows. For such a configuration the magnetic field in the middle of the inner yoke will always follow a straight line across an air gap.

![Figure 16. The Dirichlet and Neumann boundaries in a winding window.](image-url)
Along the boundaries between the core and window, the magnetic field has only normal components and Neumann boundaries, or images, are used to keep the tangential components zero.

The Dirichlet boundaries are implemented in the air gaps, if any, where the value of the MVP or the magnetic field intensity is known from the MMF distribution:

$$I_{tot} = \oint H \cdot dl$$

where $I_{tot}$ is the total current in the winding window.

Using equations (69) and the relation $B = \mu H$, and recognizing that the current flows in the z-direction only, equation (84) becomes:

$$\oint \left( \frac{\partial A}{\partial y} \hat{x} - \frac{\partial A}{\partial x} \hat{y} \right) \cdot dl = \mu I_{tot}$$

If two air gaps are present in the window, then we assume that the MMF is divided equally between them in accordance with the gap length to air gap area ratios.

For the boundaries in the left- and right-hand air gaps, respectively, in Figure 16, equation (85) reduces to:

$$\frac{\mu I_{tot}}{2 \ (NNg-1)} = \left( \frac{A_y - A}{\Delta x} \right) \quad \frac{\mu I_{tot}}{2 \ (NNg-1)} = \left( \frac{A - A_z}{\Delta x_z} \right)$$

Where $NNg$ represents the number of nodes along the air gap boundary line, and the right hand sides of the equations uses the notation in Figure 15. To accommodate finite permeability, all the Neumann boundaries on the window-core interface can be replaced with Dirichlet boundaries using the same procedure and equation (84). The MMF-distribution along all boundaries can be calculated using a reluctance model of the core and air gaps.
The Finite Element Method (FEM) appears to be the most powerful numerical method for its versatility and basically consists in constructing coordinate functions whose linear combinations approximate the unknown solutions. This section gives a brief description of the FEM for the analysis of eddy currents in conductors. For a detailed discussion of this subject, the reader may consult references [21, 24].

The finite element analysis of eddy currents involves four basic steps:

1) Discretizing the problem region into a finite number of subregions and elements, usually triangles. (See Figure 17)

2) Deriving the governing equations for the elements. The accuracy of the approximation can be improved by either subdividing the problem space into more elements, or using higher-order elements such as quadrilateral elements.

3) Assembling of the elements in the solution region and definition of boundary conditions.

4) Solving the system of equations.

Figure 17. A region divided into a number of triangular elements.
As far as eddy currents in conductors are concerned, the FEM once again solves for the MVP, $A$, and the electric scalar potential gradient, $\nabla \phi$ from Poisson's equation:

$$\nabla^2 A = -\mu J$$  \hspace{1cm} (87)

For the triangular element, $e$, in Figure 18, it can be shown that the MVP, $A$, is approximated by a linear combination of the form:

$$A_e(x, y) = \sum_{i=1}^{3} A_{ei} \alpha_i(x, y)$$  \hspace{1cm} (88)

where

$$\alpha_1 = \frac{1}{2S} \left[ (x_2 y_3 - x_3 y_2) + x (y_2 - y_3) + (x_3 - x_2) y \right]$$

$$\alpha_2 = \frac{1}{2S} \left[ (x_3 y_1 - x_1 y_3) + x (y_3 - y_1) + (x_1 - x_3) y \right]$$

$$\alpha_3 = \frac{1}{2S} \left[ (x_1 y_2 - x_2 y_1) + x (y_1 - y_2) + (x_2 - x_1) y \right]$$  \hspace{1cm} (89)

and

$$2S = \begin{vmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{vmatrix}$$  \hspace{1cm} (90)

Unlike the finite difference analysis, equation (90) gives the MVP anywhere...
inside the element instead of at vertices only. The MVP is defined positive if the
nodes are counted counter-clockwise as shown by the arrow in Figure 18. The
properties of the linear interpolation functions, \( \alpha_i \), also known as the element
shape functions, (see Figure 19), are given by:

\[
\alpha_i (x_j, y_j) = \begin{cases} 
1 & i = j \\
0 & i \neq j 
\end{cases}
\sum_{i=1}^{3} \alpha_i = 1
\]

(91)

Figure 19. Graphical presentation of the shape functions.

Under Neumann and Dirichlet boundaries, and following the calculus of
variations, the solution for the two-dimensionally reduced diffusion equation
(87), is given by:

\[
W_e = \int_\Sigma \left\{ \frac{1}{\mu} (\nabla A)^2 + j\omega \sigma A^2 - 2J_e \right\} dS
\]

(92)

Substitution into (88) gives the energy contributed by the element \( e \), where the
subscript \( e \), has been omitted for clarity:

\[
W = \frac{1 + j\omega \sigma}{2} [A]^T [S] [A] - [A]^T [T] [G]
\]

(93)
where \( [A] \) is the column vector of the MVP at the vertices and \([S]\) and \([T]\) are square matrices with the elements given by:

\[
s_y = \frac{1}{\mu} \int_{S_v} \mathbf{v}_{i} \cdot \mathbf{v}_{j} \, dS
\]

(94)

and

\[
i_y = \int_{S_v} \alpha_i \cdot \alpha_j \, dS
\]

(95)

and \([G]\) is a column vector given by:

\[
g_i = \sum_{j=1}^{3} J_{ji}
\]

(96)

The governing equation for each element is then derived from the energy function as:

\[
\{ [S] + j \omega \sigma [T] \} [A] = [T] [G]
\]

(97)

If the above procedure is repeated for all elements, then a global finite element matrix is obtained in the same form as equation (97), with \([A]\) being the column vector of the unknown values of the MVP at the active nodal points.

**A. Current Restrictions**

Similar to the finite difference analysis, current restrictions are required across the cross-sections of active conductors in order to keep the total current flowing constant and to calculate the value of \( \phi \) across such a region. Applying Galerkin's method [21], the following element equation is obtained for the element \( e \):

\[
\left\{ [S] + j \omega \sigma [T] - \frac{j \omega \sigma}{S} [T] [W] \right\} [A] = [T] [G]
\]

(98)

where \([W]\) is the column vector containing the area-weights of the nodes from
Numerical Methods

the quadrature formula of $e$:

$$\int_\mathcal{S}A\,ds = \sum_{i=1}^{3} w_i A_i$$  \hspace{1cm} (99)

\textbf{IV. Effect of Skin Depth on Mesh Size}

The generation of the mesh for eddy current problems is a complex procedure due to the skin effect and the resulting restriction on the minimum size of elements at high frequencies. The current density distribution becomes an increasingly steep function as it reaches the surface of the conductor, resulting in a minimum number of elements, (usually three for FEM and five for FDM), required within one skin depth from the conductor boundary. A typical finite element mesh for a plate wound inductor is shown in Figure 20. As shown, the mesh were generated for a symmetrical construction so that only a quarter of one winding window, together with Dirichlet and Neumann boundaries was needed for the FEM.

At high frequencies and for magnetic components for which the physical dimensions is much larger than those of the conductive filaments inside them, i.e. litz- or tape-wound structures, these restrictions demand a large amount of
elements in order to find a solution and therefore slows the convergence speed dramatically due to the increased sizes of the matrices that need to be solved for each iteration. Sometimes the amount of storage capacity needed may even exceed that of the computer at hand, necessitating redefinition of the problem, or part thereof.

Figure 21. A progressively fine mesh reduces the number of elements required at different frequencies.

Another implication is the difference in the meshes required for solutions at more than one frequency. In order to overcome this problem, a progressively fine mesh may be used, as shown in Figure 21. However, this method is also limited to a frequency band (typically 0Hz to 1MHz), for which the solution will still be accurate.

Figure 22. A gapped foil winding transformer and its mesh for a combination of the FDM and analytical techniques.
In the next chapter, a *new method* will be described where the finite difference method is used in conjunction with an extension of the analytically based methods from the previous chapter. It will be shown that this method leads to a substantial reduction in the number of nodes required and that the effect of skin depth on the size of elements becomes insignificant (see Figure 22).
Combined Analytical and Numerical Method

High frequency modelling of two dimensional eddy current problems using numerical techniques requires relatively powerful computers with large storage capacities and fast processing speeds. At frequencies in the kilohertz range, the skin- and proximity effects become small compared to the structural dimensions, leading to substantial increases in the number of nodes in the mesh.

This section introduces a technique that separates the high frequency effects related to individual conductors from those related to the winding characteristics and general configuration. The technique involves numerical procedures to find a mapping of the magnetic field distribution inside the winding window and then applying one dimensional methods to calculate losses due to eddy current effects in windings. This leads to a substantial reduction in mesh size for the numerical solution.

The method has been implemented in a CAD tool, called EddySim, for magnetic components with windings consisting of foil conductors, round wire or litz wire.
I. **Introduction**

The preceding chapters have shown that the skin- and proximity effect losses in homogeneous winding sections can be solved independently from each other and that the total losses can be written as:

\[ P_{\text{total}} = F I^2 + G H^2 \]  \hspace{1cm} (100)

where \( F \) and \( G \) are functions related to the type of winding, filament dimensions and the given frequency. Furthermore, it was shown that a strictly one dimensional solution becomes inaccurate when the peak value of the oscillating magnetic fields on the surface of a foil are not constant along its width.

![Diagram of a foil conductor with non-uniform oscillating surface magnetic field intensities for a given configuration.](image)

**Figure 23.** A foil conductor with non-uniform oscillating surface magnetic field intensities for a given configuration.
In chapter one, more flexible versions of the one dimensional equations were developed, for predicting the current distributions in foils with *non-uniform surface magnetic fields* (Figure 23) due to the physical construction of the component, such as the inclusion of one or two air gaps. These equations predict the solution for the current distribution along a particular line segment over the height of a foil cross section, with the aid of a final solution of the surface magnetic field intensity at the ends of the line. It was shown that these equations give **exact** solutions of the current distribution, provided that the magnetic field intensity on the conductor surface is a known function (See Appendix A).

Chapter one also introduced a similar variation on equation (100), the solution of the per unit length power dissipation in a foil:

\[
P = w^2 R_{DC} \frac{v}{4} \left[ \frac{\sinh v + \sin v}{\cosh v - \cos v} \left[ H_{s1} - H_{s2} \right]^2 + \frac{\sinh v - \sin v}{\cosh v + \cos v} \left[ H_{s1} + H_{s2} \right]^2 \right]
\]

where \( w \) is the foil width, \( R_{DC} \) is its dc resistance, \( H_{s1} \) and \( H_{s2} \) are the tangential components of the surface magnetic field intensities and

\[
u = \frac{h}{\delta} = \text{foil thickness/skin depth}
\]

Equation (102) was obtained by integrating the current distribution function and is valid for a foil with arbitrary but **uniform oscillating surface magnetic fields**, \( H_{11} \) and \( H_{12} \).

For a **non-uniform surface magnetic field distribution** along the foil width as in Figure 23, we may write the contribution of the losses at a line segment AB by dividing equation (2) by \( w \):

\[
P_{AB} = \frac{1}{4\sigma \delta} \left[ \frac{\sinh v + \sin v}{\cosh v - \cos v} \left[ H_A - H_B \right]^2 + \frac{\sinh v - \sin v}{\cosh v + \cos v} \left[ H_A + H_B \right]^2 \right]
\]

where \( H_A \) and \( H_B \) are the values of the surface magnetic field intensities at points A and B respectively. Note that equation (103) gives the **power**
dissipation per unit length \textit{per unit width} in \textit{watt / m$^2$}.

Equations (101) and (103) gives accurate predictions of the power dissipation provided the analytical solution of the current density distribution is accurate and the previously described requirements are met.

This variation on the one dimensional technique, provides a good foundation for developing a new hybrid method that combines the two dimensional numerical methods described in chapter two with the above mentioned one dimensional analytical solutions from chapter one. This hybrid method uses the analytical method to determine the losses in conductors related to the physical properties of the individual conductors, using the numerical procedure to calculate the magnetic field solution related to the physical construction and placement of the windings and core. It therefore eliminates the need to solve for the current distribution within the individual conductors, which is related to the skin depth requiring a very fine mesh at high frequencies.

\textit{This chapter deals with the implementation of this hybrid method for two dimensional modelling of eddy currents in transformer- and inductor windings.}

\textbf{Figure 24.} The problem domain, which includes the winding window and air gaps, for a gapped transformer core with two windings and a typical mesh superimposition.
The hybrid method, that combines the analytical and numerical procedures involves two basic steps:

1) A mapping of the magnetic field distribution and the current densities inside the winding window are obtained numerically with a coarse mesh imposition on the problem domain as shown in Figure 24. Conductors are not considered individually so that Litz- or wire windings are treated as if they own uniform current densities. It is however, necessary to solve for the lateral current distribution in foil windings.

2) This solution for the magnetic field distribution is then used to obtain the skin- and proximity effect losses in individual conductors with a linear approximation of the one dimensional solution on every element.

II. Foil Windings: The Lateral Current Distribution

The strictly one dimensional solution becomes inaccurate for foils with a non-consistent lateral current distribution in the presence of air gaps or when the condition \( w/h > 1 \) is not met for foils. If the average magnetic field, \( H_{av} \), over a particular cross section of a foil is known, so that the skin-effect term can be written in terms of \( H_{av} \) instead of \( I \), (See equations (52) and (53) in chapter one), precise agreement is obtained between the one dimensional- and finite element methods. In the FDM implementation for foil windings, it is therefore necessary to obtain both the average current densities and average magnetic fields over a finite number of divisions over the cross-section of each conductor.

To simply matters even further, a foil winding section can be divided into a finite number of elements without consideration for the individual foil conductors, so that there may be less elements than foils over the height of the winding section, as depicted in Figure 24. This simplification is justified by the fact that the magnetic field envelope over a winding window is not a strong
function of the current distributions in closely-packed windings, but rather arranges itself according to the structural dimensions of the window and the positioning and dimensions of the windings.

Figure 25. The magnetic field envelope for a loosely spaced 6-turn foil winding at 50kHz.

Figure 25 shows a three dimensional view of the magnetic vector potential in a winding window, (excluding the air gaps), for a high frequency foil inductor, which were obtained using the FEM. This so-called "magnetic field-envelope" is a smooth function and does not contain irregularities at the boundaries of individual conductors which, in this case, consisted of 6 loosely spaced foils.

Figure 26. For conductors, the mesh is shifted so that a node falls within its element area, never on a conductor boundary.
Figure 26 shows part of a grid that has been super-imposed over a foil winding. Note that the grid is redefined so that the intersections of gridlines, or nodes, never fall on conductor boundaries. In effect, the same mesh is used as the one described in the previous chapter, but the boundaries of conducting bodies are defined as being halfway between nodes adjacent to these boundaries so that the average current density and magnetic field intensity is calculated at the same positions where the MVP is calculated.

![Diagram showing grid and conductor boundaries](image)

Figure 27. In this mesh, the current density in an element and MVP are shifted relative to each other.

These adjustments to the mesh eliminate the need to test for the existence and orientation of any boundaries during the relaxation procedure and significantly improves the iterative process. It allows a finite conductivity to exist in a conductive element within a conducting region as opposed to having nodes on conductor boundaries such as shown in Figure 27, where it is a burdensome task to determine whether the conductivity should be finite or zero. The commonly used mesh, described in the previous chapter, also causes a relative shift to occur between the current in an element and the responsible MVP, resulting in an inaccurate mapping of the magnetic field envelope.

Using the notation shown in Figure 28, the lateral current distribution is calculated with the FDM numerical algorithm, by treating each row of elements,
$j$, as an insulated conducting region. The total current flowing in row $j$ is also restricted so that:

$$\sum_{i=1}^{n} J_{ij} \, dy \, dx = \frac{dy}{b} \, I_{ne}$$

(104)

This restriction, in effect, characterizes the average field envelope according to this type of winding, neglecting contributions of current distributions due to skin effect and proximity effect across the smaller of conductor dimensions. Note that the current density obtained for every element is therefore different from the average current density in the foil and an adjustment will be required for the analytical solution.

Figure 28. Notation used for a mesh superimposition over a N-turn foil winding.

Once a solution for the current density, MVP, and magnetic field intensity has
been obtained for every element in the grid, the total power dissipation due to
the skin- and proximity effect losses in the node \((i,j)\) is calculated as follows:

\[
P_y = \frac{N_{dy}}{b} \left[ F(dx_i, h, \sigma, \delta) \left( \frac{b}{N_{dy}} J_y dx_i dy_j \right)^2 + G(dx_i, h, \sigma, \delta) H_y^2 \right] \tag{105}
\]

where

\[
F(dx_i, h, \sigma, \delta) = \frac{1}{4dx_i \sigma \delta} \left[ \frac{\sinh h + \sin h}{\cosh h - \cos h} \right] \tag{106}
\]

and

\[
G(dx_i, h, \sigma, \delta) = \frac{dx_i}{\sigma \delta} \left[ \frac{\sinh h - \sin h}{\cosh h + \cos h} \right] \tag{107}
\]

III. **Round- and Litz Wire Windings**

For windings consisting of either round filaments or filaments consisting of a
number of litz strands, a relatively accurate mapping of the magnetic field
intensity in the winding window is obtained numerically by assuming a uniform
current density in the winding section. The skin- and proximity effects are then
once again calculated using one dimensional analytical solutions.

Chapter one introduced Dowell's method [1] to include round conductors in
winding sections, by replacing them with square conductors having equal cross-
sectional areas (See Figure 29). In the combined method the same approach will
be used to calculate the losses in round wire windings. However, instead of
keeping the average current densities in the round conductors equal to that of
the transformed foil conductor, the total current in the winding section will be
retained so that it is not necessary to adjust the magnetic field intensity by the
layer width packing factor, $\eta$.

Using the same procedure as in the previous paragraph for node $(i,j)$ in the mesh shown in Figure 30, we may write:

$$ P_y = \frac{1}{\eta} \frac{N_{dy} b}{\eta} \left[ \left( \frac{\eta b}{N_{dy}} \right) F_w(dx_p, d, \sigma, \delta) + H_y^2 G_w(dx_p, d, \sigma, \delta) \right] \tag{108} $$

where:

$$ F_w(dx_p, d, \sigma, \delta) = \frac{1}{4d x_1 \sigma \delta} \left[ \sinh \xi + \sin \xi \right] \cosh \xi - \cos \xi \tag{109} $$

and

$$ G_w(dx_p, d, \sigma, \delta) = \frac{dx_1}{\sigma \delta} \left[ \sinh \xi - \sin \xi \right] \cosh \xi + \cos \xi \tag{110} $$

and

$$ \xi = \frac{\sqrt{\pi} d}{2 \delta} \tag{111} $$

where $d$ is the wire diameter and $\delta$ is the skin depth.
The methods described in this section for combined numerical and analytical solutions of windings consisting foils and layers of round wire or square conductors, offers quick approximate solutions and require less computing power than pure finite elements at high frequencies. The same principles can be applied to windings consisting of layers of litz wire, where the finely divided or litz wire would require a very large number of elements or mesh points, which makes a direct numerical solution virtually impossible.

As an alternative to the round-to-square transformation method, references [3] and [4] suggests a more accurate analytical prediction by applying the orthogonality principle to the exact analytical solution of ac to dc resistance ratio.
of round conductors. For the mth layer in a round wire winding:

\[ R_{AC} \frac{R_{DC}}{R_{AC}} = \gamma \left[ \frac{\text{ber}_\gamma \text{bei}_\gamma - \text{bei}_\gamma \text{ber}_\gamma}{\text{ber}_2^2 \gamma + \text{bei}_2^2 \gamma} - \frac{2\pi(2m-1)^2 \text{ber}_2 \gamma \text{ber}_2 \gamma + \text{bei}_2 \gamma \text{bei}_2 \gamma}{\text{ber}_2^2 \gamma + \text{bei}_2^2 \gamma} \right] \]  \tag{112}

where

\[ \gamma = \frac{d}{\delta \sqrt{2}} \]  \tag{113}

and the losses per unit length for a single conductor are:

\[ P_{\text{round}} = F_{\text{round}} I^2 + G_{\text{round}} H^2 \]  \tag{114}

where

\[ F_{\text{round}} = \frac{\gamma}{\pi \sigma d^2} \frac{\text{ber}_\gamma \text{bei}_\gamma - \text{bei}_\gamma \text{ber}_\gamma}{\text{ber}_2^2 \gamma + \text{bei}_2^2 \gamma} \]  \tag{115}

and

\[ G_{\text{round}} = \frac{-2\pi \gamma}{\sigma} \frac{\text{ber}_2 \gamma \text{ber}_2 \gamma + \text{bei}_2 \gamma \text{bei}_2 \gamma}{\text{ber}_2^2 \gamma + \text{bei}_2^2 \gamma} \]  \tag{116}

Once again the current density in the round wire winding must be uniform over the winding cross-section. Using the notation in Figure 30, for a winding consisting of \( N \) layers and \( N_L \) turns per layer, the total losses in node (i,j) are obtained as follows:

\[ P_{ij} = \frac{N}{b} \frac{dy_i}{N_L dx_i} \left[ F_{\text{round}}\left( \frac{b}{N} \frac{dy_i}{N_L dx_i} I \right)^2 + G_{\text{round}} H_{ij}^2 \right] \]  \tag{117}

IV. Litz Wire Windings

The eddy current losses in windings can be reduced by weaving enamelled conductors along the entire length of a divided conductor. In addition, the
individual strands are transposed so that each one passes through every position in the conductor, relative to the two dimensional cross section of the winding window, thus ensuring that each strand carries the same current.

It is possible to treat litz wire windings using Dowell's round-to-square transformations, but a more reliable method is obtained from references [3,5], where the exact cylindrical solution is applied to each litz strand in the bundle.

For a litz bundle of diameter, $d_0$, consisting of $N_z$ strands and carrying a current, $I$, the losses are given by:

$$P_{\text{litz}} = P_{\text{skin}} + P_{\text{prox, external}} + P_{\text{prox, internal}}$$

$$= \frac{F_{\text{strand}} I^2}{N_z} + N_z G_{\text{strand}} H_e^2 + \frac{N_z G_{\text{strand}} I^2}{2\pi^2 d_0^2}$$

(118)

where $F_{\text{strand}}$ and $G_{\text{strand}}$ considers each strand as a round wire. As indicated in Figure 31, $H_e$ is the external magnetic field intensity and $H_i$ is the collective internal field.

![Figure 31. A stranded conductor and its cross section.](image)
V. Implementation of the Combined Method: *EddySim*

The new hybrid method for the analysis of winding losses in inductors and transformers were implemented in a computer program called *EddySim*, a command-line driven CAD tool which was written in Borland Pascal 7.0. *EddySim* can deal with structures having one, two or no air gaps and up to four windings, each consisting of litz wire, foil conductors or round wire. The numerical part of the solving procedure uses the finite difference method to obtain the magnetic field distribution inside the winding window and the *method of images* (Appendix B) is used as a first approximation for the FDM. The analytical method as described in the previous sections are then used to compute the solutions for the winding losses. Figure 32 shows a summarized flow chart of the analysis procedures. The reader may consult Appendix F for detailed descriptions of the *EddySim* CAD tool in *The EddySim User's Manual*.

![Flow Diagram of EddySim](image-url)

**Figure 32.** Summarized flow diagram of *EddySim*.

A. Mask Interpreter

All the configuration details and constrictive parameters are passed to *EddySim*
by means of an input file in ASCII-format, called the configuration file. This file may be created by the user himself or by another application designed for this task. The pathname of the file should be included in the command-line when *EddySim* is executed. A sample configuration file is shown in Figure 33.

![Sample Configuration File](image)

**Figure 33.** An example of a configuration file.

*EddySim* reads and interprets the configuration file according to predefined data sequences. Data sequences starts with a recognizable keyword at the beginning of a line in the file, followed by a set of related numbers, on the same line, that will be passed to the necessary parameters for the rest of the program.

**B. Mesh Initializer**

The written code for *EddySim* comprises largely of a number of intricate algorithms to create and initialize the non-uniform mesh superimposition over the space-time domain of the problem.

The creation of the mesh involves the following:

- Sizing and positioning the individual elements to fit between all the boundaries in the two dimensional cross section of the window area, including the air gaps and the windings.
- Arranging the elements in the mesh in a sequence that will be followed
by the iterative procedure.
- Linking every element to its neighbours.
- Definition and creation of the boundary conditions.

EddySim generates the mesh automatically according to the specified physical dimensions of the structure and two parameters (following the keyword mesh), also included in the configuration file, that dictates the restrictions on the size as well as the number of elements. The first parameter is the maximum distance between two adjacent elements and has significant effects on the accuracy of the final solution, but also affects the time it takes to complete one iteration and the time required to converge an accurate solution. The second parameter controls the minimum number of elements allowed between two adjacent boundaries in the structure. This may seem a superfluous restriction for a mesh that should, by definition, be relatively coarse. It is, in fact, necessary because the mesh is not finely divided. In practical configurations, conductor leads could be wound with sides of the windings being very close to the core relative to the dimensions of the structure, leading to a mesh that holds, for instance, a Neumann boundary and a conducting node separated by a single element. It was therefore thought necessary to include this parameter in order to insure enough 'breathing'-room between any adjacent boundaries, by importing elements with the material constants of air to separate them.

The initialization of the mesh involves the assigning of the material constants to all the nodes. As explained in chapter one, the permittivity is ignored at frequencies in the kilohertz range. In order to limit the required size of the data structure in computer memory, the core is not included in the problem domain and specific boundary conditions are employed. The relative permeability for each element is therefore unity and the only material constant that needs to be assigned to nodes is the conductivity, which may differ for separate windings.
C. First Approximation

In essence, *EddySim* solves for two field quantities simultaneously during the relaxation procedure. They are, respectively, the magnetic vector potential (MVP), \( A \), and the scalar potential, \( \phi \). In order to increase the convergence speed of the process, a first approximation of the MVP is derived by integrating a solution of the magnetic field intensity, obtained through the use of an analytical technique called the images method, in the winding window. For a detailed discussion of the images method, the reader may consult the Appendix B and reference [19].

D. Relaxation

The primary part of the program, namely the numerical method that employs the finite difference method (FDM), is entirely contained in a rather small algorithm that controls the whole of the iterative procedure, or so-called the relaxation process. The relaxation process embodied into *EddySim*, uses the well known Gauss-Seidel iteration technique to increase the rate of convergence. Further attempts to increase this convergence speed, by employing successive over-relaxation, (See references [23,25]), proved to be successful for only a limited number of problems. The problems encountered can be attributed mainly to the non-uniformity of the mesh, to some problems lacking symmetry in their physical configurations as well as the inconsistent boundary conditions.

E. Power Loss Calculation

*EddySim* ultimately solves for the power loss in every winding in the problem, using the methods described in this and previous chapters. Equation (100) requires both the current and the average magnetic field intensity in an element. The magnetic field intensity distribution in the winding window is calculated by differentiation of the MVP, according to the relation:

\[
B = \nabla \times A = \mu_0 H
\]
The solution of the total current in every element in the mesh, is related to \( A \), \( \phi \), \( \sigma \) and the size of the element:

\[
I = (J_s + J_i) \, dS = -\mu_0 \sigma \left( \nabla \phi + \frac{\partial A}{\partial t} \right) \, dS
\]

where \( dS \) is the area of the element under consideration.

The power dissipation in every conducting element is calculated using equation (100), where the functions \( F \) and \( G \) depends on the type of the associated winding.

**F. Datafile**

Finally, the solution is written to a textfile also specified on the command-line. The solution is in the form of a table and includes the position and size of elements, the conductivity of each element and the solutions of the MVP, source current density, induced current density, magnetic field intensity and the power dissipation.

**G. Eddy-Viewer**

As mentioned previously, it is possible to control *EddySim* from another application that may include a user interface which deals with the creation of the configuration file and the graphical presentation of the final solution. Such an application, which may well be designed to run under MS-Windows, may also
include user interfaces for other CAD tools to analyze other effects in magnetic components, such as stray capacitances between windings. As an alternative, EddySim can be used as a stand-alone application straight from the command-line, in which case the user has the option, by including the keyword eddyview in the configuration file, to activate a sub-program that generates a colourful graphical presentation of the mesh and the solutions on the monitor screen.

![Figure 35. Block diagram of integrated design environment that includes EddySim.](image)

VI. Design Example

A foil conductor consisting of a 6-turn foil winding, and stacked E-55 ferrite
cores as shown in Figure 36, was analyzed using a finite element program, the combined analytic and numeric method and the strictly one dimensional solution. The winding consists of copper foil, 0.5mm thick and 35mm wide and an air gap of 1mm is included in the 113mm long stacked core.

The normalized ac resistance values are plotted in Figure 37(a). Notice the large error made by the strictly one dimensional approximation, compared to those obtained with the two numerical methods. It is also noteworthy that the values obtained using the hybrid solution with FDM, with 456 elements are in good agreement with those using the FEM, which required 4530 triangles in order to compute the solution.

One of the disadvantages of the finite difference method, namely slow
convergence, allowed the Pascal program implementation to converge after as many as 6000 iterations using the Gauss-Seidel iterative method. The iterative method of successive over-relaxation, together with initial values for the MVP estimated from suitable analytical methods, converged after only a few hundred iterations, surpassing the speed of a well established finite element program by up to three times.

The results of practical measurements of the ac to dc resistance of the configuration shown in Figure 36 is plotted in Figure 37(b). These measurements were obtained using an HP4284 precision LCR meter. The maximum supply voltage offered by this instrument is limited to two volts and therefore does not achieve sufficient core excitation.

**Figure 37(b)** Practical measurements of ac to dc resistance values for the selected configuration.
This chapter introduces a new approach to high frequency design and analysis of magnetic components, called scant modelling. The scant transformer model allows for interactive graphical optimization of a transformer form while concentrating on a minimal set of performance and form parameters. Thermal considerations are included with derating factors influenced by heating due to conduction losses, core losses, eddy currents in windings and core losses. The losses due to eddy currents in windings are calculated using the one dimensional techniques described in chapter one.

The simplified scant representation of a transformer allows fast evaluation of design equations. This fact makes the creation of interactive design aids, that perform calculations in real time, a possibility. Although sophisticated finite element and other types of numerical calculations can provide more accurate results, their use in interactive CAD tools is restricted because of long calculation times.

The application of the method is demonstrated with the aid of an E-core design example.
I. Introduction

The introductory chapter gave a brief review of conventional transformer design and its inadequacy for dealing with high frequency devices. Undeland et al [27] proposed a high frequency extension of the conventional area products design procedure, that includes thermal considerations based on the the maximum device temperature and physical height of the device. However, the effects of eddy currents were neglected and optimizing the component size and shape could therefore not be included as part of the design function. These are important considerations for high power high frequency applications. Figure 38 shows the magnitude of eddy current distributions across the height of a foil as a function of its position from the zero MMF line inside a winding at 50kHz, as obtained with FEM (Data points) and one dimensional analytical equations (solid lines).

![Figure 38](image1.png)

**Figure 38.** Current density of mth foil in transformer winding at 50kHz.

![Figure 39](image2.png)

**Figure 39.** The zero MMF line is the position relative to the winding where magnetic field intensity is zero.

Note the linear increase in magnitude of the surface current density with each increment of the position of the foil away from the zero MMF line, together with the increase in magnetic field intensity. As a result, the internal impedance,
which includes the effective resistance and the internal inductance, also display the same increases. This phenomenon, together with the contribution to leakage inductance due to flux crossing the winding window between foils and layers of wire, restricts the height of the winding. The cross sectional shapes of the window and core affects the exposed surfaces and plays a role in the natural cooling of the device and must also be considered. Optimizing the transformer in question therefore involves the interplay of these factors against fixed design specifications. In an attempt to generalize high frequency transformer design, the scant modelling approach is presented (see reference [29]).

II. The Scant Transformer Model

Methods and means of analysis alone is not enough to optimize a design. Optimization involves varying the different parameters in a design and finding an optimum for certain criteria. The scant transformer model is a design aid which allows the user to:

*Interplay the core shape and winding composition with the derating of the core and winding and the transformer impedance, taking into account eddy current losses and thermal constraints. When an optimum is found the scant model can be transformed into a physical transformer configuration. Vice versa, a physical transformer configuration can be transformed to a scant model and evaluated against a possible optimum.*

Truly optimizing magnetic components in terms of electrical performance, shape, size and losses is a complicated process because of the large number of variables involved, and the restrictive effect of practical considerations. References [10] and [11] are examples where a specific design and a single dimension was respectively optimized and serve to illustrate the complicated nature of new generation transformer design.
The scant transformer model reduces the complexity of the transformer by ignoring some practical aspects without losing the functional relationships. The simplifications actually characterise the scant model, and are as follows:

- A two dimensional analysis is performed on the winding window and core cross section which are orthogonal to each other. Fig.40a shows the general representation of the scant model. By applying a certain form to the cross section, the scant model can be associated with specific physical models as indicated in Figure 40 (b-d).

- The third dimension is not used at all. For this reason absolute values of losses and transformer impedance cannot be calculated. A characteristic of the scant model is that it works with relative values and not absolute values.

- Fractional turns, fractional conductors per turn or fractional number
of strands per litz bundle are possible in the scant model. A two dimensional density is assigned to each winding, and is assumed to be homogeneous over the winding cross section.

**Figure 41.** The SCANT model and its parameters in relation to the physical transformer.

The scant model contains two sets of parameters; the one set is related to performance and is called *functional parameters*, while the other set is related to the geometry and is called *form parameters*. It is important to note that the functional parameters can be described by the full set of form parameters and inversely the form parameters can be described by the functional parameters. Thus as shown in Figure 41, bi-directional transformations are possible between function, form and the physical transformer configuration.

The interplay between function and form as well as the physical transformer construction is illustrated in Figure 42. One of the form parameters is made a variable which takes on a range of equally spaced values. Complete sets of functional parameters are calculated, giving N complete transformer designs. The relationship between this variable and the functional parameters can be graphically displayed and evaluated. A certain value of the parameter can be selected and after making some practical adjustments to the scant model.
parameters a physical transformer configuration is obtained.

Figure 42. The SCANT design method allows interactive optimization.

The scant model is flexible and can cater for any shape of known (and unknown) transformers as shown in Figure 40. In this section only the rectangular core and winding configuration is described (Figure 40b). The practical core shapes which can be accommodated are shown in Figure 43,

![Diagram](image)

Figure 43. The practical core geometries that can be treated using the rectangular SCANT model.
which include most of the important core shapes currently in use.

III. Thermal Constraints

The thermal design is based on a reference for a specific material, and is extrapolated from this reference by keeping the power per surface area constant. It is a well known fact that heat dissipation is caused by two mechanisms namely radiation and convection and both are proportional to the surface area. Strictly speaking the convection coefficient is related to the tallness of the structure (typically to the relation $L^{0.25}$, which may affect the area proportionality. Whereas this may be true of tall power frequency natural convection transformers, this "tallness" is often not directly attributable to the dimensions of a compact power transformer but rather to the box design.

![Diagram](image)

**Figure 44.** Thermal reference used in SCANT model.

Consequently, the scant approach assumes that a direct proportionality exists between the amount of dissipated heat and exposed surface area at thermal equilibrium.
A thermal reference is used which comprises a square cross section and unit length as shown in Figure 44. Extrapolation of this thermal configuration is done by keeping the power dissipation per exposed area constant:

\[
P_{\text{ref}} \frac{\text{cross sectional area}}{\text{exposed surface area}} = \text{constant}
\]  

(121)

where \( P_{\text{ref}} \) is the losses per unit area in the reference configuration.

In the analyzed configuration the total area may not be exposed and therefore a thermal exposure constant is defined as follows:

\[
K_T = \frac{\text{exposed surface area}}{\text{total surface area}}
\]

(122)

Setting the power dissipation per exposed area of the analyzed configuration equal to the reference configuration yields the following per unit area output power:

\[
P_1 = P_{\text{ref}} \frac{H_{\text{ref}}^2}{4H_{\text{ref}}} = \frac{P_{\text{ref}} \cdot WH}{2K_T (W + H)} \]

\[
\Rightarrow P_1 = P_{\text{ref}} \frac{H_{\text{ref}} K_T (W + H)}{2WH}
\]

(123)

IV. CORE DERATING

A constriction of high frequency power transformers is the fact that the flux density must be restricted due to a frequency dependency of typically power 1.3, of core losses. A core derating factor is defined as follows:

\[
D_c = \frac{B}{B_{\text{max}}}
\]

(124)

where \( B_{\text{max}} \) is the maximum, frequency unrestricted flux density which can be
used in the particular application, and $B$ the flux density of the analyzed configuration.

Core losses in ferrites per cubic meter at a fixed frequency is proportional to the flux density raised to power $m$;

$$P_{cl} \propto B^m \tag{125}$$

where $m \approx 2.6$ for power ferrites.

If the reference core configuration is excited to the full flux density $B_{max}$ and $H_{ref}$ is chosen to give maximum permitted temperature rise of the core then equation (123) can then be applied to the core as follows:

$$B_{max}^m = B^m \frac{2W_c H_c}{K_F (W_c + H_c)} \tag{126}$$

Where the subscript $c$ references the core.

---

**Figure 45.** Conventions for the description of round and square litz filaments in the SCANT model.
V. WINDING DERATING

The scant model composes conductors from square filaments. The dimensions of the filaments are chosen with respect to skin depth and the magnetic field is assumed to be parallel to one of the cross sectional dimensions. If the real conductor is round, the scant filament will have equal cross sectional area as shown Figure 45a. A winding is simply composed of a certain number of filaments which can be connected in series to form a number of turns or connected in parallel to increase the current capacity of the winding. When the conductors are connected in parallel, full transposition of the individual filaments are assumed to form the strands of a litz conductor as shown in Figure 45b. Provided the magnetic field in the winding (leakage field) runs parallel to the surface of parallel connected filaments they can be fused together (without transposition) forming a foil conductor as shown in Figure 45c.

The non-copper space in die window is assigned to the primary or secondary and then subdivided between the filaments of the primary and secondary. Allowance is also made for different copper density along the width and height of a winding $\Delta_w$ and $\Delta_H$ in Figure 45), which can be important in instances when foil windings are used. The two densities are combined into a single winding packing factor which is defined as:

$$F_w = \Delta_w \cdot \Delta_H$$  \hspace{1cm} (127)

The per unit winding area copper losses in a winding is given by:

$$P_w \propto F_r F_w J^2$$  \hspace{1cm} (128)

where $J$ is the average rms current density over the cross section of a winding lead, and $F_r$ is the ac to dc resistance ratio which is calculated using the one dimensional analysis and equations of Dowell [1].
The *copper reference* configuration comprises a solid square copper busbar, which is excited with a dc current density $J_{\text{ref}}$ until the required equilibrium temperature rise is achieved. The *winding reference* configuration is extrapolated from this original copper reference, using equation (121), to have a square cross sectional area equal to the winding window area, and a dc current density $J_{\text{DCref}}$ for the same temperature rise ($F_r$ and $F_w$ are unity.) The current derating factor is defined as the ratio of the copper current density of the analyzed configuration to this reference dc current for the same temperature rise:

$$D_w = \frac{J}{J_{\text{DCref}}}$$  \hspace{1cm} (129)

(Note that a winding with a larger per unit exposed surface area than the reference may result in a derating factor, $D_w$, being greater than unity, even if $J$ is not a dc current density and the winding packing factor, $F_w$, is smaller than unity.)

![Figure 46. A transformer winding window, showing the packing across the winding height.](image)

When equations (128) and (129) are combined, three possibilities exist for calculating the current derating factor. In the equations that follow, the
subscripts \( p \) and \( s \) refers to the primary and secondary respectively and \( \xi \) is the fraction of the total winding height occupied by the primary or secondary, as shown in Figure 46, and the other parameters are defined in the next section:

1. **Equal current densities in primary and secondary windings**

\[
I_{DC,ref}^2 H_{wref} = J^2 \left( F_{rp} F_{wp} \xi_p^2 + F_{rs} F_{ws} \xi_s^2 \right) \frac{2W_W H_W}{K_F (W_W + H_W)}
\]  \( (130) \)

2. **Equal primary and secondary MMF's**

\[
J_{dc} H_{wref} = J^2 \left( \frac{F_{rp}}{F_{wp} \xi_p} + \frac{F_{rs}}{F_{ws} \xi_s} \right) \left( F_{wp} \xi_p^2 + F_{ws} \xi_s^2 \right)^2 \frac{2W_W H_W}{K_F (W_W + H_W)}
\]  \( (131) \)

where the current density, \( J \), is given by:

\[
J = \sqrt{\frac{J_p^2 F_{wp} \xi_p^2 + J_s^2 F_{ws} \xi_s^2}{F_{wp} \xi_p + F_{ws} \xi_s}}
\]  \( (132) \)

3. **Arbitrary primary and secondary currents**

In this case equations (121) and (129) are solved simultaneously. The derating factor is calculated using equation (130) and the current density given by equation (132) and

\[
J_{dc} H_{wref} = (F_{rp} F_{wp} \xi_p^2 F_p^2 + F_{rs} F_{ws} \xi_s^2 F_s^2)^2 \frac{2W_W H_W}{K_F (W_W + H_W)}
\]  \( (133) \)

See Appendix C for a more detailed discussion on the winding reference and derating.
VI. FORM PARAMETERS

The dimensions of the core cross section are $H_C$ and $W_C$, referring to the height and width respectively, while similarly the winding window is characterised by $H_w$ and $W_w$. The geometry of the scant transformer is described in terms of form parameters. The winding and core aspect ratios are the most important parameters and are defined as follows:

**Winding Aspect Ratio**

The winding aspect ratio is defined as the ratio of window width and -height:

$$A_w = \frac{W_w}{H_w}$$

**Core Aspect Ratio**

The core aspect ratio is defined as the ratio of core width and -height:

$$A_c = \frac{W_c}{H_c}$$

In order to define the winding configuration two form parameters are defined:

**Primary to Secondary Area Ratio**

$$A_{ps} = \frac{\delta p}{\delta s}$$

**Winding to Window Height Ratio**

$$A_s = \frac{H'_w}{H_w}$$

where $H'_w$ is the winding primary and secondary height. The significance of $A_s$ is that it defines the active part of the winding. AC resistance is affected by the spacing along the width and between the primary and the secondary but not the space outside.
VII. THE DESIGN METHOD

An interactive design environment is created with the scant model which allows an interplay between the core and winding aspect ratio, the core and winding derating factors, the number of turns and the impedance of the transformer. Since the power rating of a transformer is determined by the permissible temperature rise of the winding and core, the temperature rise is kept constant.

Figure 47. Block flow diagram of SCANT design environment.

As is indicated in the block diagram shown in Figure 47, some parameters are required which are common to the form and functional representation of the
transformer. These include the scant dimensions which determine the shape of
the physical transformer. Other parameters concern the winding density and
available surface area ratios which are assumed to be constant during the
interactive design. Values for these latter parameters are obtained from the
physical transformer design, and need to be updated regularly as the design
progresses.

The SCANT design method entails the mapping of the complete description of
a physical transformer in terms of its physical parameters onto the minimal set
of form and performance parameters discussed above. The minimal
representation can then be manipulated in order to optimize the transformer
conceptually for material usage or cost or some other appropriate criterium.
Once the appropriate design is achieved it can be mapped back to a physical
transformer if practical restrictions will allow it.

Alternatively a design can be initialised conceptually and optimised in terms of
the minimal set of form and performance parameters. When a suitable
combination of the parameters is obtained a mapping to the physical domain, if
possible, will provide the physical information for the construction of
transformer. It is possible to vary the form parameters over a certain range and
obtain the derating or performance parameters over the range from which it is
then possible to select the combination of form parameters that gives the
required performance.

VIII. E-Core Design Examples
The scant design process is illustrated with two experimental transformers as
illustrated in Figures 48 and 49. The one uses a standard E42 core, while the
other uses an E30 core which has been elongated to achieve a larger window
area and window aspect ratio. Both are operated at 40kHz, and is excited with
Scant Modelling

a 150V square wave inverter voltage source for a peak flux density of 225mT and 200mT for the E30 and E42 respectively. The core and windings were excited to give the same temperature rise, in order to avoid the complicated heat exchange between primary and secondary. When these transformers are modelled with the scant model the parameters are as given in Table I.

Figure 48. Construction of E-Core transformers
Figure 49. Photograph of experimental transformers.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>E42</th>
<th>Elongated E30</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_p )</td>
<td>Primary litz dimension</td>
<td>0.2mm</td>
<td>0.2mm</td>
</tr>
<tr>
<td>( l_s )</td>
<td>Secondary litz dimension</td>
<td>0.2mm</td>
<td>0.2mm</td>
</tr>
<tr>
<td>( D_{d_{hp}} )</td>
<td>Density of primary winding along height</td>
<td>0.374</td>
<td>0.438</td>
</tr>
<tr>
<td>( D_{d_{wp}} )</td>
<td>Density of primary winding along width</td>
<td>0.461</td>
<td>0.456</td>
</tr>
<tr>
<td>( D_{d_{ho}} )</td>
<td>Density of secondary winding along height</td>
<td>0.445</td>
<td>0.446</td>
</tr>
<tr>
<td>( D_{d_{wo}} )</td>
<td>Density of secondary winding along width</td>
<td>0.412</td>
<td>0.471</td>
</tr>
<tr>
<td>( A_s )</td>
<td>Winding height to windog height ratio</td>
<td>0.588</td>
<td>0.583</td>
</tr>
<tr>
<td>( A_{pw} )</td>
<td>Primary to secondary copper area ratio</td>
<td>0.78</td>
<td>1</td>
</tr>
<tr>
<td>( A_{ew} )</td>
<td>Exposed winding surface to total area ratio</td>
<td>0.38</td>
<td>0.327</td>
</tr>
<tr>
<td>( A_{ec} )</td>
<td>Exposed core surface to total area ratio</td>
<td>0.934</td>
<td>0.985</td>
</tr>
<tr>
<td>( H_c )</td>
<td>Core height</td>
<td>12mm</td>
<td>7mm</td>
</tr>
<tr>
<td>( W_c )</td>
<td>Core width</td>
<td>15mm</td>
<td>21mm</td>
</tr>
<tr>
<td>( H_w )</td>
<td>Window height</td>
<td>9mm</td>
<td>6mm</td>
</tr>
<tr>
<td>( W_w )</td>
<td>Window width</td>
<td>30mm</td>
<td>21mm</td>
</tr>
<tr>
<td>( D_w )</td>
<td>Winding derating factor</td>
<td>0.92</td>
<td>1.1</td>
</tr>
<tr>
<td>( D_s )</td>
<td>Core derating factor</td>
<td>0.875</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table I. Scant model parameters for elongated E-30 and E-42 core transformer examples
The two transformers represent designs with different form parameters for similar power output for the same temperature rise. During the interactive design process (Figure 42) within the scant model, these two transformers would be
two design options. To illustrate the design environment these two transformers are shown on functional parameters graphs when the form parameters are the independent variables in Figures 50 to 53.

The following observations can be made from this example:

- The core cross sectional area $S_{\text{core}}$ decreases with increasing aspect ratio (Figure 50).
- The window cross sectional area $S_{\text{window}}$ also decreases with increasing aspect ratio (Figure 51).
- The core derating factor increases with larger aspect ratio (Figure 52). Since $D_c$ is referenced to a maximum flux density which is determined by saturation, $D_c$ is limited to a maximum value of 1.
- The winding derating factor $D_w$ at a small window aspect ratio is determined chiefly by the amount of eddy current losses and the density of the winding. At an increasing aspect ratio, as shown in Figure 53, $D_w$ increases due to the cooling surface area becoming larger. In the case of $D_w$, it is possible to exceed unity, which means that the winding is able to carry a higher current density than a square bus bar despite having less copper.

![Diagram](image)

**Figure 54.** Experimental setup for temperature measurements on transformer core and windings.
IX. Temperature Measurements

The core and winding surface temperatures were measured using the experimental setup shown in Figure 54. The core temperature, $\Delta T_{\text{core}}$, and the winding temperature, $\Delta T_{\text{winding}}$, are both measured as the rise above the constant environment temperature. Table II gives the results of these measurements.

<table>
<thead>
<tr>
<th></th>
<th>E42 $(D_c=0.875, D_w=0.92)$</th>
<th>Elongated E30 $(D_c=0.95, D_w=1.1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta T_{\text{core}}$</td>
<td>$\Delta T_{\text{winding}}$</td>
</tr>
<tr>
<td>Open Circuit</td>
<td>22.5</td>
<td>20.6</td>
</tr>
<tr>
<td>Closed Circuit</td>
<td>-</td>
<td>21.1</td>
</tr>
<tr>
<td>Full Load</td>
<td>44.2</td>
<td>45.6</td>
</tr>
</tbody>
</table>

Table II. Core and winding temperature measurements (40kHz).

The results give an indication of the effect the derating factors have on the temperature rises. In all cases, the elongated E30 transformer, with the higher core and winding derating factors, operates at a slightly lower temperature than the E42 core transformer. In contrast to the E42 transformer, the winding temperature rise in the elongated E30 at full load current is slightly higher than that of the core. This can be attributed to the fact that the winding on the E42 has additional cooling surfaces between the winding and the core, where a relatively large gap exists.
This chapter contains a summary of the goals reached within this study against the background of current design techniques. The work is critically evaluated for its accuracy and its significance with respect to current trends in power electronics, concentrating on high frequency magnetic design. The chapter concludes with a look at possible future studies in this field, and the expansion of some concepts developed here.
I. Introduction

The advent of high frequency power switch technology paved the way towards a myriad of possibilities in switching schemes and circuit topologies. Consequently, the design of high frequency magnetic components became more specialized in its application, leading to unconventional designs for enhanced performance. It is not uncommon to find power transformer designs having air gapped cores for higher leakage inductances in primary or secondary and integrated frequency resonant components [37], as integral parts of these power electronic circuits. Although industrial projects, as far as magnetic components are concerned, usually lag new technological advances by more than a decade, high frequency magnetic components have already found their place in modern applications, urging developers towards a new era of magnetic design.

In the introductory chapter the inadequacy of conventional design strategies for high frequency inductors and transformers, where losses due to eddy current effects play an important role, were outlined. Thermal limits and cooling become important considerations for these high frequency devices and an appropriate design approach does not exist due to its complex nature. The design procedure depends on sophisticated computer simulation programs and specialised computer aided design (CAD) tools. The finite element programs that are available today, have already proven their validity in the field of electromagnetics, but display disadvantages of being slow, requiring relatively powerful, expensive computers. In some cases, modelling may even be impossible. In addition, experience is a prerequisite for accurate modelling using these simulation tools, and setting up the simulation can be a burdensome task on its own, prolonging the design process. Truly optimizing a design is an iterative task and a near-complete analysis, using finite elements, should be part of the final stages of the design process, not the first. Currently an effective means of optimizing a design does not exist.
It is worth mentioning that the FEM gives accurate approximations of eddy current effects in windings, provided that the analysed geometry is simple, so that the number of elements required at a given frequency is not beyond the capability of the computer at hand. When developing a new numerical technique that overcomes these limitations, it is sufficient to measure its functionality against FEM solutions. It should be made clear that testing the validity and accuracy of FEM based predictions against measurements taken on configurations in practice is therefore not a necessity, but supplementary for the purposes of this study.

II. Summarized view of this study

Recognizing the existing needs, outlined in preceding paragraphs, with respect to high frequency magnetic components, this study basically consists in two separate areas of interest:

- Analysing eddy current losses in windings and focusing on foil windings
- Designing high frequency inductors and transformers using CAD tools

A. Eddy Current Losses in Windings of Magnetic Components

Chapter one explores the one dimensional techniques for analysing eddy current effects in isolated foils and foil windings. These methods are tested against FEM solutions and examples are given, (see appendix A), to show that these equations yield accurate predictions, complying exactly with FEM, provided the definition of the two dimensional problem in FEM can be reduced to one dimension. Dowell's methods for treating round- and litz wire windings is presented and his definition of the geometrical skin depth is investigated in appendix A, showing that the geometrical skin depth can lead to inaccurate predictions of losses for windings having poor packing densities.

It is shown that the inclusion of an air gap in a transformer or inductor can lead to significantly higher eddy current losses due to lateral current distributions in
strip conductors, and the available one dimensional methods are therefore not applicable in these circumstances. The orthogonality between skin- and proximity effects (Ferreira [5]) is presented and the principle is applied to the one dimensional equations for predicting the current distribution across the thickness of foil conductors, decoupling the contributions of skin- and proximity effects. This result leads to more flexible forms of the one dimensional solutions of current distributions and losses in foil windings, and establishes a theoretical foundation for a hybrid method that combines analytical one dimensional methods with numerical methods for calculating eddy current losses.

During the course of the study, several methods were encountered for determining current distributions and eddy losses, including the method of flux linkages, the Poynting theorem, surface impedance and integration of power loss distribution.

In chapter two, the finite difference method (FDM) and FEM for calculating eddy current losses are briefly discussed. It is recognized that pure numerical methods, including FDM and FEM, have significant disadvantages when used to analyse eddy currents in high frequency windings.

Chapter three presents the hybrid method for analysing eddy currents in foil windings, using the one dimensional techniques in combination with the FDM. This method is successfully employed in a CAD tool, (called EddySim). The program, (written in Pascal), calculates all the electromagnetic field quantities, currents and losses in windings with a coarse mesh superimposition over a two dimensional cross section of a winding window. Its accuracy is measured against FEM solutions of eddy losses in an inductor with an air gapped core for frequencies ranging from 20Hz to 50kHz. These results agree well with the FEM solutions, despite the fact that the mesh uses only a fraction of the number of elements required by FEM. Other advantages include the ease of use and setting
up a problem as well as quicker calculation speed.

The exact cylindrical solutions for round- and litz wire windings, employing the orthogonality principle, are presented in chapter three and are also implemented in *EddySim*, so that the program can handle windings with different geometries in the same structure. Although the hybrid method yields relatively accurate predictions for the geometry in the design example, its applications are limited and serves only to illustrate the advantages of specialized CAD tools designed for specific applications. The hybrid method presented here is subject to the following limitations:

- The space occupied by foil windings must stretch across the width of the window, so that eddy currents due to magnetic fields penetrating conductors at the foil edges (skin effect) are restricted.
- It is applicable to foils of infinite width or to foils in high permeability cores, for the same reason as mentioned above.
- At very high frequencies, the parasitic capacitances between windings, layers in windings and individual conductors may affect losses considerably for some geometries. The method presented does not consider any form of parasitic capacitances that may be present. The finite element package used for the comparable analysis, called 'Maxwell Engineering Software' from the Ansoft corporation, is also incapable of simultaneous calculation of time-varying transverse magnetic fields and time-varying transverse electric fields, of which the latter is responsible for this effect.

### B. High Frequency Magnetic Design

Chapter four introduces a magnetic analysis and design method that endeavours to assist the designer in optimizing high frequency inductors and transformers. It employs a minimal set of design parameters and the method is therefore appropriately named 'scant'-modelling. These parameters are divided into two
sets, namely performance and form parameters, and optimization is achieved with ease while concentrating on only these few parameters. The scant model takes into account leakage inductances and eddy currents in windings using the one dimensional techniques described in chapter one. It is based on a thermal reference for the core and for the winding and the physical shape, size and form of the device can be optimized.

To illustrate the technique, an E-Core transformer design example is presented, with results of winding- and core derating factors (functional parameters) graphically plotted over a continuous range of form parameters. Practical measurements of temperature rises in two transformers with identical design specifications, but with different form parameters in the scant modelling domain, illustrates the effect that the core shape and form have on these high frequency transformers.

Thermal reference data is required to apply the scant model to the modelling of any physical configuration. Thermal references for core and copper materials are obtained from practical temperature measurements of geometries with different sizes and shapes for the respective materials. These results are referred to one reference model for each material and plotted in appendix C, showing that the predicted results compare satisfactorily with the measured values.

The scant modelling method is specifically designed for interactive computer aided design and -analysis software and allows fast evaluation of design equations, but is not a simple step-by-step design recipe for use outside a CAD environment. This does not necessarily prohibit the use of the scant model in practice, for CAD software for other design functions has already established itself as one of the foremost aids in industrial environments.
III. Future Work

The work presented within this study is based on comprehensive theoretical principles that require further investigation and application to prove its feasibility in practice. Concerning the eddy current losses in windings, FEM analysis of eddy current effects in practical round and litz wire windings is, at this stage, virtually impossible and practical measurements should be carried out to test the accuracy of the hybrid method.

The FDM implementation of the hybrid method, *EddySim*, lacks generality and the iterative method employed is not fully optimized. Quicker, more reliable results are possible by employing other numerical techniques, such as FEM or BEM, combined with the one dimensional analytical methods. It should in theory be possible to include the core as well as different permittivities in the analysis, making it possible to simultaneously solve for core losses and stray capacitances in the magnetic components in addition to eddy current losses in windings.

The scant modelling method for high frequency magnetic design has the potential to establish itself in practice, but requires further development of the designing and optimizing approach.
References


References

vol. 24, pp.95-100, 1970.


Appendix A

Solutions of
Current Density Distributions
in Foil Conductors

The equations derived in the first chapter are substantiated with FEM solutions of several configurations in this section. They are:

1) The Isolated Foil Conductor
2) The 3rd Foil in a Foil Winding Section
3) A Single Foil Conductor inside an Airgapped Core
4) The 3rd Layer in a Square Conductor Winding Section

Note: The finite element solutions are plotted as points and analytic solutions as lines in all the graphs that follow.

Analytical: –

Fem: 0, +
I. Isolated Foil Conductor

An isolated copper (σ~5.8x10⁷) foil conductor (Figure A-1) with a width, w=20mm, a thickness, h=1mm and carrying a current 200µA at 50kHz, was analyzed using the FEM. Figure A-2 shows the FEM and analytic result of the current density magnitude along the lines AB and CD.

![Figure A-1. Configuration setup for FEM analysis of Isolated Foil Conductor.](image)

In order to plot the exact analytical solution at lines AB and CD, it is necessary to obtain the values of the tangential magnetic field intensities at the conductor surface. The FEM produced the following values at points A,B,C and D:

- A : 3.1x10⁻³ A/m
- B : -3.1x10⁻³ A/m
- C : 4.1x10⁻³ A/m
- D : -4.1x10⁻³ A/m

The analytical equation is then plotted using these values and equation (51) of chapter 1.

![Figure A-2. Magnitude of current density along lines AB and CD.](image)

![Figure A-3. Current phase angle along lines AB and CD](image)
II. The 3rd Foil in a Transformer Winding.

The problem definition in Figure A-4 is configured with a high permeability core so that all the field values are constant along the foil width. The problem is therefore truly one-dimensional and the magnetic field intensity at points A and B are easily calculated as:

A: 150A/m
B: 100A/m

Once again, equation (51) of chapter 1 gives the exact solution for the current density along line AB. Note that the current density is significantly higher than
the average current density, $\frac{I}{h_w}$. These plots are for the magnitude of the current density which is significantly higher than the average current density due to the phase shift that occur.

Using similar configurations, the results in Figures A-7 to A-9 were obtained using FEM and the analytical equations along line AB.
III. Single Foil Conductor in a Core with a Single Air Gap

Predicting the current distribution for a foil inside a structure such as the one in Figure A-11, may seem an impossible task, for the fringing that occurs close to the air gap results in increased flux densities in that region, so that the magnetic field is not uniform along the width of the foil. The problem is no longer one dimensional and the non-uniformly distributed current concentrates near the centre of the upper edge of the foil, close to the air gap. Figures A-12 and A-13 shows the current distribution along line CD for this structure with 12mA in the foil at 50kHz.
Figures A-14 and A-15 shows just how accurate the analytical prediction of the current distribution along line AB is, if the magnetic field intensities are known at points A and B:

A: 2.62 A/m  
B: 0 A/m

Note that the current density is much higher at line AB, close to the air gap, than the average current density, 1000A/m², in the foil.

These last results show the accuracy of the new flexible analytical equations for the current density distribution, compared to the finite element analysis. It is remarkable that the prediction is so accurate, regardless of the presence of orthogonal magnetic fields near the air gap in the centre of the winding window. It is worthy to mention that these equations were applied to numerous configurations, proving their validity successfully.

Concerning the numerical solution of the magnetic field distribution, and the combination of numerical and analytical methods of calculating eddy current losses, it should be mentioned that this magnetic field distribution is not a strong function of the applied frequency. At sufficiently high frequencies, the magnetic field envelope does not change much with any increase in the frequency for the same physical topology and only a few numerical solutions may be necessary.
IV. Geometrical Skin Depth

3rd Layer in a Square Conductor Transformer Winding

Although the geometrical skin depth, as explained in chapter 1, deviates from the one dimensional frame by including an adjustment in the second dimension, the following two examples will show that it does not make the solutions for either the current density distributions or the ac resistance less valid than those predicted by a strictly one dimensional treatment of the problems.

![Diagram of 3rd Layer in a transformer winding consisting of 11 turns/layer. High Packing Factor (η=0.667)](image)

**Figure A-16.** 3rd Layer in a transformer winding consisting of 11 turns/layer. High Packing Factor (η=0.667)

![Diagram of 3rd Layer in a transformer winding consisting of 11 turns/layer. Low Packing Factor (η=0.375)](image)

**Figure A-17.** 3rd Layer in a transformer winding consisting of 11 turns/layer. Low Packing Factor (η=0.375)
Figure A-16 and A-17 show the configuration setup for a 50kHz FEM analysis of the 3rd layer consisting of respectively 11 and 6 turns per layer in a transformer winding. Each conductor carries a current of 1A. The current density along lines AB is given in Figures A-18 and A-19 for the FEM result (Points), the analytical solution involving the geometrical skin depth (solid line) and the strictly one dimensional solution (dotted line), for the following magnetic field intensities obtained using FEM at points A and B:

\[
\begin{align*}
\eta &= 0.667: \\
A & = 1528.098 \text{ A/m} \\
B & = 2275.466 \text{ A/m} \\
\eta &= 0.375: \\
A & = 1463.57 \text{ A/m} \\
B & = 869.39 \text{ A/m}
\end{align*}
\]

It is clear in the figures, that there is a slight improvement in the analytical prediction involving the geometrical skin depth, compared to the one using the true skin depth.

This improvement may be attributed to the fact that the strictly one dimensional analysis do not take into account any component of the magnetic field other than the one tangential to the surface of the conductor, in the plane of the winding layer. Although the orthogonal component is already zero or becomes zero very
quickly as it penetrates the conductor from its surface, the square shaped conductor has two parallel boundaries of equal distances apart. The orthogonal component of the magnetic field must therefore also contribute to the current distribution, leading to a slightly higher surface current density than with a pure one dimensional equation. Dowell tried to correct this slight error by calculating the voltage and compensating with the geometrical skin depth.

In calculating the ac to dc resistance ratio for the conductor at line AB, Table A-1 compares the analytical solutions of Dowell and equation (53) of chapter 1 to the FEM.

<table>
<thead>
<tr>
<th>$\frac{R_{AC}}{R_{DC}}$</th>
<th>High Packing Factor $\eta=0.667$</th>
<th>Low Packing Factor $\eta=0.375$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM result</td>
<td>35.6</td>
<td>14.7</td>
</tr>
<tr>
<td>Geometrical skin depth</td>
<td>39.0</td>
<td>23.2</td>
</tr>
<tr>
<td>(Dowell's equation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>True skin depth</td>
<td>27.4</td>
<td>10.5</td>
</tr>
<tr>
<td>(Equation (53) chapter 1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A-1 Results of FEM compared to Dowell's result with the geometrical skin depth and the strictly one dimensional solution with the true skin depth.

The two preceding examples demonstrate the deviations in the results obtained using FEM compared to the strictly one dimensional solutions and Dowell's approximation, involving the geometrical skin depth. It is evident that Dowell's result compares well to FEM for a high packing factor (10%), but deviates considerably from the exact solution for the lower packing factor (58%). The strictly one dimensional solutions derived in chapter 1 is more accurate than Dowell's result for the case of a high packing factor, but the error is in the order of 25% in both instances.
Appendix B

The Method of Images

A detailed solution of the magnetic field distribution in the winding window is required to calculate the proximity effect losses for the one dimensional solutions discussed in the previous section. This technique will be applied to cross sections of rectangular winding configurations. The method plays an essential part in the numerical algorithm for calculating eddy currents in the magnetic window. It supplies a first approximation of the magnetic field mapping inside the window and significantly decreases the number of iterations required for convergence.

Concerning the hybrid method, the imaging technique is used to obtain a first approximation of the magnetic field envelope in the winding window by assigning a uniform current distribution to each rectangular winding section.
I. Imaging Technique

(The following paragraph is a summarized extract from chapter 3 of reference [6].)

"The method of images can be used to give solutions to some important problems involving straight-line or circular boundaries and in a particularly simple manner; for it offers certain ready-made solutions which eliminate the need for formal solutions of Laplace's and Poison's equations. The essence of the method consists in replacing the effects of a boundary on an applied field by simple contributions of currents or charges behind the boundary line (called images), the desired field then being given by the sum of the applied and image fields."

The sign of the image of an applied current are chosen so that the magnetic field at the air magnetic material interface have only a normal component. The simplest case is shown in Figure B-1 where a single boundary separates the applied current carrying region from the image. Assuming infinite permeability simplifies the calculations, but the method of images can also accommodate a finite permeability by the addition of a \( \frac{(\mu_r-1)}{(\mu_r+1)} \) weighing factor.
In the case of two parallel boundaries, the complexity of the solution increases along with the infinite number of images that must be accounted for in the calculations, as shown in Figure B-2. For simplicity, only the images directly bordering the window are included.

Figure B-3. Imaging technique for rectangular core with relative permeability, $\mu_r$. 
The inclusion of an air gap in the structure, can be incorporated with the imaging method by replacing the boundary containing the gap, with a 'less reflecting' boundary with lower permeability, thus spreading the gap across that boundary (See Figure B-3). For an air gap, \( g \), is inserted in a yoke of length, \( l \), and relative permeability, \( \mu_r \), an effective permeability, \( \mu_r^* \), is calculated as follows:

\[
\mu_r^* = \frac{l}{g + \frac{(1-g)}{\mu_r}}
\]

(B-1)

Here fringing around the air gap is neglected and it is left to the numerical algorithm to take these effects into account.

![Figure B-4. Notation used for a rectangular conducting region with uniform current density.](image)

**A. Magnetic field distribution of rectangular uniform current density**

An isolated rectangular conducting region with uniform current \( I \), is shown in
The two dimensional solution for the magnetic field intensity distribution is readily found in literature [6] and is given as follows:

\[ H_x = \frac{I}{8\pi ab} [y + b(\theta_2 - \theta_3) - (y - b)(\theta_4 - \theta_3 + (x + a)\log\frac{r_2}{r_3} - (x - a)\log\frac{r_1}{r_4}] \quad (B-2) \]

\[ H_y = \frac{I}{8\pi ab} [x + a(\theta_2 - \theta_3) - (x - a)(\theta_1 - \theta_4) + (y + b)\log\frac{r_2}{r_1} - (y - b)\log\frac{r_3}{r_4}] \quad (B-3) \]

where

\[ r_1 = \sqrt{(x - a)^2 + (y + b)^2} \quad \theta_1 = \arctan \frac{x - a}{y + b} \]

\[ r_2 = \sqrt{(x + a)^2 + (y + b)^2} \quad \theta_2 = \arctan \frac{x + a}{y + b} \]

\[ r_3 = \sqrt{(x + a)^2 + (y - b)^2} \quad \theta_3 = \arctan \frac{x + a}{y - b} \]

\[ r_4 = \sqrt{(x - a)^2 + (y - b)^2} \quad \theta_4 = \arctan \frac{x - a}{y - b} \]
Appendix C

Winding Derating and Thermal references

The scant transformer can be optimized by determining the physical dimensions as well as the derating factors, from the thermal reference. This procedure is described in the first part of this section for a transformer with arbitrary currents in the primary and secondary windings. The eddy current losses in the primary and secondary litz windings are included in the calculations using Dowell's equations.

In the second part of this appendix, the results of the practical measurement of core and conductor reference data are discussed and results are given.
I. The Copper and Winding References

The copper reference as described in chapter 4, consists of a square dc busbar having a width of $H_{\text{ref}}$. The choice of the excitation current density, $J_{\text{ref}}$, depends on the required design temperature for the analysis configuration. This procedure does not require that the copper reference be of the same cross sectional area as that of the analysis configuration and the source of the reference data is therefore considered to be theoretically accurate for all sizes and shapes to be considered, as long as the requirements mentioned in the paragraph on thermal references in chapter 4 are met. However, the copper reference dc current density has no physical relationship with the analyzed winding, so that this reference needs to be dimensioned towards a meaningful size.

![Diagram of copper and winding reference configurations and winding window](image)

Figure C-1. Dimensions of the copper and winding reference configurations and the winding window. Each structure is 1 meter long.
The power loss to heat flux surface area ratio for the copper reference is given by:

\[
\frac{P_{\text{ref}}}{S_{\text{ref}}} = \frac{J_{\text{ref}}^2 H_{\text{ref}}}{4\sigma H_{\text{ref}}} = \frac{J_{\text{ref}}^2 H_{\text{ref}}}{4\sigma} \tag{C-1}
\]

The winding reference is extrapolated from the copper reference and has the same square cross sectional area as the winding window so that its width, \(H_{w_{\text{ref}}}\), is given by \(\sqrt{A_w H_w}\). The power loss to exposed surface area ratios for the two references are equal for the same temperature rise:

\[
\frac{P_{\text{ref}}}{S_{\text{ref}}} = \frac{J_{\text{ref}} H_{\text{ref}}}{4\sigma} = \frac{J_{\text{DC ref}} \sqrt{A_w} H_w}{4\sigma}, \quad \text{where} \quad A_w = \frac{W_w}{H_w} \tag{C-2}
\]

and the new reference current density is obtained as follows:

\[
J_{\text{DC ref}} = \frac{H_{\text{ref}}}{\sqrt{A_w H_w}} J_{\text{ref}} \tag{C-3}
\]

This current density now references the derating factor:

\[
D_w = \frac{J}{J_{\text{DC ref}}} \tag{C-4}
\]

The calculation of \(J\) in the analysed configuration involves finding a suitable physical size, contributable to the eddy losses in the winding for the given temperature rise and form parameters. If the winding current densities are given by \(J_p\) and \(J_s\) for the primary and secondary, then the total losses are given by:

\[
P_T = \left( F_{\eta} F_{wp} \xi_p J_p^2 + F_{\eta} F_{ws} \xi_s J_s^2 \right) \frac{W_w H_w}{\sigma} \tag{C-5}
\]

where \(F_{\eta}\) is the winding ac to dc resistance ratio, \(F_w\) is the packing density, \(\xi\) is the fraction of the total winding height occupied by the primary or secondary. The subscripts p and s references the primary and secondary respectively.
The winding loss to exposed surface area ratio is given by:

\[
\frac{P}{S} = \frac{P_T}{2\alpha K_T (W_w + H_w)} \quad \text{(C-6)}
\]

Setting equations (C-7) and (C-2) equal to one another, it is possible to obtain the physical size of the window by solving these equations simultaneously, for instance, using a numerical solver.

The derating factor is calculated from the result of the above procedure and equations (C-3) and (C-4), together with the average winding current densities given by:

\[
J = \sqrt{\frac{J^2_{wp} \xi_p + J^2_{w} \xi_w}{(F_{wp} \xi_p + F_{w} \xi_w)}} \quad \text{(C-7)}
\]

*Optimizing the winding window for design purposes involves finding the particular size and form that gives the required operating temperature at equilibrium. Alternatively, the operating temperature can be calculated for analysis of a given configuration.*

A similar procedure is used for optimizing (or analysing) the core size and form, with one exception: Unlike the winding current density, the core flux excursion is limited to a maximum value that cannot be exceeded. The core derating factor is therefore limited to a value of one. This implies that a core with size and shape larger than needed for the maximum flux density, will operate at a lower temperature than the design temperature. Trying to increase the flux excursion above the maximum value, will only lead to higher losses, no matter what the core size is. It is therefore important to keep the core flux excursion within the allowed limits, and the derating factor as close to unity as possible, without exceeding it.
II. Practical Measurement of Reference Data

A suitable database of reference data for the core and conductor materials is needed for the scart modelling procedure. Obtaining the reference data involves measuring the temperature rise of a particular reference configuration over a suitable range of excitation values.

Figure C-2 shows a diagrammatic representation of the experimental setup for obtaining data for a chosen reference configuration. The temperature of the controlled temperature environment, the surface temperature of the reference structure and the power directed to the structure is being measured.

Using this experimental setup, measurements were made for type 3E1 ferrite core material and copper conductor material ($\sigma=5.8\times10^7 \ \text{W/m}$).

A. Core Material: 3E1 ferrite

Measurements were obtained from reference [38] for three core sizes, namely E30, E42 and E55 for peak flux densities ranging from 150mT to 250mT at 40kHz. The core reference was then extrapolated from these measurements to
one having a square cross section and 1 meter length. Figure C-3 shows how these results compare for a reference with a width of 12.6mm (½ inch).

![Figure C-3. Reference data for a 3E1 ferrite core reference with a height of 12.6mm.](image1)

![Figure C-4. Data for a square copper reference having height of 10mm.](image2)

As shown in Figure C-3, the error is very large at lower flux densities and low temperature rises. This can be attributed to the fact that these measurements were obtained at constant time intervals of 10 minutes for all measurements, instead of for equilibrium temperatures. The larger structures have greater thermal capacitances and surface temperatures therefore stabilizes after longer periods (up to 1½ hours) than smaller structures. Although extensive practical confirmation has still to be carried out, the author is of the opinion that the correct measuring method will conform to theoretical predictions.

**B. Conducting material: Copper**

Measurements were made for three separate windings over a range of dc current densities. The three windings consisted of 0.45mm wire which were tightly wound on standard-size bobbins for E30, E42 and E65 cores, and measurements were made without the cores. Once again, a unit length square cross section
reference with a height of 10mm was extrapolated from this reference. As shown in Figure C-4, these results compare very well, although a slight error is evident in the three plots.
Appendix D

Decoupled Skin- and Proximity Effect Currents

In this appendix the current distribution across the thickness of a foil conductor, given by equation (43) in Chapter One, is developed in a form that decouples the skin- and proximity effects.
Appendix D

Dowell's equation for the current distribution across a foil conductor is given by:

\[ J_x(y) = \frac{af}{w} \left[ \frac{\cosh \alpha y \cosh \frac{a h}{2}}{\sinh \alpha h} - (k-1) \tanh \frac{a h}{2} \cosh \alpha y + (k-1) \sinh \alpha y \right] \]  
\[ \text{(D-1)} \]

where \( k \) is a constant and \( y=0 \) at the foil surface closest to the zero-MMF line.

Replacing \( y \) with \( y+h/2 \) and moving the origin to the middle of the conductor:

\[ J_x(y) = \frac{af}{w} \left[ \frac{\cosh \alpha (y+h/2) \cosh \frac{a h}{2}}{\sinh \alpha h} - (k-1) \tanh \frac{a h}{2} \cosh \alpha (y+h/2) + (k-1) \sinh \alpha (y+h/2) \right] \]  
\[ \text{(D-2)} \]

This equation is then reduced as follows:

\[ \frac{w}{af} J_x(y) = \frac{\cosh \alpha (y+h/2) \cosh \frac{a h}{2} + \sinh \alpha h}{2 \sinh \frac{a h}{2} \cosh \frac{a h}{2}} \]
\[ + 2(k-1) \left[ \frac{\sinh \alpha (\cosh^2 \frac{a h}{2} - \sinh^2 \frac{a h}{2})}{2 \cosh \frac{a h}{2}} \right] \]
\[ + 2(k-1) \left[ \frac{\cosh \alpha (\sinh^2 \frac{a h}{2} - \cosh^2 \frac{a h}{2})}{2 \cosh \frac{a h}{2}} \right] \]  
\[ \text{(D-3)} \]

\[ = \frac{\cosh \alpha y}{2 \sinh \frac{a h}{2}} + \frac{\sinh \alpha y}{2 \cosh \frac{a h}{2}} + (2k-2) \frac{\sinh \alpha y}{2 \cosh \frac{a h}{2}} \]
\[ = \frac{1}{2} \cosh \alpha y \left( \frac{a h}{2} \right) + 2k-1 \frac{\sinh \alpha y}{2 \cosh \frac{a h}{2}} \]

and finally:

\[ J_x(y) = \frac{af}{2w} \left[ \frac{\cosh \alpha y}{\sinh \frac{a h}{2}} + (2k-1) \frac{\sinh \alpha y}{\cosh \frac{a h}{2}} \right] \]  
\[ \text{(D-4)} \]

This equation is discussed in Chapter One, Section C, "The Orthogonality Principle".
Appendix E

EddySim

Eddy current analysis tool for transformers and inductors

User Manual

This appendix contains the documentation for the EddySim CAD tool. Setting up the problem using the input configuration file with keywords and design parameters, is described. The program writes output to an ASCII text file which can be edited and transported to other applications such as spreadsheets. This document contains only the necessary information to install and use the tool, but does not include the technical or theoretical description of the eddy current phenomenon.
**Introduction**

*EddySim* is a FDM (Finite Difference Method) CAD tool for the analysis of eddy current losses in square core transformers and inductors. The program was developed using Borlan Pascal ver.7 to run under a DOS operating system. It can be used either directly from the DOS command-line or as a working component of a user interface or IDE.

*Figure D-1* *EddySim* solves for eddy current losses in windings of square magnetic cores.

Four winding types can be analyzed:

- Horizontal plate windings
- Vertical plate windings
- Solid round wire windings
- Litz wire windings

*EddySim* can treat magnetic structures with up to *four* winding sections and either one or two air gaps in the winding window. All the winding types may be present in one configuration.
INSTALLATION

EddySim requires at least a 80386 personal computer with a math-coprocessor and:
- 5 Megabytes available RAM.
- A harddisk drive with at least 2 Megabytes free for the program and one set of data.

The program consists of one file, 'eddysim.exe'. To install the program, simply copy the program to a directory on the hard diskdrive.

RUNNING THE PROGRAM

EddySim accepts two parameters on the command line:

eddysim {input filename} {output filename}

where {input filename} is the file containing the configuration data, and {output filename} is the name of the file to which the solution will be written. If a full path is not specified for either one of these files, the current directory containing the file eddysim.exe, is assumed.
INPUT: THE CONFIGURATION FILE

The structural information for the magnetic component to be analyzed, is issued to the executable file by means of an ascii text file created by the user or generated by another application. Any text-editor may be used to create the input file as long as it is ascii-readable and in the format discussed below.

EddySim's mask-interpreter recognizes and interprets data sequences in the configuration file and relays the information to the numerical processing algorithms embodied in the program.

Each data sequence starts with a keyword at the beginning of a line, followed by a single blank space and a sequence of numeric data, also separated by single blank spaces, as follows:

```
keyword number1 number2 ... numberN
```

For each keyword a specific data sequence applies. Keywords must be in lowercase letters. Numbers are either integer or real values. Real values may be written using the scientific notation, i.e. 403.2E-4.

Note that:
- the mask interpreter ignores all lines in the text file that do not start with a valid keyword.
- keywords need not be in any specific order, except for the data following the keyword section, that contains minor-keywords of its own. (see section)
- If more than one instances of keywords with valid data-sequences are found, the last one encountered will be used. It is therefore possible to keep track of changes made to a configuration by simply adding the new line of data somewhere after the one previously used.
KEYWORDS

This section describes the valid keywords and data-sequences for the ascii input file.

Valid keywords are:

- eddyview (Optional)
- mesh
- relax
- gaps
- corewindow
- frequency
- section

The keyword section requires two minor keywords on the two lines directly following the line on which it stands. They are:
- posdim

and one of the following:

- vplate
- hplate
- wire
- litz

---

Transformer no.1

eddyview
relax 8 10000
mesh 0.00085 3
frequency 1e3
gaps1 0.001 0.01 0.005
corewindow 0.0105 0.016
section1 1 00
posdim 0.001 0.002 0.014 0.007
vplate 7 0.0005 5.8e7

Figure D-2 An example of a configuration file.
eddyview

Description: Activates the EddyViewer algorithm built into the program.

After the simulation has ended, a graphical presentation of the winding window will be displayed on the screen, together with the windings in the winding window.

frequency

Description: Supplies the frequency of the applied currents.

frequency [f]

f: The frequency of all applied currents, voltages and fields [Hz].

All the time-varying quantities have the form:

\[ F(t) = F_m \cos (\omega t + \theta) \]

were \( F_m \) is the amplitude of the sinusoidal function

\( \omega \) is the frequency in radians/second and

\( \theta \) is the phase angle

In terms of phasor notation:

\[ F(t) = \Re \left( F_m e^{j(\omega t - \theta)} \right) \]
**mesh**

*Description:* Defines the size of the mesh.

```
mesh [n] [w]
```

- **n:** The minimum number of elements allowed between two adjacent boundaries
- **w:** The maximum width a rectangular element in the mesh may have.

**relax**

*Description:* Sets the parameters that will end the simulation.

```
relax [α] [t]
```

- **α:** The collective accuracy of the final result will be to the \( α^{th} \) decimal.
- **t:** The maximum number of iterations.

**Calculating the accuracy**

After each iteration process, the total deviation from an accurate result is calculated as follows:

Let \( ε_r \) and \( ε_i \) denote the percentage error of the real and imaginary parts of the magnetic vector potential respectively, associated with the \( i^{th} \) element in the mesh.

The total error, \( ε \), is then calculated as:

\[
ε = \sum \sqrt{ε_{r,i}^2 + ε_{i,i}^2}
\]

The simulation terminates if the following condition is satisfied:

\[
ε ≤ 10^{-α}
\]
Description: Supplies the dimensions of the one or two air gaps in the core, as well as the widths of the centre- and side legs of the magnetic core.

\[ \text{gaps} \ [g] \ [b1] \ [b2] \]

- **g**: Length of the air gap(s) [m]. If two air gaps are present, both must have the same length.
- **b1**: The width of the centre leg [m].
- **b2**: The width of the side leg [m], usually \( \frac{1}{2}b1 \)

**Note**: At least one air gap must be present in the structure, and \( g \) may not be zero.
Description: Supplies the dimensions of the window in the one half of the core.

corewindow \[w\] \[h\]

w: The width of the winding window, including the air gap length [m].
h: The height of the winding window [m].
Appendix E

section

Description: Supplies the information related to a winding section.

section{#} [I_{TOT}] [\theta]
{minor keywords and data sequences}

#: Any single alphanumeric character. This character is ignored by the mask-interpreter, but may be included to distinguish different sections from one another.

I_{TOT}: The magnitude of the sinusoidal current flowing in the winding section [A]. This is the current measured at the winding terminals.

\theta: The phase angle in degrees of the sinusoidal current in the section.

As many as four winding sections may be specified. If more than four valid instances of section is encountered, the mask interpreter will recognize only the last four instances.

The line directly below the one containing section must start with the minor keyword posdim.
Description: Supplies the position and dimensions of a winding section carrying the current as described in the previous line in the file.

**posdim** [Xo] [Yo] [XWidth] [YHeight]

Xo: The x-coordinate of the lower left corner of the winding section [m].
Yo: The y-coordinate of the lower right corner of the winding section [m].
XWidth: The width of the winding section [m].
YHeight: The height of the winding section [m].

Notes on valid and invalid conductor boundaries:

(i) Boundaries may never overlap one another. All winding sections have to be spaced apart by a finite distance.
(ii) The left or right edge of a winding section may not have the same x-coordinate as an air gap boundary. (This is due to the fact that magnetic edges coincide with nodes in the mesh, whereas conductor boundaries are always spaced halfway between nodes.)
(iii) A vertical boundary may not fall within the space in the window opposite an airgap.
Appendix E

Minor keyword \textbf{hplate}

\textit{Description:} Supplies the physical information for a plate wound section with the flat edges of foils facing the centre leg of the core.

\begin{equation}
\text{hplate } [N] [d] [\sigma]
\end{equation}

- $N$: The total number of complete turns around the centre leg.
- $d$: The foil thickness [m].
- $\sigma$: The conductivity of the material [\text{U/m}].

\begin{itemize}
\item Vertical Plate Winding
\item Horizontal Plate Winding
\end{itemize}

Minor keyword \textbf{vplate}

\textit{Description:} Supplies the physical information for a plate wound section with the edges of foils facing the centre leg of the core, usually for planar structures.

\begin{equation}
vplate [N] [d] [\sigma]
\end{equation}

- $N$: The total number of complete turns around the centre leg.
- $d$: The foil thickness [m].
- $\sigma$: The conductivity of the material [\text{U/m}].
Appendix E

Minor keyword **wire**

*Description:* Supplies the physical information for a section wound with solid wire.

\[
\text{wire} \ [N_i] \ [N_t] \ [d_i] \ [\sigma]
\]

- \(N_i\): The total number of winding layers.
- \(N_t\): The number of turns per layer.
- \(d_i\): The diameter of the solid wire [m].
- \(\sigma\): The conductivity of the material [\(\Omega/m\)].

Minor keyword **litz**

*Description:* Supplies the physical information for a litz wire winding section.

\[
\text{litz} \ [N_i] \ [N_t] \ [d_i] \ [d_t] \ [\sigma]
\]

- \(N_i\): The total number of winding layers.
- \(N_t\): The number of turns per layer.
- \(d_i\): The diameter of a litz bundle [m].
- \(d_t\): The diameter of a litz strand [m].
- \(\sigma\): The conductivity of the material [\(\Omega/m\)].
OUTPUT: THE OUTPUT FILE

After EddySim has completed a simulation session, it sends the results of the analysis to the ascii text file specified in the command line when executing the program. (see Running the program.) The file contains a table of all node solutions for that structure described in the configuration file. The output file can be edited or viewed by any ascii text editor. Many application software offer file conversion functions to import ascii text data for graphical presentation or further processing, i.e. spreadsheets, graphs etc.

---

<table>
<thead>
<tr>
<th>Configuration File: masktest.edt</th>
</tr>
</thead>
<tbody>
<tr>
<td>EddySim data for 352 nodes:</td>
</tr>
<tr>
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</tr>
<tr>
<td>#    #    #    #    #    #    #    #    #    #    #    #    #    #</td>
</tr>
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<tr>
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</tr>
<tr>
<td>Section 1:</td>
</tr>
<tr>
<td>Pskin #</td>
</tr>
<tr>
<td>Pprox #</td>
</tr>
<tr>
<td>Plot #</td>
</tr>
<tr>
<td>Section 2:</td>
</tr>
<tr>
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</tr>
<tr>
<td>Pprox #</td>
</tr>
<tr>
<td>Plot #</td>
</tr>
</tbody>
</table>

The format of the output data file.
Appendix F

EddySim
Borland Pascal 7.0
Source Code

This appendix contains the Borland Pascal 7.0 source code for the EddySim CAD tool for analysing eddy currents in transformers and inductors.
program EddyFDM;

Uses CRT.graph.Printer.strings,LossCalc;

const
{ The Structure dimensions are global parameters and are supplied }
{ by the procedure that calls this one. }
{ Core Dimensions in mm }
R_h: double = 0.0370;  { Height of Core Window minus Air-gap length }
R_l: double = 0.0110;  { Width of Core Window }
R_g: double = 0.0050;  { Length of Air-gap }
R_b1: double = 0.0170;  { Width of Air-gap in Centre leg (Half Centre leg }
R_b2: double = 0.0085;  { Width of Air-gap in Side leg }
MinBPts: integer = 1;  { Minimum number of Points between boundaries }
MaxMesh: double = 0.9e-3;  { Largest point-size }
Accy: integer = 3;  { For accuracy to the Accy_th decimal }
MaxIt: integer = 50;  { Maximum number of iterations allowed }
EddyView:Boolean = False;  { Displays window mesh with J & H if true }
Freq: double = 1e2;  { Frequency of applied current }
MuO: double = 4*Pi*1E-7;  { Permeability of Air }
MuR: double = 1e12;  { Core Permeability (Dummy) }
NWind = 4;  { Number of windings }
SGapExist: Boolean = False;  { Set to true if 3 Air-Gaps }
MGapExist: Boolean = False;  { Set to true if Gap in Center leg }
Phase_Zero: Boolean = True;  { Accurate prediction of the losses }  { not possible if applied phases aren't either +<0 or -<0 degrees }
{ Used for boolean evals with reals }
presision : double=1e7;

end;
{ Winding record: }

type
{ The Structure dimensions are global parameters and are supplied }
{ by the procedure that calls this one. }
{ Core Dimensions in mm }
MeshPtr = ^MeshRec;
MeshRec = Record
XX: double;
YY: double;
ReAc: double;  { Current MVP: double Component }
ImAc: double;  { Imaginary Component }
ReAp: double;  { Previous MVP: double Component }
ImAp: double;  { Imaginary Component }
ReJs: double;  { Source Current Density: double part }
ImJs: double;  { Imaginary part }
ReJe: double;  { Induced Current Density: double part }
ImJe: double;  { Imaginary part }
sgm : double;  { Conductivity of material }
dX : double;  { Distance to point on the right }
dY : double;  { Distance to point below }
Next: MeshPtr;  { Pointer of the next point }
Top : MeshPtr;  { Pointer to point ABOVE }
Bot : MeshPtr;  { BELOW }
Left : MeshPtr;  { LEFT }
Right: MeshPtr;  { RIGHT }

end;
CondRec = Record
  X1: double;  { Smallest X-coordinate (mm) }
  Y1: double;  { Smallest Y-coordinate (mm) }
  XWidth: double;  { Width (mm) }
  YHeight: double;  { Length (mm) }
  N: integer;  { Number of Layers }
  Nlayers: integer;  { Number of turns/layer }
  NLitz: integer;  { Number of strands / litzbundle }
  I: double;  { Applied Current }
  Phase: integer;  { Phase angle of applied current }
  sgm: double;  { Conductivity of conducting material }
  PlOrtn: integer;  { Orientation and type of winding: }
                 { 0: Wire }
                 { 1: Plate - Horizontal }
                 { 2: Plate - Vertical }
                 { 3: Litz }
  Thik: double;  { plate Thikness or bundle/solid wire diameter }
  Ldiam: double;  { Litz strand diameter }
  WindPt: MeshPtr;  { Pointer to left upper point in a winding }
  PSkin: double;  
  Pprox: double;  
end;

var
  h,l,b1,b2: double;
  k: integer;
  Ldx,Rdx: double;
  ReNItot: double;
  ImNItot: double;
  CondData: array[1..NWind] of CondRec;
  Point: MeshPtr;
  FirstPt: MeshPtr;
  LastPt: MeshPtr;
  GhostPt: MeshPtr;
  NextPt: MeshPtr;
  PrevPt: MeshPtr;
  OriginPt: MeshPtr;
  HeapTop: '*Word;
  PressChar: Char;
  Press: Boolean;
  Pskin, Pprox: double;
  Ptot: double;
  EndShow: Boolean;
  MeshF: File of MeshRec;
  MaxF: Text;
  DataF: Text;
  TestF: Text;
  CL_in: String[100];  { Contains name of input file from command-line }
  CL_out: String[100];  { Contains name of output file from command-line }
  JMax: double;
  JMin: double;
  sgmMax: double;
  sgmMin: double;
  AMax: double;
AMin : double;
HMax : double;
HMin : double;
NNh,
NNh1,
NNh2,
NNl,
NNg,
NNbl,
NNb2 : integer;
ColorTot: integer;
NumPts: integer;
NNWind : integer;
NoGaps:integer;

(*---------------------------------------------------------------*)
Function Mirn( Num1, Num2 : double):double;
begin
  If Num1<=Num2 then Mirn:=Num1 else Mirn:=Num2;
end;

(*---------------------------------------------------------------*)
Function Power(Base,Pwr:double):double;
begin
  Power:=Exp(Pwr*Ln(Base));
end;

(*---------------------------------------------------------------*)
function TEq( num1,Num2 : double) : Boolean;
begin
  TEq:=False;
  If Round(Presision*Num1)=Round(Presision*Num2) then TEq:=True;
end;

(*---------------------------------------------------------------*)
(*   MIMC - Mask Interpreter for Magnetic Components       *)
(*---------------------------------------------------------------*)

Procedure MIMC;
(* - Reads and validates the command-line parameters (see main block) *)
(* - Contains the mask interpreter                                *)
(* Mask Interpreter is a dedicated function for recognition of   *)
(* specified data sequences in the input textfile.              *)
(* Summary of valid data sequences:                              *)
(*                                                              *)
where: \([\text{number}]\) is 1 for gap in centre leg and two for one in side leg also.

\([\text{length}]\) is the same for two air gaps

section \([\text{Total current in Amperes}] [\text{Phase angle in degrees}]\)

posdim \([\text{Xo}] [\text{Yo}] [\text{Height}] [\text{Width}]\)

where: \((\text{Xo}, \text{Yo})\) is the coordinate of the upper left corner of the winding section.

Winding types:

* Vertical plate:
  * vplate \([\text{turns}] [\text{Thikness}] [\text{sigma}]\)

* Horizontal plate:
  * hplate \([\text{turns}] [\text{Thikness}] [\text{sigma}]\)

* Solid Wire:
  * wire \([\text{layers}] [\text{turns/layer}] [\text{strand/bundle}] [\text{diameter}] [\text{sigma}]\)

* Litz Wire:
  * litz \([\text{layers}] [\text{Turns/Layer}] [\text{bundle dia}] [\text{strand dia}] [\text{sigma}]\)

where: \(\text{sigma}\) is conductivity in Siemens/m

Note:
- Every sequence is on one line with a single blank space between string-data.
- Empty lines or lines containing other data are ignored

var

MIFile : string[12];
LineCon : string[50];
ParCon : string[20];
ConPos : integer;
ConF:Text;
kk : integer;
EndCon : Boolean;
EndSection : Boolean;
ErCon : Boolean;
ConValid : Boolean;
iWind : integer;

*******************************************************************************
(* Reads the double numeric data following the keywords in the input file *)
(* one by one. *)
*******************************************************************************

procedure VarCon(Line : string; var MainPar: double);
var
  VarChr: Char;
  VarStr: string;
  Code: integer;
begin
  if ErCon and ConValid then begin
    VarStr[0]:=chr(0);
    Repeat begin
      VarChr:=Line[ConPos];
      VarStr:=VarStr+VarChr;
      ConPos:=ConPos+1;
    end;
    until (VarChr=' ') or ((VarChr<>'0') or (VarChr>='9')) and
      ((VarChr<>')') and (VarChr<>'.');
    VarStr[0]:=chr(Length(VarStr)-1);
    val(VarStr, MainPar. Code);
    if Code<>0 then begin
      ErCon:=False;
      writeln('Error: ');
      writeln(' Incorrect or missing numeral in the following line: ');
      writeln(' ',Line);
    end;
  end;
end;

(*************************************************************************)
(*
    Reads integer data following the keywords in the input file one by one*)
(*************************************************************************)

procedure VarConI(Line: string; var MainPar: integer);
var
  VarChr: Char;
  VarStr: string;
  Code: integer;
begin
  if ErCon and ConValid then begin
    VarStr[0]:=chr(0);
    Repeat begin
      VarChr:=Line[ConPos];
      VarStr:=VarStr+VarChr;
      ConPos:=ConPos+1;
    end;
    until (VarChr=' ') or ((VarChr<>'0') or (VarChr>='9')) and
      ((VarChr<>')') and (VarChr<>'.');
    VarStr[0]:=chr(Length(VarStr)-1);
    val(VarStr, MainPar. Code);
    if Code<>0 then begin
      ErCon:=False;
writeln('Error:');
writeln('Incorrect or missing numeral in the following line:');
writeln('Line');
end:
end:
end:

**************************************************************************
(* Used to recognize and validate the keywords in the input file. *)
**************************************************************************

procedure ConCom(Line : string; keywrd : string);
var k: integer;
 Teststr: string[50];
 keysze : integer;
 code: integer;
 rkeysize: double;

begin
 Teststr:=Line;
 Teststr[0]:=keywrd[0];

 If (Teststr<>keywrd) then ConValid:=False
 Else begin
 ConValid:=True;
 ConPos:=Length(keywrd)+1;
 If Line[ConPos]<>' ' then ConPos:=ConPos+1;
 If ((Line[ConPos+1]<'0') or (Line[ConPos+1]>'9')) and
 keywrd<>'eddyview' ) then begin
 ErCon:=False;
 ConValid:=False;
 writeln('Error:');
 writeln('Line containing ",keywrd," is incorrect.');
 { Haltroutine } end;
 ConPos:=ConPos+1;
 end;
 FillChar(Line, SizeOf(Line), 32);
end:

**************************************************************************
begin
 ConValid:=False;
 ErCon:=True;
 iWind:=1;

 { /**/
 (* Subprogram to read the parameters on the command-line *)
 (* Eddy [input path & filename] [output path & filename] *)
 (* Generates error messages if: *)
 (* - either filename not specified or unrecognizable *)
 (* - input file not found or invalid path *)
 */}
If Paramcount=0 then begin
    writeln('Error:');
    writeln(' Input filename not specified on command-line');
    ErCon:=False;
end;
MIFile:=ParamStr(1);
assign(ConF,MIFile);
{SI-} Reset(ConF);
{SI+}
If IOResult<>0 then
    begin
        writeln('Error:');
        writeln(' Invalid input filename specified on command-line');
        ErCon:=False;
    end;
(*\*)
While (not EOF(ConF) and (ErCon=True) do begin
    Readln(ConF,LineCon);
    Case LineCon[1] of
    'c' : begin
        ConCom(LineCon,'corewindow');
        If ErCon and ConValid then begin
            VarCon(LineCon,h); {Core Width including airgaps}
            VarCon(LineCon,l); {Core Height}
        end;
        LineCon:= ' ';
        end;
    'g' : begin
        ConCom(LineCon,'gaps');
        If ErCon and ConValid then begin
            Varcon(LineCon,g);
            Varcon(LineCon,b1);
            VarCon(LineCon,b2);
        (* Note that if b2 is equal to zero only one airgap is present *)
        (**************************************************************************
        end;
        LineCon:= ' ';
        end;
    'e' : begin
        ConCom(LineCon,'eddyview');
        If ErCon and ConValid then begin
            eddyview:=True;
        end;
        LineCon:= ' ';
        end;
end;

'I':
begin
ConCom(LineCon,'frequency');
If ErCon and ConValid then begin
Varcon(LineCon,Freq);
end;
LineCon:= ' ';
end;

'r':
begin
ConCom(LineCon,'relax');
If ErCon and ConValid then begin
Varcon(LineCon,Accy);
Varcon(LineCon,MaxLts);
end;
LineCon:= ' ';
end;

'm':
begin
ConCom(LineCon,'mesh');
If ErCon and ConValid then begin
Varcon(LineCon,MaxMesh);
Varcon(LineCon,MinBPts);
end;
LineCon:= ' ';
end;

's':
begin
If iWind>4 then exit;
ConCom(LineCon,'section');
If ErCon and ConValid then begin
VarCon(LineCon,ConData[iWind].I);
VarCon(LineCon,ConData[iWind].phase);
end;
ConValid:=False;
ErCon:=True;
Readln(ConF,LineCon);
begin
ConCom(LineCon,'posdim');
If ErCon and ConValid then begin
VarCon(LineCon,ConData[iWind].Y1);
VarCon(LineCon,ConData[iWind].X1);
VarCon(LineCon,ConData[iWind].YHeight);
VarCon(LineCon,ConData[iWind].XWidth);
end;
Readln(ConF, LineCon);
Case LineCon[1] of
  'h':
    begin
      ConCom(LineCon,'hplate');
      If ErCon and ConValid then begin
        VarConI(LineCon,ConData[iWind].N);
        VarCon(LineCon,ConData[iWind].Thik);
        VarCon(LineCon,ConData[iWind].sgm);
      end;
      LineCon:=" ";
      ConData[iWind].pOrtn:=1;
    end;
  'v':
    begin
      ConCom(LineCon,'vplate');
      If ErCon and ConValid then begin
        VarConI(LineCon,ConData[iWind].N);
        VarCon(LineCon,ConData[iWind].Thik);
        VarCon(LineCon,ConData[iWind].sgm);
      end;
      LineCon:=" ";
      ConData[iWind].pOrtn:=2;
    end;
  'w':
    begin
      ConCom(LineCon,'wire');
      If ErCon and ConValid then begin
        VarConI(LineCon,ConData[iWind].N);
        VarCon(LineCon,ConData[iWind].Thik);
        VarCon(LineCon,ConData[iWind].sgm);
      end;
      LineCon:=" ";
      ConData[iWind].pOrtn:=0;
      ConData[iWind].N:= ConData[iWind].N* ConData[iWind].NLayers;
    end;
  'I':
    begin
      ConCom(LineCon,'litz');
      If ErCon and ConValid then begin
        VarConI(LineCon,ConData[iWind].N);
        VarCon(LineCon,ConData[iWind].Thik);
        VarCon(LineCon,ConData[iWind].Ldiam);
        VarCon(LineCon,ConData[iWind].sgm);
      end;
end;
LineCon:=" ";
ConData[iWind].plOrtn:=3;
ConData[iWind].N:= ConData[iWind].N*
ConData[iWind].NLayers*
ConData[iWind].NLitz;
end;
end;
iWind:=iWind+1;
LineCon:=" ";
end;
end;

If (ErCon=False) then begin
close(ConF);
halt;
end;

h:=h-g; {Now Window width minus airgap length}

For k:=iWind+1 to NWind do
With ConData[k] do begin
  XI:=0.000;
  YI:=0.000;
  XWidth:=0.000;
  YHeight:=0.000;
  N:=0;
  NLayers:=0;
  NLitz:=0;
  l:=0;
  Phase:=0;
  sgrn:=00000;
  PlOrtn:=1;
  thik:=0.00000;
  LDiam:=0;
  WindPt:=nil;
end;
end;

(* Write_Out creates or overwrites the output file. *)
(* The file consists of two parts: *)
(* - The configuration and *)
(* - the node solutions *)

procedure Write_Out;

var
  ConValid: Boolean;
ErCon: Boolean;
MiFile: String[12];
ReHHx,
ImHHx,
ReHHy,
ImHHy : double;
Cdx, Cdy: double;

begin
ConValid:=False;
ErCon:=True;

If Paramcount<2 then begin
  writeln('Error:');
  writeln(' Output filename not specified on command-line');
  ErCon:=False;
end;
MIFile:=ParamStr(2);
Assign(DataF,MiFile):
{SI-}
Rewrite(DataF);
{SI+}
If (IOResult<>0) or (ErCon=False) then begin
  writeln('Error:');
  writeln(' Invalid output filename specified on command-line');
  Close(DataF);
  Assign(DataF,'EddySim.dat');
  Rewrite(DataF);
end;

begin
Writeln(DataF,'Configuration File: ',ParamStr(1));
Writeln(DataF,'EddySim data for ',NumPts,' nodes:');
Writeln(DataF,' X
', ' Y
', ' dx
', ' dy
', ' Re(A)
', ' Im(A)
', ' Re(Js)
', ' Im(Js)
', ' Re(Jc)
', ' Im(Jc)
', ' Re(Hx)
', ' Im(Hx)
', ' Re(Hy)
', ' Im(Hy)
', ' conductivity
');
Point:=FirstPt;
Repeat
  With Point do begin
    ...
If Left=nil then begin
  ReHH.x:=(Right^\text{.ReAc}-ReAc)/dx/MuO;
  ImHH.x:=(Right^\text{.ImAc}-ImAc)/dx/MuO;
end else
If Right=nil then begin
  ReHH.x:=-(ReAc-Left^-\text{.ReAc})/Left^-dx/MuO;
  ImHH.x:=(ImAc-Left^-\text{.ImAc})/dx/MuO;
end else
begin
  ReHH.x:= (Right^-\text{.ReAc}-Left^-\text{.ReAc})/(dx+Left^-dx)/MuO;
  ImHH.x:= (Right^-\text{.ImAc}-Left^-\text{.ImAc})/(dx+Left^-dx)/MuO;
end;
If sgm>O then begin
  Cdx:=(Left^-dx+dx)/2;
  Cdy:=(Top^-dy+dy)/2;
end else begin
  Cdx:=dx;
  Cdy:=dy;
end;

Writeln(DataF, XX, ",
YY ",
CdX, ",
CdY, ",
ReAp, ",
ImAp, ",
ReJc, ",
ImJc, ",
ReHHx, ",
ImHHx, ",
ReHHy, ",
ImHHy, ",
sgm);

Point:=Next;
end;
until Point=nil;
end;
For k:=1 to NNWind do begin
  Writeln(DataF);
  Writeln(DataF,'Section ',k,'.');
  Writeln(DataF,'Proximity Effect Losses: ',ConData[k].pprox);
  Writeln(DataF,' Skin Effect Losses: ',ConData[k].PSkin);
  Writeln(DataF,' Total Losses: ',Condata[k].Pskin+Condata[k].pprox);
end;
Close(DataF);
end;
Function MapCol(Val: integer): integer;

begin
  Case Val of
  0: MapCol:=Black;
  1: MapCol:=Darkgray;
  6: MapCol:=Magenta;
  7: MapCol:=LightMagenta;
  9: MapCol:=Red;
  10: MapCol:=LightRed;
  11: MapCol:=Brown;
  14: MapCol:=Yellow;
  13: MapCol:=LightGreen;
  12: MapCol:=Green;
  2: MapCol:=Blue;
  3: MapCol:=LightBlue;
  4: MapCol:=Cyan;
  5: MapCol:=LightCyan;
  8: MapCol:=LightGray;
  15: MapCol:=White
  end;
end;

procedure ShowCW;

const
  StartX = 50;
  StartY = 100;

var
  GraphDriver, GraphMode: integer;
  ErrorCode: integer;
  Height, Width : double;
  pHeight, PWidth: integer;
i,x,y,z: integer;
pX0,pY0,pX1,pY1 : integer;
v1 : array[1..12] of integer;
Wx1,Wy1,Wx2,Wy2 : integer;
Title: String[20];
Xpos,Ypos: integer;
AskJ,AskA,AskSgm: Boolean;
AskT : Boolean;
TCol:integer;
Error:String[30];

(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
(* * Draws a rectangle for a cell in the mesh and fills it with the color *)
(* * according to the desired value (A.H.J or sigma) *)
(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)

Procedure PlotMesh;

var
  Value,Min,Max : double;
  RectArr : array[1..4] of Point Type;

begin
  RectArr[1].X:=XPos;
  RectArr[1].Y:=YPos;
  RectArr[2].X:=XPos+round(Point^dx/Width*pWidth);
  RectArr[2].Y:=YPos;
  RectArr[3].X:=XPos+round(Point^dx/Width*pWidth);
  RectArr[3].Y:=YPos+round(Point^dy/Height*pHeight);
  RectArr[4].X:=XPos;
  RectArr[4].Y:=YPos+round(Point^dy/Height*pHeight);

  Value:=0;
  If AskJ then begin
    If JMax=JMin then JMin:=0;
    If Point^sgm<0 then Value:=JMin
    else With point^ do begin
      Value:=sqrt(sqr(ReJs+ReJc)+sqr(ImJs+lmJc));
      Max:=JMax;
      Min:=JMin;
    end;
  end;
  If AskA then begin
    With point^ do
    Value:=sqrt(sqr(ReAc)+sqr(ImAc));
    Max:=AMax;
    Min:=AMin;
  end;
  If AskSgm then begin
    If Point^sgm <= 0 then Value:=Max else
    Value:=abs(Point^sgm);
    Max:=sgmMax;
    Min:=sgmMin;
  end;

  If (Max=Min) then
    SetFillStyle(01,MapCol(Round((Value)/max*15)))
  else
    SetFillStyle(01,MapCol(Round((Value-Min)/(Max-Min)*15)));
If AskT then begin
  SetFillStyle(01, TCol);
end;

Fillpoly(4, RectArr);

begin

Procedure PlotValues;

var
  x, y: integer;
begin
  SetColor(Black);
  Setcolor(darkgray);
  Point:= FirstPt;
  Xpos:= StartX+round((bl/2+Point\^ XX)*pWidth/Width);
  YPos:= StartY+round(Point\^ YY*pHeight/Height);
  PlotMesh:
  Repeat begin
    Point:= Point\^ Next;
    YPos:= StartY+round(Point\^ YY*pHeight/Height);
    XPos:= StartX+round((bl/2+Point\^ XX)*pWidth/Width);
  PlotMesh;
  end;
  until Point\^ Next=nil;
end;

Procedure DrawStruct;

var
  i: integer;
begin
  (* Draw the Display-Area *)
  SetColor(Red);
  Line(Startx-5, Starty-5, Startx+350+5, Starty-5);
  Line(Startx-5, Starty-5, Startx+5+350, Starty-5);
  Line(Startx-5, Starty+5+350, Startx+350+5, Starty+5);
  Line(Startx+350+5, Starty-5, Startx+350+5, Starty+5+350);

end;
(* Fit the Structure to the Display-area *)
Height:=h+g;
Width:=l+b1/2+b2;
if Height > Width then pHeight:=350
else pHeight:=round(350*Height/Width);
pWidth:=round(pHeight*Width/Height);

(* Draw the Window *)
SetColor(White);
vt[1]:=round(h/(2*Height)*pHeight);
vt[2]:=round(b1/(2*Width)*pWidth);
vt[3]:=round(g/Height*pHeight);
vt[4]:=vt[2];
vt[5]:=vt[1];
vt[6]:=round(l/Height*pHeight);
vt[7]:=vt[5];
vt[8]:=round(b2/(Width)*pWidth);
vt[9]:=vt[3];
vt[10]:=vt[8];
vt[11]:=vt[1];
vt[12]:=vt[6];
pX0:=StartX+round(b1/(2*Width)*pWidth);
pY0:=StartY;
pX1:=pX0;
pY1:=pY0;
For i:=1 to 12 do begin
  pY1:=pY0+vt[i];
  Line(pX0,pY0,pX1,pY1);
  pY0:=pY1;
  pX1:=pX0+vt[i+1];
  Line(pX0,pY0,pX1,pY1);
  pX0:=pX1;
i:=i+1;
end;

(* Draw the Windings *)
SetColor(LightRed);
For i:=1 to NWind do begin
  Wx1:=StartX+round((ConData[i].xX1+b1/2)/Width*pWidth);
  Wy1:=StartY+round(ConData[i].Y1/Height*pHeight);
  Wx2:=StartX+round( (ConData[i].xWidth+ConData[i].xX1+b1/2)/Width*pWidth);
  Wy2:=StartY+round( (ConData[i].xHeight+ConData[i].Y1)
/Height*pHeight);
  Line(Wx1,Wy1,Wx2,Wy2);
  Line(Wx2,Wy1,Wx2,Wy2);
  Line(Wx2,Wy2,Wx1,Wy2);
  Line(Wx1,Wy2,Wx1,Wy1);
end;
end;

(*)
(***************************************************************************)
(* *)

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procedure ShowBar(AMax, AMin: double);

Var
  VValue: integer;
  px: integer;
  ErrorTot: double;

begin
  SetTextStyle(7,0,3);
  px:=0;
  {errorot:=amin};
  SetTextStyle(2,0,5);
  str(NumPts, error);
  SetColor(Yellow);
  outtextxy(StartX-395,starty-62,'Nodes: '+error);

  SetTextStyle(2,0,5);
  str(errortot:15,error);
  SetColor(lightcyan);
  outtextxy(Startx+440,starty-32,error);

  For px:= 0 to 15 do begin
    Vvalue:=Mapcol(px);
    SetColor(LightBlue);
    RecTangle( StartX+380,Starty-5,
               StartX+430,StartY-5+322);
    SetFillStyle(Solidfill, Vvalue);
    Bar( Startx+381,starty-4+round(300/15*px),
         Startx+429,starty-5+round(300/15*(px+1));

    errortot:=(px)*(amax-amin)/15+AMin;
    SetColor(Cyan);
    str(errortot:15,error);
    outtextxy(startx+440,starty-3+round(300/15*px),error);
  end;
  SetColor(LightCyan);
  outtextxy(Startx+440,starty-3+round(300/15*px),error);
end:

(* Main part of VIEW display procedure *)
GraphMode:=VGAhi;
InitGraph(GraphDriver, GraphMode, 'e:\bp\bgi');
ErrorCode:=GraphResult;
If ErrorCode <> grOK then begin
  Writeln('Graphics Error: ', GraphErrorMsg(ErrorCode));
end;

DrawStruct;

SetColor(DarkGray);
Title:='EddySim';
SetTextStyle(1,0,4);
For i:=1 to 4 do begin
  OutTextXY(50+i,20+i, Title);
end;
SetColor(LightGray);
OutTextXY(50,20, Title);
SetTextStyle(2,0,4);
OutTextXY(194,44,'1994 Rand Afrikaans University');
SetColor(Yellow);
SetTextStyle(0,0,5);
OutTextXY(440,420,'A - Vector Potential');
OutTextXY(440,440,'J - Current Density');
OutTextXY(440,460,'X - Exit to DOS ');

EndShow:=False;
Repeat begin
  Press:=False;
  AskA:=False;
  AskJ:=False;
  AskSgm:=False;
  AskT:=False;
  Point:=FirstPt;
  repeat
    PressChar:=Readkey;
    If (PressChar= 'a') or (PressChar='A') then begin
      Press:=True;
      askA:=True;
      SetFillStyle(SolidFill,0);
      Bar(450,60,640,420);
      Bar(Startx-10,StartY-36,StartX+400,StartY-10);
      ShowBar(AMax,AMin);
      SetTextStyle(7,0,2);
      SetColor(Cyan);
      OutTextXY(Startx+00,starty-40,'Magnetic Vector Potential');
    end;
    If (PressChar='J') or (PressChar='j') then begin
      Press:=True;
      askJ:=True;
      SetFillStyle(SolidFill,0);
Bar(450,60,640,420);
Bar(Startx-10,StartY-36,StartX+400,StartY-10);
ShowBar(JMax,JMin);
SetTextStyle(7,0.2);
SetColor(Cyan);
outtextxy(Startx+00,starty-40,'Current Density');
end;
If (PressChar='S') or (PressChar='s') then begin
  Press:=True;
  askSgm:=True;
  SetFillStyle(SolidFill,0);
  Bar(450,60,640,420);
  Bar(Startx-10,StartY-36,StartX+400,StartY-10);
  ShowBar(sgmMax,sgmMin);
  SetTextStyle(7,0.2);
  SetColor(Cyan);
  outtextxy(Startx+00,starty-40,'Conductivity');
end;
If (PressChar='x') or (PressChar='X') then begin
  Press:=True;
  EndShow:=true;
end;
If (PressChar='t') then begin
  Point:=FirstPt;
  SetFillStyle(SolidFill,0);
  Bar(410,60,640,420);
  Bar(Startx-10,StartY-36,StartX+400,StartY-10);
  Repeat begin
    Repeat begin
      Presschar:=readkey;
      If (Presschar='8') then begin
        TCol:=Black;
        YPos:=StartY+Round(Point^ YY*pHeight/Height);
        XPos:=StartX+Round((b1/2+Point^XX)*pWidth/Width);
        PlotMesh;
        Press:=True;
        Point:=Point^.Top;
      end;
      If (Presschar='2') then begin
        TCol:=Black;
        YPos:=StartY+Round(Point^. YY*pHeight/Height);
        XPos:=StartX+Round((b1/2+Point^.XX)*pWidth/Width);
        PlotMesh;
        Press:=True;
        Point:=Point^.Bot;
      end;
    end;
  end;
end;
If (Presschar='6') then begin
   TCol:=Black;
   YPos:=StartY+Round(Point^.YY*pHeight/Height);
   XPos:=StartX+Round((b1/2+Point^.XX)*pWidth/Width);
   PlotMesh;
   Press:=True;
   Point:=Point^.Right;
end;
If (Presschar='4') then begin
   TCol:=Black;
   YPos:=StartY+Round(point^.YY*pHeight/Height);
   XPos:=StartX+Round((b1/2+Point^.XX)*pWidth/Width);
   PlotMesh;
   Press:=True;
   Point:=Point^.Left;
end;
If (Presschar='x') then begin
   EndShow:=True;
   Press:=True;
end;
end until Press;
If Not(EndShow) then begin
   SetFillStyle(SolidFill,0);
   Bar(410,60,640,420);
   SetColor(Cyan);
   With Point^ do begin
      SetTextStyle(2,0,5);
      str(YY: 15,error);
      outtextxy(startx+380,starty-3+round(300/15*0),
               error+' - X');
      str(XX: 15,error);
      outtextxy(startx+380,starty-3+round(300/15*1)
               ,error+' - Y');
      str(ReAp:15,error);
      outtextxy(startx+380,starty-3+round(300/15*2)
               ,error+' - Re(A)');
      str(ImAp:15,error);
      outtextxy(startx+380,starty-3+round(300/15*3)
               ,error+' - Im(A)');
      str(ReJs:15,error);
      outtextxy(startx+380,starty-3+round(300/15*4)
               ,error+' - Re(Js)');
      str(ImJs:15,error);
      outtextxy(startx+380,starty-3+round(300/15*5)
               ,error+' - Im(Js)');
      str(ReJc:15,error);
      outtextxy(startx+380,starty-3+round(300/15*6)
               ,error+' - Re(Ji)');
      str(ImJc:15,error);
   end;
Fitmesh doesn't test for conducting areas overlapping conductors or cores. Due to the fact that nodes are placed over core boundaries in contrast to conductor boundaries, which must fall half way between nodes, it is also assumed that conductor boundaries always differ from core boundaries and consequently a conductor may not have the same y-coordinate as any air gap boundary.

Furthermore, conductor boundaries parallel to others must be spaced apart. However, up to three conductors may be stacked above or next to one another with two opposite boundaries having the same y or x-coordinate.
Type FitData = Record
  marg : double;
  Pts : integer;
end;

var XOrder : array[0..4*NWind+1] of FitData;
YOrder : array[0..4*NWind+3] of FitData;
{ Matrixes marg: coordinate where uneven }
{ boundary lies are in Marg }
{ Pts contains the number of points to }
{ the next boundary. The LH and Top }
{ boundaries are not included, but the }
{ other two, RH and Bottom isn't. }

NI : integer;
Nh1 : integer;
Nh2 : integer;
Nb1 : integer;
Nb2 : integer;
Ng : integer;
Nh : integer;
i,k : integer;
MinPts: integer;
Order : FitData;
MinMarg:double;
TMarg:double;
marg1: double;
marg2: double;

{*******************************************************************************
(* )
(* Initializes the mesh as a single sequence of points in the heap *)
(* Neighbouring points are not calculated yet. *)
(* )
{*******************************************************************************

procedure InitMesh;

var i,k,m : integer;
  Xw,Yh : double; { Current position }
  xi,yi :integer; { Next margin }

{*******************************************************************************
(* )
(* Issues the nest point's address to previous point *)
{*******************************************************************************

Procedure MakePt:

begin
  PrevPt:=Point;
  New(Point);
}
PrevPt^.Next:=Point;
Point^.Next:=nil;
end:

(* Gets the point coordinates and the point sizes *)

Procedure GetCdt;

var m,n : integer;

begin
  { X coordinates }
  Point^.XX:=Xw;
  If (round(precision*Xw)>=0) and (round(precision*Xw)<=round(precision*1))
  then begin
    If (round(precision*Xw)=round(precision*l)) then begin
      Point^.XX:=l;
      Point^.dX:=(I-XOrder[xi-1].marg)/XOrder[xi-1].pts;
      If SGapExist then Point^.dX:=b21Nb2;
    end else
    begin
      If (round(precision*Xw)=round(precision*XOrder[xi].marg)) then begin
        Xw:=XOrder[xi].marg;
        Point^.XX:=XOrder[xi].marg;
        xi:=xi+1;
      end;
      Point^.dX:=(XOrder[xi].marg-XOrder[xi-1].marg)/XOrder[xi-1].pts;
    end;
  end;

  { Y coordinates }
  Point^.YY:=Yh;
  m:=0;
  Repeat begin
    m:=m+1;
  end;
  until (Round(Precision*Yh)<Round(Precision*YOrder[m].marg)) and
  (Round(Precision*Yh)>=Round(Precision*YOrder[m-1].marg)) or
  (YOrder[m].pts=0) or
  (Round(precision*YOrder[m].marg)=Round(Precision*(h+g))); Point^.dy:=(YOrder[m].marg-YOrder[m-1].marg)/YOrder[m-1].pts;

  If (Round(precision*YOrder[m].marg)=round(precision*(h+g))) and
  (Round(Precision*(Yh))>=Round(Precision*(h+g)))
  then begin
    Point^.YY:=h+g;
    Point^.dY:=(YOrder[m].marg-YOrder[m-1].marg)/YOrder[m-1].pts;
  end else
  If (Round(Precision*Yh)=Round(Precision*YOrder[m-1].marg)) then
begin
  Point^._YY:=YOrder[m-1].marg;
  Yh:=Point^._YY;
  Point^._dy:=(YOrder[m].marg-YOrder[m-1].marg)/YOrder[m-1].pts;
end:

With Point^ do begin
  sgm:=0;
  ReAp:=0;
  ImAp:=0;
  ReAc:=0;
  ImAc:=0;
  ReJs:=0;
  ImJs:=0;
  ReJc:=0;
  ImJc:=0;
  Next:=nil;
  Top:=nil;
  Bot:=nil;
  Left:=nil;
  Right:=nil;
end;
end:

**************************************************************************

begin {InitMesh}
  xi:=1;
  yi:=1;
  Mark(Heaptop);
  New(Point);
  FirstPt:=Point;
  (* Air-Gap in Center-Leg *)

  If MGapExist then begin
    Xw:=-b1/2;
    Yh:=h/2;
    For k:=1 to Nb1 do begin
      For i:=1 to Ng+1 do begin
        GetCdt;
        With Point^ do begin
          dX:=b1/Nb1/2;
          Yh:=Yh+dy;
        end;
        MakePt;
      end;
      Yh:=h/2;
      Xw:=Xw+PrevPt^._dx;
    end;
  end; {If MGapExist}

  OriginPt:=Point;
  Xw:=0;
  Yh:=0;

for \( k := 1 \) to \( N_l \) do begin
    for \( i := 1 \) to \( (N_h + N_l + N_g) \) do begin
        getCdt;
        with Point^ do begin
            \( Y_h := Y_h + dy \);
        end;
        MakePt;
    end;
    \( Y_h := 0 \);
    \( X_w := X_w + \text{PrevPt}.dx \);
end;

for \( i := 1 \) to \( (N_h) \) do begin
    getCdt;
    with Point^ do begin
        \( Y_h := Y_h + dy \);
    end;
    MakePt;
end;

if MGapExist then begin
    for \( k := 1 \) to \( N_b + 1 \) do begin
        \( Y_h := h/2 \);
        for \( i := 1 \) to \( (N_g + 1) \) do begin
            getCdt;
            with Point^ do begin
                \( Y_h := Y_h + dy \);
                if SGapExist then \( dX := b/2 \) else \( dX := \text{PrevPt}.dx \);
            end;
            MakePt;
        end;
        \( X_w := X_w - \text{PrevPt}.dx \);
    end;
end;

\( X_w := 1 \);
for \( i := 1 \) to \( (N_h + 1) \) do begin
    if (MGapExist) and (\( i = 1 \)) then begin
        \( i := 2 \);
    end;
    getCdt;
    with Point^ do begin
        \( Y_h := Y_h + dy \);
    end;
    MakePt;
end;

PrevPt^.Next := nil;
LastPt := PrevPt;
GhostPt := Point;
NNh1 := Nh1;
NNh2:=Nh2;
NNb1:=Nb1;
NNb2:=Nb2;
NNl:=Nl;
NNg:=Ng;
end:

(**************************************************************************)

begin {FitMesh}

MinPts:=MinBpts;
For i:=0 to 4*NWind+3 do begin
if i<=4*NWind+1 then begin
XOrder[i].marg:=0;
XOrder[i].pts:=0;
end;
YOrder[i].marg:=0;
YOrder[i].pts:=0;
end;

For i:=1 to NWind do begin
XOrder[2*i-1].Marg:=ConData[i].X1;
XOrder[2*i].Marg:=ConData[i].X1+ConData[i].XWidth;
YOrder[2*i-1].Marg:=ConData[i].Y1;
YOrder[2*i].Marg:=ConData[i].Y1+ConData[i].YHeight;
end;
XOrder[(4*NWind)+1].Marg:=h;
YOrder[(4*NWind)+1].Marg:=h/2;
YOrder[(4*NWind)+2].marg:=h/2+g;
YOrder[(4*NWind)+3].marg:=h+g;

For i:=1 to 2*NWind+2 do begin
For k:=1 to 2*NWind+2 do begin
if (k<2*NWind+1) and (i<2*NWind+1) then begin
if (XOrder[k].Marg=XOrder[k+1].Marg) then begin
XOrder[k+1].marg:=0;
XOrder[k+1].Pts:=0;
end:
end:
end;
end;
end;

if YOrder[k].Marg=YOrder[k+1].Marg then begin
YOrder[k+1].marg:=0;
YOrder[k+1].Pts:=0;
end:
end;
end;

For i:=1 to 2*NWind+2 do begin
if ((XOrder[k].Marg>XOrder[k+1].Marg) and (XOrder[k+1].marg<>0))
or (XOrder[k].marg=0) then begin
TMarg:=XOrder[k+1].Marg;
XOrder[k+1].Marg:=XOrder[k].Marg;
XOrder[k].Marg:=TMarg;
XOrder[k].Pts:=0;
XOrder[k+1].Pts:=0;
end:
end;
end;
end;
end;
end;
end;
end;
or (\(Y_{\text{Order}[k].\text{marg}=0}\)) then begin
\(TMarg:=Y_{\text{Order}[k+1].\text{Marg}};\)
\(Y_{\text{Order}[k+1].\text{Marg}}:=Y_{\text{Order}[k].\text{Marg}};\)
\(Y_{\text{Order}[k+1].\text{Pts}}:=0;\)
\(Y_{\text{Order}[k].\text{Marg}}:=TMarg;\)
\(Y_{\text{Order}[k].\text{Pts}}:=0;\)
end;
end;
end;

For \(i:=1\) to \(2*N_{\text{Wind}}\) do begin
\(X_{\text{Order}[2*N_{\text{Wind}}+i].\text{marg}}:=X_{\text{Order}[i].\text{marg}};\)
\(Y_{\text{Order}[2*N_{\text{Wind}}+i].\text{marg}}:=Y_{\text{Order}[i].\text{marg}};\)
end;

For \(i:=1\) to \(4*N_{\text{Wind}}+2\) do begin
For \(k:=1\) to \(4*N_{\text{Wind}}+2\) do begin
If \((k<4*N_{\text{Wind}}+1)\) and \((i<4*N_{\text{Wind}}+1)\) then begin
if \((X_{\text{Order}[k].\text{Marg}}>X_{\text{Order}[k+1].\text{Marg}})\) and \((X_{\text{Order}[k+1].\text{marg}}<>0)\)
or \((X_{\text{Order}[k].\text{marg}}=0)\) then begin
\(TMarg:=X_{\text{Order}[k+1].\text{Marg}};\)
\(X_{\text{Order}[k+1].\text{Marg}}:=X_{\text{Order}[k].\text{Marg}};\)
\(X_{\text{Order}[k].\text{Marg}}:=TMarg;\)
end;
end;
end;

If \((Y_{\text{Order}[k].\text{Marg}}>Y_{\text{Order}[k+1].\text{Marg}})\) and \((Y_{\text{Order}[k+1].\text{marg}}<>0)\)
or \((Y_{\text{Order}[k].\text{marg}}=0)\) then begin
\(TMarg:=Y_{\text{Order}[k+1].\text{Marg}};\)
\(Y_{\text{Order}[k+1].\text{Marg}}:=Y_{\text{Order}[k].\text{Marg}};\)
\(Y_{\text{Order}[k].\text{Marg}}:=TMarg;\)
end;
end;

\(i:=0;\)
\(NNI:=0;\)
Repeat begin
If T\(\text{Eq}(X_{\text{Order}[i+1].\text{marg}},X_{\text{Order}[i].\text{marg}})\) then
\(X_{\text{Order}[i].\text{pts}}:=1\) else
begin
\(NI:=\text{trunc}( (X_{\text{Order}[i+1].\text{marg}}-X_{\text{Order}[i].\text{marg}})/\text{MaxMesh} +0.5) ;\)
If \(NI<\text{MinPts}\) then \(X_{\text{Order}[i].\text{pts}}:=\text{MinPts}\)
else \(X_{\text{Order}[i].\text{pts}}:=NI;\)
end;
\(NNI:=NNI+X_{\text{Order}[i].\text{pts}};\)
\(i:=i+1;\)
end;
until \((X_{\text{Order}[i+1].\text{marg}}=0)\) or \((i=4*N_{\text{Wind}})\);

\(i:=0;\)
\(NNh:=0;\)
Repeat begin
If T\(\text{Eq}(Y_{\text{Order}[i+1].\text{marg}},Y_{\text{Order}[i].\text{marg}})\) then

YOrder[i].Pts:=1 else
begin
  Nh:=trunc ((YOrder[i+1].marg-YOrder[i].marg)/MaxMesh +0.5) ;
  if Nh<MinPts then YOrder[i].pts:=MinPts
  else YOrder[i].pts:=Nh;
end;
NNh:=NNh+YOrder[i].pts;
if TEq(YOrder[i+1].marg,h/2) then Nh1:=NNh;
if TEq(YOrder[i+1].marg,h/2+g) then Ng:=NNh-Nh1;
if TEq(YOrder[i+1].marg,h+g) then Nh2:=NNh-Nh1-Ng;
i:=i+1;
end;
until (YOrder[i+1].marg=0) or (i=-1-4*Nwind+2);
i:=0;
Repeat begin
  if TEq(XOrder[i+1].marg,XOrder[i].marg) then begin
    Marg1:=(XOrder[i].marg-XOrder[i-1].marg)/XOrder[i-1].pts;
    Marg2:=(XOrder[i+2].marg-XOrder[i+1].marg)/XOrder[i+1].pts;
    MinMarg:=Mim(Marg1,Marg2);
    XOrder[i].marg:=XOrder[i].marg-MinMarg/2;
    XOrder[i+1].marg:=XOrder[i+1].marg+MinMarg/2;
  end;
i:=i+1;
end;
until (XOrder[i+1].marg=0) or (i=-4*NWind);
i:=0;
Repeat begin
  if TEq(YOrder[i+1].marg,YOrder[i].marg) and (YOrder[i-1].pts<>0) or
  (YOrder[i+1].Pts<>0)) then begin
    Marg1:=(YOrder[i].marg-YOrder[i-1].marg)/YOrder[i-1].pts;
    Marg2:=(YOrder[i+2].marg-YOrder[i+1].marg)/YOrder[i+1].pts;
    MinMarg:=Mim(Marg1,Marg2);
    YOrder[i].marg:=YOrder[i].marg-MinMarg/2;
    YOrder[i+1].marg:=YOrder[i+1].marg+MinMarg/2;
  end;
i:=i+1;
end;
until (YOrder[i+1].pts=0) or (i=4*Nwind+2);
Nl:=NNl;
if MGapExist then begin
  Nb1:=trunc((b1/MaxMesh)+0.5);
if SGapExist then begin
  if Nb1<MinPts then Nb1:=MinPts;
  Nb2:=trunc(b2/MaxMesh+0.5);
  if Nb2<MinPts then Nb2:=MinPts;
  end else Nb2:=0;
end else Nb1:=0;
InitMesh;
end;
procedure GetConductor(WX, WY, Thisdx, Thisdy: double;
    var ReCDensity, ImCDensity, Csgm: double);

var
    x: integer;
    AvCDensity: double;

begin
    ReCDensity:=0;
    ImCDensity:=0;
    Csgm:=0;
    For x:= 1 to NWind do
        With Condata[x] do
            If X1<>0 then begin
                If (X1<(WX)) and ((X1+XWidth)>WX) and
                    (Y1<(WY)) and ((Y1+YHeight)>WY) then begin
                        {Point lies within conducting region}
                        ReCDensity:=(N*I)/(XWidth*YHeight)*cos(Phase*pi/I80);
                        ImCDensity:=(N*I)/(XWidth*YHeight)*sin(Phase*pi/I80);
                        AvCDensity:=Sqrt(sqr(ImCDensity)+sqr(ReCDensity));
                        If AvCDensity>JMax then JMax:=AvCDensity;
                        If AvCDensity<JMin then JMin:=AvCDensity;
                        Csgm:=ConData[x].sgm;
                        Pskin:=0;
                        Pprox:=0;
                        If (Point^.Left^.sgm<=0) and (Point^.Top^.sgm<=0) then begin
                            ConData[x].WindPt:=Point;
                        end;
                end;
            end;
end;
procedure GetNeighbours;

var
  x,y: integer;
  ToBot,ToTop,B,TT,ToRight: MeshPtr;

begin
  Point:=FirstPt;
  ToTop:=FirstPt;
  TT:=ToTop;
  ToRight:=ToTop;

  { Air-Gap in Center Leg }
  If MGapExist then begin

    { Take Right-Point to the 2nd Column }
    For y:= 1 to NNg+1 do begin
      ToRight:=ToRight^.Next;
    end;

    { lst to 2nd-Last Column }
    For x:= 1 to NNb1-I do begin

      { First Row }
      Point^.Right:=ToRight;
      ToRight^.Left:=Point;
      Point^.Bot:=Point^.Next;
      Point^.Top:=Point^.Next;
      ToTop:=Point;
      Point:=Point^.Next;

      { 2nd to 2nd-Last Row }
      For y:=2 to NNg do begin
        Point^.Right:=ToRight;
        ToRight^.Left:=Point;
        Point^.Bot:=Point^.Next;
        ToTop:=Point;
        Point:=Point^.Next;
        ToRight:=ToRight^.Next;
      end;

      { Last Row }
      Point^.Right:=ToRight;
      ToRight^.Left:=Point;
      Point^.Bot:=ToTop;
      Point:=Point^.Next;
      ToRight:=ToRight^.Next;
    end;

    { Take Right-Point to Bottom-Right Boundary on Top-Left Leg }
    For y:= 1 to NNh1 do begin

  end.

end;

end.}
ToRight:=ToRight^.Next;
end:

{ Last Column }
{ First Point }
Point^.Right:=ToRight;
ToRight^.Left:=Point;
Point^.Bot:=Point^.Next;
Point^.Top:=Point^.Next;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;

{ 2nd to 2nd-Last Points in last Column }
For y:=2 to NNg do begin
Point^.Right:=ToRight;
ToRight^.Left:=Point;
Point^.Top:=ToTop;
Point^.Bot:=Point^.Next;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
end;

{ Last Point in Column }
Point^.Right:=ToRight;
ToRight^.Left:=Point;
Point^.Top:=ToTop;
Point^.Bot:=ToTop;
Point:=Point^.Next;

{ Take Right-Point to 2nd Point on Top Window-Boundary }
For y:=1 to NNh2+1 do begin
ToRight:=ToRight^.Next;
end;
end; if
else begin

{ Take Right-Point to 2nd Point on Top Window-Boundary }
For y:=1 to NNh1+NNh2+NNg+1 do begin
ToRight:=ToRight^.Next;
end;
end:

{ Points on Top-Left Leg Boundary }
{ First Point }
Point^.Bot:=Point^.Next;
Point^.Top:=Point^.Bot;
Point^.Right:=ToRight;
Point^.Left:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
{ 2nd to Last Points } 
For y:=2 to NNh1 do begin 
  Point^\.Top:=ToTop;
  Point^\:.Bot:=Point^\.Next;
  Point^\:.Right:=ToRight;
  Point^\.Left:=ToRight;
  ToRight^\.Left:=Point;
  ToTop:=Point;
  Point:=Point^\.Next;
  ToRight:=ToRight^\.Next;
end;

{ Points between the Center Air-Gap and Center Window-Area } 
If NNg>0 then begin 
  For y:=1 to NNg do begin 
    Point^\.Top:=ToTop;
    Point^\.Bot:=Point^\.Next;
    Point^\.Right:=ToRight;
    ToRight^\.Left:=Point;
    ToTop:=Point;
    Point:=Point^\.Next;
    ToRight:=ToRight^\.Next;
  end;
end;

{ lst to 2nd-Last Points on Bottom-Left Leg Boundary } 
For y:= 2 to NNh2 do begin 
  Point^\.Top:=ToTop;
  Point^\.Bot:=Point^\.Next;
  Point^\.Right:=ToRight;
  If Not(MGapExist) then Point^\.Left:=ToRight;
  ToRight^\.Left:=Point;
  ToTop:=Point;
  Point:=Point^\.Next;
  ToRight:=ToRight^\.Next;
end:

{ Last Point } 
Point^\.Top:=ToTop;
Point^\.Bot:=ToTop;
Point^\.Right:=ToRight;
Point^\.Left:=ToRight;
ToRight^\.Left:=Point;
Point:=Point^\.Next;
ToRight:=ToRight^\.Next;
For $x = 2$ to $NNl - 1$ do begin

First Row on Top Boundary
Point'.Bot := Point'.Next;
Point'.Top := Point'.Next;
Point'.Right := ToRight;
ToRight'.Left := Point;
ToTop := Point;
Point := Point'.Next;
ToRight := ToRight'.Next;

2nd to Last Row in Upper Window Area
For $y = 2$ to $NNh1$ do begin

Point'.Top := ToTop;
Point'.Bot := Point'.Next;
Point'.Right := ToRight;
ToRight'.Left := Point;
ToTop := Point;
Point := Point'.Next;
ToRight := ToRight'.Next;
end;

Points in Mid Window Area
If $NNg > 0$ then begin

All Rows
For $y = 1$ to $NNg$ do begin

Point'.Top := ToTop;
Point'.Bot := Point'.Next;
Point'.Right := ToRight;
ToRight'.Left := Point;
ToTop := Point;
Point := Point'.Next;
ToRight := ToRight'.Next;
end;
end;

First to 2nd-Last Points in Lower Window Area
For $y = 1$ to $NNh2$ do begin

Point'.Top := ToTop;
Point'.Bot := Point'.Next;
Point'.Right := ToRight;
ToRight'.Left := Point;
ToTop := Point;
Point := Point'.Next;
ToRight := ToRight'.Next;
end:

Last Row in Lower Window Area
Point'.Top := ToTop;
Point'.Bot := ToTop;
Point'.Right := ToRight;
ToRight'.Left := Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
end:

{ 2nd-Last Column }  
{ in Upper Window Area } 
{ First Point }  
Point^.Bot:=Point^.Next;
Point^.Top:=Point^.Next;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
end;

{ Points in Side-Gap }  
If NNg>0 then begin 

{ Points in Mid-Window Area }  
For y:=2 to NNh1 do begin 
Point^.Bot:=Point^.Next;
Point^.Top:=ToTop;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
end;

{ 2nd to Last Points in 2nd-Last Column }  
For y:=2 to NNh1 do begin 
Point^.Bot:=Point^.Next;
Point^.Top:=ToTop;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
end;

{ Points in Side-Gap }  
If NNg>0 then begin 

{ Points in Mid-Window Area }  
For y:=1 to NNg+1 do begin 
Point^.Top:=ToTop;
Point^.Bot:=Point^.Next;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
end;

{ Take Right-Point to First Point in Last Column in Lower Window Area }  
If SGapExist then begin 
For x:=2 to NNb2+1 do begin 
for y:= 1 to NNg+1 do begin 
ToRight:=ToRight^.Next;
end:
end;
end;
end:

{ 1st to 2nd Last Point on Lower-Right Leg }  
For y:=1 to NNh2 do begin 
If MGapExist and (y=1) then y:=2;
Point^.Top:=ToTop;
Point^.Bot:=Point^.Next;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;
end;

{ Last Point on Lower Boundary in 2nd-Last Column }
Point^.Top:=ToTop;
Point^.Bot:=ToTop;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
Point:=Point^.Next;

{ Last Column in Window Area }
{ First Point }
Point^.Bot:=Point^.Next;
Point^.Top:=Point^.Next;
Point^.Right:=Point^.Left;
ToTop:=Point;
Point:=Point^.Next;

{ 2nd to Last Points in Upper Window Area }
for y:=2 to NNh+1 do begin
Point^.Top:=ToTop;
Point^.Bot:=Point^.Next;
Point^.Right:=Point^.Left;
ToTop:=Point;
Point:=Point^.Next;
end;

{ Points in Side-Gap Area }
If NNg>0 then begin
If SGapExist then begin
ToRight:=Point;
{ Take Right-Point to 2nd Column }
For y:=1 to NNg-1 do begin
ToRight:=ToRight^.Next;
end;
{ Mark the Last Point in 1st Column }
TT:=ToRight;
{ Take Right-Point to 1st in 2nd Column }
ToRight:=ToRight^.Next^.Next;
{ 1st Point in 1st Column }
Point^.Bot:=Point^.Next;
Point^.Top:=ToTop;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;

{ 2nd to 2nd-Last Point in 1st Column }
For y:=2 to NNg do begin
  Point^.Top:=ToTop;
  Point^.Bot:=Point^.Next;
  Point^.Right:=ToRight;
  ToRight^.Left:=Point;
  ToTop:=Point;
  Point:=Point^.Next;
end;

ToBot:=Point^.Next;
For x:=2 to NNb2+1 do begin
  For y:=1 to NNg+1 do begin
    ToBot:=ToBot^.Next;
  end;
end:

{ Last Point in 1st Column }
Point^.Bot:=ToBot;
Point^.Top:=ToTop;
Point^.Right:=ToRight;
ToRight^.Left:=Point;
ToTop:=Point;
Point:=Point^.Next;
ToRight:=ToRight^.Next;

{ 2nd to 2nd-Last Columns in Side-Gap }
For x:=2 to NNb2 do begin
  { First Row }
  Point^.Bot:=Point^.Next;
  Point^.Top:=Point^.Bot;
  Point^.Right:=ToRight;
  ToRight^.Left:=Point;
  ToTop:=Point;
  Point:=Point^.Next;
  ToRight:=ToRight^.Next;
end;

{ 2nd to 2nd-Last Rows }
For y:=2 to NNg do begin
  Point^.Top:=ToTop;
  Point^.Bot:=Point^.Next;
  Point^.Right:=ToRight;
  ToRight^.Left:=Point;
  ToTop:=Point;
  Point:=Point^.Next;
  ToRight:=ToRight^.Next;
end;

{ Last Row }
Point^.Bot:=ToTop;
Point^.Top:=ToTop;
Point^.Right:=ToRight;
ToRight\^\text{.Left}\:=\text{Point};
ToTop\:=\text{Point};
Point\:=\text{Point}\^\text{.Next};
ToRight\:=\text{ToRight}\^\text{.Next};
\text{end};

\{ Last Column \}
\{ First Point \}
Point\^\text{.Bot}\:=\text{Point}\^\text{.Next};
Point\^\text{.Top}\:=\text{Point}\^\text{.Next};
Point\^\text{.Right}\:=\text{nil};
ToTop\:=\text{Point};
Point\:=\text{Point}\^\text{.Next};

\{ 2nd to 2nd-Last Points \}
\text{for } y:=2 \text{ to } \text{NNg do begin}
Point\^\text{.Top}\:=\text{ToTop};
Point\^\text{.Bot}\:=\text{Point}\^\text{.Next};
Point\^\text{.Right}\:=\text{nil};
ToTop\:=\text{Point};
Point\:=\text{Point}\^\text{.Next};
\text{end};

\{ Last Point \}
Point\^\text{.Bot}\:=\text{ToTop};
Point\^\text{.Top}\:=\text{ToTop};
Point\^\text{.Right}\:=\text{nil};
ToTop\:=\text{Point};
Point\:=\text{Point}\^\text{.Next};
\text{end};
\text{else begin}
\text{For } y:=1 \text{ to } \text{NNg+1 do begin}
Point\^\text{.Top}\:=\text{ToTop};
Point\^\text{.Bot}\:=\text{Point}\^\text{.Next};
Point\^\text{.Right}\:=\text{Point}\^\text{.Left};
ToTop\:=\text{Point};
Point\:=\text{Point}\^\text{.Next};
\text{end};
\text{end};

\{ Lower Window Area \}
\{ Last Column, 1st Point \}
\text{If } \text{SGapExist then } \text{Point}\^\text{.Top}\:=\text{TT}\^\text{.Next} \text{ else } \text{Point}\^\text{.Top}\:=\text{ToTop};

Point\^\text{.Bot}\:=\text{Point}\^\text{.Next};
Point\^\text{.Right}\:=\text{Point}\^\text{.Left};
ToTop\:=\text{Point};
Point\:=\text{Point}\^\text{.Next};
\text{end};

\{ 3rd to 2nd-Last Points \}
y:=1;
\text{While } y<\text{NNh2+1 do begin}
If MGapExist and \( y = 1 \) then \( y := 3 \):
Point\^\^.Top := ToTop;
Point\^\^.Bot := Point\^\^.Next;
Point\^\^.Right := Point\^\^.Left;
ToTop := Point;
Point := Point\^\^.Next;
y := y + 1;
end:

\{ Last Point \}
Point\^\^.Bot := ToTop;
Point\^\^.Top := ToTop;
Point\^\^.Right := Point\^\^.Left;
end;

(******************************************************************************)
(* Calculates the number of points *)
(******************************************************************************)

Procedure GetNum;

var
k: integer;

begin
Point := FirstPt;
k := 0;
Repeat begin
Point := Point\^\^.Next;
k := k + 1;
end;
until Point = nil;
NumPts := k;
end;

(******************************************************************************)
(* Calculates the Magnetic Field intensity distribution in the Core Window *)
(******************************************************************************)

Procedure BEREKEN_H(F: Integer);

(*
Uses imaging technique to calculate the magnetic field distribution inside
the window. This result is used as an initial condition for the numerical
iteration process and significantly improves convergence speed.
*)

Var
ReTemp, ImTemp: double;
IJ.K: Integer;
x, y, k1, k2, kk, ReH\_x, ReH\_y, ImH\_x, ImH\_y: double;
Strm: array[1..NWind,-1..1,-1..1] of double;
Procedure HVELD(x, y, Lengte, Dikte : double; Var Hx, Hy : double);

Var
r1, r2, r3, r4 : double;
Theta1, Theta2, Theta3, Theta4, ThetaA, ThetaB, ThetaC, ThetaD : double;

Begin
{ Bereken afstand en hoek vanaf hoek van winding }
r1 := Sqrt(Sqr(x-Lengte/2)+Sqr(y+Dikte/2));
r2 := Sqrt(Sqr(x+Lengte/2)+Sqr(y+Dikte/2));
r3 := Sqrt(Sqr(x+Lengte/2)+Sqr(y-Dikte/2));
r4 := Sqrt(Sqr(x-Lengte/2)+Sqr(y-Dikte/2));
If (x-Lengte/2)=0
Then If (y+Dikte/2)>=0 Then
  Then Theta1 := Pi/2
  Else Theta1 := -Pi/2
Else Begin
  Theta1 := Arctan((y+Dikte/2)/(x-Lengte/2));
  If (x-Lengte/2)<0 Then
    If (Theta1<0) Then Theta1 := Pi+Theta1
    Else Theta1 := Theta1-Pi;
End;
If (x+Lengte/2)=0
Then If (y+Dikte/2)>=0 Then
  Then Theta2 := Pi/2
  Else Theta2 := -Pi/2
Else Begin
  Theta2 := Arctan((y+Dikte/2)/(x+Lengte/2));
  If (x+Lengte/2)<0 Then
    If (Theta2<0) Then Theta2 := Pi+Theta2
    Else Theta2 := Theta2-Pi;
End;
If (x+Lengte/2)=0
Then If (y-Dikte/2)>=0
  Then Theta3 := Pi/2
  Else Theta3 := -Pi/2
Else Begin
  Theta3 := Arctan((y-Dikte/2)/(x+Lengte/2));
  If (x+Lengte/2)<0 Then
    If (Theta3<0) Then Theta3 := Pi+Theta3
    Else Theta3 := Theta3-Pi;
End;
If (x-Lengte/2)=0
Then If (y-Dikte/2)>=0
  Then Theta4 := Pi/2
  Else Theta4 := -Pi/2
Else Begin
  Theta4 := Arctan((y-Dikte/2)/(x-Lengte/2));
End;
If (x-Lengte/2)<0 Then
  If (Theta4<0) Then Theta4 := Pi+Theta4
  Else Theta4 := Theta4-Pi;
End;

{ Bereken die verskil tussen die hoekes }
ThetaA := Theta1-Theta2;
If ThetaA>Pi Then ThetaA := ThetaA-2*Pi;
If ThetaA<-Pi Then ThetaA := ThetaA+2*Pi;
ThetaB := Theta4-Theta3;
If ThetaB>Pi Then ThetaB := ThetaB-2*Pi;
If ThetaB<-Pi Then ThetaB := ThetaB+2*Pi;
ThetaC := Theta2-Theta3;
If ThetaC>Pi Then ThetaC := ThetaC-2*Pi;
If ThetaC<-Pi Then ThetaC := ThetaC+2*Pi;
ThetaD := Theta1-Theta4;
If ThetaD>Pi Then ThetaD := ThetaD-2*Pi;
If ThetaD<-Pi Then ThetaD := ThetaD+2*Pi;

If r1=0 Then r1 := 1E-10;
If r2=0 Then r2 := 1E-10;
If r3=0 Then r3 := 1E-10;
If r4=0 Then r4 := 1E-10;

Hx := -1/Pi/2/Lengte/Dikte*((y+Dikte/2)*
  ThetaA-(y-Dikte/2)*ThetaB+(x+Lengte/2)*
  ln(r2/r3)-(x-Lengte/2)*ln(r1/r4));
Hy := IPi/2/Lengte/Dikte*((x+Lengte/2)*
  ThetaC-(x-Lengte/2)*ThetaD+(y+Dikte/2)*
  ln(r2/r1)-(y-Dikte/2)*ln(r3/r4));

End; { H_VELD }

(*------------------------------------------------------------------------*)

Procedure H_PUNT(x,y : double ; Var ReH_x,ReH_y,ImH_x,ImH_y : double);

Var
  I,J,K : Integer;
  ReRx,ReHy,ImHx,ImHy,Del_x,Del_y : double;

Begin
  ReH_x := 0;
  ReH_y := 0;
  ImH_x := 0;
  ImH_y := 0;

  For I := 1 to NWind do
    For K := -I to I do
      Begin
        Del_y := y-y_ss[I,K];
        For J := -I to I do
          Begin
            Del_x := x-x_ss[I,J];
            If Strm(I,J,K)<0
              Then Begin
                H_veld(Del_x,Del_y, ConData[I].YHeight,

            End;
          End;
      End;

  End;
ConData[I].XWidth, ReHx, ReHy;
ReHx := ReHx * Strn[I,J,K] * cos(Condata[I].Phase * Pi/180);
ReHy := ReHy * Strn[I,J,K] * cos(Condata[I].Phase * Pi/180);

H_veld(Del_x, Del_y, ConData[I].YHeight, ConData[I].XWidth, ImHx, ImHy);
ImHx := ImHx * Strn[I,J,K] * sin(Condata[I].Phase * Pi/180);
ImHy := ImHy * Strn[I,J,K] * sin(Condata[I].Phase * Pi/180);

{ If Bifiler[I] = 1
  Then Begin
    Hx := Hx/2;
    Hy := Hy/2;
  End;
  End
Else Begin
  ReH := 0;
  ReHy := 0;
  ImH := 0;
  ImHy := 0;
End;
End:
End:
End:

(****************************************************************************)

Begin { BEREKEN_H }
Permeabiliteit1 := MuR;
If MGapExist Then Permeabiliteit2 := (h+g)/
  (g/ MuO + (h)/Permeabiliteit1) {MuO inserted!}
  Else Permeabiliteit2 := Permeabiliteit1;
  k1 := (Permeabiliteit1-1)/(Permeabiliteit1+1);
  k2 := (Permeabiliteit2-1)/(Permeabiliteit2+1);
For I := 1 to NWind do
  Begin
    x_senter[I] := ConData[I].Y1 + ConData[I].YHeight/2;
    y_senter[I] := ConData[I].X1 + ConData[I].XWidth/2;
    x_ss[I,0] := x_senter[I];
    x_ss[I,-1] := -x_senter[I];
    x_ss[I,1] := 2*(h+g)-x_senter[I];
    y_ss[I,0] := y_senter[I];
    y_ss[I,-1] := -y_senter[I];
    y_ss[I,1] := 2*I-y_senter[I];
    For K := -1 to 1 do
      For J := -1 to 1 do
        If (K=0) and (J=0) Then Strn[I,J,K] := ConData[I].I*ConData[I].N
        Else Begin
          If Not(MGapExist) Then
If (Abs(J)*Abs(K))=1
Then Strm[I,J,K] := -k1*ConData[I].I*ConData[I].N
Else Strm[I,J,K] := k1*ConData[I].I*ConData[I].N;
If MGapExist and Not(SGapExist)
Then Begin
  If K<0
    Then kk := k2
  Else kk := k1;
  If (Abs(J)*Abs(K))=1
  Then Strm[I,J,K] := -kk*ConData[I].I*ConData[I].N
  Else Strm[I,J,K] := kk*ConData[I].I*ConData[I].N;
End;
If SGapExist
Then Begin
  If K<>0
    Then kk := k2
  Else kk := k1;
  If (Abs(J)*Abs(K))=1
  Then Strm[I,J,K] := -kk*ConData[I].I*ConData[I].N
  Else Strm[I,J,K] := kk*ConData[I].I*ConData[I].N;
End;
{If Opsie=5
Then Begin
  If (K=-1)and(J=0)
    Then kk := k2
  Else kk := 0;
  If (Abs(J)*Abs(K))=1
  Then Strm[I,J,K] := -kk*Stroom[I,F]
  Else Strm[I,J,K] := kk*Stroom[I,F];
End;}
Point^*ImJy:=-ImH_y; \{\text{This is ImHx!}\}
Point^*ImJx:=-ImH_x; \{\text{This is ImHy!}\}

end;
Point:=Point^*Next;
end;
until Point=nil;
End;

End; \{\text{BEREKEN}\_H\}

procedure Bereken_A;

(*
The result obtained so far is the H-field in the window area only,
using the imaging technique. In order to find an initial condition
for the MVP, the integral of the result is calculated across the mesh.
*)

var No\_Gaps: integer;

begin
If SGapExist then No\_Gaps:=2 else
if MGapExist then No\_Gaps:=1;

AMax:=-le32;
AMin:=le32;

If (MGapExist) then
\{ Either 1 or two Airgaps present: \}
begin
Point:=FirstPt;
Repeat
begin
Point^*ReAp:=MuO*ReNItot*(b1/2+Point^*XX)/(No\_Gaps*g);
Point^*ImAp:=MuO*ImNItot*(b1/2+Point^*XX)/(No\_Gaps*g);
Point:=Point^*Next;
end;
until Point^*Next^*XX>=0;
Point^*ReAp:=MuO*ReNItot*(b1/2+Point^*XX)/(No\_Gaps*g);
Point^*ImAp:=MuO*ImNItot*(b1/2+Point^*XX)/(No\_Gaps*g);

Point:=Point^*Right;
Point^*ReAp:=Point^*Left^*ReAp-Point^*Left^*dx*MuO*Point^*ReJc;
Point^*ImAp:=Point^*Left^*ImAp-Point^*Left^*dx*MuO*Point^*ImJc;
Repeat
begin
  Point:=Point^.Top;
  Point^.ImAp:=MuO*Point^.ImJs*Point^.dy+Point^.Bot^.ImAp;
end;
until Point=OriginPt;
GhostPt:=Point;
Repeat
begin
  GhostPt:=GhostPt^.Bot;
  Repeat
  begin
    Point:=Point^.Right;
    Point^.ImAp:=Point^.Left^.ImAp-Point^.Left^.dx*MuO*Point^.ImJc;
  end;
  until (Point^.Right=Point^.Left) or (Point^.XX>=1);
  Point:=GhostPt;
  Point^.ImAp:=Point^.Top^.ImAp-MuO*Point^.Top^.dy*Point^.ImJs;
end;
until GhostPt^.Bot=GhostPt^.Top;
end;
end;
else
begin
  Point:=OriginPt;
end;
end;}
Point^ReAp:=O;
Point^ImAp:=O;
GhostPt:=OriginPt;
Repeat
begin
GhostPt:=GhostPt^.Bot;
Repeat
begin
Point:=Point^.Right;
Point^ImAp:=Point^.Left^ImAp-Point^.Left^dx*MuO*Point^.ImJc;
end;
until (Point^.Right=Point^.Left) or (Point^.Right^.XX>I);
Point:=GhostPt;
Point^ImAp:=Point^.Top^ImAp-MuO*Point^.Top^dy*Point^.ImJs;
end;
until GhostPt^.Bot=GhostPt^.Top;
Repeat
begin
Point:=Point^.Right;
Point^ImAp:=Point^.Left^ImAp-Point^.Left^dx*MuO*Point^.ImJc;
end;
until (Point^.Right=Point^.Left) or (Point^.Right^.XX>I) or
(Point^.Next=nil);
end;
end;

*****************************************************************************
(* Procedure to calculate - total complex current in window. *)
(* - Max and Min conductivity for test proc's *)
*****************************************************************************

procedure Get_NI_total;
var i: integer;
begin
SgmMax:=-le32;
SgmMin:=le32;
ReNItot:=O;
ImNItot:=O;
i:=O;
Repeat begin
i:=i+1;
With ConData[i] do begin
If Phase=180 then begin
I:=-I;
Phase:=0;
end;
If Phase<>0 then Phase_Zero:=False;
ReNItot:=ReNItot+N*I*cos(Phase*pi/180);
ImNItot:=ImNItot+N*I*sin(Phase*pi/180);
end;
If \( sgm > SgmMax \) then \( SgmMax := sgm \);  
If \( sgm < SgmMin \) then \( SgmMin := sgm \);  
end;  
end;  
until (ConData[i+1].sgm <= 0) or (i = NWind);

\[ \text{NNWind} := i; \]  
If \( (i = 1) \) and (ConData[1].sgm <= 0) then \( \text{NNWind} := 0; \)  
end;

\((******************************************************************************)
(* Procedure to calculate average values of conductivity and *)
(* Current density in every point of the mesh *)
(******************************************************************************)

procedure Getsgm;

begin

Max:=-le32;
JMin:=le32;
AMax:=-le32;
AMin:=-le32;
Point:=FirstPt;
With Point^ do
Repeat begin

With Point^ do begin

GetConductor(Xx,Yy,dx,dy,ReJs,ImJs,sgm);
end;
If Point^.sgm>0 then begin
Writeln;
end;
Point:=Point^.Next;
end;
until point=nil;
Point:=FirstPt;

Repeat
With Point^ do begin

ReAc:=ReAp;
ImAc:=ImAp;
If Sqrt(sqr(ReAp)+sqr(ImAp))>AMax then
AMax:=Sqrt(sqr(ReAp)+sqr(ImAp));
If Sqrt(sqr(ReAp)+sqr(ImAp))<AMin then
AMin:=Sqrt(sqr(ReAp)+sqr(ImAp));

If sgm<=0 then begin
ReJc:=0;
ImJc:=0;
ReJs:=0;
end;
end;
ImJs:=0;
end else begin
  If sqrt(sqr(ReJs)+sqr(lmJs))>JMax
    then JMax:=sqrt(sqr(ReJs)+sqr(lmJs));
  If sqrt(sqr(ReJs)+sqr(lmJs))<JMin
    then JMin:=sqrt(sqr(ReJs)+sqr(lmJs));
end;
ReJc:=0;
ImJc:=0;
If (Bot=Top) and (YY>(h+g)/2) then dy:=Top^dy;
If (Right=Left) and (XX>=l*0.99) then dx:=Left^dx;
Point:=Point^Next;
end;
until point=nil;
end;

*************************************************************************
(*)
(* Calculate the MVP and Current Distribution in Core Window *)
(*)
************************************************************************* 

Procedure GetEMVP;

var
  Jtot : double; {Total Current Density in Point }
  Itot : double; {Total current in winding }
  xi : LongInt;
  q:Integer;
  MAXi : integer;
  ReJsc : double;
  ImJsc : double;
  Reltot,
  ImItot:double;
  PrevAMax:double;
  wSOR : double;
  FoilPt : MeshPtr;
  PrevError: double;
  Error: double;
  Mer:double;
  Erg:double;

(*************************************************************************)
(* Solves for the source current in conductors once after a complete iteration *)
(* Solid wire and litz wire windings have uniform current densities *)
(* and Foils are treated according to their orientation. *)
*************************************************************************

procedure JSrc;

var Lp: integer;
For \( Lp \) := 1 to \( NNWind \) do

If \( \text{ConData}[Lp].sgm > 0 \) then

With \( \text{ConData}[Lp] \) do begin

Case \( \text{PIOrtn} \) of

0: \{ Solid wire: uniform current density \}

begin

\( \text{ReItot} := 0; \)

\( \text{FoilPt} := \text{ConData}[Lp].\text{WindPt}; \)

Repeat begin

\( \text{Point} := \text{FoilPt}; \)

Repeat with \( \text{point}.\) do begin

\( \text{ReItot} := \text{ReItot} + \text{ReJs} \times (\text{dx} + \text{Left}.\text{dx}) \times (\text{dy} + \text{Top}.\text{dy}) / 4; \)

\( \text{ReJs} := 0; \)

\( \text{ImJs} := 0; \)

\( \text{ReJs} := N \times I \times \cos(\text{phase} \times \pi / 180) / (\text{XWidth} \times \text{YHeight}) - \text{ReJc}; \)

\( \text{ImJs} := N \times I \times \sin(\text{phase} \times \pi / 180) / (\text{XWidth} \times \text{YHeight}) - \text{ImJc}; \)

\( \text{Point} := \text{Point}.\text{bot}; \)

until \( \text{Point}.\sgm <= 0; \)

\( \text{FoilPt} := \text{FoilPt}.\text{Right}; \)

end;

until \( \text{FoilPt}.\sgm <= 0; \)

end;

end;

1: \{ Plate: Vertical orientation \}

begin

\( \text{FoilPt} := \text{ConData}[Lp].\text{WindPt}; \)

Repeat begin

\( \text{Point} := \text{FoilPt}; \)

\( \text{ReItot} := 0; \)

\( \text{ImItot} := 0; \)

Repeat with \( \text{point}.\) do begin

\( \text{ReItot} := \text{ReItot} + (\text{ReJc} \times (\text{dy} + \text{Top}.\text{dy}) / 2 \times (\text{dx} + \text{Left}.\text{dx}) / 2); \)

\( \text{ImItot} := \text{ImItot} + (\text{ImJc} \times (\text{dx} + \text{Left}.\text{dx}) / 2 \times (\text{dy} + \text{Top}.\text{dy}) / 2); \)

\( \text{Point} := \text{Point}.\text{bot}; \)

end; until \( \text{Point}.\sgm <= 0; \)

With \( \text{point}.\) do begin

\( \text{ImJsc} := (N \times I \times \sin(\text{Phase} \times \pi / 180) \times (\text{Point}.\text{dx} + \text{Left}.\text{dx}) / (\text{XWidth}) - 2 \times \text{ImItot}) / (\text{YHeight} \times (\text{Point}.\text{dx} + \text{Left}.\text{dx})); \)

\( \text{ReJsc} := (N \times I \times \cos(\text{Phase} \times \pi / 180) \times (\text{Point}.\text{dx} + \text{Left}.\text{dx}) / (\text{XWidth}) - 2 \times \text{ReItot}) / (\text{YHeight} \times (\text{Point}.\text{dx} + \text{Left}.\text{dx})); \)

end;

Repeat begin

\( \text{Point} := \text{Point}.\text{Top}; \)

\( \text{Point}.\text{ReJs} := \text{ReJsc}; \)

\( \text{Point}.\text{ImJs} := \text{ImJsc}; \)

end; until \( \text{Point} = \text{FoilPt}; \)

\( \text{FoilPt} := \text{FoilPt}.\text{Right}; \)
end;
until FoilPt$\cdot$sgm<=$0$;
end;

2: { Plate: Planar (horizontal) orientation }
begin
FoilPt$:= $WindPt;
Reltot$=0$;
ImItot$=0$;
Repeat begin
Point$:= $FoilPt;

Repeat begin
Reltot$:= $Reltot$+ $point$.Re$\cdot Jc$*$(point$.dx/2+point$.Left$.dx/2)*
(point$.dy/2+point$.Top$.dy/2);
ImItot$:= $ImItot$+ $point$.Im$\cdot Jc$*$(point$.dx/2+point$.Left$.dx/2)*
(point$.dy/2+point$.Top$.dy/2);
Point$:= $Point$.Right$;
end;
until Point$.sgm<=$0$;

ImJsc$:= (N*I*sin(phase*pilI80)*(point$.dy+point$.Left$.dy)/
(YHeight)-2*ImItot)/(XWidth*(point$.dy+point$.Left$.dy));
ReJsc$:= (N*I*cos(Phase*pilI80)*(point$.dy+point$.Left$.dy)/
(YHeight)-2*Reltot)/(XWidth*(point$.dy+point$.Left$.dy));

Repeat begin
Point$:= $Point$.Left$;
Point$.ReJs$:= $ReJsc;
Point$.ImJs$:= $ImJsc;
end;
until Point$= $FoilPt;
Reltot$=0$;
ImItot$=0$;
FoilPt$:= $FoilPt$.Bot$;
end;
until FoilPt$.sgm<=$0$;
end;

3: { Litz wire: uniform current density }
begin
Reltot$=0$;
FoilPt$:= $ConData[l].WindPt;
Repeat begin
Point$:= $FoilPt;
Repeat
with point do begin
{ Reltot$:= $Reltot$+ $ReJs*(dx+Left$.dx)*(dy+Top$.dy)/4;
ReJc$=0$;
ImJc$=0$;
}
ReJs$:= N*I*cos(phase*pilI80)/(XWidth*YHeight)-ReJc;
ImJs$:= N*I*sin(phase*pilI80)/(XWidth*YHeight)-ImJc;
Point$:= $Point$.bot$;
end;
until Point^sgm<=0;
FoilPt:=FoilPt^Right;
end;
until Foilpt^sgm<=0;
end:
end:
end:
end:

(*-----------------------------------------------------------------------------------------------*)

procedure EMVP:

var
  vK,vR,Jsr,Jsk,Q,O,T: double;
begin
  With Point^ do begin
    if (XX<0) then begin
      if (ReNItot>0) then
        ReAc:=(B1/2+XX)/(NoGaps·g)·(ReNItot·MuO);
      if (ImNItot>0) then
        ImAc:=(B1/2+XX)/(NoGaps·g)·(ImNItot·MuO);
    end else
    if XX>1 then begin
      if (ReNItot>0) then
        ReAc:=((-XX+1)+B2)/(NoGaps·g)·(ReNItot·MuO);
      if (ImNItot>0) then
        ImAc:=((-XX+1)+B2)/(NoGaps·g)·(ImNItot·MuO);
    end else begin
      vR:= Right^ReAc/(dx·(dx+left^dx)+
        Left^ReAc/(Left^dx·(dx+Left^dx))+
        Bot^ReAc/(dy·(dy+Top^dy))+
        Top^ReAc/(Top^dy·(dy+Top^dy));
      vK:= Right^ImAc/(dx·(dx+left^dx)+
        Left^ImAc/(Left^dx·(dx+Left^dx))+
        Bot^ImAc/(dy·(dy+Top^dy))+
        Top^ImAc/(Top^dy·(dy+Top^dy));
      T := 1/(dx·(dx+left^dx))+
        1/(Left^dx·(dx+Left^dx))+
        1/(dy·(dy+Top^dy))+
        1/(Top^dy·(dy+Top^dy));
    end;

    O:=sgm·freq·muO·Pi;
    Jsr:= muO/2·ReJs;
    Jsk:= muO/2·ImJs;

    ReAc:=((vR+Jsr)*T+(vK+Jsk)*O)/(T*T+O*O);
    ImAc:=((vK+Jsk)*T-(vR+Jsr)*O)/(T*T+O*O);
  end:
end:
end;
end;
end;

(*-------------------------------------------------------------*)

begin

Itot:=0;
Jtot:=0;
xi:=0;
ReJsc:=0;
ImJsc:=0;
MAXi:=0;
ReItot:=0;
ImItot:=0;
wSOR:=1.3;
Error:=1;
PrevError:=1;
Mer:=0;
Assign(MaxF,'max.err');
Rewrite(MaxF);
If MaxIts>0 then
repeat begin
  prevError:=Error;
  Error:=0;
  Point:=FirstPt;
  Repeat begin
    With Point do begin
      EMVP; { Calculate Ap: }
      If (sgm>0.0) and (freq>0) then begin
        ReAc:= sgm*2*pi*freq*ImAc;
        ImAc:=-sgm*2*pi*freq*ReAc;
      end;
      {$DEFINE SOR}
      {$UNDEFINE SOR}
      {$IFDEF SOR} {If (XX>=0) and (XX<=1) then}bcgin
        ReAc:=wSOR*ReAc+(1-wSOR)*ReAp;
        ImAc:=wSOR*ImAc+(1-wSOR)*ImAp;
      end;
      {$ENDIF}
      Erg:=0;
      If (ReAp<>0) then
        Erg:=Erg+sqr((ReAc-ReAp)/ReAp);
      If (ImAp<>0) then
        Erg:=Erg+sqr((ImAc-ImAp)/ImAp);
      Error:=sqrt(erg)*100;
      If ReAc>error then Error:=ReAc;
      ImAp:=ImAc;
      ReAp:=ReAc;
    end;
    NextPt:=Point^.Next;
    Point:=NextPt;
  end;
end;
until Point=nil;
J src;
If PrevError=0 then prevError:=1;
xi:=xi+1;
MAXi:=MAXi+1;
MER:=MER+Error;
If MAXi>=10 then begin
    writeln(MaxF.'xi,'.'MER/10:20:15);
    If EddyView then Writeln('I: '.xi,' Residual: 'Error,'%i: ')
        ,(Error-PrevError)*100/PrevError);

    MAXi:=0;
    MER:=0;
end;
end;
end;
end;

Close(MaxF);

(* ****************************************************************** *)
(* " Calculates the magnitudes of the MVP and current densities for  *)
(* display procedure                                             *)
(* ****************************************************************** *)

Procedure GetDisp;

var JJ:double;
AA:Double:

begin
    JMax:=-le32;
    If freq>O then JMin:=le32 else JMin:=0;
    AMax:=-le32;
    AMin:=le32;
    Point:=Firstpt;
    Repeat begin
        With Point do begin
            If Point'.sgm>O then begin
                JJ:=sqrt(sqr(ReJs+ReJc)+sqr(ImJs+ImJc));
                if JJ>JMax then JMax:=JJ;
                if JJ<JMin then JMin:=JJ;
            end;
            if sqrt(sqr(ReAc)+sqr(ImAc))>Amax then
                AMax:=sqrt(sqr(ReAc)+sqr(ImAc));
            if sqrt(sqr(ReAc)+sqr(ImAc))<Amin then
                AMin:=sqrt(sqr(ReAc)+sqr(ImAc));
            AA:=sqrt(sqr(ReAc)+sqr(ImAc));
        end;
        Point:=Point'.next;
    end;
end;
procedure Non_Foil:

var pi: integer;
    FoilPt: MeshPtr;
begin
  For pi:=1 to NNWind do
    If ConData[pi].Plortn=0 then begin
      FoilPt:=ConData[pi].WindPt;
      Repeat begin
        Point:=FoilPt;
        Repeat
          with Point" do begin
            ReJc:=0;
            ImJc:=0;
            Point:=Point" .Bot;
          end;
          until Point" .sgm<=0;
          FoilPt:=FoilPt" .Right;
        end;
        until Foilpt" .sgm<=0;
      end;
    end;
end:
(******************************************************)
(*
(* Calculates the magnetic Field Intensity Distribution
(*
(*
(******************************************************)
(procedure Calc_H:

var ReBx,
    ImBx,
    ReBy,
    ImBy : double;
begin
  Point:=FirstPt;
  Repeat begin
    with Point" do begin
      If Left=nil then begin
        ReBy:=(Right" .ReAc-ReAc)/dx;
        ImBy:=(Right" .ImAc-ImAc)/dx;
      end;
    end;
  end;
end;
If Right=nil then begin
ReBy:=(ReAc-Left^ReAc)/Left^dx;
ImBy:=(ImAc-Left^ImAc)/Left^dx;
end else
begin
ReBy:=-(Right^ReAc-Left^ReAc)/(dx+Left^dx);
ImBy:=-(Right^ImAc-Left^ImAc)/(dx+Left^dx);
ReBx:=-((Top^ReAc-Bot^ReAc)/(dy+Top^dy)));
ImBx:=-((Top^ImAc-Bot^ImAc)/(dy+Top^dy));
end:
ReAp:=sqrt(sqr(ReBx)+sqr(lmBx)/MuO;
ImAp:=sqrt(sqr(ReBy)+sqr(ImBy))/MuO;
end;
Point:=Point^Next;
end;
until Point=nil;
end;

**************************************************************************
(*
(* Calculates the Skin and proximity losses in a plate winding
(*
**************************************************************************
Procedure GetLoss;
begin
{These lines have been removed for copy protection purposes}
end:{begin}

**************************************************************************
(*
(* Main Procedure Block
(*
**************************************************************************
begin
h:=R_h;
l:=R_l;
g:=R_g;
b1:=R_b1;
b2:=R_b2;
{ Mask Interpreter for Magnetic Components }
MIMC:
NoGaps:=2;
If (g>0) and (b1>0) then MGapExist:=True else begin
  g:=0.0;
end:
b1:=0;
b2:=0;
NNg:=0;
NNb1:=0;
NNb2:=0;
NoGaps:=0;
end;
If MGapExist and (b2>0) then SGapExist:=True else begin
  b2:=0;
  NNb2:=0;
  NoGaps:=1;
end;

FitMesh:
GetNeighbours:
GetNum:
Bereken_h(1):
Get NI_total:
Bereken_A:
Getsgm:
If MGapExist then
  GetEMVP:

GetLoss:

Write_Out:
If eddysview then begin
  GetDisp:
    ShowCW:
end:

Release (HeapTop);
halt:
end.