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# FINITE ELEMENT COMPUTATION OF EDDY CURRENT LOSSES IN NONLINEAR FERROMAGNETIC SHEATHS OF THREE-PHASE POWER CABLES

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ABSTRACT - This paper presents a new method for a finite element computation of the losses in a three phase power cable. The phase conductors carry sinusoidal, steady-state and balanced currents and the sheath is made of a nonlinear ferromagnetic material. A new concept for an effective equivalent magnetic permeability is introduced that allows calculations in the complex domain. As an example, sheath losses are presented and discussed for a symmetrical configuration.

KEYWORDS: eddy current losses, power cables, nonlinear materials, finite element method.

## 1. INTRODUCTION

As the energy density of power transmission is increasing, the eddy current problems are becoming important in various fields. One of these problems is the calculation of eddy current sheath losses in i) protective steel pipes, which are used in conventional power cables and ii) pressure retaining steel pipes, which are used in gas and cryogenic cables.

The nonlinearity of the sheath material introduces a great complexity in the electromagnetic field analysis. Even in the steady-state ac operation, time has to appear as an explicit variable in the diffusion equation. The problem has been approached in [1] assuming a constant relative permeability of the sheath and using a value of $\mu_{rs} \approx 200$ that gave good results for a given geometry and load. However, this value of $\mu_{rs}$ was determined by previous loss measurements and if the currents or the conductor's location changed, the need for another estimation of $\mu_{rs}$ would arise. Other authors have introduced new concepts for an effective permeability, based on the average magnetic energy density [2] to obtain a constant permeability or based on the flux density [3] to obtain an rms reluctivity.

In [4] a new method for the eddy current loss calculation in an one-dimensional problem has been presented. This method has led to accurate loss computations, introducing an equivalent material with non time varying permeability but with different value from point to point. This value was related to the nonlinear B-H curve of the real material with the help of the stored magnetic coenergy density at every point. As a result, time effective calculations were made by solving the diffusion equation in the complex plane with phasor quantities. The purpose of this work is the extension and application of the method presented in [4] in two-dimensional nonlinear diffusion problems. Results are presented for the eddy current loss computation in the ferromagnetic sheath of a three phase power cable.

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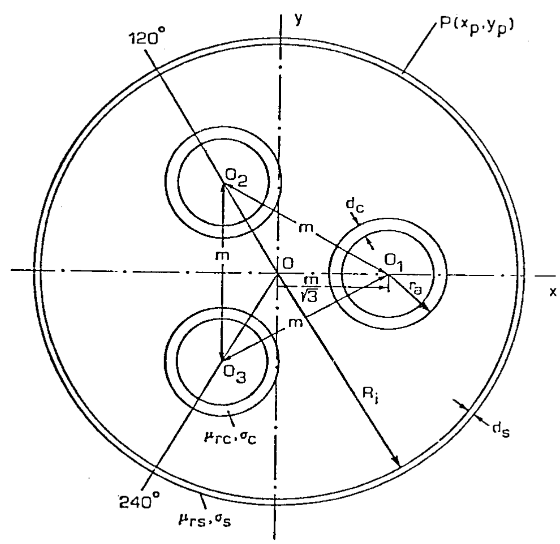


**Fig.1.** Cross section of the three-phase cable

## 2. THE MODEL

The cable consists of three tubular phase conductors in equilateral configuration within a tubular shell, as shown in Fig.1. The following assumptions are made:

1) The cable is assumed to be infinitely long and the problem becomes a two-dimensional one.
2) Charges and displacement currents are neglected.
3) The conductors have constant conductivities and relative permeabilities.
4) The sheath has constant conductivity but its relative permeability has a constant in time but different from point to point value, as it will be explained in section #5 of the paper.
5) The phase currents are sinusoidal and balanced.

The last assumption allows to introduce complex functions for the time variation of the phase currents, so that

$$I_1 = \sqrt{2}\, I_{rms}\, e^{j\omega t}$$
$$I_2 = \sqrt{2}\, I_{rms}\, e^{j(\omega t-2\pi/3)} \qquad (1)$$
$$I_3 = \sqrt{2}\, I_{rms}\, e^{j(\omega t-4\pi/3)}$$

where $I_{rms}$ is the only measurable quantity in the cable.

## 3. THE ELECTROMAGNETIC FIELD EQUATIONS

The assumptions made lead to a piecewise linear, steady-state, time harmonic, electromagnetic field. Following the analysis presented in [5], the two-dimensional diffusion problem is described by the system of equations

$$\frac{1}{\mu_0\mu_r}\left[\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2}\right] - j\omega\sigma A + J_s = 0 \qquad (2a)$$

$$- j\omega\sigma A + J_s = J \qquad (2b)$$

and the appropriate boundary relations, i.e. the continuity of the normal components of the flux density B and the continuity of the tangential components of the magnetic field H across the boundary between two media.

In this system of equations the unknowns are the magnetic vector potential A and the source current density $J_s$, while the total current density J is specified in the integral form

$$\iint_S J\, ds = I_{rms} \qquad (2c)$$

where $I_{rms}$ is the current flowing in a conductor of cross-section S.

According to the fourth assumption, the relative permeability of the sheath $\mu_{rs}$ is different from point to point. This value of $\mu_{rs}$ was connected in [4] with the nonlinear curve B-H of the material using the stored magnetic coenergy during a quarter of a period T. A generalization for the two-dimensional diffusion problem will be attempted here. From the definition of the magnetic vector potential A as having a curl equal to the flux density vector B and because the problem is limited in the x-y plane of Fig.1, the x- and y-components of the flux density in the point $P(x_p,y_p)$ will be

$$B_x(x_p,y_p) = \left.\frac{\partial A}{\partial y}\right|_{(x_p,y_p)} \qquad (3a)$$

and

$$B_y(x_p,y_p) = -\left.\frac{\partial A}{\partial x}\right|_{(x_p,y_p)} \qquad (3b)$$

or in a phasor form

$$B_x(x_p,y_p) = B_{x\,rms}\, e^{j\varphi_x} \qquad (4a)$$

and

$$B_y(x_p,y_p) = B_{y\,rms}\, e^{j\varphi_y} \qquad (4b)$$

The corresponding time variation of the components of the flux density will be

$$b_x(t) = \sqrt{2}\, B_{x\,rms}\cos(\omega t+\varphi_x) \qquad (5a)$$

and

$$b_y(t) = \sqrt{2}\, B_{y\,rms}\cos(\omega t+\varphi_y) \qquad (5b)$$

and finally the time variation of the magnitude of the flux density vector will be

$$|b(t)| = \left[2[B_{x\,rms}\cos(\omega t+\varphi_x)]^2 + 2[B_{y\,rms}\cos(\omega t+\varphi_y)]^2\right]^{1/2} \qquad (5c)$$

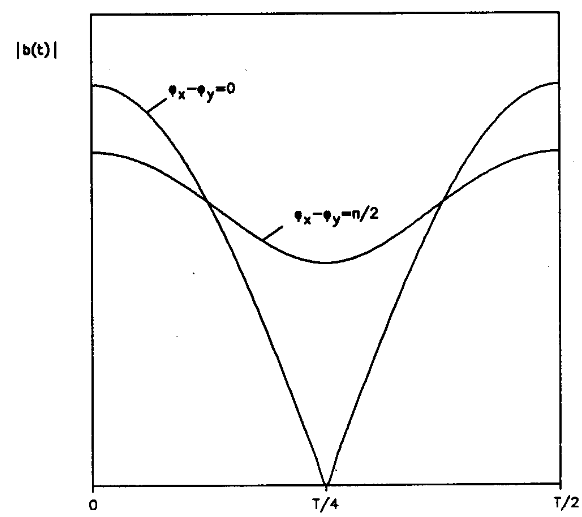


**Fig.2.** Variation of $|b(t)|$ during a half period T/2 for different values of phase angles $\varphi_x$ and $\varphi_y$.

In Fig.2 this variation is shown during a half period T/2 and for the two limiting cases where $\varphi_x-\varphi_y=0$ and $\varphi_x-\varphi_y=\pi/2$. The maximum $B_{max}$ and minimum $B_{min}$ values of (5c) can be easily computed for the point P, provided that the rms values and the phase angles are known for this point.

## 4. FINITE ELEMENT FORMULATION

Following the analysis presented in [5], the domain has been discretized into first order triangles and the unknowns A and $J_s$ were approximated in terms of linear interpolation polynomials N(x,y) and $N_s(x,y)$ as

$$A(x,y) = N^T A \tag{6a}$$

$$J_s(x,y) = N_s^T J_s \tag{6b}$$

Applying the Galerkin method to the system of equations (2) and assembling in the usual way [8] the element contributions, leads to the following matrix equation

$$\begin{bmatrix} \frac{1}{\mu_0\mu_r} S - j\omega\sigma T & -j\omega\sigma Q \\ -j\omega\sigma Q^T & j\omega\sigma W \end{bmatrix} \begin{bmatrix} A \\ G \end{bmatrix} = \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{7}$$

where the elementary matrices and vectors S,T,Q,I,W,A and G are given in [5]. The solution of the system (7) in a problem with M nodes and N conductors leads to M nodal values of the magnetic vector potential A and to N values of the source current density $J_s$, which is known to be constant over a cross-sectional area of a straight conductor [6]. Inside a finite element *'e'* of the sheath, because of the linear approximation, the flux density will be independent of the position and therefore it is assumed to be only a function of time. Thus the relations (5) for the point P are also valid for the element *'e'*, so for the following analysis this finite element will be called a *point*.

## 5. MAGNETIC COENERGY DENSITY AND NONLINEARITY

In order to work in the complex domain with the system of equations (7) and in the same time to take the nonlinear relation B and H in the sheath material into account, a fictitious material with a constant but unknown relative permeability $\mu_{rf}$ is assumed at every *point* of the sheath. This permeability will be related to the B-H curve through the unknown values of the magnetic field intensity at every *point*, which in turn will be derived by the unknown values of the flux density at every *point*. The condition to be fulfilled is that the linear fictitious material has the same eddy current average loss density as the nonlinear material has at every *point*. In order to approximate the nonlinear B-H curve, the Frohlich representation

$$B = \frac{H}{\alpha+\beta|H|} \tag{8}$$

has been used, because it is the best compromise between accuracy and simplicity. However, this relation is not a prerequisite and the method would work as well with any other approximation. From (8) the relative permeability is seen to be

$$\mu_{rf}(H) = \frac{1}{\mu_0(\alpha+\beta|H|)} \tag{9}$$

thus at every *point* $\mu_{rf}$ will be a function of H alone. In Fig.3 three different B-H curves are shown, using a coefficient $\beta$=0.59 and three different coefficients $\alpha$.

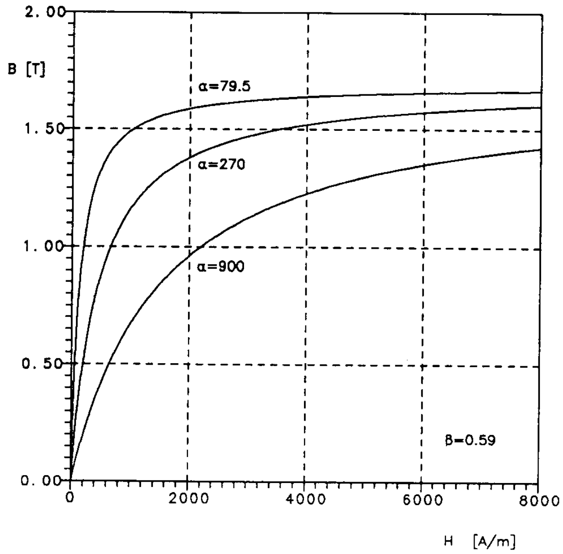


**Fig.3.** Frohlich representation of B-H curves with coefficient $\beta$ being constant and $\alpha$ varying.

At a *point* of the fictitious material, the maximum and minimum values $H_{fmax}$ and $H_{fmin}$ of the magnetic field intensity take place in a quarter of a period T. This can be shown from (5c) and from the linearity of the fictitious material at every *point*. If it is assumed that $H(t=0)=H_{fmin}$ and $H(t=T/4)=H_{fmax}$, then during this quarter of period a nonlinear material is related with a magnetic coenergy density at every *point* equal to

$$w_1 = \int_{H_{fmin}}^{H_{fmax}} b\,dh \tag{10}$$

Using (8) for the B-H relation and after integration, (10) becomes

$$w_1 = \frac{H_{fmax}-H_{fmin}}{\beta} - \frac{\alpha}{\beta^2} \ln \frac{\alpha+\beta H_{fmax}}{\alpha+\beta H_{fmin}} \tag{11}$$

and this integral is shown in Fig.4a.

The average value of the slope dB/dH during the same quarter of the period will be

$$\left\langle\frac{dB}{dH}\right\rangle = \frac{1}{H_{fmax}-H_{fmin}} \int_{H_{fmin}}^{H_{fmax}} \frac{db}{dh}\,dh \tag{12}$$

which after integration and with the help of (8) becomes

$$\left\langle\frac{dB}{dH}\right\rangle = \frac{\alpha}{(\alpha+\beta H_{fmax})\,(\alpha+\beta H_{fmin})} \tag{13}$$

This average slope is equal to the magnetic permeability given by the straight line that passes through the points $(H_{fmin},B_{min})$ and $(H_{fmax},B_{max})$ in the H-B plane of Fig.4b, where (8) is used again to relate B and H. The magnetic coenergy density of a material having this average slope during the same quarter of period will be

$$w_2 = \frac{1}{2}(H_{fmax}-H_{fmin})(B_{max}+B_{min}) \tag{14}$$

as shown in Fig.4b. With the help of (8) this integral becomes

$$w_2 = \frac{1}{2}(H_{fmax}-H_{fmin})\left(\frac{H_{fmax}}{\alpha+\beta H_{fmax}}+\frac{H_{fmin}}{\alpha+\beta H_{fmin}}\right) \tag{15}$$

The linear fictitious material, that has a constant relative permeability $\mu_{rf}$ and the same minimum and maximum values of H at the same *point*, is related to a magnetic coenergy density during the same quarter of the period equal to

$$w_f = \frac{1}{2}\mu_0\mu_{rf}(H_{fmax})^2 - \frac{1}{2}\mu_0\mu_{rf}(H_{fmin})^2 \tag{16}$$

The integrals $w_1$ and $w_2$ in the analysis presented in [4] can be considered as an upper and lower bound correspondingly in the estimation of the losses in an one-dimensional diffusion problem. Assuming that this identity still holds for the two-dimensional problem in the cable sheath, the same estimation may be considered for the magnetic coenergy density of the fictitious material that has been used with success in [4], i.e. the average of $w_1$ and $w_2$ in every *point*, given by

$$w_f = \frac{w_1 + w_2}{2} \tag{17}$$

and shown in Fig.4c. Using (16) and (17) the relative permeability of the fictitious material can be related at every *point* to the unknown values $H_{max}$ and $H_{min}$ at this *point* as

$$\mu_{rf} = \frac{w_1 + w_2}{\mu_0[(H_{fmax})^2-(H_{fmin})^2]} \tag{18}$$

where $w_1$ and $w_2$ are given from (11) and (15) correspondingly. Thus $\mu_{rf}$ is a function of $H_{fmax}$ and $H_{fmin}$ alone for a given nonlinear curve B-H and because these values are also unknown at every *point*, the solution will be based on an iterative procedure.

## 6. THE ITERATIVE PROCEDURE

The solution of the system of equations given in matrix form by (7) is based on an iterative procedure, since this system contains at every *point* of the nonlinear material tree unknowns, i.e. the magnetic vector potential A, the source current density $J_s$ and the relative permeability $\mu_r$ of the fictitious material. The iterative procedure contains five steps that will be explained in detail.

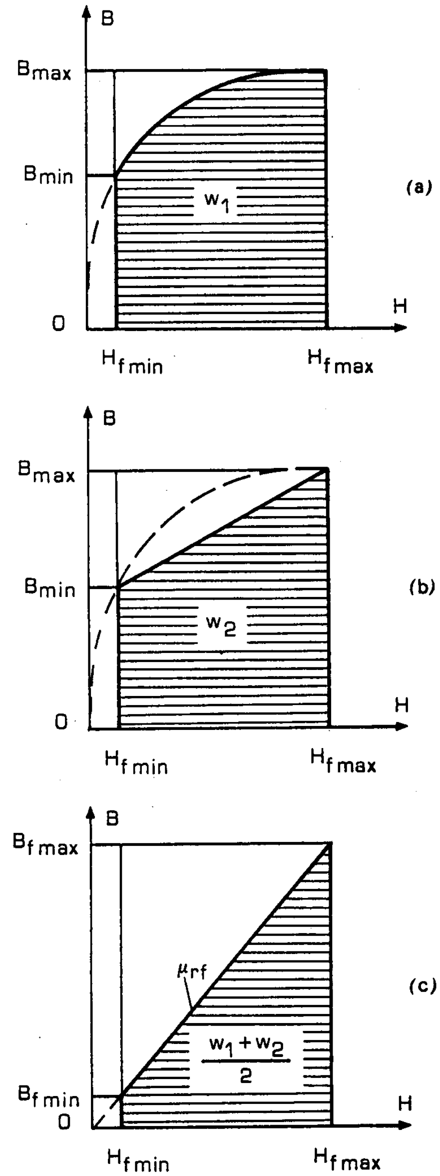


**Fig.4.** Magnetic co-energy densities during a quarter of period T using (a) the actual B-H curve, (b) the average value of the slope dB/dH and (c) the equivalent fictitious material

***Step 1***: The system of equation (2) is solved with the finite formulation (7) for the computation of the unknown values of A and $J_s$ at every *point* of the fictitious material. In the first iteration the relative permeability of the fictitious material is set equal to an initial value, which is a function of the cable load. If $I_{rms}$ is the rms current flowing in a conductor, a corresponding rms field intensity approximation may be set equal to

$$H_{rms} = \frac{I_{rms}}{2\pi r_a} \tag{19a}$$

and the initial value of the relative permeability of the fictitious material will be equal to

$$\mu_{rf} = \frac{1}{\mu_0(\alpha+\beta H_{rms})} \tag{19b}$$

and hence it has the same value at every *point*. For all the next iterations $\mu_{rf}$ will be obtained from step #5 and it will be different from *point* to *point*.

***Step 2***: Using the values of A from the solution at step #1 and the relations (3), (4) and (5), the maximum $B_{fmax}$ and minimum $B_{fmin}$ values are calculated. Finally, the maximum and minimum values $H_{fmax}$ and $H_{fmin}$ of the magnetic field intensity at every *point* are calculated as

$$H_{fmax} = \frac{1}{\mu_0\mu_{rf}} B_{fmax} \tag{20a}$$

and

$$H_{fmin} = \frac{1}{\mu_0\mu_{rf}} B_{fmin} \tag{20b}$$

***Step 3***: Using (16), the magnetic coenergy densities $w_f$ of the fictitious material are calculated at every *point*.

***Step 4***: Using (14) and (15), magnetic coenergy densities $w_1$ and $w_2$ are obtained, respectively, and the average

$$w = \frac{w_1 + w_2}{2}$$

is computed at every *point*.

***Step 5***: At every *point* of the fictitious material, the values w and $w_f$ are tested whether they differ more than a small quantity $w_{err}$. If $|w-w_f|<w_{err}$ at every *point*, the iteration procedure is terminated. If $|w-w_f|>w_{err}$ at *point 'e'*, a new relative permeability is related to this *point*, equal to

$$\mu_{rf} = \frac{2w}{\mu_0[(H_{fmax})^2-(H_{fmin})^2]} \tag{21}$$

This new value will be used at step #1 of the next iteration.

The value of $w_{err}$ is related to the precision of the iterations and it is a function of the cable load. If a characteristic magnetic coenergy density $w_b$ is defined as

$$w_b = \frac{1}{2} \mu_0\mu_{rf}(H_{rms})^2 \tag{22}$$

using the initial value of $\mu_{rs}$ defined in (19b), the quantity $w_{err}$ may be calculated from the relation

$$w_{err} = \varepsilon\, w_b \tag{23}$$

where $\varepsilon$ is a positive number less than 1.

## 7.RESULTS

The three phase gas cable presented in [7] has been considered, with geometrical and physical data given by

$$\begin{array}{ll} r_a = 0.06858 \text{ m} & d_c = 0.01270 \text{ m} \\ R_i = 0.38100 \text{ m} & d_s = 0.01270 \text{ m} \\ m = 0.33655 \text{ m} & \\ \sigma_c = 2.725\cdot 10^7 \ 1/\Omega\text{m} & \sigma_s = 2.857\cdot 10^6 \ 1/\Omega\text{m} \\ \mu_{rc} = 1 \quad \text{and} & f = 60 \text{ Hz} \end{array} \tag{24}$$

using the representation of Fig.1. The B-H curves of the ferromagnetic sheath material has been approached using Frohlich relation (8). The power loss ratio of the sheath was calculated as a function of the rms conductor current using the three B-H curves of Fig.3. and the results are presented in Fig.5. It can be seen that the maximum losses appear for load currents 20-100 kA, a range that is of no practical interest due to thermal problems. On the contrary, in the region 1-5 kA, in which gas cables usually operate, sheath losses rise

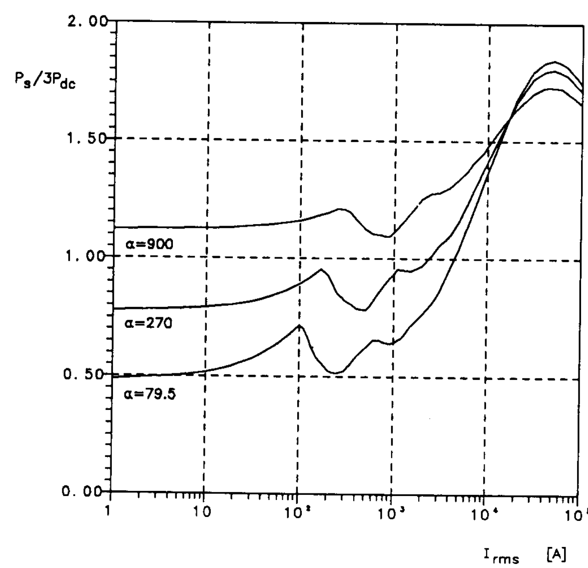


Fig.5. Power loss ratio of the sheath as a function of conductor rms current for three different classes of sheath material (Frohlich coefficient $\beta$ is considered constant and equal to 0.59).

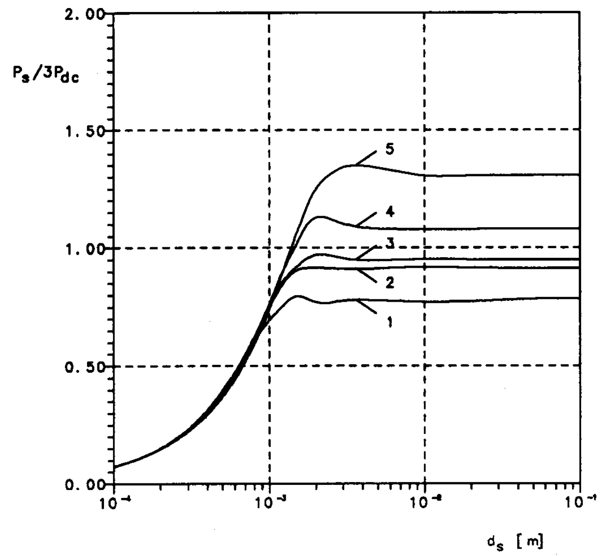


**Fig.6.** Power loss ratio of the sheath as a function of sheath thickness for five different load currents (curve #1 with Irms = 0.5 kA, curve #2 with Irms = 1 kA, curve #3 with Irms = 2 kA, curve #4 with Irms = 4 kA and curve #5 with Irms = 8 kA). Frohlich coefficients are $\alpha$=270 and $\beta$=0.59.

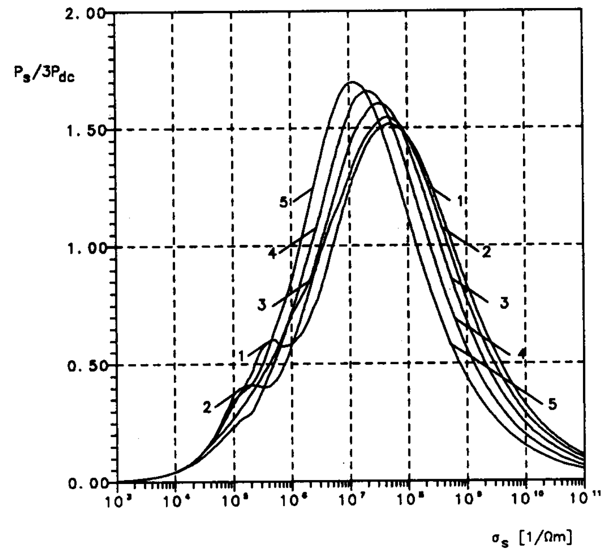


**Fig.7.** Power loss ratio of the sheath as a function of sheath conductivity for five different load currents (curve #1 with Irms = 0.5 kA, curve #2 with Irms = 1 kA, curve #3 with Irms = 2 kA, curve #4 with Irms = 4 kA and curve #5 with Irms = 8 kA). Frohlich coefficients are $\alpha$=270 and $\beta$=0.59.

significantly. With the losses for Irms=1 kA taken as a reference, sheath losses increase from 20% for the hard ($\alpha$=900) and up to 62% for the soft sheaths ($\alpha$=79.5).

In Fig.6. the sheath of the gas cable with the data given in (24) has been considered consisting of a material whose B-H curve is approximated by Frohlich constants $\alpha$=270 and $\beta$=0.59. The power loss ratio of the sheath was calculated as a function of sheath thickness $d_s$ and for five different load currents. The maximum of the losses appears in the region $1.5<d_s<3.0$ mm, while for thicker sheaths the losses depend only on the load current and not on the sheath thickness.

Finally, in Fig.7. the sheath power loss ratio of a cable with the data given in (24) was calculated as a function of the sheath conductivity $\sigma_s$, for five different load currents. The B-H curve of the sheath is approximated again by Frohlich constants $\alpha$=270 and $\beta$=0.59 and in all cases the maximum losses appear for conductivity values between $5\cdot10^7$ and $1\cdot10^9$ 1/Ωm. For usual steel conductivities in the region $2\cdot10^6$ - $3\cdot10^6$ 1/Ωm and for rms conductor currents between 0.5 kA - 8 kA, the power loss ratio of the sheath is between 0.7 and 1.4.

The convergence of the iterative procedure, using for the calculation of the quantity $w_{err}$ of (23) a value of $\varepsilon$=0.001, was very fast. The number of the required iterations is, as it can be easily seen from (22) and (19b), a function of the rms load current. The majority of the tested cases needed less than 10 iterations.

## 8.CONCLUSIONS

The iterative procedure presented in [4] for a one-dimensional nonlinear diffusion problem has been extended and applied in this paper for a two-dimensional eddy current loss computation in nonlinear ferromagnetic materials, using a finite element procedure that treats the source current density as un unknown.

An equivalent material with non-time varying permeability is introduced and it is related to the nonlinear B-H curve of the nonlinear material with the help of the stored magnetic co-energy density in every finite element of the discretization. This allows the use of complex phasors for the time variation and makes the proposed method considerably simple and fast.

Results for the sheath loss ratio of a three phase gas cable have been presented, using a variety of nonlinear materials for the cable sheath. The method can easily handle other cases of two-dimensional nonlinear diffusion problems, when the computation of the losses and not of the actual field is of importance.

Our previous work [4] in a thick steel plate showed that the method used leads to results which are in agreement with experiments. Unfortunately, we could not find experimental results or calculations to compare our present work. Therefore, experiments in this direction may be valuable.

## GLOSSARY OF SYMBOLS

| | | |
|---|---|---|
| $A$ | : magnetic vector potential | (Wb/m) |
| $\alpha, \beta$ | : coefficients of Frohlich relation (8) | |
| $B$ | : magnetic flux density | (T) |
| $d_c, d_s$ | : thickness of conductor and sheath wall respectively | (m) |
| $\delta_s$ | : skin depth of sheath | (m) |
| $f$ | : frequency | (Hz) |
| f (subscript) | : fictitious material | |
| $H$ | : magnetic field intensity | (A/m) |
| $I_{rms}$ | : rms conductor current | (A) |
| $j$ | : imaginary unit | |
| $J$ | : total current density | (A/m$^2$) |
| $J_e, J_s$ | : eddy current density and source current density respectively | (A/m$^2$) |
| $m$ | : distance between conductor centers | (m) |
| $\mu_0$ | : permeability of free space | |
| $\mu_{rc}$ | : relative permeability of conductors | |
| $\mu_{rf}$ | : relative permeability of the fictitious sheath material | |
| $P_{dc}$ | : dc loss per unit length of a conductor | (W/m) |
| $P_s$ | : ac loss per unit length of the sheath | (W/m) |
| $r_a$ | : outside radius of conductors | (m) |
| $R_i$ | : inside radius of the sheath | (m) |
| $\sigma_c, \sigma_s$ | : conductivities of conductors and sheath respectively | (1/Ωm) |
| τ (superscript) | : transposed (matrix or vector) | |
| $\omega$ | : angular frequency = $2\pi f$ | (s$^{-1}$) |

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## BIOGRAPHIES

**Dimitris Labridis** (S'88-M'90) was born in Thessaloniki, Greece, on July 26, 1958. He received the Dipl.-Eng. degree and the Ph.D. degree from the Department of Electrical Engineering at the Aristotelian University of Thessaloniki, in 1981 and 1989 respectively.

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**Petros Dokopoulos** (M'74) was born in Athens, Greece, on September 16, 1939. He received his Dipl.-Eng. degree from the Technical University of Athens in 1962 and the Ph.D. degree from the University of Brunswick, FRG, in July 1967.

During 1962-1967 he was with the High Voltage Laboratory at the University of Brunswick, FRG, during 1967-1974 with the Nuclear Research Center at Julich, FRG, and during 1974-1978 with the Joint European Torus. Since 1978 he has been full professor at the Department of Electrical Engineering at the Aristotelian University of Thessaloniki, Greece. He has worked as consultant to Brown Boveri and Cie, Mannheim, FRG, to Siemens, Erlangen, FRG, to Public Power Corporation, Greece and to National Telecommunication Organization, Greece.

His scientific fields of interest are dielectrics, power switches, generators, power cables and alternative power sources. He has 52 publications and seven patents on these subjects.

## DISCUSSION

**L. W. PIERCE** (General Electric Company, Rome, Ga.) In Figure 5 why does the loss ratio decrease between 100 and 1000 amperes? Is this a computation error?

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**D.LABRIDIS** and **P.DOKOPOULOS**: The authors wish to thank Mr. L.W.Pierce for his interest in the paper. We appreciate the opportunity to enhance our work by answering the discusser's question.

In the paper, the cable sheath is supposed to be made of a nonlinear ferromagnetic material, having a constant in time but different from *point* to *point* value of relative permeability $\mu_{rs}$. The total loss per unit length in the sheath is obtained [5] from the summation of the loss contribution of every *point* of the sheath. Considering a single *point*, the loss will be a function of $\mu_{rs}$ alone, which in turn is a function of the local magnetic field intensity. This intensity is a function of the induced eddy current at this *point*, being finally a function of the conductor rms current. As the rms current increases, the *point* moves closer to saturation and hence decreases its $\mu_{rs}$ value.

In order to explain better this behaviour of the loss ratio curve in Fig.5 of the paper in the region between 100 and 1000 A, we calculated the power loss ratio of the same three-phase cable, but with a sheath made of a linear material. The loss ratio is presented in Fig.A1 as a function of the relative permeability $\mu_{rs}$ of the linear sheath and for four different sheath conductivities. The results of Fig.A1 have been obtained with the method presented in [5] and are in agreement with analytical solution [1],[7],[A1],[A2]. Curve #2 of Fig.A1, obtained from a cable with the data given in (24), shows that the power ratio of the sheath decreases as $\mu_{rs}$ decreases from 150 to 10, while this ratio increases for $\mu_{rs}<10$ as well as for $\mu_{rs}>150$. So, the losses of the nonlinear sheath presented in Fig.5 of the paper are not expected to be a continuously increasing function of rms current.

The loss ratio value as a function of rms current will actually depend on the distribution at $\mu_{rs}$ values of every *point* of the nonlinear sheath. For example, if the cable rms current is 50 A, the majority of the sheath *points* will lie on the linear portion of B-H curves of Fig.3. With Frohlich coefficient $\alpha$=79.5, this majority of *points* will have a value of $\mu_{rs}$ almost equal to $1/\mu_0\alpha$ = 10000. Fig.A1 showes for this value and according to curve #2 a loss ratio equal to 0.65, while Fig.5 gives the same loss ratio for current 50 A. As the rms current increases, the majority of *points* will move to lower values of $\mu_{rs}$. If these $\mu_{rs}$ values lie in the region between 10 and 150 of Fig.A1, then the loss ratio is expected to decrease slightly, before it begins to rise again.

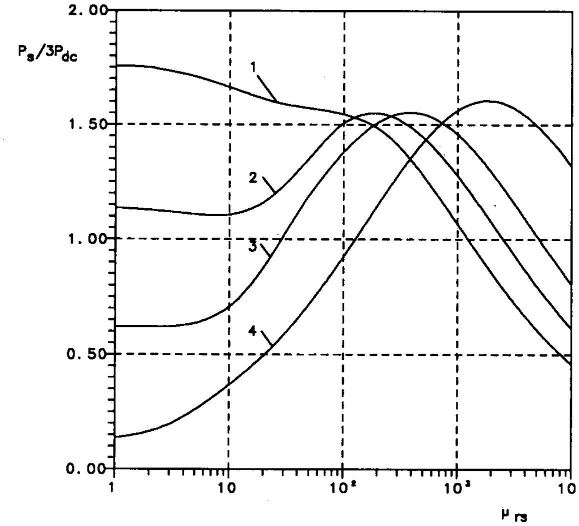


**Fig.A1.** Power loss ratio of a linear-sheath cable as a function of sheath relative permeability $\mu_{rs}$ for five different sheath conductivities (curve #1 with $\sigma_s/\sigma_S$=0.05, curve #2 with $\sigma_s/\sigma_S$=0.1, curve #3 with $\sigma_s/\sigma_S$=0.2 and curve #4 with $\sigma_s/\sigma_S$=1.0). Conductor conductivity and the cable geometry are given in (24).

### References


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