Calculating losses in a superconducting cable core and an electromagnetic field nonlinear boundary value problem solved by analytical-numerical approach

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Abstract

The paper presents calculations of power losses in a single core structure of a superconducting cable. Superconducting materials have many nonlinear properties but this article focuses on the *J-E* nonlinear curve. Because of the nonlinearity – the problem contains nonlinear continuity equations and a nonlinear boundary condition in the case when imposing the electric field strength at the edge of the analyzed structure. In order to obtain a solution of the problem, an analytical-numerical method is introduced, which involves the calculation of a partially symbolic solution. This solution contains some terms in numerical form (those that can be evaluated immediately) and others in symbolic form (those that are to be obtained). Continuity equations and the imposed boundary condition together form a system of nonlinear equations. This system can be solved with a chosen numerical method. After obtaining the unknowns that determine the field distribution, other quantities, like power loss, can be obtained. In this article, losses are calculated by Poynting method. A maximum differential equation error is also calculated, which indicates the accuracy of the obtained solution. The chosen criterion is calculated for the strongest nonlinearities taken into account while evaluating power losses. It can be observed that for a greater amount of correctional terms, the chosen errors gain values much lower than 1%.

1. Introduction

Analytical methods can be used to solve a limited variety of electromagnetic field problems. More often one can find applications of numerical methods due to the amount of commercial solvers available and computational requirements of problems that form geometrically complicated structures. Even when dealing with field parameter nonlinearities (despite required computer time) numerical methods are applied. Analytical methods however, are useful in cases where an exact solution of a problem exists or if it is necessary to validate a numerical method. When a differential equation, derived from Maxwell's equations, has an exact known solution or an approximate solution can be derived, one can obtain the electromagnetic field distribution. Naturally, this requires proper boundary conditions to be imposed. Analytical solutions can be mostly found in problems of simple geometry and linear ε, γ, μ field parameters. In the case of complicated geometries, sometimes an analytical-numerical method is used [1]. Various hybrid analytical-numerical methods can also be used when the problem has a simple geometry but is nonlinear [2] even when non-sinusoidal waves are considered [3]. The paper presents a part of the author's work related to constructing an analytical-numerical method based on the method of small parameter [4]. As an example, power losses are calculated in a wire with a high temperature superconductor.

2. Problem formulation

The core of many cable structures consists of a copper former and a superconducting tape [5], [6], [7]. These are covered by shields or return conductors in three phase or coaxial cables. In this article, only the core structure is considered (fig.1).

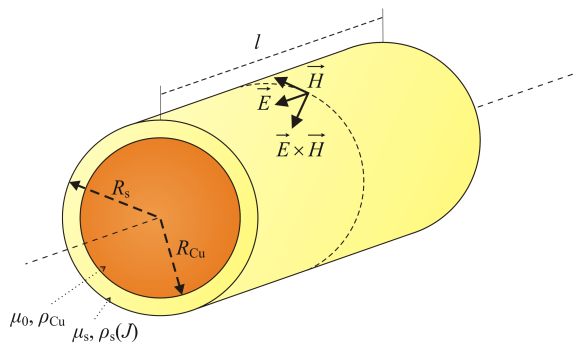

Fig.1. Model of superconducting cable core.

The material properties of copper are well known and need no further discussion. A superconducting material on the other hand, has a wide range of nonlinear properties, some of which are:

- *J-E* curve [8], [9] expressing nonlinear conductivity (the relationship becomes strongly nonlinear especially above a critical current density J_c),
- the critical current was observed as dependent on external magnetic flux density acting on the superconductor [10],
- *B-H* curve expresses nonlinear and hysteretic behavior [11] at low values (especially in the Meissner state),
- magnetic anisotropy was observed in high temperature superconducting materials used in power transfer [12],
- HTS material properties are all dependent highly on the operating temperature.

Out of the above relationships, when modeling superconducting phenomena, mostly the first is used. It is also the case for this article where the other dependencies are omitted (but require further analysis in the future). Superconductors in the mixed state express magnetic permeability values near μ_0 [13], which allows to omit *B-H* nonlinearity and magnetic anisotropy properties. The assumption of a constant temperature and steady-state analysis allows to omit the last relationship. Hence, only the conductivity nonlinearity is considered. A theoretical curve is taken into account (fig.2). The relationship is assumed to consist of a linear and nonlinear term:

$$E(J) = \rho_s(J)J = \rho_1 J + \rho_m J^m. \qquad (1)$$

In this paper, m is assumed to be 5.

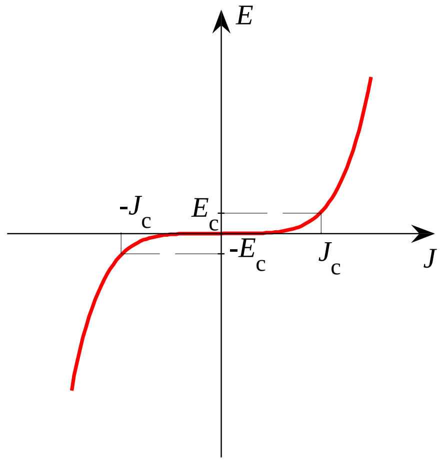

Fig.2. Nonlinear *J-E* superconductor curve (E_c is often assumed to be 1μV/cm [14])

The appointed task is to calculate losses in the analyzed structure. The problem is simplified further on by assuming that the structure is surrounded by air (hence omitting ground influence and the angular derivative) and assuming $l >> R_s$ (omitting longitudinal analysis). The two-layer structure is placed in a cylindrical coordinate system (figure 3).

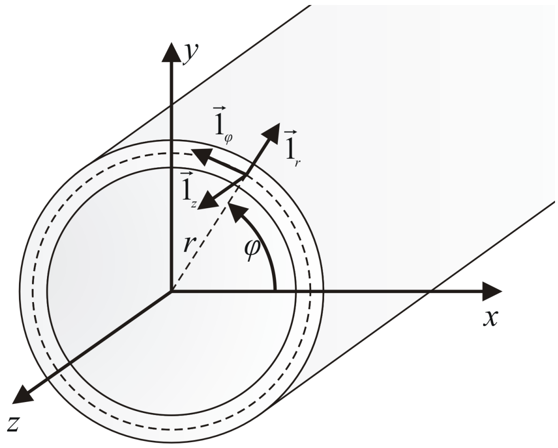

Fig.3. Superconducting cable core in cylindrical coordinates

3. Partially symbolic solution by analytical-numerical method

3.1. Calculating the current density distribution

In this chapter, field quantities of the inner conductor are written with a "Cu" lower index and all others relate to the superconducting layer. The simplifications brought forth in the previous chapter lead to the consideration of only the angular component of magnetic field strength and the *z*-axis component of electric field strength. The Poynting method is used for calculating losses in the cylindrical structure. The Poynting vector can be represented by its radial component S_r alone – subject to H_φ and E_z. Instead of assuming the magnetic vector potential as the state variable for the nonlinear region, in the case of the discussed problem, it is more convenient to derive the differential equation for current density:

$$\frac{\partial^2 J(t,r)}{\partial r^2} + \frac{1}{r}\frac{\partial J(t,r)}{\partial r} - \frac{1}{\rho_1}\mu_0 \frac{\partial J(t,r)}{\partial t} = -\frac{\rho_n}{\rho_1}\left(\frac{\partial^2\left(J^n(t,r)\right)}{\partial r^2} + \frac{1}{r}\frac{\partial\left(J^n(t,r)\right)}{\partial r}\right). \qquad (2)$$

In this case, we also derive the differential equation for the linear region in terms of current density:

$$\frac{\partial^2 J_{Cu}(t,r)}{\partial r^2} + \frac{1}{r}\frac{\partial J_{Cu}(t,r)}{\partial r} - \gamma_{Cu}\mu_0 \frac{\partial J_{Cu}(t,r)}{\partial t} = 0. \qquad (3)$$

Assuming a periodic current flowing through the entire analyzed region, the current density can be expressed by a Fourier series (this concerns both the linear conductor and the superconducting layer):

$$J(t,r) = A_0(r) + \sum_{h=1}^{\eta} A_h(r)\cos\left(h\omega_0 t + \alpha_h(r)\right). \quad (4)$$

For harmonic h (presented with the use of complex numbers), the solution of the differential equation (3) consists of Bessel functions:

$$\underline{J}_{\mathrm{Cu}\,h}(r) = \\ = \underline{c}_{1,h}\underline{I}_0(\underline{\Gamma}_{\mathrm{Cu}\,h} r) + \underline{c}_{0,h}\underline{K}_0(\underline{\Gamma}_{\mathrm{Cu}\,h} r), \quad (5)$$

$$\frac{\partial \underline{J}_{\mathrm{Cu}\,h}(r)}{\partial r} = \\ = \underline{\Gamma}_{\mathrm{Cu}\,h}\underline{c}_{1,h}\underline{I}_1(\underline{\Gamma}_{\mathrm{Cu}h} r) - \underline{\Gamma}_{\mathrm{Cu}\,h}\underline{c}_{0,h}\underline{K}_1(\underline{\Gamma}_{\mathrm{Cu}h} r), \quad (6)$$

where $\underline{c}_{0,h} = 0$ to avoid a singularity at $r = 0$. $\underline{\Gamma}_{\mathrm{Cu}\,h}$ is the propagation constant for waves of harmonic h:

$$\underline{\Gamma}_{\mathrm{Cu}\,h} = \sqrt{\mathrm{j} h\omega_0 \gamma_{\mathrm{Cu}} \mu_0}. \quad (7)$$

c are unknown distribution coefficients, dependent on the boundary condition.

The nonlinear terms are deliberately placed on the right-hand side of (2) for further use. Assuming current density as the state variable, it is expanded into the series:

$$J(t,r) = \sum_{i=1}^{n} \kappa^{i-1} J_i(t,r). \quad (8)$$

The κ parameter is assumed as:

$$\kappa = \frac{\rho_n}{\rho_1}. \quad (9)$$

Equation (2) then becomes:

$$\frac{\partial^2\left(\sum_{i=1}^{n}\kappa^{i-1}J_i(t,r)\right)}{\partial r^2} + \frac{1}{r}\frac{\partial\left(\sum_{i=1}^{n}\kappa^{i-1}J_i(t,r)\right)}{\partial r} - \\ -\frac{1}{\rho_1}\mu_0\frac{\partial\left(\sum_{i=1}^{n}\kappa^{i-1}J_i(t,r)\right)}{\partial t} = \\ = -\kappa\frac{\partial^2\left(\left(\sum_{i=1}^{n}\kappa^{i-1}J_i(t,r)\right)^n\right)}{\partial r^2} - \\ -\kappa\frac{1}{r}\frac{\partial\left(\left(\sum_{i=1}^{n}\kappa^{i-1}J_i(t,r)\right)^n\right)}{\partial r}. \quad (10)$$

Terms with the same power of κ are collected and formed into linear differential equations of the form:

$$\frac{\partial^2 J_i(t,r)}{\partial r^2} + \frac{1}{r}\frac{\partial J_i(t,r)}{\partial r} - \\ -\frac{1}{\rho_1}\mu_0\frac{\partial J_i(t,r)}{\partial t} = W_i(t,r). \quad (11)$$

The right-hand side terms depend on solutions of smaller i. Thus, for $i > 1$ one can write:

$$W_i(t,r) = \\ = W_i\left(\begin{matrix}\frac{\partial^2 J_1(t,r)}{\partial r^2}, \frac{\partial J_1(t,r)}{\partial r}, J_1(t,r), \ldots \\ \ldots, \frac{\partial^2 J_{i-1}(t,r)}{\partial r^2}, \frac{\partial J_{i-1}(t,r)}{\partial r}, J_{i-1}(t,r)\end{matrix}\right). \quad (12)$$

The solution of (11) for $i = 1$ is:

$$\underline{J}_{1,h}(r) = \underline{c}_{2,h}\underline{I}_0(\underline{\Gamma}_{\mathrm{s}h} r) + \underline{c}_{3,h}\underline{K}_0(\underline{\Gamma}_{\mathrm{s}h} r), \quad (13)$$

$$\frac{\mathrm{d}\underline{J}_{1,h}(r)}{\mathrm{d}r} = \\ = \underline{\Gamma}_{\mathrm{s}h}\underline{c}_{2,h}\underline{I}_1(\underline{\Gamma}_{\mathrm{s}h} r) - \underline{\Gamma}_{\mathrm{s}h}\underline{c}_{3,h}\underline{K}_1(\underline{\Gamma}_{\mathrm{s}h} r), \quad (14)$$

where the propagation constant:

$$\underline{\Gamma}_{\mathrm{s}h} = \sqrt{\mathrm{j}\frac{h\omega_0\mu_0}{\rho_1}}, \quad (15)$$

while for $i > 1$:

$$\begin{bmatrix}\underline{J}_{i,h}(r) \\ \frac{\mathrm{d}\underline{J}_{i,h}(r)}{\mathrm{d}r}\end{bmatrix} = \mathbf{M}_{i,h}(r), \quad (16)$$

where:

$$\mathbf{M}_{i,h}(r) = \\ = \mathbf{N}_h(r)\begin{bmatrix}\int_{R_{\mathrm{Cu}}}^{r}\underline{K}_0(\underline{\Gamma}_{\mathrm{s}h} r)\underline{W}_{i,h}(r) r\,\mathrm{d}r \\ -\int_{R_{\mathrm{Cu}}}^{r}\underline{I}_0(\underline{\Gamma}_{\mathrm{s}h} r)\underline{W}_{i,h}(r) r\,\mathrm{d}r\end{bmatrix}. \quad (17)$$

N is the Wronsky matrix:

$$\mathbf{N}_h(r)=\begin{bmatrix} \underline{I}_0(\underline{\Gamma}_{sh}r) & \underline{K}_0(\underline{\Gamma}_{sh}r) \\ \underline{\Gamma}_{sh}\underline{I}_1(\underline{\Gamma}_{sh}r) & -\underline{\Gamma}_{sh}\underline{K}_1(\underline{\Gamma}_{sh}r) \end{bmatrix}. \quad (18)$$

The definite integral in (17) implies for $i > 1$ both:

$$J_i(t, R_{\mathrm{Cu}}) = 0, \quad (19)$$

$$\frac{\partial J_i(t, R_{\mathrm{Cu}})}{\partial r} = 0. \quad (20)$$

Continuity at $r = R_{\mathrm{Cu}}$ forces tangent components of electric and magnetic field strengths to be equal:

$$\begin{aligned} &\rho_{\mathrm{Cu}} J_{\mathrm{Cu}}(t, R_{\mathrm{Cu}}) = E_{\mathrm{Cu}\,z}(t, R_{\mathrm{Cu}}) = \\ &= E_z(t, R_{\mathrm{Cu}}) = \rho_{\mathrm{s}}\big(J(t, R_{\mathrm{Cu}})\big) J(t, R_{\mathrm{Cu}}), \end{aligned} \quad (21)$$

$$H_{\mathrm{Cu}\,\varphi}(t, R_{\mathrm{Cu}}) = H_\varphi(t, R_{\mathrm{Cu}}). \quad (22)$$

The continuity equations and a boundary condition, imposed on the edge $r = R_{\mathrm{s}}$, combine into $3h_{\mathrm{n}}$ equations and unknowns, where h_{n} is the number of non-zero harmonics. Whether electric or magnetic field values are imposed, they both form nonlinear boundary conditions in reference to the state variable J. (21) and (22) are also nonlinear equations; hence, one obtains 3 nonlinear equations for each non-zero harmonic. However, first the partially symbolic solution must be obtained in order to formulate these equations. It is possible to calculate numerical values of the expressions that do not contain the unknowns – then only the unknowns are left in symbolic form. In this article, this is referred to as the partially symbolic solution. The analytical calculations of the partially symbolic expressions are complicated hence the unknowns of the superconducting layer are represented by vectors of their magnitudes:

$$\mathbf{c} = [|\underline{c}_{2,1}|, \ldots |\underline{c}_{2,\eta_1}|, |\underline{c}_{3,1}|, \ldots |\underline{c}_{3,\eta_1}|], \quad (23)$$

and phases:

$$\begin{aligned} \boldsymbol{\theta} = [&\arg(\underline{c}_{2,1}), \ldots \arg(\underline{c}_{2,\eta}), \\ &, \arg(\underline{c}_{3,1}), \ldots \arg(\underline{c}_{3,\eta})]. \end{aligned} \quad (24)$$

For term i=1 of (8) and harmonic h the solution can be presented in partially symbolic form:

$$\begin{aligned} &J_{1,h}(\mathbf{c}, \boldsymbol{\theta}, t, r) = \\ &= |\underline{c}_{2,h}| A_{1,h}{}'(r) \cos\begin{pmatrix} h\omega_0 t + \alpha_{1,h}{}'(r) + \\ + \arg(\underline{c}_{2,h}) \end{pmatrix} + \\ &+ |\underline{c}_{3,h}| A_{1,h}{}''(r) \cos\begin{pmatrix} h\omega_0 t + \alpha_{1,h}{}''(r) + \\ + \arg(\underline{c}_{3,h}) \end{pmatrix}. \end{aligned} \quad (25)$$

Where $A_{1,h}{}'$, $A_{1,h}{}''$, $\alpha_{1,h}{}'$, $\alpha_{1,h}{}''$ do not depend on $\mathbf{c}$ and $\boldsymbol{\theta}$. The remaining terms do not have such a direct relationship with the unknown coefficients. Therefore, their solutions can only be presented in a general form:

$$\begin{aligned} &\mathbf{M}_{i,h}(\mathbf{c}, \boldsymbol{\theta}, r) = \\ &= \mathbf{N}_h(r) \begin{bmatrix} \int_{R_{\mathrm{Cu}}}^{r} \underline{K}_0(\underline{\Gamma}_{sh} r) \underline{W}_{i,h}(\mathbf{c}, \boldsymbol{\theta}, r) r \mathrm{d}r \\ -\int_{R_{\mathrm{Cu}}}^{r} \underline{I}_0(\underline{\Gamma}_{sh} r) \underline{W}_{i,h}(\mathbf{c}, \boldsymbol{\theta}, r) r \mathrm{d}r \end{bmatrix}. \end{aligned} \quad (26)$$

The i-th term's relationships are:

$$\begin{aligned} &J_i(\mathbf{c}, \boldsymbol{\theta}, t, r) = A_{i,0}(\mathbf{c}, \boldsymbol{\theta}, r) + \\ &+ \sum_{h=1}^{\eta_i} A_{i,h}(\mathbf{c}, \boldsymbol{\theta}, r) \cos\big(h\omega_0 t + \alpha_{i,h}(\mathbf{c}, \boldsymbol{\theta}, r)\big). \end{aligned} \quad (27)$$

If one obtains the above in a symbolic form (relating to the unknowns), the solutions can be gathered:

$$J(\mathbf{c}, \boldsymbol{\theta}, t, r) = \sum_{i=1}^{n} \kappa^{i-1} J_i(\mathbf{c}, \boldsymbol{\theta}, t, r), \quad (28)$$

$$\frac{\partial J(\mathbf{c}, \boldsymbol{\theta}, t, r)}{\partial r} = \sum_{i=1}^{n} \kappa^{i-1} \frac{\partial J_i(\mathbf{c}, \boldsymbol{\theta}, t, r)}{\partial r}, \quad (29)$$

thus obtaining the partially symbolic solution of the nonlinear problem. The continuity equations can be expressed in the following form, for each harmonic h:

$$\rho_{\mathrm{Cu}} \underline{c}_{1,h} \underline{I}_0(\underline{\Gamma}_{\mathrm{Cu}\,h} r) = \underline{E}_{zh}(\mathbf{c}, \boldsymbol{\theta}, R_{\mathrm{Cu}}), \quad (30)$$

$$\frac{\rho_{\mathrm{Cu}}}{\mu_0} \underline{\Gamma}_{\mathrm{Cu}\,h} \underline{c}_{1,h} \underline{I}_1(\underline{\Gamma}_{\mathrm{Cu}\,h} r) = \underline{H}_{\varphi h}(\mathbf{c}, \boldsymbol{\theta}, R_{\mathrm{Cu}}), \quad (31)$$

which can be reduced to one nonlinear equation:

$$\frac{\underline{E}_{zh}(\mathbf{c},\boldsymbol{\theta},R_{\mathrm{Cu}})}{\rho_{\mathrm{Cu}}\underline{I}_0(\underline{\Gamma}_{\mathrm{Cu}h}R_{\mathrm{Cu}})}=\frac{\underline{H}_{\varphi h}(\mathbf{c},\boldsymbol{\theta},R_{\mathrm{Cu}})}{\frac{\rho_{\mathrm{Cu}}}{\mu_0}\underline{\Gamma}_{\mathrm{Cu}h}\underline{I}_1(\underline{\Gamma}_{\mathrm{Cu}h}R_{\mathrm{Cu}})}. \quad (32)$$

This equation and a boundary condition combine into two nonlinear equations, which can be solved by a chosen numerical method.

3.2. Nonlinear boundary condition and power loss

Poynting's theorem allows to represent the flow of instantaneous power through the surface Ω by:

$$S_{\Omega}(t)=\oiint_{\Omega}\left(\vec{E}(t,X)\times\vec{H}(t,X)\right)\mathrm{d}\vec{\Omega}, \quad (33)$$

X represents points on the Ω surface. In the case of the analyzed problem – Ω is the cylinder side surface. Therefore the instantaneous power dissipated in the cylindrical structure is:

$$S_{\Omega r}(t)= \\ =-\left(\rho_1 J(t,R_{\mathrm{s}})+\rho_m J^m(t,R_{\mathrm{s}})\right)H(t,R_{\mathrm{s}})\,2\pi R_{\mathrm{s}} l. \quad (34)$$

When multiplying the field quantities, the result is in form of a Fourier series where the active power is simply the constant term of the result. The result is presented in units per cable length (W/m). In this paper, the task was to obtain a curve of power loss depending on the electric field strength $E(t,R_{\mathrm{s}})$ with the assumption that this time function is only of the first time harmonic. Both E and H (and therefore S) depend on $\mathbf{c}$ and $\boldsymbol{\theta}$. A boundary condition with respect to E is imposed, which has the following nonlinear form for current density:

$$\rho_1 J(t,R_{\mathrm{s}})+\rho_m J^m(t,R_{\mathrm{s}})= \\ =E_z(t,R_{\mathrm{s}})=\Xi(t). \quad (35)$$

The following steps lead to obtaining the power loss dependence on electric field strength at the boundary surface (figure 3):

- imposing the nonlinear boundary condition (35) for every drawing step of E;
- solving the system of nonlinear equations in order to obtain $\mathbf{c}$, $\boldsymbol{\theta}$;
- calculating the active power for the unknowns evaluated in the previous step.

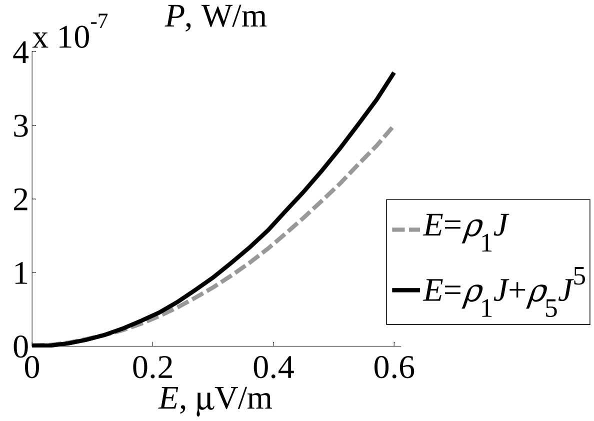

Fig.3. Superconducting cable core losses when taking into account a nonlinear *J-E* curve and those when assuming linear dependence (as a function of electric field strength at the boundary)

The results were obtained after a few simplifications had been assumed. The electric field strength on the edge of the structure contained only the first time harmonic. Furthermore, only the first time harmonic was taken into account for all field values E, J, B and H (higher harmonics have not been omitted in intermediate calculations, just in the results of J_i). In (8) it was assumed that the maximum n is 4. For this n, the power losses have been obtained. The introduced limits allowed for an analysis with smaller nonlinearities, which is why low E values were chosen in the last figure.

3.3. Differential equation error calculations

In order to ascertain the accuracy of the solution, a maximum error criterion is introduced. In the nonlinear differential equation (2), one can choose left- and right-hand sides of the equation for comparison:

$$L(t,r)=\frac{\partial^2 J(t,r)}{\partial r^2}+\frac{1}{r}\frac{\partial J(t,r)}{\partial r}= \\ =\frac{1}{\rho_1}\mu_0\frac{\partial J(t,r)}{\partial t}- \\ -\frac{\rho_n}{\rho_1}\left(\frac{\partial^2\left(J^n(t,r)\right)}{\partial r^2}+\frac{1}{r}\frac{\partial\left(J^n(t,r)\right)}{\partial r}\right)=R(t,r). \quad (36)$$

Then, assuming that the solution can be presented in complex form (first time harmonic) it is possible to formulate two different kinds of a relative differential equation error – in terms of amplitude:

$$e_{\mathrm{Amp.max}}=\max_{r\in\langle R_{\mathrm{Cu}},R_{\mathrm{s}}\rangle}\left|1-\left|\frac{\underline{L}(r)}{\underline{R}(r)}\right|\right|, \quad (37)$$

and phase:

$$e_{\text{ph.max}} = \max_{r\in\langle R_{\text{Cu}},R_s\rangle}\left|\frac{1}{\pi}\arg\left(\frac{\underline{L}(r)}{\underline{R}(r)}\right)\right|. \tag{38}$$

Taking into account various values of n, the above errors have been evaluated and put together in table 1.

Tab.1.

Error calculation results for various *n*

n	1	2	3	4
$e_{\text{Amp. max}}$ [%]	85.65	2.99e-1	1.87	1.13e-4
$e_{\text{ph. max}}$ [%]	3.20e-2	7.62	1.06e-3	6.59e-4

It can be noticed, that for the linearized case (n=1) the amplitude error is very big. For n=4, a very accurate solution can be obtained. The results speak in favor of the method for calculating similar nonlinear problems.

4. Conclusions

An electromagnetic field nonlinear boundary value problem was formulated. The nonlinear example was that of a core structure used in superconducting cables. The attention has so far focused on the nonlinear *J-E* curve. A differential equation was formulated with respect to the state variable (being the current density). The differential equation was solved by an analytical-numerical method based on the method of small parameter. The solution took a partially symbolic form hence reducing the problem into a system of nonlinear equations. Partially symbolic solutions (despite the difficulties associated with obtaining them) allow to perform analyses of various types i.e. the calculations of power loss per cable length, which were computed in the article. The evaluated errors (of chosen criteria) indicate the effectiveness of the method.

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