TEKA Kom. Mot. i Energ. Roln. – OL PAN, 2010, 10B, 33-42

THEORETICAL ANALYSIS OF A CIRCLE CURRENT CONVERTER OPERATION UNDER CONTROL OF HOLLOW CYLINDERS

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Summary. The numerical method of calculation of electromagnetic field in a control sample at a time of work of feed-through circle-current converter is offered. The method is based on a numerical solution f the two Maxwell equations, which connect a change of electrical and magnetic fields. It allows to make calculations taking into account the actual value of magnetic inductivity of metal and to get results in any form, convenient for further interpretations.

Key words: magnetic permeability, circle-current converter, defectoscope, sensitivity.

INTRODUCTION

Contemporary methods of parameters calculation of a circle current converter (C.C.C.) [1, 2] are based on proposed constancy of magnetic permeability of a cylinder material. In this case the task is aimed at finding solution of a well-known equation of parabolical type [3]

$$\frac{\partial H}{\partial t} = (\sigma \cdot \mu_d)^{-1} \cdot \Delta H \,, \tag{1}$$

under boundary condition $H(r) = H_0 + H_{0m} \cos \omega t$, with σ and μ_d – as specific conductivity and magnetic permeability of a cylinder material, H_0 and H_{0m} – as a constant magnetizing field and an amplitude of an alternating magnetic field, ω – a circular frequency of excitement.

An equation (1) is received by the solution of Maxwell equations [4]:

$$rot\vec{E} = -\frac{\partial \vec{B}}{\partial t}; \quad rot\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \tag{2}$$

and additional correlations:

$$\vec{J} = \sigma \cdot \vec{E}; \;\; \frac{\partial \vec{B}}{\partial t} = \mu_d \cdot \frac{\partial \vec{H}}{\partial t}; \;\; \mu_d = \frac{\partial \vec{B}}{\partial t}. \tag{3}$$

Equations (2) and (3) are reduced into (1) based on proposed independence μ_d upon the magnetic field tension and neglect of bias currents in comparison with conduction currents.

In real conditions of a circle current converter operation there appears a necessity of the choice of optimal magnetizing currents and excitement currents for [5, 6] getting maximum sensitivity of a C.C.C. As a result the processes of remagnetizing take place in the tension areas of a magnetic field where an assumption $\mu_d = const$ may result in erroneous results. Besides, traditional ways of an equation (1) solution with the help of Bessel function and a hodograph can't give an idea of the methods of choice of optimal control conditions in conformity with given characteristics of a controllable sample (external diameter, width of a wall, electric and magnetic properties of the material).

RESEARCH OBJECT

In this work a different method of the task solution of parameters choice of a C.C.C. is proposed. It is based on the following statements:

1. orientation on the system of equations solution (2) without its reduction to the equation of the type (1), that allows to avoid an assumption $\mu_d = const$;
2. creation of a number of programs for numerical solution of the system (2), which will allow to make obvious dependences of a sensor sensitivity upon parameters of a controllable object;
3. building an algorythm of a self-set C.C.C. creation in order to find an area of maximum sensitivity of a C.C.C.

With this purpose at first a program of the solution of a classical cylindrically symmetrical task was worked out. It allowed to compare solutions obtained with the help of developed programs with existing ones and study some regularities of an electromagnetic field behavior inside a hollow conductive ferromagnetic cylinder. In order to solve this task the system (2) was reduced to the following type

$$\frac{1}{r} \cdot \frac{\partial (rE_\varphi)}{\partial r} = -\mu_d \frac{\partial H_x}{\partial t}; \quad \frac{\partial H_x}{\partial r} = \sigma \cdot E_\varphi. \tag{4}$$

Here, as well as traditional case, bias currents are neglected. Boundary conditions are given as:

$$H(r) = H_0 + H_{0m} \cos \omega t; \quad E(r) = E_{0m} \cos(\omega t + \varphi_0),$$

φ_0 – determines the difference of fluctuations of tensions in magnetic and electric fields on the external boundary of a cylinder. For equation (4) we consider that magnetic field is directed only along the cylinder axis – *x*, but electrical one is only perpendicular to the radius E_φ. We transform an equation (4) into a final differential equation system:

$$\frac{\Delta E}{\Delta p} = -\sqrt{\frac{\mu_d}{\omega \cdot \sigma}} \cdot \frac{\Delta H}{\Delta t} - \frac{E}{(R_\delta - \rho)}, \tag{5}$$

$$\frac{\Delta H}{\Delta t} = -\sqrt{\frac{\mu_d}{\omega \cdot \sigma}} \cdot E,$$

where: $\Delta\rho, \rho$ – excessive value, which present the change of radius and a radius itself in units of skin-layer width [7, 8] $\delta = (\omega\mu_d\sigma)^{-0,5}; \Delta r = \Delta\rho\delta;$ $r = R - \rho\delta; R_\delta = \frac{R}{\delta};$ R – external radius of a hollow cylinder, r – a current radius.

The calculation algorythm an electromagnetic field is built in the following way:

1. $\Delta\rho$ is chosen to be much smaller 1 ($\Delta\rho$ «1) and H_i, E_i in the layer $\Delta\rho$ are calculated proceeding from the assumption that fields change at this distance limarly;

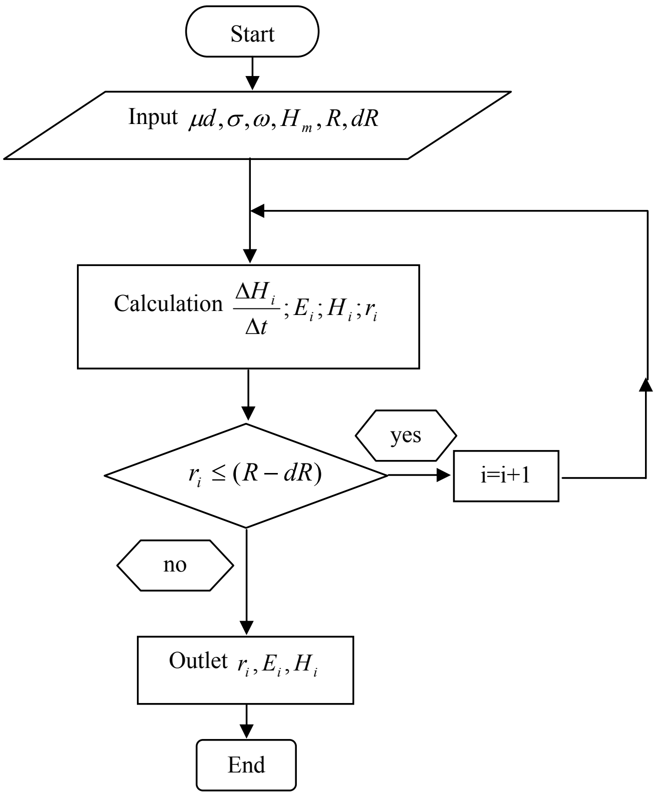

Fig. 1. A block-circuit of the calculation algorythm of *E* and *H*.
dR – is the width of a hollow cylinder wall

2. initially with the help of the first system equation (5) E_1 is calculated proceeding from initial values $H, E, \frac{\Delta H}{\Delta t}$. Then with the help of the second system equation (5) H_1 is calculated;

3. values E_1, H_1 obtained at previous stages of calculations are used as initial data under calculation of the field in the next layer $\Delta\rho_2$ and so on [9].

Calculation investigations showed that only iteration was enough for finding values H and E in the layer $\Delta\rho$ with the necessary accuracy. This solution is very sensitive to the task of the correct correlation between initial values of H and E which exist under the solution of a well-known task of permeability of an electromagnetic field into excessively long drawn-out flat surface [3]. According to the solution $E_{0m} = H_{0m} \cdot \sqrt{\frac{\mu_d \omega}{\sigma}}; \varphi_0 = \frac{\pi}{4}$. Under condition $\delta \ll R$ solution which was obtained for the cases of field permeability into a flat surface can be used for a cylinder too.

The algorythm proposed reflects physical processes which occur in the object of control. A magnetic field changing with time causes the change of an electric field in a hollow cylinder. In its turn a magnetic field caused by circle currents is directed to an external magnetic field, that is described by system of equations (5).

RESULTS OF THEORETICAL RESEARCH

A pure physical principle taken as a base for calculation algorythm results in a good coincidence of analytical and numerically found solutions, as in case of permeability of the field both inside the cylinder and in the flat surface. Figure 1 shows a block-circuit of the program realizing algorythm described above. Calculations results obtained with the help of a described above algorythm are presented in fig 2. Here amplitudes H_m and E_m dependence of alternating electromagnetic field (e.m.f.) on a cylinder radius is presented. It is clear that e.m.f. not only decreases as it penetrates inside a controllable object, but also changes its sign.

It will be proved further that this fact plays an important role in explaining sensitivity dependence of C.C.C. upon the radius and wall width of a controllable hollow cylinder.

To study further stability of the solutions, obtained with the help of the given algorythm, the calculations of the influence of parameter δ on the magnetic field behavior inside a control object and electromotive force of measuring coil were made.

The last one was calculated according to the formula (6)

$$E = -n \cdot \int_0^{R_u} 2\pi r \mu_d \frac{\partial H}{\partial t} dr, \tag{6}$$

with: R_u – as a radius of a measuring coil, n – the number of spires. Calculation results are given in figure 3. Here the dependence of average in oscillation period differential sensitivity of C.C.C. under n=1 of parameter δ – width of skin-layer is shown.

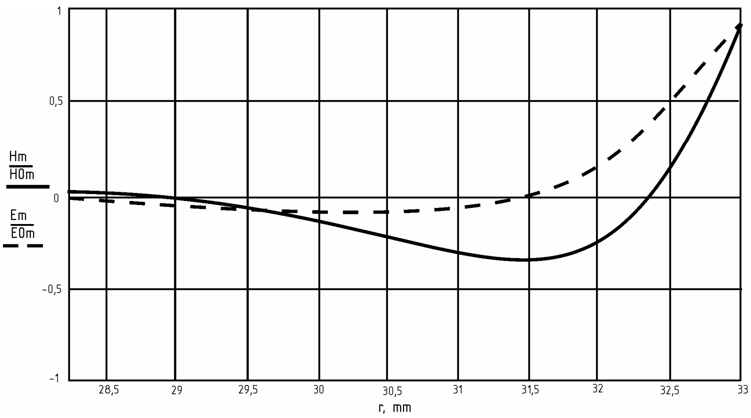

Fig. 2. Dependence of alternating electromagnetic field amplitude upon the cylinder radius: $\sigma = 10^7$; $\omega = 2\pi \cdot 1000$; $R_u = 50$ mm; $H_{0m} = 3000\ {}^{A}\!/_{m}$; $\delta = 0{,}8$ mm.

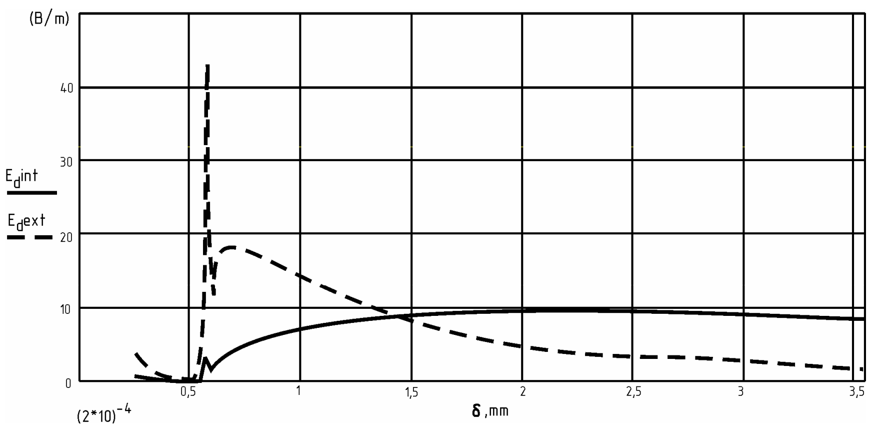

Fig. 3. Dependence of average differential sensitivity of a one-spire C.C.C. upon parameter δ for two instances ($\sigma = 10^7$; $\omega = 2\pi \cdot 1000$; $R_u = 50$ mm):

_________ internal cylinder radius is measured (31 mm);

-------------- external radius is measured (33 mm)

It was considered in calculations that $\mu_d = const$, conditioned by the necessity of comparing calculations obtained by numerical method and analytical one. Differential sensitivity E_d was defined as a change of electromotive force of one-spire coil under the change of cylinder radius Δr divided by the magnitude of this change $E_d = \dfrac{\Delta E}{\Delta t}$. Measuring coil radius didn't change in this case.

Figure 3 shows two curves corresponding the dependence of differential sensitivity upon δ for internal and external radiuses of the object. If E_d for an external radius has two maximums, one of which is sloping and small, another is acute of 45 W amplitude, E_d for internal radius has a tendency to have a constant value =9 W according an increase of δ and to come down to zero under $\delta \approx 0,6$ mm. It is interesting to note that E_d for an external radius here has a sharp maximum. This sensitivity behavior gives an opportunity to divide defects according to their depth using various frequencies of excitement.

Averaged values of E_d give a poor presentation of a real dependence of differential sensitivity on the skin-layer width. Figures 4 and 5 present two measuring dependencies E_d upon μ_d for the change of internal and external cylinder radius. It is vivid that under certain μ_d, corresponding δ=0,57 mm not only a sharp amplitude change of a signal takes place, but the phase also changes sharply. It provides an opportunity to get more sensitivity of a sensor to the change of external radius conforming to certain fluctuations phase. With the same δ, E_d of an internal radius (fig. 5) a sharp phase change also takes place, but amplitude change is much more enormous.

The cause of such behaviour of differential sensitivity is explained in figure 6. Here dependencies of amplitude of alternating magnetic field upon a cylinder radius for a number of values of skin-layer width are presented. Charts are drawn for the phase of oscillations of an external magnetic field corresponding $\omega t = \frac{\pi}{4}$. Analogous charts for $\omega t = \frac{\pi}{2}$ are given in fig. 7.

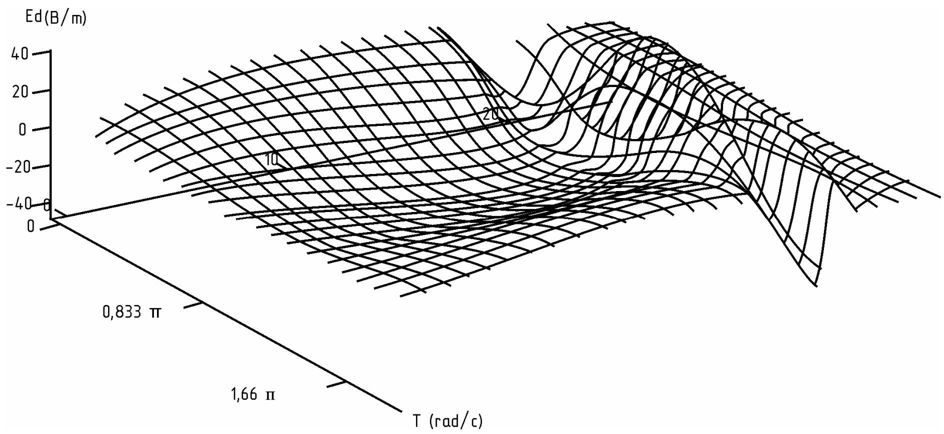

Fig. 4. Dependence of differential sensitivity of one-spire C.C.C. on the oscillations phase and a relative magnetic permeability (for external radius). Geometrical cylinder parameters are the same as in fig. 3

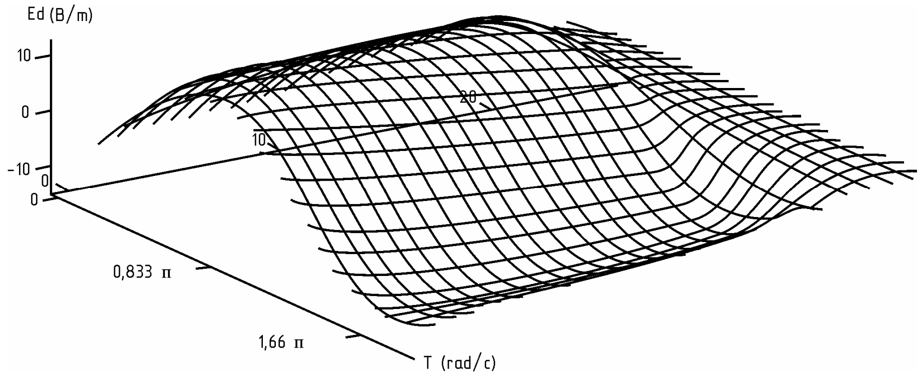

Fig. 5. Dependence of differential sensitivity of one-spire C.C.C. upon oscillations phase and relative magnetic permeability (for internal radius). Geometrical parameters are the same as in fig. 3

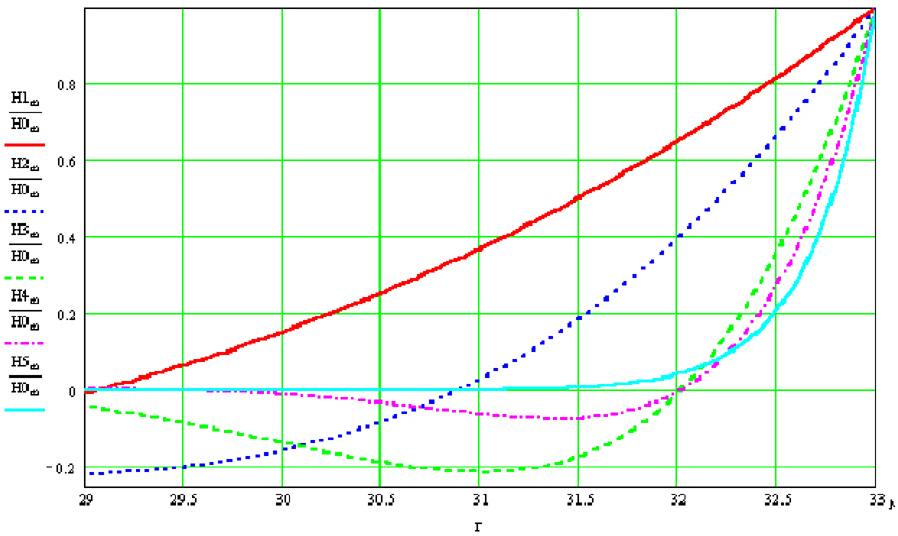

Fig. 6. Dependence of alternating magnetic field upon cylinder radius for a number of values of skin-layer (for *H1* – δ=3,56 mm; H2 – 1,45 mm; H3 – 1,07 mm; H4 – 0,89 mm; P5 – 0,777 mm; oscillation phase $\omega t = \frac{\pi}{4}$)

The values of magnetic fields amplitudes are given in relatives units. Figure 6 shows how the character of a magnetic field change along the radius also changes according to the δ decrease. At first e.m. field doesn't change its sign along the width of the hollow cylinder wall, then the field changes its sign and e.m. force proportional to integral $\Phi = -2\pi \int r^2 \omega H dr$, comes to zero. At further change of δ intensity of a magnetic field becomes positive again, electromotive force sharply increases, and a signal phase cardinally changes. Charts given at figure 7 show that under $\omega t = \dfrac{\pi}{2}$ dependence H upon δ is opposite. Under the same value of skin-layer width as in figure 6 a sharp decrease of a value of magnetic field tension up to zero takes place. It results in those dependences which are shown in fig. 4–5.

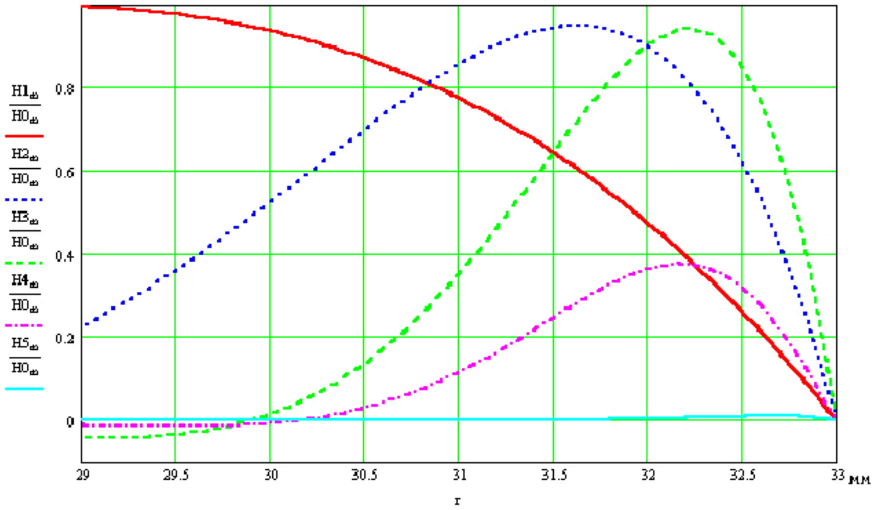

Fig. 7. Dependence of alternating magnetic field amplitude upon the radius of a hollow cylinder for a number of skin-layer width. Oscillations phase $\omega t = \frac{\pi}{4}$.

Conformity H and δ is the same as in fig. 6

CONCLUSION

Under given values of conductivity, magnetic permeability and oscillation frequency of magnetic field such change takes place under certain value of the cylinder external radius. Its character, that is dependence of differential sensitivity from a radius is defined also by the width of a wall. It means that it is necessary to consider not only excessive parameter R/δ, but correlation between internal and external dimensions of a sample and a skin-layer value. Charts, given in figure 8 illustrate it.

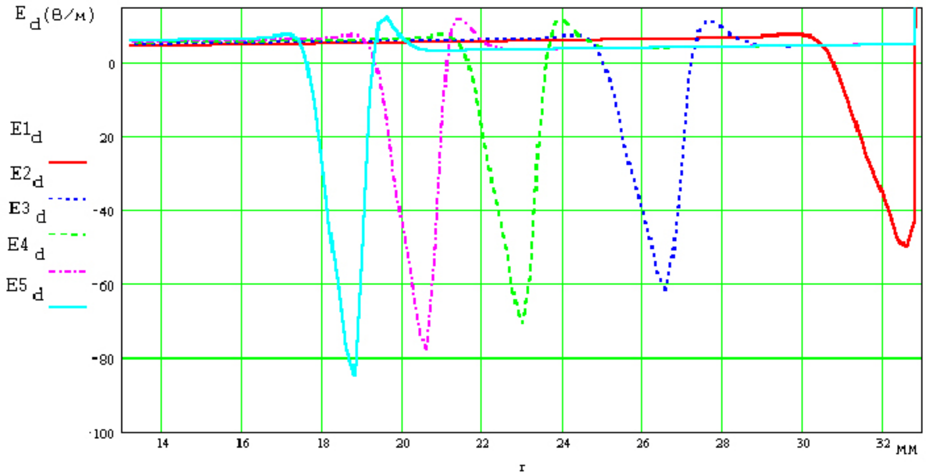

Fig. 8. Dependence of differential sensitivity for an external radius of a cylinder upon this radius value for a number of values δ (E1 – 0,56 mm; E2 – 0,46 mm; E3 – 0,4 mm; E4 – 0,356 mm; E5 – 0,325 mm), R=33 mm; dR=2 mm

The curves E_d in dependence upon the cylinder external radius for a number of δ are given here. It can be seen that a differential sensitivity has sharp minimums under certain radii values for various values of skin-layer if a wall width is not changed [10].

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ТЕОРЕТИЧЕСКИЙ АНАЛИЗ РАБОТЫ ПРОХОДНОГО ВИХРЕТОКОВОГО ПРЕОБРАЗОВАТЕЛЯ ПРИ КОНТРОЛЕ ПОЛЫХ ЦИЛИНДРОВ

Мирошников В.В., Олейви Анвер

Аннотация. Предложен численный способ расчета электромагнитного поля в контрольном образце при работе проходного вихретокового преобразователя. Способ основан на численном решении системы двух уравнений Максвелла, связующих между собой изменение электрического и магнитного поля. Он позволяет проводить вычисления с учетом реальной величины магнитной проницаемости металла и получать результаты в любой удобной для дальнейшей интерпретации форме.

Ключевые слова: магнитная проницаемость, вихретоковый преобразователь, дефектоскоп, чувствительность.