Topics area: Analytical Methods, Modeling, and Simulation

INFLUENCE OF THE FINITE SPEED OF THE FIELD PENETRATION INTO THE CORE ON THE LINEARITY OF TRANSMISSION FUNCTION FOR THE PULSED TRANSFORMERS

(Numerical Investigation)

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***Abstract* – A penetration of the magnetic field into thin-laminated core of the pulsed transformer or inductor of electronic beam accelerator is under consideration in the paper. The mode of the field excitation at the numerical simulation of this process is supposed typical for such transformer, namely, with applied rectangular pulse of voltage to the primary winding and triangle pulse of magnetizing current. There is shown that at the initial stage of the field excitation magnetic flux is concentrated in the zones near the border of the core cross section, what yields to the violation of linear growing of magnetic flux. The method of magnetizing current pulse correction is proposed for improvement of linear transmission function of the pulsed transformer.**

***Index terms* – thin-laminated core, pulsed inductor, transmission function, triangle magnetizing current, finite speed of field diffusion, concentration of flux at the edges, violation of flux increase linearity, correction of magnetizing pulse, linearity improvement.**

I. INTRODUCTION

The cylindrical magnetic cores in the form of ring bounded by ferromagnetic tape with insulating polymer base have a wide application in the pulsed power techniques, likely induction accelerator of electronic beam or high frequency repetitive pulses converters. A modern ferromagnetic material for high rate of re-magnetization is amorphous alloy likely to Metglas [1]-[3]. The specifics of the field excitation in the core consist in the presence of distributed capacitance in the volume of core due to layers of insulating tape between layers of ferromagnetics. That is why the internal medium attains the wave properties what will be noticeable at rate of re-magnetization more than ~3 T/μs. In the microsecond range of the pulses duration the analysis of the field penetration into the core can be performed from the position of diffusion theory due to influence of ferromagnetics layers resistivity (at the level 10^{-6}Ohm·m) which stipulate a damping of waves [4]. That is why in this paper the analysis of the field penetration into the cross section of the core has been done using the equation of magnetic field diffusion. Taking into account a big enough internal diameter of ring core (in the inductors of electronic beam accelerator it can reach 15 – 20 cm), the simulation was permissible to do in the rectangular coordinate system. The professional version of software program QuickField v. 6.3 [5] has been used for simulation of non-stationary electromagnetic process at excitation of magnetic induction as linear growing function of time along the contour which covers a perimeter of core cross section plus small air gap between a winding and sides of core.

II. MATHEMATICAL MODEL OF CORE FOR NUMERICAL SIMULATION

At the simulation of the field into the core cross section the numerical model of the next equation has been used in 2D representation likely [6]:

$$D_i \cdot \left(\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2} \right) = \frac{\partial B}{\partial t} \qquad (1),$$

where $B \equiv B_z$, $D_i = \dfrac{1}{\mu_i \sigma_i}$ is a coefficient of the field diffusion, which has different local meanings for each layer of core (ferromagnetics or insulation). For the layers of magnetics a magnetic permeability μ_i was defined on the base of local value of the field using typical magnetization curve of material, while coefficient of electrical conductivity σ_i was supposed constant: 1e06 Sm/m for ferromagnetics and 10 Sm/m for insulation layers. For the insulation layers μ_i was equal to μ_0 =1.26e−06 H/m. The rectangular piece of core cross section has been investigated with dimensions 600 μm × 760 μm. Its structure includes

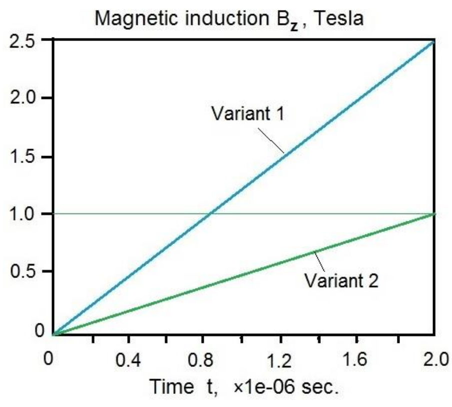

Fig.1. Time diagram of boundary value of induction at the perimeter of the core cross section.

30 sheets of ferromagnetics with thickness 15 μm each one with intermediate insulation layers thickness of 5 μm. The

small gap 10 μm was fixed between the winding which excites the field and sides the core. A current pulse for the field excitation has the triangular form as shown in the Fig.1, with maximal value 1 T (variant 1) or 2.3 T (variant 2). A duration of process was taken 2 μs in both cases. The boundary problem of 1st kind (by Dirichlet) has been solved on this time interval. To provide a use of program QuickField for this problem solution, it was necessary to apply correctly the existing algorithm of non-stationary thermal diffusion. It was possible due to formal equivalence of mathematical equations for diffusion of heat and for diffusion of magnetic field. From the equality of diffusion coefficient for electromagnetic problem D_{EM} and coefficient for thermal diffusion D_{TERM}

$$D_{EM} = \frac{1}{\mu(B)\cdot\sigma}\ [\mathrm{m^2/s}]; \quad D_{TERM} = \frac{\lambda(T)}{C\cdot\rho}\ [\mathrm{m^2/s}],$$

it was possible to create a new characteristics of medium

$$\lambda(B) = \frac{C\cdot\rho}{\sigma}\frac{f(B)}{\mu_0}\left[\frac{\mathrm{J}}{\mathrm{s\cdot m\cdot^\circ K}}\right],$$

then we apply $\dfrac{C\cdot\rho}{\sigma} = 1\left[\dfrac{\mathrm{J\cdot Ohm}}{\mathrm{m^2\cdot^\circ K}}\right]$,

thus
$$f(B) = \frac{\mu_0}{\mu(B)} = \frac{1}{\mu_r(B)} \quad [\text{non-dim.}] \tag{2}$$

(see Fig. 9 and Table 1 in Appendix) is a non-dimensional inversed magnetizing curve of material for use in the algorithm of the non-stationary thermal problem, $\mu_r(B)$ is a relative magnetic permeability.. To save a necessary scale of the field value, it was enough to put that 1°K in thermal problem is the same as 1 mT in electromagnetic problem. Orientation of ferromagnetics sheets corresponds to their disposition in the plane *y, z.*

III. Results of Simulation

Direct simulation of the non-linear problem for EM field in the set of 30 sheets of ferromagnetics on the triangulation mesh of 89863 nodes (without use of averaging parameters for medium) with time step 1 ns takes a big enough time of computation (several hours). In result it was obtained a pictures of magnetic induction across the core cross section and the graphs of induction distribution along the longitudinal and transversal axes of cross section symmetry for series time instants. The Fig.2(a, b) shows an induction distribution for the core without saturation of ferromagnetics (B < 1 T), and the Fig. 3(a, b) shows the same for a core with saturation of ferromagnetics (B < 2.5 T).

At both figures a version (a) represents the field

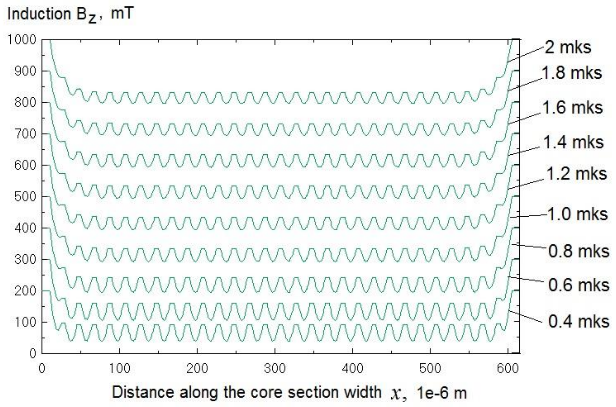

Fig. 2, a. Distribution of magnetic induction along the line of symmetry which is perpendicular to the sheets of ferromagnetics. B_{max} = 1 T.

distribution along the line of symmetry which is perpendicular to the sheets of ferromagnetics, and a version (b) at both figures represents the field distribution along the line of symmetry which is parallel to sheets of ferromagnetics. It is possible to conclude that penetration of field is going mainly along the axis of each sheet, from its edges to the center. The field diffusion across the plane of the sheets orientation is going more difficult, and a difference of the field value from sheet to sheet (Fig. 2,a) is negligible, excluding some zones near the edges of core (left and right sides). In the edge zones a some concentration of magnetic flux is observed with big prevailing of induction in comparison with mean level in center of core. In the Fig. 4, Fig. 5 the upper right angle piece of core is taken for illustration of saturation at the end of process of magnetization (t = 2 μs). When the B_{max} < 1T, the influence of saturation is seen only in 1st and 2nd sheets near the edge of core (Fig. 4), while all other sheets are being in the equal non-saturated state. At the more high level of field, when B_{max} < 2.5 T (at t = 2 μs), final distribution of induction is looking as in the uniform medium.

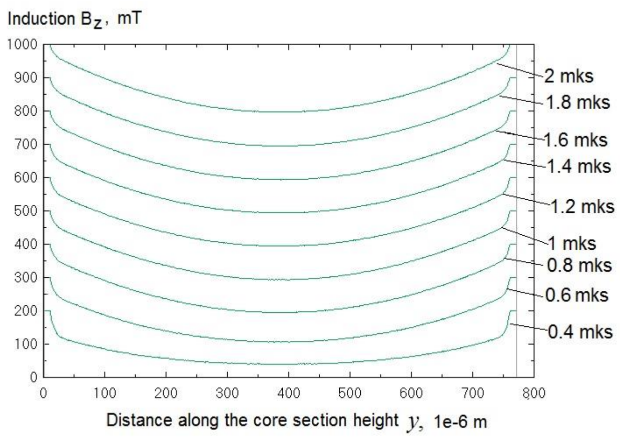

Fig. 2, b. Distribution of magnetic induction along the line of symmetry which is parallel to the sheets of ferromagnetics. B_{max} = 1 T.

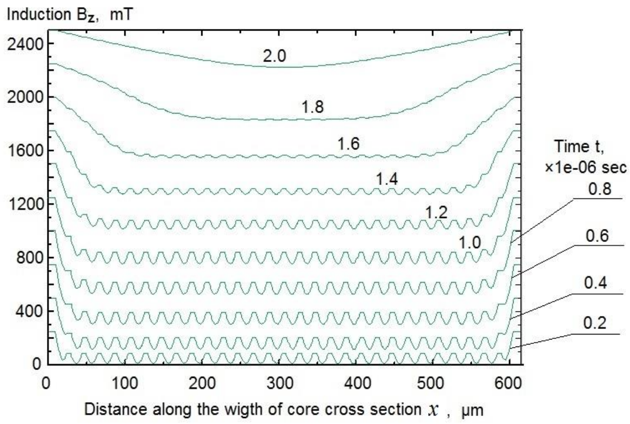

Fig. 3, a. Distribution of magnetic induction along the line of symmetry which is perpendicular to the sheets of ferromagnetics. B_{max} = 2.5 T.

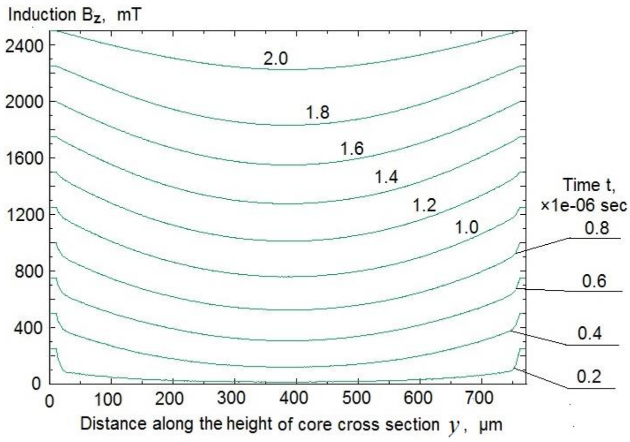

Fig. 3, b. Distribution of magnetic induction along the line of symmetry which is parallel to the sheets of ferromagnetics. B_{max} = 2.5 T.

In result of ferromagnetics saturation the structural anisotropy of package disappears, and process of the field penetration is going without connection with lamination of core (Fig. 5).

The study of the field diffusion into the thin-laminated core opens the interconnection between the speed of the field diffusion and linearity of total magnetic flux of core in time. An integral calculator of program QuickField allows to make a calculation in time a full flux of field across the any closed contour of model. In the Fig. 6 (for B_{max} < 1T) and in the Fig. 7 (for B_{max} < 2.5T) the results of total flux measurement across the full square of the core sross section are given. The average value of magnetic induction in the cross section is shown by line *2* at both figures. Through the concentration of flux near the edges and due to not enough speed of diffusion at the initial stage of process the flux development slows down. With a following steps in time the average magnetic induction (line *2* in the Fig. 6) and total flux have linear change in time, but proportionality between exciting current and magnetic flux has violation (compare line *3* and line *2* in the Fig. 6).

A similar situation was observed for example of core under saturation, when B_{max} = 2.5 T (Fig. 7). The high quality pulsed transformer evidently must provide the magnetic flux of core as linear function of time to get a rectangular form of output voltage. Improvement of transmission function linearity can be reached by some increasing rate at initial part of triangle exciting pulse in the winding. The result of corresponding numerical experiment is shown in the Fig. 8.

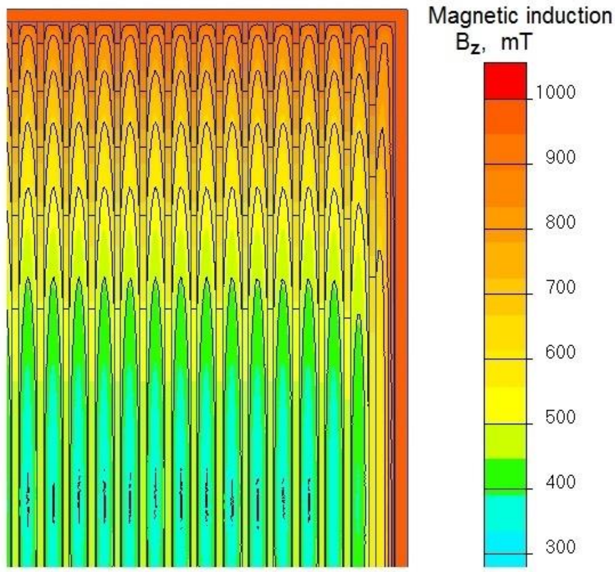

Fig. 4. 2D distribution of magnetic induction at excitation of field by linear growing current, when B_{max} < 1 T.

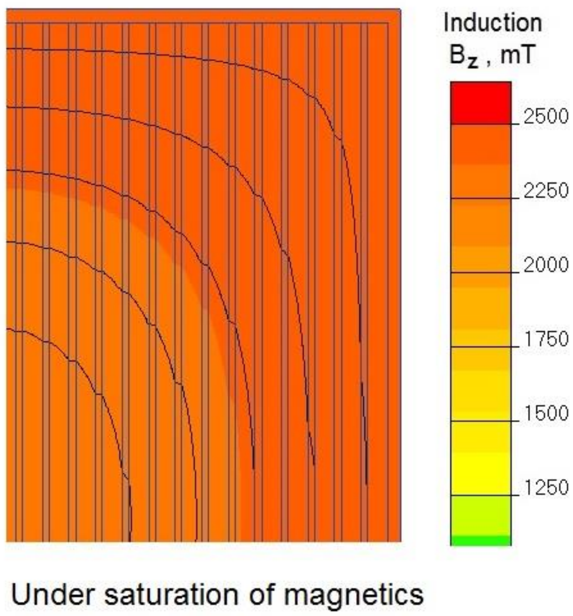

Fig. 5. 2D distribution of magnetic induction at excitation of field by linear growing current, when B_{max} < 2.5 T.

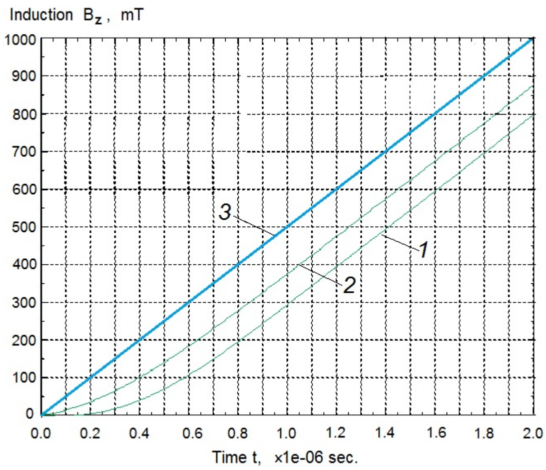

Fig. 6. Magnetic induction as function of time for $B_{max} < 1$ T. Designations: *1* – induction in the center of cross section; *2* –average induction across the full cross section of core; *3* – induction as the boundary condition at the perimeter of core including small air gap.

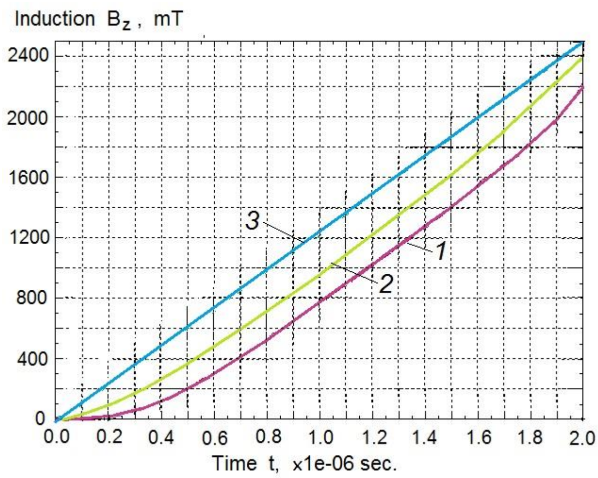

Fig. 7. Magnetic induction as function of time for $B_{max} < 2.5$ T. Designations of curves are the same as in the Fig. 6.

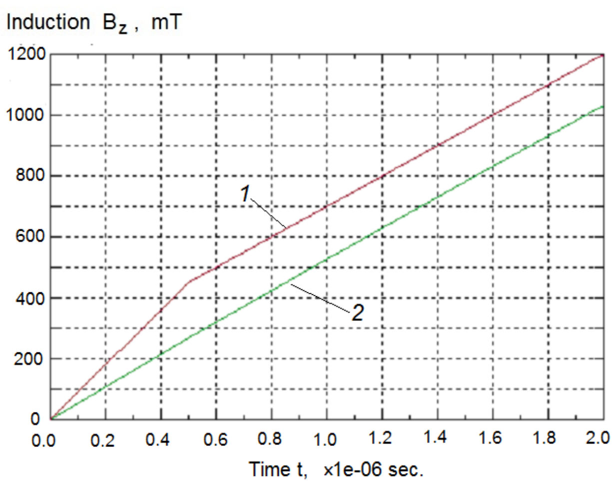

Fig. 8. Corrected mode of field excitation in the core with no saturation. . Line *1* shows the forced growth of magnetizing current; line *2* shows the improved dependence of total magnetic flux on time.

As it seen from the Fig. 8 (line *1*), the rate of exciting current was increased at the time interval from 0 up to 0.5 μs and was staying stable later as former one (likely line *3* at Fig. 6) during a following time. Due to this corrected mode of excitation the magnetic flux across the cross section of the core is growing as linear function of time (line *2* in the Fig. 8). The Fig. 9 represents the magnetic characteristics of the material which has been used in the numerical experiment. Left side of Fig. 9 is a typical magnetization curve of steel *B(H)* while the right side of Fig. 9 is the inversed magnetization curve $f(B) = \mu_0 H / B = [\mu_r(B)]^{-1}$, in accordance with (2). Both curves in the Fig. 9 has been built using Table 1 shown in the **Appendix**.

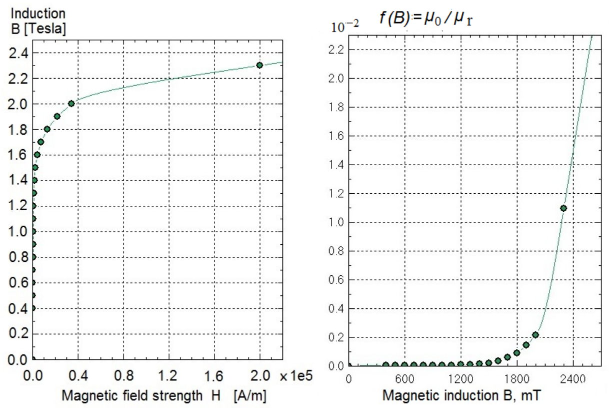

Fig. 9. Magnetization curve *B(H)* and non-dimensional inversed curve *f(B)* for ferromagnetics material under consideration.

IV. CONCLUSION

2D simulation of the magnetic induction distribution in the rectangular cross section of thin-laminated closed (circular) core of toroidal pulse transformer displayed some specifics of the flux excitation in the core by linear growing in time magnetizing current. The professional version 6.3 of software QuickField has been used as the tool for a field penetration study. The structural anisotropy of core stipulated by its lamination yields to different speed of field penetration into the core along the orthogonal axes of core cross section. The filling of sheets by magnetic flux occurs mainly along the plane of sheets disposition. The field penetration perpendicularly to this plane is going with some delay, with drop of induction near the edges and with relatively uniform distribution of induction from sheet to sheet in the central part of core. In result the linear growth of total magnetic flux in the core can be violated. The numerical experiment with accelerated growth of exciting current at initial part of pulse has shown a possibility for compensation of the flux linearity violation.

Appendix. Table 1. Magnetization curve *B(H)* and non-dimensional inversed curve *f(B)* of ferromagnetics material (graph in the Fig. 9).

Induction *B*, mT	0	400	500	600	700	800	900	1000	1100	1200
$f(B) = 1/\mu_r$, $\times 10^{-3}$	-	0.441	0.430	0.4431	0.470	0.500	0.556	0.632	0.741	0.885
Strength of field *H*, A/m	0	140	171	211	261	318	397	502	647	843

Induction *B*, mT	1300	1400	1500	1600	1700	1800	1900	2000	2300
$f(B)$) = $1/\mu_r$, $\times 10^{-3}$	1.105	1.422	2.100	3.465	5.781	9.100	14.59	21.54	109.56
Strength of field *H*, A/m	1140	1580	2500	4400	7800	13000	22000	34200	200000

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