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IMPROVEMENT OF ACCOUNT THE NONLINEARITY OF IRON MAGNETIC CHARACTERISTIC IN ELECTROMAGNET COMPUTATION*M.V. Zagirnyak, D. Sc., Prof.**Kremenchuk Ostrogradskiy State Polytechnic University**vul. Pershotravneva, 20, 39614, Kremenchuk, Ukraine**E-mail: mzagirn@polytech.poltava.ua**Yu.A. Branspiz, D. Sc., Prof., A.N. Pshenichniy, Cand. Sc.**East Ukrainian National Dal University**kvartal Molodezhniy, 20-a, 91034, Lugansk, Ukraine,**E-mail: branspiz@mail.ru*

It is shown that errors in determination of magnetic field induction at particular elements of electromagnet magnetic system may occur in magnetic field numerical computing of direct current electromagnets in saturation condition. It is ascertained that these errors are connected with limitation of the preset range of change of magnetic field strength and induction as well as linear extrapolation of induction values outside this range. Taking a shell-type electromagnet computation as an example, it is demonstrated that computation errors can be reduced if real change of iron magnetic permeability at relatively high values of magnetic field strength is taken into consideration.

Key words: magnetization curve, extrapolation, FEMM, shell-type electromagnet.

Показано, что при расчете электромагнитов постоянного тока в режиме насыщения с помощью численных методов могут возникнуть ошибки определения индукции магнитного поля на отдельных участках магнитной системы электромагнитов. Установлено, что эти ошибки связаны с ограничением заданного диапазона для изменений напряженности и индукции магнитного поля и линейной экстраполяцией значений индукции вне этого диапазона. На примере расчета броневой электромагнита показано, что ошибки расчета можно уменьшить, если учесть реальное изменение магнитной проницаемости железа при относительно больших значениях напряженности магнитного поля.

Ключевые слова: кривая намагничивания, экстраполяция, программа FEMM, броневой электромагнит.

Introduction. Nowadays application of various software products based on magnetic field numerical computing is widely spread in engineering and scientific practice to compute different electromagnets [1]. So, finite difference method realized, for example, in FEMM software product [2], is commonly used in practice to compute magnetostatic field in direct current electromagnets. Thereupon, it is of practical interest to investigate the FEMM and similar software products features which become apparent in particular computation conditions (boundary conditions, materials properties, etc.). Namely, it is of concern, to analyze the mentioned software products with the aim of determining adequacy of account of non-linear properties of iron magnetic characteristic of direct current electromagnets.

Problem statement. In computing a direct current electromagnet nonlinear properties (nonlinearity) of iron magnetic characteristic are accounted by direct representation of this characteristic as a certain magnetization curve (dependence of magnetic induction on magnetic intensity). This curve is naturally limited by the range of argument representation (intensity) and function (induction). So, when it is necessary to compute an electromagnet in the state of magnetic saturation, computing values of magnetic induction and intensity for some points in electromagnet iron may go beyond the preset

change range. If FEMM is used in such cases (magnetic saturation state) linear extrapolation by two last points of this curve is applied to connect magnetic induction and intensity beyond the assigned range of magnetizing curve. It can result in errors – overrated values of magnetic induction on particular electromagnet iron sections, which, in its turn, may lead to an error in other parameters.

General analysis of such errors presents certain mathematical difficulties. However, if it is assumed that common features of such errors become apparent in particular computations, it can be possible to define them analyzing an electromagnet of a specific type.

With this purpose in view, a shell-type electromagnet with an axisymmetric magnetic system is analyzed in this paper. It makes it possible to do without assumptions, necessary for other electromagnet types, when their 3-D field is reduced to a 2-D field for computation. Analysis of the chosen electromagnet in saturation condition with the aim of defining the character of influence of the mentioned linear extrapolation, used in FEMM for description of dependence of magnetic induction on magnetic intensity beyond the assigned range of magnetizing curve, on the computation results was one of the problems solved in this paper.

Another problem, settled in this paper, was development of practical recommendations allowing taking into account the magnetizing curve properties in order to avoid errors possible in numerical computation of electromagnets in magnetic saturation condition.

Results of computing a direct current shell-type electromagnet in saturation condition.

Consider a direct current electromagnet of solenoid starter switch type 5702.3708 (Joint-Stock Company “ZiT”, Samara, Russia), which is an axisymmetric shell-type electromagnet. There are results of experimental investigation of this electromagnet presented in [3], which caused the choice of exactly this electromagnet.

Fig. 1 shows an outline of the analyzed electromagnet with indicated main dimensions (mm) which were used during corresponding computing experiments based on FEMM.

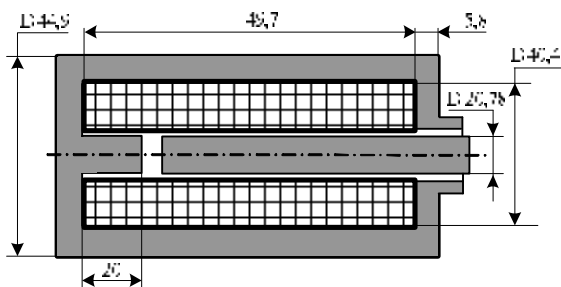


Figure 1 – Design of direct current shell-type electromagnet of solenoid starter switch (type 5702.3708)

The experiments consisted in computation of the magnetic system of the mentioned electromagnet, as a magnetostatic problem with axial symmetry, using FEMM software. In this case the value of 3684 A was adopted for magnetization coil magnetomotive force (MMF), which corresponds to magnetization coil voltage of 5V. To provide iron saturation condition the operating air gap (between the keeper and the plunger) of 5 mm was adopted.

Computation was carried out for different grades of magnetic system steel:

- structural steel St3, its magnetization curve, given in [4] in the form of a table, has an upper bound of 1.69 T for induction;
- Carpenter Electrical Iron steel from the standard materials library of FEMM program (hereinafter CEI steel), which has an upper bound of 1.85 T for induction;
- cast steel 15L, for which the known [5] magnetization curve approximation was used

$$H(B) = B \times 102(9.98 + B^8), \quad (1)$$

which made it possible to assign dependence of magnetic induction on magnetic intensity for this steel with any upper bounds for induction in a table (by means of relevant tabulation). Two values of 2 and 3 T were assumed for this computation.

The results of corresponding computation of magnetic induction in centers of three specific sections of magnetic circuit of the electromagnet under consideration (the keeper base; the medium section of that part of plunger, which is situated inside the coil; the medium section of air gap) are shown in Table 1. It can be seen from these figures that computation results in overrated values of magnetic induction for both St3 and CEI steels. It should be stressed, that the unsatisfactory results of computation are connected in this case exactly with the way of setting a magnetizing curve in the form of a table. If that is the case, the upper bound of the magnetizing curve causes its linear extrapolation performed by FEMM software for induction values exceeding tabulated ones (Meeker, 2003).

Table 1 – Results of computation

Steel grade*	Magnetic induction, T			Traction force, N
	Keeper base (maximum)	Plunger medium section	Air gap	
St 3 (1.69 T)	8.6	2.73	2.43	797.3
CEI (1.85 T)	4.24	2.2	1.97	519.6
15L (2 T)	3.06	1.92	1.74	400.7
15L (3 T)	2.54	1.92	1.74	400.8

* Induction limit for magnetization curve is given in brackets.

It is easy to make sure of it adopting two values of the upper bound of magnetic induction for 15L cast steel in corresponding checking computation. To be exact, 15L steel magnetization curve for two range variants of induction value change: from 0 to 2 T and from 0 to 3 T was adopted in FEMM, using dependence (1). In this case, as it is evident from corresponding computing data given in Table 1, enlargement of the preset range of magnetization curve induction values decreases the maximum value of iron induction, practically not affecting results of computation of induction in the gap, though.

Discussion of the obtained results.

First of all, it is necessary to point out the following fault which takes place in linear extrapolation of magnetization curve. In case of such an extrapolation by two last points of magnetizing curve, set by a table, there exists the following dependence of induction on intensity (Fig. 2)

$$B = B_{n-1}H_n - B_nH_{n-1} + H \frac{B_n - B_{n-1}}{H_n - H_{n-1}} \quad (2)$$

where H_n , H_{n-1} and B_n , B_{n-1} are two last largest values in table setting of magnetizing curve of argument (intensity) and function (induction), correspondingly.

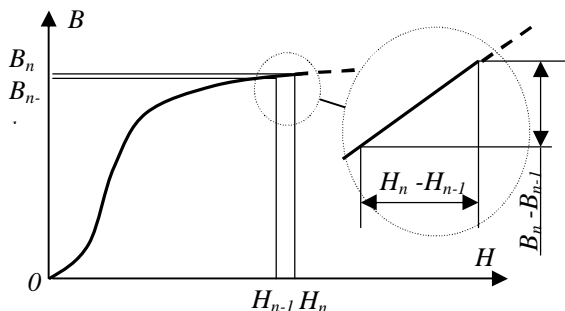


Figure 2 – Linear extrapolation of magnetizing curve

According to equation (2), in limiting case, when intensity tends to infinity ($H \rightarrow \infty$), the limit of iron magnetic permeability is the relation

$$\mu \rightarrow \frac{B_n - B_{n-1}}{H_n - H_{n-1}}. \quad (3)$$

Then, according to equation (3), the limiting value of magnetic permeability for St3 steel (when $H \rightarrow \infty$) is $5.88 \cdot 10^{-5}$ H/m, and for CEI steel it is $6.40 \cdot 10^{-5}$ H/m (both these values by far exceed the vacuum permeability $\mu_0 = 4\pi \cdot 10^{-7}$ H/m).

It is evident that in general case relation (3) does not reflect the real tendency of various materials magnetic permeability μ in high fields to the value of vacuum permeability μ_0 . And this is the fault of magnetizing curve linear extrapolation, which causes the mentioned error in the computation discussed above.

In this connection it should be mentioned, that approximation (1) does not reflect the real change of magnetization curve either, as, when $H \rightarrow \infty$, it gives $\mu = 0$ for magnetic permeability. But the fact, that in this approximation the limiting magnetic permeability is not overrated (compared with vacuum permeability μ_0), makes it possible to use it for carrying out more accurate electromagnet computations.

To prove it, Table 1 includes computed value of traction force which is often the ultimate aim of shell-type electromagnet computation. To explain the corresponding results of Table 1 it should be pointed out that, according to experimental data given in [3], when magnetization coil voltage is 6 Volts and operating gap is 0.5 mm, the traction force must be about 400 N (if data of [3], given for the case when operating gap range varies from 10 mm to 2 mm with the pitch of 0.5 mm, are extrapolated). It is evident that the value of 797.3 N, obtained when the gap is 0.5 mm and the voltage is 5 Volts for St3 magnetic circuit material (Table 1), is, obviously, an erroneous result (in this case traction force of about 333 N should be expected). And, taking into account everything stated above, it is clear that corresponding error is caused by the method of magnetization curve representation.

The aim of the further investigation, taking into consideration everything mentioned above, was to develop practical recommendations helping to avoid errors connected with magnetizing curve linear extrapolation rea-

lized in FEMM software. And this development should be based on taking into account the real change of magnetic permeability (magnetizing curve) for relatively high values of magnetic induction and intensity (in the limit of $H \rightarrow \infty$).

About magnetizing curve extrapolation.

Dependence of a substance magnetic permeability on magnetic intensity (Fig. 3) can be approximated in various ways [6]. It causes the possibility of various ways of extrapolation of this dependence (or magnetizing curve, which is the same).

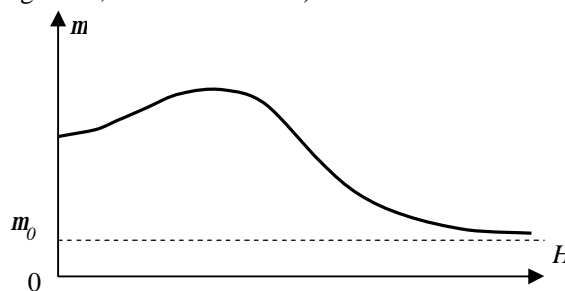


Figure 3 – Qualitative dependence of magnetic permeability on magnetic intensity

So, for example, approximation (1), to meet the condition

$$\mu \rightarrow \mu_0 \text{ at } H \rightarrow \infty, \quad (4)$$

can be presented as approximation

$$H(B) = \frac{102B(9.98 + B^8)}{1 + \mu_0 102(9.98 + B^8)}, \quad (5)$$

which coincides well with equation (1) at the induction change range from 0 to 2 T, giving the required change of magnetic permeability for high induction values.

However, a direct application of approximation of the kind equation (5) for computation of a shell-type electromagnet in a magnetic saturation condition gave practically the same results as approximation (1) at any limitation of the range of magnetizing curve table setting.

In this connection a practical recommendation from [6], reminding that magnetizing curve approximation is to serve the needs of the problem under consideration, should be pointed out. According to this recommendation, to solve the problem of reduction of errors possible in numerical computation of electromagnets in magnetic saturation condition, let us carry out extrapolation of this curve, which will meet condition (4), only beyond the range of magnetizing curve table setting.

So, taking into account the said qualitative character of the substance magnetic permeability change from magnetic intensity (Fig. 3), the following approximation, meeting equation (4), can be pointed out for magnetic permeability at magnetic intensity $H > H_n$

$$\mu = \mu_0 \left(1 - \frac{B_n - H_n \mu_0}{\mu_0 H} \right). \quad (6)$$

Using equation (6), it is not difficult to get the following dependence (extrapolation) for function $B(H)$ at $H > H_n$

$$B = \mu_0 H - B_n + \mu_0 H_n, \quad (7)$$

which presents a linear dependence.

According to equation (7), the extrapolation being analyzed, as well as the extrapolation realized in FEMM software, is linear, yet not with arbitrary angular coefficient according to equation (3), but with constant angular coefficient equal to μ_0 .

Application of equation (7) makes it possible to decrease significantly the error of computation of electromagnets in magnetic saturation condition. To prove this a computation of the same shell-type electromagnet (Fig. 1) was carried out for magnetic circuit made of St3 steel with linear extrapolation of magnetizing curve according to equation (7). Results of corresponding computation by means of FEMM software are shown in Table 2. In this case the computation was made with actual extension of the range of magnetizing curve up to induction 3 T on the basis of tabulation according to equation (7).

Table 2 – Results of computation with the offered linear extrapolation of magnetizing curve

Extra- polation of magnetizing curve of St3 steel	Magnetic induction, T			Traction force, N
	Keeper base (maxi- mum)	Plunger medium section	Air gap	
According to equation (7)	1.99	1.74	1.62	342
According to equation (8)	2.08	1.76	1.63	347

As appears from comparison of correspondent values of Table 2 and 1, the offered linear extrapolation of magnetizing curve according to equation (7) reduces the computation values of induction in the system decreasing, at the same time, the error of computation of traction force. That is why it can be recommended for practical application.

According to the possibility of various ways of extrapolation, another one is pointed out. Let us present a magnetizing curve for $H > H_n$ in the form of a straight line, corresponding to a horizontal from the point with coordinates (H_n, B_n) as it is shown in Fig. 4., i.e. in the form of a straight line

$$B = B_n. \quad (8)$$

As appears from comparison of values of Table 2 and 1, the offered extrapolation according to equation (8) also gives results, acceptable in engineering computation.

Quantitative analysis of errors for the recommended extrapolations presents the subject of further research of the authors.

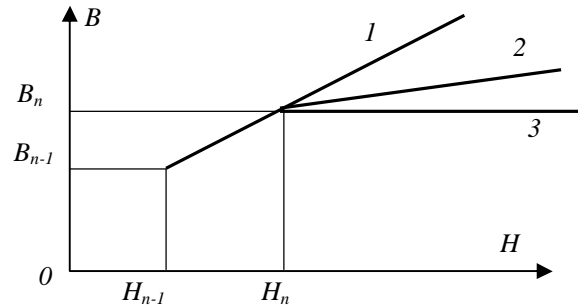


Figure 4 – Magnetizing curve extrapolation according to: 1 – FEMM; 2 – equation (7); 3 – equation (8)

Conclusion.

1. Method of magnetization curve representation in the form of a Table, having a certain limit value for magnetic induction, causes additional errors of computation of an electromagnet, when its iron is in saturation condition. These errors are connected with the fact that linear extrapolation is carried out for values exceeding the Table ones.

2. In extrapolation and approximation of magnetization curve it is necessary to take into account the following condition: if magnetic intensity tends to infinity, then magnetic permeability m should tend to the value of vacuum permeability m_0 .

3. The offered linear extrapolation of magnetizing curve beyond the range of its setting in the form of a table is applicable for practical computation.

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