Experimental research of magnetic circuits of current converters taking into account the nonlinearity of magnetic characteristics

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Abstract. The article is devoted to the development of methods for calculating magnetic circuits of current converters taking into account the nonlinearity of magnetic characteristics. At the same time, magnetic systems of current converters are of great interest, which, according to the principle of their operation, are magnetized simultaneously by constant and alternating magnetic fields (magnetomodulation converters). Analytical expressions of the magnetization curves of magnetic materials are proposed, experimental schemes are presented, and the feasibility of using a combination of oscillographic and wattmeter methods, the convergence of the calculated and experimental data are shown.

1. Introduction

There are a number of works devoted to the development of methods for calculating magnetic circuits taking into account the nonlinearity of magnetic characteristics [1÷10]. However, they were conducted mainly by methods of calculating direct current (DC) magnetic circuits taking into account the resistance of the magnetic circuit, where magnetic circuits with a gap resistance significantly less than the resistance of the magnetic circuit or commensurate with it. On the other hand, Scattering is not taken into account magnetic circuits with comparable resistances of the gaps and the magnetic core. The magnetic circuits with comparable resistances of the gaps and the magnetic core. When calculating the magnetic system of current converters, which, according to the principle of their action, are magnetized simultaneously by constant and alternating magnetic fields (magnetomodulation converters), these methods give quite large errors, because they do not take into account the influence of the alternating modulating field. Therefore, it is necessary to develop a method for calculating the magnetic circuits of current converters, taking into account the non-linearity of the magnetic characteristics, which makes it possible to solve the problem. To develop such a method for calculating the magnetic circuits, it is necessary to describe the magnetic characteristics with analytical
expressions. These types of methods can also be applied directly to the reliable control of electric motors in the textile industry [11].

2. Materials and methods

There are many analytical expressions obtained by the methods of approximation of the magnetization curve \( B = f(H) \) and the dependence of the specific magnetic resistance \( \rho_{\mu} \) on the magnetic induction \( B - \rho_{\mu} = f(B) \) [12-16]. Since the quality of the developed calculation method depends on the correct choice of the approximation formula from the existing sets of analytical expressions, it is necessary to analyze the existing analytical expressions of magnetic characteristics and apply new formulas for approximating the magnetization curve for magnetic circuits of magnetomodulation current converters.

Magnetic circuits of current converters can be with alternating or simultaneously acting constant and variable sources of magnetomotive forces (MF). Therefore, research should be conducted for the calculation of magnetic circuits of alternating current and for magnetic circuits with simultaneously acting direct and alternating currents.

Given that the scope of application of current converters is expanding, the magnetic systems of which, according to the principle of their action, are magnetized simultaneously by constant and variable magnetic fields (magnetomodulation converters), it is necessary to describe the magnetization curves of magnetic materials with simultaneous magnetization by constant and variable magnetic fields with analytical expressions. The magnetization curves of magnetomodulating magnetic circuits, in contrast to the magnetization curves \( B = f(H) \) of magnetic circuits with a single magnetic field, are described by a function with two unknowns in the form of \( B_\mu = f(H_\mu, B_\mu) \) or \( B_\mu = f(H_\mu, B_\mu) \), that is, the direct current (DC) \( B_\mu = f(H_\mu) \) magnetization curve is a function of the magnetizing value \( \phi \) or \( B_\mu \), and the alternative current (AC) \( B_\mu = f(H_\mu) \) magnetization curve is a function of the magnetizing \( H_\mu \) or \( B_\mu \).

Experimental magnetization curves for a magnetic circuit with parallel directed constant and alternating magnetic fields are given in [17, 18], and formulas for approximating the magnetization curve are given in [17]. However, these formulas are suitable for calculating magnetic circuits similar to chokes or magnetic amplifiers, and their use in the analytical calculation of magnetic modulating magnetic circuits leads to a large error. In this case, analytical expressions describing the magnetization curve of magnetomodulatory magnetic circuits with longitudinal and transverse modulations are required. In order to determine these analytical expressions, we construct an experimental magnetization curve in the form of \( B_\mu = f(H_\mu) \) at different values of the variable magnetic induction \( B_\mu \) for both a magnetic circuit with longitudinal modulation and a magnetic circuit with transverse modulation.

In [19], the design and scheme of a magnetic circuit with longitudinal modulation are given, and the dependence \( B_\mu = f(H_\mu, B_\mu) \) is presented in parametric form \( B_\mu = f(H_\mu) \).

The experimental magnetization curve of magnetic circuits with transverse modulation \( B_\mu = f(H_\mu)B_\mu \) is determined by a sample made of electrical steel type E12 in the form of a hollow toroid (Figure 1), consisting of two detachable parts.

One of them has an annular groove in which the windings \( W_{M1}, W_{M2} \) are laid. The second part consists of a cylindrical ring that closes the path of the transverse flow. Moreover, the contact surfaces of both parts of the ferromagnetic sample are carefully ground in order to reduce the resistance of the joint for the transverse field. The windings \( W_1 \) and \( W_2 \) are arranged evenly along the entire length of the toroidal core and cover the entire magnetic core.
3. Analysis of the results

From the family of magnetization curves shown in Figure 2, it can be seen that the shape of the curves shown in Figure 2 for all values is similar to the curves shown in (magnetic circuit magnetization...
curves for longitudinal modulation) [21]. The analysis of these experimental curves showed that if the magnetic material of the samples is isotropic, and the samples have the same geometric dimensions, the same values of the signals both at direct and alternating current, taking into account the influence of the windings (especially in a magnetic circuit with longitudinal modulation), then the same magnetization curves of the magnetic circuit are obtained for both longitudinal and transverse modulation.

To use these magnetization curves in the analytical calculation of magnetomodulation magnetic circuits, they must be approximated by analytical expressions, in the following form:

\[ H_a = a - \frac{a_0}{a_0 - B_a} B_1 - \theta \left( \frac{a_0}{a_0 - B_a} \right)^3 B_1^3 + c \left( \frac{a_0}{a_0 - B_a} \right)^5 B_1^5; \]  

or

\[ H_a = a'B_1 - \theta'B_1^3 + c'B_1^5; \]  

where \( a_0, a, b, c \) - constant coefficients.

\[ a_0 = (1.7 \div) \gamma; \quad a = 3.26A/\mu T; \quad \theta = 3.68A/\mu T^3; \quad c = 2.96A/\mu T^5; \]

\( B_a \) - the amplitude value of the AC magnetic induction, and \( B_a = (0 \div 1.2) \gamma; \)

\( B_f \) - DC magnetic induction in the presence of induction \( B_a \).

The curves defined by the formula (2) at \( a_0 = 0.3, 0.6, 0.9; 1.2, T \) for the transverse modulation at \( a_0 = 1.7T^{-1} \) are shown in Fig. 2 dashed lines.

The calculated curves differ from the experimental curves by little more than 5-6%, and in some part of the magnetization curve this difference is less than one percent.

### 4. Conclusion

1. Experimental magnetization curve of transversely modulated magnetic circuits, \( B_a = f(H_a) \) at different values of variable magnetic induction \( B_1 \), is determined in a special sample by measuring the instantaneous values of voltage and current using a combination of oscillographic and wattmeter methods. Subsequent processing of the data obtained using a coil and a computer for a period of the network frequency allows to obtain reliable data.

2. It is shown that the calculated magnetization curves differ from the experimental curves by less than 5-6%, and in some part of the magnetization curve this difference is less than one percent. Therefore, the proposed approximated analytical expressions can be used as the basis for calculating the magnetic circuits of magnetomodulation current converters.

### Acknowledgments

I would like to thank the people who helped me form this article, including:

To all authors.

To the organizers who organized this conference.

To the members of the editorial board.

### References

[1] Charubin T, Urbanski M, Nowicki M. 2017 Analysis of Automated Ferromagnetic Measurement System. Adv. Intell. Syst. Comput. 543, 593–600.

[2] Szewczyk R. 2014 Computational Problems Connected with Jiles-Atherton Model of Magnetic Hysteresis. Adv. Intell. Syst. Comput. 267, 275–283.

[3] Harlow J H 2012 Electric Power Transformer Engineering, (CRC Press, Taylor & Francis).

[4] Chiesa N and Hjødalen H K 2007 Modeling of nonlinear and hysteretic iron-core inductors in ATP European EMTP-ATP Conference, Leon, Spain.

[5] O’Handley C R 2000 Modern magnetic materials: principles and applications (Massachusetts Institute of Technology, John Wiley & Sons).
[6] Safarov A, Sattarov Kh, Jumaboyev S 2019 Device for conversion of equalizing current at the site of the traction ac network. E3S Web of Conferences 139 01034 https://doi.org/10.1051/e3sconf/201913901034

[7] Safarov A, Sattarov Kh, Jumaboyev S 2019 Device for detection of the phase current asymmetry in the three-phase lines of nontraction consumers. IOP Conf. Series: Materials Science and Engineering 734 012196 doi:10.1088/1757-899X/734/1/012196

[8] Baratov R J, Pirmatov N P 2020 Low-speed generator with permanent magnets and additional windings in the rotor for small power wind plants and micro hydro power plants IOP Conference Series: Materials Science and Engineering, 883 012183 https://iopscience.iop.org/issue/1757-899X/883/1

[9] Afonsky A A, Diakonov V P 2007 Measuring devices and mass electronic measurements (Moscow, SOLON-PRESS)

[10] Roman M 2011 Instrumentation and Measurement in Electrical Engineering (USA: Brown Walker Press)

[11] Baratov R, Pirmatov N, Panoev A, Chulliyev Ya, Ruziyev S and Mustafouqulov A 2020 IOP Conf. Series: Materials Science and Engineering 1030 012161 doi:10.1088/1757-899X/1030/1/012161

[12] Amirov S F, Safarov A M, Rustamov D Sh 2014 Electromagnetic current sensor for traction power supply device control systems Chemical technology. Control and management 2 26-31

[13] Research Institute of Electromechanics DC and AC current sensors, available at: http://www.niieem46.ru/current sensors/.

[14] TVELEM Current sensors, industrial design, available at: http://www.lem.com/ru/ru/content/view/478/882/

[15] Bohnert K A Guggenbach P 2005 Revolution in high dc current measurement ABB Review 1, 6-10

[16] Amirov S F, Jurayeva K K 2019 Research of magnetic circuits magnetoelastic sensors efforts with the method for creating equivalent circuits. International Conference on Information Science and Communications Technologies Applications, Trends and Opportunities ICISCT 2019, Tashkent, 4-6 November.

[17] Chekmarev A 2006 Current and voltage sensors ABB - from the printed circuit board to the giant converters Power Electronics 9 56-57

[18] Dommel H W 1969. Digital computer solution of electromagnetic transients in single- and multiphase networks IEEE Transactions on Power Apparatus and Systems. 88 (4) 388-399

[19] Matyuk V F, Osipov A A 2011 Mathematical models of the magnetization curve and magnetic hysteresis loops. Ch. I. Model analysis Non-destructive testing and diagnostics 2 33-35

[20] Naumov V A, Shvetsov V M 2003 Mathematical models of a current transformer in studies of differential protection algorithms. 37(2) 123-128

[21] Plakhtiev A M, Baratov R J, G A Gaziev, Doniyorov O Ch and Norkholboyev D Sh 2020 Estimation of the error of a magnetic modulation non-contact wide-range device for non-destructive control of high amperage currents IOP Conf. Ser.: Earth Environ. Sci. 614 012028