Approximation of dynamic characteristics of the magnetization for electromagnets

A M Lankin, M V Lankin and M Y Lankina

Federal State Educational Institution of Higher Professional Education ‘South-Russian State Technical University named after M.I. Platov’, 132, Prosvesheniya Str., Novocherkassk, 346428, Russia

E-mail: lankinjohn@yandex.ru

Abstract. The article describes the use of piecewise-polynomial approximation and approximation in the form of a power polynomial to the dynamic characteristics of the magnetization. The feasibility of this approach consists in the reduction of the amount of data used to describe the characteristics. For clarity, only the ascending branch of the dynamic characteristics of the magnetization was used. The error, arisen during approximation of the characteristic which according to the results of experimental studies did not exceed the required 5%, was estimated. As a result of the studies, it is possible to conclude about the appropriateness of approximating expressions application to describe the dynamic characteristics of the magnetization. Approximation defined as a power polynomial with the same error allows fewer approximating coefficients.

1. Introduction

Process inspection of the proportional solenoids manufacturing begins with the obtainment of the characteristic, containing information about the technical parameters depending on the mode of the process. The definition of such characteristics should be carried out based on the fully assembled product, and must be low-cost in terms of time and technical resources. This integrated feature is the dynamic characteristic of the magnetization (DCM) [6, 10] (Figure 1). It is possible to calculate the number of characteristics regulated by GOST: static and dynamic traction \( F = f(\delta) \) and \( F_d = f(\delta) \), respectively; armature movement characteristics \( \delta = f(t) \) and changing the current in the winding with time \( i = f(t) \) [1-4, 8, 9].

After the electric power supply, the coil current reaches the pick-up current, which corresponds to point 1. At this instant, the armature is in motion, during which the working air gap is reduced, the winding inductance increases and the current drops until the armature is attracted to the core, to which corresponds point 2. During the movement of the anchor, the relationship between flux \( F \) and current \( I \) is determined by curve 1-2.

At the end of the motion of the armature, current starts to increase again, reaching a steady-state value in point 3. After disconnecting the power supply of the electromagnet, the current in the coil falls, and when reaching the value of drop-out current \( I_{rel} \) (point 4), the anchor is set in motion, and the working air gap is increased from minimum \( \delta_{\min} \) to maximum \( \delta_{\max} \). Point 5 corresponds to the end point of the motion armature. Then, the current drops to zero, which corresponds to point 6. Because of the residual magnetization of the magnetic conductor, the flux corresponding to point 6 is above zero.
The dynamic characteristic of the magnetization of the electromagnetic actuator carries information about the magnetic, electrical, traction and dynamic properties of proportional electromagnet, and for its obtainment, it is possible to use so-called ‘non-sensor’ devices. It does not require disassembly of the test product and the currents, equivalent to the nominal ones, flow along the working coil [5].

![DCM of the electromagnetic drive](image)

**Figure. 1.** DCM of the electromagnetic drive.

The use of the DCM in the form of an array of points pairs of the magnetic flux current for further processing is difficult. A large amount of data (one DCM measured with an accuracy of up to 3% contains about 15,000 pairs of points) places high demands for the performance of processing facilities and increases the computation time. In this connection, it is advisable to use this approximation characteristics.

2. Materials and methods

Let us consider the use of two of the most optimal approximations for the description of DCM: the piecewise-polynomial approximation and the approximation by power polynomial [7]. For clarity, we will continue to consider only the ascending branch of the DCM, i.e. plots 0-1, 1-2, 2-3. Because of the ambiguity of DCM (one value of current response may take several flux values), let us consider not dependence $\Phi(i)$, but reverse characteristic $i(\Phi)$.

The method of piecewise-polynomial approximation consists in the replacement of sections 0-1, 1-2, 2-3, 3-4, 4-5, 5-6 DCM with approximating curves described by polynomials of the following type:

$$i^{(q)} = \sum_{1}^{m} k^{(q)}_n \Phi^n + b^{(q)},$$

where $k_n$ – coefficients describing the slope and the bends of the curve, $b$ – the coefficient describing the displacement of the curve with respect to the x-axis, $m$ – the maximum power of the polynomial, $q$ – the number of the approximated area.

The first and second areas of DCM can be described by the first degree polynomial. The first comes from the coordinate origin. Therefore, factor $b^{(1)}=0$:

$$i^{(1)} = k^{(1)}_1 \Phi.$$

The second area of DCM looks like:

$$i^{(2)} = k^{(2)}_1 \Phi + b^{(2)}.$$

The third portion may be described by a polynomial of the second or third degree:

$$i^{(3)} = k^{(3)}_1 \Phi + k^{(3)}_2 \Phi^2 + b^{(3)}, \quad i^{(3)} = k^{(3)}_1 \Phi + k^{(3)}_2 \Phi^2 + k^{(3)}_3 \Phi^3 + b^{(3)}$$

Thus, to describe the ascending branch of the DCM using piecewise polynomial approximation takes six or seven approximation coefficients and the four values of the flow and the current at the switching points of approximation segments.
The approximation method by the power polynomial consists in the replacement of DCM throughout its whole period by the power polynomial of the \( n \)-th degree of the type:

\[
i = \sum_{i=1}^{m} k_i \Phi^n.
\]

The advantage of this method is to use a smaller number of values required to describe the DCM. For example, for the same DCM, with the approximation error not more than 5\%, for approximation by power polynomial, six coefficient values are required, and for a piecewise polynomial approximation — eleven coefficient values.

3. Results

We conducted research on the approximation of the selected type of DCM \( i(\Phi) \), shown in Figure 2.

![Figure 2. DCM of \( i(\Phi) \) type of proportional electromagnet](image)

We used the piecewise polynomial approximation using approximations of the third area with the second and third degrees (Figure 3).

![Figure 3. Piecewise-polynomial approximation of DCM of \( i(\Phi) \) type](image)

The error in the application of a second degree of the polynomial was 8\%, and when using the third degree of the polynomial — 5\%, which meets the requirements for magnetic measurements.

Let us consider the use of a polynomial approximation shown in Figure 2. We use a power polynomial of the sixth degree for describing DCM (Figure 4).
When using a sixth-degree polynomial power, the error did not exceed 5%. However, when using a power polynomial for description of DCM, we need a less number of parameters than when using a piecewise polynomial approximation with the same accuracy. Thus, we can conclude about the possibility of using both types of approximation to describe the DCM.

4. Conclusions
The application of approximating expressions for description of dynamic characteristics of magnetization was studied. The studies allow concluding on the appropriateness of approximating expressions to describe the dynamic characteristics of the magnetization. The use of this approach will reduce the amount of measurement information without its losses, which will positively affect the speed of data processing. Both studied approximations demonstrated the error of the description of DCM of no more than 5%. However, a more efficient is the use of the power polynomial for describing DCM, since it allows using a small number of parameters than when using piecewise polynomial approximation.

Acknowledgment
The results obtained with the support of the project № 2.7193.2017 / BP performed within the base of the state task using equipment center for collective use "Diagnosis and energy-efficient electrical equipment" (NPI).

References
[1] Bakhtvalov Y A, Gorbatenko N I and Grechikhin V V 2015 Measurement Techniques 58 336-340
[2] Borovoi V V, Gorbatenko N I and Grechikhin V V 2015 Measurement Techniques 56 614-617
[3] Gorbatenko N I and Larkin M V 2004 Russian Electrical Engineering 8 63-66
[4] Gorbatenko N I, Larkin A M, Larkin M V and Shaykhutdinov D V 2015 Int. J. of Appl. Eng. Res. 3 6509-19
[5] Gorbatenko N I, Grechikhin V V and Shaikhutdinov D V 2015 Measurement Techniques 56 609-613
[6] Gordon A V and Slivinskaya A G 1960 Electromagnets DC power (Moscow: State Energy Publishing)
[7] Larkin A M, Larkin M V, Aleksanyan G K and Narakidze N D 2015 Int. J. of Appl. Eng. Res. 3 6489-98
[8] Shaykhutdinov D V, Gorbatenko N I, Akhmedov Sh V, Shaykhutdinova M V, Shirokov K M 2013 Life Sci. J. 10 2698-2702
[9] Shaikhutdinov D V, Gorbatenko N I and Shirokov K M 2015 Measurement Techniques 56 618-620
[10] Slivinskaya A G 1972 Electromagnets and permanent magnets (Moscow: Energy)