Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **68**, *1*, pp. 42–45, Bucarest, 2023

USE OF THE BH CURVES APPROXIMATION FOR THE CALCULATION OF MAGNETIC CIRCUITS IN ELECTRICAL MACHINES

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Keywords: BH curves, Approximation, Electrical steel, Electrical machines, Magnetic circuits, Magnetic voltage.

For the design of electrical machines, electrical steel BH curves are usually used in tabular or graphical form in magnetic circuit calculations. This is not convenient for data digitization and increases the requirement for computational accuracy. This work proposes a partial approximation of the BH curves through exponential function. The accuracy of the results obtained relative to the total approximation of these curves is demonstrated. The method for calculating the coefficients of the approximation functions is given. Applying these curves is modeled in calculating the magnetic voltage of the trapezoidal-shaped stator tooth in ac machines. Finally, a numerical calculation example is carried out using the proposed method.

1. INTRODUCTION

Electrical steel sheets are widely used for the magnetic core manufacture of electromechanical devices and are characterized by the material magnetization BH curve. In most cases, this curve is nonlinear concerning its physical quantities. It is usually given in the graphical or tabular form (used as input for CAD programs, with an interpolation operation to draw the magnetization curve). It could be more convenient to use in practice. Nevertheless, it is desirable to have an analytical expression when calculating electromechanical devices' magnetic circuits or magnetic losses. It is also helpful in compiling mathematical models describing processes associated with energy conversion in electromechanical converters.

Both hot-rolled and cold-rolled isotropic sheets of steel are used to manufacture magnetic systems of electrical machines. Cold-rolled steel has higher magnetic permeability and reduced specific losses during magnetic saturation than hot-rolled steel [1]. With a sheet thickness of 0.5 mm, the fill factor of cores assembled from cold-rolled steel is up to 0.97.

During the construction of the stator or the rotor of an electrical machine, mechanical stresses are induced at each manufacturing step (cutting, stacking, assembly, etc.). These stresses significantly change the magnetic properties of electrical steel sheets [2].

For these reasons, the BH curves of different regions (teeth and yokes) in an electrical machine's same part (stator or rotor) are different.

Standard measurement techniques are carried out to determine the magnetic properties (BH curves) of magnetic sheets and strips, for example, using an Epstein frame [3] or using a single sheet tester [4–6]. The alternating current magnetic characteristics are determined for sinusoidal induced voltages, particular peak values of the magnetic polarization, and a specified frequency.

Electrical steels are supplied to electrical engineering enterprises as rolled sheets and strips. They are used to manufacture the laminated magnetic cores of electrical machines. Considering the wide variety of electrical steel sheets, a standardized marking is made, characterizing its main properties (Maximum specific total loss [W/kg], thickness [mm], product type by structural state, and type of rolling) [7].

2. APPROXIMATION METHOD

This paper gives an example of the approximation procedure for steel Surahammars Bruk electrical steel M400-65A [8] with a thickness of 0.65 mm.

Usually, the choice of the approximating function is made according to its similarity with the curve. For example, the nature of the magnetization curves for electrical steel M400-65A after factory processing resembles an exponential function. The BH curve also appears like other functions, such as the hyperbolic sine [9] or the arctangent [10].

When approximating the magnetization curve, it is advisable to take the magnetic induction B as the variable for the function of the magnetic field strength $H = f(B)$. In the simplest case, the approximation consists of the selection of coefficients that make it possible to bring the approximating function closer to the experimentally determined magnetization curve. In this paper, the approximating function has the following form:

$$H(B) = k_1 \exp(k_2 B), \tag{1}$$

where k_1 and k_2 are the approximating coefficients; in particular, k_1 is a scaling factor with the same units as the magnetic field strength [A/m], and the coefficient k_2 is expressed in [T^{-1}]. In Fig. 1, the approximated magnetization curve of steel M400-65A for the toothed zone of the electrical machine is presented, with the coefficients of the curve approximation $k_1 = 1.222$ and $k_2 = 4.959$.

The coefficients k_1 and k_2 are determined by the least squares method to minimize the difference between the points of the approximation function and the given BH curve.

$$\min_{k_1, k_2} \sum_{i=1}^{N_m} \left[H_i(B_i, k_1, k_2) - H_{mi}(B_{mi})\right]^2, \tag{2}$$

where $H_i(B_i, k_1, k_2)$ is the i$^{\text{th}}$ element of the approximation function fitted to the i$^{\text{th}}$ element $H_{mi}(B_{mi})$ of the given BH curve, and N_m is the number of the given data.

At first sight, in Figure 1, the approximation curve coincides with the measured data [8] curve. However, enlarging the scale of Fig. 1 makes the difference between the two curves remarkable (Fig. 2–4).

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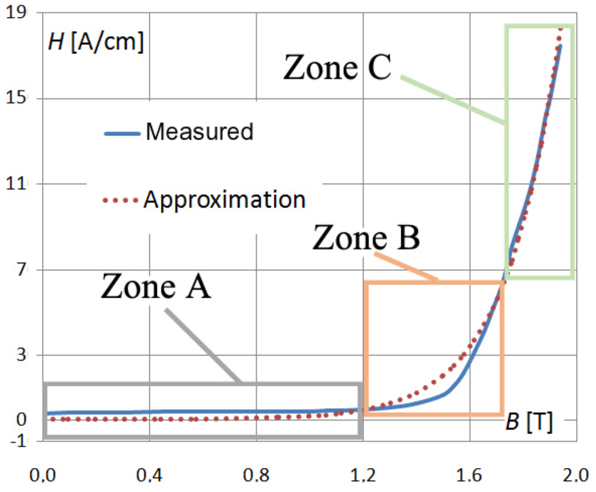

Fig. 1 – Measured and approximated BH curves of steel M400-65A

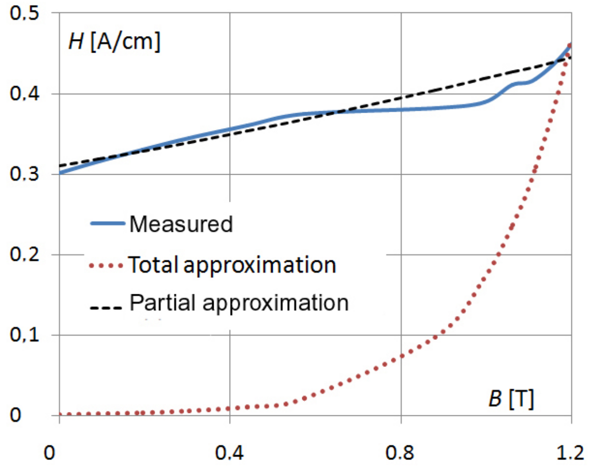

Fig. 2 – Comparison between measured and approximated BH curves of steel M400-65A in zone A

It is proposed to make partial approximations of the given BH curve, to achieve greater accuracy of coincidence between the two curves.

$$H(B)=\begin{cases} k_{A1}\exp(k_{A2}B) & \text{for} \quad 0\le B\le B_A \\ k_{B1}\exp(k_{B2}B) & \text{for} \quad B_A\le B\le B_B \\ k_{C1}\exp(k_{C2}B) & \text{for} \quad B_B\le B\le B_C \end{cases}, \qquad (3)$$

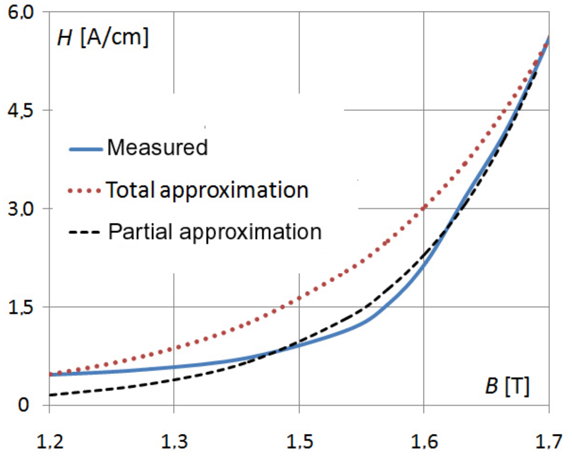

Fig. 3 – Comparison between measured and approximated BH curves of steel M400-65A in zone B

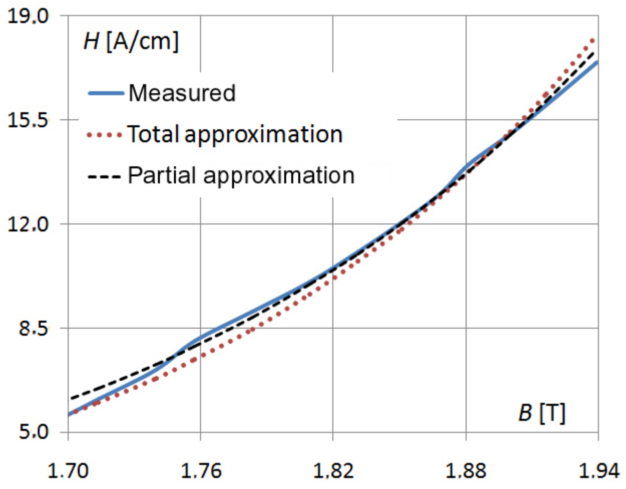

Fig. 4 – Comparison between measured and approximated BH curves of steel M400-65A in zone C

where $k_{A1;2}$, $k_{B1;2}$, and $k_{C1;2}$ are coefficients of the partial approximation functions of the given *BH* curve and B_A; B_B; B_C are values of the inductions limiting their intervals. We choose B_A, B_B, and B_C according to the change in the form of the BH curve, which has two almost linear parts (at its beginning and end) and an angled portion (in the center), as shown in Figure 5.

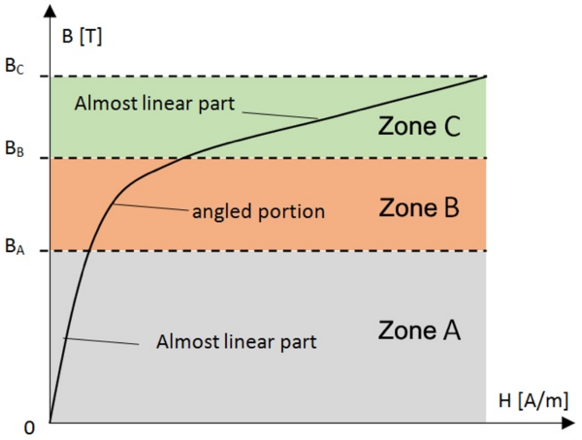

Fig. 5 – Method proposed to choose the magnetic induction intervals along the material BH curve

To further increase the precision of the two curves concordance, it is possible to increase the number of approximation intervals, but this will also involve increasing the number of coefficients and the number of approximation functions; this will result in making the calculation system difficult.

From eq. (3), we get the following coefficients and intervals points (Table 1) of the partial approximation functions:

Table 1

Coefficients of each interval of partial approximation functions

k_{A1} [A/m]	k_{A2} [T^{-1}]	k_{B1} [A/m]	k_{B2} [T^{-1}]	k_{C1} [A/m]	k_{C2} [T^{-1}]	B_A [T]	B_B [T]	B_C [T]
309	0.28	0.032	7.13	2.9	4.5	1.2	1.69	1.94

In Figs. 2, 3, and 4, the coincidence accuracy of the obtained partial approximation functions is much better than that of the total approximation function with the given magnetization curve in its different areas.

3. CALCULATION OF THE MAGNETIC VOLTAGE IN A STATOR TOOTH WITH A TRAPEZOIDAL FORM

In the absence of an analytical expression for the magnetization curve, numerical calculation methods are used. These methods only sometimes provide the required accuracy. One of the accurate methods is the approximation by Simpson's rule [11], for which it is necessary to calculate the magnetic induction in three sections of the tooth (along the apex, in the middle, and at the base).

The calculation of the magnetomotive force (MMF) by this method assumes that all the magnetic flux Φ_t in the air gap that passes through the tooth pitch t_1 passes along the tooth (Fig. 7-a). However, when the steel of the teeth is saturated (i.e., with an induction in the smallest of the sections of the tooth greater than 1.8 T), part of the magnetic flux of the tooth branches to the left and the right in the slots adjacent to this tooth (Fig.7-b).

In this part, a practical application of the magnetization curve approximation is used to calculate the MMF in the trapezoidal-shaped stator tooth. The slot and the tooth shape are defined according to the machine's power and winding type. The rectangular section conductors of the winding are housed in rectangular-shaped slots (good fill factor of conductors in the slot). The teeth of these slots have a trapezoidal form (Fig. 6), and their magnetic induction distribution is uneven.

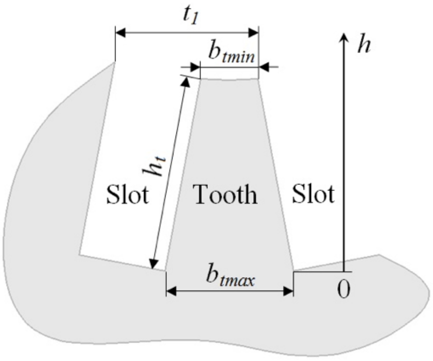

Fig. 6 – Stator tooth and slot shapes and their dimensions (h_t– tooth height, $b_{tmin;max}$– minimum and maximum tooth width)

The magnetic induction increases towards the air gap, and the width of the tooth changes linearly with the height h:

$$b_t(h)=\frac{b_{t\max}-b_{t\min}}{h_t}\cdot h+b_{t\min}\,. \tag{4}$$

Assuming that the complete magnetic flux is flowing in the tooth (Fig.7-a) and there are no ventilation ducts, its apparent flux density is:

$$\hat{B}_{ap}(h)=\frac{l_{ef}t_1}{k_{Fe}l_c b_t(h)}\cdot\hat{B}_g\,, \tag{5}$$

where l_{ef}– effective core length; $t_1=\dfrac{\pi D_1}{Q_S}$ – tooth pitch; D_1– stator bore diameter; Q_S– number of slots; k_{Fe}– space factor of the core; l_c– core length; B_g– air gap flux density.

Part of the flux always passes through the slot, especially if the magnetic induction exceeds 1.8 T (saturation of the iron of the tooth). For magnetic circuits of electric machines with magnetic induction in these circuits not exceeding 1.8 T, the relative magnetic permeability of the material μ_r is between 1000…10000. The magnetic flux passing through the slots is negligible compared to the flux passing through the teeth. Generally, it is not considered in calculating the MMF of the toothed zone. With a magnetic induction greater than 1.8 T, μ_r decreases to 100 ... 200; then, it becomes possible that part of the magnetic flux of the tooth strays to neighboring slots (Fig. 7-b). Then the real flux density in the tooth will be:

$$\hat{B}_t(h)=B_{ap}(h)-\left(\frac{\hat{B}_{ap}(h)}{\hat{B}_g}-1\right)\mu_0\hat{H}_{ap}(h), \tag{6}$$

where $H_{ap}(h)$ – magnetic field strength in the tooth (Since the tangential component of the field strength is continuous at the iron-air boundary, i.e. $H_{ap}=H_{slot}$, where H_{slot}– magnetic field strength in the slot).

From equation (1), the approximating function for the magnetic field strength in the tooth at a given height is:

$$\hat{H}_t(h)=k_1\exp\left[k_2\hat{B}_t(h)\right] \tag{7}$$

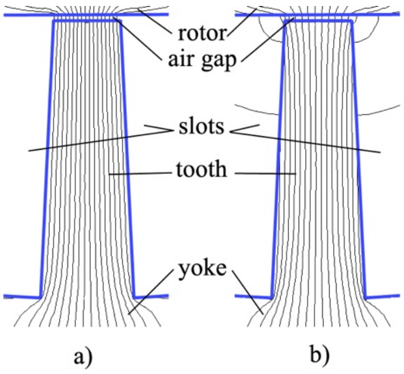

Fig. 7 – Complete magnetic flux in the tooth (a) and stray magnetic flux in the slots (b)

The expression of the MMF drop over the tooth is based on Ampere's law:

$$\hat{F}_t=\int_0^{h_t}\hat{H}_t(h)\,\mathrm{d}h\,. \tag{8}$$

4. APPLICATION OF CALCULATION FOR AN AC MACHINE

This example calculates the magnetic potential drop at a trapezoidal-shaped stator tooth, whose data are in Table 2.

Table 2

Parameters of the trapezoidal-shaped stator tooth of an AC machine.

Parameters	Symbols	Values
Tooth height	h_t	35 mm
Slot pitch	t_1	18.5 mm
Maximum tooth width	b_{tmax}	12.1 mm
Minimum tooth width	b_{tmin}	8.6 mm
Core length	l_c	190 mm
Effective core length	l_{ef}	194 mm
Core space factor	k_{Fe}	0.95
Air gap	g	0.9 mm
Flux density of the air gap	B_g	0.84 T

Figures 8 and 9 show the variation of magnetic induction and magnetic field strength along the tooth height. This can be used to calculate magnetic losses in teeth accurately. The computed value of magnetic potential drop in the tooth with equation (8) is 216 A.

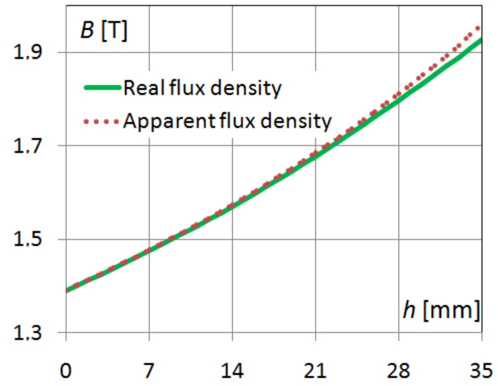

Fig. 8 – Variation of magnetic inductions along the height of the tooth

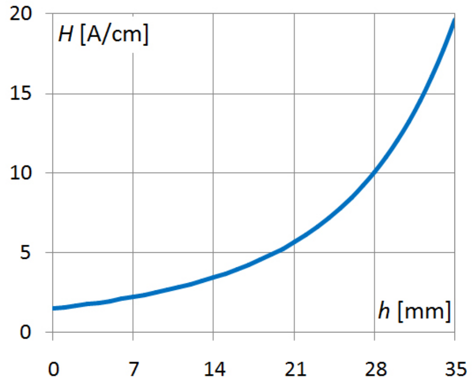

Fig. 9 – Magnetic field strength along the height of the tooth.

5. CONCLUSION

The approximation by an exponential function of the electrical steel BH curve is given. This will replace bulky experimental data tables or graphs for magnetic circuit calculations. This method provides good computation accuracy, improving these curves' partial approximations. An application of this method in calculating the magnetomotive force in a trapezoidal-shaped stator tooth of an AC machine has been modeled to replace the classical methods, such as the Simpson approximation. That gives more accurate results since it calculates the MMF in the tooth's full height and considers the leakage flux. The analytical example shows the variation of magnetic induction and magnetic field intensity along a tooth and the result of its magnetic voltage drop.

Received on 6 April 2022

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