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Method for Accounting for Saturation Nonlinearities of a Magnetic Core of a Bare-Pole Synchronous Machine Using a Mathematical Model

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ABSTRACT: In the report results of research of application of methods of piece wife-linear approximation, parabolic polynoms and cubic splines for the account of saturation prong zones are presented at calculation of jet resistance of differential dispersion of windings of an anchor of synchronous machines with various character of loading.

KEY WORDS: salient pole, differential scattering, armature windings, synchronous machine, spatial harmonics, magnetic flux, air gap.

I.INTRODUCTION

The reactance of the differential scattering of the armature windings of salient-pole synchronous machines is due to all restoring higher spatial harmonic components of the magnetic flux in the air gap [14]. The sum of all these harmonic components of the armature fluxes (starting from the sub-tooth order and above) forms the component of the differential scattering magnetic flux, otherwise called the magnetic leakage flux along the crowns of the armature winding teeth. The exact determination of the analytical expressions of nonlinear characteristics, including the scattering fluxes along the crowns of the teeth, depending on the degree of saturation of the individual parts of the magnetic circuit and the operating modes of the machines, is the most urgent task of forming their transients, designing synchronous machines [5-8].

In recent studies [1-2], in the pattern of magnetic field lines of scattering along the crowns of the teeth, it is considered that the latter, passing through the air gap of the machine, cross the air gap between the stator and the rotor only in the tangential direction. This does not take into account the nonlinearities associated with the saturation of the magnetic circuit of the machine, the gearing of the armature cores, the rotor and the non-uniformity of the air gap, which lead to significant errors in the calculations.

II. RESEARCH PROBLEM AND METHOD

The purpose of this work is to develop a method for calculating the leakage magnetic flux along the tooth crowns passing through an uneven air gap, taking into account the saturation nonlinearities of the tooth zones of the stator and rotor magnetic circuits.

If we consider changes in the operating mode of a synchronous machine in the widest range $-\pi/2 \leqslant \theta \leqslant \pi/2$, including intermediate active or mixed load patterns, then we can see that (ceteris paribus) the main harmonic component of the resulting magnetic flux saturates the tooth zone magnetic circuit to varying degrees [2]. So, for example, with an (ideal) inductive nature of the load, when the armature magnetic flux is directed along the longitudinal axis, opposite to the excitation flux, (ceteris paribus) the resulting magnetic flux is minimal, the stator tooth zone is slightly saturated. With an (ideally) capacitive load, on the contrary, the tooth zone of the stator is highly saturated. It is necessary to take into account the fact that the components of the magnetic flux of the air gap are algebraically added, and for their accurate calculation it is necessary to take into account the constantly changing nature of the degree of saturation of the parts of the magnetic circuit.

III. RESULTS

The task can be achieved by approximating the characteristics of the magnetization of the parts of the magnetic circuit of the machine. Moreover, if only individual modes of a synchronous machine of a specific design are considered, for the analytical representation of the nonlinear magnetization characteristic of the B =f(H)parts of the magnetic circuit of the machine, it is sufficient to use the methods of piecewise linear approximation or use piecewise constant functions [3-5]. So, for example, for the experimental characteristic given by the series Bk ; Hk points (where k =1,2,3,…,n), in the first case, on the section, $H_k - H_{k+1}$ the resulting function

$$B = B_k + \frac{B_{k+1} - B_k}{H_{k+1} - H_k}(H - H_k) \tag{1}$$

will look like a broken line with a break at a given point in the characteristic.
If you use the second method, this function is constant in the same section , $H_k - H_{k+1}$ for example

$$H = H_k \quad \text{or} \quad H = \frac{1}{2}(H_k + H_{k+1}) \tag{2}$$

and the resulting characteristic is a step function. Of course, the number of breaks and steps (1) and (2) for the considered nonlinear characteristic depends on the number of experimental points "k". However, these methods for approximating the nonlinear characteristics of the magnetization are less accurate. An indispensable condition for increasing the accuracy is an increase in the experimental points k.

Compared to these methods of approximation, a more accurate description of nonlinear curves is the approximation by a set of segments of quadratic or cubic polynomials - splines [4]. Having relatively the same amount of calculations, cubic splines are more accurate and have been more widely used in practice.

When using cubic splines, the approximation nodes and conjugation nodes are the same. Therefore, to determine the coefficients of cubic splines, the following conditions are used: the passage of a spline through nodes $B_k(H_k) = B_k$; equality at the nodes of the first $B'_k(H_k) = B'_{k+1}(H_k)$ and second $B''_k(H_k) = B''_{k+1}(H_k)$ derivatives of adjacent segments k and k+1. In addition, to uniquely determine the coefficients, it is also necessary to know two boundary conditions.

Approximate polynomials are expressed in terms of the values of the second derivatives at the nodes

$$M_k = B''_k(H_k),$$

Where

$$\begin{aligned} B_k(H) = \{M_{k-1}(H_k - H) + M_k(H - H_{k-1})^3\}/[6(H - H)^3] + \\ + [B_{k-1} - M_k(H_k - H_{k-1})^2/6](H_k - H)/(H_k - H_{k-1}) + \\ + [B_k - M_k(H_k - H_{k-1})/6](H - H_{k-1})/(H_k - H_{k-1}), \end{aligned} \tag{3}$$

or through the values of their first derivatives $m_k = B'_k(H_k)$, or through the slopes of the nonlinear characteristics:

$$B_k(H) = m_{k-1}(H_k - H)^2(H - H_{k-1})/(H_k - H_{k-1})^2 -$$

$$B_k(H) = m_{k-1}(H_k - H)^2(H - H_{k-1})/(H_k - H_{k-1})^2 -$$

$$+ B_{k-1}(H_k - H)^2[2(H - H_{k-1}) + (H_k - H_{k-1})]/(H_k - H_{k-1})^3 +$$

$$+ B_k(H - H_{k-1})^2[2(H_k - H) + (H_k - H_{k-1})]/(H_k - H_{k-1})^3. \qquad (4)$$

Here, the values of the coefficients m_k are determined from the following system of (n – 1) linear equations:

$$\begin{aligned} m_k = 0{,}5\{c_k - \frac{H_{k+1} - H_k}{(H_k - H_{k-1})(H_{k+1} - H_k)} B'_{k-1}(H_{k-1}) - \\ - \frac{H_k - H_{k-1}}{(H_k - H_{k-1})(H_{k+1} - H_k)} B_{k+1}(H_{k+1}) + \\ + 3\frac{H_{k+1} - H_k}{(H_k - H_{k-1})(H_{k+1} - H_k)} \cdot \frac{B_k - B_{k-1}}{H_k - H_{k-1}} + 3\frac{B_{k+1} - B_k}{H_{k+1} - H_k}\} \end{aligned} \qquad (5)$$

Where, $k = 1, 2, \ldots, n - 1$;

$$c_k = 3\mu_k (B_k - B_{k-1})/(H_k - H_{k-1}) + 3\lambda_k (B_{k+1} - B_k)/(H_{k+1} - H_k);$$

$$\lambda_k = (H_k - H_{k-1})/[(H_k - H_{k-1}) + (H_{k+1} - H_k)];$$

$$\mu_k = 1 - \lambda_k = (H_{k+1} - H_k)/[(H_k - H_{k-1}) + (H_{k+1} - H_k)]$$

To solve the system of equations (5), boundary conditions must be specified in terms of the first derivatives $m_0 = B'_0$ and $m_n = B'_n$ or in terms of the second derivatives $M_0 = B''_0$ and $M_0 = B''_n$. In the latter case, the system of equations (5) is supplemented by the following equations

$$2m_0 + m_1 = 3\frac{B_1 - B_2}{H_1 - H} - \frac{H_1 - H}{2} M_k;$$

$$m_{n-1} + 2m_n = 3\frac{B_n - B_{n-1}}{H_n - H_{n-1}} + \frac{H_n - H_{n-1}}{2} M_k.$$

If, simultaneously with the values B_k of the experimentally measured function, the values of the first m_k or second M_k derivatives of the approximated function are given, or it is possible to calculate them with respect to $m_k = (B_k - B_{k-1})/(H_k - H_{k-1})$ or $M_k = (B'_k - B'_{k-1})/(H'_k - H'_{k-1})$ at the conjugation nodes, then the system of equations (5) can not be solved.

IV. CONCLUSION

A technique has been developed for approximating the nonlinear dynamic characteristics of the JPSD by a set of segments of cubic polynomials - splines. Having relatively the same amount of calculations, cubic splines are more accurate and have been more widely used in practice.

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