The calculation of the magnetic circuit of salient-pole electric machines

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Abstract. This article deals with the development of theories of electromechanical energy converters with a lower level of external magnetic fields, a new method for calculating magnetic circuits and electromagnetic processes in the ferromagnetic space of electromechanical converters of electro technical complexes, oriented to the use of modern computer facilities, are new methods of differential investigation of the influence of various parameters of electric machines on the level of external magnetic fields. Beyond the engineering methods for calculating the magnetic circuit, it remains to determine the magnetic field in the grooves of the rotor, the relationship of this field with the field of the ferromagnetic part of the core. The article presents the results of research methods and calculations of magnetic circuits and modes of operation of explicitly salient pole machine. Developed a fairly simple method of calculating harmonic of the magnetic field in the groove of the rotor and the interpolar space, which provides the definition of the parameters of the magnetic field at the given points without calculation of this field in the whole region.

1. Introduction
In the conditions of intensive development of powerful electric receivers and their control systems based on electronic devices - microprocessors, computers, communication equipment, the interaction of these devices, their quality and reliability of teamwork is becoming increasingly relevant [1, 2]. One of the issues of ensuring their electromagnetic compatibility is the reduction of external magnetic fields (EMF) of electric machines (EM) at the design stage.

2. Main part
In this direction various schools and groups study a number of problems and problems: new technical solutions and developments aimed at reducing the level of external fields, improvement of electromagnetic compatibility of converters and control systems, technical and economic indicators [3, 4]. This article deals with the development of theories of electromechanical energy converters with a lower level of external magnetic fields, a new method for calculating magnetic circuits and electromagnetic processes in the ferromagnetic space of electromechanical converters of electro technical complexes, oriented to the use of modern computer facilities, are new methods of differential investigation of the influence of various parameters of electric machines on the level of external magnetic fields. Beyond the engineering methods for calculating the magnetic circuit, it
remains to determine the magnetic field in the grooves of the rotor, the relationship of this field with the field of the ferromagnetic part of the core. More strictly, the problem of calculating the magnetic circuit and operating modes of the pole-pole machines can be solved with the use of a modern apparatus of field theory.

When developing the method for calculating the magnetic circuit and operating modes, the following assumptions are accepted [5]:
1. The magnetic field in the grooves of the rotor and the interpolar space is considered to be plane-parallel.
2. The magnetic field is assumed to be stationary, i.e. obeys the equations:
   \[ \text{div} \vec{B} = 0, \]
   \[ \text{rot} \vec{H} = \delta \]
3. Calculation of magnetomotive force on the yoke is made along the middle line.
4. The highest harmonics of magnetomotive force of armature winding and the phenomenon of hysteresis of core is disregarded.

For exact calculation of external magnetic fields of electrical machines, it is necessary to specify and simplify as much as possible calculation of the electrical machines making magnetic field.

The article presents the results of research methods and calculations of magnetic circuits and modes of operation of explicitly salient pole machine.

The use of known methods of calculation based on the concepts of magnetic field, parameters, coefficients of reaction anchors at presenting magnetic circuit in the form of a lumped element cannot ensure currently required accuracy.

The magnetic field in the air gap is approximated using discontinuous harmonic functions. Since the distribution curve of the magnetic induction along the circumference of the stator has the character of a discontinuous periodic function, it, like any periodic function can be represented as a Fourier series. Then, the calculation of intensities, magnetomotive force and magnetic induction, and the characteristics can be numerical harmonic iteration method (taking into account the peculiarities of calculation of individual sections of the magnetic circuit) with the approach of the magnetic induction via the harmonic components of the Fourier series. However, there is another approach to solving the problem. The idea is that a complicated distribution function of the normal component of the magnetic induction logically represented as a set of simple, each of which takes place in the width of the tooth (AB) or groove (BS), as shown in Figure 1. In turn, the distribution function of the normal component of the magnetic induction over the prong, and above the groove can be approximated by a discontinuous harmonic functions [6].

In this approach, the distribution curve of magnetic induction in the air gap, the width of the tooth of the rotor can be written as follows:

\[ b_\delta = \sum \rho \cdot B_{\delta \rho} \cdot \cos \left( \frac{\rho \cdot \pi}{N} \cdot x' \right) \cdot F_{\rho}(1), \]

where \( \rho = 0, 1, 2, 3 \ldots \) is the harmonic order \( x' \) - discrete coordinate values \( 0, 1, 2, 3, \ldots, N-1; \) \( N \) - is the number of equally spaced points on the width of one tooth, \( F_{\rho}(1) = 1 \) the width of the tooth, \( F(1) = 0 \) beyond.

The distribution of normal to the bore of the stator, the magnetic induction on the width of a groove of the rotor is written:

\[ b_\delta = \sum \rho \cdot B_{N\rho} \cdot \cos \left( \frac{\rho \cdot \pi}{N} \cdot x^* \right) \cdot F_{\rho}(1), \]

where \( B_{N\rho} \) - peak value of the cutoff harmonic on the width of a groove of the rotor; \( N \) - the number of equally spaced points across the width of the groove, equal to the number of points across the width of the prong.

As can be seen from Figures 1, 2 harmonic accurately describe the function \( b_\delta(x) \).
The calculation of the cutoff harmonic of magnetomotive force of the magnetic circuit has a number of features. This is a special feature of the method of discontinuous harmonic. Breaking the zero-order harmonic \((\rho = 0)\), which determines the constant component of the magnetic field, closes the circuit of the classical scheme of the magnetic circuit from pole to pole.

Magnetomotive force in the magnetic circuit for this component \([7]\)

\[
F_{a0(p=0)} = F_{\delta(p=0)} + F_{z1(p=0)} + F_{z2(p=0)} + F_{al(p=0)} + F_{al^*(p=0)} + F_{a2(p=0)},
\]

where \(F_{\delta(p=0)}\), \(F_{z1(p=0)}\), \(F_{z2(p=0)}\) – magnetomotive forces respectively in the air gap and the teeth of the stator and rotor; \(F_{al^*(p=0)}\), \(F_{al(p=0)}\) – magnetomotive forces in the yoke of the stator, respectively on a plot of the pole tip and winding; \(F_{a2(p=0)}\) – magnetomotive force on the yoke of the rotor.

So bursting harmonic \(\rho > 0\) closed on a completely different circuit than the harmonic \(\rho = 0\), and the expression of the amplitude values of discontinuous harmonic magnetomotive force in a magnetic circuit for \(\rho > 0\).

\[
F_{a0(p=0)} = F_{\delta(p=0)} + F_{z1(p=0)} + F_{z2(p=0)} + F_{al(p=0)} + F_{a2(p=0)},
\]

Magnetic fluxes from discontinuous harmonic at \(\rho > 0\) closed at the pole tip and the body of the tooth of the rotor, as the yoke. While solving the problem of perforated layers each pole of the stator are replaced with the estimated homogeneous, the characteristic of magnetization of which in the radial direction coincides with the characteristics of the real magnetization layer, the perforated layer of the rotor is taken by real. Magnetization curve of steel is approximated by the specified points. Coefficient close \(m_{Z2}\) to one. Therefore, the steel teeth of the rotor are saturated. The penetration depth of the higher harmonic is small and it can be taken equal to half the pole division of the corresponding harmonic, or, in view of the smallness of tension in the rotor teeth, it is possible to neglect the magnetomotive force of the rotor to the higher harmonic.

For the constant component

\[
f_{Zi(p=0)} = L_{Z2} \cdot H_{Zi(p=0)},
\]

where \(L_{Z2}\) – the height of the tooth of the rotor; \(H_{Zi(p=0)} = f(B_{Zi(p=0)})\) – the magnetic field in \(i\) – the tine rotor, is determined by the magnetization curve of steel;

\[
B_{Zi(p=0)} = m_{Z2} \cdot B_{\delta i(p=0)} - \text{induction of the DC component in } i - \text{the tine rotor.}
\]

Magnetomotive force per air gap, the teeth of the stator and rotor.
\[ f_{\delta Zi} = f_{\delta i} + f_{Zli} + f_{ri} \]  

(6)

Considering expression (6) as an even periodic function with half-period equal to the width of the tooth of the rotor, and decomposing it into Fourier series, the obtained amplitude values of discontinuous harmonic magnetomotive forces in the air gap and the teeth of the stator and rotor

\[ F_{\delta Zi}(\rho = 0) = \frac{1}{N} \sum_{x'=1}^{N} f_{\delta Zi}, \]  

(7)

for harmonic \( \rho > 0 \)

\[ F_{\delta Zi}^{(p)} = \frac{2}{N} \sum_{x'=1}^{N} f_{\delta Zi} \cdot \cos(\rho \cdot \frac{\pi}{N} x'). \]  

(8)

3. Conclusions

The proposed approximation of the distribution curve of the normal component of the magnetic induction in the air gap by the method of discontinuous harmonic allows for enough high accuracy significantly reduce the range considered in the harmonic calculation. Piecewise-linear approximation of the normal component of the induction in the air gap discontinuous harmonic most closely corresponds to the idea of calculation of the different zones of the simplest - for each zone methods: field for non-ferromagnetic regions of the grooves of the rotor and numerical - harmonic - ferromagnetic. Developed a fairly simple method of calculating harmonic of the magnetic field in the groove of the rotor and the interpolar space, which provides the definition of the parameters of the magnetic field at the given points without calculation of this field in the whole region. The magnetic field in the slots of the rotor teeth and yokes, the output parameters which are a function of discontinuous harmonic magnetic induction over the rotor teeth, describes the independent variable systems of equations characterizing the modes of operation of salient pole machines [7].

Received program of the calculation of the magnetic circuit and operation modes of electric machines taking into account saturation in the presence of various types of eccentricity using a discontinuous harmonic functions. The program allows to calculate all quantities required for construction workers, energy and other characteristics, the curve of distribution of the normal component of the induction along the bore of the stator.

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