

Method of calculation of the magnetic induction of the stator winding of a spiritual synchronous motor

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Abstract. This article discusses the calculation of the magnetic fields of the differential scattering of the stator, passing in the radial direction (penetrating the body of the rotor core), taking into account the saturation nonlinearities of the tooth zones of the magnetic circuit. The results of the method for calculating the magnetic permeability of the final values of the steel sections of the magnetic circuit in the stator and rotor of a salient-pole synchronous motor for its spatial harmonic fields in the air gap are presented.

1 Introduction

High-power synchronous motors are used in water supply pumping stations, agriculture, mill aggregates, ventilation installations, other equipment such as mining and processing industries, and many different industrial enterprises. Reliable operation of a synchronous motor during design depends on the correct calculation and selection of motor parameters because, at the current stage of development of equipment and technologies, they are very demanding on accurate calculations of the parameters and characteristics of alternating current and direct current machines [1-3].

Indeed, the general theory of electrical machines (EM) is based on simplifying mathematical expressions and design processes that use some generally accepted assumptions. This allows you to replace the real machine with an idealized physical or mathematical model [4].

Studies of the leading schools of electromechanics and operation at various industrial enterprises have shown that the developed calculation methods based on analytical studies using assumptions about the idealization of machines give positive results that are quite consistent with the experiment results [4-5].

However, in recent years, when designing modern synchronous motors, the operating point is chosen much higher than the so-called "saturation knee" of the nonlinear section of the magnetization characteristic to reduce their weight and size indicators.

It leads to a change in the degree of excitation, the magnitude, and nature of the load, the rotor speed of the synchronous motor, voltage, and degree of saturation, which affect the characteristics of the machine [6-7].

In transient conditions in synchronous motors, there is a problem of considering the nature of the behavior of machine parameters that will not be constant with a change in the degree of saturation.

Several models have been created that are suitable for the analysis of transient processes in electrical machines of various designs. However, all these models are based on the application of rather rough assumptions about the idealization of electrical machines [8-10]:

- the higher harmonic components of the electromagnetic field in the air gap are not taken into account, and calculations are carried out only for the main harmonic component of the variables;

- jagged surfaces of the magnetic circuit are replaced by smooth surfaces with a gap;

- saturation of the magnetic circuit, which has a significant impact on the nature of the transient process, is either not taken into account at all or is taken into account with an approximation without taking into account the higher harmonic components of the electromagnetic field;

- components of the electromagnetic field - the main and magnetic stray fields are considered independent and do not affect each other.

Until recently, the possibilities of modern computing facilities have not been fully used. As a result, this led to the fact that to achieve an acceptable accuracy of the results, correction factors are used based on the accumulated experimental studies and calculated data [11-17].

2 Materials and methods

The physical processes in a salient-pole synchronous motor are mainly determined by the shape of the magnetic field distribution curve along the circumference of its air gap, which is directly dependent on the degree of saturation of the steel sections of the magnetic circuit of the machine.

In [1], to some extent, the issues of considering saturation in calculating the differential scattering of alternating current machines are considered. It is noted that when determining the effect of finite magnetic permeability on differential scattering, it is necessary to keep in mind that the fluxes of higher harmonics are closed along shorter paths than the flux of the fundamental harmonic. And the flows of higher harmonics are closed, mainly right along the crowns of the teeth, and therefore the influence of the final magnetic permeability of steel on the higher harmonic fields of the air gap will be small.

Further, in [2], an increase in the differential scattering coefficient of the winding concerning the field of the working harmonic of the machine is considered due to a decrease in the inductance of the winding corresponding to the first harmonic of the field, since the flow of the working harmonic is closed along the teeth and backs of the stator and rotor of the machine.

The reactance in the air gap of a salient-pole synchronous motor depends on the saturation of the steel sections of the machine's magnetic circuit. Still, this dependence is very complex and has not yet been sufficiently studied. It is also noted that the decrease in higher harmonics due to the saturation of the teeth cannot be calculated.

Further, the issues of reducing the leakage reactance of a salient-pole synchronous motor during an asynchronous start when the currents reach 5-7 multiples of the rated current of the machine are considered. However, in these works, insufficient attention was paid to the study of the effect of saturation of the magnetic circuit's steel sections on the field's individual harmonic components in the air gap of the machine.

The differential leakage magnetic field of the stator winding of a salient-pole synchronous motor is one of the main parameters determined by the field of the main air gap of modern highly used synchronous machines. As noted by several researchers [3-5],

they are complex functions of the size of the air gap between the stator and rotor magnetic circuit, the number of slots per pole and phase, the pitch, the number of phases and winding zones, the width of the groove slot, the tooth pitch, the magnetic state of the steel sections of the magnetic circuits stator and rotor and the damping effect of currents in the secondary circuits of the machine.

There is a known method for calculating the main harmonic component of the magnetic field and the differential scattering field [5, 6], which allows taking into account all the above factors affecting them, where at the first stage of calculations, the air gap δ between the stator and rotor cores is taken constantly. In addition, the damping effects of currents induced in the starting winding and the excitation winding by higher spatial harmonic fields created by the stator winding of a salient-pole synchronous motor are not considered. The influence of these quantities will be considered separately in the next stages of research [18-21].

Let us consider the most common methods for calculating the magnetic field of the differential scattering of the stator winding of a salient-pole synchronous motor to compare their accuracy and ease of use in the design of motors with a saturated magnetic circuit.

The study of the influence of the magnetic permeability of the final values of the steel sections of the magnetic circuit in the stator and rotor of a salient-pole synchronous motor on its spatial harmonic fields in the air gap created by the stator winding can be carried out using the following models of the radial component of the field.

3 Results and discussion

For a stator winding coil with the number of turns W_k , the sides, which are separated from each other along the arc of the circle of the stator bore to the internal spatial angle β , when the origin of coordinates is aligned with the axis of this coil, we have [7]

$$H_{\delta\rho q} = 2W_k \sum_{v=1}^{\infty} K_{\delta\rho v} \sin v \frac{\beta}{2} \frac{\sin v\alpha}{v\alpha} \cos v\varphi. \quad (1)$$

Since the spatial angles α, β, φ form the main harmonic of the air gap field of the machine, it will also be spatial, the order of which is determined by the number of pairs of poles p of the machine ($v=p$).

The strength component is located along the radius of the magnetic field in the air gap machine for a group of coils in the coordinate system.

$$H_{\delta\rho q} = 2W_k \sum_{v=1}^{\infty} K_{\delta\rho v} \sin v \frac{\beta}{2} \frac{\sin v\alpha \sin\left(vq \frac{\alpha_z}{2}\right)}{v\alpha \sin\left(v \frac{\alpha_z}{2}\right)} \cos v\varphi, \quad (2)$$

where q is the number of slots per pole and phase of the windings; α_z is the internal angle corresponding to the distance between the axes of two adjacent coils.

For convenience, we denote

$$K_{uv} = \text{Sin}\left(v \frac{\beta}{2}\right) \quad (3)$$

$$K_{stv} = \frac{\text{Sin}(v\alpha)}{v\alpha} \quad (4)$$

$$K_{pv} = \frac{\sin\left(vq\frac{\alpha_z}{2}\right)}{q\sin\left(v\frac{\alpha_z}{2}\right)} \quad (5)$$

Then (5) takes the following form

$$H_{\delta pq} = 2w_k q \sum_{v=1}^{\infty} K_{\delta pv} k_{uv} k_{slv} k_{pv} \cos v\varphi \quad (6)$$

Also, for convenience, we denote the winding coefficient for the v -that harmonic

$$k_{\delta pq} = k_{uv} k_{slv} k_{pv} \quad (7)$$

Here, the values k_{uv} , k_{pv} are the shortening and distribution coefficients for the components of the v -that harmonic, k_{slv} is the stator current sheet coefficient or the stator current layer coefficient for the v is that harmonic.

Transforming (5), we obtain the following expression for the radial component of the magnetic field strength in the air gap of the machine for a group of coils

$$H_{\delta pq} = 2w_k q \sum_{v=1}^{\infty} K_{\delta pv} k_{obv} \cos v\varphi \quad (8)$$

The value in (8) represents the stator winding ratio for the v -this order harmonic component.

The radial component of the magnetic field strength in the air gap of a three-phase two-layer stator winding with an integer number per pole and phase during the flow of a sinusoidal symmetrical three-phase current with a frequency f_1 is written as follows

$$H_{\delta pq3x} = 4pw_k q \sum_{v=1}^{\infty} K_v k_{obv} k_{pqv} \left[\sin v \left(\varphi - \frac{2p-1}{p} \frac{\pi}{2} \right) \sin \left(\omega_1 t + \frac{2\pi}{3} \right) + \sin \left(\varphi - \frac{2p-1}{p} \frac{\pi}{2} - \frac{2\pi}{3} \right) \sin \left(\omega_1 t - \frac{2\pi}{3} \right) + \sin \left(\varphi - \frac{2p-1}{p} \frac{\pi}{2} - \frac{4\pi}{3} \right) \right] \quad (9)$$

Where $\omega=2\pi f_1$ is the angular frequency, in rad/sec; t is time, in sec.

The value $B_{\delta pq.v}$ is determined by the formula:

$$B_{\delta pqv} = \frac{H_{\delta pqv}}{\mu_0}$$

Mathematical models of the radial component of the magnetic field strength in the air gap make it possible to calculate the field, considering the effect on its spatial harmonic components of the radial dimensions of the air gap between the stator and rotor cores. And also, the number of slots per pole and phase, the pitch, the number of phases and winding zones, the width of the slot of the stator slot, the tooth pitch, and the final values of the magnetic permeability of the ferromagnetic sections of the stator and rotor of a salient-pole synchronous motor. In them, the air gap is assumed to be uniform, and the stator slot current is concentrated in a thin layer along the circular arc of the smooth surface of the stator core, with a width equal to the slot opening width.

When determining the differential magnetic field, it is proposed to use the difference between the resulting magnetic field and the fundamental harmonic of the field in the air gap [8-21].

$$B_{\delta pq\sigma} = B_{\delta pq\nu} - B_{\delta pq1}. \quad (10)$$

On this basis, with the help of analytical expressions (1) - (10), the curves of the main harmonic components of magnetic inductions $B_{\delta pq1} = f(\theta)$ and their higher harmonic $B_{\delta pq\nu} = f(\theta)$ components along the circumference of the stator bore within one pole division were constructed for a three-phase two-layer stator θ winding of a synchronous motor. Type of synchronous motor MCA 72-4, voltage 400 V, rotor speed 1500 rpm. and power 15 kW. The characteristics were taken at various degrees of saturation of the magnetic circuit of the machine $B_{\delta pq1} = 1.0; 1.1; 1.2; 1.3$ values from the nominal value of induction (Fig.1-4).

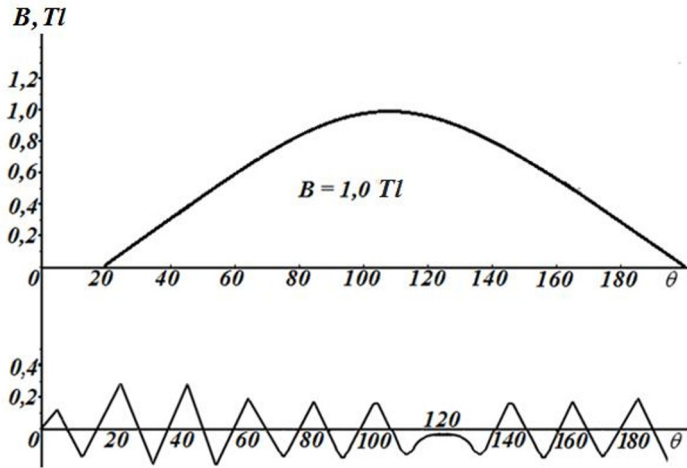


Fig. 1. Curves of magnetic inductions $B_{\delta pq1} = f(\theta)$ and $B_{\delta pq\nu} = f(\theta)$, and taken at induction of $B_{\delta pq1} = 1.0$ Tl.

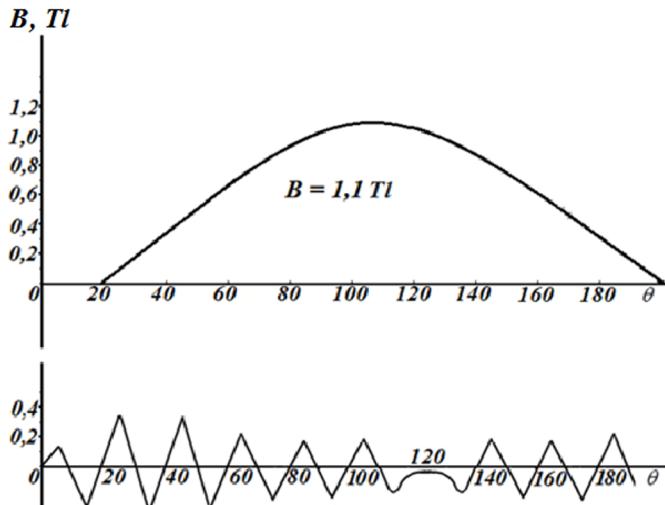


Fig. 2. Curves of magnetic inductions $B_{\delta pq1} = f(\theta)$ and $B_{\delta pq\nu} = f(\theta)$, and taken at induction of $B_{\delta pq1} = 1.1$ Tl.

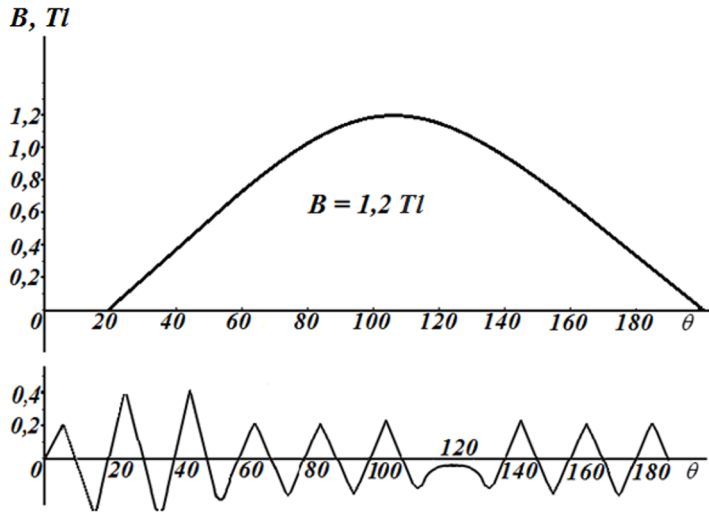


Fig. 3. Curves of magnetic inductions $B_{\delta pq,1} = f(\theta)$ and $B_{\delta pq,v} = f(\theta)$, and taken at induction of $B_{\delta pq,1} = 1.2 \text{ Tl}$.

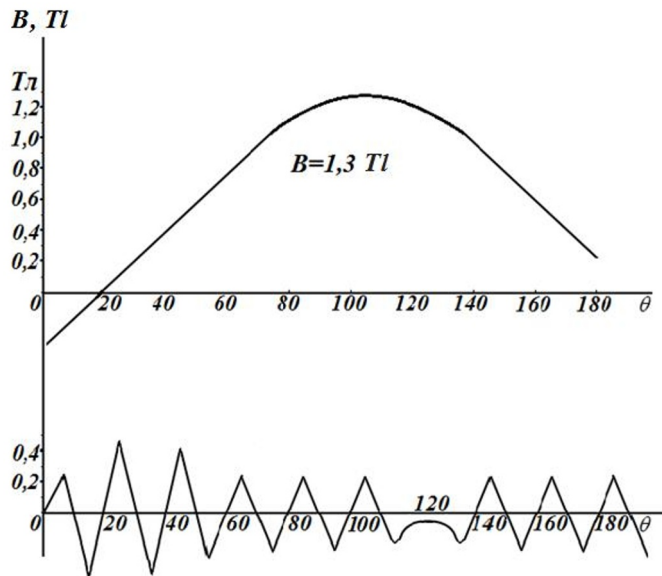


Fig. 4. Curves of magnetic inductions $B_{\delta pq,1} = f(\theta)$ and $B_{\delta pq,v} = f(\theta)$, and taken at induction of $B_{\delta pq,1} = 1.3 \text{ Tl}$.

These dependencies are obtained with the accepted assumptions, which are given above, and without considering the damping actions of the windings with individual components of the air gap field.

From a comparison of the curves of the magnetic field of the differential scattering of the stator winding of the YPSD, it can be seen that with an increase in the degree of saturation of the magnetic circuit, the amplitude of the third harmonic of the resulting field, as well as the maximum of the differential scattering field, grow at the beginning according

to a linear law, then more rapidly (Fig. 5). The dotted line in the figure was constructed using a computational experiment.

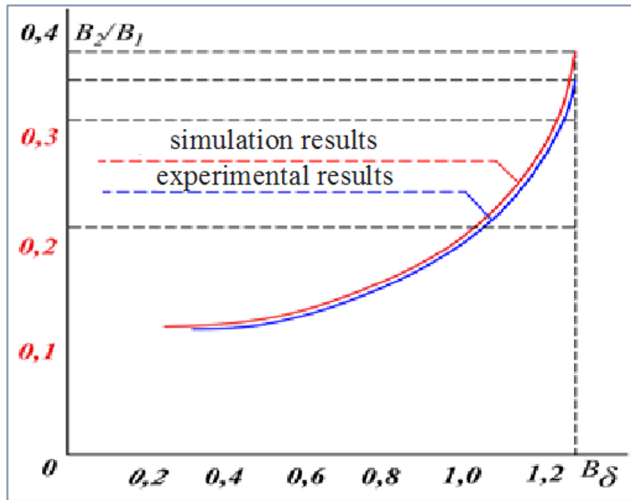


Fig. 5. Change in third harmonic component of magnetic field on degree of saturation of magnetic circuit: 1 is results of experiment; 2 is simulation results

A computational experiment to determine the influence of the degree of saturation of the magnetic circuit, therefore, the third harmonic magnetic field of the air gap on the nature of the flow of transients of the asynchronous start of a salient-pole synchronous motor was carried out by increasing the applied voltage of the stator winding. For this, oscillograms of the third harmonic magnetic field of the air gap were taken at various voltage $U_1 = (1,0 \div 1,3)U_H$ values - the main harmonic component of the air gap magnetic induction $B_1 = 1,0 \div 1,3 B_{\delta H}$. At these values of the applied voltage, the dependences of the electromagnetic moment on time were taken (Fig. 6).

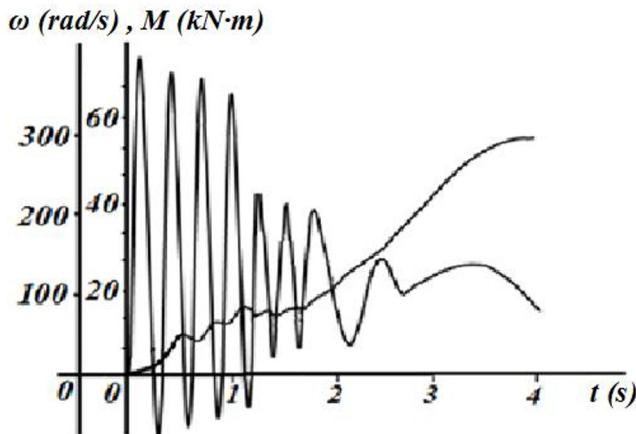


Fig. 6. Dependence of torque and angular velocity of rotation on time at $B = 1,2 Tl$

Thus, the higher harmonic magnetic fields of the rotor, formed due to the design features of the excitation winding, on the one hand, and the starting windings of the salient pole synchronous machine rotor, on the other hand, create electromagnetic moments that, when added to the resulting moments, cause dips in the mechanical characteristic of the engine.

With an increase in the degree of saturation of a salient-pole synchronous machine, the proportion of higher harmonic components of the magnetic field and the magnetic circuit also grows.

The analysis of the obtained curves of the harmonic components shows that the third harmonics in the conductors of various grooves located under one pole have different amplitudes, depending on their location. This is because the conductors are in different magnetic conditions.

4 Conclusion

Analysis of existing methods for calculating magnetic fields differential stator leakage passing in the radial direction (penetrating the body of the rotor core) is carried out when the saturation of the nonlinearity of the tooth zones of the magnetic circuit is taken into account. The influence of the magnetic permeability of the final values of the steel sections of the magnetic circuit in the stator and rotor of a salient-pole synchronous motor on its spatial harmonic fields in the air gap created by the stator winding was carried out.

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