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Study of the influence of steel saturation on the spatial harmonic fields of the stator in the machine air gap

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Abstract. The operation of AC electric machines depends largely on the characteristics of the magnetic field in the air gap, including its spectral composition. The saturation of the magnetic core is one of the factors influencing the field distribution. This paper examines the influence of magnetic saturation of magnetic core steel on the spatial harmonic components of the magnetic field in the air gap of AC electric machines. It is shown that despite extensive research on saturation in the context of integral machine parameters, its impact on the field spectral composition, particularly in designs with a fractional number of slots per pole per phase, remains understudied. Accounting for saturation in harmonic analysis allows for more accurate calculations of torque pulsation, noise levels, and heating. Therefore, developing models that reflect the effect of saturation on the magnetic field spectrum is of interest for more accurate design and modeling of electric machines.

INTRODUCTION

The operation of an AC electric machine is mainly determined by the shape of the magnetic field distribution curve around the circumference of its air gap that in turn is deeply dependent on the degree of saturation of the steel sections of the machine's magnetic circuit [1]. The papers [2-3] consider the issues of taking saturation into account when calculating the differential leakage of AC machines. In [2] it is noted that when determining the influence of the finite magnetic permeability on differential scattering, it is necessary to keep in mind the fact that the flows of higher harmonics are closed along shorter paths than the flow of the fundamental harmonic or the flows of the 5th and 7th harmonics, and the flows of higher harmonics are closed mainly directly along the crowns of the teeth and therefore the influence of the finite magnetic permeability of steel on the higher harmonic fields of the air gap will be small. Further, in [4], the increase in the differential leakage coefficient of the winding in relation to the field of the operating 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. In [3] it is noted that the reactance in the air gap of AC machines, and especially in induction machines, depends on the saturation of the steel sections of the machine's magnetic circuit; however, this dependence is of a very complex nature and has not yet been sufficiently studied. It is also noted that the reduction of higher harmonics due to saturation of the teeth cannot be calculated. Further, in [3], the issues of reducing the leakage reactance of asynchronous motors during direct connection to the grid are considered when currents reach 4-6 times the machine's rated current. However, in [2-3], insufficient attention was paid to studying the effect of saturation of steel sections of the magnetic circuit on individual harmonic components of the field in the machine's air gap.

METHODS AND MATERIALS

The study of the influence of finite values of magnetic permeability of steel sections of the magnetic circuit in the stator and rotor of the machine on its spatial harmonic fields in the air gap created by the stator winding can be carried out using models of the radial component of the field described by expressions (1):

$$H_0 = 4w_\kappa pq\sum_{n=1}^{\infty} K_n \kappa_{ban}\kappa_{pqn} \sin n\left(\varphi - \frac{2p-1}{p}\frac{\pi}{2}\right), \tag{1}$$

where

$$\kappa_{pqn} = \frac{\sin(-n\pi)}{2p\cos\left(n\frac{\pi}{2p}\right)} \tag{2}$$

for single-phase two-layer, (3)

$$H_m = 4pw_k q\sum_{n=1}^{\infty} K_n k_{ban} k_{pqn}\left[\sin n\left(\varphi - \frac{2p-1}{p}\frac{\pi}{2}\right)\sin\left(\omega_1 t + \frac{2\pi}{3}\right) + \sin\left(\varphi - \frac{2p-1}{p}\frac{\pi}{2} - \frac{2\pi}{3p}\right)\sin\left(\omega_1 t - \frac{2\pi}{3}\right) + \sin n\left(\varphi - \frac{2p-1}{p}\frac{\pi}{2} - \frac{4\pi}{3p}\right)\sin\omega_1 t\right] \tag{3}$$

where $\omega_1 = 2\pi f_1$ – angular frequency; t – time.
for three-phase two-layer, (4)

$$H_0 = 2w\sum_{n=1}^{\infty} K_n \kappa_{ban}\kappa_{0qn}\cos n\varphi' \cdot \tag{4}$$

for single-layer single-phase, (5)

$$\kappa_{pqn} = \frac{\sin(-n\pi)}{2p\cos\left(n\frac{\pi}{2p}\right)} \tag{5}$$

for a three-phase single-layer stator winding with a whole q, and also according to (6)

$$H_0 = 2w_\kappa p\sum_{n=1}^{\infty} K_n \kappa_{сл.n}\kappa_{yn}\left[u_n \cos n\left(\varphi + \frac{\pi}{p}\right) + \vartheta_n \cos n\varphi\right] \tag{6}$$

for single-phase two-layer and (7)

$$H_m = 2w_\kappa p\sum_{n=1}^{\infty} K_n \kappa_{yn}\kappa_{сл.n}\kappa_{oqn}\left\{\left[u_n \cos n\left(\varphi + \frac{\pi}{p}\right) + \vartheta_n \cos n\varphi\right]\times\sin\left(\omega_1 t + \frac{2\pi}{3}\right) + \left[u_n \cos n\left(\varphi + \frac{\pi}{p} - \frac{2\pi}{3p}\right) + \vartheta_n \cos n\left(\varphi - \frac{2\pi}{3p}\right)\right]\times\right.$$
$$\left.\times\sin\left(\omega_1 t - \frac{2\pi}{3}\right) + \left[u_n \cos n\left(\varphi + \frac{\pi}{p} - \frac{4\pi}{3p}\right) + \vartheta_n \cos n\left(\varphi - \frac{4\pi}{3p}\right)\right]\times x\sin\omega_1 t - \right\} \tag{7}$$

for three-phase, two-layer windings with fractional q, with the fractional value equal to two. Similar models can be constructed for stator windings with other turns distributions around the machine’s circumference, for example, based on expression (8).

$$H_o = 2w_\kappa\sum_{n=1}^{\infty} K_n \kappa_{сл.n}\kappa_{yn}\left\{u_n\left[\cos n\left(\varphi + \frac{\alpha_z}{p}\right) - \cos n\left(\varphi - \frac{\pi}{p}\right) + \cos n\left(\varphi - \frac{\alpha_z + 2\pi}{p}\right)\right] - \right.$$
$$-\vartheta_n\left[\cos n\left(\varphi + \frac{\alpha_z - 6\pi}{2p}\right) - \cos n\left(\varphi - \frac{\alpha_z + 8\pi}{2p}\right)\right] - u_n\left[\cos n\left(\varphi + \frac{\alpha_z - 5\pi}{p}\right) - \cos n\left(\varphi - \frac{6\pi}{p}\right) + \cos n\left(\varphi - \frac{\alpha_z + 7\pi}{p}\right)\right] +$$
$$\left. + \vartheta_n\left[\cos n\left(\varphi + \frac{\alpha_z - 16\pi}{2p}\right) - \cos n\left(\varphi - \frac{\alpha_z + 18\pi}{2p}\right)\right]\right\}. \tag{8}$$

These models allow for the calculation of the field, taking into account the influence on its spatial harmonic components of the radial air gap between the stator and rotor cores, the number of slots per pole and phase, the pitch, the number of phases and winding zones, the stator slot width, the tooth pitch, and the finite magnetic permeabilities of the ferromagnetic sections of the machine’s stator and rotor. These models assume a uniform air gap, and the stator slot current is concentrated in a thin layer located along a circular arc of the smooth surface of the stator core and with a width equal to the slot opening.

RESULTSANDDISCUSSION

The calculation studies of the influence of finite values of magnetic permeability of stator and rotor cores on spatial harmonic fields of the air gap created by the stator winding will be carried out for an asynchronous machine of the DAZO-14-69-6U1 type [5-6], which has a two-layer three-phase winding with q=5 and for an asynchronous machine of the MTF 112-6U2 type [7], the stator of which has a two-layer three-phase fractional winding with q=2(1/2). The calculations of the harmonic components were carried out on a computer by expressing the dimensions of the active zone of machine in relative units and taking the value of the radius of the stator bore circle c=1, and the equivalent magnetic permeabilities of the stator cores μ_1 and rotor μ_2 in fractions of the magnetic permeability of air μ_0 =4π10–7 H/m. Then for the DAZO-14-69-6U1 machine we have: a=0.698; b=0.9953; α=0.01765 rad; α_z =0.0698 rad; β=0.908 rad. The number of turns and the coil current are assumed to be equal to one. Under these conditions, the values of individual spatial harmonics are obtained in arbitrary relative units. The quantity represents a harmonic component of the order of n=p, i.e. the fundamental harmonic component of the machine field. The calculation results for the most strongly expressed harmonics created by one phase winding on the surface of the stator bore, i.e. at ρ=c, are shown in Fig.1. It is seen from the given figure, the saturation of the magnetic circuit differently affects the various spatial harmonic components in the air gap of the machine. In magnitude, all harmonic components decrease due to the reducing in magnetic permeability of the steel sections of the machine magnetic circuit. In the gap field, harmonic components that are multiples of the fundamental one, i.e. the number of pole pairs of the machine by 3-5 times (i.e. *n*=9; 15), as well as harmonic components of the tooth order are clearly expressed.

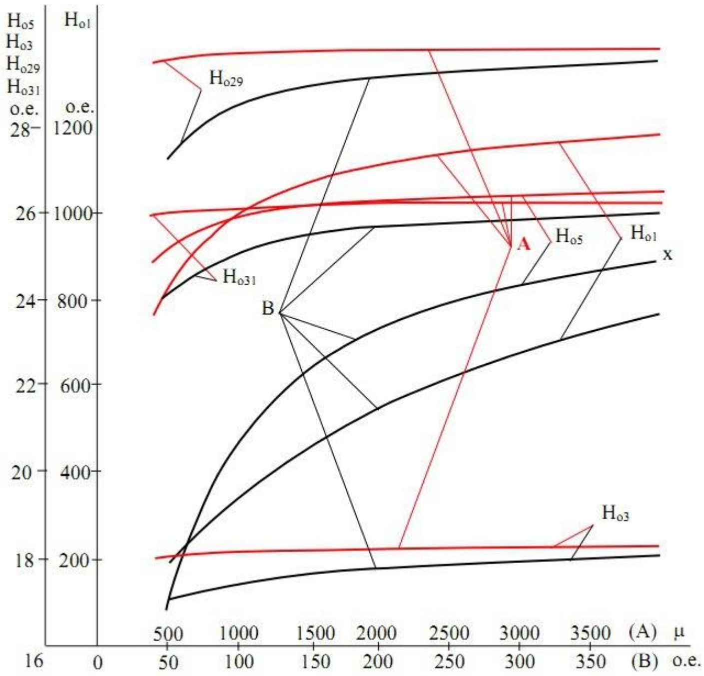

FIGURE 1. Calculation results for the strongly expressed harmonics

For the machine under study, the orders of the fundamental harmonic components *n*, are 29 and 31 times the number of pole pairs of the machine. When the machine transitions from a state in which the relative values of the equivalent magnetic permeabilities of the ferromagnetic sections of the machine's magnetic circuit in the stator and rotor are assumed to be identical and equal to μ=4000 to μ=100, the fundamental harmonic component (n=p) decreases by a factor of 1.5, and the quintuple harmonic component by a factor of 1.28. Under these conditions, the harmonic components of the teeth with orders n=29 and 31 decreased by 1.05 and 1.048 times, respectively. Thus, as the order of the harmonic components increases, the influence of magnetic circuit saturation, i.e., the decrease in the magnetic permeability of the steel sections of the magnetic circuits on the stator and rotor of the machine, on the field magnitude weakens. The relative magnitudes of the harmonic components of the field with n/p=3 in relation to the fundamental harmonic component increased by 2.27 times with saturation, n/p=5 by 2.68 times, and the fundamental harmonic tooth components by 3.23 and 3.24 times.

The weakened influence of saturation on the values of the higher-order harmonic fields can be explained as follows. The magnetic circuit of each harmonic component consists of steel sections in the stator and rotor of the machine and an air gap. Saturation affects the magnetic resistances of the ferromagnetic sections of the magnetic circuit of each spatial harmonic, the length of which decreases with an increase in the order of the harmonic components, since the pole division of the machine for a given harmonic component and, accordingly, the length of the steel sections of the magnetic circuits decrease. The state in which μ_1=2000 and μ_2=1, basically corresponds to the state of the machine with the rotor removed. In this case, harmonic components whose orders are multiples of the order of the fundamental harmonic component by 3 times, as well as tooth harmonics, are especially pronounced [8-14, 29].

As noted above, an asynchronous machine of the MTF 112-6U2 type was selected for the computational study of the influence of finite values of magnetic permeability of ferromagnetic cores in the stator and rotor magnetic circuits on individual harmonic components of the air gap field generated by a stator winding with a fractional number of slots per pole and phase and with a fractional base of two. The calculations are performed for one phase of the stator winding [15-20, 29].

The calculation results for the most strongly expressed harmonic components of the air gap field strength with simultaneous changes in the magnetic permeability of the stator and rotor cores are shown in Fig.2. As can be seen from the figure, the stator winding single-phase field curve most strongly expresses harmonic components whose orders are three times the order of the fundamental harmonic, even orders (n/p=2, 6, 12, 14, 16), as well as tooth harmonic components (n/p=29, 31) [21-29].

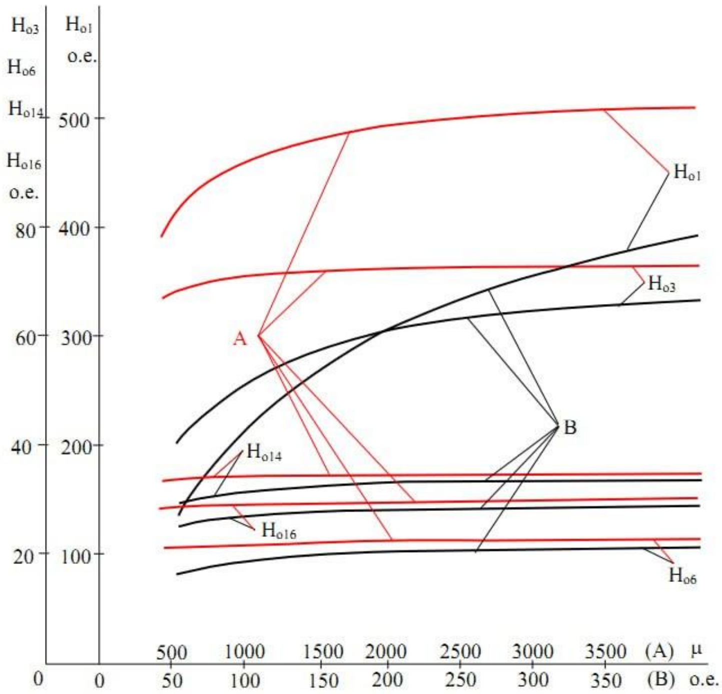

FIGURE 2. Results of calculations of the most strongly expressed harmonic components of the air gap field strength

The results obtained show that in machines with a fractional number of slots per pole and phase, as well as in machines with an integer value of q, the degree of reduction of the harmonic components of the air gap field decreases as the order of the spatial harmonic component increases. Calculations for the case of an extracted rotor, which can be characterized mainly by the values μ_1=2000 and μ_1=1, showed that in this case the harmonic components of even and tooth orders are most strongly expressed [30-39]. Thus, both in machines with integer and in machines with fractional q, the higher harmonic fields of the air gap, of both even and odd orders from the saturation of the magnetic field, i.e. from the decrease in the values of the equivalent magnetic permeabilities μ_l and μ_1, decrease to a lesser extent compared to the fundamental harmonic component of the air gap field [6, 40-56].

CONCLUSION

Saturation of the steel sections of the magnetic circuit in the stator and rotor of an AC machine has a greater effect on the low-order spatial harmonics of the air gap field than on the higher-order spatial harmonics. The influence of finite magnetic permeabilities of the steel sections of the machine's magnetic circuit on the latter is observed only in conditions of deep saturation of the machine's magnetic circuit.

Methods have been developed for calculating the equivalent magnetic permeabilities of the ferromagnetic sections of the magnetic circuit in the stator and rotor for each component of the air gap field, taking into account the magnetic state of individual sections in a given machine operating mode.

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