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Analysis of the Method for Calculation of Differential Scattering Reactivities of Synchronous Machines with According to Saturation Effects

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ABSTRACT: The results of the analysis of methods for calculating the reactive resistances of differential scattered magnetic fluxes are presented, taking into account the nonlinear connections of the magnetization of synchronous machines. It is noted that in all the studies analyzed, the effect of magnetic saturation was taken into account using the superposition method, which leads to a gross error in the calculations.

KEY WORDS: synchronous machine, alternating current, nominal parameters, reactive and active resistances,generator, electrical and electromechanical process, transient process, inductive parameters, air gap.

I.INTRODUCTION

Synchronous machines (SM) are used in all power plants of power systems, in pumping stations, ball mills and other installations of industrial enterprises. Ensuring their trouble-free operation largely depends on the correct calculation of the CM parameters during design, which ensure reliable and long-term operation with the successful fulfillment of the tasks assigned to them. Inconsistency of the parameters with the specified values can lead to a significant discrepancy between the ongoing transient processes and their recommended values [1-4]. Therefore, at the present stage of technology development, rather high requirements are imposed on the accuracy of calculating the parameters and characteristics of the SM. One of these parameters of the SM is the reactance (for brevity - reactivity) of differential scattering.

The difference between the calculated values of the inductive scattering parameters and their actual values obtained on manufactured machines is mainly due to the imperfection of the calculation methods, as well as the unaccounted for the influence of technological factors [5-6, 11-13].

In this paper, an attempt is made to analyze the existing methods for determining the reactivity of differential scattering of synchronous machines, in order to further improve them.

The reactivity of differential scattering, although its size differs significantly from other reactivity, is one of the main parameters of the SM equivalent circuit, is part of the equations describing the static and dynamic electromagnetic processes of an electromechanical energy converter (turbine - synchronous generator or SD - production mechanism) and is the initial value when using programs for calculating transient processes of an electric machine.

Calculation methods based on the classical theory of electrical machines (transformers, asynchronous and synchronous machines) involve the use of constant parameters of equivalent circuits that do not depend on the values that determine their operating modes. In fact, it is known that the parameters of the windings of machines are not constant: the active resistance depends on a number of factors, such as, for example, the temperature that changes over time and the load current; reactance - on the degree of saturation of the sections of the magnetic circuit, as well as on the design features of the active zone of the machine. For these reasons, in the first works [1,2,3] after the invention of AC machines, devoted to the determination of parameters, the differential scattering of the magnetic flux was determined with significant assumptions. These assumptions boiled down to the fact that instead of a toothed stator and rotor, a machine with a smooth stator and rotor was taken into account in the calculations, and also, the damping effect from the side of the secondary circuits, the explicit polarity of the rotor and the saturation of the magnetic circuits were not taken into account. In the future, approximately [4], then more strictly [5] began to take into account the toothing of the stator and rotor cores, the influence of currents induced in the secondary circuits. In works [5,6,7], the serration of the ferromagnetic stator and rotor, the salient polarity and damping actions of the secondary circuits are taken into account by the analytical method. The same authors use the numerical methods developed by them for calculating the electromagnetic processes of electrical machines and take into account the influence of the above factors on differential scattering, and propose a method for taking into account the effect of saturation.

Unfortunately, in the works cited above, the influence of saturation on differential scattering was estimated approximately or was not taken into account at all. In addition, none of the listed works considers the influence of the operating modes of electrical machines on differential scattering.

II. RESEARCH PROBLEM AND METHOD

The author of [8] believes that using the numerical methods of finite differences and finite elements, which are widely used in the calculation of the magnetic fields of AC electrical machines, it is very difficult to reveal the physical features of the magnetic field of differential scattering. Therefore, taking into account the fact that the distribution of the magnetic field along the circumference of the air gap in the region of the crowns of the teeth is uneven, the author proposes to use an analytical method for calculating the magnetic field of the air gap. At the same time, in this work, when studying the effect of saturation on the values of differential scattering fields using the analytical method for calculating the magnetic field of the air gap, the following assumptions are made:

- damping effects on the magnetic field of differential scattering of windings and circuits located on the opposite side of the air gap of the machine are not taken into account;
- when calculating the fields of differential scattering of the stator winding, the toothed core is replaced by a smooth one by bringing all the conductors in the grooves to the surface of the stator bore in the form of a thin layer located along the arc of a circle with a width equal to the width of the open groove and a current equal to the full current of the stator groove;
- similarly to the above, when calculating the fields of differential scattering of the rotor winding, all conductors in the slots are brought to the smooth surface of the rotor core in the form of a thin layer located along the arc of the circumference of the surface of the rotor core with a width equal to the width of the open slot and a current equal to the full current of the rotor slot;
- the toothed core, located on the other side of the air gap in relation to the part where the winding is located, is replaced by a smooth one by introducing an air gap coefficient.

Thus, the author of the work accepts the same assumptions, which are mentioned in the works [1,2,3].

The reactivity of the differential phase dissipation of the armature winding is defined as the difference between the total reactivity from the field of the main air gap and the inductive resistance, which is due to the main harmonic of the air gap field [2,3,8]. The differential leakage inductance is determined, which is the difference between the winding inductance due to the real field in the air gap and the inductance of the fundamental harmonic field in the air gap

$$x_\sigma = x_\delta - x_1 \tag{1}$$

Analytical expression of the instantaneous value of the magnetic field strength in the air gap of the machine (hT) , created by a three-phase stator winding, for the instantaneous value of the current of one of the phase windings when the v-order harmonic current flows in it (at the moment it passes through zero), when in the other two they (of the same harmonic) are equal in magnitude and opposite in sign, is written in the following form

$$\mathrm{hT} = \sqrt{3}\cdot \mathrm{w1}\cdot \mathrm{a1}\cdot \sum_{v=1}^{\infty}[\mathrm{k}_{v}\cdot \mathrm{k}_{об.v}\cdot \mathrm{k}_{pqv}]\ \mathrm{x}$$

$$\mathrm{x}\{\sin v\cdot[\varphi - (2p - 1)/p\cdot(\pi/2)] - \sin v\cdot[\varphi - (2p - 1)/p\cdot(\pi/2) - (2\pi/3\mathrm{p})]\} \qquad (2)$$

where a_1 is the number of parallel branches of the stator winding; w_1 - number of effective turns of one winding phase $w_1 = 2\cdot p\cdot q\cdot w_k / a_1$;$v$ - is an index that determines the serial number of the harmonic component; k_v - winding shortening factor for harmonic v - order; $k_{об.v}$ - winding factor for harmonic v - order; $k_{pq.v}$ - coefficient of distribution of the coil groups of the winding phase for harmonics v - order.

It is also known [9-10] that the teeth of the stator and rotor are the most saturated parts of the magnetic circuit of AC machines. The magnetic field lines of the differential scattering flows mainly pass along the teeth of the stator and rotor (Fig. 1). Despite this, in all analyzed studies to determine the influence of the saturation nonlinearity of the magnetic circuit on the reactivity of the differential scattering of machines, the harmonic components of the current in the winding are determined by expanding in a Fourier series, which provides for applications only to linear systems. The use of the superposition method in calculations of the leakage magnetic flux in saturated sections of the machine's magnetic circuit leads to significant errors.

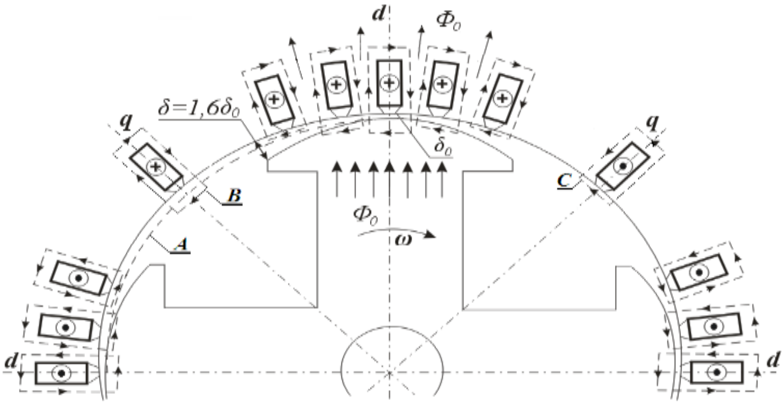

Fig.1. Stray magnetic fluxes

III. RESULTS

The saturation of the sections of the magnetic circuit, where the magnetic field lines of differential scattering pass, is formed both by these scattering fluxes themselves and by other machine fluxes. The leading role in this is assigned to the sum of the main harmonic component of the resulting magnetic flux of the $\varPhi$ machine - the sum of the magnetic flux of excitation $\varPhi_0$ and the armature $\varPhi_a$ flux, with which the considered components of the differential scattering magnetic flux are added.

$$\varPhi = \varPhi_0 + \varPhi_a \qquad (3)$$

Depending on the change in the nature of the load of the armature of the machine within $-\pi/2 \le \varphi \le \pi/2$, the magnetic fluxes of the main harmonic reaction of the armature with maximum instantaneous values, therefore, the main harmonic fluxes of slot leakage with maximum instantaneous values will be displaced with respect to the longitudinal and transverse to the axes of the rotor (Fig. 1).

With the reactive nature of the load current of the armature of the machine, these pairs of poles of magnetic leakage fluxes along the tooth crowns with maximum instantaneous values of magnetic induction are located along the transverse axis of the rotor q, and with an active load - along the longitudinal axis d.

In non-salient-pole synchronous machines, due to the cylindrical surface of the rotor (dashed line "A" in Fig. 1), the working air gap between the rotor and the stator is uniform along the entire length of the inner circumference of the stator (δ=δ0). Therefore, the curves of the magnetic field lines of differential scattering of all armature slots are closed in the same way - through the back, the tooth zone of the armature core, through a uniform air gap δ and the core of the rotor magnetic circuit (like the magnetic field lines of the slot "B" in Fig. 1). In this regard, the influence of the air gap δ on the saturation of these sections will be the same along the entire circumference of the rotor.

In explicitly pole synchronous machines, the air gap between the rotor and the stator in the interpole zone and the pole zone is uneven. With the reactive nature of the load of the machine, the magnetic conductivity of the medium of pole pairs of magnetic fluxes of differential scattering with maximum instantaneous values of magnetic induction is less than along the longitudinal axis. The magnetic field lines of the differential scattering flows will close through the adjacent tooth zones of the stator, the stator yoke and the air space between the crowns of adjacent teeth. At the same time, due to the significant air gap between the stator and the rotor in the interpolar zone, these flows will not be closed through the magnetic circuit of the rotor (Fig. 2).

On the other hand, in the pole zone, an uneven air gap between the tip of a clearly pole rotor and the inner cylindrical surface of the stator forms a value δ0 in the middle of the poles, and δ=1.6δ0 along the edges of the poles. Therefore, the magnetic field lines of differential scattering flows in the middle of the pole pieces will be closed through the adjacent tooth zones of the stator through the rotor body, and along the edges of the pole pieces they will be closed only through the adjacent tooth zones of the stator, and through the rotor yoke they will not be closed.

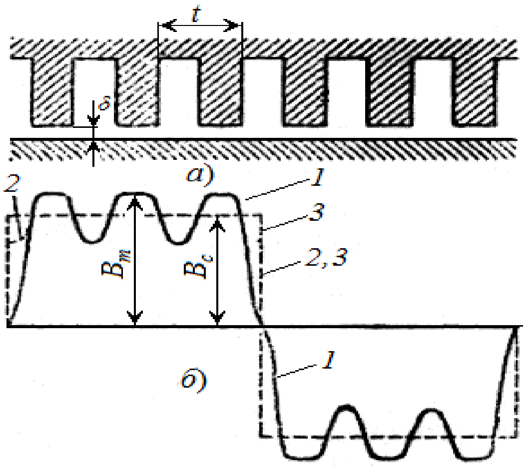

Fig.2. Stator toothing (a) form of magnetic induction (b)

Thus, the magnetic fluxes of differential scattering with a different nature of the load will be influenced by a different degree of saturation of the magnetic system of the machine.

IV. CONCLUSION

1. The high accuracy of the calculated degree of influence of saturation of the sections of magnetic circuits on the differential scattering of the magnetic flux is doubtful due to the assumption made that instead of a toothed stator and rotor, a machine with a smooth stator and rotor was taken in the calculations, while it is the gearing that creates differential scattering.

2. To take into account the effect of saturation nonlinearity on the scattering reactivity using the superposition method - will lead to a significant discrepancy between the calculated and actual parameters.

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