

# Determination of the parameters of the scheme of substitution of the anchor winding of the inductive sup-exciter of the combined multifunctional brushless exciter

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**Abstract.** The picture of the magnetic field of scattering and mutual induction of the anchor winding of the exciter for the three types of configuration of the tooth-groove layer is considered. The inductive resistance is calculated for the entire phase.

## 1. Introduction.

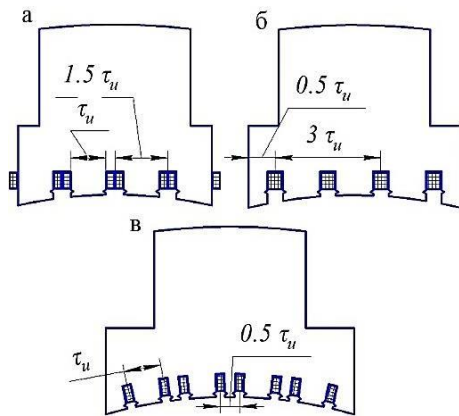
With the development of small-scale power generation, there is a growing need to develop new designs of diesel-generator sets that can work in various emergency situations and in extreme climatic conditions, including in fire-hazardous conditions when repairing gas and oil pipelines that require a high degree of reliability of power supply. For operation under such conditions, it is advisable to have a closed version of the generator with a combined brushless exciter (CBE).

One of the pathogens developed at the Department of Electrical Machines of the UrFU is an exciter for a diesel generator (DG) with a capacity of 60 kW, 1500 rpm and located inside the generator housing. In this pathogen, one of the determining functional elements is a combined inductor sub-exciter (ISE). To simplify the manufacturing process in the design of CMBE with a large number of poles, it is advisable to apply a 4-phase anchor winding of the exciter (AWE) [1], which is located in the tooth layer of the polepiece of the synchronous exciter. Technological design of the AWE structure and ISE power, developed both in nominal and forcing mode, largely depends on the structure of the tooth-groove construction and the layout of the pole coil groups of the nuclear reactor. The choice of structure can be made on the basis of a comparative evaluation of the indicated capacities under the same operating conditions of the ISE. As is known, the maximum value of the ISE power is determined by the equivalent inductive resistance of the substitution circuit of the exciter, an essential part of which is the inductive reactance of the scattering of AWE [2].

In this regard, in this article, an estimation of inductive scattering of AWE is carried out with three different variants of the construction of the notch-groove layer.

In figure 1 shows the variants for the construction of the notch-groove layer and the variants for placing the pole coil groups of adjacent phases of the ISE winding, which are used in industrial CBE samples for medium- and high-power generators (variant 1b) and in the bigarm exciton pilot for powerful synchronous motors figure 1, c. In DG pathogens under conditions of restriction on the outer diameter of the inductor, it is advisable to apply a 4-phase double-row winding (figure 1, a) [1]. This winding is placed in the notch-groove layer, which is formed by removing from the circuit of figure 1, c of the outer teeth and teeth having a small width.





**Figure 1.** - Various variants of the construction of the tooth-groove layer of the pole piece and methods for constructing the ISE winding.

## 2. Formulation of the problem

The purpose of the experiment is to find the inductive phase resistance for three different configurations of the tooth-groove layer. The investigation of the magnetic field was carried out by the finite element method.

The current density for all three variants is  $j = 220 \text{ A/m}^2$ . The number of turns in the phase  $w = 12$ . The number of turns in one groove for the variant of figure 1, b is 2 times more than for other options. The winding is concentrated  $q = 1$ . The frequency of the inductor EMF is  $f = 1000 \text{ Hz}$ . The air gap is  $\delta = 0$ . The length of the machine is  $l = 50 \text{ mm}$ . The magnetic flux on the back of the inductor is equal to 0 V/m.

In order to simplify the task, the coils of each phase are modeled in such a way that one equivalent loop is located in the groove instead of the calculated number of turns. The cross-section of the equivalent loop is such that the coil creates the same MDS as for a real number of turns.

The calculation of the coefficient of the channel conductivity of the scattering was carried out for the circuits in figure 1, a and figure 1, b by a numerical method and analytic for the circuit in figure 1, b, separately for each section of the groove of each configuration of the tooth-groove layer. We break each slot into 2 sections: 1) the space occupied by the coil of the investigated phase with a given current density 2) the rest of the slot, the field lines of force in which do not pass through the regions occupied by the coils of the phase under investigation.

To determine the conductivity by the numerical method for the circuits in figure 1, a and figure 1, b, a calculation of the magnetic field of the slot scattering of the NRWR was performed. The problem is solved by a pair of poles. Since a mutually inductive coupling between adjacent phases over the scattering field is practically absent in the 4-phase SNR [5], the calculation of the field is made when feeding only the investigated phase.

In accordance with the pattern of the magnetic field, the groove was divided into tubes of equal magnetic flux (regions bounded by two adjacent lines of force). Based on the formula for calculating the coefficients of conductivity of slotted scattering:

$$\lambda_s = \int_0^{h_s} \left( \frac{S_x}{S_s} \right)^2 \frac{dx}{b_x} \quad (1)$$

where  $S_s$  and  $S_x$  are the cross-sectional areas of the groove occupied by the winding conductors;  
 $b_x, l_x$  - width and length of the power line, respectively.

The conductivity calculation method is similar to the method described in [3].

By analytical method, the coefficient of slot conductivity of scattering was determined as the average of the sum of the slots filled with a coil of one phase; The calculation was carried out in the middle of the groove for the circuit in Figure. 1b. by the standard formula [4]:

$$\lambda_s = \lambda_{s1} + \lambda_{s2} \quad (2)$$

$$\lambda_{s1} = \frac{h_s}{3b_s} \quad (3)$$

$$\lambda_{s2} = \frac{h_k}{b_s} \quad (4)$$

where  $\lambda_{s1}$  - the conductivity of the first section;  $\lambda_{s2}$  - groove conductivity of the second section;  $h_s$  – the depth of space occupied by the coil;  $h_k$  - the thickness of the wedge, the height of the slot, the insulation under the wedge;  $b_s$  - is the width of the groove.

In the case of the circuit in figure 1, a, an analytical method for determining the coefficient of slot conductivity of scattering was not used, since there are no analytical expressions for the side of the coil in the interpolar space.

The coefficient of magnetic conductivity of the frontal scattering and the coefficient of magnetic conductivity of the scattering along the crowns of the teeth were calculated by the standard formulas [4].

The calculation of the inductive scattering resistance was carried out according to the standard formula [4]:

$$x_\sigma = 15,8 \frac{f}{100} \left( \frac{w}{100} \right)^2 \frac{l}{pq} (\lambda_s + \lambda_l + \lambda_k) \quad (5)$$

The calculation of the inductive resistance of mutual induction was also carried out by analytical and numerical methods.

Analytic method, the resistance of mutual induction was calculated by the formula:

$$x_m = 2\pi f w^2 \lambda_m \quad (6)$$

$$\lambda_m = \mu_0 \frac{y_k}{8\delta''} \quad (7)$$

where  $\lambda_m$  is the coefficient of magnetic conductivity of mutual induction;  $y_k$  is the step of the coil;  $\delta''$  -

equivalent air gap.

By numerical method, the resistance of mutual induction was calculated by formula (6):

$$\lambda_m = \frac{\Phi_m}{F} \quad (8)$$

where  $\Phi_m$  is the flux of mutual induction;

F is the magnetizing force.

Inductive resistance of the winding phase was calculated by the formula:

$$x_{ph} = x_\sigma + x_m \quad (9)$$

### 3. Results and Conclusions

The pattern of the magnetic scattering field is shown in figures 2, 3 and 4, the magnetic field of mutual induction - in figures 5, 6 and 7 for the circuits in figure 1, a, figure 1, b and figure 1, c respectively.

The results of calculating the coefficient of shear conductivity of scattering are presented in Table 1. The results of calculating the inductive resistances are presented in Table 2.

**Table 1.** Results of calculation of the coefficient of slot conductivity of scattering.

Scheme	$\lambda_{s1}$		$\lambda_{s2}$	
	Analyte. method	Numbers method	Analyte. method	Numbers method
Figure 1, a	-	0,425	-	0,459
Figure 1, b	0,407	0,507	0,56	0,468
Figure 1, c	0,674	0,659	0,577	0,597

Based on the calculations in Table. 1, the use of standard formulas for calculating the coefficient of shear conductivity of scattering introduces a large error. In this regard, it is necessary to introduce a correction factor (see Table 3) for each section of the groove.

It is advisable to write the expression for the calculation of the conductivity of slotted scattering in the following form:

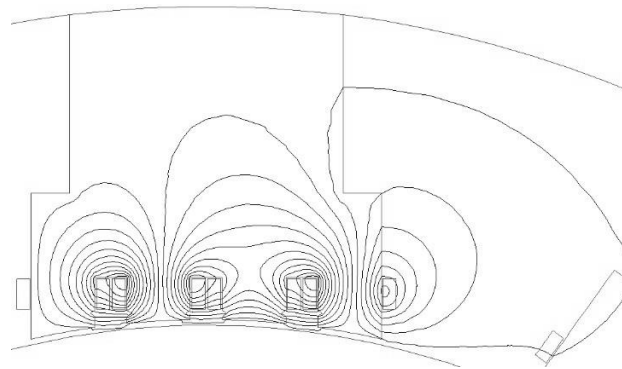
$$\lambda_s = k_{c1} \frac{h_s}{3b_s} + k_{c2} \frac{h_k}{b_s} \quad (10)$$

where  $k_{c1}$  is the correction factor for section 1;  $k_{c2}$  is the correction factor for section 2.

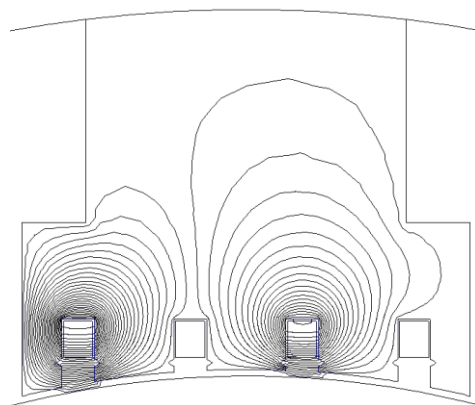
As studies have shown, the application of the standard formula for calculating the slot conductivity of scattering for the circuit in Figure. 1b, which was used in the biharmonic exciter, the use of the standard formula does not introduce a significant error and it can be used to calculate the coefficient of

magnetic conductivity of slotted scattering without introducing correction coefficients. The calculation of the conductivity of the slot scattering for the circuit in Figure. 1b can be performed only with the introduction of correction factors in the standard formula. For the circuit in Figure. 1a it is necessary to obtain an analytical expression for the coefficient of slot conductivity of scattering for the side of the coil located in the interpolar space.

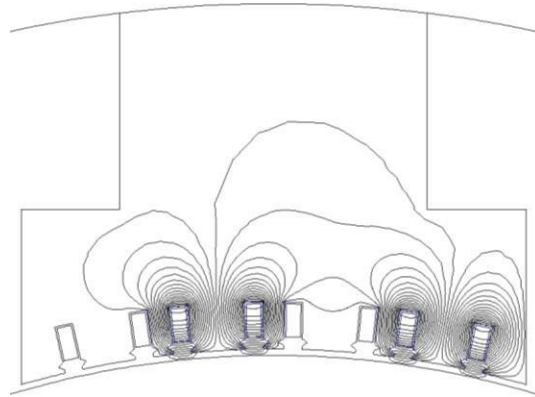
The calculation of the inductive resistance of mutual induction showed that the difference between the analytical method and the numerical method is insignificant. Also, the calculation showed that the inductive resistance of mutual induction is smaller than the inductive scattering resistance. The mutual resistance of the circuits in Figure. 1a and Figure. 1c to the resistance for the circuit in Figure. 1b, determined analytically, do not differ much from analogous relations determined by numerical methods (see Table 4).



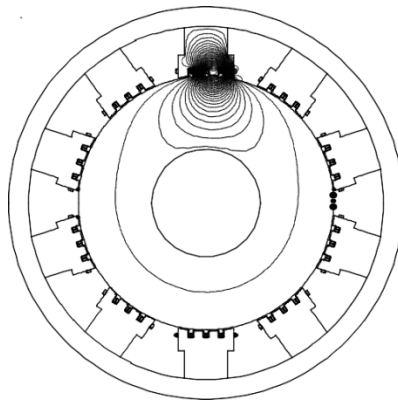
**Figure 2.** Scattering magnetic field pattern.



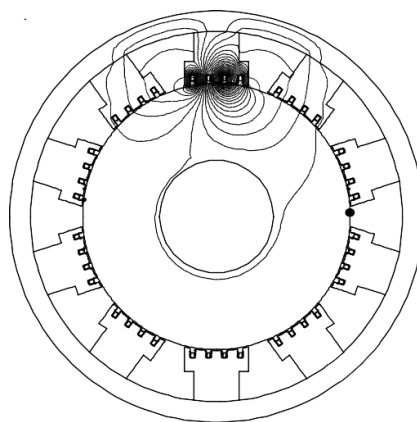
**Figure 3.** Scattering magnetic field pattern.



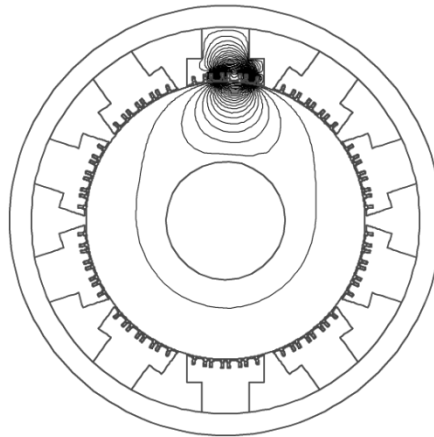
**Figure 4.** Scattering magnetic field pattern.



**Figure 5.** A picture of the magnetic field of mutual induction.



**Figure 6.** A picture of the magnetic field of mutual induction.



**Figure 7.** A picture of the magnetic field of mutual induction.

**Table 2.** Results of calculation of inductive resistances.

		Figure 1, a	Figure 1, b	Figure 1, c
$X_{\sigma}$	Analyte method	-	0,039	0,040
	Numbers method	0,039	0,0399	0,041
$X_m$	Analyte method	0,011	0,022	0,0079
	Numbers method	0,011	0,024	0,0074
$X_{ph}$	Analyte method	-	0,061	0,0479
	Numbers method	0,05	0,0639	0,0484

**Table 3.** Correction factor value.

Symbol	Site	Value
$k_{c1}$	Site 1	1,246
$k_{c2}$	Site 2	0,836

**Table 4.** Ratio of inductive resistances of mutual induction.

Method	$X_{m1a}/X_{m1b}$	$X_{m1c}/X_{m1b}$
Analytical method	0,5	0,36
Numbers method	0,46	0,31

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