An Approach to Permeance Calculation of a Teeth Zone of a HIA Using MATLAB

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***Abstract*— The paper shows an approach to determining the permeance of the teeth zone of a Homopolar Inductor Alternator (HIA) using MATLAB tools. A HIA with a concentrated type armature winding is considered. Only the ratios of certain sizes of the tooth zone are used as initial data, which makes it possible to preliminarily evaluate the main performance indicators without resorting to the design of the entire generator. The results are presented in conditional units, which are convenient to compare with performance indicators of other teeth zones.**

Keywords—homopolar inductor alternator; HIA; teeth zone; permeance, method

I. Introduction

The principle of operation of a Homopolar Inductor Alternator (HIA) with concentrated armature coils (i.e. armature coils are on the stator teeth) is based on an alternation of the magnetic permeance of the air gap due to the alternation of the rotor teeth and slots during rotor rotation. Since the magnitude and form of the EMF induced in the armature winding is primarily determined by the alternation in the permeance in the air gap, the main characteristics of a HIA primarily depend on the parameters of the teeth zone. Typically, in the process of designing a HIA, these parameters preliminary are considered, after which they can be repeatedly changed in the process of optimizing the design of the generator.

As a rule, when designing a HIA, the theory of conventional synchronous generators with a salient-pole rotor is used (i.e. two-reaction theory), where it is assumed that the rotor tooth is the N pole, and the rotor slot is the S pole. This approach is classical [1]–[3], but it [4]–[6] or its slightly modified version [7] is still in use. This approach makes it possible to speed up the process of calculating a HIA but makes it impossible to use the advanced features of the tooth zone of a HIA that are not available in conventional synchronous generators. The main limitation of the application of the two-reaction theory is that the magnetic circuit must be symmetrical with respect to the longitudinal and transverse axes, i.e. in HIA the width of the rotor slot must be equal to the width of the rotor tooth.

Since the principle of operation of a HIA is based on an alternations in the magnetic flux through the armature winding due to an alternating permeance of an air gap, it is advisable to perform the designing of a HIA based on the permeance calculation of the air gap. This is especially important in generators with a tooth-type armature winding, where the permeance of the stator slots (in which the armature winding fits) can be neglected due to the large depth of these slots, and therefore it can be assumed that the entire magnetic flux passes only through the stator teeth. The approach with the calculation of the air gap permeance would provide the opportunity to more completely use all the advanced features of the teeth zone of a HIA, including the possibility of not only changing the longitudinal [8] or transverse [4], [9], [10] shapes of the rotor teeth, but also the introduction of overlays / overlaps between the teeth of the rotor and the stator [11] (overlays can occur when the width of the tooth differs from half the pole division of the rotor and is possible only in generators with a tooth-type armature winding).

In a contrast to the application of the two-reaction theory in a HIA designing, determining the air gap permeance is a time-consuming process, and therefore developers either use analytical expressions or tables (derived for the most common tooth zone shapes) or resort directly to modeling a three-dimensional generator model using the finite element method, followed by multiple design optimization, as, for example, in [7], [12].

A method for approximate calculation of the air gap permeance was given in [9]. This method allows to operate with teeth of any shape. The advantage of the method [9] is the simplicity of the calculations with the possibility of obtaining the final result in conventional units (both the magnitude of the EMF and its sinusoidality, as well as the sizes of the tooth zone are given in conventional units), which can later be converted into real measurement units. The disadvantage is that in the method [9] it is assumed that the field is plane-parallel, which in reality is far from always the case. On the other hand, the use of more complex models of the magnetic field would greatly increase the complexity both in the calculations and in the development of tools for their implementation.

In this paper, the reader is presented with an approach to calculating the permeance of the tooth zone of a HIA with a concentrated, tooth-type armature winding. The *pdetools* tool of the MATLAB is used as a calculation tool, which greatly simplifies the process of implementing the calculation method, and also makes this method available for repetition by readers. The results of the calculations are the values and form (determined by the harmonic composition) of the magnetic flux and the no-load EMF of the armature turn. All values are expressed in conditional units, which makes it possible not to consider particular dimensions and parameters of the generator at the stage of preliminary design. Note that the results obtained in conventional units for various teeth zones can be directly compared with each other, which provides ample opportunities for comparing different tooth zones with each other without considering generator properties, such as rated power, speed, etc.

II. Determination of the Key Performance Indicators of a Teeth Zone of a HIA

A Homopolar Inductor Generator (HIA) with a tooth-type concentrated armature winding is considered. This type of armature winding has advantages in generators of low and medium power [3]. The armature winding of the tooth-type is made in the form of coils mounted on the stator teeth. That is, half of the coil is in the stator slot to the right, and the second half is in the stator slot to the left of the corresponding stator tooth. A fragment of the package of such a generator is shown in Fig.1. The field (excitation) winding of the ring type is also mounted on the stator and is located either between the stator packs (in the case of a two-pack generator) or closer to the technological gap on the flange housing (in the case of a single pack generator). In both cases, the field winding on the illustration of the cross section of the teeth zone in Fig.1. will not be visible.

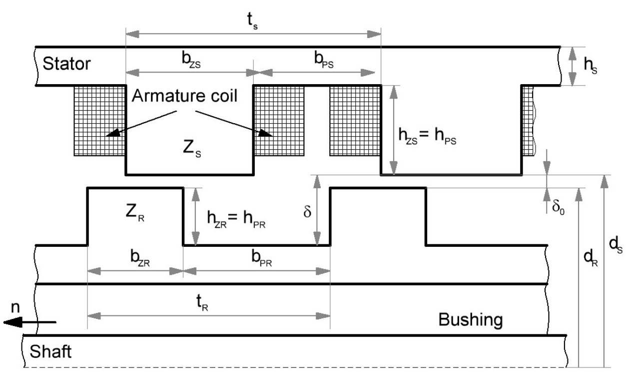

Fig. 1. Sweep of the teeth zone of a HIA with concentrated-type armature winding (one pack is shown)

The magnetic flux Φ, created by the MMF of the field winding, within the rotor pole pitch is closed through the stator, then through the stator tooth / teeth, then through the air gap between the stator tooth / teeth and the tooth-slot zone of the rotor, and then from the rotor through the technological gap (single-package generator) or the tooth-slot zone of the second stator package (two-pack generator) and then is returned to the stator. When the rotor rotates, the air gap δ under the stator tooth alternates due to the alternation of the teeth and slots of the rotor under the stator tooth. That is, the air gap varies from δ_0 (the stator tooth is opposite the rotor tooth) to $\delta_0 + h_{ZR}$ (the stator tooth is opposite the rotor slot). As a result, the air gap permeance Λ alternates, where Λ_{MAX} occurs when the gap is equal to δ_0 (i.e., rotor tooth opposite the stator tooth), and Λ_{MIN} (i.e., when rotor tooth opposite the stator slot). The modulation of permeance $\Delta\Lambda = \Lambda_{MAX} - \Lambda_{MIN}$ causes the corresponding magnetic flux pulsations $\Delta\Phi = \Phi_{MAX} - \Phi_{MIN}$, and since the magnetic flux closes through the stator teeth, then, accordingly, the flux linkage with the armature winding too $\Delta\Psi = \Psi_{MAX} - \Psi_{MIN}$. Note that the flux through the stator slot can be neglected since, as a rule, $h_{ZS} \gg h_{ZR}$.

Alternating, due to the rotation of the rotor, the magnetic flux through the stator teeth ΔΦ induces an EMF in the turns of the armature coils located on the stator teeth. Accordingly, the magnitude and form of the no-load EMF is determined by the derivative of the magnetic flux Φ. Thus, the problem is reduced to determining the value of the magnetic flux depending on the rotor angle of rotation α.

If we neglect the permeance of the stator slot, then the magnitude of the magnetic flux through the rotor tooth will be determined by two factors: field winding MMF and permeance of the magnetic circuit. The iron permeability, from which the magnetic circuit is made of, is several thousand times greater than the air permeability in the gap *δ*. For this reason, further we will assume that the permeance of the magnetic circuit is determined by the air gap permeance, which is between the stator tooth and the tooth-slot zone of the rotor.

The permeance Λ of the air gap alternates due to the rotation of the rotor. That is, there is a dependence of Λ on the angle of rotation α of the rotor, where α can be conveniently expressed in electrical degrees (i.e. within the rotor tooth pitch t_R^E the $\alpha^E = (0^E \div 360^E)$). Since the value of magnetic induction is directly proportional to Λ, the problem is reduced to determining the dependence $\Lambda = f(a^E)$.

III. Permeance Calculation of a Teeth Zone

The main problem for the implementation of the above solution is to obtain the dependence $\Lambda = f(a^E)$. In turn, the main problem of the analytical solution is the calculation of the magnetic field at the moment when the stator tooth partially overlaps the rotor tooth and slot. To simplify the solution of the calculation, we will use the *pdetools* tool available in the MATLAB package. Note that the *electromagnetic solution* becomes available since MATLAB version R2021a.

To begin with, note that the curvature of the surface and the slope of the rotor slot sides (caused by the fact that the rotor has a cylindrical shape) can be ignored if the rotor has a large number of teeth. So, for generators with the number of rotor teeth $Z_R > 4$, the use of a tooth zone sweep instead of a real rounded structure will lead to an error in determining the EMF value, not exceeding 0.5% [13]. For this reason, further we will use a linear sweep of the tooth zone.

Further, let's assume that the teeth have a large axial length *l* in relation to their other dimensions, which allows to ignore the end buckling of the magnetic field, and therefore the problem can be solved in a two-dimensional domain.

Also let's assume that the magnetic circuit is not saturated. This convention makes it possible not to set the value of the field winding MMF during the analysis.

To get rid of the need to consider the layout of a particular generator, let's assume that the permeability of air is negligible compared to the permeability of iron, and therefore the entire flux closes through the stator tooth, and leakage fluxes can be neglected.

An elementary section of the tooth zone is considered, i.e. section within one rotor tooth division t_R of a rotor, i.e. one stator tooth and one rotor tooth-slot. Since the results are obtained in conditional units, there is no need to preliminary set exact values for the dimensions of the tooth zone.

When creating the geometry of a tooth sweep, it is necessary to predetermine the relationships, such as: b_{ZS}/t_R; b_{ZR}/t_R; h_{ZR}/δ_0. A 2D model is created according to these relationships, where the size absolute values are not important. The magnetic circuit should be created symmetrical to minimize the effect of changing the length of the magnetic circuit of the model due to the movement of the rotor tooth. The field winding should also be divided into two coils: one for each magnetic circuit path. It is desirable to make the side of the field coil so that its axial length is at least twice as large as its height. The cross-sectional area of the field coil, as well as the magnitude of the current density in it, do not matter. The field coils should be located as far as possible from the end of the rotor tooth.

To minimize the influence of the leakage flux, the relative magnetic permeability of the magnetic circuit should be chosen to be several thousand greater than the permeability of the air, which will be demonstrated in the next chapter.

Next, a magnetostatic calculation of the created model is performed. In this case, the average value of the magnetic induction in the cross section of the stator tooth is calculated in the place where the armature winding coil is usually located. The magnetostatic calculation is repeated for different positions of the rotor tooth relative to the stator tooth within the rotor tooth pitch t_R, i.e. $\alpha^E = (-180^E \div +180^E)$. Thus, the dependence of the value of magnetic induction in the core of the armature coil on the angle of rotation of the rotor is obtained (1).

$$B_{arm} = f(\alpha^E) \quad (1)$$

Recall that the absolute value of the magnetic induction B_{arm} does not make sense, since many parameters of the magnetic circuit were not initially set, and the parameters of the two-dimensional model are not equivalent to a generator of any real design.

Now let's determine the value of the specific magnetic permeance Λ of the air gap. It is known [14] that the permeance of the gap can be determined as (2).

$$\Lambda = S\mu/\delta \quad (2)$$

Taking the cross-sectional area of the rotor tooth pitch within tooth division as $S_{t_R} = 1$, as well as the relative magnetic permeability of the medium as $\mu = 1$, we can obtain the value of permeance, expressed in conditional units of permeance Λ.c.u. as (3), for the case when the rotor tooth is in front of the stator tooth.

$$\Lambda = \frac{1}{\delta} \cdot \frac{b}{t_R}, \Lambda.c.u. \quad (3)$$

where $b = \min(b_{ZR}, b_{ZS})$ – consider tooth cross section with respect to rotor tooth pitch area.

Note that (2) is valid only for the case when the gap is formed by two parallel planes and the gap is many times smaller than the width of the teeth. So, at $\delta/b \geq 0.04$, the error in determining the magnetic permeance according to (2)-(3) will be ≥10% [14].

Using (3), the value of the maximum specific magnetic permeance $\Lambda_{\alpha=0^E}$ can be calculated for the moment when the rotor tooth is located opposite the stator tooth, i.e. for $\alpha = 0^E$. Note that the value of the magnetic induction $B_{arm_{\alpha=0^E}}$ obtained at $\alpha = 0^E$ will be determined by the given specific permeance $\Lambda_{\alpha=0^E}$.

Since the value of the induction is directly proportional to the magnetic permeance, then the remaining values of Λ at $\alpha \neq 0^E$ can now be calculated as (4), also in conditional units.

$$\Lambda_{\alpha^E} = B_{arm\_\alpha^E} \cdot \frac{\Lambda_{\alpha=0^E}}{B_{arm_{\alpha=0^E}}}, \Lambda.c.u. \quad (4)$$

Thus, according to the dependence $B_{arm} = f(\alpha^E)$ obtained as a result of simulation, the dependence $\Lambda = f(\alpha^E)$ is determined.

Once the dependence $\Lambda = f(\alpha^E), \Lambda.\text{c.u.}$ is obtained, the determination of the harmonic components of the armature no-load EMF can be found as shown in [9].

A. *Determination of the Influence of Medium Permeance on the Calculation Results*

The value of the relative magnetic permeability μ affects the resistance of the magnetic circuit, and, accordingly, the value of its magnetic permeance. The greater the core permeance in relation to the air permeance, the smaller the scattering of the magnetic field, and, accordingly, the parasitic connections between the field coil and the rotor and stator teeth.

The structure of the two-dimensional model of the magnetic circuit for $b_{ZR} = b_{ZS} = 0.5 \cdot \tau_R$ teeth zone is shown in Fig.2. The technical gap between the stator and rotor is not shown due to the fact that, firstly, it does not alternates during the rotation of the rotor, and secondly, it has a disproportionately large area of the magnetic contact compared to the area of magnetic contact between the stator tooth and the tooth-slot division of the rotor, and therefore its influence can be ignored.

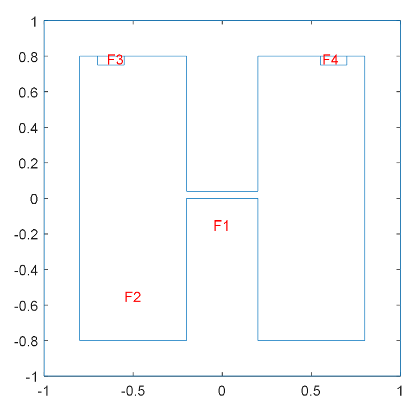

Fig. 2. Structure of the Magnetic Circuit: F1 – iron, F2 – air, F3,F4 – field coils

Successively moving the rotor tooth (lower tooth in Fig. 2) relative to the stator tooth (upper tooth in Fig. 2) we obtain the dependence of the magnetic induction on the rotor tooth position.

The typical value of the magnetic permeability of air is $\mu_{air} = 1$, and of silicon steel $\mu_{iron} = 4 \cdot 10^3$. We will also carry out the calculation for cases when $\mu_{air} = 1$, and $\mu_{iron} = 4 \cdot 10^3 \div 1 \cdot 10^{10}$, i.e. $\mu_{iron} \gg \mu_{air}$. All parameters are given in Table 1. The value of the magnetic inductance is found by calculating the average value in the stator tooth, i.e. in the place where the armature coil is usually located. The calculation results are shown in Fig. 3.

TABLE I. THE PARAMETERS FOR THE SIMULATION TO DETERMINE THE RESULTS DEPENDENCE ON THE CORE PERMEANCE

Parameter	Values for various rotor slot depths	
	"extremely deep" rotor slot	*"real" rotor slot*
μ_{air}	1	1
μ_{iron}	$4 \cdot 10^4 \div 1 \cdot 10^{10}$	$4 \cdot 10^4 \div 1 \cdot 10^{10}$
Arm. coil coordinates	On stator tooth y=0.7÷0.75	On stator tooth y=0.7÷0.75
b_{ZR}	$0.5 \cdot \tau_R$	$0.5 \cdot \tau_R$
b_{ZS}	$0.5 \cdot \tau_R$	$0.5 \cdot \tau_R$
δ_0/b_{ZR}	0.0125	0.0125
h_{ZR}/δ_0	800	25
b_{ZR}/h_{ZR}	0.1	3.2

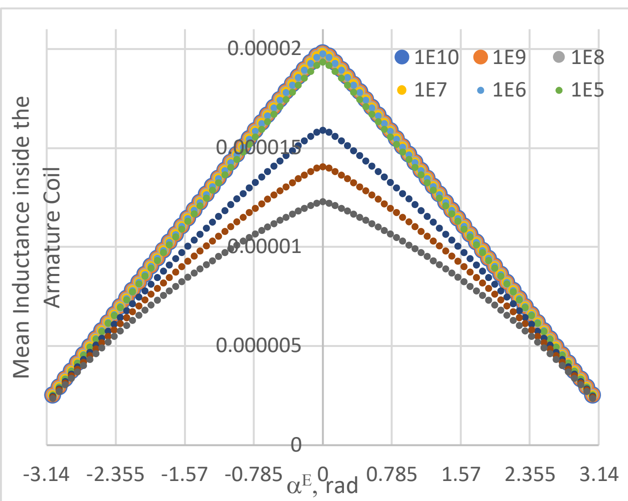

Fig. 3. Mean magnetic inductance vs rotor rotation angle of elementary tooth section of a HIA with various iron magnetic permeability and "deep" rotor slot

As can be seen, the increase in the difference between the magnetic permeability of the air and the magnetic circuit has a noticeable effect, especially noticeable at the moment when the rotor tooth is opposite the stator tooth (α^E=0, el.deg.). Let's consider the structure of the magnetic field for the position α^E=0 in more detail in Fig. 4 and Fig. 5 obtained for various μ_{iron} values. In both figures, for better clarity, the maximum value of the induction was normalized, reducing the maximum value of the induction by a factor of five hundred.

As can be seen, the stray field of the field coils, as well as the parasitic connections between the stator tooth and the field coils, is noticeably smaller in the case when $\mu_{iron} \gg \mu_{air}$ (see field in Fig. 5 compared to Fig. 4).

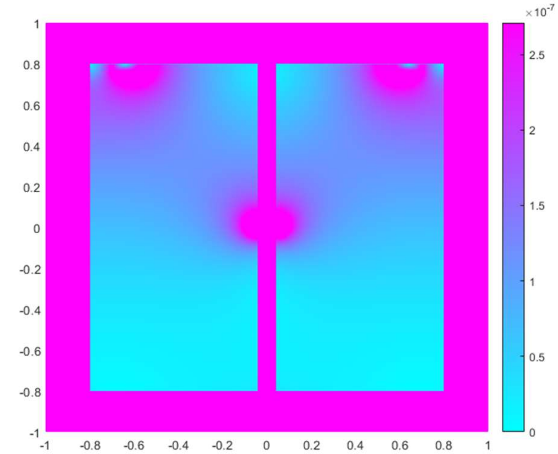

Fig. 4. Magnetic flux density when rotor and stator tooth are in front of each other (α^E=0) and μ_{iron}= $4 \cdot 10^4$

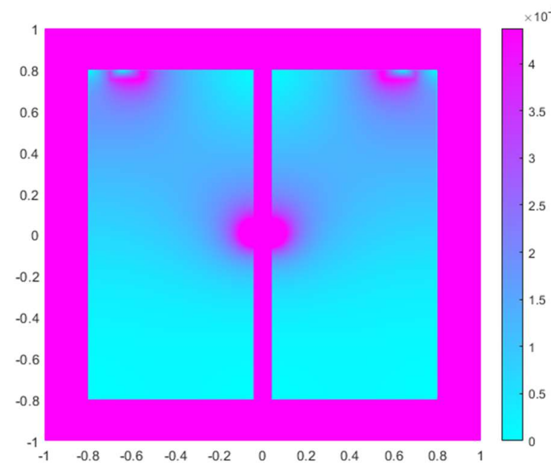

Fig. 5. Magnetic flux density when rotor and stator tooth are in front of each other (α^E=0) and μ_{iron}= $1 \cdot 10^{10}$

Now let us make sure that an excessive increase in the magnetic permeability of the magnetic circuit did not affect the ability to determine the permeance of the rotor slot. To do this, let's reduce the size of the rotor slot to $25\delta_0$ to make the slot depth close to the real one typically used in HIAs. The results are shown in Fig. 6.

Obviously, with a decrease in the depth of the rotor slot $h_{ZR} = h_{PR}$, its permeance increases, thus the magnetic induction at the moment when the stator tooth is located opposite the rotor slot (α^E= -180, el.deg.) increases too. This can be seen in Fig. 6 were compared to Fig. 5 the induction at $\alpha^E = \pm\pi, rad$ increased by 1.6 times. In turn, the influence of the magnetic permeability of the magnetic circuit remained the same: with an increase in $\mu_{iron} \geq 1 \cdot 10^6$, the influence of stray field becomes imperceptible. For clarity, the structure of the magnetic field for the moment when the stator tooth is opposite the rotor tooth is shown in Fig. 7.

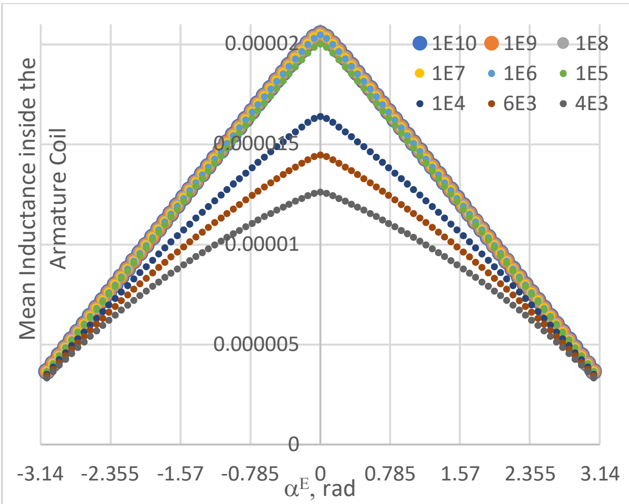

Fig. 6. Mean magnetic inductance vs rotor rotation angle of elementary tooth section of a HIA with various iron magnetic permeability and typical rotor slot depth

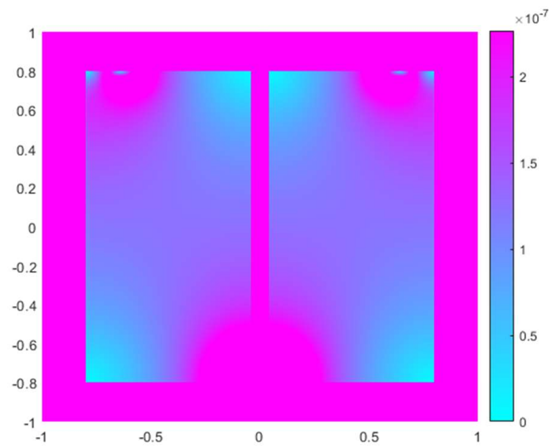

Fig. 7. Magnetic flux density when rotor and stator tooth are in front of each other (α^E=0) and μ_{iron}= $1 \cdot 10^{10}$ for a typical rotor slot depth

Recall that the structure shown in Fig. 2 is not an equivalent magnetic circuit of an inductor generator, if only because in a HIA the field coil is located on the end bell, and not on the sides of the stator teeth, and therefore parasitic connections between the stator tooth and the field winding in the cross section of the generator cannot occur at all. For this reason, to minimize parasitic connections between the field coil and the rotor teeth, the value of the magnetic permeability of the magnetic circuit should be chosen as large as possible, and air - as little as possible. As can be seen from Fig. 3 and Fig. 6, to ensure that the condition $\mu_{iron} \gg \mu_{air}$ is met, $\mu_{iron} \geq 1 \cdot 10^6$ should be selected.

B. Errors in the Maximum Permeance Calculation

Calculating the value of the maximum permeance $\Lambda_{\alpha=0^E}$, Λ. c. u. (for the case when the rotor tooth is in front of the stator tooth), we assume that the size of the gap is negligibly small in relation to its width, and therefore the field is plane-parallel, thus (2) can be used. In a real design, this is not entirely true. Let us determine the difference between the values of the air gap permeance, determined by (3) with the value calculated considering the buckling of the magnetic field using the electromagnetic solution in MATLAB *pdetools*. The structure of the two-dimensional model of the magnetic circuit for $b_{ZR} = b_{ZS}$ is shown in Fig. 2, and the field structure for the case when $\delta_0/b_{ZR} = 0.1$ is shown in Fig. 8.

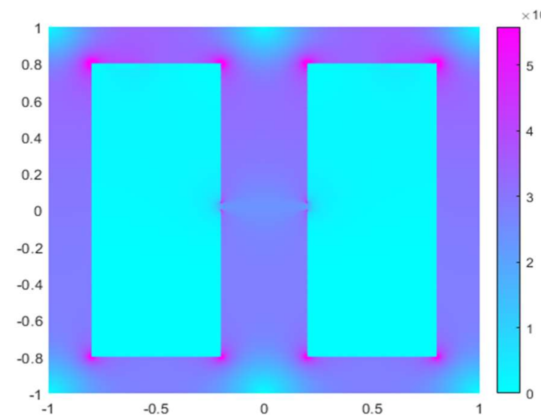

Fig. 8. Magnetic field pattern in the air gap when $\delta_0/b_{ZR} = 0.1$

Having calculated the values of the $\Lambda_{\alpha=0^E}$ according to (3) for various gaps δ, it is possible to determine the error in determining the permeance by (4) using result from (3), associated with ignoring the buckling of the magnetic field. In turn, (4) uses the results of the calculation of the electromagnetic solution, and therefore takes into account the buckling of the magnetic field, but requires a known value $\Lambda_{\alpha=0^E}$, which itself is determined by (3) for the air gap δ_0. Since the value δ_0 cannot be set infinitely small, the value $\Lambda_{\alpha=0^E}$ was determined by (3) for the smallest gap $\delta_0 = 0.1\ mm$, i.e. for $\delta_0/b_{ZR} = 0.00025$. The values of the error in determining the permeance according to (3) are shown in Fig. 9.

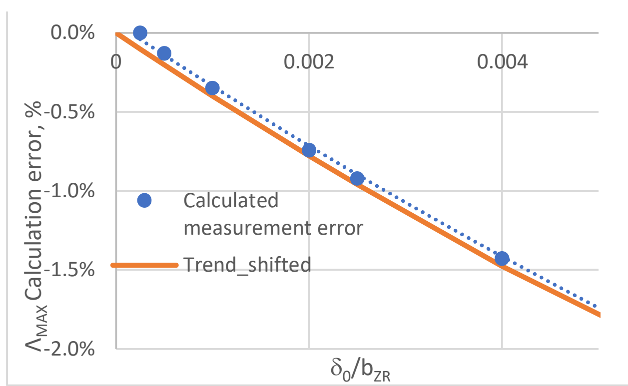

Fig. 9. Estimation of calculation error for (3)

Further, to eliminate the influence of the fact that it was not possible to obtain the value of the permeance of the air gap at $\delta_0 = 0$ (i.e. at $\delta_0/b_{ZR} = 0$) for the error estimation, the error values were approximated by a 6th degree polynomial, after which the curve was shifted so that the error was equal to zero at the point $\delta_0/b_{ZR} = 0$. The results are also shown in Fig. 9.

The dependence of the correction factor K_Λ for (3) on δ_0/b_{ZR} is shown in Fig. 10. Thus, the error in determining $\Lambda_{\alpha=0^E}$ can be taken into account when performing calculation (3) to obtain the value of $\Lambda_{\alpha=0^E}$ using the error correction factor from Fig. 10, so (3) should be written as (5).

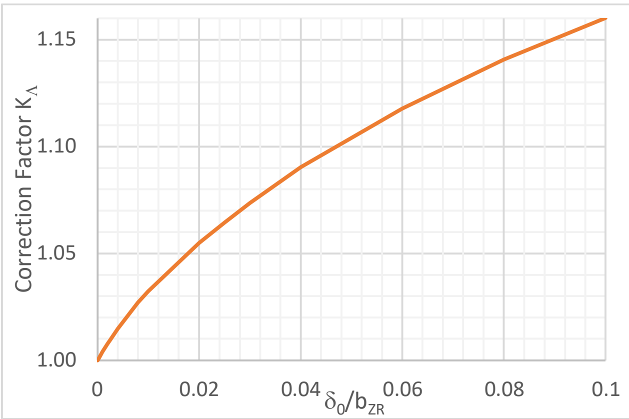

Fig. 10. Correction factor K_Λ for the maximum permeance calculation

$$\Lambda_{\alpha=0^E} = \frac{1}{\delta_0} \cdot \frac{b}{t_R} \cdot K_\Lambda, \Lambda.c.u. \tag{5}$$

IV. Conclusion

It is proposed to use an air gap permeance in the HIA calculations instead of two-reaction theory to be able fully utilize advanced configurations of the teeth zone of a HIA. The paper shows an approach to calculating the permeance of the air gap of a HIA with a tooth-type armature winding. The proposed approach makes it possible to obtain the dependence of the permeance of the stator tooth depending on the angle of rotation of the rotor using the widely used MATLAB tool. The proposed approach complements [9], which, in turn, allows to set the parameters of the teeth zone in the form of ratios, and therefore, for the calculation, it is not necessary to predefine (and therefore to pre-calculate) exact geometric dimensions of the generator.

The main disadvantage is that to implement the proposed approach, a paid MATLAB tool of version 2021a or higher with *pdetools* installed is used. Also, the limitations are that the end buckling of the field is not taken into account (i.e., the axial length of the rotor must be noticeable greater than the width of the teeth and slots of the rotor), and it is also assumed that the magnetic circuit is not saturated, which eliminates the need to pre-calculate the magnetic circuit and field winding, but may affect the final result if the machine is operated with high saturation.

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