Interrelation and Selection of Teeth Zone Parameters of a Homopolar Inductor Alternator

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Abstract— **This paper is devoted to the problem of choosing the parameters of the teeth zone in order to speed up the process of designing inductor alternators both for experimental development, virtual models and prototypes. The object of study is a Homopolar Inductor Alternator (HIA) with a concentrated-type armature winding. The paper contains recommendations and relationships for the selection of teeth pitch, rotor teeth height and width, minimum air gap length and bore diameter values.**

Keywords—homopolar inductor alternator; HIA; teeth zone; parameter selection, recommendations

I. Introduction

An important task in the calculation of Homopolar Inductor Alternators (HIA) is the choice of the type of teeth zone and its geometric dimensions. The existing variety of recommendations, as well as a large range of recommended values for the parameters of the teeth zone, makes it difficult to choose the appropriate value for the parameters of the teeth zone. In addition, sometimes the existing recommendations are given without considering the main parameters of a HIA (such as rated power and speed, stator and rotor bore diameter, etc.). As a result, the choice of values for the parameters of the teeth zone is often random, which complicates the process of choosing the optimal values for a particular HIA.

Improving the quality of the choice of parameters of the teeth zone should be carried out taking into account their mutual relationships and linking them to the main parameters of a HIA and technological capabilities of manufacturing facilities. An attempt to solve this problem is the purpose of this paper. The object of the research is an axial three-phase HIA with a uniform teeth zone and a concentrated tooth-type armature winding. The choice of the concentrated-type armature winding is due to its technological advantages for machines of low and medium power [1].

II. Basic Analytical Relationships of the Teeth Zone Parameters of a HIA

The design of the teeth zone of a HIA is determined by a number of interdependent geometric parameters. The geometric parameters are shown in Fig.1, where the fragment of a teeth zone sweep with a rectangular shape of the rotor teeth is illustrated.

Teeth zone parameters can be expressed in linear units, such as meters– t_R, b_{ZR}, b_{ZS}, etc., in geometrical degrees – t°_R, b°_{ZR}, b°_{ZS}, etc., as well as in electrical degrees– t^E_R, b^E_{ZR}, b^E_{ZS}, etc. wherein parameters in electrical degrees are expressed as: $t^E_R=t^{\circ}_R{\cdot}Z_R$; $b^E_{ZR}=b^{\circ}_{ZS}{\cdot}Z_R$; $b^E_{PR}=b^{\circ}_{PS}{\cdot}Z_R$; $t^E_S=t^{\circ}_S{\cdot}Z_R$, etc.

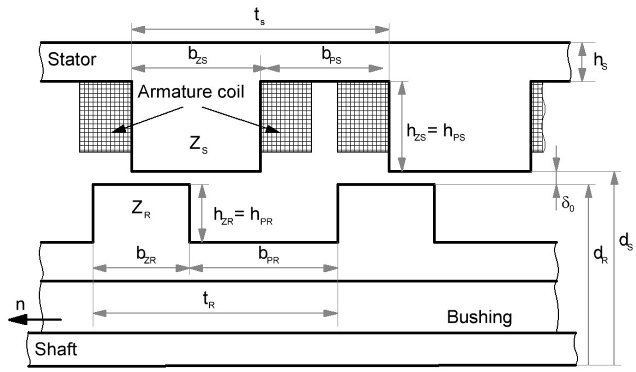

Fig. 1. Sweep of the teeth zone of a HIA with concentrated-type armature winding

On the generator stator, along the inner bore diameter D_S, Z_S stator teeth are evenly located with a tooth pitch t_S. The t_S is generally selected as (1).

$$t_S = t_R(K_S \pm 1/qm) \quad (1)$$

where t_R – rotor teeth pitch; K_S – integer value, selected in accordance to give sufficient space for the armature winding coils to be located in the stator slots; q – number of slots per pole and phase; m – number of phases.

Selecting $q=1$ results in a winding factor $K_W=1$. In turn, the value of t_S must provide the necessary phase shift of the magnetic permittivity of the stator teeth and, accordingly, the phase shift of the EMF in the armature coils to form a multi-phase armature winding.

The number of stator teeth Z_R can be found using (2) [2], [3].

$$Z_S = m \cdot k_Z \quad (2)$$

where $k_Z=1,2,3,\ldots$ - teeth zone divisible factor; $m=3$ – number of armature winding phases.

Generators with such minimum Z_S values are considered elementary. In the final design of the inductor generator, there may be several such elementary machines. In this case, the values Z_S and Z_R must be multiplied by the chosen value $k_Z=2$, *3, 4,…* . Thus, it is possible to create composite, as well as sector generators, and consider the operation of an inductor generator in relation to an elementary inductor generator (where $k_Z=1$).

The number of coils in the armature winding can be defined as (3).

$$N_K = Z_S/m \quad (3)$$

It should be noted that minimizing the values of Z_S and N_K provides an increase in the reliability of a generator.

The number of rotor teeth Z_R defines synchronous properties of a HIA as $f=Z_R n$. Therefore, Z_R depends on the output frequency $f[Hz]$ and the speed of a generator $n[sec^{-1}]$ as in (4).

$$Z_R = f/n \quad (4)$$

The rotor teeth are evenly spaced along the rotor bore D_R with tooth pitch t_R. One EMF alternation period corresponds to the pass of one rotor tooth under the stator tooth, therefore $t^E_R=360^E=const.$ The value of t_R includes the width of the rotor tooth value b_{ZR} and the width of the rotor slot b_{PR}, so $t_R = b_{ZR} + b_{PR}$.

The ratio between them b_{ZR}/b_{PR} can be either greater or less than unity. Studies [4] have shown that the teeth zone with the ratio $b_{ZR}/t_R=0.5$ provides the highest EMF value per armature turn. Thus, if the goal is to obtain the highest EMF value, then we can recommend choosing the width of the tooth and the slot of the rotor as (5).

$$b_{ZR} = b_{PR} = 0.5t_R \quad (5)$$

Without taking into account the value of the minimum radial air gap δ_0 between the stator and rotor teeth, the diameters of the stator and rotor bores can be considered equal ($D_S=D_R=D$), and therefore equality (6) will be upheld.

$$Z_S t_S = Z_R t_R \quad (6)$$

Values Z_S and Z_R define phase shift of the EMF in the armature coils as (7).

$$\gamma^E_K = t^E_S = t^E_R\, {}^{Z_R}/_{Z_S} \quad (7)$$

For three-phase armature winding the γ^E_K value can be 120^E (direct phase sequence) or 240^E (reverse phase sequence). Pitch of winding – from the stator slot to the next stator slot. In this case, the phase of the armature winding is formed by $N_K=Z_S/m$ accordant series-connected armature coils. If $\gamma^E_K=const$ and $q=1$ the winding coefficient will be $K_W=1$.

If f and n are not preliminary defined (for instance, when the generator output is fed to rectifier), then based on the assumed Z_S and γ^E_K values the Z_R can be calculated as (8); otherwise the Z_R value should be defined by (4).

$$Z_R = \gamma^E Z_S/t^E_R = \gamma^E Z_S/360^E \quad (8)$$

The t^E_S value includes stator tooth width b_{ZS} and stator slot width b_{PS}, therefore $t^E_S = b^E_{ZS} + b^E_{PS}$.

The stator slot width b_{PS} and the stator slot height h_{PS} determine the slot area S_{PS} which is used to accommodate the armature winding. The armature winding consists of coils laid on the stator teeth with the location in the open slot of the two sides of the armature winding coils. To ensure the normal placement of coils in the stator slots, it is necessary to ensure the ratio b_{PS}/b_{ZS} as (9) [1].

$$0.5 \le (b_{PS}/b_{ZS}) < 1.2 \quad (9)$$

If the value is selected as $b^E_{PS}=(0.5\div1.2)b^E_{ZS}$, then (9) can be transformed into (10), where the parameters are expressed in electrical degrees.

$$t^E_S = (1.5 \div 2.2)b^E_{ZS} = K_P b^E_{ZS} \quad (10)$$

where $K_P = (1.5\div2.2)$ is stator slot width factor.

The stator teeth with width $b^E_{ZS}=t^E_S-b^E_{PS}$ are evenly spaced along the inner bore of the stator D_S with the step (10), forming an open trapezoidal slot.

To reduce the number of structural elements (and thus to improve the reliability of a HIA), it is advisable to choose a tooth zone where $Z_S<Z_R$, considering the selected values of γ^E_K (8). In this case, the value of b^E_{ZS} can be preselected as $b^E_{ZS} \cong 0.5t^E_R$.. Note that the use of $b^E_{ZS} < 0.3t^E_R$ leads to a significant decrease in the magnetic permittivity of the stator tooth and, as a result, to a decrease in the EMF value. An increase in $b^E_{ZS} > 0.5t^E_R$ causes an increase in the radial dimensions and weight of the machine. In addition, at $b^E_{ZS} << 0.5t^E_R$ *or* $b^E_{ZS} > 0.5t^E_R$ a significant decrease in EMF occurs due to the appearance of overlaps between the stator and rotor teeth [5]. For these reasons, the choice of b^E_{ZS} can be recommended as (11) of the rotor teeth have rectangular shape.

$$b^E_{ZS} = (0.3 \div 0.5)t^E_R = K_b t^E_R \quad (11)$$

where $K_b=(0.3\div0.5)$ – stator tooth factor.

From the equality of values (1) and (7) the Z_R can be expressed as (12).

$$Z_R = Z_S(K_S \pm 1/qm) \quad (12)$$

Then, if number of slots per pole and phase $q=1$ and number of phases $m=3$, we have $Z_R=Z_S(K_S\pm1/3)$.

By setting the Z_S values in accordance with (12), the + or - sign before the fraction $1/qm$, and certain values $K_S=1,2,3,…$, the corresponding value of the number of rotor teeth Z_R and the phase shift γ^E_K is calculated by (8). At the same time, even the value $K_S=2$ already causes some excessiveness in the choice of the width of the stator slot b_{PS}, i.e. condition (12) is violated. An excessive increase in b_{PS} leads to an increase in the diameter of the bores D_S and D_R. An increase in D_S causes an increase in the transverse dimensions of the generator and its weight (which can be partially compensated by a decrease in the height of the stator slot). An increase in D_R provides an increase in Z_R, which in some cases can be a decisive argument. Based on the foregoing, the values of $K_S>2$ can be chosen in special, non-standard situations.

The need to take into account the width of the stator slot $b_{PS}=(0.5\div1.2)b_{ZS}$ when determining t_S subject to condition (7) significantly reduces the possible number of options of elementary teeth zones of a HIA. The parameters of some recommended elementary teeth zones are given in Table 1. The preliminary selected value of Z_R allows to choose the required number of elementary teeth zones when designing high-frequency HIA.

From equalities (1) and (10), as well value of b_{ZS} (11), where $K_b=(0.3\div0.5)$, the (13) equality can be expressed.

$$(K_S \pm 1/qm) - K_b K_P = 0 \tag{13}$$

TABLE I. THE PARAMETERS OF SOME RECOMMENDED ELEMENTARY TEETH ZONES

K_S	Sign	t^E_S	Z_S	Z_R
0.5	+	300	6	5
1.0	+	480	3	4
2.0	-	600	3	5

Then, for a three-phase generator ($m=3$) given the values $K_S=1,2$; $K_P=(1.5\div2.2)$; $q=1$, the most favorable combinations of them can be selected, taking into account the ranges of their values.

Consequently, (6), (11)-(13) can be considered the basic equations for the relationship of interdependent factors of the teeth zone of a HIA with concentrated armature winding. Considering these expressions, the initially preliminary assumed values of Z_S, Z_R, t_S, γ^E, b_{ZS} can be calculkated more accurately.

III. Recommendations on Teeth Zone Parameters Selection

There are various recommendations for choosing the value of the minimum air gap length δ_0 between the rotor tooth and the stator tooth, depending on the bore diameter D, in meters (14) [2], (15) [6], (16) [1], (17) [7]:

$$\delta_0 = (10^{-3} \div 10^{-5})D \tag{14}$$

$$\delta_0 = (1/100 \div 1/400)D \tag{15}$$

$$\delta_0 = D/350 \tag{16}$$

$$\delta_0 = (1/200 \div 1/400)D \tag{17}$$

All the above recommendations have wide ranges of δ_0. This is due to the difficulty of taking into account the influence on δ_0 of such factors as bearing wear, shaft whipping, operating conditions, technological level of manufacturing, as well as the required value of the alternating magnetic resistance of the air gap for the induced EMF. For this reason, the choice of δ_0 must be carried out stepwise, optimizing its value in several iterance.

There are also more strict equations that do not provide for any deviation from the recommended δ_0 value at all: (18) [6], (19) [8].

$$\delta_0 = 0.0012D + 0.10, mm \tag{18}$$

$$\delta_0 = 0.2 + \left(\sqrt{Dl}/500\right), mm \tag{19}$$

All of the above recommendations imply a previously known value of the rotor diameter D. Assuming that the rotor stack length is equal to the bore diameter $l=D$, the value of the D can be selected taking into account the rated power of the generator P_N *[kW]*, EMF frequency f *[Hz]*, rotor speed n *[sec^{-1}]* as (20) [6].

$$D = \sqrt[3]{\frac{P_N}{\pi^2 \cdot n \cdot C_m}} \tag{20}$$

where $C_m = P_N/\pi^2 D^2 l n$ – machine utilization factor, kW/m^2·m/s; l – stator stack length, m.

The C_m values shown in Table 2 are obtained from [6] and were not additionally verified.

TABLE II. MACHINE UTILIZATION COEFFICIENT C_M FOR (20)

n, rpm	Cm					
6'000	-	-	-	3.0	2.2	1.2
3'000	-	-	3.4	2.5	1.6	0.8
1'000	-	3.4	2.8	2.0	1.1	-
500	1.3	1.1	0.8	0.5	-	-
f, Hz	100	500	1000	5000	10000	50000

In case $l \neq D$, the calculated result must be multiplied with the fudge factor: for $l/D=0.25$ the fudge factor is *0.7*; for $l/D=0.5$ is *0.8*; for $l/D=0.75$ is *0.9*.

With such wide ranges of recommended values, the choice of the minimum air gap length δ_0 value is largely random, because of which it is necessary to refine its value several times at the design stage. Meanwhile, the value of δ_0 has a great influence on the magnitude of the EMF in the armature winding, which will be further demonstrated in Fig.3.

To speed up the process of choosing a suitable value of δ_0, and also to reduce the likelihood of unreasonable overestimation of this parameter, one can use the experience of inductor alternators in manufacturing. In Table 3 the technical specification of a number of routine fabrication [1], [9]–[13] and experimental design [3], [6]–[8], [14], [15] HIAs are given. In Table 4 the technical characteristics of theoretically calculated [16]–[19] as well as prototyped [20]–[28] HIAs are given.

According to the values of δ_0 from Table 3, a graph of the dependence of the minimum air gap length δ_0 *[mm]* on the diameter D *[mm]* is plotted. The graph also shows the values of the air gap obtained from (10) and (19) (recommendations [6] and [8] respectively). In addition, the graph shows the values of δ_0 taking place in a number of theoretically calculated [16]–[19], as well as prototyped (i.e. generators that were not prepared for routine production) [20]–[28] HIAs.

TABLE III. SPECIFICATION OF HIAS IN ROUTINE FABRICATION

Source	P_N, kW	n, rpm	F, Hz	D_S, mm	δ_0, mm
[9]	1.5	8000	400	80	0.3
[10]	8	700÷2500	50÷200	290	0.6
[11]	8.95	700	50	290	0.6
[12]	1.7	2200	175	158	0.6

Source	P_N, kW	n, rpm	F, Hz	D_S, mm	δ_0, mm
[1]	8	1000÷4000	100÷400	230	0.7
[1]	8	6000	600	180	0.5
[1]	10	3000	400	245	0.7
[1]	10	3000	400	240	0.7
[13]	0.5	375	400	152	0.4
[14]	4	3000	400	154	0.7
[15]	2.6	2500	500	148	0.6
[6]	100	3000	8000	480	0.8
[3]	50	1500	500	500	1

TABLE IV. SPECIFICATION OF THEORETICALLY CALCULATED / PROTOTYPED HIAS

Source	P_N, kW	n, rpm	F, Hz	D_S, mm	δ_0, mm
[20]	3.6	20000	2600	61	0.5
[21]–[24]	300	8000	660	245	2
[25]	30	14000	700	70	1
[26]	8.3	18000	3000	295	1.5
[27]	?	8000÷12000	2100÷3200	467	1
[28]	?	3000	200	40	0.4
[16]	123	6000	2400	200	0.8
[17]	1.4	60000	2000	38	1.12
[18]	150	4500	5500	428	1.25
[19]	12	400	50	290	0.75

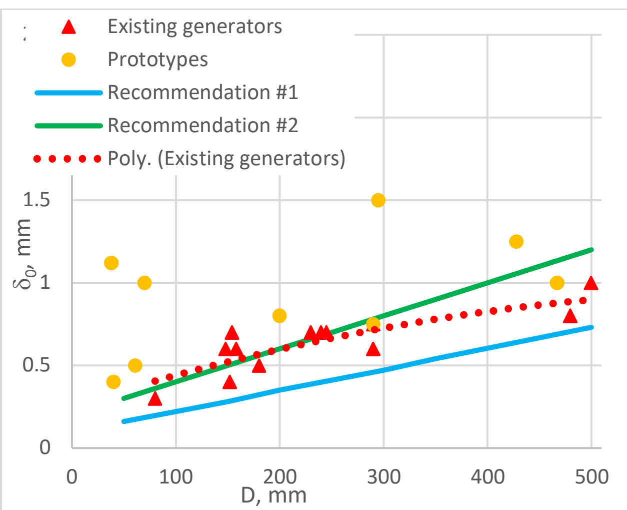

Fig. 2. The dependence of air-gap length δ_0 on stator bore diameter D_S of HIAs

It is obvious that the air gap in several prototypes (yellow round markers in Fig. 2) is chosen with a large overestimation of the δ_0 value. This once again confirms the fact that the choice of the value δ_0 is not unambiguous and obvious. You can also see that the value δ_0 obtained according to the recommendations [6], [8] are underestimated, i.e. too optimistic.

By interpolating the δ_0 values from Table 3, where the δ_0 value was refined at the stage of preparing the generator for production, it is possible to more accurately express the relationship between the diameter D and the air gap δ_0 as (21).

$$\delta_0 = -1 \cdot 10^{-6} D^2 + 2 \cdot 10^{-3} D + 0.25, mm \quad (21)$$

Further, given the values of D and δ_0, it is possible to select the height of the stator teeth. So, for a HIA with $D=(250 \div 400)\delta_0$, the stator tooth height (stator slot depth) can be defined as (22) [2].

$$h_{ZS} = h_{ps} = (0.11 \div 0.22)D \quad (22)$$

In this case, the height of the yoke can be selected from (23).

$$h_s = (0.2 \div 0.3) b_{zs} \quad (23)$$

In contrast to the stator tooth height, the choice of the rotor tooth height h_{ZR} value (which is equal to rotor slot depth h_{PR}) affects the value of the EMF induced in the armature winding. Thus, an increase in h_{ZR} causes a decrease in the magnetic permittivity of the rotor slot and, consequently, its magnetic flux Φ_{min}, which results in an increase in the pulsations of the excitation magnetic flux $\Delta\Phi = \Phi_{max} - \Phi_{min}$ during rotation of the rotor, which, in turn, leads to an increase in the EMF induced in the armature winding. However, an increase in h_{ZR} also leads to an increase in the MMF of the tooth, a decrease in the overall excitation flux, an increase in the weight of the rotor teeth, as well as an increase in the noise and vibrations of the rotor teeth.

Considering the influence of the depth of the rotor slot h_{ZR} (which is equal to rotor tooth height h_{ZR}) on the value of the EMF induced in the armature winding, it is possible to recommend the values $h_{ZR} = h_{PR}$ based on the value of the width of the rotor slot b_{PR} as (24) [29]. If D is previously unknown, $h_{ZR} = h_{PR}$ can be selected depending on the air gap length δ_0 as (25) [30] (for a rectangular slot) and (26) [31] (for a curved slot).

$$h_{ZR} = h_{PR} \geq 0.8 b_{PR} \quad (24)$$

$$\mathrm{h}_{ZR} \geq 16\delta_0 \quad (25)$$

$$\mathrm{h}_{ZR} \leq 18\delta_0 \quad (26)$$

The values 16 and 18 in (25) and (26) should be understood as maximum, further increase of which is not advisable, since it does not lead to a noticeable increase in the magnetic flux alternations, and, consequently, to an increase in the armature EMF.

However, the height of the rotor tooth h_{ZR} (rotor slot depth h_{PR}) is limited by the rotor mechanical strength, which also depends on the rotor diameter. Considering this, it is recommended to choose the height of the rotor tooth considering the value of D as (27) – (30) [8].

$$h_{ZR} = h_{PR} = (8 \div 12)\delta_0 \; for \; D = (100 \div 200)\delta_0 \quad (27)$$

$$h_{ZR} = h_{PR} = (13 \div 17)\delta_0 \; for \; D = (200 \div 300)\delta_0 \quad (28)$$

$$h_{ZR} = h_{PR} = (18 \div 25)\delta_0 \, for \, D = (300 \div 400)\delta_0 \quad (29)$$

$$h_{ZR} = h_{PR} = (25)\delta_0 \, for \, D \geq 400\delta_0 \quad (30)$$

As just mentioned, in HIA with concentrated-type armature winding, the armature EMF value depends on the alternations (pulsations) of the excitation magnetic flux $\Delta\Phi = \Phi_{max} - \Phi_{min}$. Pulsations occur as a result of the rotation of the rotor, which causes the alternation of rotor teeth and slots under the teeth of the stator, on which the armature winding coils are located (see Fig.1). Since in a particular machine the cross-sectional areas of the teeth are constant, the variations in the magnetic flux $\Delta\Phi$ is mainly due to a variation in the air gap between the stator tooth and the tooth-groove zone of the rotating rotor.

The alternations in the magnetic flux $\Delta\Phi$ are determined by the change in the magnetic permittivity of the stator tooth. Having set the parameters of the teeth zone, and also assuming that the cross-section area of the teeth is $1\ m^2$, the magnetic field has no bulging and the magnetic circuit is not saturated, it is possible to calculate the dependence of the specific magnetic permittivity Λ of the stator tooth on the rotor angle of rotation $\Lambda=f(\alpha)$, where α is in electrical degrees. Further, considering that the number of turns in the armature coil is 1, the MMF of the field winding is 1 A and the magnetic constant (vacuum permeability) is $\mu=1$, the value of the EMF induced in one turn of the armature coil can be found as a derivative of the variation in magnetic permittivity Λ. The calculation method is described in more detail in [4].

Fig. 3 shows the dependence of the armature EMF rms value on the value of the minimum air gap length δ_0 between the stator and rotor teeth, where the EMF value is expressed in conditional units (E.c.u.), and δ_0 is in millimeters. The values are calculated for teeth and slots of a rectangular shape, and the width of the rotor and stator teeth is equal to half of the rotor tooth pitch: $b_{ZS}=b_{ZR}=0.5t_R$. In the first case, the height of the rotor tooth h_{ZR} is selected according to the recommendations (27)-(30) for a given diameter D; in the second case, the height of the rotor tooth is $h_{ZR}= 25\cdot\delta_0$, which is obviously more than recommended in (25) and (26), and also not less than in (27)-(30). Numerical values are given in Table 5 and illustrated on Fig.3.

TABLE V. AIR-GAP LENGTH IMPACT ON EMF OF HIA AT VARIOUS ROTOR TEETH HEIGHTS

D, mm	h_{ZR} found by (27)-(30)				$h_{ZR}= 25\cdot\delta_0$		
	δ_0, mm	Multiplier	h_{ZR}, mm	E, E.c.u	Multiplier	h_{ZR}, mm	E, E.c.u
100	0.45	8	3.6	0.314	25	11.3	0.339
150	0.55	10.5	5.8	0.264	25	13.8	0.278
200	0.60	12.5	7.5	0.245	25	15.0	0.255
250	0.70	15	10.5	0.213	25	17.5	0.218
300	0.76	17.5	13.3	0.198	25	19.0	0.201
350	0.83	19.3	16.0	0.182	25	20.8	0.184
400	0.90	25	22.5	0.170	25	22.5	0.170
450	1.00	25	25.0	0.153	25	25.0	0.153

Fig. 3 shows that the value of δ_0 has a significant impact on the EMF value. Thus, an unjustified overestimation of the air gap value δ_0 leads to a significant drop in the EMF value, which cannot be compensated by increasing the height of the rotor teeth (depth of rotor slots). For clarity, Fig. 3 shows the EMF value obtained for the gap size $\delta_0= 2\ mm$ and $h_{ZR}=40\cdot\delta_0=40\cdot 2$ *(red dot)*, which, in fact, does not differ from the EMF value obtained for the smaller rotor tooth height $h_{ZR}= 25\cdot\delta_0=25\cdot 2\ mm$ (value from the yellow line at $\delta_0= 2$). In addition, results in Fig. 3 confirms the fact that an increase in h_{ZR} over $(16\div 18)\cdot\delta_0$ does not bring any noticeable increase in the value of armature EMF.

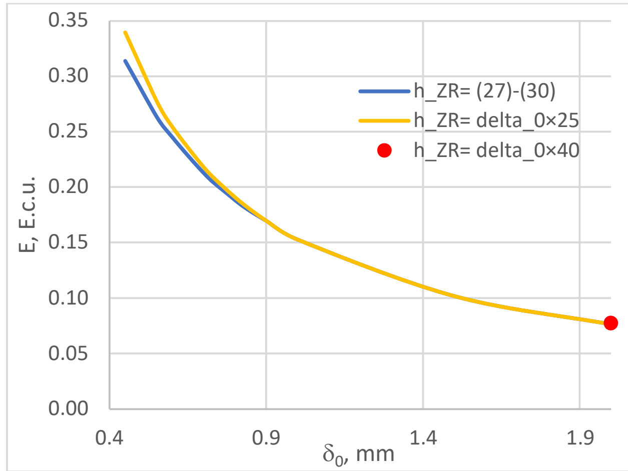

Fig. 3. Armature EMF (in conditional units) depending on air-gap length δ_0.

Finally, the shape of the rotor tooth must be selected. The shape of the rotor tooth is taken into account when calculating the specific magnetic permittivity of the air gap and the corresponding function $\Lambda=f(\alpha)$, and, accordingly, the zero, fundamental and higher harmonic components of the permittivity and EMF, i.e. the value and sinusoidality/THD of no-load EMF. Quantitative values of the influence of various shapes of rotor teeth on the magnitude and sinusoidality of the EMF can be found in [4], [32], [33].

IV. CONCLUSION

The considered dependencies, reflecting the relationship between the geometric parameters of the teeth zone and some technical parameters of a HIA, form a system of interrelated parameters. This system can be used to evaluate the considered variants of the HIA teeth zone to select the optimal solution for the given operating conditions of a HIA.

The recommendations on the selection of rotor and stator teeth pitch, as well as rotor teeth width and number of rotor and stator teeth are provided in Chapter 2. The recommendations on the selection of bore diameter, minimum air gap length and rotor teeth height optimum values are given in Chapter 3. The impact of overestimated selection of the minimum air gap length on the armature EMF is demonstrated in Chapter 3. It is also demonstrated that it cannot be compensated by increasing the rotor teeth height.

The provided set of recommended values and relationships can serve as the basis for an algorithm to accelerate the design process of the homopolar inductor alternators with concentrated-type armature coils. It can be especially useful when making a realistic 3D model of a hypothetic HIA to prove some ideas via FEM analysis if further manufacturing of the proposed HIA is not planned (so the manufacturing tolerances can be ignored).

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