UDC 621.313 **doi: 10.20998/2074-272X.2016.6.04**

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A TURBO-GENERATOR DESIGN SYNTHESIS BASED ON THE NUMERICAL-FIELD CALCULATIONS AT VARYING THE NUMBER OF STATOR SLOTS

Purpose. The work is dedicated to the presentation of the principle of construction and implementation of an automated synthesis system of the turbo-generator (TG) electromagnetic system in the case of its modernization. This is done on the example of changing the number of the stator core slots. Methodology. The basis of the synthesis is a TG basic construction. Its structure includes the mathematical and physical-geometrical models, as well as the calculation model for the FEMM software environment, providing the numerical calculations of the magnetic fields and electromagnetic parameters of TG. The mathematical model links the changing and basic dimensions and parameters of the electromagnetic system, provided that the TG power parameters are ensured. The physical-geometrical model is the geometric mapping of the electromagnetic system with the specified physical properties of its elements. This model converts the TG electromagnetic system in a calculation model for the FEMM program. Results. Testing of the created synthesis system is carried out on the example of the 340 MW TG. The geometric, electromagnetic and power parameters of its basic construction and its new variants at the different numbers of the stator slots are compared. The harmonic analysis of the temporal function of the stator winding EMF is also made for the variants being compared. Originality. The mathematical model, relating the new and base parameters of TG at the changing of the number of the stator slots is created. A Lua script, providing the numerical-field calculations of the TG electromagnetic parameters in the FEMM software environment is worked out. Construction of the constructive and calculation models, the numerical-field calculations and delivery of results are performed by a computer automatically, that ensures high efficiency of the TG design process. Practical value. The considered version of the TG modernization on the example of changing the number of the stator core slots provided an opportunity for the presentation of the principle of construction and implementation of design synthesis system. For the practical use in the TG designing process, the developed and presented system can be more detailed with specifying the individual components of the mathematical model and expanded for varying other parameters of TG and optimizing its design. References 11, tables 2, figures 7.

Key words: turbo-generator, modernization, design synthesis, mathematical model, Lua script, FEMM program, numerical-field calculations, electromagnetic parameters.

Представлен пример проектного синтеза электромагнитной системы турбогенератора (ТГ) при его модернизации. Создана математическая модель, связывающая новые и базовые параметры ТГ при изменении числа пазов статора. Разработан скрипт Lua, обеспечивающий численно-полевые расчеты электромагнитных параметров ТГ в программной среде FEMM. Построение конструктивной и расчетной моделей, численно-полевые расчеты и выдача результатов выполняются компьютером автоматически, что обеспечивает высокую эффективность процесса проектирования ТГ. Апробация системы синтеза проведена на примере ТГ мощностью 340 МВт. Библ. 11, табл. 2, рис. 7.

Ключевые слова: **турбогенератор, модернизация, проектный синтез, математическая модель, скрипт Lua, программа FEMM, численно-полевые расчеты, электромагнитные параметры.**

Introduction. Powerful turbo-generators (TG) are the most complicated, expensive and effective in operation electric machines [1]. Design and the subsequent creation of new models take months and even years.

Therefore, the process of improving the TG is often reduced to modernize their samples after long test operation [2]. At the same time seeking to improve the parameters of the TG with minimum changes as the global innovations in the complex can lead to unpredictable consequences and require long experimental refinement which requires large capital investments.

One option to speed up the modernization of TG is reduction of terms of computational and design works. They require a significant amount of time due to the complexity of classical methods of calculation as such because of the complexity of TG themselves. These methods are often adapted to specific design elements of standard sizes and need to be improved after their changes.

Numerical methods for calculating magnetic fields [3, 4] coupled with high-speed computers and efficient software provide new opportunities for improving the design system of the TG. This contributed to the novelty of the results provided, as an example of created on this basis an automated design synthesis system of the TG electromagnetic system in the case of their modernization at the change of certain key elements of the design is considered.

The goal of the work. The work is dedicated to the presentation of the principle of construction and implementation of an automated system of electromagnetic TG system synthesis in the case of its modernization that is being done on the example of changing the number of slots of the stator core.

Structure of synthesis is based on the basic design of the TG available and includes a mathematical model, a physical and geometrical model, a calculation model in conjunction with the program environment FEMM [5] which provides the numerical calculations of the magnetic field and electromagnetic parameters of the TG. The mathematical model relates the changing sizes and parameters of the electromagnetic system with its basic dimensions and parameters with the condition for the output power parameters of the TG. Physical and geometric model is a geometric mapping of the electromagnetic system with given properties of its components - the windings and cores. This model converts the electromagnetic system of the TG and the results of the mathematical model operation to the calculation model for the FEMM program.

Creation of the physical and geometric model, its transformation into a calculation model, providing the FEMM program operation, the definition of the electromagnetic and power parameters based on numerical calculation of the magnetic field, output results of the synthesis of the updated TG electromagnetic system to a text file - all is done automatically by the control program written in the Lua language integrated in the FEMM [5].

Universalism of created models of available and developed software is that they are adapted to the typical structural shapes of TG as a whole and their elements. Numerical methods for the calculation of the magnetic field remove restrictions on the account of real constructive shapes of electric machines as a whole and their elements, on account of the magnetic saturation.

Largely developed software is based on investigations that have presented earlier in papers by the author [4, 6-10] and others.

Object of investigations. Demonstration of calculation results is carried out on a three-phase TG [2] the basic electromagnetic system of which is shown in Fig. 1. It has a rated: power P_N=340 MW; phase voltage U_{sN}=11547 V and current I_{sN}=11547 A; power factor $\cos\varphi_{sN}$=0.85; frequency f_s=50 Hz. Its number of pole pairs p=1; active length l_a=5.308 m; non-magnetic gap δ=77.5 mm; radius of the rotor surface r_{re}=0.56 m; number of turns of its phase winding N_s=10, relative shortening β_s=0.8; number of effective conductors of the stator winding rod N_{cs}=1; number of turns of the rotor winding N_r=126.

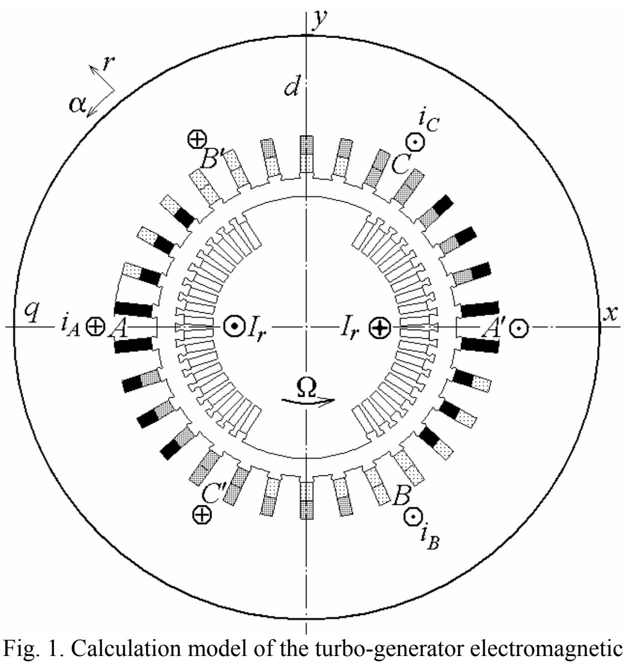

Fig. 1. Calculation model of the turbo-generator electromagnetic system

The basic values of the TG conserved in its modernization. Fig. 2 shows the TG structure with the indication of main dimensions of the cores of the stator and rotor. Taking into account the decisive role in the formation of the magnetic fields of the tooth-slot stator structure, it is shows by fragments with required dimensions marked in Fig. 3.

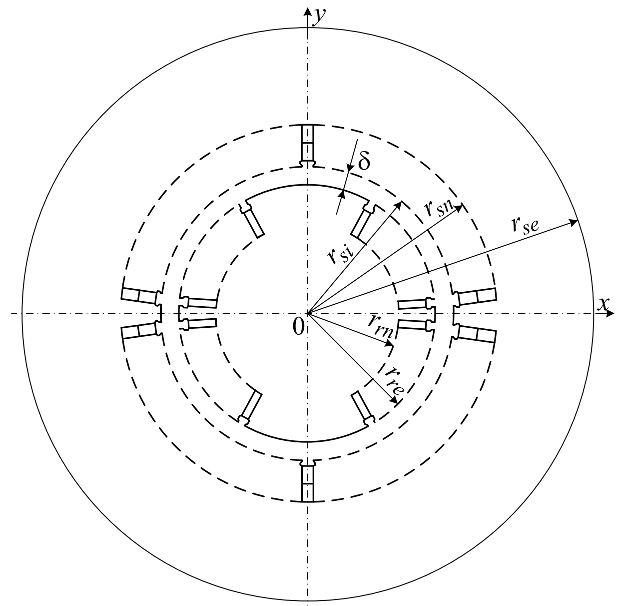

Fig. 2. Geometrical model of the turbo-generator

In order to in visualized form evaluate changes in the TG at the change of the number of stator slots, the presented TG output parameters are reserved: power, phase voltage and current, power factor. Also given in the long history of the TG design values of magnetic field strength in the gap, teeth and the back of the stator core as well as a gap characterized for the TG of corresponding power level are conserved.

Assuming the continuation of the stator current and the distributed current density in the conductors of its winding, sections of its rods must be preserved. Since the stator winding voltage is conserved, the insulating gaps in the slot are conserved, too (Fig. 3).

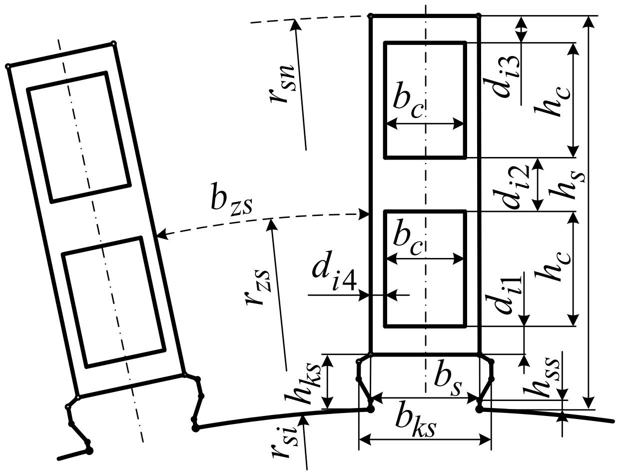

Fig. 3. Tooth-slot structure of the stator

When conserving the TG voltage, EMF of the phase stator winding should be conserved, too

$$E_s = \pi\sqrt{2} \cdot f_s \cdot N_s \cdot \Phi_s \cdot K_{Ws}, \quad (1)$$

where Φ_s is the magnetic flux in the gap; K_{Ws} is the stator winding factor.

For convenience, hereinafter we refer to the same indications of the same base and new values but for the first ones the letter b in the indexes is added everywhere.

Stator rods are characterized by their height h_c and width b_c, the surrounding insulation in the slots – by thicknesses d_{i1}, d_{i2}, d_{i3} and d_{i4}. In the basic design of the cross-sectional area of the stator winding rod $S_{cb}=h_{cb}\cdot b_{cb}$. Taking into account the conditions set, at varying of h_c and b_c the following must be provided: $h_c\cdot b_c = S_{cb}$.

This variation accompanies the change in the size of the stator slots - their height h_s and width b_s. Here, we must preserve the height of the spline h_{ss} and the depth of the wedge h_{ks} as well as two-way wedge recess in the wall of the slot $d_{ks} = b_{ksb} – b_{sb}$. The width of the grooves under the wedge should change and be $d_{ks} = b_{ksb} – b_{sb}$.

Note that in the basic design the following conditions must be satisfied: $b_c = b_s – 2d_{i4}$; $h_c = (h_s – d_{hs})/2$, where the constant addition by the height of the stator slot

$$d_{hs} = h_{ks} + d_{i1} + d_{i2} + d_{i3}.$$

Mathematical model of the TG electromagnetic system synthesis.

First of all, we consider what changes need to occur in the stator and its slot and when the number of its slots is changed from the base value Q_{sb} to the new one Q_s which will be characterized by the coefficient of change in the number of stator slots:

$$k_{Qs} = Q_s / Q_{sb} . \quad (2)$$

We assume that the ratio of number of turns of the winding of the stator core of the base and the new design corresponds to the ratio of slots, i.e. $N_s = k_{Qs} N_{sb}$.

Then, from the condition of conservation of the EMF of the phase stator winding (1), the new value of the magnetic flux in the pole pitch $\varPhi_s = \varPhi_{sb} / k_{Qs}$.

By the magnetic flux, the magnetic flux density in the gap to the bore of the stator core (in this case, the average value) is determined

$$B_\delta = \frac{\varPhi_s}{\tau_p \cdot l_a} , \quad (3)$$

where we know the expression of the pole pitch on the radius of the stator bore r_{si}:

$$\tau_p = \frac{\pi \cdot r_{si}}{p} . \quad (4)$$

As already stated, the value of B_δ should remain as one of the fundamental quantities of TG and other electric machines.

The expression (3) includes two values, which, in principle, can be changed to conserve in the TG the previous value B_δ, namely, the active length l_a and the radius of the stator bore r_{si}.

In this paper we restrict ourselves to the second option - to change the radius of the stator bore r_{si} as more complicated in the analysis. Active length l_a is preserved such it was in the TG basic design.

Modernization of the TG electromagnetic system with changing the radius of the bore of the stator core. From a combination of the above relations a new value of this radius is obtained

$$r_{si} = r_{sib} / k_{Qs} . \quad (5)$$

To preserve the value of the magnetic flux density in the teeth of the stator core with the new number of slots, respectively the total width of the teeth changes

$$b_{zss} = b_{zssb} / k_{Qs} , \quad (6)$$

Basic total width of all the stator teeth in their average radius of location r_{zsb} (Fig. 3)

$$b_{zssb} = 2 \cdot \pi \cdot r_{zsb} - b_{sb} \cdot Q_{sb} , \quad (7)$$

where $r_{zsb}=r_{sib}+h_{sb}/2$; r_{sib} is the radius of the bore of the stator core; h_{sb} is the its slot height.

With the new value of the radius r_{si} by (5), we carry out a number of preparatory transformations of TG stator parameters for the new number of its teeth Q_s in order to obtain the new value of the average radius of stator teeth r_{zs}, and then the other quantities.

The width of the new slot at the new value Q_s

$$b_s = \frac{2 \cdot \pi \cdot r_{zs} - b_{zss}}{Q_s} . \quad (8)$$

The width and height of the stator winding rod

$$b_c = b_s - 2 \cdot d_{i4} ; \qquad h_c = S_{cb} / b_c . \quad (9)$$

The height of the slot

$$h_s = 2\, h_c + d_{hs}. \quad (10)$$

For expressing the average radius of the tooth-slot structure we make substitutions based on relationships of written values above:

$$r_{zs}=r_{si}+ h_s/2 =r_{si}+ (2\, h_c + d_{hs})/2 =r_{si}+ h_c + d_{hs}/2 =$$
$$= r_{si}+ S_{cb}/b_c + d_{hs}/2 = r_{si}+ S_{cb}/(b_s – 2\, d_{i4}) + d_{hs}/2 =$$
$$= r_{si} + \frac{S_{cb}}{\frac{2 \cdot \pi \cdot r_{zs} - b_{zss}}{Q_s} - 2 \cdot d_{i4}} + \frac{d_{hs}}{2} = e + \frac{Q_s\, S_{cb}}{2 \cdot \pi \cdot r_{zs} - d} ,$$

where the notations are introduced for brevity $d = b_{zss} + 2 \cdot d_{i4} \cdot Q_s$; $e = (r_{si}+ d_{hs}/2)$.

In fact, an equation is obtained from which, after incremental transformations we obtain the quadratic equation with respect to r_{zs}:

$$r_{zs}^2 - r_{zs}\, [d/(2 \cdot \pi) + e)] + [d\, e - S_{cb} \cdot Q_s]/(2 \cdot \pi) = 0. \quad (11)$$

Its solution gives two roots, the meaning of which has an option with a plus sign before the radical:

$$r_{zs} = -\frac{b}{2} \pm \sqrt{\frac{b^2}{4} - c} , \quad (12)$$

where $b = –e – d / (2 \cdot \pi)$; $c = (d\cdot e – S_{cb} \cdot Q_s) / (2 \cdot \pi)$.

After obtaining r_{zs} we determine for the new TG design values b_s, b_c, h_c, h_s by (8)-(10).

Besides, we obtain the new values of the width of the stator wedge

$$b_{ks} = b_s + d_{ks}, \quad (13)$$

stator core backrest height

$$h_{as} = h_{asb} / k_{Qs} , \quad (14)$$

outer radius of the stator core

$$r_{se} = r_{si} + h_s + h_{as} \quad (15)$$

number of serial turns of the two-layer stator windings is verified

$$N_s = N_{cs}\cdot Q_s / m_s, \quad (16)$$

where N_{cs} is the number of effective conductors in the rod; m_s is the number of TG phases.

In the process of calculating TG electromagnetic parameters we use stator phase winding active resistance $R_s=R_{sb}\cdot k_{Qs}$ and reactance of frontal scattering $X_v = X_{vb} \cdot k_{Qs}^2$ [4, 7] which are recalculated for the changes in the number of turns (16) by the same quantities of the basic model.

With the change of the radius of the bore of the stator core it is necessary to correct the rotor structure (Fig. 2). In this regard, we consider two options: retaining and changing its dimensions of its slots which are separately designated in Fig. 4.

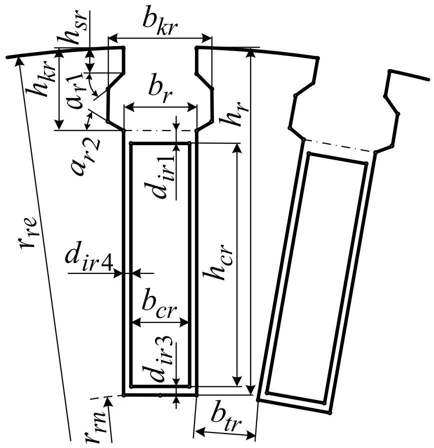

Fig. 4. Tooth-slot structure of the rotor

Correction of the rotor with maintaining its slots dimensions. With the new value of the radius of the bore of the stator core, the new radius of the rotor surface

$$r_{re} = r_{si} - \delta . \quad (17)$$

Therefore, correction of the number of rotor slots is need so as not to reduce the critical values of a rotor core - the width of the base of the rotor teeth

$$b_{tr} = \frac{2 \cdot \pi \cdot r_{rn}}{Q_{ru}} - b_r , \quad (18)$$

where Q_{ru} is the conditionally total number of rotor slots; b_r is the rotor slot width; r_{rn}=$r_{re} - h_r$ is the location radius of the rotor teeth base (Fig. 4).

When choosing the number of actual rotor slots Q_r we conserve about the filling ratio of the rotor surface by the slots

$$k_{Qr} = Q_r / Q_{ru} . \quad (19)$$

By these formulas (18), (19) for the base version of the TG we must take basic values Q_{rub}, Q_{rb}, b_{rb}, h_{rb}, and then we obtain the values of the parameters k_{Qrb}, b_{trb} which further by varying the rotor sizes should be about conserved.

To transform the rotor design the following formulas are used.

New conditionally total number of rotor slots

$$Q_{ru} = 4 \cdot ceil\left(\frac{0{,}5 \cdot \pi \cdot r_{rn}}{b_{rb} + b_{trb}} - 0{,}99 \right), \quad (20)$$

where the symbol *ceil* means rounded to the nearest whole number in the direction of greater value of the argument in parentheses.

The new number of coiled rotor slots

$$Q_r = 4 \cdot ceil\left(0{,}25 \cdot Q_{ru} \cdot k_{Qrb} - 0.99\right). \quad (21)$$

Number of serial turns of the rotor winding

$$N_r = N_{cr} \cdot Q_r / 2, \quad (22)$$

where N_{cr} is the number of effective conductors in the rotor slot, for the base variant it was N_{crb}=2 N_{rb} / Q_{rb}.

Correction of the rotor with a change in its slots dimensions. For more detailed correction of the rotor design we can change the basic dimensions of its slot (Fig. 4).

At the correction of the rotor we conserve:

- cross-sectional area of the rotor winding rod

$$S_{crb} = h_{crb} \cdot b_{crb}; \quad (23)$$

where h_{crb}, b_{crb} are the height and width of its winding rod;

- insulation gaps in the slot d_{ir1}, d_{ir3} and d_{ir4}, height of the wedge with spline h_{kr};
- constant addition to the height of the rotor rod

$$d_{hr} = h_{kr} + d_{ir1} + d_{ir3}; \quad (24)$$

- two-side wedge deepening to the slot wall $d_{kr} = b_{kr} - b_{rb}$, where b_{rb} is the width of the rotor base slot;
- width of the base of the rotor teeth b_{trb} (18);
- base filling factor of the surface of the rotor slots k_{Qrb} determined by (19).

To keep the magnetic flux density in the base of the rotor teeth at the change of the number of stator slots, we change the radius of the location of the bottom of rotor slots proportionally to the magnetic flux change

$$r_{rn} = r_{rnb} / k_{Qs} . \quad (25)$$

By formulas (21) and (22) we calculate values Q_{ru} and Q_r.

Keeping base value b_{trb} calculated by the formula like (18) we obtain new rotor slot width

$$b_r = \frac{2 \cdot \pi \cdot r_{rn}}{Q_{ru}} - b_{trb} . \quad (26)$$

New values of rotor rod dimensions

$$b_{cr} = b_r - 2 \cdot d_{ir4} ; \; h_{cr} = S_{crb} / b_{cr} . \quad (27)$$

New values of the slot height and width in the area under the wedge recess

$$h_r = h_{cr} + d_{hr} ; \; b_{kr} = b_r + d_{kr} . \quad (28)$$

The radii of the rotor surface and the stator core bore

$$r_{re} = r_{rn} + h_r ; \; r_{si} = r_{re} + \delta . \quad (29)$$

Taking into account this new value of the radius r_{si} after that by (12) we calculate r_{zs} for the new number of its teeth Q_s and then other new values h_s, b_c, h_c, b_s by the above formulas (12), (8) - (10) as well as the new values of the stator wedge width

$$b_{ks} = b_s + d_{ks}, \quad (30)$$

outer radius of the stator core

$$r_{se} = r_{si} + h_s + h_{as}. \quad (31)$$

As a result as before, the corresponding geometric model of the TG is formed

The presented set of formulas from (2) to (31) together with intermediate formulas and is a mathematical model of the TG electromagnetic system synthesis at the changing the number of its stator slots.

The structure of an automated synthesis system of the TG electromagnetic system. The basis for the use of a mathematical model, as stated above, are the parameters of the TG basic design and the new value of the number of stator slots. Since then the automated program complex synthesis of a new TG electromagnetic system synthesis begins. A block diagram of the synthesis program is shown in Fig. 5.

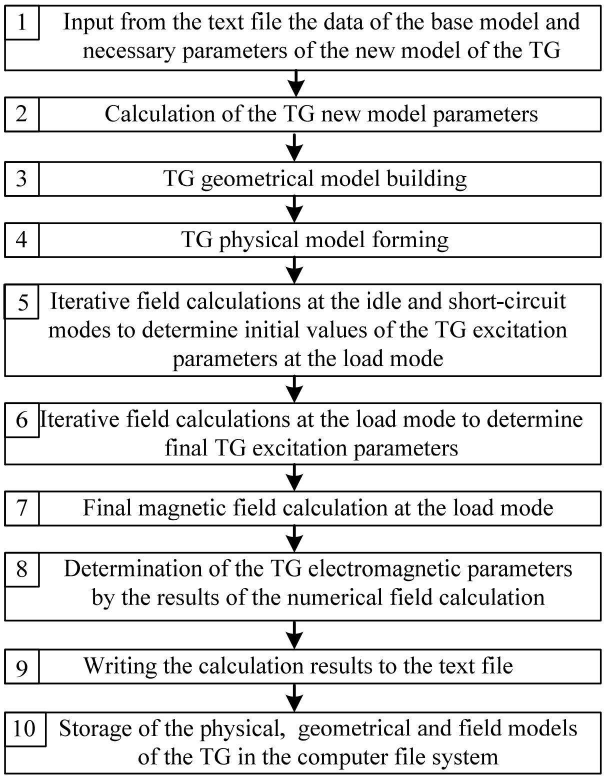

Fig. 5. A block diagram of the program for the TG electromagnetic system synthesis

All steps shown in Fig. 5 are organized and executed by the program written on the algorithmic language Lua-script. The program starts and runs in the FEMM software environment [5] performing numerical calculation of the magnetic field by the finite element method.

The meaning of the blocks 1, 2, 7, 8, 9 and 10 in Fig. 5, in principle, obvious by given in these texts. However, for the remaining blocks we give explanations.

The essence and software implementation of the blocks 3 and 4 are presented in [9]. In them on the base of the input and calculated information on the geometrical dimensions of TG the geometrical model of the TG is built as shown in Fig. 2, Fig. 3 and Fig. 4. For the parts of this model magnetic and current properties are defined - a physical model is formed. And in general a physical and geometric model of the TG for the magnetic field in the software environment FEMM is obtained.

Power parameters of the TG are set by values of power, phase voltage and current, power factor. And to achieve them in each new version of the TG we need to know the parameters of the excitation of the magnetic field at the load mode. These parameters include excitation current in the rotor winding I_r and phase shift β of the stator winding EMF relative to the rotor windings EMF.

Theory and principle of their determination are described in [7] and they are based on iterative calculations of magnetic fields at the idle, short-circuit and the load modes. All this is done in blocks 5 and 6 (Fig. 5), and software implementation is presented in [10]. Besides, in them necessary electromagnetic parameters of the TG are determined that corresponds to the block 8 in Fig. 5 in which also harmonic analysis of the angle function of the magnetic flux linkage the temporal function of EMF of the phase stator winding in accordance with the theory presented in [8] is carried out.

Results of operation of the software complex for the TG electromagnetic system synthesis.

First of all, the developed software system has been tested on the base model with the number of TG stator slots Q_{sb}=30. That is based on the basic model, the same one is synthesized. Next, the synthesis of new models with slot numbers Q_s equal to 24 and 36 has been carried out. They are closest to basic model minimal and greater values of Q_s taking into account that

$$Q_s = 2 \cdot p \cdot m_s \cdot q_s , \qquad (32)$$

where the number of slots per pole and phase q_s must be an integer.

Step of the stator winding by slots y_s is calculated in the program on the condition of ensuring the coefficient of relative shortening β_s nearest or equal to 0.833 which gives the most suitable harmonic structure of the stator winding EMF [1].

Each of the TG models with their values Q_s is synthesized in two considered above rotor correction variants: 1) while maintaining its slot dimensions; 2) changing them. Further number of these options added to the values of the numbers of stator slots.

It should be noted that the calculation of one variant on a computer of sufficiently high level taken about 10 minutes, with the number of nodes of the finite element structure according to the variant was 30-40 thousand, the number of triangles 60-80 thousand.

A geometrical model of the TG base variant was already presented in Fig. 1 and is repeated in Fig. 6 together with the calculated magnetic field distribution. Models of synthesized electromagnetic systems are shown in Fig. 7 – each one by fourth cross-section with the corresponding parts of the picture of the magnetic field at the load mode.

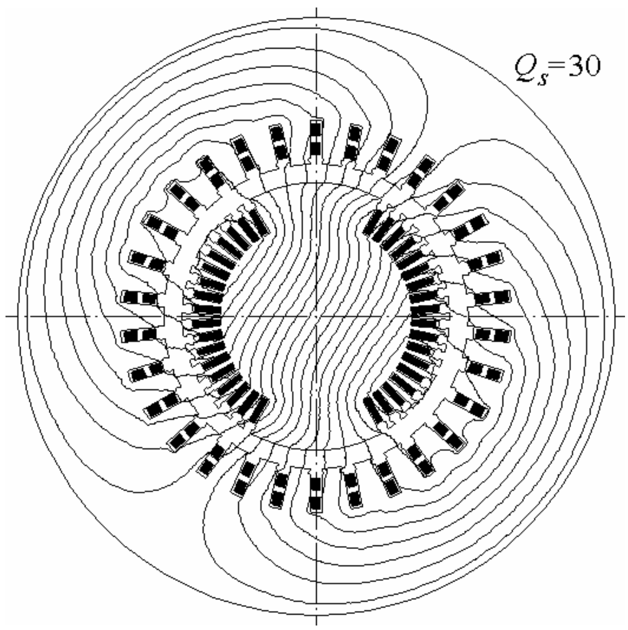

Fig. 6. Base electromagnetic system of the TG

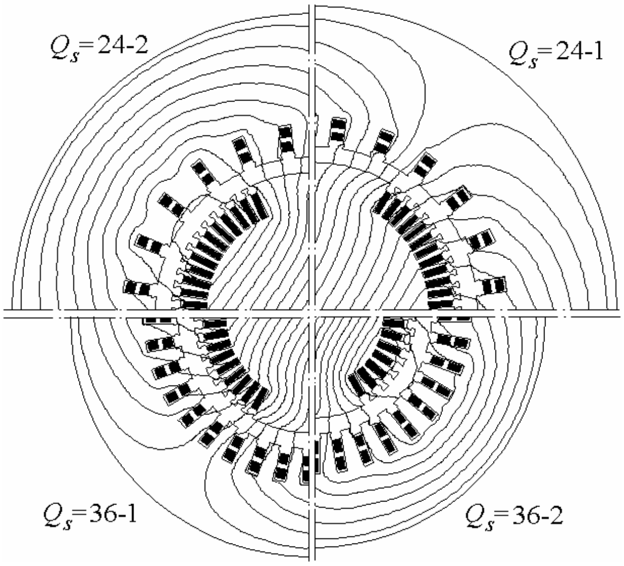

Fig. 7. Variants of the TG electromagnetic system

In the numeric form part of information about these models is presented in Table 1.

Table 1
Parameters of the TG electromagnetic system in various its variants

Q_s	24-1	24-2	30	36-1	36-2
y_s	10	10	12	15	15
β_s	0.833	0.833	0.8	0.833	0.833
Q_r	48	48	36	36	36
N_r	168	168	126	126	98
N_s	8	8	10	12	12
r_{si}, mm	797	749	637.5	637.50	570
r_{se}, mm	1482	1451	1250	1167	1126
h_s, mm	148	165	183	171	199
b_s, mm	68.8	58.5	50.8	55.5	46.0
h_c, mm	36.1	44.4	53.5	47.6	61.4
b_c, mm	55.4	45.1	37.4	42.1	32.6
h_r, mm	160	171.5	160	160	158.7
b_r, mm	33,9	34.	33.9	33.9	37.9
I_{ro}, A	715	840	1028	847	1269
I_r, A	1896	2121	3159	3419	5020
β, degree	-158.56	-156.98	-160.42	-166.13	-162.78
F_r, кА	319	356	398	431	492
F_s, кА	196	196	245	294	294
AW_s, кА	277	277	346	416	416
k_{Mm}	1.748	1.820	1.712	1.548	1.666
P_{ems}, MW	343.5	340.9	341.2	342.3	342.1
ΔP_{rs}, кW	851	851	1064	1277	1277
Φ_{so}, Wb	1.339	1.328	1.102	0.920	0.919
Φ_s, Wb	1.459	1.475	1.248	1.065	1.080
B_δ, T	1.309	1.224	1.306	1.139	1.260
B_{zr}, T	1.682	1.809	1.910	1.773	2.018
B_{yr}, T	1.393	1.597	1.771	1.563	1.978
B_{zs}, T	1.629	1.512	1.635	1.738	1.703
B_{ys}, T	1.604	1.607	1.639	1.699	1.668

Here, in addition to already represented values we present: I_{ro} - rotor current at the idle mode; F_r=N_r·I_r - EMF of the rotor winding under load; F_s =1.5 $\sqrt{2}$ ·I_s·N_s - EMF amplitude of the stator windings; AW_s= m_s·I_s·N_s - ampere-turns of the stator winding which in contrast to F_s characterize not electromagnetic nature but just design filling of the winding like F_r; k_{Mm} - TG overload capacity; $P_{em\ s}$ - electromagnetic power determined by the electromagnetic torque; ΔP_{rs} - electric power loss in the stator winding; Φ_{so}, Φ_s - magnetic fluxes in the gap on the pole division at modes of idle and load; maximum values of the magnetic flux density at the load mode in the center points by parts of the magnetic system: B_δ - in the gap; Bzr, Byr - in the teeth and the yoke of the rotor core; B_{zr}, B_{yr} - in the teeth and the yoke of the stator core.

In more detail the meaning and procedure for determining the values presented can be found in the works, which list is in [11].

Table 2 presents a harmonic composition of the temporal function of EMF of the phase winding which is determined in accordance with [8]. Here we present the amplitude of the first harmonic $E_{m,1}$ in absolute terms, as well as the amplitudes of the odd harmonics with numbers ν - in relative form $E_{m,\nu,*} = E_{m,\nu} / E_{m,1}$.

Table 2
Harmonic composition of the stator winding EMF at various variants of the TG electromagnetic system

Q_s	24-1	24-2	30	36-1	36-2
E_{m1}, V	16715	16715	16930	17198	17196
E_{m3*}	0.0564	0.1112	0.0647	0.0745	0.0719
E_{m5*}	0.0087	0.0044	0.0048	0.0125	0.0125
E_{m7*}	0.000	0.0024	0.0069	0.0024	0.0051
E_{m9*}	0.0038	0.000	0.0083	0.0061	0.0063
E_{m11*}	0.0205	0.0166	0.0192	0.0191	0.0221
E_{m13*}	-	-	0.0105	0.0181	0.0209
E_{m15*}	-	-	-	0.0024	0.0037
E_{m17*}	-	-	-	-	0.0052
d_{distE}	0.9982	0.9937	0.9976	0.9968	0.9968

The total content of series is characterized by the distortion factor

$$d_{dist} = \frac{E_{m,1}}{\sqrt{\sum_{\nu=1,3,5,...}^{N_g} E_{m,\nu}^2}}, \qquad (33)$$

where N_g is the number of accounted harmonics equal Q_s/2.

This ratio (33) for «pure» sine wave is equal to one, and its reduction indicates increase the role of higher harmonics. Although, in principle, obtained harmonic compositions for considered options of the TG electromagnetic systems are quite acceptable in terms of quality of generated electricity, the more that the main higher harmonic - the third, which at the connection of the stator windings in a «star» in the three-phase system of line voltages theoretically disappears.

Presented in Tables data and models in Fig. 6, 7 give a clear picture of developments during the modernization of the TG electromagnetic system. However, their detailed analysis is beyond the scope of this paper. Their role is to demonstrate the capabilities and efficiency of the developed system of the TG electromagnetic system synthesis on the example of changing the number of slots of the stator core.

Conclusions.

1. A synthesis system for the TG electromagnetic system is made possible by numerical methods for calculat-

ing magnetic fields in conjunction with high-speed computers and efficient software.

2. Considered variant of synthesis as an example of the TG modernization by changing the number of the stator core slots provided an opportunity for the implementation of principles of construction and implementation of the design synthesis system, in general, and can be, in particular, expanded for the possibility of variation and other parameters of the TG in order to optimize its design.

3. For the practical use in the design of TG the developed and presented synthesis system can be more detailed, specifying the individual components of the mathematical model at maintaining the principles of design and implementation of such a system.

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Received 18.08.2016

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How to cite this article:
Milykh V.I. A turbo-generator design synthesis based on the numerical-field calculations at varying the number of stator slots. *Electrical engineering & electromechanics*, 2016, no.6, pp. 19-25. doi: 10.20998/2074-272X.2016.6.04.