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DETERMINATION OF ELECTROMAGNETIC PARAMETERS AND PHASE RELATIONS IN TURBO-GENERATORS BY THE AUTOMATED CALCULATION OF THE MAGNETIC FIELD IN THE SOFTWARE ENVIRONMENT FEMM

The theoretical bases of calculation of electromagnetic quantities and time-phase relationship are presented for the turbo-generators. This is done by numerical calculations of the magnetic field in the software environment package FEMM (Finite Element Method Magnetics). A program which controls calculations and organizes the issuance of the results to a text file is created on the algorithmic language Lua. The program is universal in terms of a turbo-generator models, as well as steady-state modes of their work with a minimum of input data. The exciting current of the rotor and the phase currents of three-phase stator winding in accordance with their initial phase are given for the calculation of the magnetic field. The key function for the analysis of electromagnetic parameters is the calculated angular function of the magnetic flux phase stator winding. The expansion in the harmonic series is carried out and amplitude and initial phase are received for this function. Next, the phase EMF and voltage, phase shifts between all values, active power, electromagnetic torque, the magnetic flux in the gap and other parameters are determined. The presented Lua script is a prototype for a similar calculation software of electric machines of other types. References 9, figures 6.

Key words: Finite Element Method Magnetics, program FEMM, turbo-generator, electromagnetic parameters, phase relationships, automated calculations, Lua script.

Представлены теоретические основы расчета электромагнитных величин и их фазовых соотношений для турбогенераторов. Это реализуется путем численных расчетов магнитного поля в программном пакете FEMM. Расчеты автоматизированы посредством созданной программы на алгоритмическом языке Lua. Она управляет расчетами и организует выдачу результатов в текстовый файл. Представленный скрипт Lua универсален и может послужить прототипом аналогичного программного обеспечения для других типов электрических машин. Библи. 9, рис. 6.

Ключевые слова: программа FEMM, турбогенератор, электромагнитные параметры, фазовые соотношения, автоматизированные расчеты, Lua скрипт.

Introduction. Widely known software FEMM [1] is effective for the calculation of three-dimensional magnetic fields (MF) of electrical machines (EM), classic design with almost in-plane plane MF within their active part. For example, this applies to the turbo-generators (TG) [2]. This program is freed calculators from the development of implemented mathematical models and programming and has a fairly user-friendly interface.

An additional means of facilitating the work of users of the program FEMM are scripts in the algorithmic language Lua, integrated into it. For example, in [3] our program is described, which automated construction of simulation models of TG, in [4] the program of automated calculations of their electromagnetic processes is given. Efficiency of Lua script is that programs are written once, and used countless times, and by any number of users.

This paper continues the series of works started in [3, 4]. And its **purpose** is to present the script Lua, automating the preparation of a series of electromagnetic parameters and phase relations in EM by the numerical MP calculations in the software environment FEMM. It is made on the example of TG – one of the largest and responsible of their representatives [5].

Object of investigations. For illustration here, as in [3, 4], we have TG 340 MW. Its parameters are further presented in the file of initial data.

Electromagnetic system of the TG shown in Fig. 1 by its cross-section. Highlighted phase zones of a two-layer shortened three-phase stator winding $A-A'$, $B-B'$ and $C-C'$. Shown used rectangular (x, y) and polar (r, α)

coordinate system, the longitudinal d transverse q axis of the rotor.

The basis of the developed Lua script is prepared in advance for the environment FEMM computational model of the electromagnetic system of the TG. We do this through a script Lua, presented in [3], and in the absence of such – in «manual» mode, in accordance with the instructions of the software FEMM.

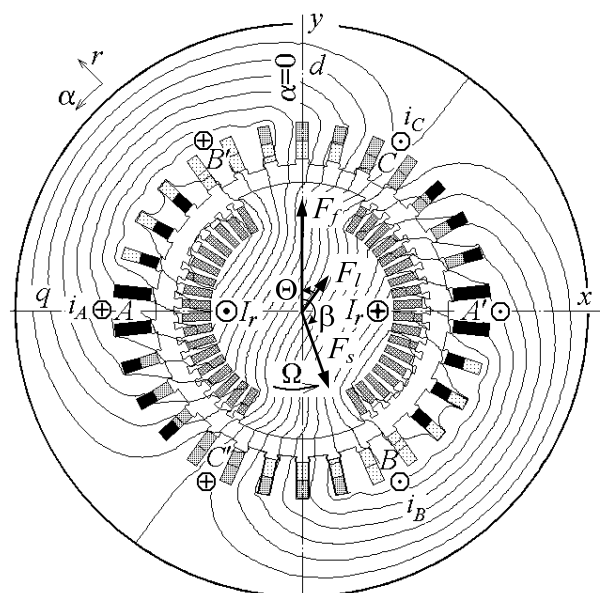


Fig. 1. Model of the electromagnetic system of the TG

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in its cross-section

View on the computer screen in the environment FEMM (file type – Femme Document) of the calculation model of the TG presented as a whole in Fig. 2, and in Fig. 3 its fragment is presented. Visible marks of physical properties of the *blocks* – limited regions of the calculation area. Marks Fe1, Fe2 and Fe3 set the magnetization curves of ferromagnetic materials, m0 – permeability, m0 – magnetic permeability $\mu_0=4\cdot\pi\cdot10^{-7}$ H/m, marks iA, iB, iC – phase currents, Ir – rotor current. Addition of + or – to the mark of current indicates its direction: if the current at this time is positive, then at this point it is taken with the appropriate sign. The number after the colon indicates the number of effective conductors in this block. Circles around marks indicate the maximum size of the triangles in the structure of the finite elements formed by program FEMM.

The fragment in Fig. 3 is taken from the right half of a complete model from Fig. 2, the rest of all similarly formed in accordance with and model in Fig. 1. In particular, the left half of the signs of currents is opposite to that seen in Fig. 3.

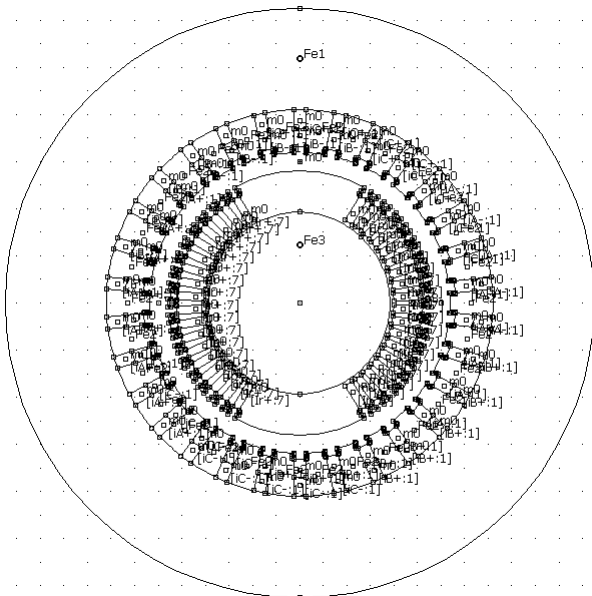


Fig. 2. Initial physico-geometrical model of the TG

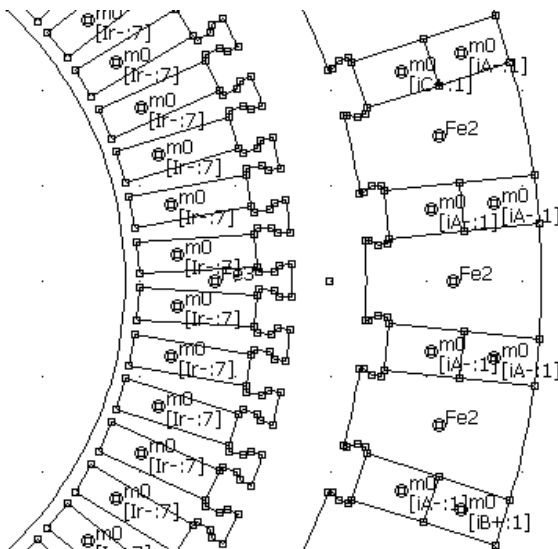


Fig. 3. Fragment of the physico-geometrical model of the TG

Mentioned blocks in the FEMM-model are combined in groups to operate with them as units of the calculation area. From the designated group number [3] is here used: 2, 3, 4, 5, 6, 7 – the phase zones *A, B, C, A', B', C'* of the stator winding, 9 – entire rotor (see Fig. 1).

Theoretical basics. The steady-state MF calculation by the program FEMM is carried out on the base of the numerical solution of the differential equation:

$$\text{rot} \left[\frac{1}{\mu} \text{rot} (\vec{k} A_z) \right] = \vec{k} J_z, \quad (1)$$

where A_z, J_z are the axial components of the magnetic vector potential (MVP) and current density; μ is the absolute magnetic permeability; k is the ort.

On the external boundary of the calculation area for the MVP the know Dirichlet condition $A_z = 0$ is accepted.

In the model TG (Fig. 2) for calculating of the the instantaneous distribution of MP of the particular steady state mode it is necessary to have the corresponding currents. In generalizing load mode (LM) [9] is given a constant rotor current I_r and the instantaneous values of the symmetrical system of stator phase currents: $i_A = I_m \cos(\beta)$; $i_B = I_m \cos(\beta - 2\pi/3)$; $i_C = I_m \cos(\beta + 2\pi/3)$, where $I_m = \sqrt{2} I_s$ is their amplitude and I_s is the effective value; β is its initial phase [6-9] specifies the shift of the stator winding MMF F_s from rotor winding MMF F_r (Fig. 1). Here conditional resultant for the MMF at LM is given

$$\vec{F}_l = \vec{F}_f + \vec{F}_s. \quad (2)$$

At no-load (NL) conditions only the rotor current is given, at steady mode of short circuit – only the stator currents. Directions of currents (Fig. 1) are regulated according to the system adopted in [7].

For TG the result is a distribution of MF in its cross-section as a function $A_z(x,y)$. Picture of MF in the calculation area is represented by a structure of field lines – lines of equal MVP $A_z = \text{const}$. An example of this for the TG at the mode to its rated load (RL) is shown in Fig. 1.

One of the key quantities in the analysis of electromagnetic parameters of the TG is the magnetic flux linkage (MFL) [2] and it is determined by the distribution of MVP. For example, for any of the six phase areas (Fig. 1) MFL is determined based on

$$\Psi = \frac{N_s l_a}{S_\phi} \int_{S_\phi} A_z dS \approx \frac{N_s l_a}{S_\phi} \sum_{j=1}^{K_\phi} A_{z,av,j} \Delta S_j, \quad (3)$$

where S_ϕ is the section square by current-carrying elements of the phase zone; K_ϕ is the number of elements of its discretization; $A_{z,av,j}$ is the average MVP value in the j -th element.

In the formula (3) the active length of the TG l_a and the number of turns of the phase stator winding N_s are taken into account, and to determine S_ϕ and integral in Lua script there are appropriate procedures [1].

The initial basis for identifying the *phase relations* in any of the design modes is a temporary phase or direction of the vector MFL of the phase winding $A-A'$. MMF of this base winding in Figure 1 is oriented along the longitudinal axis of the rotor d .

The direction of the vector MFL of the phase

winding $A-A'$ is determined by the structure of a particular MF of the actual calculated mode. So, in Fig. 1 this direction is becomes apparent by orientation of field lines of the MP and generally corresponds to the direction of the vector MMF F_l (2). But as long as the vector is constructed a priori, taking into account the results that will be obtained even further based on the methodology, which was published in [4-6]. Here, it shall be presented briefly to understand the meaning of the developed and submitted further the Lua script.

The mentioned techniques will be described with reference to the NL conditions, and then it will be effective for any other mode. Specifically, we assume that the MF at the NL conditions is calculated by the program FEMM. The structure of this field is shown in Fig. 4.

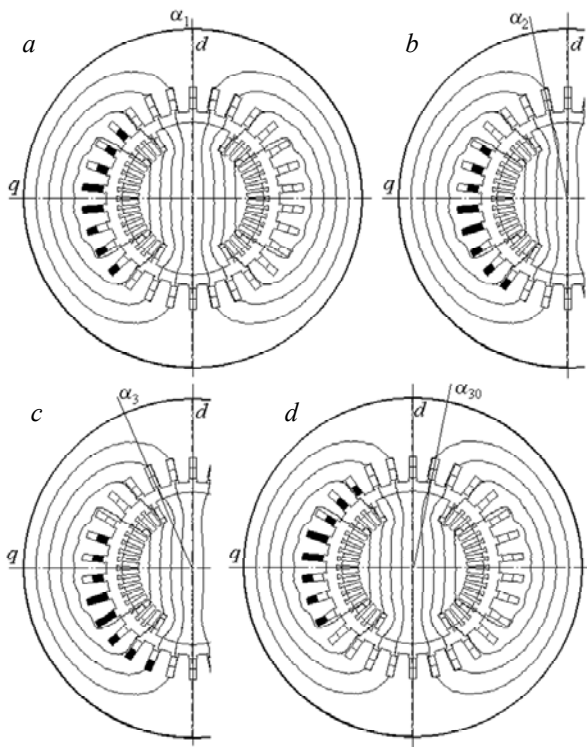


Fig. 4. Displacement of the phase zone of the stator winding against a background of the calculated MF to select the MFL values

In the initial angle position α_1 of the phase zone A in Fig. 4,a on the basis of formula (3) the MFL Ψ_1 is determined. Now move this zone conditionally on the tooth division to the position α_2 (Fig. 4,b) and find the corresponding value of the MFL Ψ_1 . The same repeat α_3 at position α_3 (Fig. 4,c), etc. – until the position α_{30} (Fig. 4,d). In general, the number of positions equals to the number of stator slots Q_s . A phase shift of each phase zone is made on angle $\Delta\alpha=360/Q_s$ (in degrees).

As a result we will have a discrete angular function of the MFL of one phase zone at its period T , i.e.

$$\Psi_k(\alpha_k); \quad \alpha_k = (k-1) \cdot \Delta\alpha; \quad k = 1, 2, 3, \dots, Q_s, \quad (4)$$

where k are number of angular positions of this zone.

For each position of the phase zone between 1 and $Q_s/2$ there is a diametrically opposite position between $Q_s/2+1$ to Q_s . They mutually create a conditionally movable phase winding $A-A'$, for which the angular

function of the MFL at its half-period:

$$\Psi_{A,k} = \Psi_k - \Psi_{k+Q_s/2}; \quad k = 1, 2, 3, \dots, Q_s/2. \quad (5)$$

By obtaining results, taking into account the periodicity of values in the TG type $\Psi(\alpha+T/2) = -\Psi(\alpha)$ we supplement the half-period of the MFL (5) to full period:

$$\Psi_{A,k+Q_s/2} = -\Psi_{A,k}; \quad k = 1, 2, 3, \dots, Q_s/2. \quad (6)$$

The number series of the MFL (5) is illustrated in Fig. 5 by set of highlighted points on the curve of the NL in the range of k from 1 to 15. On the basis of (6) the curve is extended to a full period (points 16 to 30) and point 31 repeated the first point (point 1) through a period T .

Similar actions were carried out and after calculating the MF at the RL mode, and the results are presented by the RL curve in the same Fig. 5. To display the initial phases of functions of the MFL the curves are continued to the left.

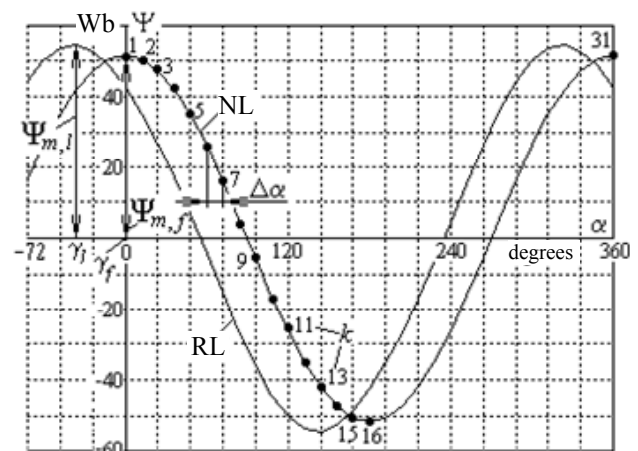


Fig. 5. Angular dependences of the MFL of the TG phase winding

Obtained numerical full angular function $\Psi_{A,k}(\alpha_k)$, $k = 1, 2, 3, \dots, Q_s$, can be presented as harmonic series expansion [6, 7]. Because of typical for the TG periodic condition $\Psi(\alpha+T/2) = -\Psi(\alpha)$ in this series there is no constant component and even harmonics. Assumed in [6] cosine series for the MFL is the following

$$\Psi_A = \sum_{v=1,3,5,\dots} \Psi_{m,v} \cos(v\alpha + \gamma_v), \quad (7)$$

There amplitudes and arguments (initial phases)

$$\Psi_{m,v} = \sqrt{s_v^2 + c_v^2}; \quad \gamma_v = -\text{arctg} \frac{s_v}{c_v} \quad (8)$$

Are obtained by sinus-cosine coefficients:

$$s_v = \frac{2}{Q_s} \sum_{k=1}^{Q_s} \Psi_{A,k} \sin(v\alpha_k); \quad c_v = \frac{2}{Q_s} \sum_{k=1}^{Q_s} \Psi_{A,k} \cos(v\alpha_k).$$

In (8) arctangent function $\text{arctg}(s_v/c_v)$ should be extended to give a value in the range of -180° до $+180^\circ$ depending on the signs c_v and s_v . In Lua there is a corresponding function $\text{atan2}(s_v, c_v)$.

In EM including TG analysis of the phase relationships is carried out for the first harmonics. For the first cosine harmonic of the MFL (7) at the NL the amplitude and initial phase $\Psi_{m,f}=51.97$ Wb and $\gamma_f=0$, at

the RL – $\Psi_{m,l} = 53.89$ Wb and $\gamma_l = -35.75^\circ$ are obtained (in the notation we do not show the harmonic number). The remaining harmonic, in principle, were negligible.

Illustration of angles γ_f and γ_l is presented in Fig. 5, where we see that the amplitude and hence the vector of the MFL at the RL mode are shifted toward negative value of the angle α relatively to the MFL at the NL mode.

The shift angle $\Theta = \gamma_f - \gamma_l$ is a load angle of the TG (in this case, it has a positive value). The vectors F_l and F_f in Fig. 1 have a similar shift.

Taking into account that in the TG the rotation angle is connected with time, i.e. $\alpha = \Omega \cdot t$, where Ω is the angular velocity, it is possible to go to the common temporal vector diagrams (VD) to illustrate and other phase relationships and the definition of other parameters. Such a VD is shown in Fig. 6, where as the origin of the angles vertically disposed longitudinal axis of the rotor d , as well as the angles in Fig. 1 is taken.

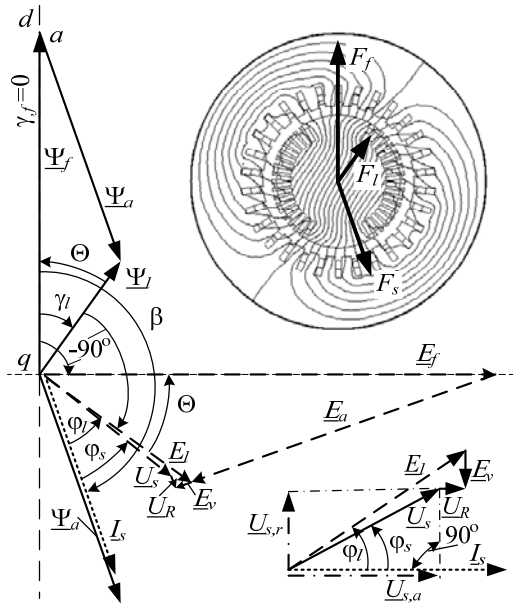


Fig. 6. Vector diagram corresponding the load mode of the TG

Phase current vector I_s is produced relatively the d -axis with respect to the previously caused β angle (in this case, it equals to -160.43°). The vector of the MFL Ψ_a phase windings, caused by the MF of the armature reaction corresponding to the vector F_s has the same direction. Vectors of the MFL Ψ_f from the rotor winding and the resulting MFL Ψ_l are carried out under already determined angles γ_f and γ_l .

Actually, selection of Ψ_a и Ψ_f from the MFL Ψ_l is conditional at the LM, and here the value Ψ_f is completely different compared to the NL mode. Parts of the MFL are determined by the procedure adopted here.

Namely, we adopt a base already defined MFL Ψ_l and from the end of its vector draw a line parallel to the vector Ψ_a to the intersection with a line oriented as Ψ_f at an angle γ_f . This intersection in the point a and identifies specific length of vectors Ψ_a and Ψ_f and their values in the scale of the vector Ψ_l .

Based on the known theory [2] by the amplitude of

the MFL at frequency f_s we have root-mean-square value of the first harmonic of the phase EMF, including and at the LM:

$$E_l = \sqrt{2} \pi f_s \Psi_{m,l}. \quad (10)$$

The vector of this EMF, as it is known, behind the vector of its MFL Ψ_l at -90° . Vectors of the EMF E_a and E_f from the MFL Ψ_a and Ψ_f are defined and constructed similarly.

It turns out that the triangle of the EMF E_l , E_a and E_f is similar to the triangle of the MFL Ψ_l , Ψ_a and Ψ_f . Therefore, between the vectors E_l and E_f will be the same angle of the load Θ .

In order to determine phase voltage U_s , it is necessary to take into account the voltage drop $\underline{U}_R = R_s \underline{I}_s$ at the active resistance R_s and EMF $\underline{E}_v = -jX_v \underline{I}_s$ from the flux of the phase winding end leakage, where X_v is the corresponding inductive reactance.

Obviously, the vector \underline{U}_R is parallel to the vector \underline{I}_s , and the vector \underline{E}_v – perpendicular (in the direction of lag). So they are attached to the end of the vector E_l and give as a result the vector of the phase voltage $U_s = \underline{U}_s = \underline{E}_l + \underline{E}_v - \underline{U}_R$.

It is known that in the TG the U_R value is negligible compared with E_l и U_s , but here they appear to demonstrate the full-factor approach.

From the geometric relationships on the VD, a fragment of which in the rotated form is shown in detail below on the right (without observing proportions), the active and reactive components of the voltage U_s , its root-mean-square value and the phase shift from the vector of current \underline{I}_s :

$$U_{s,a} = E_l \cos \phi_l - U_R; \quad U_{s,r} = E_l \sin \phi_l - E_v; \quad (11)$$

$$U_s = \sqrt{U_{s,a}^2 + U_{s,r}^2}; \quad \phi_s = \arctg(U_{s,r} / U_{s,a}), \quad (12)$$

Where by the VD the angle between \underline{I}_s and \underline{E}_l equals to $\phi_l = -\beta - 90 + \gamma_l$.

As a result, by the field calculation a lot of already considered electromagnetic parameters as well as active electric power of the TG are determined:

$$P_a = m_s U_s I_s \cos \phi_s. \quad (13)$$

Besides, it is possible to determine the electromagnetic torque of the TG which is made by the tensor of magnetic tension [2] in the correspondence with the formula

$$M_{em} = \frac{l_a}{\mu_0(r_s - r_r)} \int_0^{2\pi} \int_{r_r}^{r_s} r \cdot B_r \cdot B_\alpha \cdot r \cdot dr \cdot d\alpha, \quad (14)$$

where r_r and r_s are radii of circles limiting the gap from the sides of rotor and stator; B_r и B_α are radial and angular components of the magnetic flux density.

The magnetic flux through a surface bounded by the contour l , has the expression [2]:

$$\Phi = (A_{z1} - A_{z2}) \cdot l_a, \quad (15)$$

where A_{z1} , A_{z2} are the MVP values at the points 1 and 2 in a plane of calculation, through which in the axial direction lateral sides of the mentioned circuit l pass.

To automate all conditioned calculations, the presented further Lua script according to the purpose of

this work is intended.

File of initial data of the TG for the Lua script.

Requirements to create the program, as in [3, 4] are its flexibility in terms of the geometry and dimensions of the TG, as well as steady-state modes of operation – with a minimum of input data.

The values of various parameters of the TG and serving local constants and variables can be defined directly in the Lua script, or input from a pre-prepared text files. In this work, all the parameters that characterize this problem and perhaps changing for different variants of the TG, entered from a separate file.

Text files of Lua-scripts and data files are written in the editor *Notepad*.

Here is a data file that may have any name with the extension txt. Data have a form of numbers or text strings in quotation marks " " and accompanied by commentaries. To mark the beginning of comments the colon been have chosen.

Text of the file of initial data.

"FemC_TG340" : name_fem – name of the model in FEMM

"RezC_TG340" : name_rez – name of the file of results

3 : ms – number of stator winding phases

1 : p – number of pairs of poles

50 : fs – frequency, Hz

-160.47 : beta – initial phase of the stator currents, degree

3151.4 : Ir – rotor excitation current, A

11547 : Is – stator phase current, A

0.8 : bs – relative stub of the stator winding

0.00266 : Rs – active resistance of the stator winding, Ω

0.063 : Xv – inductive reactance of the end part of the stator winding, Ω

0.0 : gf – initial phase of the MFL at the NL mode, degree

30 : Qs – number of rotor slots

10 : Ns – number of series turns in the stator phase

1 : as – number of parallel branches of the stator winding

5.308 : la – turbo-generator active length, m

637.5 : rsi – radius of the stator core bore, mm

699 : rv – average radius of the upper layer of the stator winding, mm

778 : rm – average radius of the lower layer of the stator winding, mm

General characteristics of Lua language.

Language Lua, as well as other programming languages, can create loops, conditional statements, procedures, perform calculations on mathematical formulas for standard and created their own functions. There are functions: *sqrt* – square root; *sin*, *cos*, *atan2* – sine, cosine, arctangent, and others. There is built-in π number – Pi. Trigonometric functions operate with radians, but when dealing with geometric objects Lua uses degrees, rectangular coordinates are measured in millimeters, which are predetermined in the formulation of the problem in FEMM menu *Problem*, what has been done in [3].

The Lua script commands that begin with *mo_* or *mi_* are its procedures. Their description can be found via the *Help* button in the working window of FEMM, then

entered the section *Lua Scripting* [1].

Strings of the program or the right side, starting with a double hyphen - - are comments and do not affect its work.

External data file name Lua script asks after its launch by the operator with a "tip":

```
File_dan=prompt("Введите имя файла")
```

This name is entered from the keyboard and entered by press Enter. Script opens the file for reading ("r") and assign it internal name *f_d*, i.e.

```
f_d = openfile(File_dan .. ".txt", "r")
```

```
Reading operator read(f_d, "*n", "*l")
```

from the next line reads value of numeric and string data, how many times in it the option "* n" appears, and the option "* l" will make a transfer to a new line, i.e. remaining in the string any text is ignored and used by the user as a comment (we separate by symbol :).

In operators write to write to the results file the option "\r\n" gives a pass to new line, and the use of symbols such as % 6.3f is the format (format) of printing, i.e. in this case 6 position are reserved for the number, including 3 – for a fractional part.

Further a program is presented that after its call in the environment FEMM organizes input of the initial information and the calculation of the MF, forms an angular function of the MFL of the phase winding, determines its amplitude and the initial phase, as well as a number of electromagnetic parameters and phase relationships of different values in the TG.

Lua script.

```
--Definition of the file of initial
--data
File_dan=prompt("Input the file name")
--Opening of the data file
f_d = openfile(File_dan .. ".txt", "r")
--INITIAL DATA from the text file
name_fem=read(f_d, "*n", "*l")
--nameFEMM
--File name for the results writing
name_rez=read(f_d, "*n", "*l")
ms=read(f_d, "*n", "*l")
--number of phases
p=read(f_d, "*n", "*l") --pole pairs
fs=read(f_d, "*n", "*l") --frequency
```

By the same way all data from the above-mentioned file are read till rn, i.e.:

```
rn=read(f_d, "*n", "*l")
-- average radius of the lower layer
--of the stator winding
closefile(f_d) --closing the data file
--Organization of the file of results
writeto(name_rez) --name_rez file name
--Name of geometrical
--model of TG-type fem
name_fem=name_fem .. ".fem"
mi_saveas(name_fem) --to store model
--ADDITIONAL DATA FOR CALCULATION:
gr=Pi/180 --multiplier degree=>radian
beta=beta*gr --value of angle beta, rad
Ur=Rs*Is --voltage drop on Rs
Ev=Xv*Is --voltage drop on Xv
ts=360/Qs --angle of stator tooth step
tp=Qs/(2*p) --pole step in
```

```

--tooth division
qsp=tp/ms --slot number per pole and
--phase
qsn=0.5*(qsp-tp*(1-bs)) --slot number
-- of the lower layer of the stator
-- winding under q-axis
qsv=qsp-qsn -- slot number
-- of the upper layer of the stator
-- winding under q-axis
--Angle of the first lower bar of the
-- phase A
anl=180-(qsn-0.5)*ts
--Angle of the first upper bar of the
-- phase A
avl=180-(qsv-0.5)*ts
Im=Is*2^0.5/as --amplitude of the phase
-- current in the parallel branch
--Writing of some TG parameters
write("TG exciting data","\r\n")
write(format(" Is= %5.0f",Is),
format(" Ir= %5.0f",Ir),
format(" beta=%7.2f",beta/gr),"\r\n")
F = {} --massive creation to store
-- MFL values of phase winding
--Phase currents of the stator winding
c=2*Pi/3 Ia=Im*cos(beta)
Ib=Im*cos(beta-c) Ic=Im*cos(beta+c)
--Definition of currents of phases and
-- rotor in FEMM
mi_modifycircprop("iA+",1,Ia)
mi_modifycircprop("iA-",1,-Ia)
mi_modifycircprop("iB+",1,Ib)
mi_modifycircprop("iB-",1,-Ib)
mi_modifycircprop("iC+",1,Ic)
mi_modifycircprop("iC-",1,-Ic)
mi_modifycircprop("Ir+",1, Ir)
mi_modifycircprop("Ir-",1,- Ir)
--In FEMM-model there are names of
--marks of currents
--MF calculation in FEMM and path to
--demonstration and extraction of
--calculation results
mi_analyze(1) mi_loadsolution()
--Cycle of conditional displacement of
--the phase zone A with slot step ts
for k=1,Qs,1 do ak=(k-1)*ts --angle
--Cycle of calculation of conductors
--angles of phase A
for i=1,qsp,1 do ai=ak+(i-1)*ts
--Calculation of coordinates of
--conductors of lower layer and their
--extraction
ani=(anl+ai)*gr x=rn*cos(ani)
y=rn*sin(ani) mo_selectblock(x,y)
--Calculation of coordinates of
--conductors of upper layer and their
--extraction
avi=(avl+ai)*gr x=rv*cos(avi)
y=rv*sin(avi) mo_selectblock(x,y)
end --end of the cycle by i
--Reading of allocated blocks square
S = mo_blockintegral(5)
--MVP integral's value by square S
A = mo_blockintegral(1)
mo_clearblock() -allocation emptying
--MFL of the phase zone of winding A
F[k] = Ns*A/S
end -end of slot steps by k
--MFL of phase winding obtaining by
--MFL of phase zone and prolongation
--on period
q2=Qs/2 --a half of phase zone
-- positions
for i=1,q2,1 do F[i]=F[i]-F[i+q2]
F[i+q2]=-F[i] end
--Amplitude and phase shift
-- calculation
--MFL first harmonic by Fourier series
Fsin=0 Fcos=0 --storages nulling
for k=1,Qs,1 do --cycle by MFL array
ak=ts*(k-1)*gr --angular position
--Aplitudes of sin and cos components
Fsin=Fsin+2*F[k]*sin(ak)/Qs
Fcos=Fcos+2*F[k]*cos(ak)/Qs
end --sweep of k array elements
Fm1=sqrt(Fsin^2+Fcos^2) --amplitude
gl=atan2(Fsin,Fcos) -initial phase
--Electromagnetic parameters of TG
--RMS value of the phase EMF
El=Pi*2^0.5*fs*Fm1
--phase shift EMF El from current Is
fil=-(beta+Pi/2-gl)
--active and reactive components of
--phase voltage
Usa=El*cos(fil)-Ur Usr=El*sin(fil)-Ev
--RMS value of phase voltage
Us=sqrt(Usa^2+Usr^2)
--phase shift between Us and Is
--TG power ratio
fis=atan(Usr/Usa) cosfi=cos(fis)
teta=gf*gr-gl --TG load angle
Pa=ms*Us*Is*cosfi --active power
--Results writing to file
write(" MFL, phase shifts, EMF,
voltage and active power","\r\n")
--Angles recalculation (radians to
-- degrees)
gl=gl/gr fil=fil/gr fis=fis/gr
teta=teta/gr beta=beta/gr
write(format(" Fm1=%5.2f",Fm1),
format(" gl=%7.2f",gl),"\r\n")
write(format(" El=%5.0f",El),
format(" fil=%7.2f",fil),"\r\n")
write(format(" gf=%4.1f",gf),
format(" teta=%6.2f",teta),
format(" Us=%5.0f",Us),"\r\n")
write(format(" fis=%7.2f",fis),
format(" cosfi=%4.2f",cosfi),
format(" Pa=%6.1f",Pa*1e-6),"\r\n")
write("Electromagnetic torque
and power","\r\n")
--Rotor block groups allocation
mo_groupselectblock(9)
--Electromagnetic torque reading
Mem=mo_blockintegral(22) Mem=Mem*1e-3
mo_clearblock()--allocation emptying
--Electromagnetic power
Pem=Mem*2*Pi*fs*1e-3
write(format("Mem=%5.0f",Mem)," kN*m",
format("Pem=%6.1f",Pem)," MW","\r\n")
--Magnetic flux per pole
--in gap on the stator bore

```

```

--Cycle of angular steps in da degrees
for i=1,180,1 do da=1
--Coordinates of two neighbor points
ai=da*(i-0.5)*gr ai0=da*(i+0.5)*gr
x=-rsi*sin(ai) y=rsi*cos(ai)
x0=-rsi*sin(ai0) y0=rsi*cos(ai0)
--MVP reading in two points
A=mo_getpointvalues(x,y)
A0=mo_getpointvalues(x0,y0)
--MVP maximum search on the circle
if A0<A then Pot=2*A*la i=181 end
end --sweep of I points by the circle
write("Magnetic flux per pole, Wb",
format(" Pot=%5.3f",Pot),"\r\n")
writeto()--Results file closing
mi_close()--Closing of documents of
--magnetism preprocessor

```

Indications on the program utilization.

To use the script of the field calculation of parameters and phase relationships of the TG it is necessary:

1. The script file with the extension *.lua and file with initial data with the extension *.txt should be in the same folder on the computer disk.

2. Run the program FEMM – the TG model. Editor Lua is called from the working window in FEMM by the «key» *Open Lua Script* in menu *File*, and then in the window that opens, the desired file *lua* is started.

3. At the request of the program in the opened window we enter the data file name and press the button Enter. Further action the program executes itself.

4. The calculation results are in a text file with a name given in the data file with name RezC_TG340 and are read by the editor *Notepad*.

Content of the file of results.

The data presented correspond to the NL mode and are already illustrated in Fig. 5 and Fig. 6. For convenience of representation in the format of this paper the text of the file of results is partially reformatted.

```

TG excitation data
Is=11547 beta=-160.43 Ir=3153
MFL, phase shifts, EMF, voltage and
active power
Fml= 53.89 gl= -35.75
El=11971 fil= 34.68
gf= 0.0 teta= 35.75 Us=11547
fis= 31.79 cosfi=0.85 Pa=340.0
Electromagnetic torque and power
Mems=-1086 kN*m; Pems=-341.2 MW
Magnetic flux per the stator pole, Wb
Pot=6.608

```

In the full version of the Lua script other results are calculated in inputted to the text file, too.

Conclusion. The presented theoretical basics and Lua scripts provide wide opportunities for users of the

program FEMM for automated obtaining of electromagnetic parameters and phase relations of the TG on the basis of the calculation of the magnetic field. This script is universal in terms of the structure of the electromagnetic system of the TG within their wide-spread structure, and steady-state modes of their operation. Designed Lua script may be a prototype for similar software for calculations of EM of other types.

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