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THE NUMERICAL-FIELD ANALYSIS OF THE MAGNETIC FIELD AND THE ELECTRICAL QUANTITIES IN THE TURBOGENERATOR STATOR UNDER AUTONOMOUS UNBALANCED LOADING

Purpose. Assessing the impact of load asymmetry of turbogenerator (TG) on the magnetic field distribution, on the electrical and energy processes in it based on the numerical-field analysis within the constraints regulated by the standards. Methodology. The calculation model of TG has been constructed on the method of symmetrical components of the three-phase current system. The formed asymmetric system of the currents is used for multi-position numerical calculations of rotating magnetic fields. The temporal functions of the electromagnetic quantities which are subjected to the harmonic analysis are obtained on this basis. Results. Test calculations are conducted on a three-phase 35 MW TG during his work under autonomous unbalanced loading. The analysis of the temporal functions of the magnetic induction at different points of the TG stator and also similar functions of the magnetic flux linkage, EMF phase stator windings and other variables have been executed. Originality. Problems of exploitation of turbo-generators under unbalanced loading are detected by the consideration of their electromagnetic system on the whole, but not their simplified local parts, as usual. It has been shown that the temporal functions of EMF of the phase stator windings under unbalanced loading significantly differ in shape from sine waves and from each other and contain a number of significant upper harmonics. It has been detected that the phase currents would contain not only the first but also significant upper harmonics under unbalanced loading. Practical value. Analysis of the work of TG under unbalanced loading showed the «top» level of problems of electromagnetic character. It has been established that the function of the magnetic induction at the fixed points of the magnetic system on the whole have been changed but not in principle. The temporal functions of EMF, and, hence, the voltage of the stator phase windings significantly differ in shape from sine waves and from each other, there is a considerable imbalance of active powers generated by the individual phase windings of the stator. The information provided will allow the measures to ensure a durable and reliable operation of turbo-generators. References 14, tables 2, figures 9.

Key words: **turbo-generator, unbalanced loading, magnetic fields, numerical calculations, electromagnetic processes, temporal functions.**

На основе численных расчетов вращающегося магнитного поля проведена оценка работы турбогенератора при несимметричной нагрузке. Анализируются временные функции магнитной индукции в неподвижных точках магнитной системы статора, форма и гармонический состав ЭДС его обмоток, их мощности. Результаты расчетов при несимметричной нагрузке сопоставляются с аналогичными результатами при симметричной нагрузке. Библ. 14, табл. 2, рис. 9.

Ключевые слова: **турбогенератор, несимметричная нагрузка, магнитные поля, численные расчеты, электромагнитные процессы, временные функции.**

Introduction. Along with the basic mode of operation of turbo-generators (TG) to the symmetrical loading for which they usually are designed [1], by the interstate standard DSU 533-2000 and long-term operation at unbalanced loading is regulated. And this applies both to an autonomous work of TG, and to work on the power system [2].

Operation at unbalanced load leads to a number of additional problems in the operation of TG which are of electromagnetic nature and result increased thermal and power stresses, vibration problems and poor-quality of the three-phase power supply system.

So, for example, for TG up to 100 MV·A, according to the standard and normal VDE 0530, it is allowed a long-term unbalanced load with the negative sequence current up to 8 % of the rated current. At higher power, due to increased exploitation, the permissible unbalanced load should be reduced.

These limitations are the result of numerous studies of unbalanced modes of turbo-generators [3] which showed that we need to strengthen structures for sufficient thermal stability of the rotor.

Calculations at unbalanced loading conducted earlier by analytical methods could not reach the fullness of the electromagnetic processes in the TG. With the development of numerical methods for the calculation of electromagnetic fields, the possibilities of mathematical modeling have increased significantly. However, the attempts to study mainly concern the calculation of eddy currents (EC) in the local conductive elements on the surface of the rotor from the magnetic field of the negative sequence with very serious easy simplifications of the calculated area.

For example, in [4] and [5] computer modeling of electromagnetic processes in the TG of 300 MW in two-dimensional formulation at long-term unbalance loading is carried out. The focus is on the study of EC and additional power losses in the rotor slot wedges. However, such conflicting results in these two works are given that we have to doubt their authenticity: the current density and heat generation differ by several orders of magnitude.

To identify problems of operation of TG at unbalanced loading from different sides, and not only in terms of EC in the rotor wedges, with a sufficient degree of adequacy we can only considering TG in general, not limited to its local simplistic parts. The complete formulation is a task of extreme complexity. So here, keeping the overall structure of the TG electromagnetic system, we consider another extreme case of assumptions – the lack of EC response in the rotor elements.

This makes it possible to identify the «top» level of the problems of the electromagnetic nature which in reality will be smoothed by damping reaction of currents in the electrically conductive array of the rotor body and its individual elements.

New opportunities for the study of the problems of the electromagnetic nature at the operation of the TG at unbalanced loads are provided by numerical methods of magnetic fields calculation [6, 7] in conjunction with high-speed computers and efficient software. This contributed to the novelty of the results presented, as TG electromagnetic system as a whole is considered.

The goal of the work. This work is devoted to assessing the influence of TG unbalance loading on the distribution of the magnetic field, electrical and power processes in them based on the numerical-field analysis within indicated limitations of Standards. This is carried out through the identification and analysis of temporal functions of the magnetic flux density (MFD) at different points of the TG stator and similar functions of the magnetic flux linkage (MFL) and the EMF of phase stator windings.

Numerical methods for the calculation of the magnetic fields are removed restrictions on the account of actual constructive shapes of electric machines as a whole and their elements, on account of the magnetic saturation. Here, powerful modern computers allow you to do this in the statics and dynamics. Examples of such studies are presented in papers by the author [7, 8] and other researchers, for example, in [9].

Object of investigations. Demonstration calculations are carried out on a three-phase two-pole TG, a cross section of the electromagnetic system of which is shown in Fig. 1. It has rated: power P_N = 35 MW, phase voltages U_{sN} = 6.3 kV and current I_{sN} = 2315 A at the stator winding circuit – «triangle»; power factor $\cos\varphi_{sN}$ = 0.8; frequency f_s = 50 Hz. Active stator length l_a = 2.7 m; nonmagnetic gap – 27 mm; rotor radius – 0.408 m; on the phase stator winding there are N_s = 18 consecutive turns, its relative shortening β_s = 22/27; phase winding resistances: active R_s = 0.00537 Ω; reactive from a frontal scattering X_v = 0.134 Ω; in the rotor winding the turns number N_r = 224.

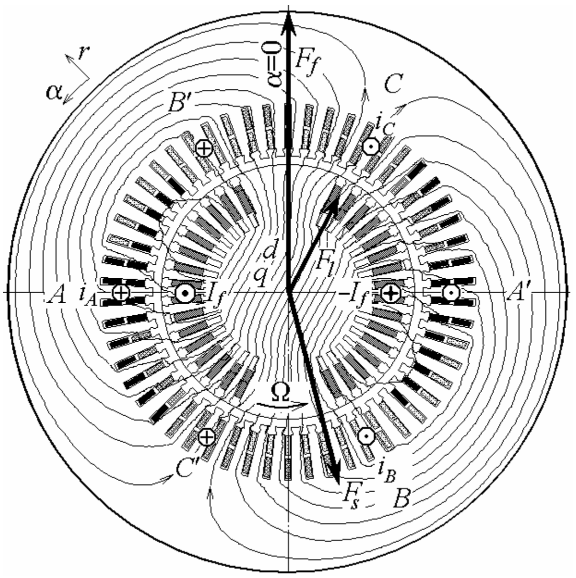


Fig. 1. Calculation model of the turbo-generator with magnetic field distribution at the unbalanced load

Theoretical basics of the TG unbalanced operation mode analysis. Unbalanced modes in three-phase TG are results of phase currents difference because of different stator phase windings loadings. These modes are investigated by using the method of symmetrical components [2, 3]. Actually, phase currents of direct $\underline{I}_{A1}$, $\underline{I}_{B1}$, $\underline{I}_{C1}$ and negative $\underline{I}_{A2}$, $\underline{I}_{B2}$, $\underline{I}_{C2}$ sequences as well as resulting currents $\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$ are considered. Their assumed initial system is presented in Fig. 2 by vector diagram.

In the correspondence with DSU 533-200 RMS of negative sequence currents are assumed $0.08 \cdot I_{sN}$. Besides, maximal RMS of all resulting phase currents is limited by rated value I_{sN}.

On this basis, by calculation it is determined that the phase currents RMS are I_A=2170.2 A; I_B=2314.7 A; I_C=2015.3 A, and more detailed methods of their calculation is presented in [10].

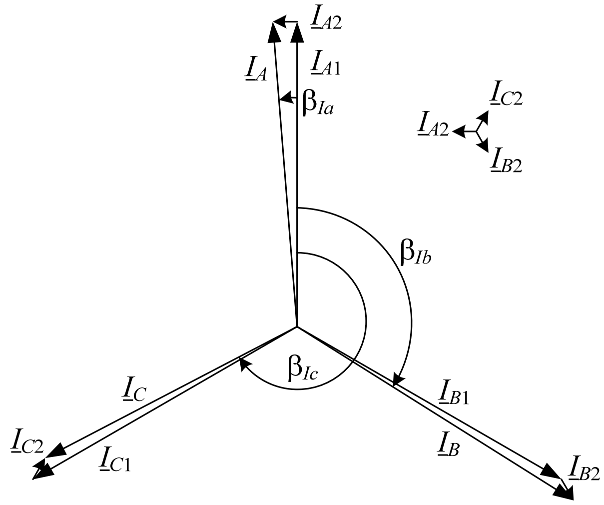


Fig. 2. Phase currents of direct and negative sequence and resulting TG currents

In the calculations of rotating magnetic fields instantaneous values of phase currents are used [7, 8]. In this paper, at unbalanced loading phase currents are defined by their temporal functions:

$$i_A = I_{ma} \cdot \cos(\omega \cdot t + \beta_{Ia} + \beta);$$
$$i_B = I_{mb} \cdot \cos(\omega \cdot t + \beta_{Ib} + \beta); \qquad (1)$$
$$i_C = I_{mc} \cdot \cos(\omega \cdot t + \beta_{Ic} + \beta),$$

where ω=2 πf_s is the angular frequency; I_{ma}, I_{mb}, I_{mc} are the amplitudes of currents determined by their above-mentioned RMS.

The initial phase of currents β_{Ia}, β_{Ib}, β_{Ic} determined initially by summing the vectors in Fig. 2 and therefore rigidly connected with each other. They were then turned on all selected by numerical experiments a certain angle so that when β = 0 resulting MMF of the stator winding F_s is directed along the longitudinal rotor axis d which is shown in Fig. 1. In such a way the necessary initial phase are received: β_{Ia} = 9.15°; β_{Ib} = –117.56°; β_{Ic} = –237.88°.

In (1) additional rotation angle β for all currents, respectively, rotates vector F_s of MMF at the same angle with the proviso that when at predetermined stator currents and excitation current to provide the required output electric power of TG as presented in [11]. Placed in such a position vector F_s is shown in Fig. 1. Together with the vector of MMF of field winding F_f they form a conditional resulting MMF at the load mode F_l.

The system of phase relationships of electromagnetic quantities in TG is presented in detail in [11] for the mode of its symmetrical loading. This angle β and field current I_f are determined by a special technique from the condition that they must provide the nominal output data of the TG: U_{sN} voltage and power factor $\cos\varphi_{sN}$ which makes at a rated current of the stator I_{sN} rated active power P_N. Specifically, for the considered TG at the symmetrical loading β = –165.12° and I_f = 632 A are detected. The RMS of the phase currents were I_A=I_B=I_C=2315 A and in the system (1) β_{Ia} =0; β_{Ib} =–120°; β_{Ic} =–240° were adopted.

To adequately reflect changes that occur in the TG at the transition from symmetric to unbalanced loading, it was found that here the control actions on TG absent. That is, from the turbine to the TG shaft the same mechanical power is supplied and excitation current is stored, as that at the symmetrical loading. On this basis by numerical experiments using already called β value as the first approximation, it was found that the rated power at unbalanced loading is obtained at β = –167.2° and presented excitation current I_f = 632 A. The vector diagram of formed asymmetrical current system and obtained as results of computation other electromagnetic quantities calculation is presented below.

For the analysis of electromagnetic processes in the active part of the TG magnetic field at given its winding currents is calculated in 2D formulation in its cross section (Fig. 1). This field is described by the known differential equation

$$\mathrm{rot}\left[\frac{1}{\mu}\mathrm{rot}\left(\vec{k}\,A_z\right)\right]=\vec{k}\,J_z\,, \qquad (2)$$

where A_z, J_z are axial components of the magnetic vector potential (MVP) and current density; μ is the absolute magnetic permeability; $\vec{k}$ is the ort by axial axis z.

Organization of calculation of temporal functions of electromagnetic quantities. The values stated with the purpose of the work of values of MFD, MFL and EMF are determined based on the calculation of the magnetic field of TG and their temporal functions by such multi-position calculations [7, 8] for time series with step Δt:

$$t_k=\Delta t\cdot(k-1);\ k=1, 2, ..., K, \qquad (3)$$

at corresponding angular positions of the rotor

$$\alpha_k=\Delta\alpha\,(k-1);\ k=1, 2, ..., K, \qquad (4)$$

and with synchronous stator magnetic field rotation by changing of phase currents (1) in its winding in the correspondence with series t_k (3).

In (3) and (4) $\Delta\alpha$=$\Omega\cdot\Delta t$, Ω=ω/p are the angular step and the rotor rotation speed; p is the number of pole pairs.

Symbol K in (3), (4) denotes the number of positions permitting to adequately form temporal functions on their period T.

Considered in this work functions have semiperiodic asymmetry with a condition like

$$\Gamma(t_k + T/2) = -\Gamma(t_k),\ k=1,2,...,K, \qquad (5)$$

where Γ is the yet generalized letter.

Therefore, functions of actual quantities taking into account the TG magnetic field periodicity are formed at the rotor rotation from 0 to 180° with angular step of 1°, i.e. K equals to 180.

The magnetic field based on (2) is calculated by the finite element method taking into account the saturation of the core by the FEMM software [12]. Operations during its work on the calculation of the field, the definition of electromagnetic parameters and the formation of temporary functions are carried out by the control program written on the algorithmic language Lua [13].

Magnetic field distribution at the unbalanced loading mode at initial time is shown in Fig. 1 by magnetic field lines. Note that the structure of the magnetic field corresponds approximately to what was the case in the symmetrical loading.

Temporal functions of the magnetic flux density. The base quantity used in electromagnetic calculations is the magnetic flux density in the form of its radial and angular components as well as its module:

$$B_r=\frac{1}{r}\frac{\partial A_z}{\partial\alpha}\,;\ B_\alpha=-\frac{\partial A_z}{\partial r}\,;\ B=\sqrt{B_r^2+B_\alpha^2}\,. \qquad (6)$$

Note that in areas of the laminated cores the FEMM software «outputs» MFD values «smeared» for the whole of their axial length. Therefore, it is necessary to divide these values into k_{Fe} – filling factor of the core by steel. Then we obtain the MFD values directly for the steel sheets. For the considered TG taking into account laminating and packaging of the stator core, this ratio was 0.78.

In the fixed points of the TG electromagnetic system by already represented principle temporary MFD functions in discrete form are obtained:

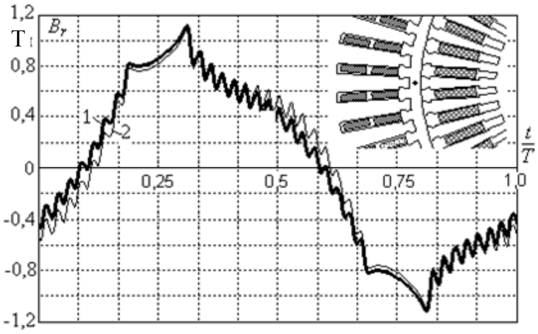
$$B_r(t_k),\ B_\alpha(t_k),\ B(t_k),\ k=1,2,...,K. \qquad (7)$$

Note that at the expansion of the values obtained to the second half period by the condition (5) for the module of B it is not necessary to change the sign.

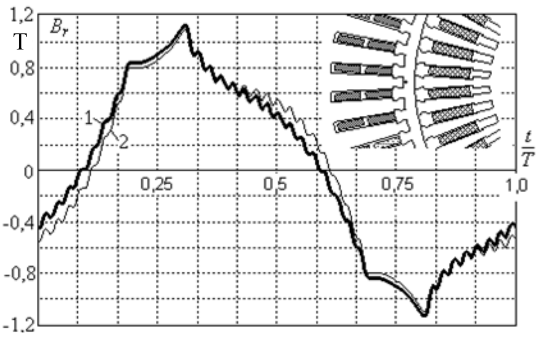
Distributions of temporal functions (7) for two fixed points in the gap are shown in Fig. 3 where time is given in relative units. Variant *a* corresponds to the point in the middle of the gap, *b* – on the bore of the stator core.

The presented functions are far from sinusoidal. In these charts there are clear zones of influence of the large rotor teeth and claw tooth pulsations from the rest of its teeth. The pulsations are amplified as they approach the surface of the rotor (from Fig. 3*b* to Fig. 3*a*). In temporary functions in fixed points tooth pulsation from the stator core are not shown as it is presented more in [8].

Fig. 4 shows the temporal function of the radial component of the magnetic flux density in the tooth of the stator core in the indicated on the fragment of the Figure points *z*1 and *z*2 – in its crown and the base. Functions $B_r(t)$ again far from sinusoidal, and substantially are formed by toothed rotor structure, although with some damping of tooth pulsations compared to what it was in the gap (Fig. 3). Obtained charts indicate that adopted in the design of TG sinusoidal character of the magnetic flux density in the teeth is a very rough approximation.



a



b

Fig. 3. Temporal functions of the MFD radial component in the indicated points in the gap on the stator core tooth axle:
1 – asymmetry; 2 – symmetry

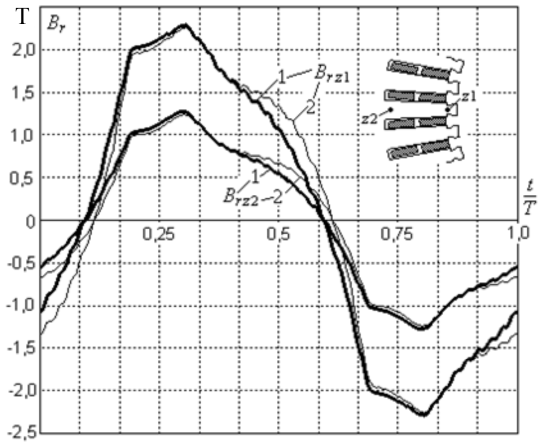


Fig. 4. Temporal functions of the radial component B_r of the magnetic flux density in the stator core tooth:
1 – asymmetry; 2 – symmetry

Fig. 5 shows the temporal functions of the angular component B_α and the MFD module B in the indicated point at the back of the stator core. Functions $B_\alpha(t)$ are close to sinusoidal, although experiencing some distortions, reaching from the functions already present in the gap and teeth.

In general, in Fig. 3 – 5 differences for various types of the TG loading though are noticeable but not fundamental. A general interest is the nature of these functions the obtaining of which is, in principle, it has been possible on the basis of multiposition calculations of the magnetic fields. This is a non-trivial approach to electric machines in general.

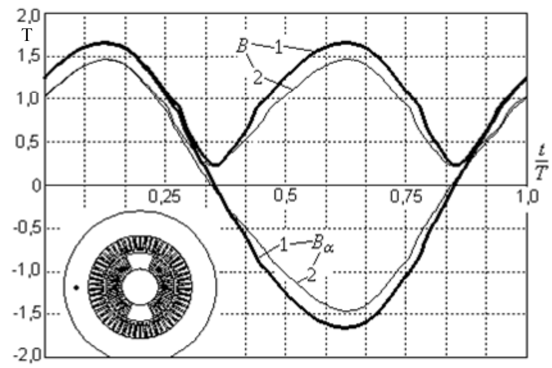


Fig. 5. Temporal functions of the angular component B_α and module B of the magnetic flux density in the stator core:
1 – asymmetry; 2 – symmetry

Magnetic flux leakage and EMF of stator phase windings. As it was already presented in [7] the base of the EMF is the temporal MFL function of the stator phase winding.

MFL is obtained by the MVP distribution. For example, for each of the six phase zones (Fig. 1) MFL is determined by the formula

$$\Psi = \frac{N_s l_a}{S_\varphi} \int\limits_{S_\varphi} A_z dS \, , \qquad (8)$$

there S_φ is the sectional area by conductive phase zone's elements.

Determination of the MFL by the formula (8) is not difficult since to determine S_φ and the integral in the integrated in the FEMM software Lua script there are appropriate procedures [14].

For all phase winding, for example for the phase A, MFL is obtained by the formula

$$\Psi_A = \Psi_{sA} - \Psi_{sA'} \, , \qquad (9)$$

there Ψ_{sA} и $\Psi_{sA'}$ are the MFL in the phase zones A and A' (Fig. 1) determined by formula (8).

On this base in the process of already described calculation of the rotating magnetic field the discrete temporal MFL function is formed

$$\Psi_s(t_k),\ k=1,2,...,K, \qquad (10)$$

where the index s is the generalized letter of any phase windings: A, B, C.

The function $\Psi_s(t_k)$ is decomposed as in [7, 8] according to known rules in the cosine harmonic series of odd harmonics taking into account the condition (5)

$$\Psi_s = \sum_{\nu=1,3,5...}^{N_g} \Psi_{m,\nu} \cos(\nu\,\omega\,t + \gamma_\nu) \, , \qquad (11)$$

where the summation over harmonics numbers ν is possible until N_g number which, in principle, is limited by accepted in (5, 10) value of K.

Based on the law of electromagnetic induction a transition from (11) to the phase winding EMF is carried out:

$$e_s = -\frac{d\Psi_s}{dt} = \sum_{\nu=1,3,5...}^{N_g} \nu\,\omega \Psi_{m,\nu} \cos(\nu\,\omega\,t + \gamma_\nu - \pi/2) \, , \qquad (12)$$

from here amplitudes of harmonics $E_{m,\nu}=\nu\omega\Psi_{m,\nu}$ are obtained.

Temporary functions of MFL (11) and EMF (12) were determined for each of the phase windings and at the unbalanced loading were, of course, different. They are shown in their full period of the change in Fig. 6.

For comparison, calculations were carried out using the same procedure and under TG symmetric load. The corresponding results are shown in Fig. 7.

Obviously, at the symmetric loading the temporal MFL functions are close to sinusoidal, but in the nature of the EMF a marked influence of the higher harmonics has shown, which, unlike similar MFL harmonics multiplied by their numbers.

At the unbalanced load EMF functions difference of different phases and how they differ from regular sine waves appeared a much greater extent, and the distortions and the differences are already noticeable and for source for EMF the MFL functions.

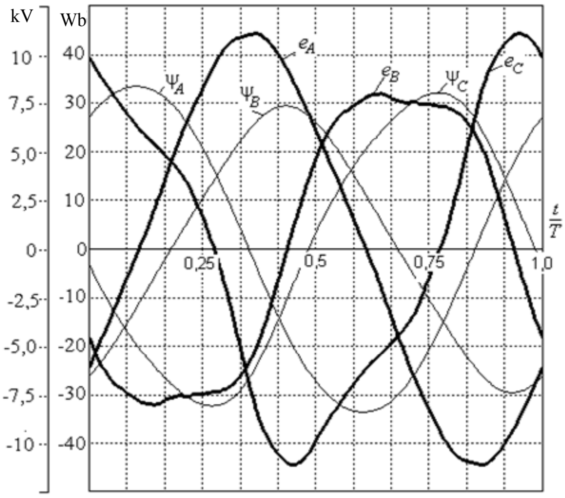


Fig. 6. Temporal functions of the phase MFL and EMF at the TG unbalanced loading

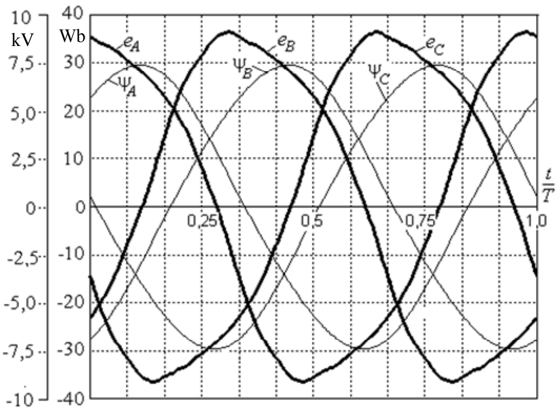


Fig. 7. Temporal functions of the phase MFL and EMF at the TG symmetric loading

Sense shown «top» level of the electromagnetic nature of the problems is that understood: for their «anti-aliasing» to an acceptable level requires an adequate response these currents, which actually transports them to a problem with the current, which is also a serious problem with asymmetrical operation TG load. Table 1 shows the numerical data for the phase EMF at the TG unbalanced loading. Here, the amplitude of the first EMF harmonic $E_{m,1}$ and its RMS $E_{s,1}$ are given in absolute terms, and the amplitude of the higher harmonics – in the relative form $E_{m,\nu,*} = E_{m,\nu} / E_{m,1}$. In general, the influence of higher harmonics is estimated by the distortion coefficient

$$d_{dist} = \frac{E_{m,1}}{\sqrt{\sum_{\nu=1}^{N_g} E_{m,\nu}^2}} . \quad (13)$$

Table 1

Harmonic composition of the stator winding EMF

Phase	$E_{m,1}$, V	$E_{s,1}$, V	$E_{m,3,*}$	$E_{m,5,*}$
A	10702	7568	0.043	0.007
B	8865	6268	0.144	0.018
C	10071	7121	0.183	0.015
Phase	$E_{m,7,*}$	$E_{m,9,*}$	$E_{m,11,*}$	d_{dist}
A	-	0.005	0.003	0.999
B	0.003	0.007	0.003	0.990
C	0.004	0.008	0.004	0.983

The large proportion of the third harmonic is obvious which at the «triangle» scheme will also create a problem of significant parasitic circulating currents in the three phase windings [5].

In addition to the already mentioned values of phase relations in (1), from the expansion type (11) for each phase winding by the argument γ_ν the initial phases of the MFL $\gamma_{\psi a}$, $\gamma_{\psi b}$ and $\gamma_{\psi c}$ for the first harmonics are determined. Phase EMF behind their MFL for $\pi/2$ or 90°, respectively (12). Then the initial phases of the EMF are $\gamma_{Ea}=\gamma_{\psi a}-90°$; $\gamma_{Eb}=\gamma_{\psi b}-90°$; $\gamma_{Ec}=\gamma_{\psi c}-90°$. Determined are the phase shifts of the EMF with respect to currents of their phase windings:

$$\varphi_{IEa} = \gamma_{Ea} - \beta_{Ia} ; \varphi_{IEb} = \gamma_{Eb} - \beta_{Ib} ; \varphi_{IEc} = \gamma_{Ec} - \beta_{Ic} . \quad (14)$$

All these phase relationships and relationships of values of the phase currents, MFL, EMF and voltages are represented in scale in Fig. 8 by means of the vector diagram. This corresponds to the first harmonics of the electromagnetic quantities of the TG at unbalanced loading for all the phase windings.

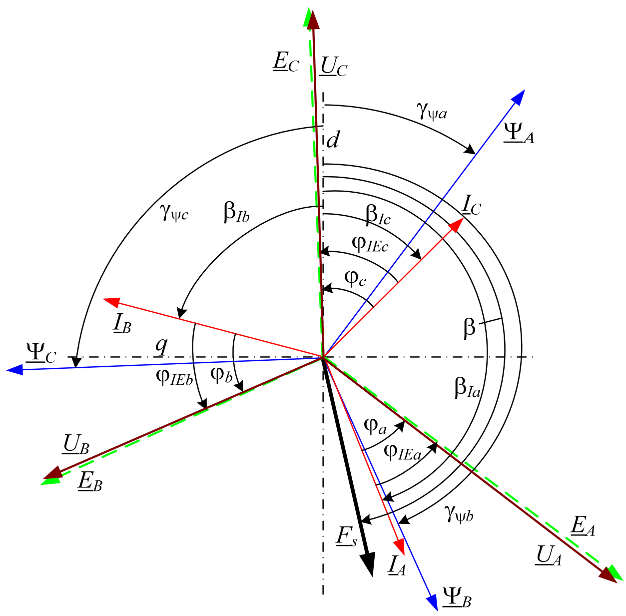


Fig. 8. Vector diagram of the electromagnetic quantities at the TG unbalanced loadings

The definition of the phase voltage we conduct on an example of the phase winding *A*. Necessary for this fragment to the vector diagram of Fig. 8 is shown in Fig. 9*a* in original and with the increase of the scale, and in the rotated view without observing the proportions is shown in Fig. 9*b*. Here, in addition the voltage drop on the active resistance of $\underline{U}_R=R_s\,\underline{I}_A$ as well as EMF from the flow of frontal scattering $\underline{E}_v=-jX_v\,\underline{I}_A$ are shown.

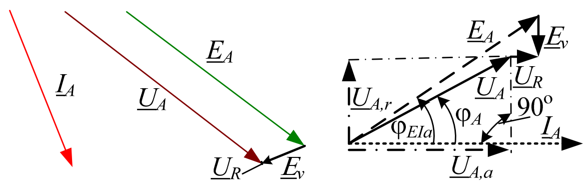


Fig. 9. Fragments of the vector diagram

From geometrical relations in Fig. 9*b* active and reactive voltage components, its RMS and phase shift from the vector of current, as well as active power are obtained:

$$U_{A,a}=E_A\cos\varphi_{IEa}-U_R;\ U_{A,r}=E_A\sin\varphi_{IEa}-E_v;\ (15)$$

$$U_A=\sqrt{U_{A,a}^2+U_{A,r}^2};\ \ \varphi_{sA}=\mathrm{arctg}(U_{A,r}/U_{A,a})\ ;\ (16)$$

$$P_{aA}=U_A I_A\cos\varphi_{sA}\,. \qquad (17)$$

Similarly, all done for the other phase windings and calculation results with the generalizing index *s* are presented in Table 2. Obviously, the total active power of the TG was 34.90 MW, i.e. almost nominal power is generated. At the reduced stator currents but at rated excitation current this was due to the increase in EMF and voltage due to the increase of the MFL with reduced armature reaction.

Table 2

Calculation data at the unbalanced loading

Phase	I_s	U_s	$\cos\varphi_s$	φ_s, grad	P_a, MW
A	2170	7489	0.861	30.55	14.00
B	2315	6174	0.785	38.28	11.22
C	2015	7029	0.684	46.86	9.69

In Table 2 we should pay attention to the difference of the phase windings loadings – by active power and the nature set by specified power factor. This means that one of the reasons of the specifically considered unbalance is different nature and value of the phase resistances of the three-phase loading.

The value of the phase voltages in Table 2 is not very different from the phase EMF in Table. 1. Therefore, the voltages have approximately the same harmonic composition as EMF. So, the phase currents will have the similar composition. Thus, the unbalanced loading is always accompanied by not sinusoidal and more complicated functions as harmonic series of about the same composition as in Table. 1.

From all of this it follows that the adopted sinusoidal character of currents here (1) and in the Standard is another major assumption of the calculation method adopted in this paper and in the calculations of the unbalanced loading in the mentioned [4, 5] and other similar works.

Apparently, the more precise formulation of the problem of calculation of unbalanced modes of operation is to harmonize the temporal function of the phase currents and EMF – perhaps by the iterative way or another effective technique.

Defined in [10] and continued here research theme does not exhaust the possibilities of the developed method of analysis of the TG unbalanced operation mode. This method allows you to continue the study started, and, above all, the consideration of the electromagnetic processes in the rotor and force actions in the entire electromagnetic system of the TG.

Conclusions.

1. Problems of exploitation of TG at asymmetrical loading it is possible to fully identify in quite considering the TG as a whole, and not its local simplified parts. Here, to analyze a wide range of problems of the electromagnetic nature an effective base is the multiposition numerical calculations of rotating magnetic fields allowing to form temporal functions of the considered quantities.
2. An extremely difficult problem of analyzing the electromagnetic phenomena in the overall structure of the TG electromagnetic system is just solved under the assumption of lack of response of the EC in the rotor design elements, as well as how it was identified, sinusoidal nature of the TG phase currents. It is possible to reveal the ultimate level of the problems of the electromagnetic nature which in reality will be smoothed by the damping reaction of indicated currents.
3. By the considered complex of the electromagnetic phenomena within standard limits of the TG unbalanced mode it was found that:
   - functions of the magnetic flux density in the fixed points of the magnetic system in general have changed, but not the principle, in the gap and the teeth of the stator core they are far from sinusoidal and in addition they even have a tooth pulsations due to the rotor core, in the back of the stator it is close to sinusoids;
   - temporal EMF functions and, hence, the stator windings phase voltages by the shape are significantly different from sine waves and each other, differences of such EMF are obvious by values, too;
   - there is a significant imbalance of active powers generated by the individual stator phase windings.
4. Sense shown «top» level of the problems of the electromagnetic nature is that understood: for their «smoothing» to the acceptable level an adequate reaction of indicated currents is required which actually transports problems from them to these currents that is also a serious problem of the TG exploitation at the unbalanced loading.

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