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INVESTIGATION OF OPERATING MODES OF HOMOPOLAR SHOCK GENERATOR W--ETC(U)
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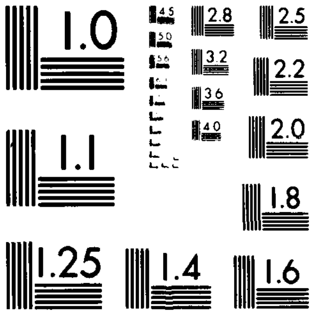
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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

INVESTIGATION OF OPERATING MODES OF HOMOPOLAR SHOCK GENERATOR WITH REGULATION OF EXCITATION FLOW

BY

V.V. Kharitonov

FOREIGN TECHNOLOGY DIVISION

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	sinh^{-1}
cos	cos	ch	cosh	arc ch	cosh^{-1}
tg	tan	th	tanh	arc th	tanh^{-1}
ctg	cot	cth	coth	arc cth	coth^{-1}
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

INVESTIGATION OF OPERATING MODES OF HOMOPOLAR SHOCK GENERATOR WITH REGULATION OF EXCITATION FLOW

V. V. Kharitonov, Cand. tech. sciences.

The method of calculation of transient processes is examined in the excitation circuit of homopolar shock generator with massive magnetic circuit, during which equivalent circuit diagram is used. On the basis of the method there are analyzed several operating modes of the generator with regulation of excitation flow.

At the present time one of the most important directions of development of homopolar generators is the development of pulse-action machines - homopolar shock generators (UUG). Massive rotors of UUG are used as flywheels with large kinetic energy reserve, being converted in the process of generator discharge into energy of pulsed electromagnetic field. The normal operating mode of UUG is sudden closing of the load circuit of the excited generator, the rotor of which is rotated at prescribed speed, with simultaneous disconnection from the network of the drive motor (or separation of the shafts of generator and motor).

A promising area of application of UUG is the technology of obtaining strong magnetic fields, where they are used for pulsed supply of windings of different electrophysical equipment. Here the UUG successfully compete with other sources of pulsed supply, exceeding them in such indices as maximum and specific energy, relative weight and cost, and conforming to the most complete series of specific requirements.

The main structural diagrams of performance of UUG are shown in Fig. 1.

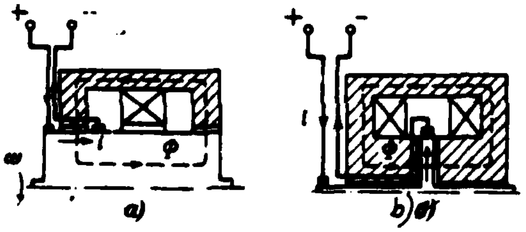


Fig. 1. Main structural diagrams of performance of UUG. a - cylindrical type generator; b - disk-type generator; I - armature current; Φ - working magnetic flux; ω - angular velocity of rotation of rotor.

The current-carrying elements of UUG are made so as to most fully compensate the flow of the armature reaction. In the cylindrical type generator (Fig. 1a) the current-carrying elements are made, for example, in the form of hollow coaxial cylinders, through which armature current passes in opposite directions. One cylinder is attached on the massive rotor and accomplishes the role of armature "winding", the other is pressed into the bore of the stator and is the compensating "winding". In disk-type UUG (Fig. 1b) the compensation of the flow of armature reaction is provided by arrangement of a compensating disk in the working clearance of the generator, through which armature current passes in the direction, opposite its direction in the rotor. The system of current-lead buses in the UUG is also made so as to eliminate magnetization of the magnetic circuit by the armature current.

During the shaping of current pulses of UUG of a certain configuration there is widely applied regulation of the excitation flow of the generator. During investigation of such operating modes of UUG it is necessary to take into account the action of eddy currents, appearing in the massive magnetic circuit of the generator with change of the excitation flow. A convenient basis of investigation in this case is the equivalent circuits. In Fig. 2b is shown a linear equivalent circuit of the excitation circuit of two-pole UUG.

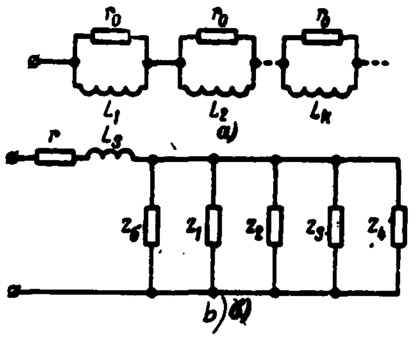


Fig. 2. Equivalent circuits. a - massive section of magnetic circuit; b - excitation circuit of UUG.

The magnetic circuit of the machine enters it in the form of a dual electric circuit, the parameters of which are determined, proceeding from equivalent operator resistances of the characteristic sections of the magnetic circuit [1]. To the massive sections of the magnetic circuit correspond small circuits with theoretically infinite number of series-connected circuits with identical effective resistances r_0 and inductances L_k decreasing with increase of the number of circuit (Fig. 2a). They enter the equivalent circuit in the form of parallel branches z_1, z_2, z_3, z_4. All inductances of the circuit depend on the magnetic permeability of material of the massive section, whereas effective resistances r_0 do not depend on the level of saturation of the magnetic circuit. Effective resistance r in the unbranched part of the circuit is the resistance of the excitation circuit of the generator and generally equals $r=r_{в}+r_{п}$, where $r_{в}$ - resistance of the excitation coil, and r_x - added effective resistance in the circuit. Inductance L_s considers the leakage of excitation winding.

The equivalent circuit of Fig. 2b can be used also for multipolar UUG with symmetric magnetic system. Its parameters in this case are calculated by proceeding from the geometric dimensions of the magnetic circuit for the pair of poles and the number of segments of one excitation coil. In this case for series connection of coils of excitation winding $r=r_n+r_x/p$, where p - number of pairs of poles, and voltage on the terminals of the circuit comprises 1/p part of the excitation voltage of the generator. With parallel connection of coils $r=r_n+pr_x$ the voltage on the circuit terminals corresponds to the total excitation voltage of UUG, and current in the unbranched part of the circuit comprises 1/p part of the total excitation current of the generator. The application of linear equivalent circuit, presented in Fig. 2b, is limited to those cases when the working section of the curve of magnetization of the magnetic circuit is rectilinear or is sufficiently well approximated by a segment of the straight line, since the parameters of the circuit are derived in the assumption of constancy of magnetic permeability of material of the magnetic circuit. In the case of substantial nonlinearity of the working section of the magnetization curve, this circuit can be used only after the appropriate correction, based on the introduction into it of nonlinear inductances, approximately considering the nonlinearity of ferromagnetic material. The method of correction of linear equivalent circuits is developed in [2]. Its application for the magnetic circuit of UUG requires special discussion.

The parallel branches of the circuit, corresponding to massive sections of the magnetic drive, have theoretically infinite number of circuits. However, during practical calculations they are limited by a finite number of circuits, determined by the required accuracy of solution. Their number can be substantially reduced, if we simplify the expression, obtained for equivalent operator resistance of the massive section. For example, by finding the operator resistance of the section from calculation of the magnetic field in its mass, it is possible to approximate an infinite series, determining magnetic flux, with maximum approximation by exponential dependence, having taken as the basis in this case constant time T_1, corresponding to the first term of the series. As a result, to the massive section will correspond only one circuit, consisting of equivalent inductance and effective resistance. The equivalent circuit of the excitation circuit of UUG in this case is significantly simplified and takes the form shown in Fig. 3.

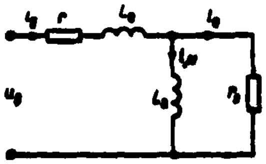


Fig. 3. Simplified equivalent circuit of excitation circuit of UUG.

Some equivalent circuit corresponds to the massive magnetic circuit in the simplified schematic. Its parameters L_0 and r_0 are calculated, proceeding from the geometric dimensions of the magnetic circuit (Fig. 4) and the number of segments of excitation coil, corresponding to the pair of poles, on the basis of the following relationships [1]:

$$L_0 = \frac{w(\Phi_2 - \Phi_1)}{i_{\mu 2} - i_{\mu 1}}, \quad r_0 = \frac{w^2}{\sum_{i=1}^{k} \frac{T_{1i} l_i}{\mu_i S_i \sigma_i}},$$

where w - number of segments of excitation coil; Φ_2; Φ_1; i_{μ_2}, i_{μ_1} - magnetic fluxes on the pair of poles and excitation currents in one coil, corresponding to final and initial points of the working section of the magnetization curve; l_i, S_i, μ_i - calculated length, calculated cross section and magnetic permeability of material of the i massive section; σ_i - correction factor, corresponding to i massive section; k - number of massive sections of magnetic circuit.

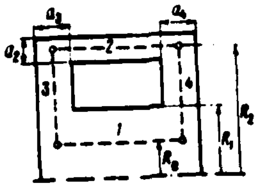


Fig. 4. Sketch of magnetic circuit of UUG on pair of poles (air gaps are not shown) with designation of the characteristic sections. 1 - central core; 2 - yoke; 3, 4 - disks.

The correction factor σ_1 for central core is σ_1=1.4, and for the yoke and disks 3 and 4 (Fig. 4) $\sigma_{2,3,4} = 1.25$. The calculated section of disks 3 and 4 is determined by expression

$$S_{3,4} = \frac{2\pi l_{3,4} a_{3,4}}{\ln R_3/R_0},$$

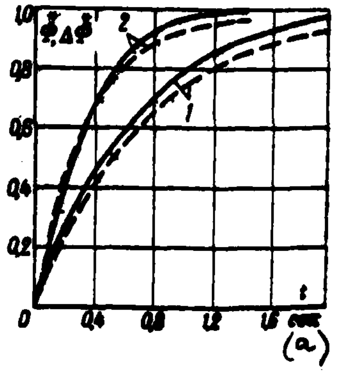
The constant time for central core

$$T_1 = \frac{\mu\gamma R_1^2}{2,405^2},$$

where γ - electrical conductivity of core material. For the yoke and disks 3 and 4

$$T_1 = \frac{4\mu\gamma a^2_{2,3,4}}{\pi^2}.$$

For experimental check of the possibility of application of simplified equivalent circuit (Fig. 3) for engineering calculations there was investigated the process of establishment of magnetic flux in a number of tested UUG with connection of the excitation winding under direct voltage or with abrupt change of excitation voltage. The tests showed rather good coincidence of experimental and calculated data. So, in Fig. 5 are presented experimental and calculated dependences of change of magnetic flux during experimental cylindrical type UUG with completely unstratified magnetic circuit (description of its construction is given in [3]).



(a)

Fig. 5. Experimental (solid lines) and calculated (broken line) dependences of change of excitation flow of experimental UUG.

$$1 - \Phi = \frac{\Phi}{\Phi_0};\ 2 - \Delta\overset{*}{\Phi} = \frac{\Phi - \Phi_1}{\Phi_s - \Phi_1}.$$

Curves 1 correspond to connection of excitation winding under direct voltage in the case of unsaturated magnetic circuit of the generator, and curves 2 - to abrupt change of excitation voltage with saturated magnetic circuit, when the working section of the magnetization curve was located beyond its bend. The greatest divergence between calculated and experimental data is 8 o/c, which is fully acceptable during the solution of practical problems.

The simplified equivalent circuit makes it possible to develop simpler and rather precise approximation methods of calculation of transient processes in UUG. Let us examine the simplest case of connection of excitation winding of the generator under direct voltage with closed load circuit. Such an operating mode of UUG can occur with the necessity of elimination of the switching element in the generator-load circuit, and also in some special cases of shaping of current pulses. The transient processes are described by the following equations:

$$\left.\begin{aligned} L\frac{di}{dt}+iR&=\frac{\Phi\omega}{2\pi},\\ J\frac{d\omega}{dt}+\frac{\Phi}{2\pi}i&=0,\\ w\frac{d\Phi}{dt}+L_s\frac{di_s}{dt}+i_s r_s&=u_s. \end{aligned}\right\} \quad (1)$$

where L, R - inductance and effective resistance of circuit generator-load; i - discharge current; Φ - working magnetic flux; ω - angular velocity of rotation of rotor; J - moment of inertia of rotating mass; w, L_s - number of segments and leakage inductance of excitation winding; r_s - effective resistance of excitation circuit; u_s, i_s - voltage and current of excitation. In compensated UUG the flow of the armature reaction does not leave the mass, and its action is spread to a small area, limited by the current-carrying elements. The third equation of system (1), thus, has a solution independent from the first two equations. Disregarding the leakage of winding, which in UUG is usually small (coefficient of scattering is around 1.05-1.2), and using the simplified equivalent circuit of UUG excitation circuit, it is possible to obtain

$$\Phi=\Phi_\infty\left(1-e^{-\frac{t}{T_e}}\right), \quad (2)$$

where

$$T_e=T_s+T_k,\ T_s=\frac{L_0}{r},\ T_k=\frac{L_s}{r_s}. \quad (2a)$$

Here Φ_∞ - steady-state value of working magnetic flux; T_e - effective time constant of change of working magnetic flux; T_s - time constant of excitation circuit without taking into account leakage of winding and eddy currents in the magnetic circuit.

For convenience of practical calculations into the first two equations of system (1) it is expedient to introduce the following dimensionless values:

$$\overset{*}{i}=\frac{iR}{e_{\infty}},\quad \overset{*}{\omega}=\frac{\omega}{\omega_0},\quad \tau=\frac{t}{T_0},\quad q=\frac{T_e}{T_0},\quad \delta=\frac{T_0}{T_м}.$$

Here e_{∞} - emf of generator, corresponding to steady-state magnetic flux and no-load speed; ω_0 - angular velocity of rotation of rotor with generator idling; $T_e=\frac{L}{R}$ - electromagnetic time constant of circuit generator - load; $T_м=\frac{2A_0R}{e_{\infty}^2}$ - electromechanical time constant; A_0 - kinetic energy stored in rotating masses.

As a result, taking into account relationship (2), we have:

$$\left.\begin{aligned}\frac{d\overset{*}{i}}{d\tau}+\frac{1}{q}\overset{*}{i}-\frac{1}{q}\overset{*}{\omega}(1-e^{-\tau})&=0,\\ \frac{d\overset{*}{\omega}}{d\tau}+\delta\overset{*}{i}(1-e^{-\tau})&=0.\end{aligned}\right\}\qquad (3)$$

The initial equations of the transient process are written out, thus, in relative units $\overset{*}{i}$, $\overset{*}{\omega}$ and dimensionless similarity criteria q, δ. Thanks to this, having assigned a number of values of q and δ and solving equations (3) in numerical form with the use of a computer, it is possible to construct a series of diagrams, maximally simplifying the practical calculations. In Fig. 6 are provided dependences $\overset{*}{i}$, $\overset{*}{\omega}=f(\tau)$ with q=0 and δ=var.

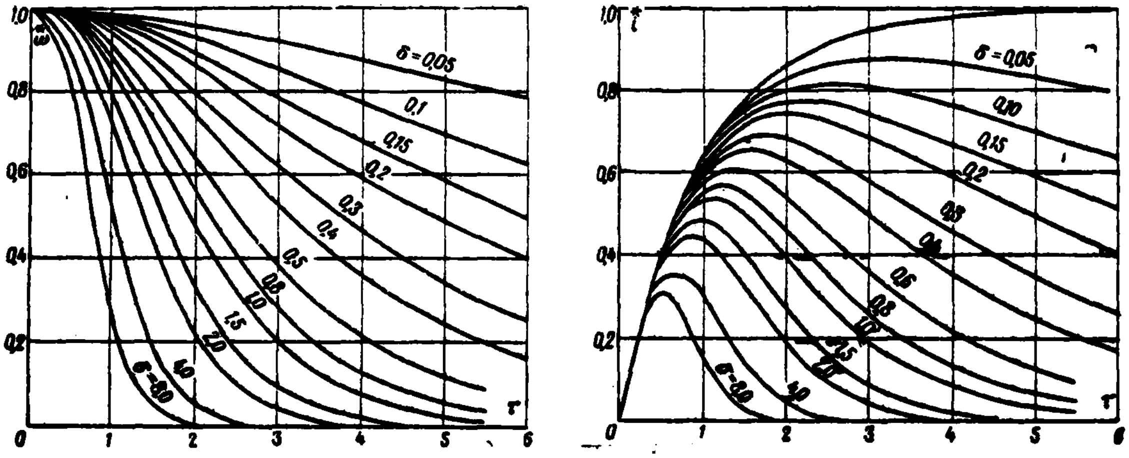


Fig. 6. Dependences $\dot{i}, \dot{\omega}=f(\tau)$ with connection of UUG excitation winding to direct voltage with closed load circuit.

During the calculation of these dependences we were limited to a particular case of purely active load (q=0), since the obtaining of current pulses by the examined method is expedient only in those cases when the load is characterized by comparatively small time constant (in the opposite case the operation of the generator is ineffective, since due to increase of the duration of current pulse front the energy losses are great). During calculation of curves is taken $\dot{i}(0)=0, \dot{\omega}(0)=1$. The diagrams in Fig. 6 make it possible to easily evaluate the expediency and effectiveness of application of the examined method of shaping of UUG current pulses.

An important assignment of pulsed supply is the obtaining of current pulses, having a flat part of certain duration on their horizontal part. With comparatively large energy, transmitted to the load, and long sustaining of constancy of discharge current the obtaining of such pulses is conjugated with considerable difficulties. During operation of UUG this problem is solved effectively with the aid of forcing of excitation of the generator in the process of its discharge.

Let us examine the case of maintaining maximum discharge current, when the forcing mode is started at moment t_1 of its establishment. The rotor of the generator at this moment is rotated with angular velocity ω_1 and stores kinetic energy A_1. Subsequently all the values, corresponding to the moment of time t_1, we will also mark by subscript 1. Values t_1 and ω_1 are calculated by formulas, presented in [4], and they can be considered assigned. With constant parameters R and L of circuit generator - load and with the absence of additional sources of energy the condition of constancy of discharge current denotes the constancy of emf being generated e_1, proportional to working flux Φ and angular velocity of rotation of the rotor ω. Since in the process of discharge the generator rotor loses speed due to withdrawal of energy, then for fulfillment of condition e_1= const it is necessary to increase the magnetic flux Φ in the appropriate manner. Let us determine the necessary law of its growth. Motion of the rotor in the forcing mode is described by equation

$$J\frac{d\omega}{dt}+\frac{e_1 i}{\omega}=0,$$

by solving which, we obtain:

$$\omega=\left(\omega_1^2-\frac{2e_1 it}{J}\right)^{\frac{1}{2}}, \qquad (4)$$

where t - current time, reading of which is done by starting from moment of time t_1.

The condition of constancy of generated emf is written out in the following manner:

$$\Phi_1\omega_1=\Phi\omega,$$

whence taking into account relationship (4) we have:

$$k_\Phi=\frac{\Phi}{\Phi_1}=\left(1-\frac{2t}{T_{\text{м}}}\right)^{-\frac{1}{2}}, \qquad (5)$$

where

$$T_{\text{м}}=\frac{2A_0R}{c_0^2}.$$

Let us determine how the output voltage of the exciter should be changed in time, so that the growth of the working magnetic flux of the generator would occur in accordance with expression (5). Let us do the calculations, using the simplified equivalent circuit of Fig. 3 and disregarding winding leakage. The voltage, applied to the excitation winding of the generator,

$$u_{\text{в}}=L_{\text{в}}\frac{di_\mu}{dt}+(i_\mu+i_{\text{в}})r, \qquad (6)$$

where

$$i_в = T_в \frac{di_\mu}{dt}.$$

By approximating the working section of the magnetization curve by a linear segment, we have:

$$\frac{\Phi - \Phi_1}{\Phi_2 - \Phi_1} = \frac{i_\mu - i_{\mu1}}{i_{\mu2} - i_{\mu1}}. \qquad (7)$$

From (5) and (7) it follows that in the forcing mode

$$\overset{\bullet}{i}_\mu = \frac{i_\mu}{i_{\mu1}} = \frac{k_{im}(k_\Phi - 1) + k_{\Phi m} - k_\Phi}{k_{\Phi m} - 1}, \qquad (8)$$

where

$$k_{\Phi m} = \frac{\Phi_2}{\Phi_1}, \quad k_{im} = \frac{i_{\mu2}}{i_{\mu1}}.$$

By solving equation (6) taking into account relationship (8), we obtain:

$$\overset{\bullet}{u}_в = \frac{u_в}{ri_{\mu1}} = \overset{\bullet}{i}_\mu + \frac{T_в k_\Phi^3 (k_{im} - 1)}{T_м (k_{\Phi m} - 1)}. \qquad (9)$$

By performing similar calculations, we find that with the expression for excitation current $\overset{\bullet}{i}_в = i_в/i_{\mu1}$ is written in the same form as for $\overset{\bullet}{u}_в$, it is sufficient only to replace $T_в$ by $T_м$. Relationship (9) makes it possible to calculate the examined operating mode of UUG taking into account the action of eddy currents in the massive magnetic circuit. The value of $T_м$ entering it gives the possibility of easily evaluating the effectiveness of scattering of separate massive sections.

For change of the excitation voltage of UUG in accordance with expression (9) the application of different circuits of systems of regulation is possible. Let us note a simpler method, when supply of the excitation winding of UUG is done from the direct-current generator, and the forcing of excitation of UUG is accomplished by shunting of the added resistance in the excitation circuit of the exciter. The output voltage of the exciter in this case grows exponentially, however, having selected the appropriate time constant, it is possible in the necessary time interval to provide rather close coincidence of actual and calculated dependences of change of excitation voltage of UUG and to obtain discharge current virtually constant in value. In [5] is presented an oscillogram of rectangular current pulse, obtained by the examined method during discharge of experimental UUG to active load.

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