REFERENCES

1. Apasov A.M., Valuev D.V., Danilov V.I. On possible reasons of defects of large-capacity billets of low-carbon manganese steel at «Yurmash» // Bulletin of the Tomsk Polytechnic University. – 2007. – V. 310. – № 3. – P. 90–92.
2. Tushinskiy L.I., Bataev A.A., Tikhomirova L.B. Perlite structure and constructive strength of steel. – Novosibirsk: Nauka, 1993. – 280 p.
3. Lyubimova L.L. The technique of roentgenometric analysis of instructure stresses // Bulletin of the Tomsk Polytechnic University. – 2003. – V. 306. – № 4. – P. 72–77.
4. Malinina R.I., Malyutina E.S., Novikov V.Yu. et al. Practical metallography. – Moscow: Intermet Engineering, 2004. – 230 p.
5. Structural-phase states of metal systems / Ed. by A.I. Potekaeva. – Tomsk: Press of NTL, 2004. – 356 p.
6. Metal research and steel thermal treatment. Reference book. V. II. The fundamentals of thermal treatment / Ed. by M.L. Bernshtein, A.G. Rathshtadt. – Moscow: Metallurgiya, 1995. – 336 p.
7. Sorokin V.G., Gervasiev M.A., Paeev V.S. et al. Steels and alloys. – Moscow: Intermet Engineering, 2001. – 608 p.

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COMPUTATION OF CURRENT PULSED SOURCES WITH INDUCTIVE ENERGY STORAGES

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Formulas for computation of efficiency and parameters of current pulsed sources at charging and discharging of the inductive energy storage on active loading have been obtained. For charging the inductive storage the electric and capacitor batteries, unipolar and synchronous electric generators with the rectifier, equivalent circuit of which can be presented by consecutive connection of equivalent capacity, inductance and resistance are considered. Formulas, at which high efficiency of charge is reached, are obtained for computation of parameters of the inductive storage in the form of the multilayered coil. It is shown that current pulsed sources are the most effective at oscillatory charging of the inductive storage when more than 50 % of the generator energy can be transferred to loading.

Currently, pulsed sources with resistive («hot») inductive storages of electromagnetic energy W and open (explosive) switches K_2 (Fig. 1) are one of the most powerful current pulse generators with specific accumulated energy in inductive storage to 5 J/g and more [1–3]. Therefore, computation of the efficiency and parameters of such source is the topical problem.

To charge the inductive storage with energy W let us examine such electromagnetic energy generators as accumulator and capacitor batteries charged from internal source as well as unipolar and synchronous electric generators with rectifier in electrodynamic braking mode [1–3].

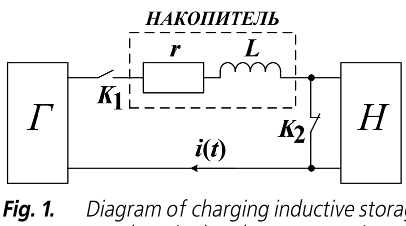

Fig. 1. *Diagram of charging inductive storage and pulse loading supply: Г is the electromagnetic energy generator; H is the loading; K_1 and K_2 are the switches; L and r are the inductance and resistance of storage wire*

The equivalent circuit of these generators may be approximately introduced in the form of series connection of capacity C_g, inductance L_g and resistance r_g [2, 3], then, for equivalent parameters of a circuit of inductive storage loading

$$C_g = \frac{2W_g}{U_g^2}; \quad r_z = r_g + r; \quad L_e = L_g + L, \qquad (1)$$

when switches K_1 and K_2 are closed, one determines the roots of characteristic equations

$$p_{1,2} = -\frac{r_z}{2L_e} \pm \sqrt{\frac{r_z^2}{4L_e^2} - \frac{1}{L_e C_g}} \qquad (2)$$

and charging time of inductive storage ($p_1 \neq p_2$)

$$t_z = \frac{\ln(p_2 / p_1)}{p_1 - p_2}, \qquad (3)$$

corresponding to current maximal value $i(t)$

$$I_m = i(t_z) = \frac{C_g U_g p_1 p_2}{p_1 - p_2}[e^{p_1 t_z} - e^{p_2 t_z}] \qquad (4)$$

and maximal energy accumulated by the storage

$$W = \frac{L I_m^2}{2} \qquad (5)$$

at voltage magnitude at capacitance C_g

$$U_z = u_C(t_z) = \frac{U_g p_2}{p_1 - p_2}\left[e^{p_1 t_z} - \frac{p_1}{p_2} e^{p_2 t_z}\right], \qquad (6)$$

where W_g and U_g are the initial values of accumulated energy and voltage of generator at open switch K_1, respectively (Fig. 1).

For all types of generators on charging time intervals of inductive storage $0<t<t_z$, current $i(t)$ may be taken equal to

$$i(t)=\frac{I_m(e^{p_1t}-e^{p_2t})}{e^{p_1t_z}-e^{p_2t_z}}\approx I_m\left[\sin\left(\frac{\pi t}{2t_z}\right)\right]^q, \qquad (7)$$

where $q\approx0,5$ at aperiodic charge when roots of $p_{1,2}$ are real, negative and different; and $q\approx1$ at oscillating charge when roots of $p_{1,2}$ are complex and conjugate.

If heat energy loss in inductive storage and generator are taken into account

$$W_T=r_z\int_0^{t_z}i(t)^2dt=I^2r_zt_z, \qquad (8)$$

where I is the effective (quadratic) current value on time interval $0<t<t_z$, then at total accumulated energy in magnetic field of generator and storage

$$W_M=\frac{L_eI_m^2}{2} \qquad (9)$$

the efficiency of accumulation (charging) of energy in magnetic field subject to (1, 7–9) we determine as

$$\eta_z=\frac{W_M}{W_M+W_T}=\frac{1}{1+\frac{2t_z}{\tau_z}\cdot\left(\frac{I}{I_m}\right)^2}\approx$$

$$\approx\frac{1}{1+\frac{2t_z(1+r_g/r)}{\tau(1+L_g/L)(1+q^{2/3})}}, \qquad (10)$$

where $\tau_z=L_e/r_z$ and $\tau=L/r$ are the constants of charge and storage, respectively.

At charging, taking into account (10), average power of generator equals

$$P_z=\frac{W_T+W_M}{t_z}=\frac{W_M}{t_z\eta_z}. \qquad (11)$$

Then, if we assume, that the switch K_2 opens at point of time $t=t_z$ instantly rapidly and the load H (Fig. 1) is characterized by constant resistance r_H, then at equivalent resistance of generator and storage discharge circuit

$$r_p=r_z+r_H, \qquad (12)$$

the roots of characteristic equation

$$p_{3,4}=-\frac{r_p}{2L_e}\pm\sqrt{\frac{r_p^2}{4L_e^2}-\frac{1}{L_eC_g}} \qquad (13)$$

and current at initial conditions $i(t_z)=I_m$ and $u_C(t_z)=U_z$ may be determined:

$$i(t)=\frac{p_3I_m}{p_3-p_4}\left[\begin{array}{l}\left(1-\frac{C_gp_4U_z}{I_m}\right)e^{p_3(t-t_z)}+\\+\left(\frac{p_4}{p_3}-\frac{C_gp_4U_z}{I_m}\right)e^{p_4(t-t_z)}\end{array}\right]. \qquad (14)$$

As a result, at maximum values of voltage

$$U_m=r_HI_m \qquad (15)$$

and load capacity

$$P_m=I_m^2r_H \qquad (16)$$

from conditions of transformation of all magnetic field energy into heat after opening the switch K_2

$$I_m^2r_pt_p=\frac{L_eI_m^2}{2}$$

we get the design duration of generator and storage discharge to the load

$$t_p=\frac{\tau_p}{2} \qquad (17)$$

and determine the efficiency of generator energy transfer to the load

$$\eta=\frac{W_M}{W_g}, \qquad (18)$$

where $\tau_p=L_e/r_p$ is the constant of discharge.

The power amplification due to current pulse compression ($t_p<t_z$) subject to (10) amounts to

$$K_p=\frac{P_m}{P_z}=2\frac{r_H}{r_z}\eta_z\frac{t_z}{\tau_z}, \qquad (19)$$

and this coefficient increases by growing of load resistance r_H.

The calculations were carried out and the diagrams were plotted (Fig. 2) by the formulas (1–19) at change of the equivalent inductance L_e. It follows from them that pulsed source functioning is the most efficient at oscillating charging when L_e is rather lower than critical inductance ($\lambda=L_e/L_{kp}<<1$)

$$L_{kp}=\frac{4\tau_z^2}{C_g}, \qquad (20)$$

i.e. the inductance supporting equal roots (2). However, at L_e reduction the charge time t_z decreases in comparison with τ_z that results in increase of generator average power P_z.

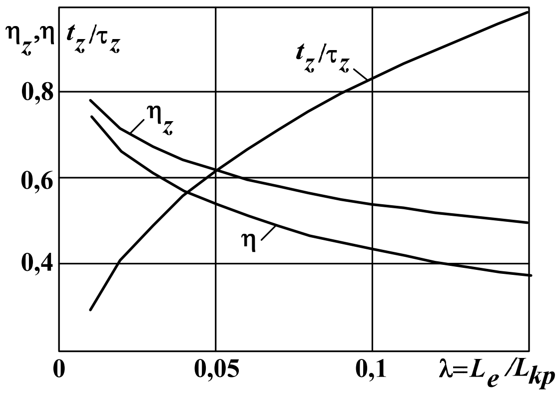

Fig. 2. *The design dependences of efficiencies η_z, η and relative charge time t_z/τ_z*

Thus, to support high efficiencies η_z and η at lower average generator power P_z it is necessary to have $L_e<<L_{kp}$ at maximal constant of the charge τ_z.

As

$$\tau_z = \tau \frac{1 + L_g / L}{1 + r_g / r},$$

then, obviously, the constant of the storage τ should be maximal as well.

Let us determine the inductive storage parameters at which the constant τ is maximal. Let us consider that the inductive storage is made in the form of multilayer coil of rectangular cross-section (Fig. 3) the inductance of which is calculated by the approximate formula [4]:

$$L \approx \frac{0,32 \cdot 10^{-4} R^2 w^2}{6R + 9l + 10a}, \quad (21)$$

and, if the summands in denominator are of the same order then the calculating error does not exceed 1 %.

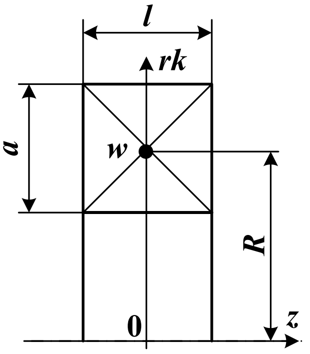

Fig. 3. *The coil of rectangular cross-section: w is the number of turns; R is the average radius of turns; a is the winding thickness; l is the coil length; z and rk are the coordinate axes*

Let us denote the coil length $l=ka$ by a certain coefficient $k>0$ then the coil resistance amounts to

$$r = \frac{2\pi R w^2}{\gamma K_Z k a^2}, \quad (22)$$

where γ is the specific conductivity of the conductor material; K_Z is the coefficient of filling the winding section with the conductor.

As a result, taking into account (21) and (22) we write down the constant of the storage

$$\tau = \frac{L}{r} \approx \frac{0,16 \cdot 10^{-4} \gamma K_Z k R a^2}{\pi[6R + (9k+10)a]}, \quad (23)$$

whence

$$R \approx \frac{\pi(9k+10)a\tau}{0,16 \cdot 10^{-4} \gamma K_Z k a^2 - 6\pi\tau}. \quad (24)$$

As the internal radius of winding is $R_1=R-0,5a\geq 0$, then $R/a\geq 0,5$, then on the basis of (24) we obtain

$$\tau \approx \frac{0,08 \cdot 10^{-4} \gamma K_Z k a^2}{\pi[9k+13]} n, \quad (25)$$

where $n\geq 1$ is the certain coefficient.

Let us write down the maximal value of current as

$$I_m = \frac{K_Z a l}{w} j_m, \quad (26)$$

where j_m is the maximal current density in winding conductor.

Substitution of formulas (21), (24–26) into (5) allows obtaining the ratio for calculation of winding thickness

$$a \approx 12 \left[\frac{(9k+13)(9k+13-3n)W}{(K_Z j_m k n)^2 (9k+10)} \right]^{0,2}. \quad (27)$$

The volume of winding

$$V = 2\pi R a l = \frac{2\gamma W}{K_Z j_m^2 \tau} \quad (28)$$

and mass of the conductor with specific volume density ρ is determined by the formulas (21), (23), (5) and (26)

$$m = \rho K_Z V = \frac{2\gamma\rho W}{j_m^2 \tau}. \quad (29)$$

Then, taking into account (29), let us get specific stored energy

$$pw = \frac{W}{m} = \frac{j_m^2}{2\gamma\rho}\tau \quad (30)$$

and specific constant of the storage

$$p\tau = \frac{\tau}{m} = \frac{j_m^2}{2\gamma\rho W}\tau^2. \quad (31)$$

It is obvious that the maximum of the constant (25) corresponds to the maximal specific parameters (30) and (31). It is written down as follows

$$\tau \approx 3,67 \cdot 10^{-4} \cdot \frac{\gamma K_Z^{0,2} W^{0,4}}{j_m^{0,8}} f(k,n), \quad (32)$$

taking into account (27), where

$$f(k,n) = \left[\frac{kn(9k+13-3n)^2}{(9k+13)^3 (9k+10)^2} \right]^{0,2}. \quad (33)$$

The design function of the coil (33), which is shown in Fig. 4, has maximal value equals approximately 0,169 at $k\approx 1$ and $n\approx 2,5$.

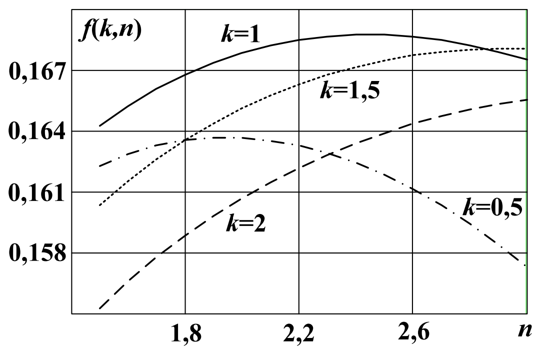

Fig. 4. *The design function of the coil*

As a result, we finally obtain the thickness of winding equal the coil length from the formulas (26–28, 32) at $f(k,n)\approx 0,169$

$$a = l \approx 14,622 \frac{W^{0,2}}{K_Z^{0,4} j_m^{0,4}}, \quad (34)$$

average radius of winding turns

$$R \approx 1,643a \qquad (35)$$

and maximal constant of the storage

$$\tau \approx 0,62 \cdot 10^{-4} \frac{\gamma K_Z^{0,2} W^{0,4}}{j_m^{0,8}}, \qquad (36)$$

and the inductance

$$L \approx 0,03 \cdot 10^{-4} a w^2 \qquad (37)$$

and resistance of the coil are obtained from the formulas (21, 22).

$$r \approx 10,312 \frac{w^2}{\gamma K_Z a}. \qquad (38)$$

It should be noted that the obtained ratios of the coil sizes $a=l$ and $R\approx1,643a$ coincide with the results given in [5], where it is appointed, as well, that the coils with such sizes have rather high constant τ than the toroids.

If the values I_m and W are specified then L may be calculated from (5). And then, using the formulas (34, 37), the number of coil turns may be determined selecting such current density j_m that this number comes out to be the integral:

$$w \approx 150,986\sqrt{L} \frac{K_Z^{0,2} j_m^{0,2}}{W^{0,1}}. \qquad (39)$$

Total temperature of coil winding conductor is determined by charging and in time point $t=t_z$ at adiabatic heating and constant specific conductivity γ amounts to

$$\theta_m \approx \theta_0 + \frac{j_m^2 t_z}{(1+q^{2/3}) C_\rho \rho \gamma}, \qquad (40)$$

where θ_0 is the initial temperature; C_ρ is the specific heat capacity of conductor material.

On the basis of calculation of the coil magnetic field (fig. 3) the approximate formulas for determining maximal values of inductance

$$B_m \approx \frac{L I_m}{\sqrt{3}\pi w a^2} \qquad (41)$$

and magnetic field pressure on coil internal turns are obtained

$$\sigma_m \approx \frac{B_m I_m}{a}. \qquad (42)$$

At specified parameters U_g, L_g, r_g of generator and W, j_m, K_Z, γ of the storage for oscillating charging, when $0,02<\lambda<0,15$, from formulas (2–4, 34, 38, 39) at equivalent generator capacity

$$C_g = 4\frac{\tau^2 \lambda}{L} \frac{(1+L_g/L)}{(1+r_g/r)^2} \qquad (43)$$

the approximate ratios for calculating maximal values of current

$$I_m \approx \frac{\lambda U_g}{2(\lambda^{0,6}-0,01) r_g} + \sqrt{\frac{\lambda^2 U_g^2}{4(\lambda^{0,6}-0,01)^2 r_g^2} - \frac{3,22 \cdot 10^4 j_m^{0,8} W^{0,6}}{\gamma K_Z^{0,2} r_g}} \qquad (44)$$

and accumulated energy of generator are obtained

$$W_g \approx 4W(1+L_g/L)\frac{(\lambda^{0,6}-0,01)^2}{\lambda}. \qquad (45)$$

So, if the values W=1 MJ; K_Z=0,5; γ=58 Mmho/m; ρ=8900 kg/m^3; C_ρ=385,5 J/kg·°C; θ_0=20 °C; r_H=1,1 mOhm; λ=0,1132 are specified and the generator with U_g=250 V, r_g =0,1 mOhm and L_g=0,1 mkHn is used, then at j_m=145 A/mm^2 by the formulas (1–45), the parameters of the pulsed source: I_m=1 MA; L=2 mkHn; $a=l\approx$0,166 m; $R\approx$0,273 m; w=2 turns; $r\approx$8,57 mkOhm; $\tau\approx$233 ms; $\tau_z\approx$19 ms; $\tau_p\approx$1,76 ms; t_z=17 ms; t_p=0,88 ms; $\theta_m\approx$20,9 °C; B_m=6,64 T; σ_m=39,9 MPa; $V\approx$0,047 m^3; $m\approx$211 kg; $pw\approx$4,7 J/g; $p\tau\approx$1,1 ms/kg; C_g=80,7 F; W_M=1,05 MJ; W_g=2,52 MJ; $\eta_z\approx$0,512; $\eta\approx$0,417; $P_z\approx$121 MW; $P_m\approx$1086 MW; $K_p\approx$9; U_m=1086 V may be calculated. For the source with the given parameters the typical diagram of standard current pulse calculated by the formulas (7) and (14) is introduced in Fig. 5. And dependences for its maximal value obtained by the ratio (44) are shown in Fig. 6.

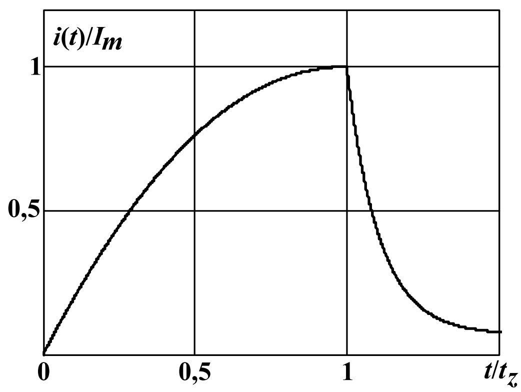

Fig. 5. The design standard current pulse of the source

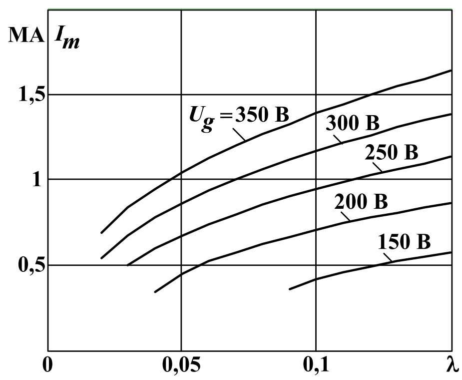

Fig. 6. Maximal values of current pulse

Thus, the derived formulas may be used for calculating parameters of pulsed current sources with inductive energy storages. On the basis of analysis of formulas and carried out calculations the following conclusions may be stated.

1. The oscillating charge is the most efficient when the equivalent inductance is rather lower than the critical one (λ<<1) and more than 50 % of generator energy may be transferred to the load.
2. To support high efficiency of the source at low average power of generator it is necessary to have maximal constants of the charge τ_z and storage τ.
3. Increasing initial stress of generator U_g at constant parameters W, j_m, γ, K_Z and r_g the efficiencies of the charge η_z and generator energy transfer to the load η grow as the current achieves the required maximal value I_m at low magnitudes of λ.
4. Application of accumulator batteries, unipolar and synchronous generators as generators for aperiodic charge of inductive storage is inefficient owing to low magnitudes η_z and η; use of these generators at oscillating charge requires implementation of special constructive solutions directed to increase of rate of current rise, i.e. to increase of stress U_g and decrease of inductance L_g and resistance r_g.
5. Oscillating charge of inductive storage from a capacitor bank is the most efficient and appropriate especially if the battery has high density of accumulated energy W_g, which can exceed 3 J/g [6].

REFERENCES

1. Explosive generators of electric current power pulses / E.I. Asinovskiy, E.F. Lebedev, A.A. Leontiev et al; ed. by V.E. Fortov. – Moscow: Nauka, 2002. – 398 p.
2. High power pulsed systems / Ed. by E.I. Asinovskiy. – Moscow: Mir, 1981. – 248 p.
3. Glebov I.A., Kasharskiy E.G., Rutberg F.G. Synchronous generators of short-term and impact action. – Leningrad: Nauka, 1985. – 224 p.
4. Electrotechnical reference book: 3 volumes, V. 1. General questions. Electrotechnical materials / Ed. by professor of MEI V.I. Gerasimov et al. – Moscow: Energoatomizdat, 1985. – 488 p.
5. Physics and engineering of power pulsed systems / Ed. by E.P. Velikhov. – Moscow: Energoatomizdat, 1987. – 352 p.
6. Aviation week and space technology. – 1990. – V. 132. – № 19. – P. 88–89.

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UNIVERSAL MATHEMATICAL MODEL OF POWER THREE-PHASE TRANSFORMERS AND AUTOTRANSFORMERS

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The substantiation of necessity in essential increase of completeness and reliability of modeling processes in energy systems has been shown. The results of synthesis of universal mathematical model of one of the main elements of energy systems – power transformers and autotransformers are given. The demanded quality of reproduction of processes is confirmed by experience of using the developed model in structure of all-mode multiprocessing modeling complexes of real time of the hybrid type. The examples illustrating quality of process modeling are shown.

According to statistics [1, 2] about 50 % of severe failures in electric systems (ES), including EES, occurs due to incorrect actions of dispatcher staff, relaying, manufacturing and emergency automation, the main reason of which is the use of under-complete and under-reliable information on possible processes, especially emergency ones, in EES, at design, commissioning and maintenance.

EES specific character excludes practically a possibility of obtaining this information in a full-scale way and extraordinary complication of up-to-date EES restricts considerably applicability of their physical modeling. As a result, the main method of obtaining information on various normal and emergency processes in EES is mathematical modeling, the possibilities of which depend on presence:

- and use of rather accurate mathematical models for all kinds and types of equipment;
- means capable of solving reliably and efficiently the EES equation systems formed by these models.

The stated constantly high emergency component in EES indicates objectively the fact that the existing implementations of these factors do not support the completeness and reliability of mathematical modeling required for its considerable decrease and in particular, for efficient dispatcher control of its operability.

The detailed analysis of these facts and their interaction is given in [3–8]; the urgent need and topicality of further development of these factors follows from this. It is obvious also that the first of them becomes logically first-priority.