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# ON THE POSSIBILITY OF USING LINEAR CURRENT GENERATORS FOR GEOPHYSICAL RESEARCH

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*A procedure was developed to obtain analytical estimates of the operating modes of linear electric generators* (LEGs) *of the railgun type with current supply to active inductive loads. An analysis of the solutions obtained shows a low effectiveness of using generators of this type to power geophysical dipoles in electrical prospecting* (*the efficiency does not exceed* 20%). *Induction coil-type* LEGs *provide for much higher efficiency. Numerical modeling was performed of the operating modes of one design of such generators. Versions of nonlinear-inductance* LEG *circuits that produce quasirectangular load current pulses and are of interest for solving electrical prospecting problems were proposed and studied.*

**Key words:** *linear electric generators, geophysical research, electrical prospecting, numerical modeling.*

**Introduction.** Pulse linear electric generators (LEGs), which convert kinetic energy of translationally moving bodies to electric energy, have a much smaller warm-up period (about a few milliseconds) and a simpler and cheaper design than shock compression machine generators. The specific energy output of LEGs can be brought to values of 1.5–2.0 J/g, and the energy conversion efficiency increases with increasing caliber of the generator channel and reaches 40–50%. Such electric generators, which ensure a load energy of up to 1 MJ in a few milliseconds, can be used as independent pulsed power sources for powering geophysical dipoles or as power sources for electromagnetic guns. Some ideas on the design of such systems and methods of their analysis, in particular, those taking into account the processes in the fuel combustion chamber are presented in [1].

In the present work, emphasis is placed on an analysis of the general electrophysical laws of LEG operation, primarily, as applied to geophysical problems. An analysis is performed of the operating modes of LEGs based on the deceleration of a preaccelerated armature by a magnetic field in the channel of an inverse multiturn railgun. A wide range of useful electric-load parameters, including the parameters of typical geophysical dipoles, is considered. A procedure for obtaining approximate analytical estimates of the LEG performance is constructed. Recommendations on the choice of LEG designs for geophysical dipoles are proposed. Induction-type coil LEGs are shown to hold promise for this purpose. A study is performed of the operating modes of a special design of an induction-type LEG which provides for a current pulse of up to 50 kA in a geophysical dipole with a pulse duration of 2–3 msec and a voltage of up to 25 kV. An analysis is made of nonlinear-inductance LEG circuits capable of providing quasirectangular load current pulses, which is also of interest in electric prospecting. The results can be useful in developing and designing portable LEG-based power supply systems for various applications.

**1. Analysis of Simplified Models of LEGs.** The idea of designing LEGs based on the deceleration of a preaccelerated armature in a magnetic field was first proposed in [2]. A qualitative theory of LEGs that predicts the operation of railgun-type electric generators was developed in [3–5].

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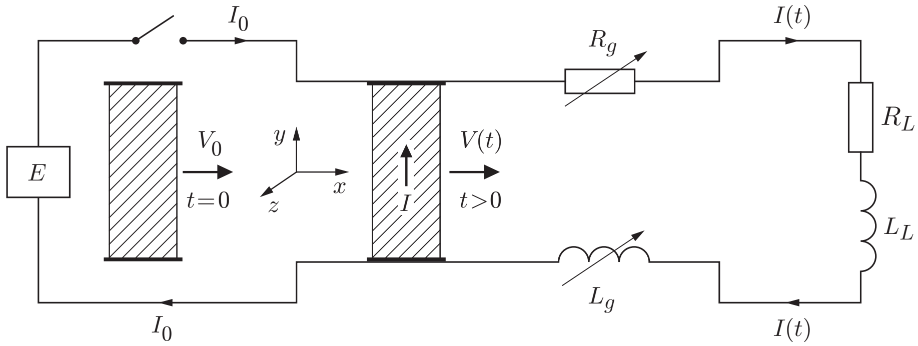


Fig. 1. Diagram of an inverse railgun generator.

An analysis of the theoretical findings of [3, 4] and their extension to the case of high-resistance loads is given below. The current generator circuit is presented in Fig. 1. If the load resistance $R_L$ far exceeds the bus resistance $R_g$ in the armature deceleration channel, the total resistance $R \approx R_L$ can be considered constant. Then, the heating of the buses has little influence on the load current excitation. This considerably simplifies the LEG model [3, 4]:

$$\frac{d\xi}{d\tau} = v, \qquad \frac{dv}{d\tau} = -\frac{\beta i^2}{2}, \qquad \frac{d\lambda i}{d\tau} = -\alpha i,$$
$$\tau = 0: \qquad \xi = 0, \quad v = 1, \quad i = 1. \tag{1.1}$$

Here $\lambda = 1 + \gamma - \xi$ is an auxiliary parameter (the nondimensionalized total inductance of the generator and load), $\gamma = L_L/L_g$, where $L_L$ is the load inductance and $L_g = L'l$ is the generator inductance ($L'$ is the inductance per unit length of the buses and $l$ is the length of the generator), $\alpha = Rl/(L_g V_0)$ ($V_0$ is the starting velocity of the armature), $\beta = (1+k_f)L_g I_0^2/(mV_0^2)$ ($I_0$ is the initial current in the circuit, $m$ is the mass of the armature, and $k_f$ is the specific resistance of the LEG walls and buses to the motion of the armature), $\xi = x/l$ ($x$ is the longitudinal coordinate of the armature), $v = V/V_0$ ($V$ is the velocity of the armature), $i = I/I_0$ ($I$ is the load current), and $\tau = V_0 t/l$ ($t$ is time).

According to the data of [3, 4], of practical interest is the range of parameters

$$\gamma \ll 1, \qquad 0 \leqslant \alpha < 1, \qquad \beta \leqslant \beta_* = \gamma/(\gamma + 1). \tag{1.2}$$

Here the first condition implies that the generator inductance far exceeds the load inductance, which ensures a considerable current gain by a value of about $1/\gamma$. The second condition guarantees a monotonic increase in the load current with time due to armature motion in the generator channel. The third relation eliminates stop of the armature and its return motion in the absence of active ohmic loads ($\alpha = 0$). For $\alpha \neq 0$, the Joule energy dissipation in the load leads to a decrease in the current and, hence, and in the armature decelerating force. As a result, the maximum admissible value of the parameter $\beta_*$ increases with an increase in the circuit resistivity parameter $\alpha$.

The physical meaning of the determining dimensionless parameters introduced above is as follows. The quantity $\alpha$ is equal to the ratio of the load resistance $R$ to the bus resistance $L'V_0$ due to armature motion at a velocity $V_0$. The parameter $\beta$ is the ratio of the sum of the magnetic energy in the generator bus with a current equal to the field current ($I = I_0$) and the work of resistance to armature motion at a velocity $V_0$ to the kinetic energy of the armature. The variable $\gamma$ is the ratio of the load inductance to the inductance of the generator buses. In the chosen dimensionless variables, the quantity $i$ is the current gain. System (1.1) is investigated in the interval from $\xi = 0$ to $\xi = 1$ (the moment of start) or to $\xi = \xi_{\max}$ and $V(\xi_{\max}) = 0$ (stop of the armature).

To analyze the results, it is expedient to introduce the electromagnetic energy gain $K$ in the load relative to the initial energy in it:

$$K = i^2 + 2\frac{\alpha}{\gamma}\int_0^\tau i^2(\tau)\, d\tau.$$

The generation efficiency $\eta$ is equal to the ratio of the load energy to the total initial energy:

$$\eta = \frac{K\beta\gamma}{(1+\gamma)\beta + (1+k_f)}.$$

Using the quantity $N_* = (L_L I_0^2/2)/(l/V_0)$ as the scale of the generator capacity, for the dimensionalized capacity we obtain

$$N = \frac{dK}{d\tau} = 2i^2\Big(\frac{\alpha}{\gamma} + \frac{v-\alpha}{\lambda}\Big).$$

The capacity averaged over the generation period and referred to the quantity $N_*$ is

$$\langle N\rangle = \frac{1}{\tau_{\max}} \int\limits_0^{\tau_{\max}} N(\tau)\, d\tau.$$

Here $\tau_{\max}$ is defined by the condition $\xi(\tau_{\max}) = 1$ or $\xi(\tau_{\max}) = \xi_{\max}$, which corresponds to the moments of start or stop of the armature.

It can be shown that the Cauchy problem (1.1) can be reduced to one Volterra nonlinear integral equation for current or velocity. This equation can be represented as a system of two integral equations for two variables (velocity and current) with a variable upper limit:

$$v^2(\xi) = 1 - \beta \int\limits_0^{\xi} i^2(p)\, dp,$$

$$i^2(\xi) = \Big(\frac{\gamma+1}{\gamma+1-\xi}\Big)^2 \exp\Big(-2\alpha \int\limits_0^{\xi} \frac{ds}{v(s)(\gamma+1-s)}\Big). \tag{1.3}$$

According to (1.2), it is reasonable to investigate (1.3) for small values of the parameter $\beta$. Here the subscript 0 corresponds to the zero approximation, and the subscript 1 to the first approximation. Then, for $\alpha \neq 1/2$, we obtain

$$v_0^2(\xi) = 1, \qquad i_0^2(\xi) = \Big(\frac{\gamma+1}{\gamma+1-\xi}\Big)^{2(1-\alpha)}; \tag{1.4}$$

$$i_*^2(\xi) = \Big(\frac{\gamma+1}{\gamma+1-\xi}\Big)^{\mu}, \qquad \mu = 2\Big[1 - \alpha\Big(1 + \frac{\beta(\gamma+1)}{2(2\alpha-1)}\Big)\Big],$$

$$v_1^2(\xi) = 1 + \beta\,\frac{(\gamma+1)^{2(1-\alpha)}}{2\alpha-1}\,[(\gamma+1-\xi)^{2\alpha-1} - (\gamma+1)^{2\alpha-1}], \tag{1.5}$$

$$i_1^2 = i_*^2\Big(1 + \frac{\beta(\gamma+1)}{2(2\alpha-1)}\Big)\Big(1 + \frac{\alpha}{2\alpha-1}\,(1 - v_1^2)\Big).$$

For $\alpha = 1/2$, the solution is also easy to obtain but it is more cumbersome and is therefore not given here. The zero approximation provides an accuracy of up to 96%. The next (first) approximation gives a relative error of not more than 0.6%. This is valid for a wide range of load resistance and current excitation conditions.

The load current gain for some values of the resistance is shown in Fig. 2. From (1.4) and Fig. 2, it follows that the current gain depends exponentially on the load resistance (the resistivity parameter $\alpha$). Thus, according to [3], for $\alpha = 0$, the maximum rise in the current is equal to $(\gamma+1)/\gamma$ and for $\alpha \neq 0$, it is $[(\gamma+1)/\gamma]^{1-\alpha}$. From Fig. 2 it is evident that during armature motion in the railgun channel, there is a monotonic increase in the current and the rate of the increase also increases.

Figure 3 gives a curve of the load energy gain $K$ versus the longitudinal coordinate of the armature. It is evident that on the initial segments of current generation (armature deceleration), the load resistivity favors the enhancement of energy release and storage. As the armature moves toward the generator edge ($\xi = 1$), the load resistivity leads to a sharp reduction in the net energy in the load.

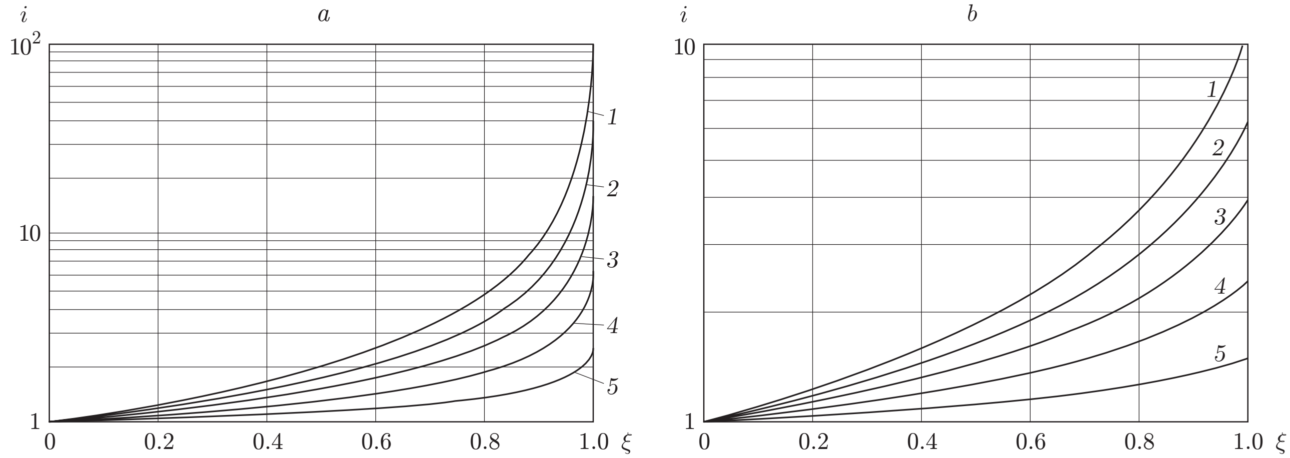


Fig. 2. Current gain versus the longitudinal coordinate of the armature for $\beta = \gamma = 0.01$ (a) and $\beta = \gamma = 0.1$ (b): $\alpha = 0$ (1), 0.2 (2), 0.4 (3), 0.6 (4), and 0.8 (5).

A curve of the efficiency $\eta$ versus the longitudinal coordinate of the armature is presented in Fig. 4. It is evident that as the load resistivity (the parameter $\alpha$) increases, the efficiency decreases. This is due to the fact that the armature velocity has no time to decrease to the required value because of the current limitation.

A curve of the generator capacity $N$ versus the longitudinal coordinate and the parameter resistivity is presented in Fig. 5. The quantity $N$ is referred to the quantity $N_* = (L_L I_0^2/2)/(l/V_0)$. In the absence of an ohmic load, the decrease in the capacity as the armature approaches the channel exit is due to the deceleration and stop of the armature because the third condition of stable current generation in (1.2) is violated.

The calculation results show that for small values of the parameter $\beta$, characteristics such as the generator capacity and current and energy gains weakly depend on this parameter. In particular, their deviation from the average values does not exceed 7% over a wide range of the determining parameters of the LEG: $0 < \alpha < 0.8$ and $0 < \beta/\gamma < 1$. The dependence of the efficiency $\eta$ on the relation $\beta/\gamma$ at the moment of start or stop of the armature has a different shape (Fig. 6). As $\beta$ increases, the efficiency rises, which favors fuller extraction of kinetic energy from the armature.

The analysis of the LEG operation performed above over a wide range of determining parameters provides qualitative estimates of the generator characteristics with current supply to various inductive–ohmic loads. As an example, we consider a geophysical loop [5] with parameters $L_L = 0.273$ $\mu$H and $R_L = 0.66$ m$\Omega$. Then, setting $L' = 5$ $\mu$H/m, $V_0 = 800$ km/sec, and $l = 1$ m, we obtain $\alpha \approx 0.2$ and $\gamma \approx 0.05$; in this case, allowance should be made for the typical geophysical load resistivity. The parameter $\beta$ should not exceed the value of $\gamma$. This allows one to find the upper admissible boundary for the field current $I_0$ if the mass of the armature is additionally specified.

To obtain the result for data different from those considered above, it is not necessary to solve the complex system of equations (1.1). Use can be made of the analytical solution (1.4), (1.5).

As another example, we consider the current supply to a geophysical dipole [6] with parameters $R_L = 10$ m$\Omega$ and $L_L = 300$ $\mu$H. In this case, $\alpha \approx 2.5$, i.e., the current generation condition $\alpha < 1$ is violated. Further increasing the initial armature velocity is difficult; therefore, to decrease in the parameter $\alpha$, it is necessary to increase the inductance per unit length. In multi-turn rail systems, its value can be increased to 20 $\mu$H/m [7]. In this case, $\alpha = 0.6$. Then, the maximum efficiency is $\eta =$ 10–25% (see Fig. 6). The real efficiency is even lower since in the calculations performed, the internal resistance of the current source was ignored. Thus, for current supply to high-inductance geophysical dipoles, induction-type (coil) LEGs are apparently preferred over railgun-type LEGs.

Below, we analyze the operating modes of some versions of coil-type LEGs, including operation with geophysical loads.

**2. Power Supply of a Geophysical Dipole.** The requirements imposed on the power supply of a geophysical dipole are due to the nature of the load. In the case considered, the power supply is intended to power a geophysical dipole with an inductance $L_d = 300$ $\mu$H and an active resistance $R_d = 10$ m$\Omega$ [6]. The maximum current supply is $I_d = 50$ kA. In this case, the insulating strength is limited by $E_{\max} = 30$ kV.

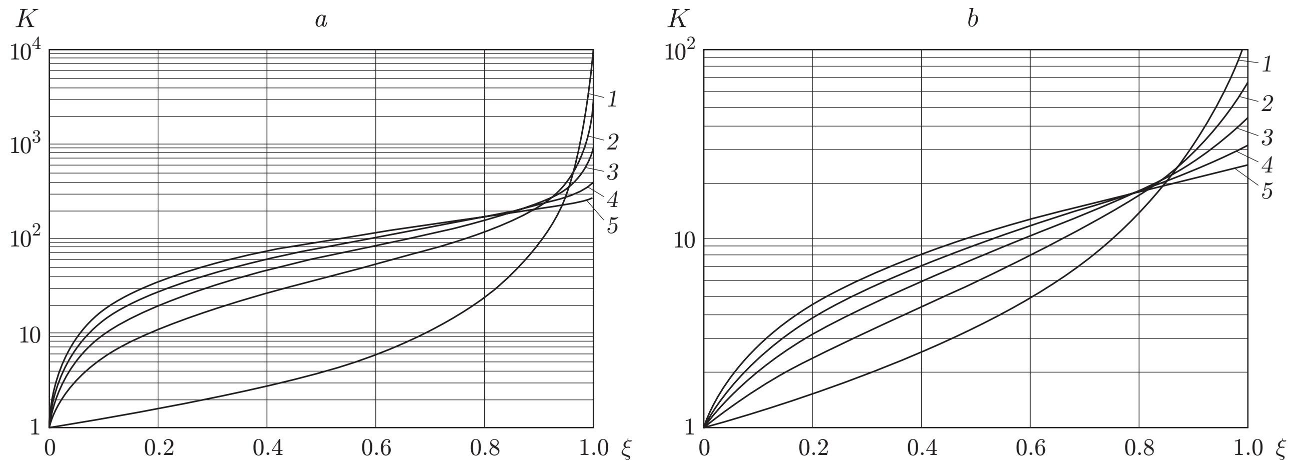


Fig. 3. Load energy gain versus the longitudinal coordinate of the armature (notation the same as in Fig. 2).

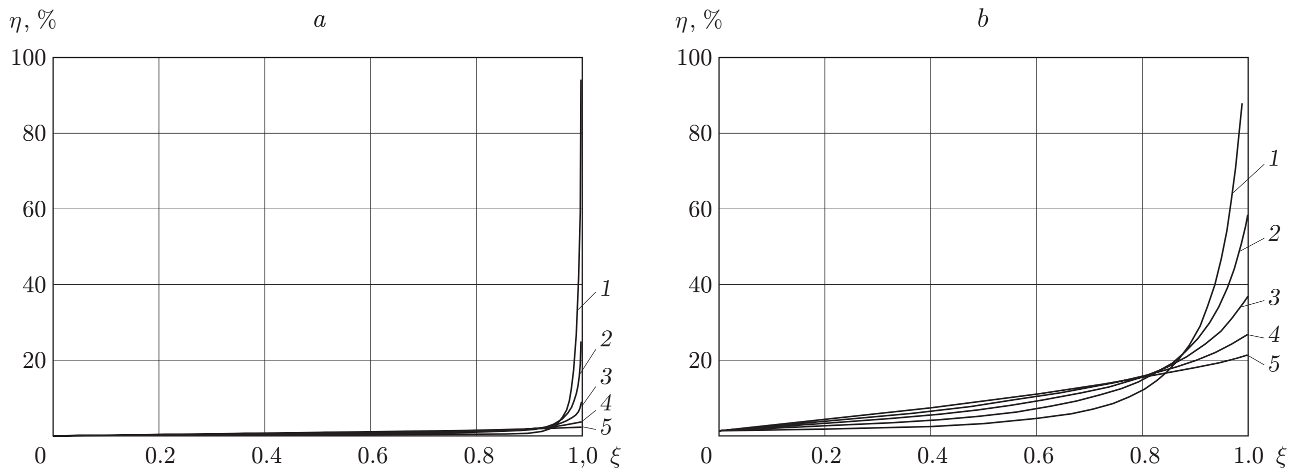


Fig. 4. Efficiency versus the longitudinal coordinate of the armature (notation the same as in Fig. 2).

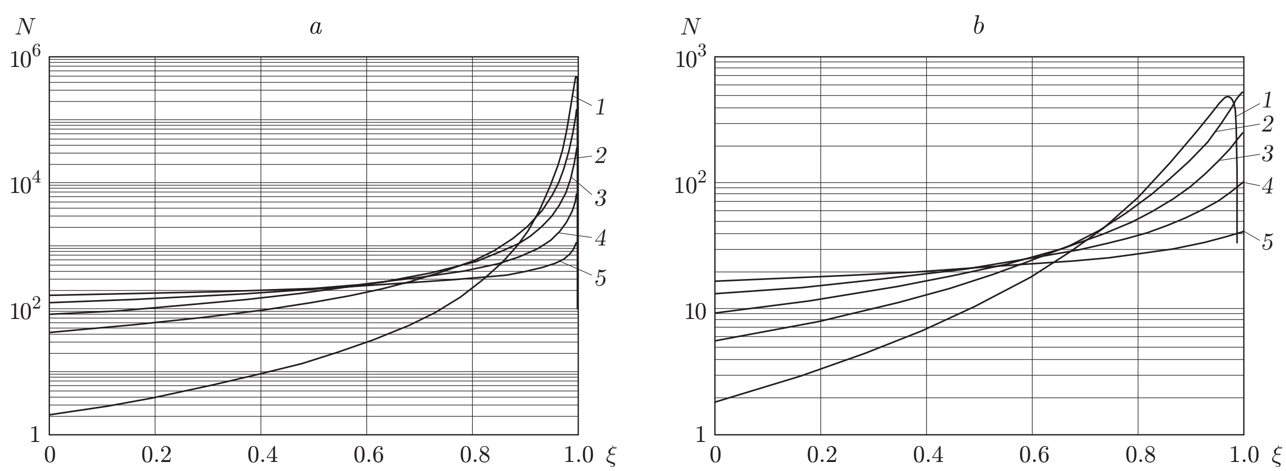


Fig. 5. Generator capacity versus the longitudinal coordinate of the armature (notation the same as in Fig. 2).

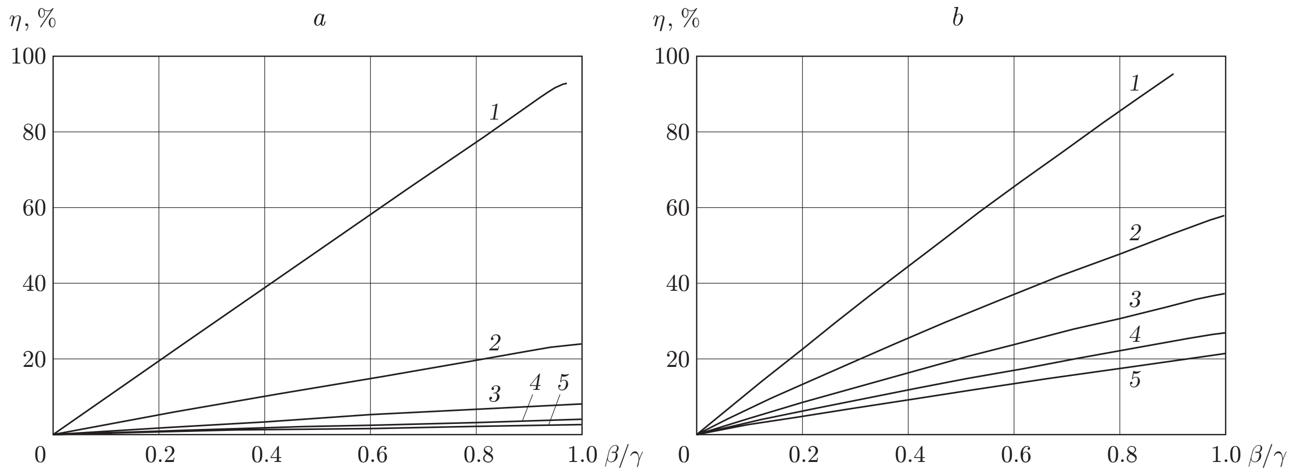


Fig. 6. Efficiency versus the ratio $\beta/\gamma$ at the moment of start or stop of the armature ($\xi = \xi_{\max}$) for $\gamma = 0.01$ (a) and 0.1 (b): $\alpha = 0$ (1), 0.2 (2), 0.4 (3), 0.6 (4), and 0.8 (5).

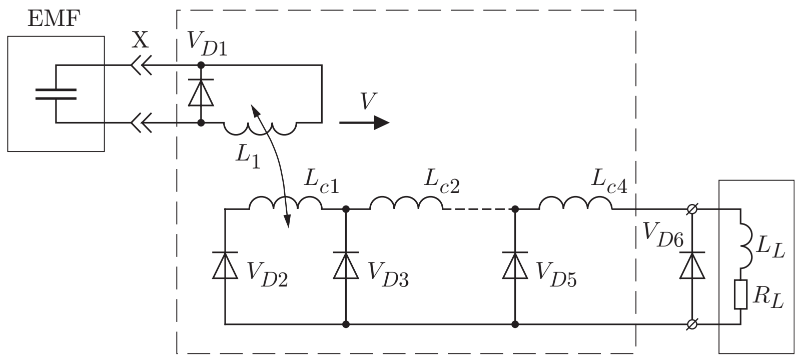


Fig. 7. Diagram of a generator model with a sectioned coil armature.

For the powering of a geophysical dipole, it is proposed to use a coil-type linear electric generator. Existing LEGs contain a stator coil and an inductively coupled armature coil, which is mounted so that it can be moved inside or outside the stator coil by an accelerator [2]. This generator has a number of disadvantages that limit its application as a power supply of a geophysical dipole. One of the main disadvantages is the necessity of producing the stator and armature coils with high self-inductances for a large value of the coupling coefficient between them (due to the high load inductance). This leads to a need for a massive armature and, hence, to a reduction in the conversion efficiency of the kinetic energy of the armature. In addition, energy is generated in such LEGs when the armature moves until its position is aligned with the stator position (the middles of the windings coincide); during further motion, the magnetic-field energy is converted to the kinetic energy of the armature (the armature is accelerated). At a high velocity, the armature motion on a short useful path is accompanied by the generation of elevated voltage across the LEG elements. The disadvantages of coil-type LEGs can be reduced by sectioning the stator coil and by connecting diode switches to the generator circuit.

The LEG model studied here (Fig. 7) contains $n$ sections of the stator ($L_{c1}$–$L_{cn}$), which are connected is series and mounted on the axis of armature motion so that they form a single channel. In the calculations, we set $n = 4$.

The armature contains a winding $L_1$ with a length equal to the length of one section of the stator and is mounted in such way that it can perform axial motion in the stator-winding channel. In the initial position, the armature winding is connected to an initial-field EMF source. The terminals of the stator winding sections are connected to a common wire through inverse valves $V_{D2}$–$V_{D6}$. The geophysical load ($L_L$, $R_L$) is switched between the second terminal of the last section of the stator winding and the common wire. In addition, the inverse valve $V_{D1}$ shunts the armature winding $L_1$.

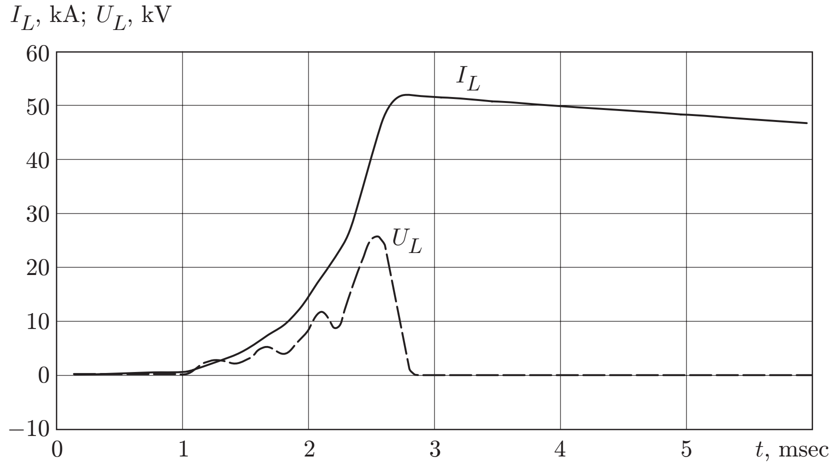


Fig. 8. Load voltage $U_L$ and current $I_L$ versus time.

The electric generator considered operates as follows. The armature winding $L_1$ is powered from the initial-field EMF source by means of a connector X. Once the required field current is attained, the accelerator (not shown in the diagram) causes the armature to move in the channel along the axis of the stator winding sections. After disconnection of the armature winding from the initial-field EMF source, the winding current closes through the inverse valve $V_{D1}$. When the armature moves, EMF is induced sequentially in each section of the stator winding, and an electric current flows in the circuit of the series-connected sections of the stator and load windings.

At the moment of passage through the aligned position of the armature winding and a stator winding section, the EMF changes sign at terminals of this section, the current decreases to zero, and the magnetic field of the armature induces an EMF in the next section. In this case, the current of the next section closes through the inverse valve connected to the first terminal of this section. The previous (traveled) section is eliminated from the further operation. Thus, the energy losses in the traveled section cease, resulting in an increase in the generator efficiency. As the armature moves along the stator sections, each of them sequentially energizes the next section and load along almost the entire length of the stator. This ensures a reduction in the maximum voltage across the load and generator winding. The short, fairly light armature allows a several fold decrease in the kinetic energy supplied to it from the accelerator. At the moment the armature passes through the position aligned with the last section of the stator, the load current closes through the last inverse diode $V_{D6}$ and the generator stator current decreases to zero.

Calculation results for the powering of a geophysical dipole ($L_L = 300$ $\mu$H and $R_L = 10$ m$\Omega$) by means of a four-section coil LEG are given in Fig. 8. It was assumed that the coil conductors are $5 \times 2$ mm copper buses (strip-on-edge winding). The physicotechnical and geometrical parameters of the generator are as follows: self-inductance of one stator section 0.608 mH, self-inductance of the armature 0.565 mH, active resistance of one stator section 0.0706 $\Omega$, active resistance of the armature 0.0673 $\Omega$, capacitance of the initial-field source 2 mF, charging voltage of the initial-field capacity 9 kV, average diameter of the stator 257 mm, length of the stator 600 mm, mass of the stator 150 kg, length of the armature 150 mm, mass of the armature 20 kg, length of one section 150 mm, number of stator turns 50, average diameter of the armature 245 mm, number of armature turns 50, and initial armature velocity 400 m/sec.

The calculations show that the sectioning of the stator allows a considerable (a factor of 3 to 4) increase in the current gain. This LEG version provides for the powering of the dipole with a current in excess of 50 kA in about 2 msec. During the powering, the voltage does not exceed 25 kV.

**3. Modeling of the Operating Modes of LEG with a Nonlinear Inductance per Unit Length.** In LEGs with a constant inductance per unit length, most of the generated energy falls on the final segment of the armature motion; therefore, the load current pulse is short and peaked [3, 4]. The specific shape of the output pulse limits the region of applicability of the generator.

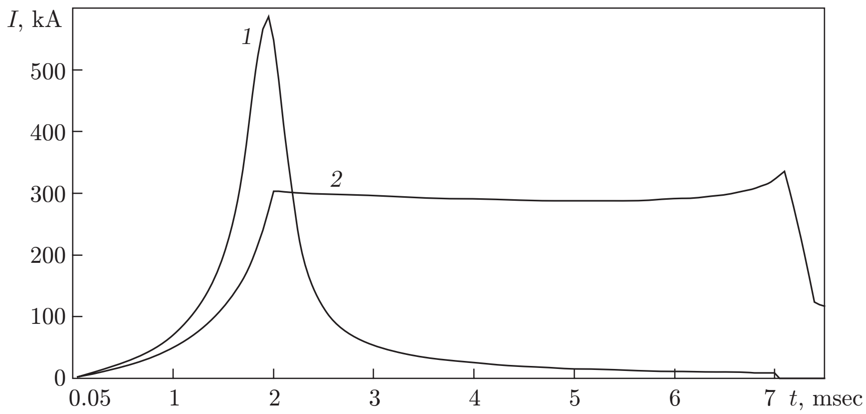


Fig. 9. Load current for various laws of variation of the inductance per unit length $L'$: curves 1 and 2 refer to $L' = \text{const}$ and $L' = f(x)$, respectively.

By upgrading the LEG design so that the inductance per unit length can be reduced during armature motion, it is possible to obtain a quasirectangular load current pulse [3, 4, 8]. The computation procedure for this generator is based on mathematical modeling using the PSPICE software package. Results of numerical experiments can be used to choose and optimize the model parameters required to design the LEG. The computation scheme can be represented in the form of an electric circuit or its description in a text file using built-in models of electric elements. Nonlinear electric elements are modeled by controlled voltage and current sources, and nonelectric parameters are specified in the form of mathematical expressions using built-in mathematical functions. The model can be modified if the formulation of the problem is changed.

Figure 9 gives current pulse shapes for powering of an active inductive load by means of electrical generators with a linear (LEG) and a nonlinear (modified generator) inductance per unit length. Curve 1 corresponds to the load current pulse shape for powering from a generator with a linear inductance of 160 $\mu$H/m on a length of 0.45 m, and curve 2 to the load current pulse shape in the case of a modified generator with a nonlinear inductance (the value of $L'$ decreases linearly from 160 to 12 $\mu$H/m on a length of 2.5 m). It is evident that the modified generator is capable of providing a flat current pulse.

It should be noted that a special banding of the armature and stator coils is provided in the experiments. Periodic pulse modes with multiple starts of the generator will probably require additional development of a cooling system. In particular, estimates show that the specific current action integral for the coil turns does not exceed 25% of the critical value that corresponds to the beginning of melting of the buses. The greatest power loads act in the zone of contact interaction of the armature and the stator coils, in which the magnetic field is maximal. In this case, the elastic stresses in the coils do not exceed 2.5% of the ultimate stress limit.

**Conclusions.** The theoretical study of the operation of linear ballistic generators with current supply to various loads, including rail accelerators and radiating magnetic dipoles used in electric prospecting, made it possible to develop simplified physical models and software for calculating the operating modes of inverse-railgun LEGs. For resistive loads, analytical solutions of the Cauchy problem modeling the generator operation over a wide range of determining parameters were obtained and investigated. Nonlinear-inductance generator models producing quasirectangular load current pulses, which are of interest for the solution of electrical prospecting problems, are considered. The theoretical computational study showed the possibility in principle of designing LEGs and employing them for geophysical research. However, the working capacity and efficiency of the generator designs considered can be proved only by manufacture and testing.

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