SIMULTANEOUS OPERATION OF A STRONG-CURRENT ELECTRODYNAMIC PLASMA ACCELERATOR AND AN ELECTRIC POWER SOURCE IN THE FORM OF A SINGLE-PHASE SALIENT-POLE MAGNETOELECTRIC GENERATOR

P. M. Kolesnikov and N. N. Smolovich

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Electrodynamic plasma acceleration in a coaxial is investigated on the basis of an idealized model of a current arch, when no mass is released during the acceleration. A computer is used to solve the corresponding system of differential equations describing the simultaneous operation of such a strong-current plasma accelerator, a capacitor, and a synchronous magnetoelectric generator. A system of differential equations for electrodynamic plasma acceleration in an autonomous accelerator is obtained with allowance for the mass-transfer processes and resistance forces.

The operation of a strong-current plasma accelerator was investigated on the basis of the well-known idealized model of a current arch with an accumulator of electric energy in the form of a capacitor by a number of workers [1-7]. The electric supply source and the process of charging the capacitor were not considered in these studies. However, the development of an autonomous strong-current plasma accelerator raises the question of the character of plasma acceleration when the electric supply source, the storage device, and the accelerator operate jointly, since their parameters and characteristics influence the operation of the system as a whole. The steady-state processes in a synchronous generator feeding a pulsed load were investigated in [8, 15, 16], but the simultaneous operation of a generator and an accelerator has never been considered.

In the present paper we investigate an electrodynamic plasma accelerator operating simultaneously with capacitive electric-energy device and an electric supply source in the form of a single-phase salient-pole synchronous magnetoelectric generator. The choice of a magnetoelectric generator as the source of electric energy was dictated by its many advantages [9-13]: high operating reliability and simplicity of design, owing to the absence of a winding on the rotor and on the exciter; high efficiency and lower heating owing to the absence of losses to excitation and in the slip rings; lower radio interference because of the absence of sparking contacts; low ratio of generator weight to output power for high-speed machines with effective utilization of high-grade materials; low time constant of the armature winding; and others.

Recently, in connection with the development of materials for permanent magnets with higher specific energy (e.g., anisotropic alloys with columnar structure [10]), magnetoelectric generators have started to compete in a definite range of power rating with electric generators that use electromagnetic excitations. In a number of cases, generators with permanent magnets afford the only solution to the arising problems.

The generator together with the capacitor and the plasma accelerator form a charge–discharge circuit. The equivalent electric circuit of the charging loop is a series circuit consisting of a source of sinusoidal electromotive force, the lumped active resistance R_0 of the stator winding and of the connecting leads, the inductance L_a of the stator winding, and a load in the form of a capacitor. The system in question operates as follows. When the generator rotor turns, an electromotive force is excited in its winding. The

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capacitor is connected to the generator with the discharge circuit (accelerator) open, in which case all that happens is the charging of the capacitor. When a specified voltage is reached, the plasma accelerator is connected to the capacitor, and the simultaneous operation of the generator, capacitor, and accelerator begins. Currents of 100-400 kA and magnetic fields of 1-5 T are produced in the discharge circuit and accelerate the plasma to high velocities.

The capacitor can be charged to a definite voltage within a fraction of a cycle or in one or more cycles. It is easy to see that to obtain a high efficiency of the discharge circuit, it is desirable to charge the capacitor within the first quarter-cycle.

We have investigated only one-shot turning on of the strong-current plasma accelerator when operating simultaneously with the generator.

Taking [1-5] and [8-16] into account, the in dimensionless equations describing the operation of an autonomous electrodynamic plasma accelerator, reduced beforehand to cannonical form, are

$$\frac{d\bar{I}}{d\tau}=\frac{\nu_1\Omega\sin\Omega\tau}{1+\nu_2\cos 2\Omega\tau}+\frac{2\nu_2\Omega\sin 2\Omega\tau-\alpha}{1+\nu_2\cos 2\Omega\tau}\bar{I}-\frac{\beta\bar{V}}{1+\nu_2\cos 2\Omega\tau}, \tag{1}$$

$$\frac{d\bar{V}}{d\tau}=\bar{I}+\bar{I}_1, \tag{2}$$

$$\frac{d\bar{I}_1}{d\tau}=-\frac{\alpha_1+\bar{v}}{1+\bar{z}}\bar{I}_1-\frac{\beta_1\bar{V}}{1+\bar{z}}, \tag{3}$$

$$\frac{d\bar{v}}{d\tau}=q\bar{I}_1^2, \tag{4}$$

$$\frac{d\bar{z}}{d\tau}=\bar{v}, \tag{5}$$

where the dimensionless variables and parameters are defined by the formulas

$$\begin{gathered}\tau=\omega_0 t,\quad \bar{I}=\frac{I}{C_0V_0\omega_0},\quad \bar{V}=\frac{V}{V_0},\quad \bar{v}=\frac{vb}{L_0\omega_0},\quad \bar{z}=\frac{b}{L_0}z,\quad \bar{I}_1=\frac{I_1}{C_0V_0\omega_0},\\ \nu_1=\frac{\psi_{0\mathrm{M}}}{C_0l_0V_0\omega_0},\quad \nu_2=\frac{l_2}{l_0},\quad \alpha=\frac{R_0}{l_0\omega_0},\quad \alpha_1=\frac{R_1}{L_0\omega_0},\\ \beta=\frac{1}{C_0l_0\omega_0^2},\quad \Omega=\frac{\omega}{\omega_0},\\ \beta_1=\frac{1}{C_0L_0\omega_0^2},\quad q=\frac{b^2C_0^2V_0^2}{2ML_0}.\end{gathered} \tag{6}$$

It is assumed in Eqs. (1)-(2) that the magnetic flux due to the magnetization of the permanent magnets in the rotor is linked with the winding distributed over the stator, and the magnetic flux linkages ψ_M of the generator winding can be represented in the form

$$\psi_{\mathrm{M}}=\psi_{0\mathrm{M}}\cos\omega t. \tag{7}$$

A sinusoidal distribution of the magnetic induction is produced in the gap between the stator and the rotor [10], and the generator is not damped. When determining the electromotive force in the stator winding, only the fundamental harmonic of the excitation field is taken into account, as is usually done in theoretical investigations of transients in electrical machinery [11-13]. It is assumed that during the simultaneous operation of the generator, capacitor, and plasma accelerator, the generator rotor velocity is maintained constant, and the magnetic-circuit nonlinearity due to magnetic saturation of the individual circuit elements is disregarded.

Since the analysis considers not the axial distribution of the induction in the gap between the stator and the rotor but only the first harmonic of this distribution, the inductness of the winding of a salient-pole magnetoelectric generator is given by [11-13]

$$L_a=l_0+l_2\cos 2\omega t. \tag{8}$$

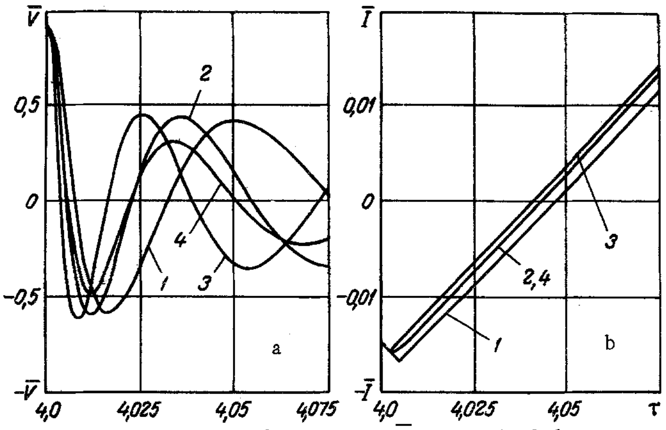

Fig. 1. Variation of the voltage $\overline{V}$ (a) and of the current $\overline{I}$ (b) in the charging circuit with time τ during simultaneous operation of the accelerator, capacitor, and generator, and with the parameters (6) of the system (1)-(5): $\nu_1 = 1$, $\nu_2 = 0.2$, $\alpha = 0.01$, $\beta = 1$, $\Omega = 0.5$, q = 1 [1) $\beta_1 = 0.5 \cdot 10^5$, $\alpha_1 = 20$; 2) $\beta_1 = 10^5$, $\alpha_1 = 20$; 3) $\beta_1 = 2 \cdot 10^5$, $\alpha_1 = 20$; 4) $\beta_1 = 10^5$, $\alpha_1 = 80$].

If we put in (1)-(5) formally $I_1 = 0$ and $\beta_1 = 0$, then this system of equations will describe the operation of the generator in question when connected in a charging circuit with a capacitive load. To solve (1)-(5) it is necessary to specify also five initial conditions. Their values will be chosen in each concrete case.

The character of the solution of the system (1)-(5) depends essentially on the dimensionless parameters (6) and on the generator rotor circular frequency Ω. The value of the parameter q was discussed in [1-7], and lies in the range 10^{-3}-10^2. The dimensionless parameter ν_1 characterizes the amplitude ψ_{0M}. Since ψ_{0M} can range from 1 to 10 V · sec, it follows that at the chosen values of the discharge current I $= C_0 V_0 \omega_0 = 1000$ A and $l_0 = 20 \cdot 10^{-4}$ H the value of ν_1 calculated from (6) is $\simeq 0.5$-5. The parameter ν_2 characterizes the ratio of the ac component of the stator-winding inductance to its dc component, and its values are assumed, according to [10], to be 0.2-0.5. The dimensionless parameter α corresponds to the values of the ohmic losses in the winding and in the connecting leads. Choosing $R_0 = 0.05\ \Omega$, we obtain $\alpha = 0.1$-0.01. The parameter α_1 is proportional to the ohmic resistance of the accelerator and at $L_0 = (15$-$150) \cdot 10^{-9}$ H and $R_1 = 0.001\ \Omega$ it takes on values in the interval 10-80. The parameter β_1 can vary in this case in the interval $\beta_1 = (1$-$60) \cdot 10^4$. The parameter β at specified C_0, l_0, and ω_0 is always equal to unity. β can be varied only by changing the nominal value of ω_0.

Equations (1)-(5) with the chosen values of the parameters (6) were solved with the "Minsk" computer. We first investigated only the charging current at different generator parameters (defined the instant of time τ_0 at which the accelerator and the capacitor are to be connected and to obtain the missing initial conditions for the system of equations of the autonomous electrodynamic plasma accelerator), after which we investigated the complete system (1)-(5).

The calculations have shown that when a single-phase synchronous salient-pole magnetoelectric generator feeds a capacitor load, two operating modes are possible, one with a limited amplitude of the oscillations of the voltage $\overline{V}$ and the current $\overline{I}$, and one with a theoretically unlimited growth of the amplitudes of $\overline{V}$ and $\overline{I}$ (resonant excitation). The second mode can be eliminated by suitable choice of the parameters (6), especially by varying the circular frequency Ω of the generator rotor. It was observed in the frequency interval $0.8 < \Omega < 1.2$ at parameter values $\nu_1 = 0.5$-1; $\nu_2 = 0.2$; $\alpha = 0.1$-0.01; and $\beta = 0.5$-1. The use of resonant excitation of the generator makes it possible to charge the capacitor to high voltages in the considered autonomous electrodynamic accelerator, but only after a prolonged time and with large losses.

The complete system of equations (1)-(5) was solved numerically for different values of the parameters (6) with the following initial conditions:

$$\text{at} \quad \tau = \tau_0 = 4.0 \ \overline{V} = 0.89887, \ \overline{I} = -0.014837, \ \overline{I_1} = \overline{v} = \overline{z} = 0, \tag{9}$$

where τ_0 corresponds to the instant of time when the voltage amplitude normalized to unity reaches its maximum value.

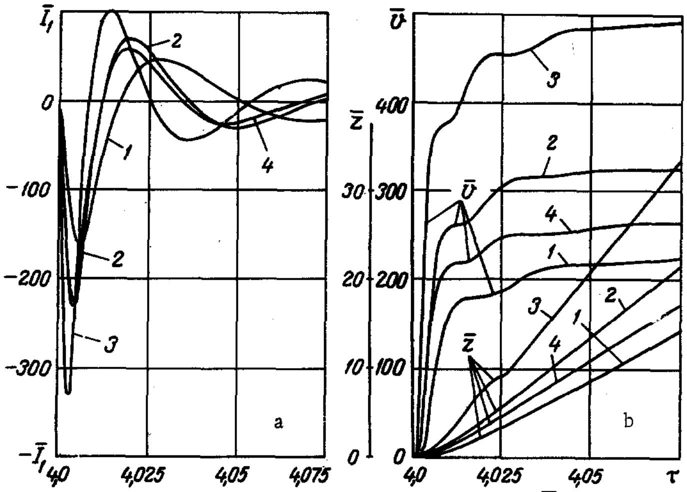

Fig. 2. Variation of the accelerator current $\bar{I}_1$ (a) and of the velocity of the mass center of the accelerated plasma $\bar{v}$ and of the path $\bar{z}$ (b) with time τ. The notation and the parameters of the curves are the same as in Fig. 1.

The results of the numerical calculations are shown in Figs. 1 and 2. Curves 1-3 of these figures make it possible to estimate the influence of the parameter β_1 on the integral plasma characteristics developed by the accelerator, and the values of this parameter are varied in the range $(0.5\text{-}1.0)\cdot 10^5$. Curves 4 of Figs. 1 and 2 are shown for the purpose of estimating the parameter α_1. It is seen from the figures that during the simultaneous operation of the generator, capacitor, and accelerator the current flows mainly through the accelerator and its value at the chosen parameters reaches 320 kA (cf. Fig. 2a). As seen from Fig. 1b, the current in the generator is 15 A in this case.

Voltages of opposite polarities are produced on the capacitor electrodes, but they do not exceed the initial charge of the capacitor at the instant of time $\tau_0 = 4.0$. It is seen from Fig. 2 that after a time $\tau = 4.05$ the plasma is accelerated to a velocity 220-480, and the acceleration process is practically stopped. The time of simultaneous operation of the generator and accelerator is shorter by an approximate factor 100-3000 than the time of charging of the capacitor. Thus, when a 150-200 μF capacitor is connected to a generator with a rotor speed n = 10,000-30,000 rpm, the capacitor can be charged to 1-10 kV within 0.001-0.002 sec, thereby accelerating the plasma in the strong-current autonomous electrodynamic accelerator to 10^5 m/sec. We note that the appearance of a reversed voltage polarity on the capacitor, if necessary, can be prevented by limiting the acceleration time or the accelerator length. It is possible to stop the operation of the accelerator as soon as the voltage on the capacitor electrodes reaches zero. A discharge of this type into an ohmic load was investigated in [8], but in the accelerator considered here, with such a limitation, the plasma velocity will be smaller by an approximate factor 2-3 than its maximum value, as seen from Fig. 2b.

Table 1 shows a comparison of the results obtained in the present paper by solving the system of equations (1)-(5) with the results of a solution of the same system of equations when $\nu_1 = \nu_2 = \alpha = \beta = \Omega = 0$, i.e., without the electric supply source. An analysis of the table, and also a comparison with the results of [1-7], shows that the character of the plasma acceleration as a whole remains unchanged.

Taking into account our earlier investigations [3-7, 17-19], we can easily obtain a system of differential equations describing the operation of such an autonomous electrodynamic accelerator with coaxial geometry, with allowance for the processes of electrode erosion, charge exchange, and ambipolar diffusion and recombination of the plasma particles, and the friction and resistance forces; these equations take the form

$$\frac{d\bar{v}}{d\tau} = \frac{q}{\mu}\bar{I}_1^2 - \frac{\bar{v}}{\mu}[\delta_1\sqrt{\beta_1} + \delta_2\sqrt{\beta_1}\mu + \delta_3|\bar{I}_1| + \delta_4\bar{v}] - \frac{\bar{v}}{\mu}\left[-\gamma_1\sqrt{\beta_1}\mu - \gamma_2\sqrt{\beta_1}\mu^2 + \gamma_3|\bar{I}_1| + \frac{1}{\sqrt{\beta_1}}\gamma_4\bar{I}_1^2\right], \tag{10}$$

TABLE 1. Comparison of the Characteristics of an Accelerator

	With the generator				Without the generator			
Parameter of the system of equations (1) - (5)	$\Omega = 0{,}5;\ \nu_1 = 1;\ \nu_2 = 0{,}2;\ \beta = 1;$ $\alpha = 0{,}01;\ q = 1;\ \beta_1 = 10^5;\ \alpha_1 = 20$				$\Omega = \nu_1 = \nu_2 = \beta = \alpha = 0;$ $q = 1;\ \beta_1 = 10^5;\ \alpha_1 = 20$			
Initial conditions	for $\tau = 2{,}6\ \overline{I} = 0{,}44470,\ \overline{V} = 0{,}50375,$ $\overline{I}_1 = \overline{v} = \overline{z} = 0.$				for $\tau = 2{,}6\ \overline{I} = 0,\ \overline{V} = 0{,}50375,$ $\overline{I}_1 = \overline{v} = \overline{z} = 0.$			
Acceleration time	2,605	2,625	2,650	2,675	2,605	2,625	2,660	2,675
Accelerator characteristics								
$\overline{V}$	0,02458	0,3076	—0,24412	0,2025	0,02310	+0,3074	—0,2447	0,2023
$\overline{I}$	—141,04	7,9097	5,8059	5,7287	—140,66	8,0222	6,4968	6,0271
$\overline{v}$	56,236	141,57	159,75	168,08	56,044	141,72	159,44	168,20
$\overline{z}$	0,08740	2,3554	6,1550	10,259	0,08717	2,3505	6,1481	10,250

$$\frac{d\mu}{d\tau} = -\gamma_1 \sqrt{\beta_1}\mu - \gamma_2 \sqrt{\beta_1}\mu^2 + \gamma_3 |\overline{I}_1| + \frac{\gamma_4}{\sqrt{\beta_1}} \overline{I}_1^2, \tag{11}$$

and must be solved simultaneously with (1)-(3) and (5).

The mass-transport parameters γ_1-γ_4 and the resistance-force parameters δ_1-δ_4 which enter in the system of equations (1)-(3), (5), (10)-(11) were already discussed by us in [5, 6, 17, 19].

We present the equation of the overall energy balance in the electrodynamic autonomous plasma accelerator with the described electric supply source. According to [5, 6], taking (6) into account, this equation can be written in the form of a dimensionless energy conservation law

$$1 = \frac{W_E}{W_{\tau_0}} + \frac{W_M}{W_{\tau_0}} + \frac{W_{J_1}}{W_{\tau_0}} + \frac{W_K}{W_{\tau_0}} + \frac{W_P}{W_{\tau_0}}$$
$$= \frac{\overline{V}^2}{\xi^2} + \frac{(1+\overline{z})\overline{I}_1^2}{\xi^2\beta_1} + \frac{2\alpha_1}{\xi^2\beta_1}\int_{\tau_0}^{\tau} \overline{I}_1^2\, d\tau + \frac{\mu\overline{v}^2}{2q\xi^2\beta_1} + \frac{W_P}{W_{\tau_0}}, \tag{12}$$

where

$$\xi = \frac{V_{\tau_0}}{V_0}. \tag{13}$$

Unlike in [6], as seen from (12)-(13), Eq. (12) is normalized not to the quantity $C_0V_0^2/2$, but to the quantity $W_{\tau_0} = C_0\xi^2V_0^2/2$. The reason is that in our system we cannot choose the normalizing voltage to be the maximum amplitude of the capacitor voltage, as was done in [6, 17], since the amplitude of the voltage V increases without limit when the generator is resonantly excited.

NOTATION

- l_0 is the constant component of stator winding inductance;
- l_2 is the amplitude of second harmonic connected with difference in magnetic resistances along longitudinal and transverse axes of generator rotor;
- t is the time;
- R_0 is the active resistance of generator winding and wires;
- R_1 is the active resistance of accelerator;
- I is the current in charging circuit;
- ω is the angular frequency of generator rotor revolution;
- C_0 is the capacitor capacitance;
- V is the voltage on capacitor plates;

ψ_M	is the magnetic linkage of generator winding;
ψ_{0M}	is the amplitude of magnetic linkage defined as the product of magnetic flux and number of windings with regard for winding coefficient;
I_1	is the current in accelerator;
M	is the mass of accelerated plasma;
z	is the coordinate of center of accelerated plasma mass;
L_0	is the initial inductance of plasma accelerator;
L	is the inductance of plasma accelerator;
b	is the distributed inductance of accelerator per unit length;
W_E/W_{τ_0}, W_M/W_{τ_0}, W_{J_1}/W_{τ_0}, W_K/W_{τ_0}	are the electric, magnetic energy, losses for Joule heat in accelerator, and kinetic energy of plasma jet, respectively, divided by the energy W_{τ_0} accumulated in capacitor by the time τ_0;
Ω, ν_1, ν_2, α, β, α_1, β_1, q, γ_1–γ_4, δ_1–δ_4	are the dimensionless parameters;
$\bar{I}$, $\bar{I}_1$, $\bar{V}$, $\bar{v}$, $\bar{z}$, μ	are the dimensionless variables of current for charging circuit in the accelerator, of the voltages, velocity, length traversed by the plasma and of the mass, respectively;
ω_0, V_0	are the nominal values of angular velocity of generator rotor and of the voltage, respectively.

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