Conference materials
UDC УДК 533.95-629.7.036
DOI: https://doi.org/10.18721/JPM.161.150

Working process calculation of the control circuit for pulsed operation regime of the MPD accelerator

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Abstract. A circuit for controlling the discharge current of an MPD accelerator based on the Morgan circuit is considered. It is shown that theoretically operation regime of the accelerator, depending on the parameters of the circuit, can be stationary, modulation, and pulsed. The necessary condition for the accelerator operation in the periodic mode is established. Calculations of the pulse shape of the discharge current are carried out. The experimentally observed pulse forms are compared with the calculated ones.

Keywords: plasma accelerators, pulsed mode, discrete plasma formations, discharge current, pulse shape, Morgan scheme

Citation: Tashayev Yu.N., Working process calculation of the control circuit for pulsed operation regime of the MPD accelerator, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.1) (2023) 301–308. DOI: https://doi.org/10.18721/JPM.161.150

Материалы конференции
УДК УДК 533.95-629.7.036
DOI: https://doi.org/10.18721/JPM.161.150

Расчет рабочего процесса схемы управления импульсным режимом работы МПД ускорителя

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Аннотация. Рассмотрена схема управления током разряда МПД-ускорителя, основанная на схеме Моргана. Теоретически показано, что режим работы ускорителя в зависимости от параметров схемы может быть стационарным, модуляционным и импульсным. Найдено необходимое условие работы ускорителя в периодическом режиме. Проведены расчеты формы импульса разрядного тока. Найдено условие перехода от модуляционного режима к импульсному. Экспериментально наблюдаемые формы импульсов сравниваются с расчетными.

Ключевые слова: плазменные ускорители, импульсный режим, дискретные плазменные образования, разрядный ток, форма импульса, схема Моргана

Ссылка при цитировании: Ташаев Ю.Н. Расчет рабочего процесса схемы управления импульсным режимом работы МПД ускорителя // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.1. С. 301–308. DOI: https://doi.org/10.18721/JPM.161.150

Introduction

The Plasma accelerators were widely used as plasma sources when conducting research on the Earth's magnetosphere with the help of artificial plasma formations [1]. Among the numerous questions posed to the researchers were: studying the structure and dynamics of artificial plasma formations in the ionosphere, studying shock waves, generation of MHD waves, plasma instabilities, studying the interaction of "artificial" plasma formations created by the accelerator with the rocket body and the environment. In particular, when studying low-frequency radiation and magnetic field disturbances in ionospheric plasma, it is necessary to create pulsed plasma formations – plasma clouds or modulated plasma flows. The possibility of using a magnetoplasmodynamic accelerator (MPDA) as a source of discrete plasma formations with a repetition frequency of up to 10 kHz is described in the proposed work.

The implementation of the pulsed and modulation regimes of the accelerator was achieved by including a semiconductor discharge current interrupter based on the Morgan scheme in the pulsed power supply of the accelerator [2]. The proposed circuit of the current interrupter made it possible to obtain not only flows of plasma clouds with a given repetition rate, but also modulated plasma flows with different modulation depths.

Materials and Methods

Fig. 1 shows the Morgan schematic diagram used to control the discharge current of the MPD accelerator. The circuit consists of a semiconductor valve controlled by a rectangular pulse generator assembled on the basis of an asymmetric multivibrator, and connected in parallel with the valve LC chain. The pulse generator was used in the frequency range $f \sim 500 \div 1000$ Hz and $f \sim 5 \div 10$ kHz. In the pulsed operation mode, (Fig. 2) the accelerator emitted plasma formations with a certain repetition frequency. When generating plasma flows in the modulation mode, the intensity of the plasma jet was a periodic function of time. It was noted in [3] that in a wide range of discharge currents, the volt-ampere characteristic of the MPDA in stationary mode is linear.

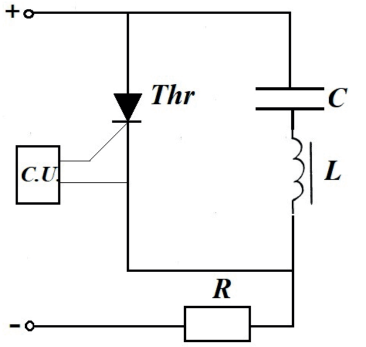

Fig. 1. Schematic diagram of discharge current control

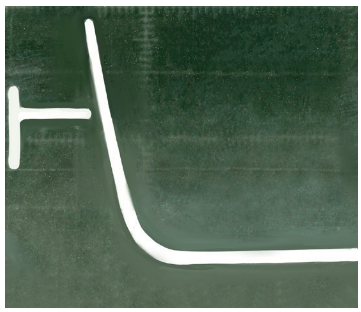

Fig. 2. Pulsed operation regime: discharge current waveform

In the first approximation, the analysis of the operation of the power supply circuit of the accelerator was carried out under the assumption that, in the electrical sense, the discharge chamber of the accelerator is equivalent to the active resistance R, the value of which is fixed and determined by the plasma parameters and the external magnetic field inside the discharge chamber [4]. Preliminary laboratory studies of the stationary operating mode of the accelerator confirm the linearity of the volt-ampere characteristics of the discharge current in a wide range of its values. The resistance of the discharge circuit practically did not depend on the magnitude of the discharge current, but was determined by such parameters as the cathode glow current, the flow rate of the working fluid, the pressure in the vacuum chamber, the shape of the magnetic field created by the solenoid. The analysis of the operation of the scheme will be divided into two stages. The first stage begins when the thyristor is opened by a control signal from the control unit (C.U.) and ends when the current disappears through the thyristor, which leads to its blocking. The second stage begins from the moment the thyristor is turned off and stops at the moment it is opened by a signal from the C.U. For the periodic repeatability of the processes occurring in the circuit, it is necessary that the values of the current in the circuit and the charge of the capacitor corresponding to the beginning of the first stage coincide with the values of the current and charge at the end of the second stage. Now we will focus in more detail on the work of the scheme. When a voltage pulse is applied from the C.U. on the control electrode of the thyristor, it opens, and the voltage of the power source (ε) is directly applied to the resistance R (i.e., the anode voltage is applied to the plasma accelerator). Through the resistance R almost instantly (neglecting the inductance of the discharge circuit) a current is set to $I_0 = \varepsilon/R$ which means the appearance of a discharge current in the plasma accelerator. At the same time, the capacitance (C) is short-circuited to the inductance (L), and electric current oscillations occur in the circuit, described by the equation

$$I = I_m \cdot \sin(\omega t + \varphi_0),$$

where $\omega = (LC)^{-1/2}$ is the eigen frequency of oscillations. The amplitude I_m and the initial phase φ_0 are related to the initial values of the capacitor charge q_n and the current in the circuit I_n by the relations:

$$\frac{LI_m^2}{2} = \frac{q_n^2}{2C} + \frac{LI_n^2}{2}; \quad \sin\varphi_0 = \frac{I_n}{I_m}. \tag{1}$$

It should be noted that the values of qn and I_n during the periodic operation of the circuit are set after some relaxation time has passed since the first opening of the thyristor. At the beginning of the circuit operation (at the time of the first opening of the thyristor) there is no current in the circuit, and the charge on the capacitor $Q = C\cdot\varepsilon$. At the same time the maximum value of the current in the LC circuit $I_{m0} = \sqrt{(C/L)}\cdot\varepsilon = \omega Q$, so that the thyristor will be locked only when $I_{m0} \geq I_0$, or $\sqrt{(C/L)}\cdot\varepsilon \geq \varepsilon/R$. Entering the parameter $\alpha = 1/R\sqrt{(L/C)}$ we get that the inequality $\alpha \leq 1$ is a necessary condition for the operation of the circuit. Taking into account that the current through the thyristor is the algebraic sum of the discharge current and the current in the LC circuit, then for the thyristor locking time, determined from the condition $I_{\text{tir}} = I_0 - I = 0$, we obtain:

$$t_1 = \frac{1}{\omega}(\arcsin\frac{I_0}{I_m} - \varphi_0 + 2\pi). \tag{2}$$

The charge of the capacitor at this time is negative and can be found from the energy conservation law for the LC circuit:

$$Q_0 = -\frac{I_m}{\omega}\sqrt{1 - \frac{I_0^2}{I_m^2}}. \tag{3}$$

Obviously, for the implementation of the periodic operation mode of the accelerator, the following condition must be met:

$$I_m \geq I_0. \tag{4}$$

Time t_1 (2) determines the duration of the stationary value of the discharge current $I = I_0$ and corresponds to the beginning of the second stage of the circuit operation. At the second stage ($t > t_1$), damped electrical oscillations will occur in the RLC circuit. Below are the expressions of the current in the circuit $I(t)$ and the capacitor charge $Q(t)$ satisfying the condition of continuity of functions I and Q, both during the transition to the second stage at time $t = t_1$, and at the time of reopening of the thyristor at $t = T$, where $T = f^{-1}$ is the period of operation of the circuit. During the calculations, the current in the circuit was considered positive if it flowed in the direction of the positive bypass of the circuit (clockwise). It can be shown that at $t = 0$, at the time of thyristor opening, either $I = I_n > 0$, $Q = q_n > 0$, or $I_n = 0$ and $q_n = I_m\omega^{-1}$. In the LC circuit at $t < t_1$, the dependences of the current and charge of the capacitor on time can be written as:

$$I = I_m \cdot \sin(\omega t + \pi - \arcsin\frac{I_n}{I_m}), \; Q = -\frac{I_m}{\omega}\cdot\cos(\omega t + \pi - \arcsin\frac{I_n}{I_m}). \tag{5}$$

It is taken into account here that in $I = I_m \cdot \sin(\omega t + \varphi_0)$ the initial phase is determined by the expression $\varphi_0 = \pi - \arcsin(I_n/I_m)$, $I_n > 0$, respectively:

$$\left.\frac{dI}{dt}\right|_{t=0} = -I_m\omega\sqrt{1-\frac{I_n^2}{I_m^2}} < 0, \quad q_{\text{n}} = \frac{I_m}{\omega}\sqrt{1-\frac{I_n^2}{I_m^2}} > 0.$$

By the time $t_D = \omega^{-1}\cdot\arcsin(I_n/I_m)$ the positive charge of the capacitor reaches its maximum, and by the time $\omega^{-1}\cdot(\pi + \arcsin(I_n/I_m))$ the capacitor is fully recharged. From this moment, the current opposite to the discharge current will begin to increase in the LC circuit, which will lead to the

completion of the first stage by the time t_1, determined by the expression:

$$t_1 = \omega^{-1}\cdot\left(\pi + \arcsin\frac{I_n}{I_m} + \arcsin\frac{I_0}{I_m}\right). \tag{6}$$

The second stage begins when the thyristor is locked at $t = t_1$ and ends at $t = T$. The dependence of the discharge current on time at $t_1 < t < T$ satisfies the equation of damped oscillations with

initial conditions: $I\big|_{t=t_1} = I_0$, $dI/dt\big|_{t=t_1} = \omega\sqrt{I_m^2 - I_0^2} > 0$, and at $0.5 < \alpha \le 1$ can be represented as:

$$I = I_0\cdot\frac{e^{-\beta(t-t_1)}}{\sin\theta_0}\cdot\sin(\Omega(t-t_1)+\theta_0), \text{ where } 2\beta = \frac{R}{L}, \ \Omega = \sqrt{\left|\omega^2-\beta^2\right|},$$

$$\theta_0 = \text{arcctg}\left[\Omega^{-1}\cdot\omega\left(\sqrt{\frac{I_m^2}{I_0^2}-1}+\frac{\beta}{\omega}\right)\right]. \tag{7}$$

The dependence of the capacitor charge on time at the stage of damped oscillations can be represented as:

$$Q = C\cdot\varepsilon + I_0\omega^{-1}\cdot\frac{e^{-\beta(t-t_1)}}{\sin\theta_0}\cdot\sin\left[\Omega(t-t_1)+\theta_0+\theta_1+\pi\right], \tag{8}$$

where $\theta_1 = \text{arcctg}(\Omega^{-1}\cdot\beta)$ If the circuit parameters are such that $\alpha < 0.5$, then

$$I = I_0\cdot\frac{e^{-\beta(t-t_1)}}{sh\ \eta_0}\cdot sh\left[\Omega(t-t_1)+\eta_0\right], \quad \eta_0 = \text{arccth}\left[\Omega^{-1}\cdot\omega\left(\sqrt{\frac{I_m^2}{I_0^2}-1}+\frac{\beta}{\omega}\right)\right],$$

$$Q = C\cdot\varepsilon + I_0\omega^{-1}\cdot\frac{e^{-\beta(t-t_1)}}{sh\eta_0}\cdot sh\left[\Omega(t-t_1)+\eta_0+\eta_1+i\cdot\pi\right], \tag{9}$$

where $\eta_1 = \text{arccth}(\Omega^{-1}\cdot\beta)$. I_n the special case $\alpha = 0.5$, the expressions for current and charge are obtained by passing to the limit $\Omega\to 0$:

$$I = I_0\cdot e^{-\tau}\left[1+\tau\left(1+\sqrt{\frac{I_m^2}{I_0^2}-1}\right)\right], \ Q = C\cdot\varepsilon\left[1-e^{-\tau}\left(1+\frac{1}{2}\sqrt{\frac{I_m^2}{I_0^2}-1}+\frac{\tau}{2}\cdot\left(1+\sqrt{\frac{I_m^2}{I_0^2}-1}\right)\right)\right], \tag{10}$$

where $\tau = \omega\cdot(t - t_1)$. The shape of the discharge current pulse at different $\alpha \le 1$ is schematically shown in Fig. 3.

At $t < t_1$, the discharge current is constant, and at $t < t_1$, immediately after locking the thyristor, ($I_m > I_0$), there is an increase in current to a certain maximum value $I_{\max} < 2\cdot I_0$, reached at the time tmax. Later on ($t > t_{\max}$), the current monotonically decreases at $\alpha \le 0.5$ and at $0.5 \le \alpha \le 1$ would oscillate with an exponentially decaying amplitude if the accelerator operation did not depend on the direction of the current in the discharge space. In this case, the reversal of the current to zero at the time

$$t_2 = \omega^{-1}\cdot\left(\pi + \arcsin\frac{I_n}{I_m} + \arcsin\frac{I_0}{I_m}\right) + \Omega^{-1}\cdot(\pi - \theta_0), \tag{11}$$

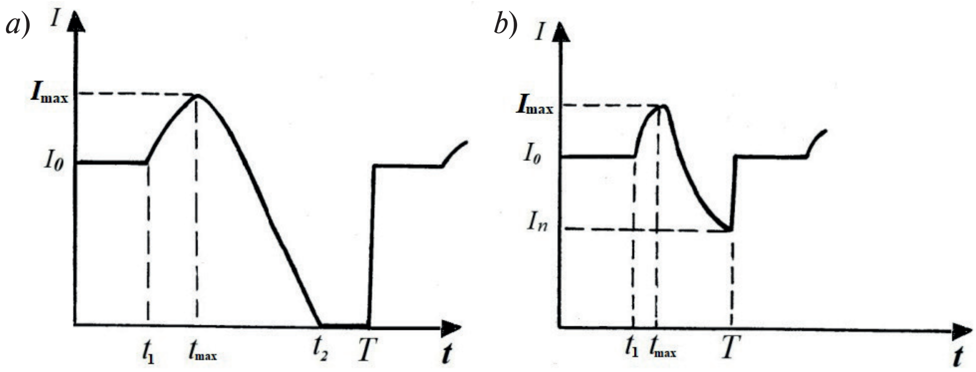

Fig. 3. The shape of the discharge current pulse: pulsed regime (*a*), modulation regime (*b*)

will complete the second stage of the accelerator operation. When operating in the modulation mode, the current decreases to the minimum value I_n. The initial discharge current I_n and the initial charge on the capacitor Q_n are determined by the period of operation of the circuit T, set by the rectangular pulse generator, and the dependence of I_n and Q_n (or rather I_m and φ_0) on T is obtained from the solution of a transcendental equation expressing the equality of the initial energy stored in the LC circuit and the energy in it at a time T. By applying external control signals from the C.U, following with a period T, it is possible to achieve a periodic dependence of the discharge current on time. In this case, the choice of the response period of the circuit T will completely determine the initial values of the current and charge of the capacitor, and, consequently, I_m and φ_0. The characteristic times t_1, t_{max}, t_2 and the maximum value of the current I_{max} will also be uniquely determined. To find the relationship between T and the listed values, it is more effective and convenient to solve the inverse problem: for a fixed I_m ($I_m > I_0$) determine the period T (i.e. the moment when the energy contained in the inductance and capacitance takes the initial value $E = LI_m^2/2$), and then the phase φ_0. The possibility of solving the inverse problem follows from the following considerations. The change in energy E over time at the second stage ($t > t_1$) is determined by the equation $dE/dT = \varepsilon \cdot I \cdot (1 - I/I_0)$ from which it follows that from the moment the thyristor is locked ($I = I_0$), the energy decreases ($dE/dT < 0$, $I > I_0$), reaching a minimum value $E_{min} < LI_m^2/2$ at the time when the current again takes the value I_0. Further, the energy monotonically increases, either approaching for a value $E_\infty = C\varepsilon^2/2$ at $\alpha \le 0.5$, or takes this value at $0.5 \le \alpha \le 1$ when the current turns to zero. Note that at $\alpha \le 0.5$, the initial energy in the circuit cannot exceed the values of E_∞, and, consequently, the possible values of I_m belong to the interval

$$1 \le \bar{I}_m \le \alpha^{-1}. \tag{12}$$

In this case, there will always be a moment in time (T) when the energy in the circuit will take a value corresponding to the first stage of the circuit operation. This will be the period of discharge current oscillations for this value $\bar{I}_m < \alpha^{-1}$. When the circuit is operating on an active load passing current in both directions, the energy in the circuit at the second stage approaches E_∞ with decreasing amplitude when the inequality $0.5 \le \alpha \le 1$ is fulfilled. In this case the initial value of the energy E_n may significantly exceed E_∞. This means that in the process of relaxation of vibrations, energy can be accumulated in the oscillatory circuit. The possibility of periodic operation of the circuit in this case will be determined by the value of the first energy maximum achieved at the time t_2 – the time of the first current vanishing (11)

$$E_{max} = \frac{LI_0^2}{2}\left(\frac{2\beta}{\omega} + \frac{\Omega}{\omega \cdot \sin\theta_0} \cdot e^{-\frac{\beta}{\Omega}\cdot(\pi-\theta_0)}\right)^2. \tag{13}$$

It can be shown that in this case periodic operation of the scheme is possible only when the inequality is fulfilled: $(LI_m^2)/2 \le E_{max}(I_m)$, so the possible values of Im belong to the interval I_m where $1 \le \bar{I}_m \le \bar{I}_m^*$ is a solution to the equation:

$$\bar{I}_m = \frac{2\beta}{\omega} + \frac{\Omega}{\omega \sin\theta_0} \cdot e^{-\frac{\beta}{\Omega}\left(\pi - \theta_0(\bar{I}_m)\right)} \quad \text{or} \quad \bar{I}_m(\alpha) = \alpha^{-1} + \frac{\Omega}{\omega \sin\theta_0} \cdot e^{-\frac{\alpha^{-1}\omega}{2\Omega}\left(\pi - \theta_0(\bar{I}_m)\right)}. \tag{14}$$

The numerical solution of the equation (14) is shown in Fig. 4, where it is taken into account that for $\alpha \le 0.5 \Rightarrow \bar{I}_m^* = \alpha^{-1}$. To determine the dependence $\bar{I}_m$ on $\bar{T} = \omega \cdot T$ for various α and possible values $\bar{I}_m$ the following equation was solved numerically by the Newton method:

$$\bar{I}^2(\bar{T}) + \bar{Q}^2(\bar{T}) = \bar{I}_m^{\,2}, \tag{15}$$

where $\bar{I} = I/I_0$, $\bar{Q} = Q\omega/I_0$, I and Q are determined by formulas (7)–(10), and $\omega t = \bar{T}$, so that the initial phase φ_0 is determined by the expression

$$\varphi_0 = \pi + \arcsin\left(\bar{I}(T)/\bar{I}_m\right). \tag{16}$$

Fig. 5 shows the results of the numerical solution of equation (15) for the values of $\alpha^{-1} = 1.1$; 1.6; 2; 4; 6. Calculations allow for any α for a given period T to determine the corresponding values $\bar{I}_m$, as well as $\bar{I}(T) = \bar{I}_n$.

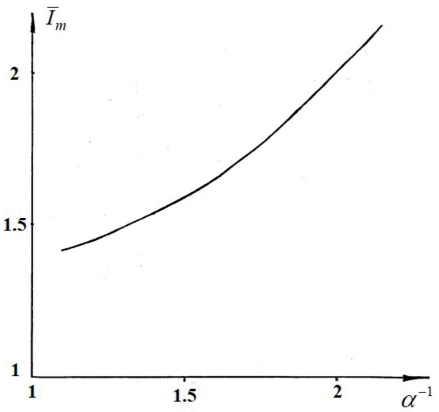

Fig. 4. Function dependence graph of the maximum possible values of the discharge current amplitude $\bar{I}_m$ from α (pulsed regime)

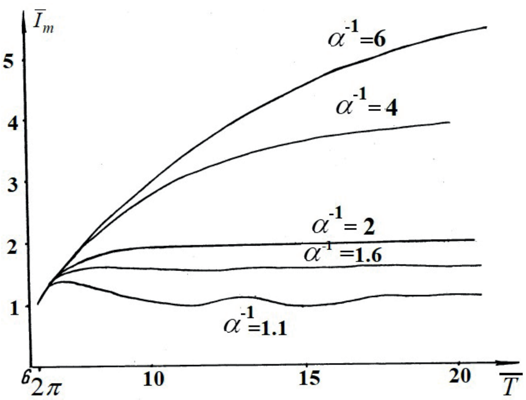

Fig. 5. Function dependence graph of the maximum discharge current amplitude $\bar{I}_m$ from the circuit operation period T for various α

Results and Discussion

The analysis of the obtained results shows the possibility of the existence of two modes of operation of the circuit: modulation and pulse. In the first case, the current does not have time to turn to 0 by the time T, so that the considered discharge current control scheme only modulates it, and does not lead to a complete rupture. In the pulse mode, the discharge current is different from zero during the time $T_{\text{imp}} < T$, and in the remaining time interval $T - T_{\text{imp}}$ is zero. With α belonging to the interval: $0.5 < \alpha \le 1$ it is always possible to specify such a moment in time ($t = t_2$) at which the discharge current turns to zero. Note that when α decreases to a value of 0.5, the value of t_2 increases indefinitely, and when α values are less than 0.5, the current never turns to zero. Therefore, the duration of the current pulse (for all $\alpha < 1$) meant the time during which the current decreases to a certain minimum value, conditionally assumed to be equal to $I_{\min} = 0.2 \cdot I_0$. Then, at $I_n > I_{\min}$, the circuit will provide a modulation regime of the accelerator operation with a modulation depth of $\gamma = 1 - I_n/I_0$ and at $I_n \le I_{\min}$ – a pulse regime, which can be characterized by a relative pulse duration, defined by the formula $S = T/T_{\text{imp}}$. Fig. 6 shows the dependences of $\gamma(T)$ and $S(T)$ at the same values of α. As follows from the results of numerical calculation, the modulation mode is possible only at T, satisfying the inequality $2\pi < \bar{T} \le \bar{T}^*(\alpha)$. The dependence $\bar{T}^*(\alpha)$ is shown in Fig. 7.

When $\bar{T} > \bar{T}^*(\alpha)$ there is a pulse mode of operation of the circuit. The dependences $\bar{I}_m(\bar{T})$ and $\varphi_0(\bar{T})$ obtained as a result of numerical calculation allow for each fixed value of the parameter α to establish a relationship between the time t_1, during which the current has a stationary value I_0, the time $t_{\max}$, at which the current reaches the maximum value, the maximum ($I_{\max}$) and minimum (I_n) possible values of the discharge current with the period of operation of the circuit T. In addition, a dependence of dimensionless time $\bar{t}_1$ on $\bar{T}$ at the values of α selected above was found.

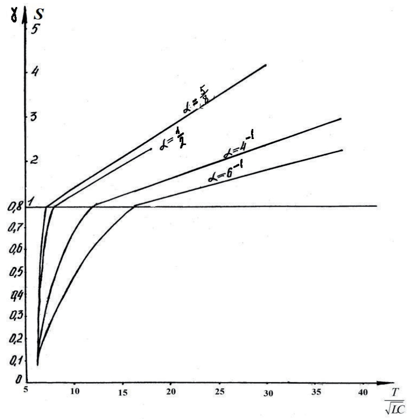

Fig. 6. Function dependence graph of the modulation depth γ and the relative pulse duration S from the circuit operation period T for various values of α

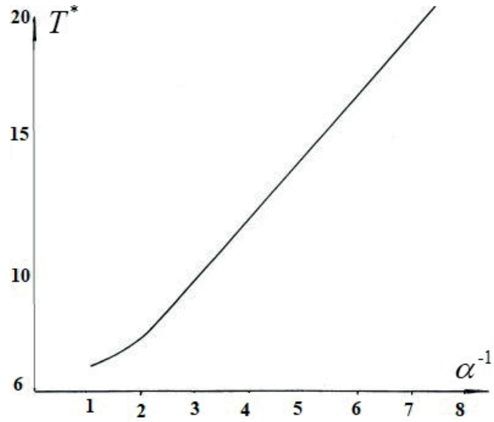

Fig. 7. Function dependence graph of the period T^* of operation of the circuit, corresponding to the transition from the modulation mode to the pulse mode, from α

It shows that at $\alpha < 0.5$, $\bar{t}_1$ monotonically decreases with an increase $\overline{T}$ from the maximum value equal to 2π (coinciding with $\overline{T}_{\min}$) to the minimum $t_{1\min}$:

$$\bar{t}_{1\min} = \pi + \arcsin(\alpha). \tag{17}$$

At $0.5 < \alpha < 1$, the dependence is nonmonotonic. The duration of the stationary value of the current decreases rapidly at first, reaching a minimum, and then increases, tending to the value determined by the formula (17). This feature of the dependence $t_1(T)$ at $\alpha > 0.5$ is due to nonmonotonicity $I_m(T)$ at these values of α. Finally the dependences $\tau_{\max} = \omega \cdot (t_{\max} - t_1)$ and the maximum value of the current in the pulse $I_{\max}$ on T at the same α were found.

Conclusion

To create pulsed plasma formations, as well as modulated plasma flows required in active geophysical experiments, the pulse mode of operation of the MPD accelerator was studied. As a result of bench tests, the possibility of operation of the MPD accelerator in pulsed mode with a pulse repetition frequency of up to 10 kHz was experimentally confirmed. The use of a discharge current control scheme based on the Morgan scheme made it possible to provide a pulse mode of operation of the accelerator. The calculations have shown that the operating mode of the accelerator, depending on the parameters of the circuit, can be stationary, modulated and pulsed. The duration of the stationary value of the current, the maximum value of the discharge current, the time when the current reaches the maximum value, the shape of the pulse are determined at a fixed value of the parameter $\alpha = 1/R\sqrt{(L/C)}$ by the period of the circuit operation. The numerical analysis of the circuit operation makes it possible to predict its operating regime as well as parameters such as the modulation depth (in the modulation mode), the relative pulse duration (in the pulse mode), the duration of the stationary current value, the time at which the current reaches the maximum value. The dependences of the modulation depth (for the modulation mode) and the relative pulse duration (for the pulse mode) on the period of operation of the circuit at different values of α, as well as the dependence on α of the period of operation of the circuit T^* corresponding to the transition from modulation ($T < T^*$) to pulse ($T > T^*$), have been calculated numerically. The minimum possible values of the circuit operation period are found, as well as the maximum possible values of the duration of the first stage, which turned out to be independent of α. The magnitude of the discharge current, being one of the main parameters characterizing the operation of the accelerator, significantly affects plasma parameters such as the concentration of charged particles, electron temperature, directional velocity of ions, etc. Therefore, the shape of the current pulse in the considered discharge circuit control scheme directly determines the parameters of plasma formations generated by the accelerator. The presented discharge current control scheme was used to implement pulse and modulation modes of operation of the MPD accelerator in laboratory conditions. The graphs of the analytically obtained functional dependence $I(t)$ at different values of the parameter α were compared with the current waveforms obtained during bench experiments. A comparative analysis of the waveforms and graphically presented functional dependencies $I(t)$ showed a fairly good qualitative agreement between them in the frequency range $f \sim 500-1000$ Hz. In the frequency range $f \sim 10$ kHz, the discharge inertia determined the volt-ampere characteristic of the circuit, so the estimated duration of the stationary stage of plasma formation was markedly different from that found experimentally.

REFERENCES

1. **Avdyushin S.I., Podgorny I.M., Popov G.A., Porotnikov A.A.,** Plasma accelerators using to study physical processes in space, Plasma accelerators and ion injectors, Nauka, Moscow, 1984, 232–250.
2. **Gentry F., Gutzwiller F., Gologniak N., von Zastrow E.,** Controlled semiconductor valves, Mir, Moscow, 1967.
3. **Rosinsky S.E., Kubarev Y.V.,** Pulse mode of MPD accelerator operation, In: Proceedings of the All-Union seminar on the physics of fast plasma processes, Grodno, Grodno University, 1986, 70.
4. **Tashayev Y.N.,** On the creation of a magnetic field of a given geometry in the accelerating channel of the MPD accelerator, In: Proceedings 3rd International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA), IEEE Conference 10.1109 (2021) 1083-1087. DOI: 10.1109/SUMMA53307.2021.9632102

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Received 27.10.2022. Approved after reviewing 08.11.2022. Accepted 08.11.2022.