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IMPROVING THE DYNAMIC CHARACTERISTICS OF ELECTRIC DISCHARGE INSTALLATIONS, WHICH ARE SIGNIFICANTLY DISTANT FROM THE SPARK-EROSION LOAD

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The paper identifies the features of the influence of the characteristics of different connecting conductors on the dynamic characteristics of electric discharge installations (EDIs), which are distant significantly (several meters) from the spark-erosion load. In the electric spark production of dispersed powders, such a load is the interelectrode gap (IEG) in the technological dispersion apparatus (TAD), filled with a layer of metal granules and a low-conductive (preferably dielectric) flowing liquid. The influence of the design parameters of such long connecting conductors as twisted pair, litzendraht with bifilar winding of conductors and coaxial cable on the dynamic characteristics of the indicated EDIs (including on the average rates of rise and fall of the discharge pulse current) is experimentally investigated. It is substantiated that the use of power coaxial cables with modern cross-linked polymer electrical insulation is practically the most expedient for connection of significantly distant TAD under the condition of insignificant (up to 0.5 μH) self-inductance of EDIs. References 11, figures 4, tables 3.
Key words: electric discharge installation, capacitor discharge, transients, rate of discharge current change, coaxial cable, litzendraht, twisted pair.

Intensive development of impulse electrical engineering is based on the improvement of electric discharge installations (EDIs) with reservoir capacitors, which provide the highest electrodynamic characteristics in the electrical load (including the rate of change of discharge current and pulsed electric power in the load) compared to other energy storage devices (electromechanical devices, induction and electrochemical ones, etc.) [1–3]. Such EDIs with reservoir capacitors are successfully used for the implementation of modern spark-erosion electro-technologies for the production of finely dispersed metal powders with unique performance properties using EDIs for volumetric electro-spark dispersion (VESD) of a layer of metal granules in flowing low-conductive (preferably dielectric) liquids in the interelectrode gap (IEG) [4, 5].

The main problems of improving the discharge pulse shapers (DPSs) for EDIs are taking into account the energy exchange between capacitors and the stochastic change in load resistance, as well as achieving an increase in the rate of rise of discharge currents, since it is desirable to reduce the size of spark eroded powders [3, 6, 7].

Taking into account that the active power released in the IEG of the technological dispersion apparatus (TAD) of the installation is directly proportional to the value of its active resistance and the quadratic value of the discharge (pulse) current, an increase in the force effect on metal granules is achieved by the formation of high pulsed currents of short duration in the IEG.

In particular, in the installations for VESD of metals in dielectric liquids, the force effect increases due to an increase in the rate of change of discharge currents and a decrease in their duration, which makes it possible to significantly (several times) reduce the maximum dimensions of the produced spark eroded powders [6, 8].

In industrial conditions, the distance between the DPS and TAD can be several meters, which is determined by electrical safety requirements and technological operating conditions of such installations. In this case, the active resistance and inductance of the connecting conductors can increase significantly, de-

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creasing the main dynamic characteristics of the EDI and undesirably increasing the size of the produced spark powders and changing their properties.

Therefore, the **purpose of this work** was to determine the influence of the design parameters of long connecting conductors, such as twisted pair, litzendraht with bifilar winding of conductors and coaxial cable, on the dynamic characteristics of the EDI (including the average rates of rise and fall of the discharge pulse current) under the condition of a significantly distant spark-erosion load, in order to select the type of conductor that is effective in practice.

In accordance with the goal set in the article, the authors do not pretend to a deep analysis of pulse processes in conductors as field diffusion processes. The issues of spatio-temporal distribution of the density of pulsed currents in the cross section of the conductors under study, as well as the spectral analysis of these currents, were not considered in the article, since these issues go far beyond the goals of the work. The article also did not consider the influence of the proximity effect and the surface effect on the frequency dependence of the inductance of the studied conductors, as a slight change in these parameters does not have a significant effect on the processes in the EDI.

Twisted-pair connecting conductors are usually used to connect the DPS to the spark-erosion load of the EDI. The inductance per unit length (running inductance) for this type of conductors has a significant value. In addition, conductors of this type must have an increased cross section of conductive cores when operating in a pulsed mode, which is explained by a significant decrease in their effective cross section. The above circumstances significantly limit the possibility of using conductors of this type to connect semiconductor DPS with several meters distant spark load. The running inductance of this type of conductors begins to exceed significantly the output inductance of the DPS when a distance between the DPS and the TAD is several meters. This leads to a decrease in the maximum values of the discharge currents in the IEG, a decrease in the rate of their rise, an increase in the total duration of the discharge pulses, and an undesirable increase in the size of spark eroded powders [6, 8, 9].

The experimental studies were carried out to compare the effect of connecting conductors of different types on the dynamic characteristics of the discharge pulse currents of the EDI for the implementation of technologies of VESD of layer of metal granules in flowing dielectric liquids between two electrodes.

Fig. 1 shows a circuit diagram of the DPS discharge circuit of EDI with a spark-erosion load represented by a resistor R_l = const. In the general case, the resistance of the spark-erosion load changes stochastically during the discharge of reservoir capacitor with a capacity C. Therefore, in order to analyze steady-state transient processes in the EDI discharge circuit, the effective value of the active resistance of such load was introduced: R_l = const. In R_l the same energy is dissipated during one discharge pulse as in a real layer of conductive granules [7].

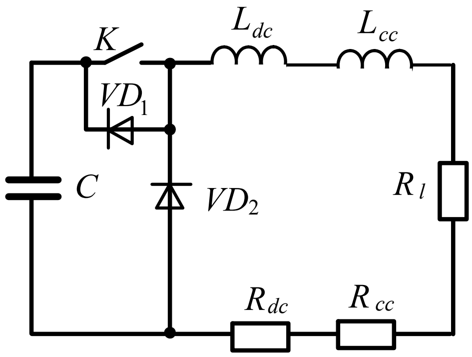

Fig. 1

In the experiment a high-frequency IGBT transistor was used as a fully controlled semiconductor switch K. Reverse diodes VD_1 and VD_2 are necessary for the safe operation of the circuit. Self-inductance and intrinsic resistance of all DPS elements of the discharge circuit in Fig. 1 is represented by the values of L_{dc} and R_{dc}. The inductance and active resistance of additional connecting conductors of considerable length, which connect the DPS with the load R_l, are represented by the corresponding values L_{cc} and R_{cc}. The calculations assumed that all semiconductor elements are ideal (i.e., their active resistances in the switch on state were assumed to be zero) and switching was carried out instantly.

In order to increase the rate of pulsed current rise in the load, a low-impedance electrostatic capacitor with an electric capacitance (300 μF) was used as the reservoir capacitor of DPS. The energy capacity of such capacitor was several orders of magnitude higher than the energy that was delivered to the load during one current pulse (and the DPS output voltage practically did not change during this time). Therefore, when analyzing the transient processes of this circuit, the assumption was used that the voltage at the DPS output was unchanged: U_{DPS} = const. With this assumption in mind, it was reasonable to assume that the transient process after turning on the switch K can be considered as the connection of the RL-circuit to a source of direct electromotive force with voltage U_{DPS}.

The following equipment was used for experimental research: current meter, voltage divider, two-beam storage digital oscilloscope HAMEG-HM-1507 and connecting conductors of such types as twisted pair, coaxial cable and litzendraht with bifilar winding of conductors.

The output electrical parameters of such DPS and limits of its operation were determined experimentally. The discharge circuit inductance of the DPS (L_{dc}) was determined by the self-oscillation method. The energy efficiency of the EDI and the stability of the discharge pulses were determined as in [10]. The *RC* circuit (low-impedance capacitor C_1 = 0.15 μF and non-inductive resistor R_1 = 108 Ohm) was connected in parallel to the DPS output terminals. The parameters of the capacitor and resistor were chosen in such a way that an oscillatory process without overvoltage occurred in the circuit. The current was measured using a current sensor with a conversion factor of 100 A : 1 V. The sensor was connected to an oscilloscope. The inductance L_{dc} was determined from the well-known analytical expression: $T = 2\pi\sqrt{L_{dc}C_1}$ [11], as

$$L_{dc} = T^2 / 4\pi^2 C_1, \quad (1)$$

where *T* is a period of self-oscillations (determined from the oscillogram: *T* = 1.65 μs). Hence L_{dc} = 0.46 μH.

To determine R_{dc} – active resistance of the DPS discharge circuit, the short circuit method was used. To do this, the output terminals of the DPS were connected to each other by short-circuit, which passed through a measuring current transformer connected to the oscilloscope. The τ – time constant of such a discharge circuit was determined from the oscillograms (τ = 37.08 μs), and R_{dc} was determined by the formula:

$$R_{dc} = L_{dc} / \tau, \quad (2)$$

hence R_{dc} = 12.4 mOhm.

The electrical characteristics and output parameters of the existing DPS are presented in Table 1.

Table 1

Parameter	Operating voltage range, V	Maximum pulse current, A	Output inductance, L_{dc}, μH	Output active resistance, R_{dc}, mOhm	Discharge pulse duration, μs
Value	0-600	1000	0.46	12.4	0.75-3.25

Fig. 2 shows the oscillogram of the current in the resistive load with a resistance of R_l = 1 Ohm, connected directly to the DPS without long connecting conductors (L_{cc} = 0, R_{cc} = 0). The switch *K* was turned on at time t_{on} and turned off at time t_{off} after 3.25 μs. Voltage U_{DPS} = 450 V. The value of divisions was: along the *x* axis – 1 μs/div, along the *y* axis – 100 A/div.

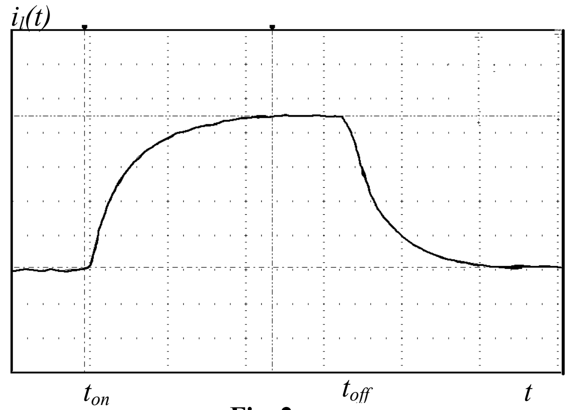

Fig. 2

To exclude some distortion of the current on the oscillogram at the beginning and end of the transient, the duration of the rise of the pulsed current in the load ($t_\uparrow$) was determined from 0.1 $I_{max\,fig2}$ up to 0.9 $I_{max\,fig2}$ (where $I_{max.\,fig2}$ is the maximum value of the current, which can be calculated as: $I_{max\,fig2} = U_{DPS} / (R_l + R_{dc})$ = 446 A). This duration was: $t_\uparrow$ = 1,05 μs, and the average rate of current rise: $I_{max\,fig2} / t_\uparrow \approx$ 340 A/μs.

Taking into account the above mentioned assumptions the expression for the current flowing in the load after turning on the switch *K* (at $t_{on} \le t \le t_{off}$) was determined as [11]:

$$i(t) = U_{DPS}\left(1 - e^{-t/\tau_1}\right) / \left(R_l + R_{dc}\right), \quad (3)$$

where $\tau_1 = L_{dc} / (R_l + R_{dc})$ is constant time of the discharge circuit when the load is connected to the DPS directly without long connecting conductors.

The current flowing in the load after turning off the switch *K* (at $t > t_{off}$) decreased exponentially and it was defined as [7]:

$$i\ (t) = U_{DPS}\left(1 - e^{-t_{off}/\tau_1}\right) e^{-t/\tau_1} / \left(R_l + R_{dc}\right). \quad (4)$$

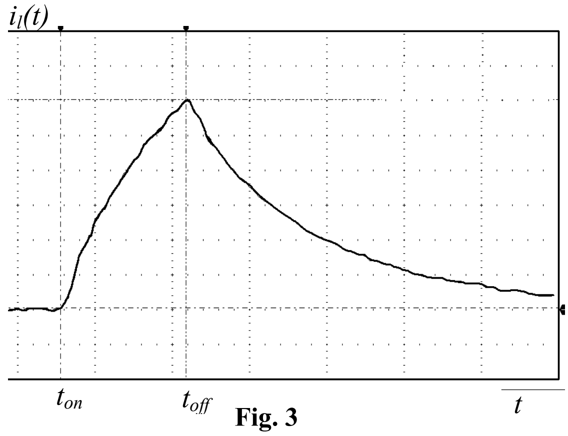

Fig. 3

Fig. 3 displays the oscillogram of the current in the same load (1 Ohm), connected to the DPS by 5 m-long conductors of the twisted pair type with copper cores 2×50 mm^2. The switch *K* turns on and turns off at the same time points and the DPS voltage was the same: U_{DPS}=450 V. The value of divisions was: along the x axis – 2 μs/div, along the y axis – 50 A/div.

Comparison of the maximum values of currents shown in Fig. 2 and Fig. 3, showed that the peak current in Fig. 3 is smaller. Its value is: $I_{max\,fig3}$ = 300 A and it does not have time to reach its maximum possible value: $I_{max.\,possible}$ (where $I_{max.\,possible} = U_{DPS} / (R_l + R_{dc} + R_{cc})$. This value would practically not differ from $I_{max\,fig2.}$ in Fig. 2 due to the smallness of R_{cc}) up to the moment of turning off switch K. However, the duration of the current rise from 0.1 to 0.9 $I_{max\,fig3}$ in Fig. 3 increased and amounted to 2.48 μs, and the average rate of current rise decreased to 121 A/μs.

The duration of the rise of the pulsed current in Fig. 2 to the smaller of the two peak values: 300 A (more precisely from 0.1 $I_{max\,fig3}$ to 0.9 $I_{max\,fig3}$) was 0.38 μs, and the average rate of current rise was 632 A/μs.

Thus, the presence of connecting conductors of the twisted pair type increases the duration of the current rise (and reduces its rate of rise) in the load under these conditions by 6.5 times.

To determine the influence of different connecting conductors on the dynamic parameters of discharge pulse currents in the load of electric discharge installations of VESD of metals in conditions of distant DPS from the load of such installations, the parameters (inductances L_{cc} and active resistances R_{cc}) of these connection conductors were experimentally determined. Conductors of three types were studied: twisted pair with copper cores 2×50 mm^2, coaxial cable with core and screen cross sections of the 70 and 16 mm^2, respectively, and litzendraht with bifilar winding of conductors 2×7 mm^2.

For this purpose, these connecting conductors were connected to the DPS. Their active resistances and inductances were determined by the same methods that were used to calculate R_{dc} and L_{dc} (the short circuit method and the self-oscillation method were used, respectively). Despite the fact that the active resistance of conductors with a strong skin effect is proportional to the square root of the frequency and, therefore, in a real process it can differ by several times from the measured one, it follows from the measurement results and taking into account this circumstance that this resistance is significant (by several orders of magnitude) less load resistance. Its influence on the general nature of transient processes in EDI circuits is insignificant and this resistance can be neglected. The differences between the experimentally measured currents in the EDI load and the results of the analytical analysis are insignificant. The inductance of L_{cc} was defined as:

$$L_{cc} = T^2 / 4\pi^2 C_1 - L_{dc}, \qquad (5)$$

where the period of self-oscillations T was determined from oscillograms.

The resistance R_{cc} was calculated using the formula:

$$R_{cc} = \left(\left(L_{dc} + L_{cc}\right)/\tau_2\right) - R_{dc}, \qquad (6)$$

where τ_2 is the time constant of the discharge circuit of the DPS in the presence of connecting conductors and the absence of load. τ_2 was determined from oscillograms.

On the other hand:

$$R_{cc} = \rho\, l / S_{eff}, \qquad (7)$$

where ρ is the electrical resistivity (for copper is 0.0175·10^{-6} Ohm·m), l and S_{eff} are the respectively, the length and effective cross section of the current-carrying cores of these connecting conductors.

The expression for the effective cross section S_{eff} was obtained after substituting (6) into (7) and performing mathematical transformations:

$$S_{eff} = \rho\, l\, \tau_2 / \left(L_{dc} + L_{cc} - R_{dc}\tau_2\right). \qquad (8)$$

The results of calculations of inductances and active resistance of the connecting conductors are presented in Table 2. It also presents the actual and effective cross sections of the current-carrying cores and their ratios.

Table 2

Parameters / Type of conductor	Period of self-oscillations T, μs	Inductance, L_{cc}, μH	Time constant of circuit τ_2, μs	Resistance R_{cc}, mOhm	S, mm^2	S_{eff}, mm^2	S_{eff}/S, r.u.
Twisted pair	4.22	2.547	131.15	11	2×50	2×15.9	0.3
Coaxial cable	2.68	0.752	44.46	15	70+16 (core+screen)	2×9.3	0.2
Litzendraht with bifilar winding	1.88	0.114	19.46	17	2×7	2×6.2	0.9

Table 2 shows that the best performance in terms of inductance and the ratio of the effective cross section of the current-carrying core to the actual one has the litzendraht with bifilar winding of the conductors. Coaxial cable has the lowest ratio of the effective cross section of current-carrying core to the actual one. Inductance of the coaxial cable is much less than that of twisted pair, but greater than that litzendraht.

An experimental study of the operating modes of the EDI was carried out in order to determine the dynamic characteristics (rates of rise and fall of discharge pulse currents in the load) when connecting the DPS and the load of such installations using the above-considered connecting conductors. The oscillograms of the current in the resistive load R_l = 1 Ohm, connected to the EDI by means of twisted pair, coaxial cable and litzendraht are shown in Fig. 4, *a*, *b*, *c*. The duration of the current rise (time $\Delta t = t_{off} - t_{on}$ between turning off and turning on of the switch *K*) was 3.25 µs. The output voltage of the EDI was 400 V. The value of divisions along the *x* axis in Fig. 4, *a* was 2 µs/div, and in Fig. 4, *b*, *c* – 1 µs/div. The value of divisions along the *y* axis in Fig. 4, *a*, *b*, *c* was 50 A/div.

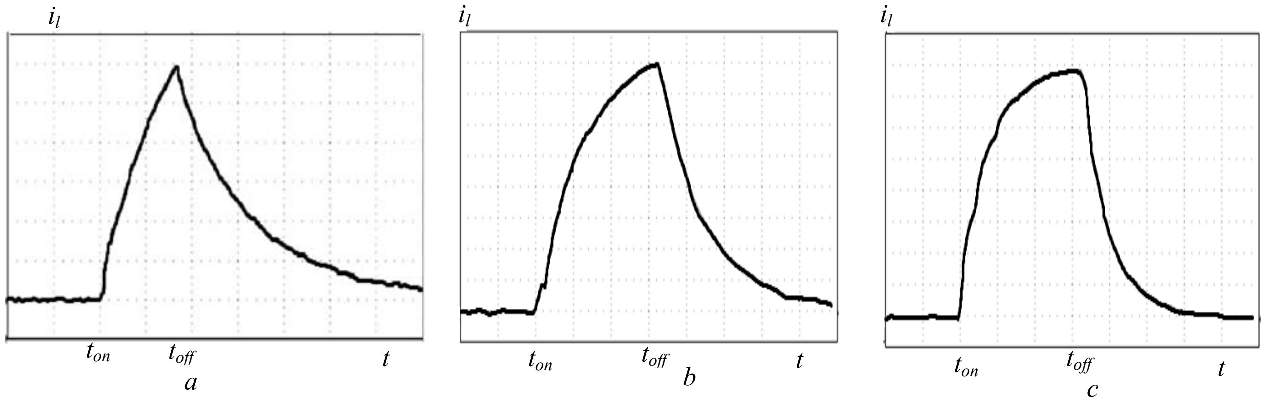

Fig. 4

The Table 3 shows the experimental results of the dynamic characteristics: the average rates of rise and fall of pulse currents in the load over a time interval Δt = 3.25 µs when using three different types of conductors to connect the DPS and the load.

Table 3

Parameters / Type of conductor	I_{max}, A	$I_{max}/\Delta t$, A/µs
Twisted pair	300	92.3
Coaxial cable	400	123.1
Litzendraht	390	120.0

From the experimental and calculated parameters given in Table 3, it follows that the average rate of current change is the highest when using litzendraht with bifilar winding of the conductors.

Coaxial cable has slightly lower inductance L_{cc} compared to litzendraht (see Table 2), but it is three times higher than twisted pair one. Since the manufacture of litzendraht with bifilar winding of conductors is too laborious, and its insulation strength is much less than the strength of modern coaxial cable insulation, in practice it is more advisable to use a coaxial cable as connecting conductors. In addition, the litzendraht has a large capacitance per unit length (it was 12 nF/m for the test sample), which causes significant displacement current (tens of amperes) in litzendraht insulation in pulse mode of operation. This current additionally loads the controlled semiconductor switches and causes a significant overheating of the insulation, which, in turn, causes its accelerated electrical and thermal aging, and the electromechanical forces that occur between separate insulated conductors lead to its mechanical aging.

Conclusions. In this paper, an experimental study of the influence of such connecting conductors as twisted pair, coaxial cable and litzendraht with bifilar winding of conductors, on the dynamic characteristics of electric discharge installations, the spark-erosion load of which should be significantly distant from the discharge pulse shaper, was carried out.

It was substantiated that in case of insignificant (up to 0.5 µH) self-inductance of electric discharge installations, it is most expedient to use power coaxial cables with modern cross-linked polymer electrical insulation to connect a significantly distant load.

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ПІДВИЩЕННЯ ДИНАМІЧНИХ ХАРАКТЕРИСТИК ЕЛЕКТРОРОЗРЯДНИХ УСТАНОВОК, ЗНАЧНО ВІДДАЛЕНИХ ВІД ІСКРОЕРОЗІЙНОГО НАВАНТАЖЕННЯ

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Визначено особливості впливу характеристик різних з'єднувальних провідників на динамічні характеристики електророзрядних установок (ЕРУ), значно (на декілька метрів) віддалених від іскроерозійного навантаження, яким за електроіскрового виробництва дисперсних порошків є міжелектродний проміжок (МЕП) технологічного апарату диспергування (ТАД), заповнений шаром металевих гранул і проточною слабко провідною (бажано діелектричною) рідиною. Експериментально досліджено вплив на динамічні характеристики вказаних ЕРУ (зокрема на середні швидкості наростання та спадання в них розрядного імпульсного струму) конструктивних параметрів таких довгих з'єднувальних провідників, як вита пара, коаксіальний кабель і літцендрат з біфілярною намоткою струмопровідних жил. Обґрунтовано, що за незначної (до 0,5 мкГн) власної конструктивної індуктивності ЕРУ для підключення суттєво віддаленого ТАД практично найбільш доцільним є використання силових коаксіальних кабелів із сучасною зшитою полімерною електроізоляцією. Бібл. 11, рис. 4, табл. 3.

Ключові слова: електророзрядна установка, розряд конденсатора, перехідні процеси, швидкість змінення розрядного струму, коаксіальний кабель, літцендрат, вита пара.

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