DOI: https://doi.org/10.15407/techned2025.03.003

INTERDEPENDENT TRANSIENT PROCESSES IN CIRCLES OF BIPOLAR DISCHARGE PULSE CURRENT GENERATOR WITH R-L-C LOAD AND LIMITED POSITIVE VOLTAGE FEEDBACK

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The paper analyzes the interdependent transient processes in the discharge circuits of a bipolar discharge pulse generator (DPG) with R-L-C load and limited positive voltage feedback. The analytical dependence of the value of the initial voltage on the capacitor connected in series with the load on the value of the Q factor of the discharge circuit of the DPG was obtained. The optimal electrical parameters of these circuits have been determined to ensure high dynamic and energy indicators of impulse currents in an electric spark load. It is substantiated that the serial connection of a capacitor with an electric spark load in the discharge circuit of a bipolar DPG with a capacitive storage of electrical energy of high energy capacity allows to increase (maximum twice) the initial rate of current rise in the electric spark load of a bipolar DPG and significantly improve the energy indicators of discharge impulse currents. The short-circuit currents value of the DPG load is limited by the value of the characteristic resistance of the DPG discharge circuit, and their flow time corresponds to the self-oscillation period of the DPG discharge circuit in this mode of operation. At the same time, electrical energy is not dissipated in the discharge circuit of the DPG, but it is almost completely recovered to the capacitors on output of direct voltage formers. References 15, figures 6.

Keywords: transient, bipolar discharge pulse generator, discharge, pulse current, voltage feedback.

Electric discharge units (EDUs) with storage capacitors have been widely used in the implementation of many modern technologies [1–3], in particular, to produce electric spark powders with unique properties by the method of volumetric electric spark dispersion (VESD) of a layer of metal granules in flowing dielectric liquids [4–6].

In the development of installations for the VESD of metals in liquids, it is necessary to solve the problem of intensifying the effect of pulsed electric discharge currents on the layer of metal granules to increase the productivity of EDUs during the production of electric spark powders [7, 8], as well as to reduce the duration of pulsed currents in the EDUs load, in order to reduces the average size of electric spark powders [9]. For this purpose, the rate of discharge currents rise is increased in a stochastic load [10, 11] and power losses reduced by adjusting the initial and final voltages during charging [11] and discharging of the capacitive energy storage(CES) of EDUs, as well as duration of discharge pulse currents in the load is forcibly limited [10, 12].

An increase in the rate of rise of pulse currents, as well as an increase in their peak values in the load of such EDUs, can be achieved by increasing the voltage and capacitance of discharge capacitors. It is known that the maximum value of the oscillating discharge current I_{max} at the quality factor of circuit $Q > 2$ is directly proportional to the initial voltage of capacitor during its discharge and the $\sqrt{C}$ value, s well as it inversely proportional to $\sqrt{L}$ [13]. Therefore, in most EDUs, the inductance L is reduced to the lowest possible value. It is possible to increase the current amplitude by increasing both the capacitor charging voltage and its capacitance. However, increasing the charging voltage of storage capacitors above 1000 V has serious

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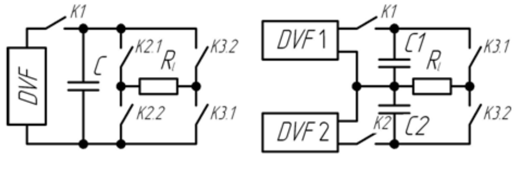
technical limitations and significantly increases the hazard of EDUs maintenance, and increasing the capacitance leads to an undesirable increase in the discharge pulse duration t_{DP} (since $t_{DP} \approx \pi\sqrt{LC}$) and the size of the obtained spark-eroded powders. Therefore, with an increase in the capacity of the capacitor C during its discharge to the load, we suggest using a forced limitation of the duration of the pulse current t_{DP} by means of a fully controlled semiconductor switch (IGBT or MOSFET transistors) that breaks the discharge circuit at the required time [10]. That is, a significant reduction in the duration of discharge currents with a simultaneous increase in their energy performance can be achieved by using large-capacity discharge capacitors and fully controlled power semiconductor switches instead of semi-controlled ones (thyristors). It should be noted, however, that fully controlled switches have a much lower overload capacity than semi-controlled switches, and also require a more complex control scheme and protection against unacceptable operating conditions (short circuit in the load circuit).

Usually, EDUs for metal VESD use unipolar pulse currents arising during the discharge of a storage capacitor to the EDUs load. Generation of such pulse currents in the EDUs load, which is a layer of metal granules between the electrodes, inevitably leads to well-known processes of electrochemical dissolution of one of the electrodes (anode), which increases the length of the interelectrode gap, reducing the stability and productivity of VESD of granules. Therefore, during the VESD of a layer of metal granules in a liquid medium, it is advisable to use bipolar discharge pulse generators in order to equalize the rate of wearing out of electrode in the technological chambers of electric discharge units, which is especially relevant when granules are dispersed in an electrolytic medium. A significant increase in the productivity of obtained spark-eroded powders in such EDUs is no less important when using bipolar discharge pulse generators compared to unipolar ones.

In the construction of such DPG, the bridge schemes (Fig. 1, *a* – *H*-bridge scheme) or semi-bridge ones (Fig. 1, *b* – *T*-bridge scheme) of discharge circuits of EDUs are usually used [14].

Designations in these diagrams: DVF, DVF1, DVF2 are direct voltage formers, C, $C1$, $C2$ are storage capacitors of EDU, $K1$, $K2$, $K2.1$, $K2.2$, $K3.1$, $K3.2$ are semiconductor switches, R_l is load resistance.



a ***b***

Fig. 1

Comparing these circuits, we note that the *H*-bridge circuit requires double number of power switches, and the *T*-bridge circuit requires twice the double number of DVFs and capacitors to generate bipolar pulse currents in the load.

It is possible to significantly reduce the duration of pulse currents in the discharge circuit of bipolar DPGs, as well as to increase their energy characteristics, due to changing the nature of its transients with the simultaneous use of positive voltage feedback. It is proposed to achieve this by introducing a capacitor in series with the load into the discharge circuit.

The aim of the work is to analyze the interdependent transients in the discharge circuits of bipolar DPGs with *R-L-C* load and positive voltage feedback, as well as to determine the optimal electrical parameters of these circuits to ensure optimal dynamic and energy performance of pulse currents in an electric spark load.

Fig. 2 shows the circuit diagram of a bipolar DPG with a *T*-bridge discharge circuit, *R-L-C* load, and positive voltage feedback.

In this diagram, $C1$ and $C2$ are discharge capacitors directly connected to the DVF1 and DVF2, L_0 and R_0 are the output inductance and active resistance of the DPG, L_K, C_l, and R_l are the inductance of the connecting conductors, capacitance, and active resistance of the load circuit respectively, $K1$ and $K2$ are semiconductor electric switches (SESs), $VD1$ and $VD2$ are reverse diodes.

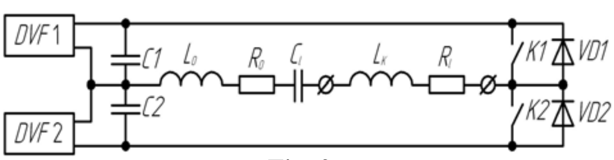


Fig. 2

The use of *R-L-C* load allows the use of semi-controlled SESs (thyristors), eliminates the need for electric switches between the DVFs and discharge capacitors, and significantly limits the short-circuit currents in the discharge circuit.

The principle of operation of the scheme shown in Fig. 2 is as follows. When the thyristor switch $K1$ is turned on, the load circuit is connected to the capacitance $C1$, and a current begins to flow in the discharge circuit. Energy begins to accumulate on the inductive elements of the discharge circuit, and an electric charge accumulates in the load capacitance and the voltage increases. The leading edge of the pulse current is formed. After the current reaches its maximum value, it begins to decline, and the trailing edge of the pulse current is formed. At the same time, the electric charge continues to accumulate on the capacitance in the load circuit and the voltage increases, and the current in the circuit is maintained mainly due to the magnetic field energy accumulated in the inductive elements of the circuit during leading edge time of the pulse current. Semi-controlled SES *K1* is locked when the current decreases below value its holding current. At the same time, after the end of the transient process, if the quality factor of the discharge circuit is lower than 0.5, the voltage value on C_l will be equal in modulo to the value of the reference voltage *E* at the output of the DVF1. If the quality factor of the discharge circuit is higher than 0.5, the voltage on C_l will exceed the value of the reference voltage *E*, and the transient process will continue. The current in the load will change its direction flowing through *VD1* and bypassing *K1*. Part of the energy accumulated in C_l will be transferred to the load, and part of it will be partially recuperated in *C1*. At the same time, the transient process will have a damped oscillatory nature, the duration of which will be determined by the full period of current oscillations *T* in the DVG load.

When the thyristor *K*2 is unlocked, the load circuit is connected to the capacitance *C*2. The current in the load will change its direction. A transient process begins in the discharge circuit, which is similar to the above-considered process when *K*1 is unlocked, but already with non-zero initial conditions for the voltage on the capacitor C_l. The voltage applied to the discharge circuit at the moment of switching on the *K*2 increases and, as a result, the pulse current in the load will increase. After the end of the transient process, the voltage on C_l will change its polarity. When the SES is subsequently switched off, both the direction of the current in the load and its magnitude are changed. Thus, these transients are interconnected with a limited (due to energy recuperation) positive voltage feedback.

In addition, instead of fully controlled semiconductor electronic switches (transistors), the scheme uses semi-controlled power SES (thyristors), which have a much higher overload capacity and do not require complex control and protection schemes. At the same time, a "soft" switching of the power SESs is provided, i.e. they lock naturally when the current in the discharge circuit of the DPG decreases less then thyristor holding current in the open state (the value of which is close to zero).

Since R_l is a given value, and L_K, L_0 and R_0 are design values, the only variable electrical parameter of the discharge circuit is C_l. To determine the optimal value of the capacitance of this capacitor, it is necessary to analyze the interdependent transients occurring in the discharge circuit with the *R-L-C* load of the bipolar pulse current generator. For this purpose, we have drawn up an operator calculation scheme (Fig. 3) corresponding to the scheme in Fig. 2.

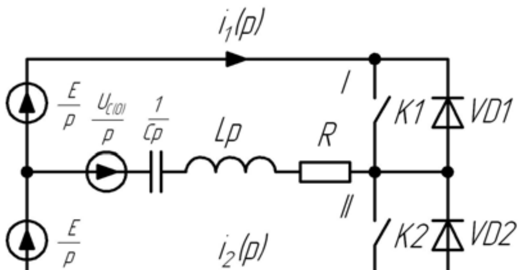


Fig. 3

The designations in Fig. 3: $L=L_K+L_0$ and $R=R_0+R_l$ are, respectively, the total inductance and active resistance of the discharge circuit, $C=C_l$ is the capacitance of the capacitor in the load circuit, $E1=E2=E$ are the EMF values of the DVF1 and DVF2.

In the operator calculation scheme, the discharge capacitors *C*1 and *C*2 with the corresponding DVFs were replaced by EMF sources *E*. This replacement is correct when capacitors *C*1 and *C*2 are directly connected with DVFs and their capacitances are orders of magnitude larger than the value of the capacitance C_l. In this case, the voltage on *C*1 and *C*2 during transient processes in the discharge circuit can be considered unchanged, and the quality factor of the discharge circuit will be determined mainly by the value of the capacitance C_l. The source of the EMF $U_C(0)$ reflects the presence of the initial voltage on the capacitor in the load circuit.

The equation in the operator form according to Kirchhoff's second law for the circuit I in Fig. 3, when the *K*1 is unlocked, is as follows:

$$i_1(p)\left(R+Lp+\frac{1}{Cp}\right)=\frac{E}{p}+\frac{U_{1C}(0)}{p}. \quad (1)$$

The analytical expression for the load current in the operator form at zero initial conditions for the voltage on *C* capacitor – $U_{1C}(0)=0$ is

$$i_1(p)=\frac{EC}{LCp^2+RCp+1}. \quad (2)$$

To find the roots of the characteristic equation, we equate the denominator of the right-hand side of equality (2) to zero and solve the resulting quadratic equation:

$$LCp^2 + RCp + 1 = 0\,;\; p_{1,2} = -\frac{R}{2L} \pm \sqrt{\frac{R^2C - 4L}{4L^2C}}\,. \tag{3}$$

The first derivative of the denominator of dependence (2) with respect to p is:

$$\frac{d}{dp}\left(p^2 + \frac{R}{L}p + \frac{1}{LC}\right) = 2p + \frac{R}{L}\,. \tag{4}$$

Applying the decomposition theorem, we find the expression for original function of current as a function of time:

$$i_1(t) = \frac{EC}{2p_1 + R/L} \times e^{tp_1} + \frac{EC}{2p_2 + R/L} \times e^{tp_2}\,. \tag{5}$$

Having the expression for the time dependence of the current in the discharge circuit of the DPG, we can determine the maximum current value and the time of its achievement. To determine the time of reaching the maximum value of the pulse current t_{max}, we find the extremum of the time dependence. To do this, equate the first time derivative of equation (5) to zero and solve the resulting equation with respect to t:

$$\frac{d}{dt}i_1(t) = \frac{EC\,p_1}{2p_1 + R/L} \times e^{tp_1} + \frac{EC\,p_2}{2p_2 + R/L} \times e^{tp_2} = 0\,;\quad t_{max} = \frac{1}{p_2 - p_1} ln\left(-\frac{p_1(2Lp_2 + R)}{p_2(2Lp_1 + R)}\right). \tag{6}$$

To determine the maximum value of the load current, it is necessary to substitute the time it reaches the maximum t_{max} (6) into the time dependence (5).

When the SES $K2$ is unlocked, the transient process in the circuit II will be similar to the above-considered process in the circuit I when $K1$ is unlocked, but taking into account the non-zero initial conditions for the voltage on the capacitor C ($U_{2C}\ (0) \neq 0$).

When the quality factor of the discharge circuit $Q = \sqrt{L/C}\,/\,R \leq 0.5$, the initial voltage on the capacitor is $U_C\ (0) = E$. If the quality factor of the discharge circuit $Q > 0.5$, the transient will be of a damped oscillatory nature and will last for one full period of oscillation, after which $U_C(0) \leq E$.

The value of the capacitor voltage can be determined by the value of the electric charge on C at the end of the transient in the circuit I:

$$q_C = \int_0^T i_1(t)dt\,,\; U_{2C}(0) = \frac{q_C}{C} = \frac{1}{C}\int_0^T i_1(t)dt = -\frac{E}{LC}\frac{1}{\omega^2 + \beta^2}\left(1 - e^{-\beta T}\right), \tag{7}$$

where $\beta = R/2L$ is the attenuation coefficient; $\omega = \sqrt{1/LC - R^2/4L^2}$ and $T = 2\pi/\omega = 2\pi/\sqrt{1/LC - R^2/4L^2}$ are the cyclic frequency and period of the damped oscillations of load current, respectively.

The equation of Kirchhoff's second law in the operator form for the circuit II is similar to (1), and the load current dependence, given in the operator form, is described by the following equation:

$$i_2(p) = \frac{C(E + U_{2C}(0))}{LCp^2 + RCp + 1}\,. \tag{8}$$

To find the time dependence of the load current, we define the original function for equation (8) similarly to (3)–(5):

$$i_2(t) = \frac{C(E + U_{2C}(0))}{2p_1 + R/L} \times e^{tp_1} + \frac{C(E + U_{2C}(0))}{2p_2 + R/L} \times e^{tp_2} = \frac{E + U_{2C}(0)}{\omega L} sin(\omega t)e^{-\beta t}\,. \tag{9}$$

All subsequent current pulses in the DPG load will be described by the analytical dependence (9) with non- zero initial conditions for the voltage on C.

To find the mode in which the current in the load does not change from pulse to pulse, we write the energy balance equation for the discharge circuit:

$$W_E = W_l\,, \tag{10}$$

where W_E is the energy that the source gives to the discharge circuit; W_l is the energy consumed by active elements of the discharge circuit.

For the case of oscillatory discharge (at $Q > 0.5$), the energy balance equation for the above schemes is as follows:

$$E\int_0^T i(t)dt = R\int_0^T i^2(t)dt, \tag{11}$$

and for the case of aperiodic discharge (at $Q < 0.5$) the energy balance equation is:

$$E\int_0^\infty i(t)dt = R\int_0^\infty i^2(t)dt, \tag{12}$$

but, as noted above, with an aperiodic discharge $|U_C(0)| = E$.

Let us substitute the formula for the current (9) into equation (11):

$$\frac{E}{\omega L}\left(E+U_C(0)\right)\int_0^T \sin(\omega t)e^{-\beta t}dt = \frac{R}{\omega^2 L^2}\left(E+U_C(0)\right)^2\int_0^T\left(\sin(\omega t)e^{-\beta t}\right)^2 dt. \tag{13}$$

The equation for finding the steady-state value of $U_C(0)$ can be expressed from (13):

$$U_C(0) = E\left(\frac{\omega L}{R}\frac{\int_0^T \sin(\omega t)e^{-\beta t}dt}{\int_0^T\left(\sin(\omega t)e^{-\beta t}\right)^2 dt} - 1\right) = E\left(\frac{4L}{R}\frac{\omega^2\beta\left(e^{-\beta T}-1\right)}{\omega^2\left(e^{-\beta^2 T^2}-1\right)+\beta^2 e^{-\beta T(2+\beta T)}} - 1\right). \tag{14}$$

The typical parameters of the discharge circuit of units for VESD were used for the calculations: L = 1.5 μH, R = 1 Ohm, E = 500 V.

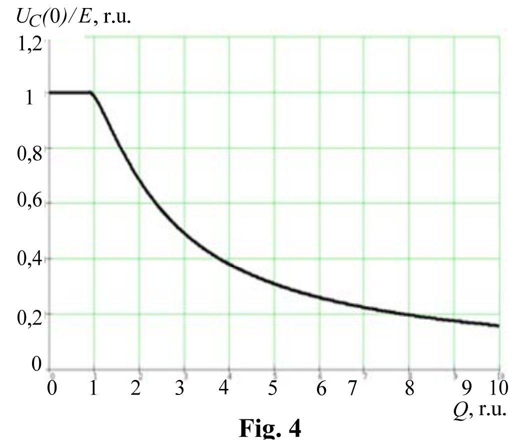


Fig. 4

Fig. 4 shows the analytically obtained dependence of $U_C(0)/E$ on the value of the quality factor of the discharge circuit of the DPG.

In the steady-state operation mode, the dependence of the current pulses in the DPG load on the time will take the form:

$$i(t) = \pm\frac{E+U_C(0)}{\omega L}\sin(\omega t)e^{-\beta t}. \tag{15}$$

Fig. 5 shows the dependence of pulse currents in the DPG load on time at different values of the discharge circuit quality factor:

1 – in the absence of a capacitor in the load circuit;
2 – at Q = 0.25 and C = 24 μF;
3 – at Q = 0.5 and C = 6 μF;
4 – at Q = 1 and C = 1.5 μF;
5 – at Q = 2 and C = 0.375 μF.

As can be seen from Fig. 5, the introduction of a capacitor into the discharge circuit increases the initial rate of current rise in the circuit, reduces the time the reaching its maximum, and also increases its maximum value in the range of Q from 0 to 1. An increase in the value of C leads to an increase in the maximum values of the load current pulses with a simultaneous increase in its duration. When the quality factor of the discharge circuit is higher than the critical one, the current in it changes its direction during the transient process.

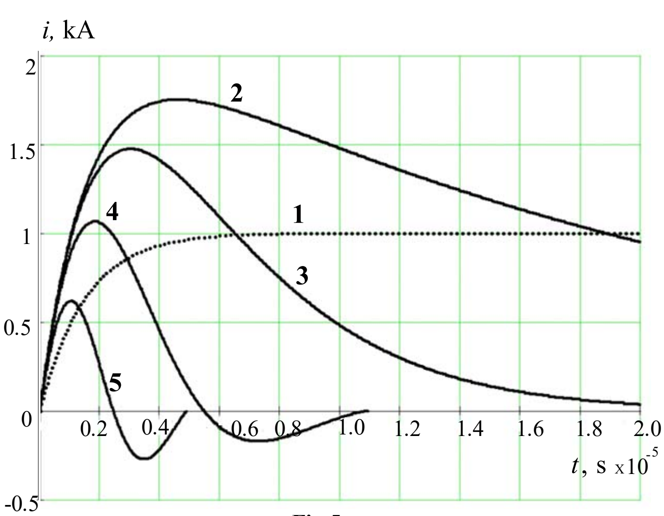


Fig.5

From a technological point of view, the

passage of a negative half-wave of pulse currents with small amplitude in the load is undesirable, and a significant increase in their duration is also undesirable. Based on this, the optimal value of the discharge circuit quality factor should ensure the maximum average pulse power P_{av} at energy transfer to the load. If the quality factor of the discharge circuit is $Q > 0.5$, this power is determined by the following formula:

$$P_{av} = \frac{1}{T} R \int_0^T i^2(t) dt \, . \tag{16}$$

At $Q < 0.5$, the transient process in the discharge circuit becomes aperiodic. Its duration tends to infinity, and the average pulse power in the load tends to zero. Therefore, in the case of aperiodic discharge, to calculate the average pulse power, it is necessary to set either a certain duration of the transient process at which the current in the discharge circuit can be considered conditionally zero, or the value of the discharge current at which the transient process can be considered conditionally completed. Since during an aperiodic transient the rate of decay of current pulses along the trailing edge will be determined by the quality factor of the discharge circuit of the DPG, it is advisable to set the current value at which the transient can be considered conditionally completed, for example, at $0.1 i(t)_{max}$, in order to calculate the average pulse power of such pulses.

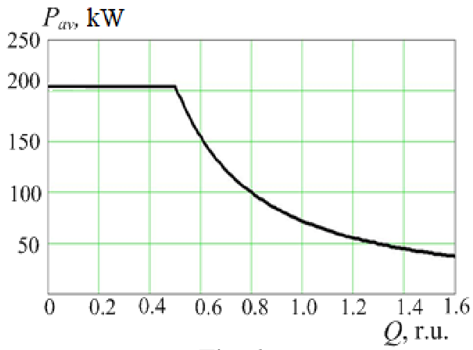


Fig. 6

Fig. 6 shows the approximate dependence of the average pulse power in the DPG load on the quality factor of its discharge circuit at the above-considered electrical parameters of its elements.

As can be seen, the value of the average pulse power in the DPG load is practically unchanged at the Q-factor of the discharge circuit $Q < 0.5$ and sharply decreases with an increase in the $Q > 0.5$. Decrease in the quality factor of the discharge circuit of the DPG below the critical value causes an undesirable increase in the duration of pulse currents in the load at almost unchanged value of the average pulse power, and an increase in the quality factor above the critical value leads to a sharp decrease in the average pulse power. That is why, the critical value $Q = 0.5$ is optimal value for these schemes. In this case, the optimal value of the capacitance of the capacitor in the load circuit of the DPG is determined by the following analytical dependence:

$$C = \frac{L}{Q^2 R^2} = 0{,}25 \frac{L}{R^2} \, , \tag{17}$$

in which the roots of the characteristic equation are $p_1 = p_2 = -\beta$, and the time dependence of the current in the load in the steady-state mode of operation will be as follows [15]:

$$i(t) = \pm \frac{2E}{L} t e^{-\beta t} \, . \tag{18}$$

At a critical value of the Q-factor of the discharge circuit of the DPG as follows from (18), further growth of the pulse currents is possible only with an increase in the value of the reference voltage E, since the inductance of the discharge circuit is a design value and cannot be significantly reduced, and the value of the active resistance is determined by the parameters of the technological load.

In the short-circuit mode in the spark load of the DPG (at $R \to 0$), the time dependence of the current in the discharge circuit is described by the following equation:

$$i(t) = \pm \frac{2E}{\omega_0 L} \sin\left(\omega_0 t\right) = \pm \frac{2E}{\rho} \sin\left(\omega_0 t\right), \tag{19}$$

where $\omega_0 = 1/\sqrt{LC}$ and $\rho = \sqrt{L/C}$ are the natural cyclic oscillation frequency and the characteristic impedance of the discharge circuit of the discharge circuit. The duration of the short-circuit current in the discharge circuit will be equal to the oscillation period, which can be determined by Thomson's formula, and its amplitude will be limited by the characteristic resistance.

Conclusions. The series connection of a capacitor with an electric spark load in the discharge circuit of a bipolar DPG with a capacitive electric energy storage device of high energy capacity allows:

– to use semi-controlled power SES (thyristors), which have a much higher overload capacity and do not require complex control and protection schemes instead of fully controlled semiconductor electronic switches (transistors);

– to provide "soft" switching of the power SESs. The locking of the power SESs occurs naturally when the current in the discharge circuit of the DPG decreases below the thyristor holding current in the open state (the value of which is close to zero);

– to increase (by a maximum of two times) the initial rate of current rise in the electro-spark load of bipolar DPG and significantly improve the energy performance of discharge pulse currents;

– to limit the magnitude and time of short-circuit currents in the discharge circuit of the DPG. The magnitude of short-circuit currents is limited by the value of the characteristic resistance of the discharge circuit of DPG, and their duration corresponds to the period of self-oscillations of the DPG discharge circuit in this mode of operation. At the same time, the electrical energy is not dissipated in the discharge circuit of the DPG, but is almost completely recovered to the capacitors of output of DVFs.

It is determined that the optimal value of the Q-factor of the discharge circuit of the DPG in order to ensure the maximum value of the average power at the minimum duration of pulse currents in the load under this condition is critical value $Q = 0.5$.

Роботу виконано за держбюджетною темою "Розробка основ теорії і методів дослідження впливу несинусоїдних напруг і струмів та виникаючих електротермодинамічних процесів на надійність і ресурс сучасних кабельних ліній електропередачі та на енергоефективність електротехнічних установок резонансного типу" (шифр: "Елрес") КПКВК 6541030.

The work was carried out on the state budget theme "Development of the foundations of the theory and methods for studying the influence of non-sinusoidal voltages and currents and emerging electrothermodynamic processes on the reliability and service life of modern cable transmission lines and on the energy efficiency of electrical installations of resonant type" (Code "Elres").

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УДК 621.365.51

ВЗАЄМОЗАЛЕЖНІ ПЕРЕХІДНІ ПРОЦЕСИ В КОЛАХ БІПОЛЯРНОГО ФОРМУВАЧА РОЗРЯДНИХ ІМПУЛЬСНИХ СТРУМІВ З R-L-C НАВАНТАЖЕННЯМ ТА ОБМЕЖЕНИМ ПОЗИТИВНИМ ЗВОРОТНИМ ЗВ'ЯЗКОМ ПО НАПРУЗІ

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У роботі проведено аналіз взаємозалежних перехідних процесів в розрядних колах біполярного формувача розрядних імпульсів (ФРІ) з R-L-C навантаженням та обмеженим позитивним зворотнім зв'язком за напругою. Отримано аналітичну залежність величини початкової напруги на конденсаторі, послідовно з'єднаному з навантаженням, від величини добротності розрядного кола ФРІ. Визначено оптимальні електричні параметри цих кіл задля забезпечення високих динамічних та енергетичних показників імпульсних струмів в електроіскровому навантаженні. Обґрунтовано, що послідовне з'єднання конденсатора з електроіскровим навантаженням в розрядному колі біполярного ФРІ з ємнісним накопичувачем електричної енергії великої енергоємності дає змогу збільшити (максимально удвічі) початкову швидкість наростання струму в електроіскровому навантажені біполярних ФРІ та значно покращити енергетичні показники розрядних імпульсних струмів. При цьому значення струмів короткого замикання навантаження ФРІ обмежується величиною характеристичного опору розрядного кола ФРІ, а час їхнього протікання відповідає періоду автоколивань розрядного кола ФРІ в цьому режимі роботи. Водночас електрична енергія не розсіюється в розрядному колі ФРІ, а майже повністю рекуперує до ФПН. Бібл. 15, рис. 6.
Ключові слова: перехідний процес, біполярний формувач розрядних імпульсів, розряд, імпульсний струм, зворотний зв'язок по напрузі.

Received 04.11.2024