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Solid discharger for the systems forming a current pulse in low-impedance loads of inductive storages of electromagnetic energy

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The paper considers the use of a solid discharger with a cathode localized enhancement of electric field working together with an opening switch of an inductive storage to form a quick-rising current pulse in a low-impedance load. The physical factors bringing to an increase in pulse sharpening efficiency are specified. The discharger geometry variant is proposed. The technique for a determination of its parameters depending on the experimental requirements and conditions is described. The paper presents the results of the experiments on a stationary facility demonstrating a possibility to generate the current pulses with a rise front ~ 100 ns in the inductive loads ~ 10 nH. The obtained results allow giving a recommendation to use this type of dischargers to form multi-megaampere current pulses with submicrosecond rise front (up to ~ 100 ns) for the inductive energy storages and, in particular, for the explosive magnetic (magnetocumulative) generators., in the circuits with low-impedance loads.

Keywords: solid (condensed) dielectric, breakdown delay, overvoltage.

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Introduction

The inductive storages of the electromagnetic energy are used in a physical experiment as intermediate devices for storing the energy, which comes thereto from the primary current sources, like, for example, condenser batteries and explosive magnetic (magnetocumulative) generators. The advantage of the inductive storages is that it is possible to concentrate significant energy in relatively small volumes (the energy density can be higher by several orders in comparison with the capacitive accumulators), and that it can use a relatively simple method of outputting the energy to the load by opening its electric circuit. The circuit is opened, for example, by explosive or electric-explosive current releases. The less time required for opening the circuit, the more power can be transferred to the load. Presently, there are the current releases designed to open the circuit of the inductive storage for the time $\sim 0.5{-}1\,\mu$s and to transfer multi-megaampere current to the low-impedance load with the physically meaningful inductance ~ 10 nH almost at the same time [1]. However, solving a number of the important tasks (for example, generation of powerful fluxes of soft X-ray radiation) requires current pulses with a rise front of ~ 100 ns within the range from $5{-}20$ MA for simulation studies and up to 80 MA to light the thermonuclear synthesis in microtargets [2,3].

It is known that the energy output time can be reduced (to increase the power transferred to the load) by using a low-inductance discharger to be installed in the load circuit in series, which is actuated when reaching a relatively high level of voltage (close to the amplitude value), which occurs when opening the inductive storage circuit [4–6]. At the same time, it is important to have the discharger breakdown prior to the beginning of the voltage drop at an opening switch in order to avoid reduced peak power being transferred to the load. The maximum efficiency of the current sharpening is obtained in case of the ideal discharger, whose resistance instantaneously drops to zero. In practice, in combination with passability of the multi-megaampere currents the ideality requirement was the main obstacle in creating such switching devices. The present study investigates a method to be used to obtain such behavior of the solid discharger.

The discharger type was selected by the following considerations. The discharger has been initially developed to use it together inside a single structural unit with the explosive or electric-explosive current release. For this reason, the low cost and the design simplicity were prioritized for the discharger. No multiple usage thereof was required.

These priorities are satisfied with a solid discharger, which is easily built into a short low-inductance transmission line, has a high dielectric strength and which is simple and cheap in comparison with, for example, a vacuum discharger as proposed in [3].

The problem is the „ideality“ requirement of the solid discharger contradicts the simplicity requirement, at least for commutation of the mega-ampere currents and it is higher due to significant energy losses at the active resistance of the breakdown channel. For example, in order to reduce the energy losses in the breakdown channel the study [4] has proposed to install a multitude of parallel solid dischargers with introducing a force system of synchronization of their start. But even this does not provide for the ideal commutation system: in the study [5], the researchers have specified the breakdown instability of the solid dielectric materials in the dischargers of the type [4] in terms of the voltage level. It results in the time dispersion of breakdowns in the multi-channel system and, consequently, delays a process of drop of the resultant resistant of the dischargers.

It follows from the above-said that the practical task was to realize a breakdown mode of the solid discharger which would not require using the forceful start system, would be characterized by a relative stability of breakdown in terms of the voltage and accompanied such fast and deep drop of the discharger resistance that it behaves almost as an ideal switch. The method of solving this task is considered below for the discharger designed to operate in a pair with the opening switch of the inductive storage.

1. Commutation mode of the solid discharger with breakdown delay and its influence on the rate of switching the current to the load

The process of electric breakdown of the solid dielectric material by the voltage pulse can be divided into two stages: a stage of loss of dielectric material's dielectric strength and a stage of its collapse ([7]).

The stage of loss of the dielectric material's dielectric strength is a stage of discharge generation, which includes formation the breakdown channel moving from one electrode to another. The channels starts developing from the moment of the voltage's breakdown level, i.e. when the voltage of the maximum electric field strength reaches the value of the dielectric strength of an insulation material. The stage of loss of dielectric material's dielectric strength finishes at the moment of electrode closure. The electrode closure moment is considered to be a moment of discharge actuation (breakdown of the dielectric material).

The second stage of the collapse of the dielectric material includes the resistance drop of the breakdown channel. It is this stage which determines the rate of switching the current to the load. The rate and depth of the resistance drop can be increased by creating electric overvoltage at the discharge insulation to the moment of electrode closure. The overvoltage results in higher power of energy release in the breakdown channel, intensification of the destructive impact of breakdown on the dielectric material, expansion of the channel and the higher temperature of the plasma generated therein. It results in high increase in the channel conductivity, whose dependence on the temperature can be in the first approximation expressed as follows (see [8]):

$$\sigma \approx 1.9 \cdot 10^2 \cdot \frac{T^{\frac{3}{2}}[\mathrm{eV}]}{\ln \Lambda}\,\Omega^{-1} \cdot \mathrm{cm}^{-1},$$

where σ — the conductivity, T — the electron temperature, $\ln \Lambda$ — the Coulomb logarithm. The more overvoltage level, the more expressive this effect.

It is possible to reach the significant overvoltage level by substantially increasing the interelectrode voltage during the breakdown channel movement from one electrode to another. The rise rate of this voltage in case of opening of large (multi-megaampere) currents is limited by a response rate of existing opening switches, which is relatively small ($\sim 0.5{-}1\,\mu$s in comparison with the required value ~ 100 ns). That is why the task is reduced to obtain a reduced development rate of the breakdown channel (i.e. to cause the breakdown delay) at the background of surge voltage (its fast rise), which occurs in opening the circuit.

It is known that the rate of development of the breakdown channel inside the solid dielectric materials is significantly lower (often by one or two orders: see [7]), when the breakdown develops from the cathode to the anode, in comparison with the typical case of the near-anode start of the discharge. This breakdown development takes place (see [7]) when creating locations of localized amplification of the electric field intensity in the near-cathode zone of the dielectric material, for example, by fabricating the cathode as one or more needle electrodes inserted into the dielectric material. Simultaneously, with this arrangement of the needle electrodes the breakdown voltage increases by 30−50% in comparison with the case when they are installed on the anode (see [7,9]).

The rate drop is caused by the fact that the near-cathode start of the discharge make it difficult to generate electron avalanches (a mechanism of shock ionization) which lay a path for the breakdown channel (see [7]). That is why there is a bigger delay in the duration of the breakdown in reference to the moment of the voltage breakdown. The occurrence of the breakdown delay is also indicated by results of the experiments specified, for example, in the studies [10,11]. In accordance with them, the rate of development of the discharge from the cathode for the studied specimens of the dielectric materials did not exceed the speed of sound in the material. For the common technical dielectric materials the speed of sound is relatively small (for example, for polyethylene — 2.48 mm/μs [12]). In case of the reverse direction (i.e. from the anode), as per results of the experiments [10] the discharge development rate always exceeded the speed of sound. In the strong electric fields it stays within the range 10−2000 mm/μs ([7,11,13,14]), wherein, in accordance with [10], with increase in the voltage and its time derivative dU/dt also increases and weakly depends on the distance between the electrodes (on the thickness of the dielectric material).

In addition to creating the breakdown delay, the available local amplification of the electric field in the near-cathode area of the discharger reduces a potential barrier for exit of the electrons out of the cathode and additionally contributes to accelerated and deep drop of its resistance at the second process stage, i.e. after finalization of the breakdown channel.

The sharp drop of the resistance results in in-load generation of a fast-rising current pulse, whose rise front duration is already not limited below by the duration of the circuit opening process for the inductive storage. At this, in the limit case of the instantaneous actuation of the discharger the current rise curve and, hence, the minimum front duration will be defined by the relationship [15]:

$$I_W(t) = I_\infty \cdot \left[1 - \mathrm{Exp}\left\{-\left(\frac{R_{sm}}{L_i} + \frac{R_{Sm}}{L_W}\right) \cdot t\right\}\right]. \qquad (1)$$

Here $I_\infty = I_i \cdot L_i/(L_i + L_W)$ — the amplitude value of the in-load current; $I_W(t)$ — the dependence of the in-load current on time; I_i, R_{Sm} — the current in the inductive storage and the resistance of the opening switch at the moment of the discharger actuation; L_i and L_W — the inductances of the storage and the load.

Using the expression (1), it is easy to make sure that the time of current rise to any give value $I_W < I_\infty$ is determined by the formula

$$\tau_f = \frac{L_i L_W}{R_{Sm}(L_i + L_W)} \ln\left(1 - \frac{I_W}{I_\infty}\right)^{-1}. \qquad (2)$$

It follows therefrom that it is always possible to select such a relationship of the release resistance R_{Sm} and the circuit inductances so as to ensure the in-load current rise front τ_f at 100 ns or even less. The value R_{Sm} is found by numerically simulating the electric explosion process of the conductor [16], by optimizing its parameters, as a rule, by the level of maximum voltage attained during the electric explosion.

Being a stronger factor, the availability of the localized amplification locations of the electric field intensity in the dielectric material's near-cathode zone suppresses the influence of random heterogeneities, micro-inclusions and contaminants in the insulation material on the breakdown. In accordance with the experimental data, which are specified, for example, in [6], artificial concentrators of the electric field intensity are input to reduce the dispersion of the breakdown voltage to 2–6%, thereby increasing the stability of the process of commutation of the inductive storage to the load to ensure a stable manifestation of the effect of the reduced in-load current rise front duration. Simultaneously, as follows from [6], it contributes to generation of the multi-channel breakdown provided that the voltage is quite quickly growing at the discharger electrodes. At the same time, the paper [6] specifies that if the number of the needle electrodes is above 30, then the dispersion of the breakdown voltage tends to the lower edge of the above-said range, i.e. to 2%. In the conditions of our experiments on a stationary unit the criterion of occurrence of the multi-channel breakdown was not satisfied. For this, the rise rate of this voltage at the discharger electrodes should at least exceed 1 MV/μs (see ibidem in [6]), and actually it was ~ 0.25 MV/μs. That is why there was single-channel commutation. However, the authors note the possibility of multi-channel commutation as an accompanying positive effect, which can manifest itself in the bigger power sources, thereby, as per [6], both substantially reducing the inductance of the discharge circuit and increasing the steepness of the front of the formed pulse.

Thus, in order to cause the breakdown delay and thereby improve the efficiency of the in-load current pulse sharpening, in case of the opening of the circuit of the inductive storage, it is necessary, first of all, to implement the discharger insulation breakdown in the mode of the localized amplification of the electric field intensity in the near-cathode zone of the dielectric material (it causes the breakdown delay), secondly, to create the said breakdown delay at the surge background (fast rise) of the interelectrode potential difference (it causes the overvoltage).

The bigger voltage surge for the breakdown delay time, the bigger level of overvoltage at the discharger insulation, and its resistance will drop faster and deeper, while the in-load current rise front will be closer to the minimum value, which is defined, for example, for the purely inductive load by the formula (2).

Note that essentially, the overvoltage level increase means a reduced thickness of the interelectrode insulation at the fixed amplitude voltage, at which the discharger will be actuated. We also note that in general the solid dielectric material can be substituted by a liquid one, if its physical properties can ensure the breakdown delay to be sufficient for creating the required overvoltage.

2. Technical design of the solid discharger, the connection diagram and the procedure of prediction estimation of the commutation parameters

Figure 1 shows the technical design and the diagram of connection of the solid discharger to the discharger circuit of the inductive storage. The diagram differs from the typically used one (see, for example, [4–6]) only by a necessity of strictly observing the polarity of the discharger electrodes.

The solid discharger G consists of a plane-parallel anode *1* and cathode *2*, which are separated by the solid dielectric material *3*. The discharger cathode is fitted with the built-in needle electrodes *4* designed to create the locations

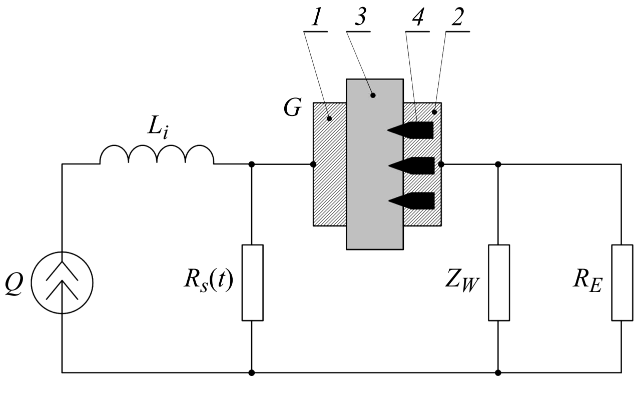

Figure 1. Technical design of the solid discharger and the diagram of its connection with the discharger circuit of the inductive storage. Explanations are given in the text.

of localized amplification of the electric field in the near-cathode zone. At the same time, a specific distance of protrusion of the needle electrodes inside the dielectric material is determined by the specifics of the problem to be solved in each case.

The inductive storage of energy L_i is powered by the current source Q. The current source can be represented, in particular, by the condenser batteries or explosive magnetic (magnetocumulative) generators. Then the electric circuit of the inductive storage is opened, for example, by means of the explosive or electric-explosive opening switch $R_S(t)$. When actuating the opening switch $R_S(t)$, the voltage pulse is generated to be applied between the electrodes *1* and *2* of the discharger G with the solid insulation *3* (if initially the load Z_W is open, then the circuit is closed by means of an additional resistance R_E). Then there is the discharger breakdown and the inductive storage is closed to the load.

The breakdown is delayed due to the elements of localized near-cathode amplification of the electric field. During the delay, the interelectrode potential difference increases in comparison with the breakdown voltage U_r (i.e. the voltage of the breakdown start) by the value $\Delta U_S \approx \langle dU_S/dt \rangle \cdot \tau$, where $\langle dU_S/dt \rangle$ — the average rate of rise of the voltage $U_S(t)$, as generated when the opening switch is actuated. As a result, by the time of closing the discharger electrodes the voltage is $U_G = U_r + \Delta U_S$, i.e. there is the overvoltage appearing on the discharger insulation.

In general, it is possible to estimate the dielectric material's overvoltage level, the time of the beginning of generation of the breakdown channel from the cathode t_r, the breakdown delay τ, the discharger insulation thickness h by solving the system of the equations:

$$\begin{cases} U_r(h) = U_S(t_r), \\ \int\limits_{t_r}^{t_r+\tau} v(t)dt = h, \\ U_S(t_r + \tau) = U_{com}. \end{cases} \tag{3}$$

Here $U_r(h)$ — the dependence of the breakdown voltage on h; $U_S(t)$ — the calculated dependence of the discharger voltage on the time when operating the opening switch for opening (we assume that it is specified); U_{com} — the required voltage of the discharger commutation above the level, from which the voltage surge comes, but it does not exceed the maximum voltage generated during opening the circuit of the inductive storage; $v(t)$ — the dependence of the longitudinal rate of the increment of the breakdown channel length on the time t.

The first and third equations in (3) express the obvious conditions of the potential balance at the discharger electrodes, while the second one describes the development of the breakdown channel.

The increment of the discharger voltage above the breakdown level is determined by the equation

$$\Delta U_S = U_S(t_r + \tau) - U_r(h).$$

The value of U_{com} is given based on the results of calculation of the process of current pulse generation of the inductive storage for the diagram shown on Fig. 1, if assuming the „ideality" of the discharger (commutation with instantaneous drop of its internal resistance to zero). The criterion for selecting U_{com} can be an acceptable level of energy losses when opening the circuit of the inductive storage in combination with getting the desirable in-load current rise front to the required value.

In doing so, it should be noted that due to continuous rise of the interelectrode voltage during the time of the channel development from the cathode a counter discharge can start from the anode, when the electric field strength near it exceeds the level of the dielectric material's dielectric strength. That is why, generally speaking, $v(t)$ should be understand a velocity which is a combination of the counter velocities of the development of the breakdown channels from the cathode and the anode of the discharger:

$$v(t) = v_c(t) + v_a(t), \tag{4}$$

wherein $v_a(t) = 0$ at the initial stage of the breakdown development (at $t < t_a$, where t_a — the time of start of the discharge from the anode).

In practice, $v_c(t)$ and $v_a(t)$ in (4) can be substituted by averaged values of the velocities obtained from the experiment, as usually it is not possible to establish their exact time dependences. If, as per [10], it is possible to expect that the rate of development of the breakdown channel from the cathode will be close to the speed of sound, then the second equation in (3) can be simplified as follows:

$$v_{cs} \cdot \tau + v_a \cdot \big(\tau - \Delta t_a(h, U_r(h))\big) = h, \tag{5}$$

where v_{cs} — the speed of sound in the dielectric material, $\Delta t_a(h, U_r(h))$ — the dependence of the delay time of start of the counter breakdown from the anode on the insulation thickness h and the breakdown voltage U_r (in accordance with the first equation in (3) the voltage U_r defines the time of breakdown start t_r).

If for the case when the rate of development of the breakdown channel from the cathode is much less than the rate of the anode channel, which, as a rule, occurs in practice, instead of (5) we obtain

$$\tau \approx \Delta t_a(H, U_r(h)).$$

The dependence of the breakdown voltage on the insulation thickness $U_r(h)$ is experimentally established when testing the discharger model at various values h — by supplying test pulses from the high-voltage generator with the rise front duration close to that which is supplied to the discharger when the opening switch is actuated. At the same time, one determines the dielectric strength of the dielectric material used (the limit electric field strength which causes the material breakdown) in the plane-parallel geometry of the electrodes. Then, at the various thicknesses h and the values U_r corresponding thereto one calculates the delay time of the counter breakdown from the anode Δt_a. The start of the anode breakdown is determined as the time when in approaching the cathode breakdown channel to the anode (or the channels, if the multi-channel breakdown is generated) and in rising of the voltage $U_S(t)$ of the opening switch, the electric field strength comes to the dielectric material's dielectric strength level. When calculating the electric field strength at the anode, the potential of the head of the breakdown channel developing from the cathode can be assumed to be equal to $U_S(t)$, and in the first approximation its shape can be assumed to be semi-spherical. The radius of the breakdown channel at the first stage of its development as per the data, for example, in the paper [9] can be evaluated by the value of $R_c \sim 50\,\mu$m.

The so-obtained dependences $U_r(h)$ and $\Delta t_a(h, U_r(h))$ can be used to obtain the closed system of the equations (3) relative to the variables h, τ, t_r and, consequently, determine the discharger insulation thickness h and the achieved overvoltage level $U_{com}/U_r(h)$ for the given dependences of the voltage on the time $U_S(t)$ at the opening switch.

As estimations of the values R_c, which can be obtained from the experimental data and the calculation models are quite approximate due to the significant dispersion of the polymer characteristics and no strict theory of breakdown of the solid dielectric materials, the radius R_c is desired to vary in order to establish a degree of its influence on the breakdown delay time.

Knowing the commutation voltage U_{com} and the insulation thickness h, it is possible to finally calculate the mode of generation of the current pulse in the inductive storage load by correlating the process of energy release in the discharger channel resulting in collapse of its insulation with the parameters of the discharger circuit (in the most simple situation it can be done, for example, in the approximation of the electric arc channel model [8]).

When performing the prediction estimations of the commutation mode, it is necessary to take into account whether the expected breakdown mode is a single-channel or multi-channel one, as it substantially changes the process of electric field strength rise near the anode (i.e. the conditions of the start of the counter channels of the discharge) and the dynamics of the change of the discharger resistance during the breakdown process.

As mentioned earlier, as per [6], for occurrence of the multi-channel breakdown, it is required that the rate of rise of the dielectric material's voltage satisfies with the empiric condition $dU/dt \geq 1$ MV/μs. In doing so, as follows from [10,11], the growth of the derivative dU/dt will result in the rise of the movement velocity of the counter channels of breakdown from the anode, but it will weakly affect the rate of propagation of the cathode channels.

Besides, it can be expected that the rate of the development of the counter anode channels of breakdown will be always higher than the initial near-anode ones, as the case of the near-cathode breakdown start has a typical higher rate of rise of the near-anode electric field strength, which is equivalent to the growth of the derivative dU/dt. Indeed, as the counter breakdown is delayed, prior to its start the electric field strength at the anode continuously increases not only due to increase in the voltage U_S at the opening switch, but as well as to channels' transfer of the cathode potential towards the anode. And when the electric field strength at the anode reaches the breakdown level, then the field strength across the entire thickness of the dielectric material from the anode to the cathode channels will increase this level.

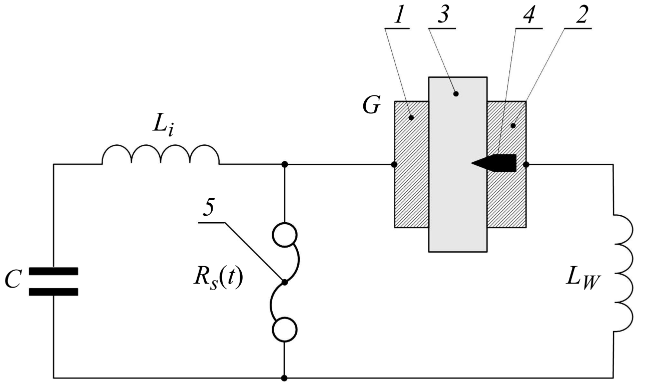

Figure 2. Experimental diagram. Explanations are given in the text.

3. Experimental diagram

The proposed commutation method with delay of the discharger breakdown was checked in the two experiments. The experimental diagram is shown on Fig. 2. The current source used for feeding the inductive storage L_i with the electromagnetic energy was the condenser battery (CB) with the capacitance of $C = 492\,\mu$F to be charged to the voltage of 43 kV. The condenser battery was commutated by 12 controllable solid dischargers of the same type as in [17], whereas each of them has two breakdown channels. The storage had the inductance of $L_i = 100$ nH. The opening switch is the electric-explosive current release $R_S(t)$ designed similar to [18] as 32 copper foil strips of the length of 60 cm, the total width of 32 cm and the thickness of 15 m. They were placed in a slit space between the two polyethylene insulators, which is filled with an arc-extinguishing medium.

Both the assemblies were manufactured in a united design documentations, so they had no structural differences at all. The experimental setups were different only in conditions of the electric explosion of the foil due to making physical differences to the properties of the arc-extinguishing medium surrounding the exploded conductor. That is why the voltage pulse shape at the opening switch and, consequently, the in-load current rise shape were different.

Both the cases used an identical solid discharger G, which was commutated in the single-channel mode. The dielectric material used for separating the electrodes was polyethylene. The polyethylene was selected because it is a material with quite well-known properties, which is available, processable for insulation fabrication and has satisfactory dielectric strength. The needle electrodes *4* were cylindrical steel rods of the 3 mm diameter tapering at the angle 36°. The needle electrodes were pressed into the cathode *2* and pressed into the polyethylene for the depth of 2.1 mm. The thickness d of the dielectric material *3* between the needle electrode *4*, installed on the cathode *2* and the anode *1* was $d = 0.7$ mm. The load inductance L_W was 10 nH.

The experimental assembly had a coaxial form and was installed in a center of the current collector with uniform current input through the coaxial cables connected along its perimeter. The derivatives of the current pulses in the inductive storage and in the load were measured using single-loop inductive sensors. These three sensors with the loop diameter of 8 mm at the radius of 127 mm were installed at the input of the inductive storage. The radial transmitting lines of the load included the three sensors with the loop of the area of 50 mm^2, which were placed at the radius of 180 mm. In addition to it, the active wire resistance of 330 Ω connected to the input of the inductive storage was used to measure the current flowing across the resistance by means of the Rogowski coil. As the product of this current to the resistance gives the voltage at the inductive storage input, it allowed additionally controlling (independently) the nature of the voltage rise at the electric-explosive release during electric explosion of the conductor.

All the measurements were performed by means of the LeCroy 24Xs digital oscillographs with the time step of 2 ns. The oscillographs starting their devices and the sensors were separated from „the earth“. The instruments were at 25 mm to the commutation place. The measuring equipment was powered by batteries in order to avoid significant interference on the measurement path.

As a result of discharge of the condenser battery, the inductive storage was receiving the current increasing to 1.23 MA for 3.1 μs in the first experiment and to 1.19 MA for 3.8 μs in the second experiment. Then, the current was switched to the load as a result of the electric explosion of the foil of the opening switch and the discharger breakdown. Note that some difference in the discharge currents of the unit can be due to the dispersion of the energy losses in its multi-channel switching system, which has no ideal stability, or due to manifestation of impact of the electromagnetic interference on the measurement path, which can not be fully avoided (slight interference can create noticeable error when integrating the signal from the inductance sensors).

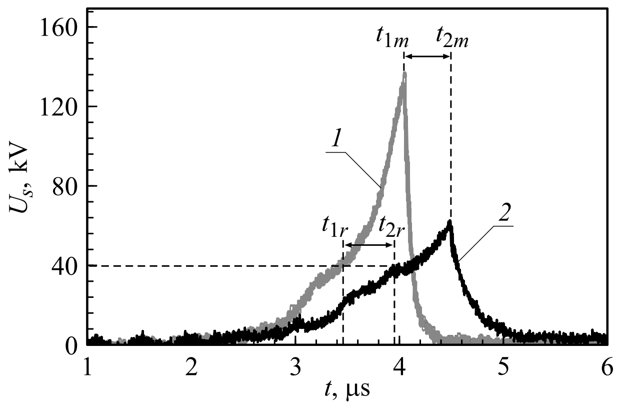

Figure 3. Curves of the voltage pulses generated by the electric-explosive current release in the experiments: *1* — the first experiment, *2* — the second experiment.

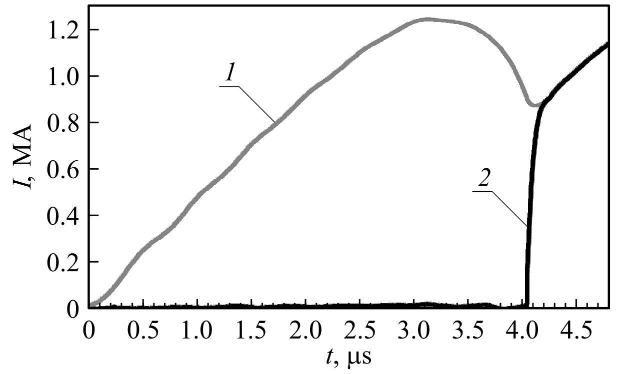

Figure 4. Curves for switching the current of the inductive storage to the load, as obtained in the first experiment: *1* — the input current, *2* — the load current.

4. Experimental results and discussion thereof

Figure 3 shows the curves obtained in the first and second experiments for the voltage pulse, which is generated by the electric-explosive current release, while the Figs. 4 and 5 show their corresponding curves for switching the inductive storage current to the load.

Let us analyze the results presented.

In accordance with the experimental data, which are obtained during investigating the breakdown process for a number of the solid dielectric materials by Yu.N. Vershinin [10,11], the rate v_c of development of the breakdown channel from the cathode is determined only by the level of voltage U_r, at which the breakdown starts. At the same time, it has been found that the rate of rise of the interelectrode voltage dU_S/dt at the time of breakdown did not affect the said rate. Taking it into account as well as that our experiments used the same-type equal-thickness dielectric material, we assume that its breakdown voltage U_r can be considered the same for each of the experiments (within the statistical dispersion of 2–6%, see Section 1). Hence, it follows that the start rates of development of the cathode channels are equal. When the rates are equal, the overvoltage level at the discharger insulation at its breakdown time (closure of the electrodes) should be the higher, the higher the rate of rise of the voltage $U_S(t)$ at the opening switch, which is confirmed by comparing the experimental curves of Fig. 3. As the load inductance is much lower than the storage inductance $L_W \ll L_i$, the closure of the discharger electrodes results in sharp voltage drop at the opening switch. That is why the overvoltage level can be estimated by the ratio of the amplitude voltage at the opening switch to the discharger breakdown voltage U_r. If assuming that the influence of the voltage rise rate dU_S/dt on the breakdown delay is relatively small, then the time interval $\Delta t_m = t_{2m} - t_{1m}$ between the peaks of the voltages U_{1m} and U_{2m} should be approximately equal to the time interval $\Delta t_r = t_{2r} - t_{1r}$ between the times of getting to the breakdown voltage U_r. Determining from the curves of Fig. 3 the voltage at which this condition is fulfilled we found that $U_r \approx 40$ kV and the breakdown delay corresponding thereto is $\tau = t_{1m} - t_{1r} \approx t_{2m} - t_{2r} \approx 0.55\,\mu$s. Taking into account that $U_{1m} \approx 137$ kV, $U_{2m} \approx 63$ kV, we obtain that in the first experiment the overvoltage was $U_{1m}/U_r \approx 3.4$, so was in the second one $U_{2m}/U_r \approx 1.6$. The electric field strength at which the breakdown starts from a tip of the needle electrode was $E_r \approx 470$ kV/mm. The average rate of development of the breakdown channel from the cathode at this delay did not exceed $d/\tau = 0.7/0.55$ mm/μs≈ 1.27 km/s.

Now, let us assume that with the growth of dU_S/dt the rate of development of the breakdown channel increases. At the same time, under otherwise equal condition the breakdown still starts at the same voltage. Then, as dU_S/dt in the first experiment is higher than in the second one, the breakdown delay in the first experiment should be less than in the second one: $\tau_1 < \tau_2$. It is clear from the curves of Fig. 3 that this condition is satisfied by the breakdown start at the voltage $U_{1r} = U_{2r} < 40$ kV, which is the result of the inequation $(dU_S/dt)_1 > (dU_S/dt)_2$. The latter means higher breakdown delays τ_1 and τ_2 in comparison with $\tau\,(\tau_2 > \tau_1 > \tau = 0.55\,\mu\text{s})$ and as a consequence the lower rates of development of the breakdown channels: $\bar{v}_2 = d/\tau_2 < \bar{v}_1 = d/\tau_1 < d/\tau = \bar{v} = 1.27$ km/s (the overline of the symbol means time averaging).

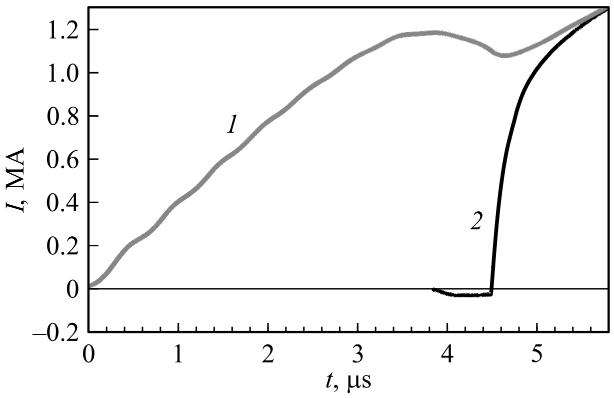

Figure 5. Curves for switching the current of the inductive storage to the load, as obtained in the second experiment: *1* — the input current, *2* — the load current.

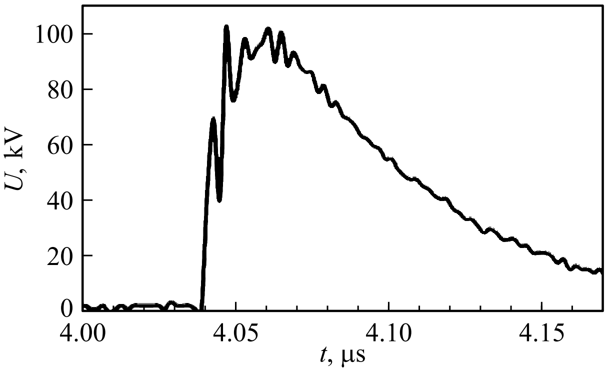

Figure 6. Voltage pulse at the load in the first experiment.

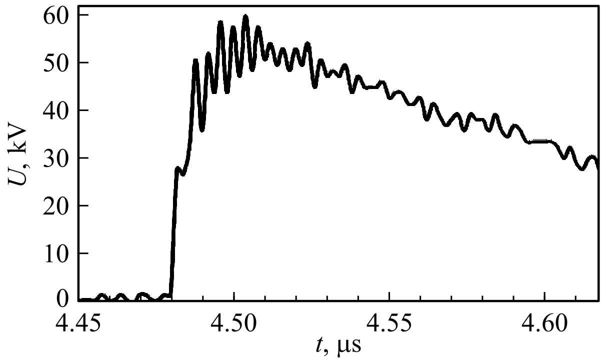

Figure 7. Voltage pulse at the load in the second experiment.

Therefore, the average rate of propagation of the breakdown from the cathode in both the experiments was admittedly less than the speed of sound in the polyethylene equal to 2.48 mm/μs, i.e. it did not exceed the boundary specified by Yu.N. Vershinin.

It follows from the Figs. 4 and 5 that the higher overvoltage level is in correspondence with the higher in-load current rise rate. In the first experiment, the current rise front to the level of 0.8 MA was approximately 110 ns, so was in the second one — 270 ns. The discharger commutation process was also accompanied with the fast voltage rise at the load. The time of the voltage rise at the load from zero to the maximum was 9 ns in the first experiment, so was — 16 ns in the second one (Figs. 6 and 7).

Finally, the experimental results obtained at the stationary unit confirm the viability of the current pulse sharpening principle of the inductive storage, which is laid in the device operation.

The results of these experiments were based to apply for an invention and to have obtained a patent [19].

The above-described experiments were performed in 2017 and 2018.

In 2019, the discharger of the said type was used for load commutation of the inductive storage powered by a spiral explosive magnetic generator, in the study presented by a team of employees from RFNC-VIIEF in the publication [20]. The experiment (Fig. 1) has used the electric-explosive current release, whose actuation generated the voltage pulse $U_S(t)$ of the amplitude of 600 kV with the rise front duration of about 1.25 μs (as per the level of 0.1−0.9 of the amplitude value). The interelectrode insulation of the discharger was made of the polyethylene. Its thickness between the needle electrodes and the anode was 3 mm. The needle electrodes were configured as follows: one in the center and the six ones around it at the radius of 7 mm. This experiment with the load of the inductance of 10 nH had shaped the current pulse rising to 5 MA for 120 ns. The experimental results coincided with the calculation assuming the „ideality“ of the discharger.

Conclusion

The results presented indicate promising application of the solid dischargers (the dischargers with the condensed dielectric material) with the near-cathode localized amplification of the electric field, which operate in the breakdown delay mode in a pair with the opening switches of the inductive storages electromagnetic energy, for generation of the fast-rising current pulses in the low-impedance loads.

The described commutation mode and the technical solution of the discharger allow switching the multi-megaampere currents with the rising time of up to 100 ns. The discharger is designed to be simple and for single use. That is why the dischargers of this type can be applied, for example, in output cascades of generation of the current pulse of the explosive magnetic generators, not leading to substantial complication and the rise in the price of the structure.

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Conflict of interest

The authors declare that they have no conflict of interest.

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