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Electrically Exploded Current Opening Switch for Fast Transfer of Energy from an Inductive Storage to a Load

© A.A. Bazanov,[1] A.N. Erofeyev,[1] A.V. Ivanovskiy,[1,2] V.I. Mamyshev,[1] E.V. Shapovalov[1]

[1] Russian Federal Nuclear Center, All-Russia Research Institute of Experimental Physics, Sarov, Russia
[2] Sarov Physicotechnical Institute of National Research Nuclear University, Sarov, Nizhniy Novgorod region, Russia
e-mail: aab@elph.vniief.ru

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The paper presents the results of model testing of the electrically exploded current interrupter (opening switch) designed for the switching system used to release the electromagnetic energy from the inductive storage to the load through a closing switch-discharger. A capacitor bank was used as a source of energy for the inductive storage. Some features of the interrupter were varied in order to increase its reliability and operation speed. The obtained experimental data allowed making recommendations on practical implementation of the opening switch. The optimized version demonstrated a possibility to form current pulses with submicrosecond rise time, up to ~ 100 ns, in the low-impedance loads of the inductive storages. The obtained result is true for the currents of megaampere and multimegaampere level that makes it possible to use the opening switch for commutation of the energy sources with high energy capacity, for example, of the explosive magnetic generators.

Keywords: electrically exploded current opening switch, inductive energy storage, load current rise time.

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Introduction

Currently, to carry out physical experiments that require the generation of large pulsed electrical power, inductive energy storage devices (in particular, explosive magnetic ones) found widespread use, they are equipped with an output switching system that forms a rapidly increasing current pulse in the load [1]. One of the possible options for making such a switching system is the use of an electrically exploded opening switch that breaks the current circuit of the inductive storage device, paired with a discharger (closing switch) connected in series to the load [2–6]. The latter is activated during the process of electric explosion of the opening switch conductor when a specified voltage level (usually close to the maximum) is reached in it. If we consider the discharger (closing switch) to be an ideal device (it operates instantly, the resistance drops to zero), then the time of current rise in the inductive load to any given value $I_W < I_\infty$ in accordance with [7,8] is determined by formula:

$$\tau_f = \frac{L_W \cdot L_\infty}{R_{Sg} \cdot I_{ig}} \ln\left(1 - \frac{I_W}{I_\infty}\right)^{-1}. \tag{1}$$

Here I_∞ — amplitude value of the current in the load

$$I_\infty = \frac{I_{ig} \cdot L_i}{L_i + L_W}, \tag{2}$$

I_{ig} and R_{Sg} — current in the inductive storage and resistance of the interrupter at the moment the discharger is activated, L_i and L_W — inductance of the storage and load, respectively.

From (1) it follows that, at other conditions being equal, the time τ_f will be inversely proportional to the resistance of the opening switch (the voltage across it $U_{Sg} = R_{Sg} \cdot I_{ig}$) at the moment the discharger is activated. Therefore, to increase the power transferred to the load, it is necessary to increase the resistance R_{Sg} (voltage U_{Sg}). The maximum resistance achievable during the electrical explosion of conductors depends on a number of design and technological features of the interrupter, for example, on the material, shape and size of the conductors, as well as the properties of their environment. In this paper, the task was to carry out experimental testing of such a design of an electrically exploded interrupter, which, when used in tandem with an „ideal" discharger would provide a submicrosecond time for switching current to a low-impedance load with inductance ~ 10 nH (up to ~ 100 ns for currents of about one or more megaamps).

1. Scheme of experiments and tested options of electrically exploded current interrupters

The experimental scheme is shown on Fig. 1.

A capacitor bank with capacitance $C = 492\,\mu$F, charged to a voltage of 43 kV, was used as the primary energy source in the experiments. Its discharge circuit contained an electromagnetic energy storage device L_i with inductance 100 or 80 nH. The electrically exploded current interrupter $R_S(t)$ was installed at the output of the inductive storage device. A load L_W of magnitude $\sim 10\,\text{nH}$ was connected to the inductive storage through a single-channel solid-state discharger G, described in the paper [8] (the discharger contains flat electrodes *1* and *2*, separated by a polyethylene insulator *3*, into which a needle-shaped near cathode electrode is pressed *4*). In accordance with [8] to a first approximation, such discharger in this case can be considered as „ideal“ and not considering the energy dissipation in it during the switching process. Inductive sensors were used to measure current derivatives in the inductive storage device and the load.

In the papers [5,6] it is shown by means of computational modeling that at microsecond duration of the energy accumulation process it is possible to achieve rapid switching of the current from the inductive storage device to the load in a time $\sim 100\,\text{ns}$, if the electrically exploded interrupter is made of copper foil $10-14\,\mu\text{m}$ thick. The relatively small thickness of the foil makes it possible to reduce the time of diffusion of the magnetic field into the conductor and, as a consequence, the duration of the electrical explosion process. With the above parameters of the electrical circuit, the time for energy transfer from the capacitor bank to the inductive storage is several microseconds, therefore the thickness of the conductors shall not significantly exceed the upper limit of the given range and was chosen to be equal to $15\,\mu\text{m}$.

To reduce the dimensions of the interrupter, its design was made by analogy with [9]. The interrupter (Fig. 2) was made in the form of copper strips *1* 60 cm long, which were installed radially between the outer *2* (diameter 456 mm) and inner *3* (diameter 310 mm) coaxial electrodes at the output of the inductive storage and were placed in the slot space *4* (narrow zigzag gap) between two fin-tooth polyethylene insulators *5* and *6* installed „tooth in groove“. The cross-sectional shape of the teeth is — an isosceles triangle with a base of 5 mm and a height of 25 mm. The gap between the walls of the slot *4* was 0.4 −0.5 mm. The slot space was previously evacuated and then filled with an arc-extinguishing medium *7*. The number of strips and their width were selected in such a way that for

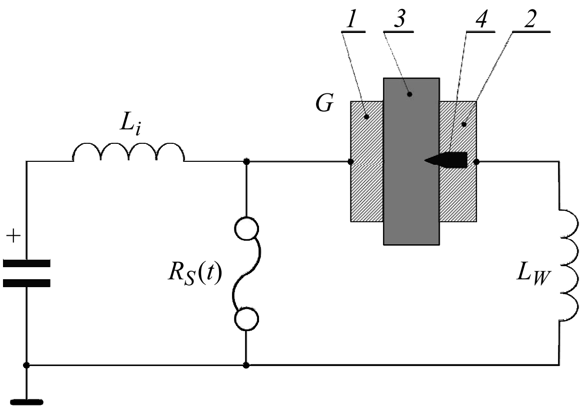

Figure 1. Experimental diagram.

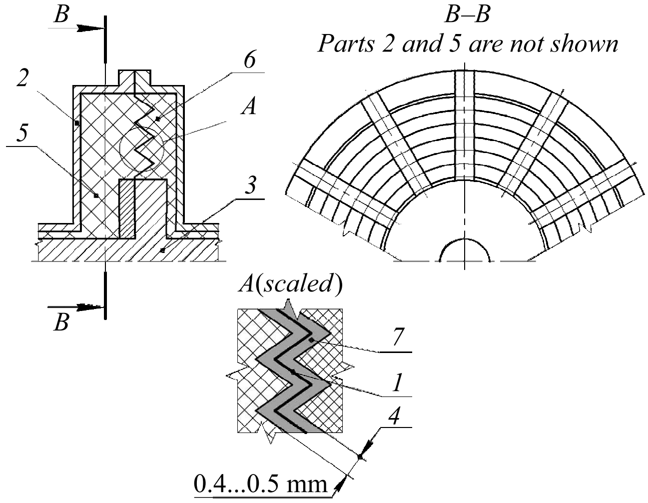

Figure 2. Electrically exploded current interrupter.

the storage with inductance of 100 nH their total width was 32 cm (32×1 cm), and for the storage with inductance of 80 nH — 27 cm (18×1.5 cm).

Four options of the electrically exploded interrupter were tested.

In the first option, the electrically exploded elements were installed in the slot gap as is, which caused difficulties during their installation, since thin conductors easily broke on the teeth of the overlapped insulators with little mechanical impact.

Therefore, measures were taken to facilitate the assembly process of the interrupter and reduce the likelihood of conductor breaks by securing them to a reinforced dielectric substrate.

In the second and third options the copper strips were glued to a polypropylene substrate $100\,\mu\text{m}$ thick, on the other side of which a reinforcing layer of durable cellulose $60\,\mu\text{m}$ thick was glued. Moreover, in the second option, the copper strips were located in such a way that under the influence of magnetic field they were pressed into the polypropylene substrate (H-pressed discharge), in the third option they were separated from it (H-released discharge).

In all of the above options (including the first one), the slot space between the teeth insulators was filled with glycerin.

The fourth option of the current interrupter coincided with the second one, except that instead of glycerin, the slot gap was filled with sulfur hexafluoride (SF_6) under pressure of 0.4 MPa.

2. Experimental results

The experiments were conducted in two stages.

First, the first three options of the interrupter with glycerin in the slot gap were tested in order to select from

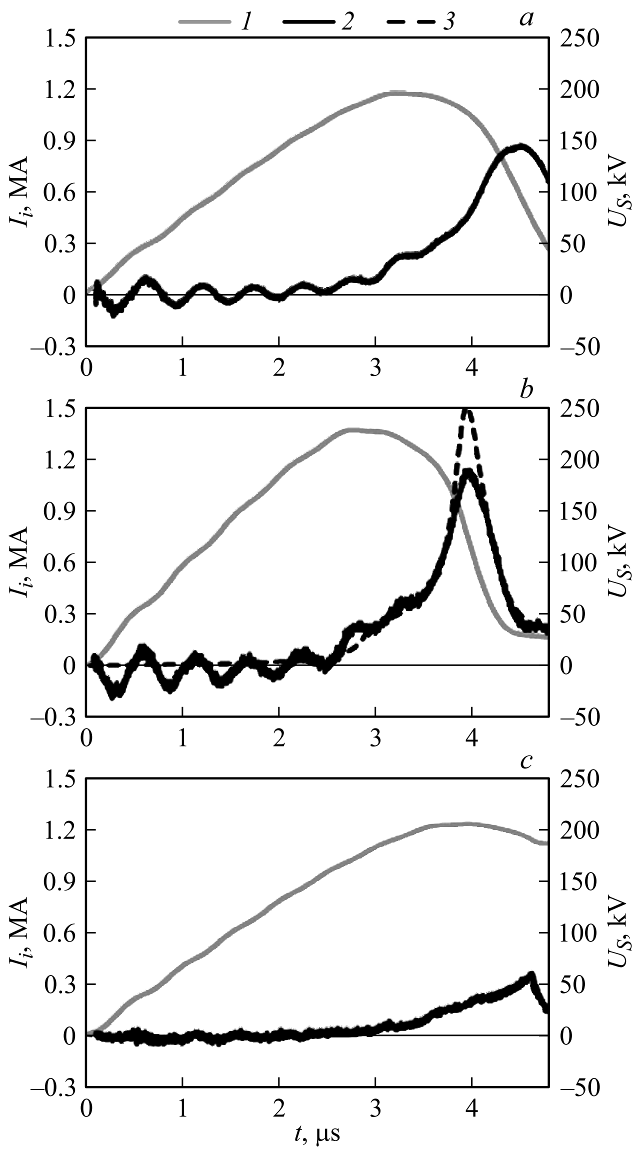

Figure 3. Curves of current pulses I_i in the inductive storage circuit and voltage U_S on the electrically exploded interrupter for the first stage experiments: *1* — current, *2* — voltage, *3* — calculated voltage on electrically exploded interrupter with uniform current distribution. Foil electrically exploded elements are made: *a* — without reinforced polypropylene substrate; *b* — on reinforced polypropylene substrate, H-pressed discharge; *c* — on reinforced polypropylene substrate, H-released discharge.

them the best one in terms of the level of voltage achieved during the electrical explosion of conductors.

At the second stage, the selected option was used to conduct two experiments in which the inductive storage was switched with the discharger G to the load at a voltage on the interrupter close to the maximum. In one of them the slot gap was filled with glycerin, in the other with SF6 gas.

Fig. 3 shows the restored by signals of inductive transmitters curves of current pulses $I_i(t)$ in the circuit of the inductive storage and voltage $U_S(t)$ on the electrically exploded interrupter, obtained in the first stage experiments. With first and third options of the interrupter design (Fig. 3, *a, c*) the storage with inductance 100 nH, with second option (Fig. 3, *b*) — with inductance 80 nH was used.

From a comparison of the voltage curves for various options of the interrupter design, it follows that the highest voltage, equal to 189 kV at time 3.9 μs, was obtained in the case of applying electrically exploded elements to the substrate and implementing H-pressed discharge (Fig. 3, *b*). If the substrate is not used, the maximum voltage is 145 kV (Fig. 3, *a*). In the case of H-released discharge, the result (Fig. 3, *c*) is the worst due to the slow increase in resistance, and hence the voltage on the interrupter, which by the time 4.5 μs reaches a level of 63 kV only.

The results obtained indicate, in particular, that the conductors fastening on the reinforced dielectric substrate and the organization of H-pressed discharge prevent the development of the process of inhomogeneous destruction of thin foil conductors under the influence of a spatially inhomogeneous pressure field arising from inhomogeneous current distribution. This makes it possible to reduce the duration of the voltage rise front on the electrically exploded interrupter and increase its amplitude.

At the same time, the maximum voltage level achieved in this series of experiments (189 kV) turned out to be approximately 25% lower than the calculated value (250 kV) obtained by numerical modeling of the electric explosion process in the approximation of an azimuthally homogeneous current distribution along a hollow cylindrical conductor with the same length, thickness and cross-section, tightly clamped (without a gap) between polyethylene insulators (curve *3* in Fig. 3, *b*). The calculation method is described in [5,6].

The design option of the interrupter with conductors H-pressed to the substrate was used to carry out experiments at the second stage.

The experiments of the second stage were carried out with storage with the inductance of 100 nH. Their task was to obtain empirical data on the characteristic rise time of the current in the load, and also to compare the levels of generated voltage in the case of filling the gap with glycerin and SF6 gas.

When using glycerol to fill the slot gap, the discharger G was set to breakdown at voltage of 135–140 kV (the thickness of the polyethylene between the tip of the needle electrode *4* and the anode *1* was 0.7 mm) in order to ensure that the inductive storage device is switched to the load until the voltage at the interrupter reaches the amplitude value of 189 kV.

When using SF6 gas, the breakdown voltage on the discharger was set at the level of 240–250 kV, close to the calculated maximum value of 264 kV for the above „ideal„ design of the interrupter with azimuthally homogeneous current distribution (curve *4* in Fig. 4, *b*). It was assumed that during the electrical explosion in SF6 gas environment the voltage on the interrupter could rise to

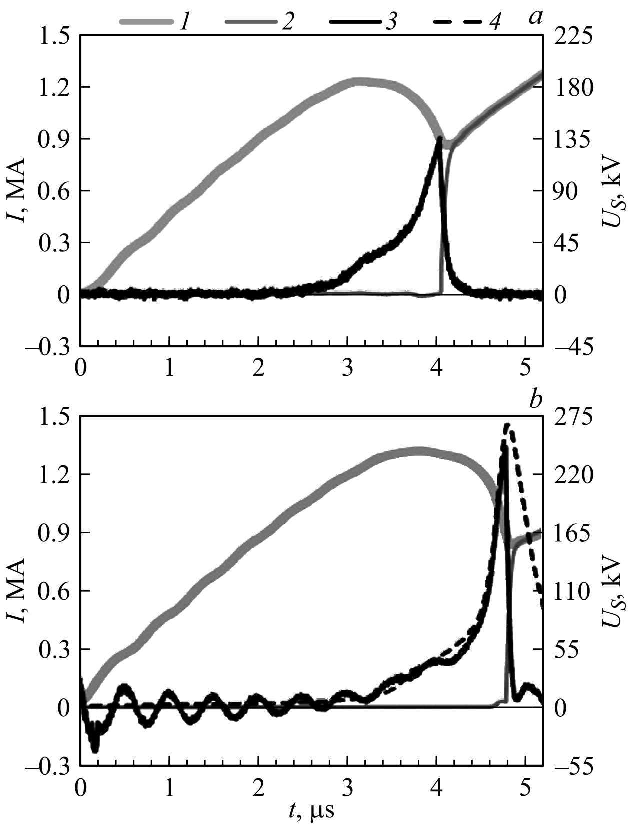

Figure 4. Curves of voltage pulses on the electrically exploded interrupter and currents in the inductive storage and in the load for the second stage experiments using glycerin (*a*) and SF6 gas (*b*): *1* — current I_i in the inductive storage circuit, *2* — current I_W in the load, *3* — voltage U_S on the electrically exploded interrupter, *4* — calculated voltage U_S on the electrically exploded interrupter with homogeneous current distribution.

this level, since SF6 gas to a lesser extent than a dense liquid medium prevents the expansion of the products of the electrical explosion, during which their conductivity decreases. At the same time, it has relatively high electrical strength, which prevents the development of breakdown that shunts the interrupter. Accordingly, the thickness of polyethylene between the tip of the needle electrode *4* and the anode *1* was increased to 1.1 mm.

Fig. 4 shows the restored from the signals of inductive transmitters curves of voltage pulses $U_S(t)$ on the electrically exploded interrupter and currents in the inductive storage $I_i(t)$ and in the load $I_W(t)$, obtained in these two experiments. Switching of the discharger during the electrical explosion of the interrupter conductors in glycerin occurred at voltage close to 137 kV (Fig. 4, *a*), during the electrical explosion in SF6 gas — at voltage of about 245 kV (Fig. 4, *b*). The characteristic time of the current rise in the load to level of 0.8 MA was about 110 ns for glycerin, and — 90 ns for SF6 gas.

From the comparison of the calculated and experimental graphs in Fig. 4, *b* and 3, *b* it follows that the best agreement between the experiment and the „idealized" calculation occurs in case of slot gap, in which electrically exploded elements are located, filled with SF6 gas. At the same time, for SF6 gas the voltage obtained at the electrically exploded interrupter turned out to be by maximum 7% lower than the maximum calculated value versus 25% deviation from the calculation for glycerin (note that the actual achieved voltage level for SF6 gas could exceed the value of 245 kV specified by discharger settings).

Thus, the proposed electrically exploded interrupter is capable of providing relatively high response and efficiency of current switching. At the same time, it has the advantage that, due to the radial layout and corrugated shape of the conductors, it creates the possibility of low-inductance connection to the load [5,6].

From formulas (1), (2) it follows that for a fixed ratio I_W/I_∞, the increase in the switched current does not result on change in the characteristic time τ_f of its increase in the load, if the ratio remains the same $L_i/R_{Sg}(L_i + L_W)$ due to the appropriate selection of parameters R_{Sg}, L_i and L_W. This allows you to increase the energy intensity of the source (switched currents) without loss of response of the switching system. In particular, use explosive magnetic generators.

The above model experiments with electrical explosion in glycerin were carried out in 2017 and 2018 , in SF6 — in 2021 .

In 2019 the electrically exploded interrupter of the type under consideration with glycerin filling paired with solid-state discharger [8] was used to switch to the load of the inductive storage with energy capacity of 2.4 MJ ($L_i = 75$ nH), powered from spiral explosive magnetic generator. The details of the experiment and the results are presented in the article [10], presented by a group of employees of the RFNC-VNIIEF. This experiment with the load of the inductance of 10 nH had shaped the current pulse rising to 5 MA for 120 ns. Thus, the possibility of forming current pulses in the multimegaampere range with submicrosecond rise time in low-impedance loads of inductive storage was demonstrated.

Conclusion

The presented results serve as experimental confirmation of the theoretically substantiated in papers [5,6] possibility of generating, with the help of electrically exploded interrupters, working in tandem with low-inductance closing switches, rapidly increasing current pulses of the megaampere and multimegaampere ranges (with characteristic rise time of up to 100 ns) in low-impedance loads of inductive electromagnetic energy storages.

In relation to the used interrupter design, taken from [9], the best result (minimum characteristic time of current rise in the load) is achieved when the following conditions are simultaneously met:

– manufacturing electrically exploded elements of the current interrupter in the form of thin strips of copper foil fixed on polypropylene substrate reinforced with reinforcing tape (used materials have thickness: foil — 15 μm, polypropylene substrate — 100 μm, cellulose reinforcing tape —60 μm);

– implementation of H-pressed discharge (the conductors of the electrically exploded interrupter are pressed into the polypropylene substrate when current flows);

– filling the slot gap, in which electrically exploded elements are installed between two polyethylene insulators, with glycerin or SF6 gas.

Under the conditions of the experiments performed, the use of SF6 gas made it possible to achieve the higher voltage level at the interrupter (its maximum resistance) compared to the electrical explosion in glycerin (245 kV versus 189 kV).

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Conflict of interest

The authors declare that they have no conflict of interest.

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