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Some possibilities for reducing erosion of the triggered vacuum switch ignition system

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The results and analysis of experiments are presented, the purpose of which is to search and study the possibilities of reducing the erosion of the triggered vacuum switch ignition system. The results indicate that the introduction of a compact limiting resistance into the ignition system of the triggered vacuum switch, which separates the cathode into two galvanically connected parts, makes it possible to spatially separate the area of operation of a high-current arc discharge from the ignition system. Thus, it is possible to significantly weaken the destructive effect of the arc discharge on the ignition system.

Keywords: vacuum arc, spark discharge, switcher, erosion.

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The effect of arc discharge in vacuum initiated by a control low-current short-term (spark) discharge has been widely used in electrical engineering for a long time. It gave rise to a whole class of switchboards — three-electrode triggered vacuum arresters [1,2].

Such arresters comprise two main electrodes (cathode and anode) and one control (trigger) electrode, which is separated from the cathode with a dielectric insert (mica). The combination of the cathode, dielectric insert and trigger electrode is usually called an ignition system of the arrester.

The specified arresters in miniature design found their application in high-voltage high-current circuits of high-capacity pulse electronics. They are able to switch the currents of kiloampere amplitude in a wide range of voltages inside a compact leak-tight casing of high strength. Their small dimensions (volume below $2\,cm^3$) and mass (usually below 5 g) make it possible to use such devices for fast switching of currents, including in highly aggressive conditions, for example under a strong mechanical shock or vibrations, possibly simultaneously with exposure to extreme temperatures [3]. The specified application provides for literally custom-made nature of making triggered spark arresters of miniature design. Therefore, their improvement is not caused by searching for the ways to expand the application capabilities, but is related to solving certain narrow technical problems. The number of the corresponding publications in the scientific periodicals is rather small.

Flow of the switching current in the vacuum cathode–anode gap of the arrester is coupled with functioning of cathode spots localized mostly near the dielectric insert. This causes the erosion of the specified areas of the cathode, erosion and dusting of the dielectric insert, which changes the conditions for the emergence of an auxiliary discharge along the dielectric surface in the ignition system [4,5]. As a result, the characteristics of arrester actuation (time delay in actuation, puncture voltage on the dielectric surface, resource etc.) change [1,6].

A method is known to reduce the erosion of electrodes, which is based on using the effect of arc discharge interaction with the magnetic field. Use of the magnetic field is an effective method, however, it suggests using permanent magnets, which substantially increases the dimensions of the systems, where the arresters are used, and in some cases the magnetic field would totally distort the operation of such systems [7,8]. Authors [3] used hard-melting materials with the same purpose: for example, the auxiliary spark discharge is executed on the surface of the ceramic (corundum) isolator. Besides, the developers in some cases refuse to use the auxiliary discharge in favor of laser ignition. In this case the switching arc discharge emerges in the torch of laser plasma formed under the action of the focused radiation of the pulse laser on the surface of, for example, cathode [9–11].

The objective of this paper — to search for and study new options for reduction of erosion of the triggered vacuum arrester ignition sistem.

The possible solution to reduce the ignition system erosion is use of two spatially separated interelectrode gaps with galvanic uncoupled cathodes. The first of them — the main switched gap, the second — the ignition system. The main gap is closed by ionization of residual gas by a flow of fast electrons and emission from the auxiliary spark discharge in the ignition system [12]. However, in this option it is possible to increase a pause between the control discharge in the ignition system and the start of the arc discharge in the main gap due to-reduction of the fast electron flow density and emission [12]. This paper proposed the option with inclusion of the resistor between the two used cathodes. In this case at the first stage one may expect a puncture and fast development of the spark

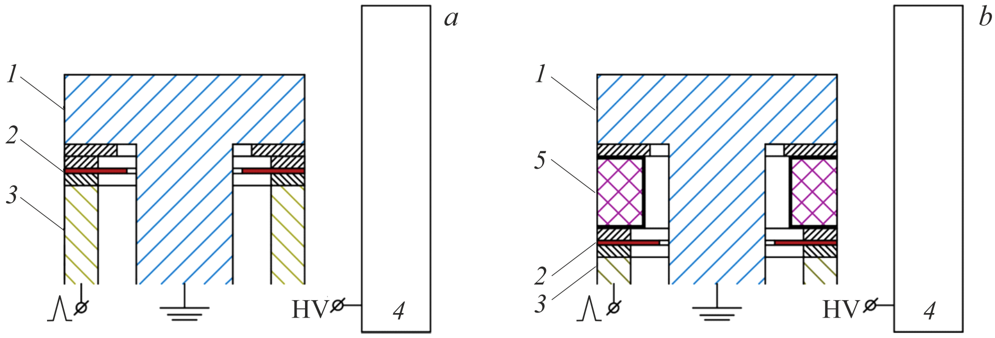

Figure 1. Schematic image of the ignition systems used in the experiments, their location together with the anode for photography. *a* — regular ignition system: *1* — cathode, *2* — dielectric insert, *3* — trigger electrode, *4* — anode. *b* — ignition system with modification: *1* — cathode, *2* — dielectric insert, *3* — trigger electrode, *4* — anode, *5* — bead resistor (the bold line shows the areas of application of the conducting metal film with the specified resistance).

discharge on the dielectric surface in the ignition system due to the charge accumulated in its capacitance. As a result of the fast electron emission, in the first instance, from the surface discharge and ionization of the residual gas by the electron impact [12], the primary conducting medium will occur in the cathode–anode gap. The resistor limits the force of current flowing in the gap between „the first" cathode that participates in the flowing of the auxiliary spark discharge, and the anode, and provides for the support of high voltage in the gap between „the second", short-circuited grounded cathode and anode. Therefore, the conditions will be created for the appearance of the cathode spot on the surface of the short-circuited grounded cathode. Further the second stage of the switching process will come. Development of the spark discharge in the main gap will provide for the quick spreading of the plasma torch from the short-circuited grounded cathode to the anode thanks to the mechanism of ambipolar diffusion. Therefore, the development of the spark discharge will be provided, which may short-circuit the switched circuit.

A rather simple and reliable method to create a compact resistor is formation of a film with the specified parameters on the dielectric surface. At the same time it should be taken into account that the specified structural element will be located near the region of the arc discharge, but must not be exposed to it. Otherwise such exposure will inevitably result in the damage and change in the characteristics of the film resistor.

When the limiting resistor is included in the ignition system, the voltage applied from the high-voltage generator will be divided between the capacitance of the ignitor gap ans the limiting resistance. The division coefficient will be determined by the ratio of the values of reactive resistance of the gap (Z_c) and added resistance R_{lim}. For the puncture to happen, móst supplied voltage must cover the ignitor gap:

$$Z_c \gg R_{\text{lim}},$$

$$Z_c = \frac{1}{\omega C} \approx \frac{\tau}{C} \approx 10^4\,\Omega,$$

where $\tau \approx 10^{-7}$ s — puncture duration in the ignition system, $C \approx 10^{-11}$ F — capacitance of the ignitor gap (depends on the thickness and material of the dielectric insert). Therefore, $R_{\text{lim}} \ll 10^4\,\Omega$. This condition will be met by the resistance value $\sim 1000\,\Omega$ and below, in this case its voltage at the average puncture voltage 2 kV will not exceed 200 V, which will make it possible to use such compact resistance and at the same time will reduce the value of current flowing through the cathode located near the dielectric bead, approximately 1000 times at the stage of the arc discharge burning.

Experimental testing of the above scheme of discharge diversion was done using photography of the discharge in the gap between the cathode and the anode. Besides, the ignition system erosion pattern was analyzed by visual evaluation of the extent of erosion damage to the ignition system elements using a stereoscopic microscope. The corresponding experiments used both a reference mock-up with a regular ignition system, which includes a single cathode, and a mock-up with two cathodes galvanically coupled via a resistor. Both mock-ups were made as geometrically similar structures (fig. 1).

The ignition system had a coaxial configuration. The resistor — is a thin film formed in the inner surface of the ceramic bead (fig. 1, *b*). The anode is flat. The thickness of the dielectric insert in the ignition system is 0.1 mm. The electrode material — is aluminum alloy, therefore rather hard-melting metal (covar) inserts were used, directly between which the dielectric insert was pressed, and which provided for the stable actuation of the ignition. The aluminum alloy as the electrode material was selected because, first of all, it provides a clearly observed relief pattern of erosion. Second, it provides high thermal speed of ions in the discharge and, accordingly, high speed of cathode torch spreading. Besides, the high thermal speed of ions means high speed of ion sound, and this circumstance contributes to stabilization of the discharge at the spark stage [13]. The discharge device was placed in the vacuum chamber pumped to pressure of 0.1–1 Pa.

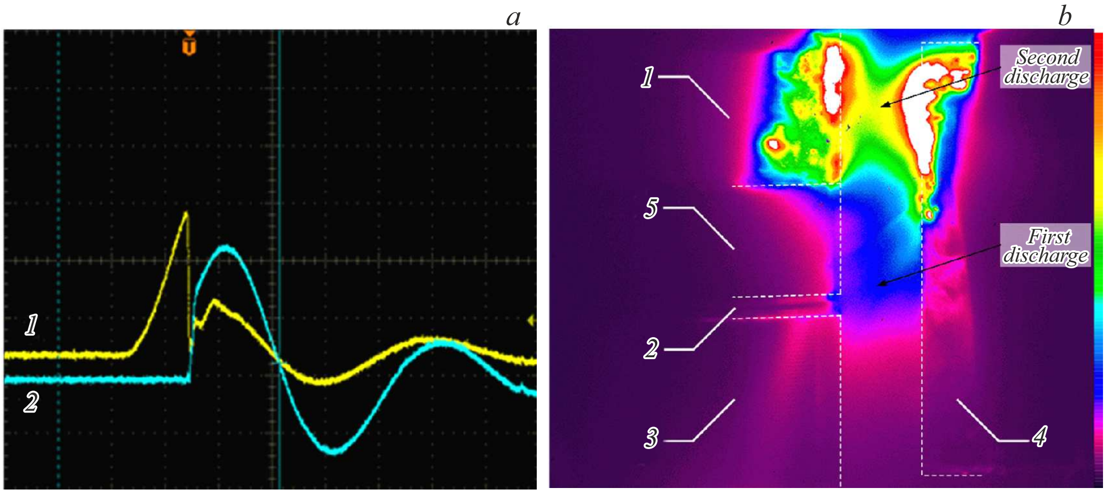

Figure 2. *a* — oscillograph charts of signals recorded in the experiment. Trace *1* — voltage in the cathode–trigger electrode gap, trace *2* — current in the cathode–anode gap. Sensitivity: trace *1* — 1 kV/div, trace *2* — 2 kA/div. Sweep 400 ns/div. *b* — image of discharge in the gap between the anode and the ignition system with modification. *1* — cathode, *2* — dielectric insert, *3* — trigger electrode, *4* — anode, *5* — bead resistor. The dashed lines show the borders of the discharge device parts. The frame exposure exceeds the discharge duration substantially. When moving from the bottom to the top along the color scale shown on the right, the radiation intensity increases. A color version of the figure is provided in the online version of the paper.

The anode prior to the start of the switching process was under constant potential +3 kV. With the purpose of current registration in the switched circuit, a low-inductance resistor with resistance 0.1 Ω was included therein. The switching process started when the pulse of the positive polarity potential with amplitude of 5 kV was supplied to the trigger electrode. The voltage in the ignition system was measured using a resistive voltage divider. The currents and voltages were recorded using digital oscilloscope Wavesurfer 510R (Teledyne LeCroy). The auxiliary spark discharge had the duration of 30–50 ns and amplitude of 10 A. Under such conditions, an arc discharge developed in the vacuum gap with amplitude of sinusoidal current of 5 kA and the period of 1.6 μs (fig. 2), which was photographed using high-speed video camera OPHIR Spiricon BGS-USB-SP928-OSI through a sight glass of the vacuum chamber in the spectral range of 190–1100 nm with frame exposure of 60 μs. The frame exposure time substantially exceeded the duration of the discharge, which made it possible to record the image of the discharge region for the time of its occurrence. Fig. 2, *b* shows one of the recorded discharge images. The color shows the spatial distribution of the relative fluence of the emission energy, emitted by the discharge plasma or, in other words, the average intensity of the emission sources for the time of the discharge.

The given image (fig. 2, *b*) shows that in the space between the ignition system and the anode there are two burning discharges: the first one — the discharge between the cathode located between the dielectric insert, and the anode in the lower part of the system, the second one — the discharge between the cathode located above the bead resistor, and the anode in the upper part of the system. In general the average intensity of the second discharge emission by duration clearly exceeds the similar parameter for the first one, which is in favor of the preferable energy release in the second discharge. The similar pattern of the discharge flow was observed in every subsequent switching. In its turn, when the discharge was photographed with the regular ignition system in use, as previously [12], the discharge coupling to the cathode regions was observed near the mica bead. It should be noted that no changes were seen in the amplitude-time characteristics of the recorded oscillograph charts (fig. 2, *a*). Localization of the erosion traces on the elements of the used ignition systems (fig. 3) fully confirms the results obtained by the discharge photography. For the mock-up with a single cathode, substantial erosion of the cathode is observed on the border with the dielectric insert as the confirmation of the coupling of the cathode spots thereto in the switching arc discharge (fig. 3, *a*). For the mock-up with the modified discharge device (i. e. with the two cathodes isolated by the resistor) the erosion of the cathode in the ignition system is nearly absent. Substantial erosion of the cathode in the main gap is observed, with the erosion in the region adjacent to the ceramic bead (bead resistor in fig. 3, *b*) being most prominent. Therefore, the erosion pattern also confirms the realization of the expected mode with the discharge diversion in the main gap from the ignition system to the area spatially remote from the ignition system.

The experiments demonstrated that inclusion of the resistor into the arrester ignition system made it possible to spatially separate the area of the auxiliary spark and main arc discharges. As a result, the damaging effect of the switching arc discharge at the ignition system substantially

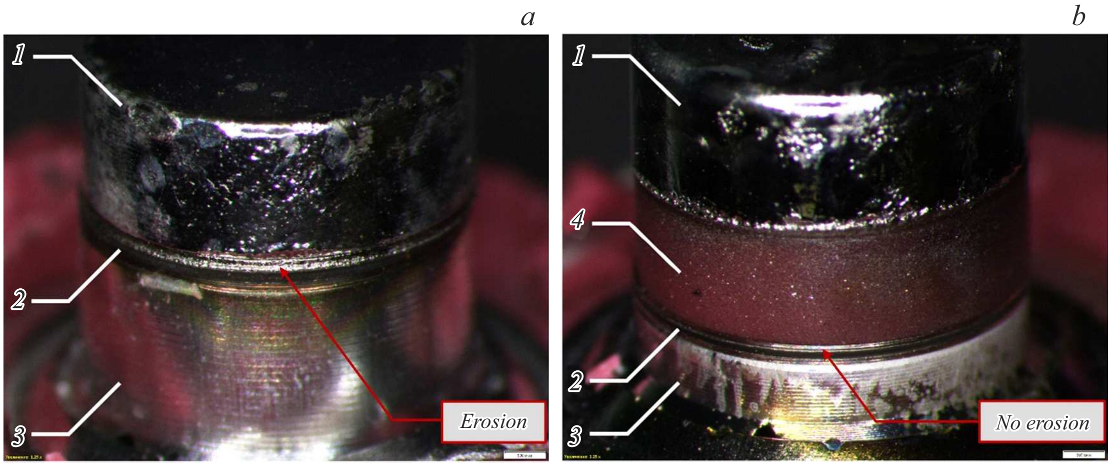

Figure 3. Patterns of ignition system erosion. *a* — regular ignition system: *1* — cathode, *2* — dielectric insert, *3* — trigger electrode. *b* — ignition system with modification: *1* — cathode, *2* — dielectric insert, *3* — trigger electrode, *4* — bead resistor. In the regular ignition system the surface of the metal bead located above the dielectric insert *2* is badly molten, in the ignition system with modification no melting of this bead is seen, which confirms the reduction of the ignition system erosion.

decreases, and the time parameters and the amplitude of the switched current pulse are maintained.

Conflict of interest

The authors declare that they have no conflict of interest.

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