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SWTICHING CHARACTERISTICS OF EXPLOSIVE DISCONNECTORS WITH RAPID DESTRUCTION OF THE CONTACT ELEMENT

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The extension of the range of application of inductive stores, including their use to obtain high-power electron beams and to supply plasma-dynamic systems with energies greater than 1 MJ, involves the design of ultra-low-resistance ($\sim 10^{-6}$ Ω) switches for power levels of 10^{11}-10^{12} W and switching rise times of 10^{-6}-10^{-7} sec. It would seem that such switches can be designed using the principles of the rapid destruction of a contact element by an explosive charge [1, 2]. However, a number of problems arise in this direction which can only be solved experimentally:

1) What should the length of the destroyed part of the contact for a given switching voltage be, and how does it depend on the current and geometry? The so-called "cold" characteristics (without turning off the current) of the electric strength of the products of the explosion in the area of the destruction obtained at the present time are not altogether suitable for choosing the length of the contact element. There are practically no data on the value of the switching voltage when currents of greater than 10 kA are switched off.

2) What is the minimum switching time determined by the interaction between the explosion products and the arc which occurs at the points of destruction?

3) The relation between the ratio of the masses of the explosive charge M_S and the contact junction m, $\alpha = m/M_S$, and the switching power for a given thermal stability of the current-carrying elements. The parameter α, which defines, on the one hand, the nature of the destruction and the velocity of separation of the fragments of the contact element and, on the other hand, the technological quality of the construction, is related, in the final analysis, to the absolute dimensions of the expanding region, in which the pressure of the explosion products differs only slightly from the pressure in the detonation wave. If to ensure the required explosive power the value of α is too large, the advisability of using this technique under laboratory conditions becomes doubtful.

There are also other problems, without the solution of which it is difficult to determine the practical possibility of designing high-speed high-voltage breakers.

In this paper we present the results of a study of the switching characteristics of some versions of explosive switches (ES) with rapid destruction of the contact element.

The characteristics of the explosive switches were studied using the arrangement shown in Fig. 1. The energy source was a capacitor battery supplying an inductive store L_S through an explosive switch. A load R_H with an inductance L_H was connected in parallel with the explosive switch. At the instant when the current reaches a value I_{max}, the explosive charge is detonated in the switch and the current in the load circuit is interrupted. The currents in

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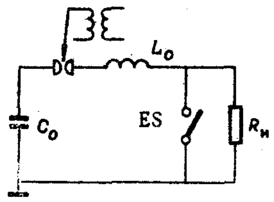

Fig. 1

TABLE 1

Type	Inductive store, mH	Switching current, kA	Load parameter Ω, μH	Plug material	Oscillogram number
ES-1	0,8	0,8	0,7; 0,17	Plasticfoam PTFE Copper	
ES-2	1,2	33	0,16; 3 0,32; 3	Copper	Fig. 2d
		53	0,32; 3 0,16; 3		Fig. 2b
ES-3	0,1	18	0,1; 1		Fig. 2a
			0,4; 1	PTFE	Fig. 2c

the circuits were measured with Rogovskii loops, and the voltage was measured with a low-inductance divider.

We examined three versions of the explosive switch (see Table 1). In them the contact element was made of Duralumin D16T. We used plasticized hexogen with a density of 1.6 g/cm^3 and a detonation velocity of $7.5 \cdot 10^5$ cm/sec as the explosive charge.

In the first version of the switch (ES-1) the contact element was made from a tube of diameter 40 mm and length 36 mm. The explosive charge had a diameter of 36 mm and a length of 14 mm and was closed at the ends with plugs of different materials. In the second version (ES-2) the contact element was made from a tube 66 mm in diameter and 48 mm long with an internal conical cut of width 14 mm and an angle of 120° at the vertex. The explosive charge completely filled the volume of the cut. The third version (ES-3) was a section of tube of diameter 26 mm × 24 mm and length 25 mm containing a PTFE insert with an opening 10 mm in diameter filled with the explosive charge. The electrical detonator was placed in the open end. On the external side of the insert at distances of 15 mm from one another ring flow channels of semicircular profile and radius $\rho = 2.5$ mm were constructed.

The velocity of motion v_d of the destroyed part of the contact element was estimated using the empirical relations given in [3]. The conditions under which the experiments were carried out and the number of the corresponding oscillograms are shown in Table 1, and the oscillograms themselves are shown in Fig. 2a-d (in Fig. 2a, curve 1 is the current through the breaker, and curve 2 is the current through the load, 10 kA/cm, 50 μsec/cm; in Fig. 2b, the curve represents the current through the breaker at the instant when switching starts, 10 kA/cm, 25 μsec/cm; in Fig. 2c, curve 1 is the current through the breaker and curve 2 is the current through the load, 29 kA/cm, 50 μsec/cm; and in Fig. 2d, the curve represents the current through the breaker at the instant when switching starts, 11.5 kA/cm, 25μsec/cm).

It follows from the results obtained that:

1. At currents up to 1 kA the switching time τ_k of ES-1 lies in the range from 5 to $8 \cdot 10^{-6}$ sec. The maximum velocity v_d of the shell in the middle part is $2.2 \cdot 10^5$ cm/sec. The value of τ_k depends on the amount of explosion products blowing through the destroyed part. This amount is controlled by the mass of the plugs. The value of τ_k is a minimum in the case of copper plugs. An increase in the impedance of the load Z_n simultaneously with an increase in the switching voltage U_H up to 10 kV results in τ_k increasing to 10 μsec. It was also established that the switching process changes when a layer of air of thickness 10 mm is introduced between the explosive charge and the walls of the tube. In this case, together with a reduction in v_d to $1.4 \cdot 10^5$cm/sec, there is also multistage switching with a considera-

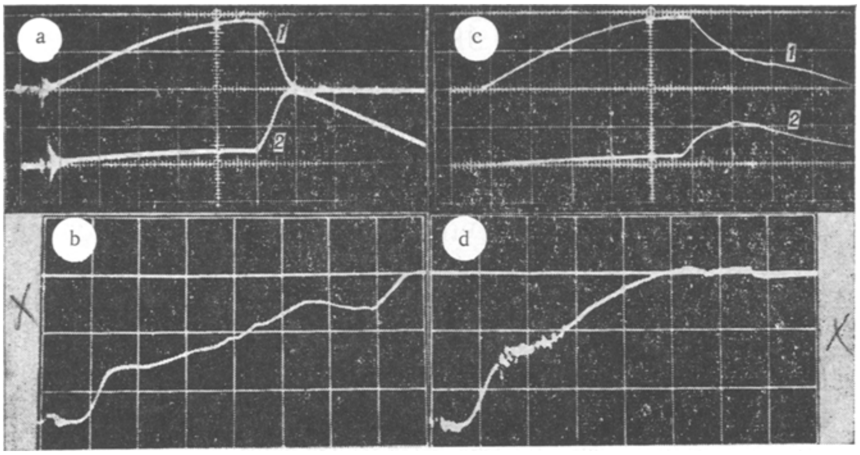

Fig. 2

ble increase in τ_k and weak reproducibility. In addition, the reduction in the parameter α in the ES-2 switch due to the increase in the diameter and thickness of the tube leads to a reduction in v_d to $1.8 \cdot 10^5$ cm/sec and to an increase in τ_k to 9 μsec for U_k = 2.5 kV and to 25 μsec for U_k = 10 kV.

2. Experiments with ES-2 at currents of several tens of kiloamperes showed a considerable increase in τ_k, which changed the nature of the switching process. For I = 33 kA and U_k = 5.5 kV two switching stages were observed: the first with $dI/dt \simeq 10^9$ A/sec of duration ~15 μsec up to the instant when $U_n \simeq 3.0$ kV, and the second with $(dI/dt)_{max} = 4 \cdot 10^8$ A/sec. The total switching time reached 50 μsec. An increase in U_k up to 11 kV had practically no influence on the first stage ($dI/dt \simeq 10^9$ A/sec, 5•10 μsec). In this stage after 5•10 μsec, the drop in current ceased, and the current was then switched very slowly ($dI/dt < 3 \cdot 10^8$ A/sec). In a number of cases, time switching of part of the current in the ES-2 circuit was observed.

However, in all the experiments current switching from the ES-2 circuit into the load circuit occurred, although with a considerable spread in τ_k. For I = 53 kA and U_k = 9 kV the characteristics of the first stage did not undergo any changes, but the stage when the switching process was interrupted with U_H = 3 kV increased sharply up to 30-40 μsec. The subsequent slow switching of the current into the load varied in the same way as the slow reverse switching of the main part of the current in the ES-2 circuit.

3. Switching of the current I = 18 kA using the ES-3 having a dielectric filler of PTFE occurred with $dI/dt = 6 \cdot 10^8$ A/sec in 30 μsec. An increase in R_H to 0.4 Ω led to a situation where switching practically ceased after switching about half the current into the load in a time of approximately 60 μsec. On a high-speed photograph of the process in the first mode one could see initially intense illumination in the circulation region. Then an arc appeared, burning the products of the explosion at the boundary in approximately 60 μsec. In the second mode several arcs, which combined into a single channel, appeared.

The experimental results obtained enable the following conclusions to be drawn. Rapid switching occurred in the initial stage of the destruction when the disconnecting arc burned the rapidly spreading products of the explosion at the boundary with a pressure of ~10^5 atm. In this time interval the length and surface of the arc discharge burning on the external boundary of the dispersing gases increase with high velocity. However, because of the sharp fall in pressure ($p \sim r^{-8}$) for spherical dispersion, it is possible for an ionization wave to propagate and for a current to appear inside the region filled with the products of the explosion. Hence, the velocity of expansion of the arc should be reduced and the switching speed correspondingly decreased. At high switching voltages thermal instability is probable at this stage, giving rise to spreads and persistence of the switching process.

A more complex picture is observed when there is an air layer between the explosive charge and the thickened shell. In this case destruction occurs not due to the pressure of the detonation wave, but due to the pressure of the compressed and heated multiple transit of the shock wave of the air layer, which simultaneously constricts the expanding products of the explosion. As a result, the shell is destroyed by pressures less than the pressure of the detonation wave and hence the velocity of flight of the fragments and the switching speed are reduced. The switching instability which was found is obviously due to the fact that in the initial stages of the separation the arc burns in a strongly heated layer of air which is at first expanding nonspherical, since $\Delta r \ll r$. This affects the uniformity of the azimuthal current distribution and, correspondingly, the switching process.

The value of α has a considerable effect on the switching speed, since it determines the velocity of separation of the fragments and the expansion of the explosion products in the initial stages. This is seen particularly clearly in experiments with the ES-2, where the value of α varied more than twofold. A feature of switching currents of tens of kiloamperes is the fact that the switching has a gradual nature. It is somewhat weak at switching powers up to $2 \cdot 10^8$ W. At higher powers the multistage nature of the process is more pronounced.

It is noteworthy that irrespective of the length of the destroyed part of the contact element of the switched current and the low resistance, the first switching stage occurs with the same speed. Then after the same time interval in all modes this speed falls sharply until switching is completely interrupted. The switching interruption interval and the subsequent development of the process depend on the geometry of the switch and the switching parameters. At the present time, it is difficult to determine the specific physical reasons for the observed multistage nature of the switching. However, it is obvious that to obtain high switching powers it is necessary to make a careful choice of the mechanical characteristics and parameters of the load circuit.

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