EXTINCTION OF AN ELECTRIC ARC BY MEANS OF EXPLOSIVES

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The use of explosives for tripping heavy-current circuits allows the switching-off time to be reduced considerably. Designs for explosive trips having a triggering time of 10 sec for currents of 100 kA are described in [2]. It is stressed that a large part of the total switching-off time is comprised by the time of extinction of the electric arc, resulting from breakage of the current-carrying busbar. Because of this, a study of the arc extinction process by means of the explosion products becomes necessary in order to create more efficient explosive switches. The interaction of the shock waves with the electric arc plasma is also of independent interest.

In this paper, experimental data which have been obtained during the extinction of electric arcs at currents of 0.5 to 3.0 kA by means of explosives are presented. It is shown that the extinction of an electric arc is effected by the shock waves, and in the initial stage the increase in resistance is determined by the compression of the arc in the shock front. The results of the investigations can be used for the design of explosive contact-breakers, operating without destruction of the current-carrying busbars.

Contact breakers which use explosives in the electric arc extinction process are affected by such factors as destruction and dispersion of the current-carrying busbars, the origination and development of an arc discharge, and interaction of the arc with the shock waves and with the detonation products.

In the experiment, we carried out the extinction of a developed arc burning between fixed electrodes (Fig. 1), which permitted the effect of the shock waves and detonation products on the process to be investigated (other factors having only a very slight effect).

The electric arc 1 was struck between the electrodes 2 connected with a discharge circuit (C = 280 μF, L = 3 μH, and R = 0.7-2.9 Ω). The value of the current in the circuit was varied by varying the initial potential on the capacitor and by the resistance R.

Extinction was effected by means of explosive 3, placed in a steel case 4 at a distance of 20 mm from the axis of the electrodes, the diameter (thickness) of which was equal to 6 mm; the fixed distance between the electrodes was 14 mm. The current in the circuit and the voltage across the gap were recorded by means of compensation probes on an OK-25 oscilloscope. Simultaneously, the process was recorded by Töpler photography on a streak camera. The extinction time was reckoned from the start of the current drop until it reached the oscilloscope zero. We used PETN powder as the explosive. The mass of the charge did not exceed 1 g.

Cylindrical Electrodes

Figures 2 and 3 show a characteristic oscillogram (upper trace — voltage across the gap; lower trace — current in the circuit) and photograph of the process in which the formation of the arc 1 and the position of the shock wave 2, 4 and the detonation products 3 can be traced. The wave (see Fig. 3) resulting from detonation of the explosive is being propagated through the undisturbed air with a velocity of 5.6 km/sec in the direction of the charge axis. Near the boundary of the arc it is accelerated to a velocity of 10 km/sec, moving through it with almost constant velocity; at the boundary with the air, the wave decelerates again. A luminous region, identified with the current-conducting channel, follows behind the shock front and, as the framing photographs show (Fig. 4), assumes the shape of the latter. As a result, the length of the arc is increased and its spot is freely displaced along the lateral surface of the electrodes. The experimental data are given in Table 1, where τ_1 is the time

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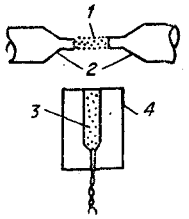

Fig. 1

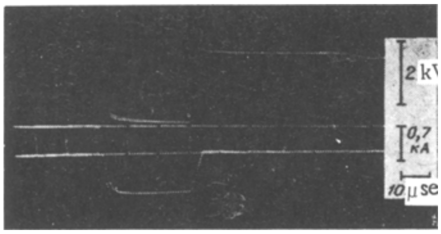

Fig. 2

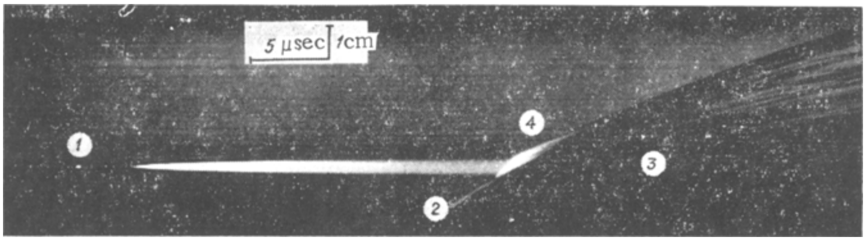

Fig. 3

of extinction and D_1 is the shock-wave velocity in air. The use of insulation makes the displacement of the spot difficult and leads to a reduction in the time of the process by approximately 25%.

The pattern described occurs for currents which are smaller than a certain critical value that depends on the resistance of the circuit. For large currents, the nature of the process changes. At a time close to the emergence of the shock wave at the arc–air boundary, in the vicinity of the current-carrying channel a breakdown originates, which evolves into a new current-carrying channel, subsequently driving a considerably slower wave front and leading to a rapid extinction of the first one. The extinction time in this case is increased by approximately an order of magnitude and is found to be dependent on the velocity of the shock wave. With increase of the latter, it decreases.

In the region of the electrodes, the shock front and the explosion products follow one another at a distance of 5 mm; therefore, it is not possible to separately distinguish the effect of each on the process. The necessary data were obtained during a series of experiments in which the charge was located at a distance of 45 cm from the axis of the arc. In order to reduce damping because of lateral discharge, the flow toward the discharge gap was directed inside an indestructible steel tube. At the start of the interaction with the arc, the explosion front was in advance of the products by 10^{-5} sec.

It was established that for the same shock-wave velocities, the current decay time was almost unchanged. Interaction of the wave led to a brief extinction of the arc, in consequence of which breakdown of the gap occurred ahead of the explosion products.

"Oblique" Electrodes

Extinction of the arc with less than critical currents was investigated on oblique electrodes (Fig. 5). The experiments show that the nature of the process depends on the aperture angle of the electrodes α. Thus, for $\alpha > 40°$ it is almost the same as in the experiments with cylindrical electrodes. For $\alpha \leq 40°$, the current-carrying channel is moving together with the shock front, having retained the original parallel position. The extinction times τ_2 at "oblique" electrodes are given in Table 1. It is characteristic that $\tau_2 > \tau_1$. Furthermore, Table 1 gives the length of the arc l before extinction. It is significantly increased with increase of the tripping current, but increases slowly with increase of the shock-wave velocity.

It should be noted that extinction takes place even without increase of length ($\alpha = 0$), and the time of the process in the range investigated increases together with the shock-wave velocity. For example, for a current of 500 A and D_1 = 4.2, 5.2, and 6.1 km/sec, τ_2 = 2.9, 3.4, and 3.1 μsec, respectively.

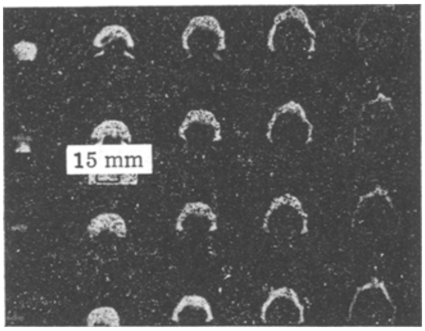

Fig. 4

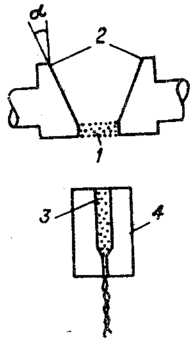

Fig. 5

TABLE 1

I, A	D_1, km/sec	τ_1, μsec	τ_2, μsec	l, mm
1300	6,0	5,3	6,1	38
	5,2	6,1	6,8	36
	4,1	7,7	9,0	40
1000	6,1	4,1	4,8	32
	5,3	5,1	5,0	30
	4,4	4,8	5,3	29
700	6,2	3,2	3,8	29
	5,1	3,5	4,0	27
	4,2	3,7	4,2	26
500	6,1	2,7	3,5	25
	5,3	2,9	3,3	24
	4,3	3,0	3,2	22

Rectangular Channel

In order to reduce the effect of the considerable lateral loadings in the shock wave, the arc can be extinguished successfully in a rectangular channel (1.5 cm × 1.5 cm × 12 cm) formed by plane electrodes (copper) and insulators (plastic). With currents which are less than critical, the nature of the process is almost the same as in the experiments with "oblique" electrodes ($\alpha = 0$), and with large currents, breakdown and multiple flare up of the arc moving subsequently with mass velocity behind the front occur in the vicinity of the current-carrying channel, whereupon the arc travels with the post-shock particle velocity. The resistance of the gap in this case is 0.7–1.0 Ω, which is an order of magnitude greater than the initial resistance. Total extinction of the arc occurs after emergence from the channel.

On the Töpler photograph (Fig. 3), after the explosion of the conductor, the formation and development of the current-carrying channel of the arc and the motion of the cylindrical shock waves originating in this case can be seen clearly. At the instant of the start of extinction, the development of the channel is completed and its dimensions are only slightly changed. Judging by the oscillogram (see Fig. 2), an almost constant current flows in the arc. The diverging cylindrical waves are moving at this time with a velocity approaching that of sound, and, therefore, the absence of a marked movement of gas leads one to assume that the pressure in the region enveloped by the waves is close to atmospheric. The temperature in the channel [$(9\text{–}10)\cdot 10^3$ °K] is estimated by the average electrical conductivity on the assumption that the main current flows through the luminous part of the arc; according to [4, 5], 90% of the current flows through this region. With the parameters mentioned, the mean free path of the electrons is determined by their scattering at ions; i.e., the arc plasma can be assumed to be strongly ionized, and the electrical conductivity is $\sim T^{3/2}$, neglecting the logarithmic dependence on the density.

In the experiments, the velocities of the shock waves formed by the explosion of explosive charges varied from 4.1 to 6.2 km/sec, which corresponds to pressures, temperatures, and mass velocities varying within the limits of 100–440 atm, 5400–8900°K, and 3.7–5.7 km/sec, respectively [6]. Recording of the shock waves was effected by the self-luminescence which originated at the shock front and was damped in the relief wave formed because of the nonuniformity of motion.

In the region of change of gas density from almost normal ρ to the density in the arc ρ_1, a gradient acceleration of the shock wave of a stepwise nature occurs. We shall consider this region as the interface surface. When the discontinuity collapses at this surface, a shock wave which moves through the ionized gas and a rarefaction wave which propagates upward through the stream are formed. The almost constant velocity of the front in the arc plasma confirms the weak dependence of the gas parameters on the coordinates.

At the wave front, if we disregard its structure, the electrical conductivity together with the temperature undergoes a discontinuity. Estimates and a numerical calculation for the plane case with the equation of state $E = 8.3\ (T/10^4)^{1.5}(\rho/\rho_1)^{0.12}$ eV/mole, taken from [7] on the assumption that thermal equilibrium is established instantaneously, show that the temperature, because of additional ionization of the gas, increases by a factor of approximately 1.5 for the velocities observed in the experiments, causing at most a twofold increase of the electrical conductivity. This increase in the electrical conductivity cannot compensate the decrease in the cross section of the current-carrying channel due to compression (which, depending on the initial current in the circuit and the velocity, varies from 4 to 10). This explains the fact that the resistance of the arc starts to increase almost simultaneously with the refraction of the wave at the interface surface.

In the plane case, this pattern of the process should give a reduction of the conductivity which is linear with time (since the velocity of the front is constant). Figure 6 shows its dependences on time for currents of 1.3 and 2.0 kA with a plane channel. On the greater part of the graph, the decay can be assumed to be linear, the significant differences at the beginning and end of the graph probably being due to nonuniformity of the process. The electrical conductivities calculated by Fig. 6, using experimental and measured parameters, give its increase as a factor of 2 to 2.5, which coincides with the estimates by temperature.

On passing to the second interface, a refraction wave is formed, observed in the experiments and, as estimates and a numerical calculation show, also a reflected wave leading to further compressionof the arc and an increase of its resistance. The refracted wave travels with a velocity which is somewhat less than the initial velocity.

Subsequently, the gas-dynamic pattern should be as follows. The interface separating the air compressed in the refracted wave from the current-carrying channel moves with the post-shock particle velocity. The temperature difference at the interface is $\sim 10^4$ °K, which should lead to its diffusion. The reflected wave, on being alternately reflected from the interfaces, will continue to constrict the arc.

It should be mentioned that in the experiments this pattern is not observed. The current-carrying channel starts to follow immediately behind the front of the refracted shock wave. It is not possible in every case to distinguish its luminosity from the luminosity in the front. Moreover, considerable emission of the channel is observed at those places where the shock conversion in the experiments without extinction is almost nonluminous. The conducting zone in this case is found to be bounded from one side by the wave front and, obviously, from the other side by the gas cooled in the rarefaction wave, resulting because of the nonuniformity of the motion. This behavior of the arc during interaction with the shock wave leads to a continuous exchange of gas in the current-carrying channel. Together with the flow of gas through the conducting zone, there is also a flow of energy. The excess of the energy dissipation over the power of its extraction from the circuit causes extinction of the channel.

The gas-dynamic pattern considered, which is close to one-dimensional, coincides qualitatively with the experimental results. In particular, the increase of the wave intensity reduces the flow of energy in the case of an unchanged length of the arc and increases the extinction time. An increase of the length of the channel in the case of cylindrical and "oblique" electrodes increases the flow, which leads to an acceleration of the process.

Extinction of the current-carrying channel is accompanied by the recombination of charged particles, because of which the need arises to consider the role of nonequilibrium recombination radiation.

According to [7], the mean free path of quanta in the case of bound—free transitions for our densities are of the same order as the size of the compressed shock-wave channel; there-

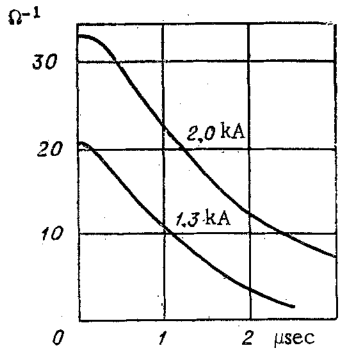

Fig. 6

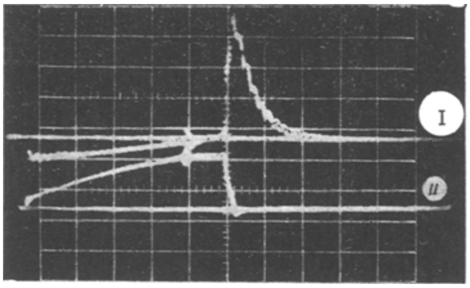

Fig. 7

fore, we shall assume that the radiation is untrapped. When estimating the power of the radiation, we shall suppose that initially the shock wave converts the arc plasma into a new thermodynamic state, corresponding to equilibrium behind the front, and that then recombination of all electrons at the ground levels in the atoms occurs. For the parameters of the gas specified above, with a wave velocity of 10 km/sec, the emission power of the arc in nitrogen is 10^6 W. Hydrogen-like atoms, existing under similar conditions, radiate 10^6–10^7 W [7]. The emission power of air in the thermodynamically equilibrium state (with a density of 10^{-3} g/cm^3 and a temperature of $25 \cdot 10^3$ °K) amounts to $1.2 \cdot 10^6$ W [8].

Estimates carried out show that when considering the energy balance in the arc compressed by the shock wave, the radiation cannot be neglected, since its power is found to be of the order of that released in the channel. Moreover, under certain circumstances, radiation can play the decisive role. For example, if a rigid wall is placed above the arc in a plane channel, then the gas flow together with the conductive transfer of energy through the current-carrying channel will be nonexistent. Despite this, extinction in this arrangement is observed with currents of >3 kA (the critical current without the wall is 1.8 kA). In this case, it is obviously the radiation which is responsible for extinction. The fact that the current-carrying channel is moving immediately behind the wave front also can be explained by radiation. Radiative thermal conductivity in this case must provide a velocity of the boundary of heating of 500 m/sec relative to the gas, since when D_1 = 5.6 km/sec in air, the mass velocity u = 5.07 km/sec [6]. A power of 10^6–10^7 W is necessary to provide a velocity of 500 m/sec.

As already said above, with larger than critical currents the process is of another nature. After refraction of the shock wave at the second interface, a breakdown originates near the constricted arc and evolves into a new current-carrying channel moving with the particle velocity. The breakdown occurs because during the decay of the shock wave at the first interface, a rarefaction wave is propagated upward through the flow. If we assume that the region of constant solution with the gas parameters of the previous rarefaction wave adjoins the arc, then we obtain for the density a value close to normal, and the temperature will be of the order of $4 \cdot 10^3$ °K. Furthermore, according to [8], with this density the electrical stability of the air falls strongly, starting from $2 \cdot 10^3$ °K. It is characteristic that in our experiments breakdown occurred at a voltage of 1.3 kV, almost independently of the initial current in the circuit.

It follows from what has been said above that the squeezing of an electric arc by strong shock waves can be used effectively for switching currents. Figure 7 shows an oscillogram of the switching process of a current of 18 kA (trace II, time base 25 μsec/div.) from an inductive storage element with L_1 = 13.6 μH into a load of R_1 = 1.09 Ω (trace I, 3.9 kA/div.). The maximum voltage on the gap of length 14 mm at the instant of extinction of the electric arc was 20 kV.

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LITERATURE CITED

1. P. I. Zubkov and L. A. Luk'yanchikov, "Tripping heavy-current circuits by means of explosives," Fiz. Goreniya Vzryva, No. 3 (1973).

2. A. E. Voitenko, V. I. Zherebnenko, I. D. Zakharenko, V. P. Isakov, and V. A. Faleev, "Tripping an electric current by an explosion," Fiz. Goreniya Vzryva, No. 1 (1975).
3. G. I. Kiselev and L. A. Luk'yanchikov, "Compensation method of measuring current and voltage," Prib. Tekh. Eksp., No. 4 (1974).
4. A. M. Zalesskii, Electric Arc Tripping [in Russian], Gosénergoizdat, Moscow (1963).
5. G. V. Butkevich, Arc Processes in Switching Electrical Systems [in Russian], Energiya, Moscow (1967).
6. Explosion Physics [in Russian], Nauka, Moscow (1975).
7. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena, Academic Press (1966-1967).
8. T. H. Lee, "Plasma physics and tripping electrical circuits," Inst. Eng. Electrotechnol. Radioelectron., 57, No. 3 (1969).

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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