Fuse Selection for the Two-Stage Explosive Type Switches

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Abstract. In the two-level explosive switch destruction of a delay happens in the form of electric explosion. Criteria of similarity of electric explosion in transformer oil are defined. The challenge of protecting the power electrical equipment from short circuit currents is still urgent, especially with the growth of unit capacity. Is required to reduce the tripping time as much as possible, and limit the amplitude of the fault current, that is very important for saving of working capacity of life-support systems. This is particularly important when operating in remote stand-alone power supply systems with a high share of renewable energy, working through the inverter transducers, as well as inverter-type diesel generators. The explosive breakers copes well with these requirements. High-speed flow of transformer oil and high pressure provides formation rate of a contact gap of 20 - 100 m/s. In these conditions there is as a rapid increase in voltage on the discontinuity, and recovery of electric strength (Ures) after current interruption.

1. Introduction

In a two- stage disconnection method of high current circuit [1-6] the fuse is connected parallel to the power contacts. This solution allows to dramatically increase the length of the disconnection arc and reduce the limiting level of fault current. When the explosive breaker used as the first step, the destruction of a parallel wire takes the form of an electrical explosion. In turn, the electric explosion of the wire generates short voltage spike on the scattering of metal products (Figure 1). In the further process of fault current disconnection the high heat absorption capacity of burst absorber provides an increase of the voltage on disconnection arc and creates the conditions for the extinction of disconnection arc. Resulting at the fuse wire explosion the peak voltage must be matched with the air-gap electric strength of the first stage. Otherwise the electric breakdown between the moving contacts and further device failure are possible. The peak voltage can not be taken into account for the arc chute gap size choosing, and therefore the wire size (length and cross section) as well. Getting characteristics of an exploding wire was the purpose of the present study (Figure 1).

2. Theoretical Study

Experiments were carried out in the LC circuit (GIT (generator of pulse currents)) simulating the fault current.

In the investigated setting range, successful current changeover to the second stage and the subsequent disconnection was observed in the wire cross-sections (0.03-0.2)$\cdot 10^{-6}$ M^2. Larger cross-sections did not provide a sufficient voltage growth rate on the air-gap and lengthen out disconnection process, smaller cross-sections lead to electric breakdown in the intercontact gap of the first stage. The current densities at the moment of wire destruction were within $(0.3\text{-}1)\times10^{-11}$ A/M^2, which proves existence of an electrical explosion mode [7, 8].

Detailed examination of the voltage waveform on the fuse wire shows a typical electric explosion (Figure 1b). After the current is transferred in the wire, at the first time its value is determined by wave impedance of the loop because of small wire impedance. The wire absorbs energy, is melted (t_1), and further heated in a liquid state until the moment (t_2). At this moment the step of heating the wire comes to an end and the rapid expansion of the wire is begun.

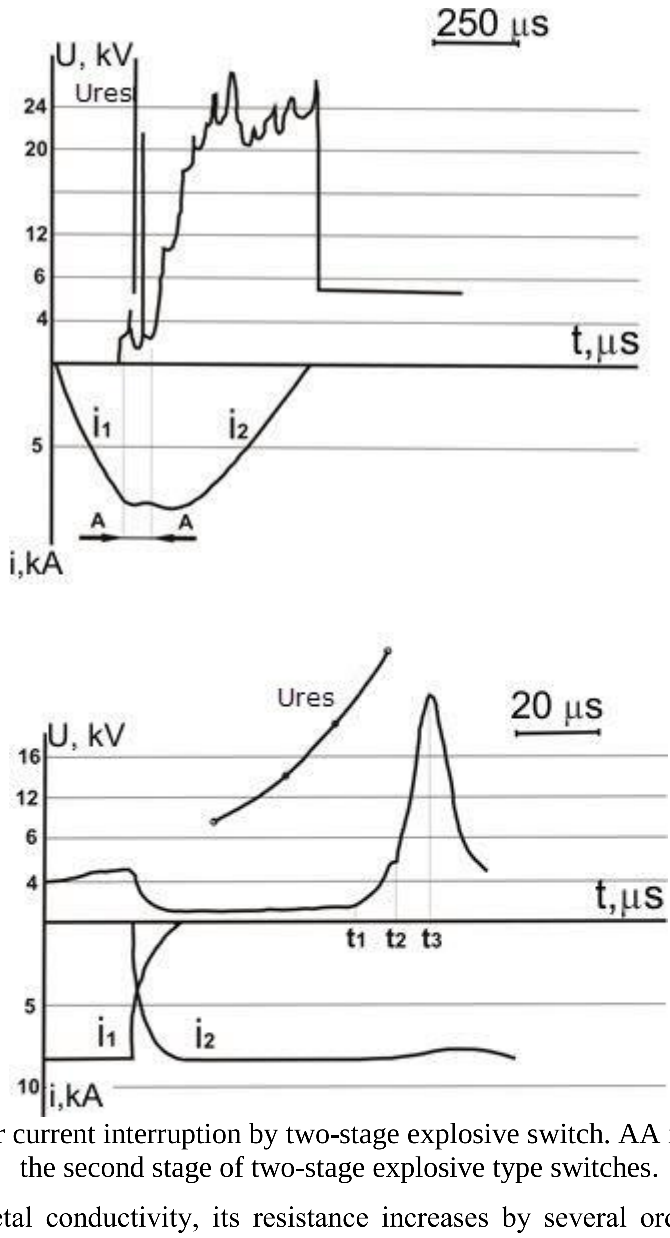

Figure 1. Pictures for current interruption by two-stage explosive switch. AA is switching current to the second stage of two-stage explosive type switches.

The wire loses metal conductivity, its resistance increases by several orders of magnitude, the current in the circuit is changed, the inductance generates a voltage peak on the resistance of fuse wire This stage is wire explosion actually. It is less studied as at the same time there are several process and its relative influence on the explosion process depends on the initial conditions. At the time of (t_3) the gap breakdown on a wire occurs and that initiates the arc.

For the best understanding the phenomena in the disconnection gap is enough to simplistically divide the whole process at the stage of the heating and destruction. At the heating stage wire cross-section is practically unchanged. Heating time from the beginning of current flow to the voltage peak is connected with current density j by ratio, which has been called the "specific action integral" [7].

$$\int_0^{t_n} j^2(t) \times dt = h \quad (1)$$

The value h depends mostly on wire material and selected with possibly lower resistivity for the current switching conditions. According to the degree of increase *g* metals are located as follows: Au, Ag, Cu, Al. For economic reasons, we choose the last two. Moreover, a review of research on exploding wires [4] shows that the most studied and give the best characteristics at explosion the copper conductors of circular cross-section, it have h≈2×10^{17} A^2c/M^4 for a wide range of current densities. In the case the fuse wire operates in the second stage of a circuit breaker and the current through the wire will change only slightly at the heating stage, $t_н$ is defined as

$$t_n = h/j^2 \quad (2)$$

At the destruction stage there is a sharp increase of the wire resistance and transformation of its material into a vapor-drip blend. The way of destruction and the way of resistance growth depends on the rate of energy input, determined by the current density j.

This criterion divides explosions into several types [4], but these can be broadly grouped into "fast" and "slow" on the basis of a comparative process uniformity along the length of the wire [9]. Data [9] on exposure of the wire in the water clearly show the boundary between these types of electrical explosion. It is within the range the considered fuse. In this connection, it is expedient to identify the main factors influencing on the electrical characteristics of the “fast” and “slow” explosion.

Defining process for a quick explosion are relatively uniform along the length of the wire metal boiling and scattering of metal particles. Assuming that the destruction occurs as an evaporation wave moving from the surface wire to its axis [10], it is possible to introduce the typical scattering speed ϑ, which depends on the injected energy. Scattering time is proportional to the diameter of the wire $t_p=d/2\vartheta$, and the time ratio $t_p/t_н$ form fast explosion similarity criteria

$$P = t_\mathrm{p}/t_n = j^2 d/2h\vartheta \quad (3)$$

This dependence the scattering time of the wire diameter is observed for fast enough explosions in the air [6]. It leads to the fact that the maximum voltage is different for conductors with different diameters, but with the same general cross-section, exploded in the same conditions. This fact is the basis for conclusion of electrical explosion similarity criteria laid down in [11].

Similarity criteria containing complex j^2d has been obtained in [12] by a few other prerequisites. At constant characteristics of the wire material and environmental values of $h$and ϑ can be omitted **and** the criterion takes the form j^2d. All the explosion characteristics will be functions of j^2d, in particular, specific resistance *ρ_m* at the time of the maximum voltage

$$\rho_m = U_m/lj = f(j^2 d) \quad (4)$$

* Specific values: current density and resistivity are calculated per unit of the initial cross-section of the conductor.

With energy input rate decreasing a decisive role in the process EVP acquire the magnetic field forces, leading to the formation of instabilities along the length of the wire [9, 13]. As a result, there are briges, which release nearly all the injected energy. In place of the briges formed arc, the number of which is increasing over time, and which causes a voltage growth on the conductor [14]. The time constant of the MHD instabilities is back proportional to the current density:

$$\tau_{MHD} = \sqrt{2\gamma/\mu_0/j},$$

where μ_0 is the magnetic permeability of vacuum, γ is the metal density.

In this model the voltage on the conductor should depend on the current density. At explosion in the water short wires, which does not completely off the current in the circuit, there is evidence [15] that the maximum voltage varies by 25% only when the diameter change to 4 times while maintaining the general cross-sections. At the [16] for electrical explosion in condensed media noted dependence $E_m=U_m/l$ on the wire diameter. There is a graph of changes E_m of the current density for copper conductors in the range $j=(10^9\text{-}10^{11})\ A/M^2$.

Unfortunately, wide zone E_m (gradient values differ by about 2.5 times) is not possible to solve the problem of calculating the electrical characteristics of an exploding wire in the oil.

3. Experimental Part

Due to such a controversial baseline information on the independent variables and the relationship between them, as well as the insufficient number of published data for engineering calculations for choosing the length and cross sections of exploding wires, the experiments to investigate the characteristics of exploding wires in transformer oil media and water media are conducted.

In processing the results of experiments as the dependent variable is taken maximum apparent resistivity ρ_m, because it is more stable than the maximum a voltage gradient and, in addition, it is possible to specify the scale of it - initial resistivity ρ_0, while for the large-scale gradient values of the parameters that define our phenomenon it can not be created.

Using the obtained data the maximum resistivity dependence $\rho_m=E_m/j$ in functions of j^2d and j, i.e. from the standpoint of "fast" and "slow" explosion, have been constructed (Figure 2).

Preliminary analysis showed that the spread of the points about the regression line in both cases is approximately the same - 20%. Due to the same accuracy of the description, a more simple dependence for the practical use are encouraged - dependence on the current density. Approximating all the experimental point line (Figure 2) can be described by the expression

$$\rho_m = -0.29 \times 10^{17} \times j + 5.25 \times 10^{-6} \quad (4)$$

This dependence is consistent with the results of [16] with the appropriate terms (in the E_m and j coordinates). The experimental results are also determined by the dependence of the specific action explosion h from the current density (Figure 2).

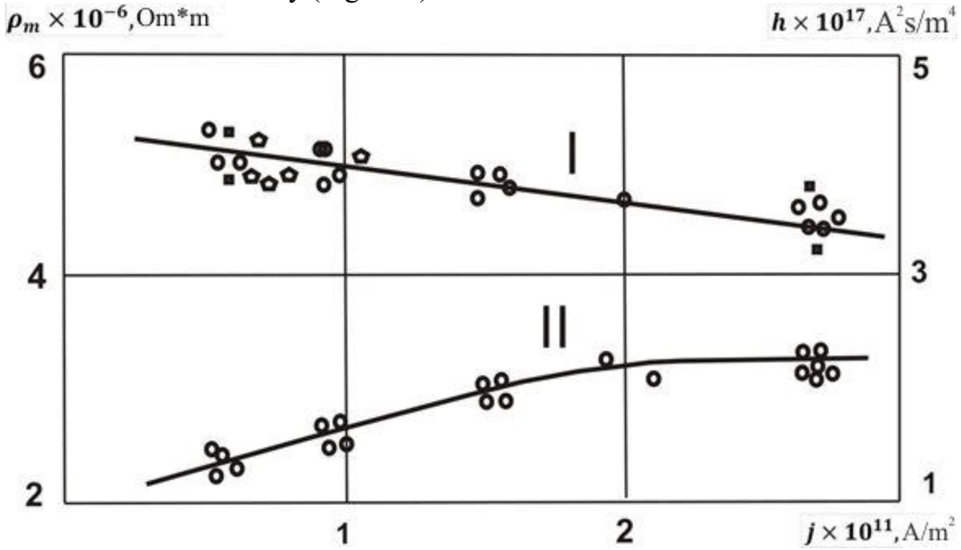

Figure 2. The dependence of the maximum resistivity ρ_m and specific actions h on the current density j, where ● are experiments in the LC circuit in the transformer oil medium; ■ are experiments LC circuit in the raw water; ⬟ are experiments on the model of the DRV.

The graph shown in Figure 3, is the basis for the choice of the cross-section of an exploding wire at known its length. In this case, it is required to determine the overvoltage value and the moment of its appearance after the current switched to the second stage. The amplitude of the voltage peak is determined by the approximating expression (5).

$$U_m = l(-0.29 \times 10^{17} j^2 + 5.25 \times 10^{-6} j) \quad (5)$$

Heating time is determined from the equation (1). However, the value depends on the current density. Therefore, it is expedient to use a graphical method of finding the optimal cross-sections of the wire.

Figure 3 shows the electrical characteristics match of exploding fuse wires and in the LC-circuit and second stage of two-stage explosive type switches (in transformer oil and water media). Latter allows to identify the impact on the voltage impulse of the two media and transfer obtained data to other applications of exploding wires.

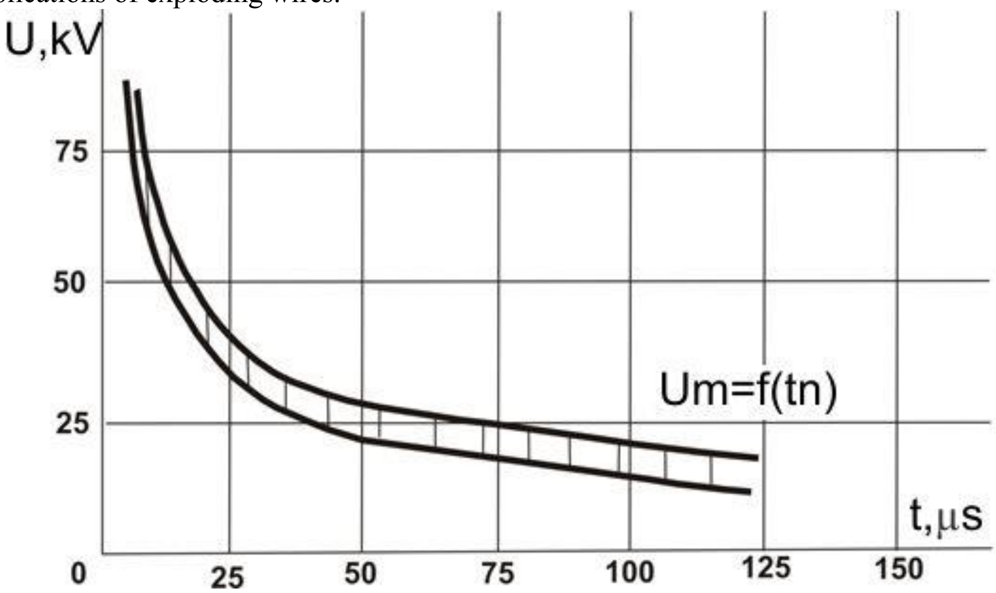

Figure 3. Overvoltage dependence on the wire heating time. Overvoltage range specified for the wire length of 100 mm.

4. Conclusion

The experiments conducted to investigate the characteristics of exploding wires in transformer oil media and water media made it possible to conclude about the typical scattering speed, which depends on the injected energy, scattering time and the time ratio form fast explosion similarity criteria.

Using the obtained data the maximum resistivity dependence in functions of $j^2 d$ and j, i.e. from the standpoint of “fast” and “slow” explosion, have been constructed. It made possible to identify the impact on the voltage impulse of the two media and transfer obtained data to other applications of exploding wires.

The obtained results help to reduce the tripping time as much as possible, and limit the amplitude of the fault current, that is very important for saving of working capacity of life-support systems.

References

[1] Babinovich D E *and* Shutov E A 2014 *WIT Transactions on Ecology and the Environment* **190** 501–510 DOI: 10.2495/EQ140481

[2] Lukutin B V *et al* 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **127(1)** 012005 DOI: 10.1088/1757-899X/127/1/012005

[3] Lukutin B V *et al* 2014 *Proc. of the Int. Conf.* EEEIC’14 459-463 DOI: 10.1109/EEEIC.2014.6835913

[4] Obuhov S *et al* 2016 *MATEC Web of Conferences* **91** 01036 DOI: 10.1051/matecconf/20179101036

[5] Korol'kov V. L. *and* Sivkov A. A. 1983 *Elektrotekhnika* **4** 21–23 (in Russian)

[6] Rozanov J K *et al* 2001 *Electric and electronic devices* (Moscow: Informelectro) (in Russian)

[7] Rukhadze A A (Ed) 1965 *Electric explosion of conductors* (Moscow: Mir) (in Russian)

[8] Burtsev V A *et al* 1977 *Electric explosion of conductors* (Moscow: NIIEFA) (in Russian)

[9] Litvinenko V P 1983 *Physical basis of electric explosion* (Kiev: Naukova Dumka) (in Russian)

IOP Conf. Series: Materials Science and Engineering **189** (2017) 012004 doi:10.1088/1757-899X/189/1/012004

[10] Bennett F D 1974 *Evaporation wave* (Moscow: Mir) (in Russian)
[11] Azarkevich E I *et al* 1975 *Sov. Phys. Tech. Phys.* **20(1)** 111–112
[12] Ivanov V V 1983 *TVT* **21(1)** 146–154
[13] Abramova K B *et al* 1966 *DAN SSSR* **67(4)** 778–781 (in Russian)
[14] Bakulin Y D *et al* 1976 *Sov. Phys. Tech. Phys.* **21(9)** 1144–1151
[15] Krivitskiy E V and Litvinenko V P On the mechanism of explosion of conductors by current pulses. - Technical Physics, 1976, t.46, №10, p. 2081-2087
[16] Krivitskiy E V *and* Litvinenko V P 1976 *Sov. Phys. Tech. Phys.* **46(10)** 2081–2087
[17] Budovich V L *and* Kuzhekin I P 1975 *Proc. of the MEI* **224**
[18] Korol'kov V L *et al* 1986 *Electrical* **9** (in Russian)