THE ELECTRICALLY EXPLODING WIRES APPLICATION
IN THE POWER CIRQUIT BREAKERS.

N. Akhmerov, E. Aziziv, V. Jagnov.

Kurchatov Instiute of Atomic Energy, Moscow, USSR.

Abstract.

Pulsed power systems based upon the inductive energy storage require circuit breakers. For this purpose a three-staged-switch has been developed comprising a relatively slow mechanically-driven current breaker, a fuse switch and a resistor. This switch has been designed, assembled and experimented on. Recent experiments have shown that the three-staged-switch operates safely and is able to provide current pulses of all the required shapes in the loads with the broad parameter range.

2. Introduction.

In the large energetic pulsed devices for the switch-off the current or its commutation many-step commutation schemes are preferable. Usually the mechanical contact breakers are used in the scheme for the first step. The combination of tyristors with fuse or an other element with nonlinear property are used for the second and next stages. Similar schemes are discussed for example in [1,2].

In the operation regime the total current is flowing through the contacts of a mechanical key but the next keys have not a current. The commutation process proceeds in some steps: the first- mechanical break of contacts by a fast destruction. As a result, the total current is commutated for some time in the next key ( an example, a shunting wire - "SW"). Then the electrical of the wire happens and the current must be switched-off or commutated to the next electrical chain.

The agreement of two processes for the stable operation in that scheme is necessary: the arc blows out in the first key and the electrical exploding occurs in the wire in the next steps.

The voltage grouth rate and the voltage value should be correlated with the media condition in the contact for the recovery of electrical strength.

The key of the second step as a rule is fuse. When the operation current increases one have to make the parallel connetion of a similar fuse design.

In our report the operation of the many -step switch-off in the power supply based upon the inductive energy storages discussed.

3. About the commutation process model.

As an example of the three-staged circuit breakers, which is shown in figure 1 the process of commutation is considered.

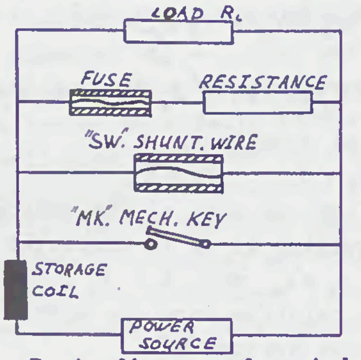


Fig.1. Basic diagram of an inductiv energy storage system.

Here, the fuse and the resistor connected seriesly were used as the third key. It is necessery to form the front of the current impulse in the loading (in scheme $R_L$). It is assumed , that initial resistance $R_{L_0}$ is essentially more than the resistance of the second shunting wire at the moment of explosure, which makes it possible to disregard the loading current in the analysis.

For the contact key the model of the linear increase of the voltage is

$$U_p = Evt = at \qquad (1)$$

It's assumed, that "a" doesn't depend on the current value, the scheme inductance and fuse parameters.

The growth of the fuse resistance is defined by a specific energy $q = Q/m$ , where $Q = \int_0^t i_s^2 R_s \, dt$ - total deposite energy in the fuse, $m$ -wire mass.

the specific deposite energy $q_t$ and

resistance $R_t$ are related to the melting point (for the copper wire $q_t$ =0.468 kJ/g, $R_t/R_o$ =5.96), for the total melting of wire - $q_m$ and $R_m$ and for boiling point $q_b$ and $R_b$.

For the heating stage in the solid state( $q \le q_t$ , $R_s \le R_t$ )

$$R_s/R_o = 1+(\alpha/c_p)\cdot q = 1+q/q_1 \quad (2)$$

Where $-\alpha$ - temperature coefficient of resistance,

$c_p$ - specific heat capacity of metal

$q_1$ -specific energy deposit, when specific resistance doubles.

For the other two stages this coefficient can be written in the form of

$$R_s/R_o = f(q/q_1) = f(Q/Q_1) \quad (3)$$

where $Q_1 = q_1 \cdot m$.

The current commutation from MK to SW is described as

$$L(di_s/dt) + i_s R_s = at \quad (4)$$

$$(1/R_o)(dR_s/dt) = (i_s^2 R_s/Q_1) \pm R_s/R_o \quad (5)$$

with initial conditions

$$i_s = 0 \; ; \quad R_s = R_o \quad (6)$$

To define the time of the ending time this equation is to be completed by the condition $i_s = i_o$ when $t = \tau_*$ .

In the relative form the system equation shall be written as

$$\beta y' \;\; yx = x \;, \;\; z' = y^2 x^2 \quad (7)$$

wtih an initial conditions

$$x = 0, \;\; y = 0, \;\; z = 1 \quad (8)$$

$$x = x_* \;\; y = \gamma \quad (9)$$

where

$$x = t/\tau_4 ; \;\; y = i_s/i_1 ; \;\; z = R_s/R_o \quad (10)$$

$$\tau_4 = (R_o Q_1/a)^{1/3} ; \;\; i_1 = (aQ_1/R_o^2)^{1/2} \quad (11)$$

$$\beta = L\left(\frac{a^2}{R_o \cdot Q_1}\right)^{1/3} = \frac{L_e}{l^{5/3}}\left(\frac{a^2}{\rho_o^4 q_1 \delta}\right)^{1/3} \quad (12)$$

$$\gamma = i_o\left(\frac{R_o^2}{a \cdot Q_1}\right)^{1/3} = \frac{i_o l^{1/3}}{S}\left(\frac{\rho_o^2}{a q_1 \delta}\right)^{1/3} \quad (13)$$

here, $l$ - length of SW; $S$ -section square

$\rho_o$ - specific resistance

$\delta$ - metal density.

Two independent relative parameters and $\gamma$ can be concidered as dimensionless inductance and relative current, accordingly.

The solution of (7) and (8) is the function family $y(x,\beta)$ and $z(x,\beta)$. The curves $y(x,\beta)$, $z(x,\beta)$ are dependences of the dimentionless current in the SW and resistance SW on the relative time (fig.2)

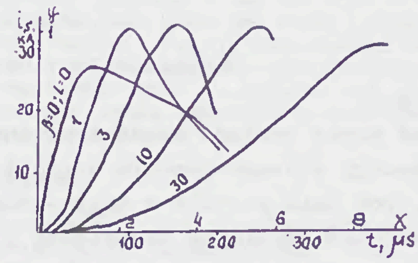


Fig 2a. Variation of relative current as a function of relative time

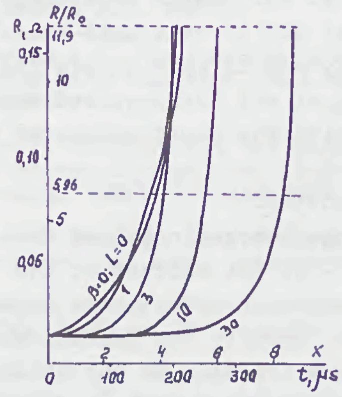


Fig.2b. Curves showing the SW resistance as a function of time.

Here, $i$ and $\tau_4$ are calculated for the support points (a =$10^7$V/s, l=80cm, S=1mm$^2$, Q=676 J, $R_o$ = $1.38 \cdot 10^{-2}$ Ω ).

The condition of successful commutation is given by the unequality $y < y_{max}(\beta)$, when $\gamma > y_{max}(\beta)$ the current changes its direction (here we denote term "contr-current" as "CC")and equation (10) isn't true in this case. Thus, $y_{max}$ is a critical value, which definies a boundary of commutative field $y_{max}(\beta) = \gamma_{cr}(\beta)$.

Figure 3 shows the field boundary of the successful commutation in the $(\beta, \gamma)$ plane as well as the direct lines where the relative parameters are constant.

The proposed current commutation model provides possibility to predict, that at some regimes, in which a correlation takes place the first key aro current starts to increase again. The current direction changes from a very small value of specific energy deposition. For example, the CC arises at the first stage of the heating SW when $R_s/R_o$ = $\sqrt{3}$ and $T^o$= 160° C. Therefore, for $g_o$ > 1.35 kj/g the commutation will be impossible.

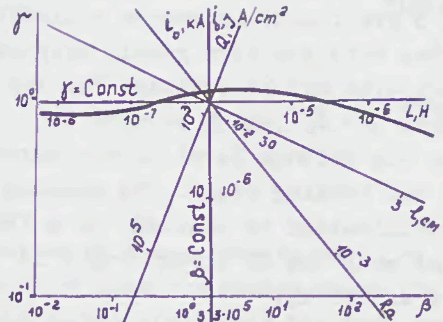


Fig.3 Curves showing the boundary of the successful commutation.

The critical current density for is definited as

$$J_c = 0.83(aq_1\delta/\rho_0^2\ell)^{1/3} \quad (14)$$

For the copper wire

$$J_c = 5.5\cdot 10^4 (a/\ell)^{1/3},\ [A/cm^2] \quad (15)$$

where $a$ is the rate in V/cm, $\ell$-in cm.

4. Experiments.

The experimental investigation of the commutative processes was carried out in two stages: 1) the investigation of the wire electrical explosion and the current commutation by fuse to loading; 2) the study of the three-step scheme commutation.

At the first stage of wire explosion electrical characteristics were investigated as a dependence of the tube channel diameter upon the wire diameter $\gamma = d_{ch}/d_w$ ratio. It was shown that the wire explosion in the fuse is similar to the air case when $\gamma \geq 10$. The current and voltage characteristics very rapidly change when $\gamma \leq 7$ and the explosion time is decreasing. The high speed shocking have been performed for better understunding of wire explosion processes in the tube channel. The wire (0.7 mm diameter, 0.38 mm$^2$ section area, 100 mm long and $R_{W_0} \simeq 1.5\ 10^{-5}\ \Omega$) exploded in the glass tube, $\gamma$=2.83. The standard scheme of the capacitor impulse power supply was used with the storage voltage and the energy U=1500 V and W=6.2 kj, respectively. It melts down to U=1300 V after the wire explosion. So the explosion energy were $W_w$= 2.2kJ and $W_S$ =6.4 kJ/g, respectively.

A typical explosion result in the glass tube is shown in fig.4

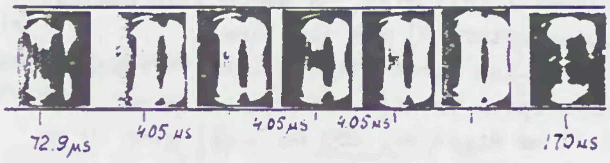


Fig.4 The frames of the wire explosion.

This picture was taken with the high-speed SFR-camera. The time interval between the frames is 4.05μs. The melting stage as a light wave is spreading with average speed 2 km/s and intimating to the middle of the wire. The wire is explosed after intimatation of the light wave. The commutation of the current I = 10 ÷ 100kA to the loading was investigated. By means of several fuses ($d_w$ = 0.7mm) with the tube channel diameter $d_{ch}$ = 3.5 mm and 220 mm long the commutation was performed the specific energy $W_S$ =12÷ 15 kJ/wire.

We will pick out three problems : 1) the mechanical forces action on the fuse tube; 2) the flow of the wire explosion products from the channel appertures and the possible face breakdown; 3) the channel breakdown and the arc development in the channel.

The solution of the first problem lies in the strengtening of chamber design. For the second case we developed spesial chambers on the dielectric tube ends (see fig. 5).

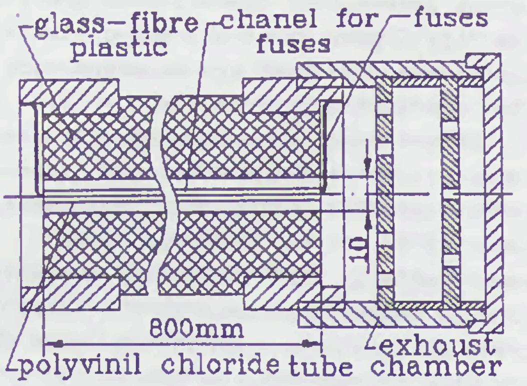


Fig.5. Cross-sectional wiev of the shunting wire element.

The most complicated problem is the third one. The choice of the channel length and the parameter $\gamma = d_{ch}/d_w$ can help solved this problem, though.

The previuos experiments permited to

begin the investigation using the total scheme (fig.1)with the mechanical contact unterrupter [3] and the fuse.

On the first step we used the explosive high-speed breaker. It was the dural tube ( 76 mm diameter, 200 mm long) with 10 mm wall thickness. The tube was filled with paraffin. A cilindrical explosive of 10 mm diameter was on the tube axis.In order tu catch the splinters the tube breaker was placed into the closed dielectric chamber.

As a result of the explosion the metal cylinder is destructed,the arc is burned. When the splinter velocity $v \approx 10^4$ cm/s the voltage ise rate reached up to $a = Ev = 10^7$ V/s . It should be noted that this parameter is weakly dependent on the current initial value from 10 to 100 kA.The arc voltage drop is increasing when =const during $\tau$=0.5 $\cdot$ $10^{-3}$ s to $U_p \approx 3$kV. When $\tau \approx 1 \cdot 10^{-3}$ s the contact voltage drop was fast decre-ased to $U_p \approx 10^2$V. The dynamical voltage-amper characteristics ( VAC) for the current commutation shows that the current is almost constant in a large time interval.

On the second stage one or several wires ( 200 + 300 mm long, $R \approx 10^{-2}$ ) are connected in parallel to the mechanical switch.On figure 5 the design of SW is shown.This design allows us to solve all problems of the commutation when the current changes from 10 kA and the voltage from 10 kV to 30 kV. An advantage of that design is the presence of special chambers ( on the fig. 5 pos. 5) at the end of the dielectric tube that are catching wire electric explosure products.

SW and resistor connected with each other are used in the loading to form the current profile.The initial resistance of assembly R =0.1+10 . It was shown experimentally that the energy characteristics is weakly dependent on the length, cross section area,quantity of wire when the wire is warmed up to the melt; temperature and the current denssity j = 10+35 kA/mm$^2$.A deviation from monotonous character of function $R/R_o = f(Q)$ tabes place on explosion when $q > 1.5$kj/g.

More rapid growth of the relative resistance is observed when the SW length (for $i_o, R_i, S$ are fixed) increases exploding wire regime with the veri gently sloping characteristics may be realized for the wire length $l < l_c$ ,which permits to stabilize the voltage level on the current input to the loading stage. The voltage level stabilization is reached in a few hundred $\mu s$ when the SW enrrgi input is as large as 20? kj.

In the mentioned above current interval and switch design the electrical breaking strength of the explosure products was no more E=1 kV/cm. The input energi limit was 2 + 3 kj on the length unit.

Summary.

Thus,we have created the elements of many--staged commutation scheme.They are: the explosion breaker [3] and many-shut commutator,which is discussed in detail in [4]and switch on the wire electrical explosive bases. All switches have been tested in experimental installations. Using this devices the current commutation was produced from the inductive energy storage with the storage energy of several dozens MJ to the different loading.

This equipment may also be used on the energy plats.

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