Simulation and Analysis of Electro Explosive Wires Breaker Based On Specific Action Model

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Abstract. In order to study the impacts of the length and diameter of the electric explosive wire on the breaking current characteristics of the electric explosive wire breaker, the physical model of the electric explosive wire breaker is analyzed theoretically, the calculation method of the relevant design parameters is deduced, the simulation model based on the time-varying resistance is established, and the breaking time, the breaking current and the breaking effect are analyzed etc. The results show that the model is in good agreement with the experimental results, and can obtain the general rule of current cut-off of electric explosive breaker accurately, conveniently and intuitively, which provides a reference for the design of electric explosive wire breaker parameters.

1. Introduction

The energy and power of magnetic explosive ammunition such as electromagnetic pulse projectile and magnetic explosive loaded ammunition are provided by magnetic flux compression generator. Magnetic flux compression generators often use high-speed circuit breaker to load the energy stored in their inductance onto the load [1]. The combined operation of high-speed circuit breaker and magnetic flux compression generator can separate the energy storage stage from the energy extraction stage, and ensure impedance matching and pulse shaping. Electric explosive wire circuit breaker has the advantages of short on-off time, high breaking current, high power and low cost, so it is widely used in pulse forming network of magnetic flux compressor [2].

Many works have been done to find out the ST (The Switching Time), SC (Switching Current), PV (Peak Voltage), performance, and controllability of Electro Explosive Wires Breaker under different circumstance by simulation. The HD (Hydrodynamic) and MHD (Magnetohydrodynamic) based models were applied for predicting the behavior of Electro Explosive Wires Breaker by Stephens, et al [3]. Numerical modeling of exploding wire fuse resistance was used to predict the length requirements for Electro Explosive Wires Breaker in inductive energy storage pulsed power systems by O’Connor, et al [4]. Phenomenological model building and 2-D gas-dynamic approximation methods were carried out to study the explosive current of Electro Explosive Wires Breaker by Demidov et al [5].

Although these models can well explain and conform to the experimental data, they are complex to establish and inconvenient to debug parameters, which is not conducive to switch design. Compared with numerical simulation, SIMULINK simulation model is more intuitive, and does not need to write a large number of program formulas and functions, but also avoids the complexity and universality of
numerical simulation. Therefore, this paper uses SIMULINK software based on time-varying resistance model to simulate and analyze the breaking characteristics of explosive wire breaker, and studies the effects of the length and diameter of electric explosive wire on the breaking time and current.

2. The Physical Model of Electric Explosive Wire Breaker

Electric explosive wire breaker is composed of metal filaments. When electric explosive wire passes through high current rapidly, it undergoes several processes, such as solid state, melting, liquid heating, vaporization, arc growth and explosion. At the early stage of circuit breaker of the electric explosive wire breaker, resistivity increases with the increase of injection energy. When the injected energy is large enough, the metal conductor material disintegrates, the gasification wave front moves toward the conductor and explodes, thus the switch is disconnected [6].

In this paper, the resistivity calculation model of electric exploding wire is derived from the Tucker model [7]. When the current flows through the conductor, the specific action is

\[ g = \int_{0}^{t} J^2 dt \]  

Neglecting heat conduction, according to Joule's law [7]

\[ \frac{\partial \omega}{\partial t} = \rho J^2 \]  

In the formula (2), \( \omega \) is energy density of electrical exploding wire; \( \rho \) is electrical resistivity of wire exploded wire; \( J \) is current density for input.

The relationship between the energy density of explosive wire and the resistivity of exploded wire is proportional to each other, that is

\[ \rho = \rho_s (1 + \beta_s, \omega) \]  

In formula (3), the subscript \( s=0,1 \), corresponding to solid state and liquid state respectively; \( \rho_s \) is initial resistivity; \( \rho_s \) is heating efficiency.

According to formula (2) ~ (3), the following equation was deduced

\[ \rho = \rho_s \exp[g / g_{\text{max}} \ln(\rho_{\text{max}} / \rho_s)], 0 \leq g \leq g_{\text{max}} \]  

Among equation (4), \( g_{\text{max}} \) is the specific action of the critical point of phase transition of electric explosive wire that is vaporization point, \( \rho_{\text{max}} \) is the resistivity of critical point of phase transition of electric explosive wire. Equation (4) shows that under the approximate condition of single-phase heating, the resistivity of electric exploding wire is exponentially related to the specific action.

The energy expression of explosive metal conductor in the process of transition from solid state to liquid state and from liquid state to vapor state is as follows:

\[ gS^2 = S^2 \int J^2 dt = H \int \frac{1}{R} \frac{1}{R_1 + R_2} dm = H \int \frac{R_1 + R_2}{R_1 R_2} dm \]  

In equation (5), \( H \) is the latent heat of phase transformation; \( S \) is the cross-sectional area of metal conductor; \( m \) is the initial mass of metal conductor; \( R \) is the total resistance of phase 1 and phase 2; \( R_1 \) and \( R_2 \) are phase 1 and phase 2 resistance respectively. Equation (4) and (5) deduce the function relationship between resistivity and specific action [8, 9], as follows
\[
\frac{\rho}{\sqrt{1 - \left[ (\rho_2^2 - \rho_1^2) / \rho_2^2 \right] g / g_{\text{max}}}}, 0 \leq g \leq g_{\text{max}}
\]  

(6)

Through the above analyses and deductions, it can be seen that there is a functional relationship between the resistivity and specific action of the electric explosive wire. For the parameters in the resistivity-specific action model, we adopt the data given by Tucker [7], and the curves are shown in Figure 1.

**Figure 1.** Experimental curve of resistivity and specific action (Cu).

3. **Model Establishment**

The SIMULINK module of MATLAB software is used to establish the simulation model of electric explosive wire breaking, some of which are shown in Figure 2.

According to the theoretical analysis and deduction formula in the previous section, the current square is integrated by the integral module, and the corresponding specific action is obtained by Gain module. The copper electric exploding wire resists \( R = \frac{4\rho l}{\pi d^2} \), so the Gain module is used again to get the corresponding resistance. According to \( U = IR \), the Controlled Voltage Source is controlled by the voltage at both ends. When conducting, the charging voltage of capacitor in SIMULINK can be preset directly without charging. The circuit is discharged through energy storage inductance, loop resistance and electric exploding wire. It was simplified to an equivalent RLC loop, and the electrical characteristics of electrical explosion process are studied.

**Figure 2.** SIMULINK simulation model of electric explosive wire breaker (parts).
4. Simulation and Analysis of Circuit Breaker Characteristics

Table 1. Influence of length on current breaking characteristics.

| l (mm) | ST (μs) | SC (kA) | PV (kV) |
|--------|---------|---------|---------|
| 40     | 1.65    | 4.6     | 48      |
| 60     | 1.70    | 4.9     | 85      |
| 80     | 1.75    | 5.2     | 115     |
| 100    | 1.80    | 5.5     | 100     |
| 120    | 1.90    | 5.8     | 95      |

It can be seen from Table 1 that the change of length l has little effect on the time of cut-off current and the peak value of cut-off current. Figure 3 shows that the length l affects the process of cutting off the current of the electric exploding wire switch. When the length l is less than a certain value, the internal high voltage will breakdown the conductor and will not be cut off current. This will lead to the phenomenon that the current cannot be completely cut off and the zero value cannot be restored. The simulation cut-off curve accurately reflects this phenomenon. With the increase of the length of the explosive wire, the peak voltage of the energy storage inductor increases and then decreases. There is an optimal value of the length L from the voltage point of view.

Figure 3. Impact of length on electric explosive breaker and inductor’s voltage

Fixed length l=80mm, changing diameter d from 0.01 mm to 0.05mm, the current cut-off characteristics of electric explosive wire are studied. The simulation results are shown in Table 2 and Figure 4.
Figure 4. Impact of diameter on electric explosive breaker and inductor’s voltage

Table 2. Influence of diameter on current breaking characteristics

| d (mm) | ST (μs) | SC (kA) | PV (kV) |
|-------|--------|--------|--------|
| 0.01  | 1.90   | 4.9    | 94     |
| 0.02  | 2.45   | 6.2    | 98     |
| 0.03  | 3.00   | 7.6    | 96     |
| 0.04  | 3.80   | 9.1    | 92     |
| 0.05  | 5.15   | 11.8   | 77     |

As can be seen from Table 2 and Figure 4, with the increase of the diameter d of the electric explosive wire, the time of cutting off the current becomes longer and the value of cutting off the current becomes larger. The peak voltage at both ends of the energy storage inductor becomes larger and smaller with the increase of the diameter of the electric exploding wire. As the diameter increases, the cross-sectional area increases, the current density decreases, and the time to reach the specific action g required by the explosion becomes longer. When d is greater than a certain value, the current density is too small, the energy supplied will not be enough to cut off the electrical explosion wire.

5. Conclusion
In order to study the current-breaking characteristics of copper conductor used as electric explosive wire breaker, the physical model of electric explosive wire breaker is analyzed theoretically, and the simulation model based on time-varying resistor module is established by SIMULINK. The model uses capacitor pulse discharge to analyze the circuit breaking characteristics of copper explosive wire, and obtains the influence law of length and diameter of explosive wire on the circuit breaking time and current. Compared with other models, the simulation model of electric exploding wire breaking based on SIMULINK is more intuitive and convenient. The simulation results correspond to the simulation results based on PSpice in literature [2] and the influence of parameters such as length and diameter on the interruption characteristics is also consistent. The simulation results are also in good agreement with the experimental results in literature [10]. Therefore, the simulation can accurately reflect the general law of electric explosive wire. The theoretical analysis, derivation and simulation study in this paper provide a reference for the design of the parameters of the electric explosive wire breaker.

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