

# Analysis and Design of High-Current Arc-Triggering Hybrid Current-limiting Fuse

Chao Dai<sup>+</sup>, Jinwu Zhuang, Feng Yang, Bo Chen, Chen Wang and Zhuangxian Jiang

College of Electrical and Information Engineering, Naval University of Engineering Wuhan, P.R.China

**Abstract.** The arc-triggering hybrid current-limiting fuse use the heat effect of fault current for detecting and triggering, which has the advantage of excellent current-limiting capability and reliability. Limited to the level of research, the fuse has been applied only to low current occasion, and the continuous rating is limited to 600A. The key technologies has been studied in this paper, the design of arc-trigger has been optimized to shorten its reaction time under the premise of temperature rise. A prospective short-circuit current of 100kA (time constant: 4.17ms) is limited to 19kA by a 2000A/640V prototype, the melting  $I^2t$  is only 1/28 of the same specification fast fuse.

**Keywords:** High current; Hybrid current-limiting fuse; Arc-triggering

## 1. Introduction

With the ever-increasing demand for electrical energy, power systems have been forced to expand and grow, which contribute to subsequent increases in available fault currents. This short circuit current may exceed the thermal, mechanical and interrupt capability of equipments. Conventional circuit breakers are not current limiting and are relatively slow interrupting devices. The current limiting fuse has provided good over current protection on systems but its continuous rating is limited. To overcome the continuous rating limitation, Fault current limiter is an effective facility.

There are many FCL designs developed during the past few decades. Liquid metal current limiter (LMCL) use the self pinch-off effect of liquid metal in applied strong magnetic field for current limiting, which is self-healing and compact, but its continuous rating is limited [1,2]. Superconducting fault current limiter (SFCL) utilizing superconducting materials which are capable of providing instantaneous (sub cycle) current limitation abilities, can prevent the buildup of fault currents and have been studied for years. Because of immaturity and high cost, this kind of FCL is not available in real application yet [3,4]. The main advantages of Solid State fault current limiter are small size, fully controlled and fast response, its bottleneck is high conducting loss of the semiconductor component, especially in high-current circuit [5-7]. Hybrid current-limiting circuit breaker which has both the static characteristics of mechanical switch and dynamic characteristics of solid-state switch, its disadvantage are complex control strategy and bulk mass [8-10].

For systems rated above 1000A, electronically controlled hybrid current-limiting fuse is most commonly used [11,12]. The device has a current sensor and an electronic circuitry which monitor the current and trigger the chemical charge at the high speed isolator, the isolator can break in only 100 $\mu$ s. The parallel current limiting fuse melts and extinguishes the fault current before the first peak of the fault current. The device has a significant limiting effect but also many disadvantages:

- A reliable control power supply is needed, once the control unit loss of power, the device will not be able to protect the system;
- The control unit may be out of order because of electromagnetic interference;

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<sup>+</sup> Corresponding author.  
E-mail address: dc117@126.com.

- Large size, high cost and complexity maintenance.

Referring to the reference [13], a new concept called Arc-triggering Hybrid Current-limiting Fuse (AHCLF) was developed in 1988 to replace the electronic unit with an arc-trigger, which utilizes the thermal effect of fault current for detecting and triggering directly. The technology has higher level of integration, higher reliability and lower cost. But limited to the level of research, its continuous rating is limited to 600A, which can not be used for high current system.

Based on the current level of research, the key technologies, especially the optimization of the arc-trigger have been studied in this paper, which aims to overcome the continuous rating limitation.

## 2. Composition and Principle of AHCLF

Fig.1 shows the main components of the AHCLF which contains the arc-trigger, the high-speed isolator and the quenching fuse.

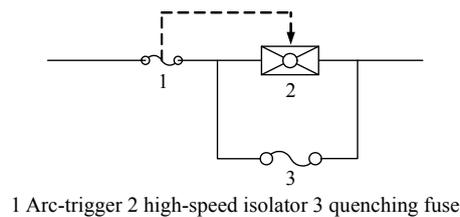


Figure 1. Main circuit of AHCLF

Fig.2 shows the construction of arc-trigger, which contains the connecting terminals, the fuse link and the enclosure. Two connecting terminals are spaced apart from each other and bridged by the fuse link. During the normal operation, the full load current is flowing through the arc-trigger and the isolator. After a fault occurs, the arc-trigger blows out, then the isolator is cut and the fault current is forced to the quenching fuse, the fuse is designed to extinguish the fault current immediately.

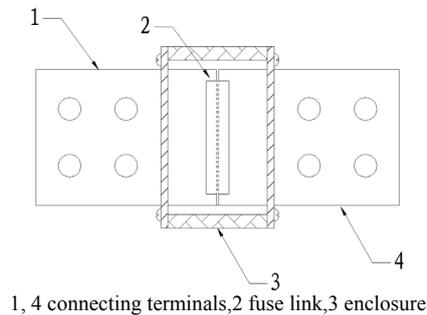


Figure 2. Construction of arc-trigger

For a good current-limiting effect, it can be seen from the principle that the basic requirement for the arc-trigger is the shortest possible reaction time. Therefore the sectional area of the notches should be as small as possible when designing the fuse link. But the full load current is flowing through the arc-trigger during the normal operation, the conducting loss and temperature rise should be considered. The key point is how to raise the current density of the notch under the premise of temperature rise.

## 3. Model for Arc-trigger

To optimize the design, a thermoelectric coupling model was developed to study how the dimensions of fuse link influence the temperature rise and the pre-arcing character. According to the theory of electromagnetic and heat transfer[14], the distribution of current density and temperature at the fuse link is described by the equation:

$$\begin{cases} \frac{\partial}{\partial x}(\gamma \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(\gamma \frac{\partial \phi}{\partial y}) + \frac{\partial}{\partial z}(\gamma \frac{\partial \phi}{\partial z}) = 0 \\ \frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) \\ + Q(x, y, z, t) = \rho c \frac{\partial T}{\partial t}, (x, y, z) \in V \\ Q = \gamma(E_x + E_y + E_z) \end{cases}$$

where  $\gamma$  is the conductivity of the fuse link;  $\phi$  is the electric potential;  $k_x, k_y, k_z$  are the anisotropic thermoconductivity;  $Q$  is the heat generated by internal heat source;  $T$  is Kelvin temperature.  $\rho, c$  are the density and specific heat;  $E_x, E_y, E_z$  are the electric-field intensity.

The model is thermoelectric coupled and the process is nonlinear, and the solution is based on ANSYS. The SOLID69 element is selected in the model, which has 8 nodes and 6 faces, two freedoms as temperature and electric potential. Pure silver is selected as the material,  $\rho$  of which is  $10500\text{kg/m}^3$  and  $c$  is  $234\text{J}/(\text{kg} \cdot \text{K})$ . The value of  $\gamma$  and  $k$  in the different temperature are input as a table.

Because of the special construction and application, the model was simplified. For the simulation of temperature rise:

- The contact resistance and thermoresistance between the connecting terminal and the fuse link are ignored;
- The boundary condition is defined according to the provision of the national standards about temperature rise test;
- The influence of contact resistance and thermoresistance at joints is ignored.

For the simulation of pre-arcing process:

- Only the heavy and general short-circuit is considered, the pre-arcing time is short, the temperature change of connecting terminals, the heat transfer and emission from fuse link to air are ignored;
- Due to the extremely short time-interval from melting to vaporizing of fuse link, it is supposed to the striking time when the temperature of all notches reach the melting point.

Fig.3 shows the figure of the fuse link. Various fuse links are compared in simulation by changing the dimensions of the fuse link as the thickness  $h$ , the width of the notch  $w$ , the aperture  $d$  and the width of the gap  $b$ . The influence of parametric variation on the temperature rise and pre-arcing character is analyzed which aims to the optimum dimension.

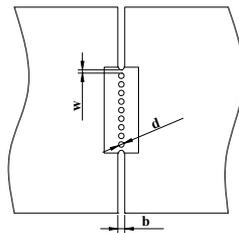


Figure 3. Figure of fuse link

## 4. Analysis of Simulation Results

### 4.1 Simulation of temperature rise

The current load applied to the model is  $2000\text{A}$ ; the current density is adjusted by changing the number of notches. The influence of parametric variation on the temperature rise is observed at different current density. Fig.4 shows the simulation results.

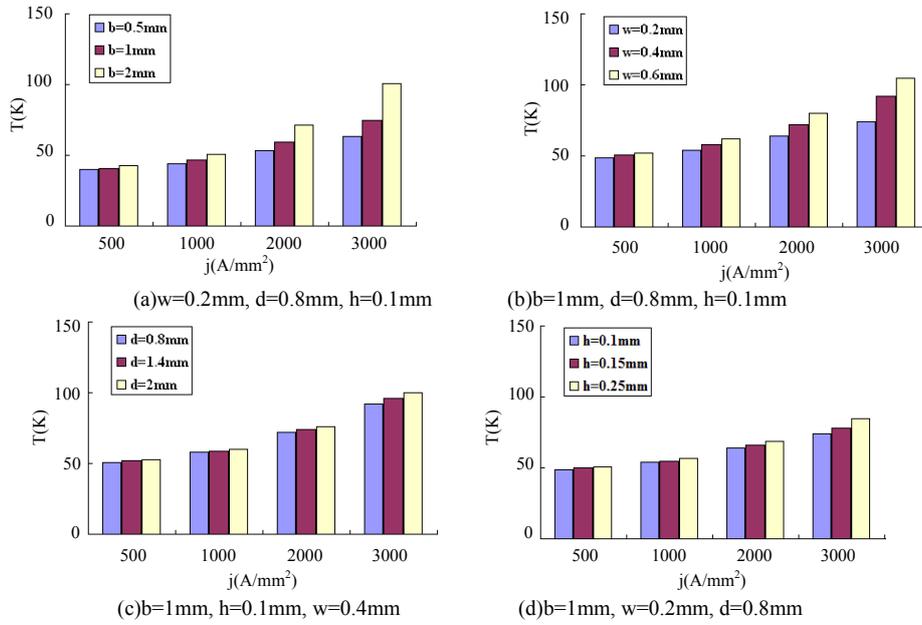


Figure 4. Simulation of temperature rise

The simulation results suggest:

- When the current density is lower than  $1000A/mm^2$ , the influence of parametric variation on the temperature rise can be ignored;
- When the current density is higher than  $1000A/mm^2$ , the temperature rise increases significantly with the increase of  $b$  and  $w$ , the  $d$  and  $h$  have less influence on the temperature rise;
- The maximum current density of the notch can reach  $3000A/mm^2$  under the premise of temperature rise.

#### 4.2 Simulation of pre-arcing time

To simplify the analysis, the current load with the same  $di/dt$  has been applied to the different fuse links. Fig.5 shows the pre-arcing time against the  $di/dt$ .

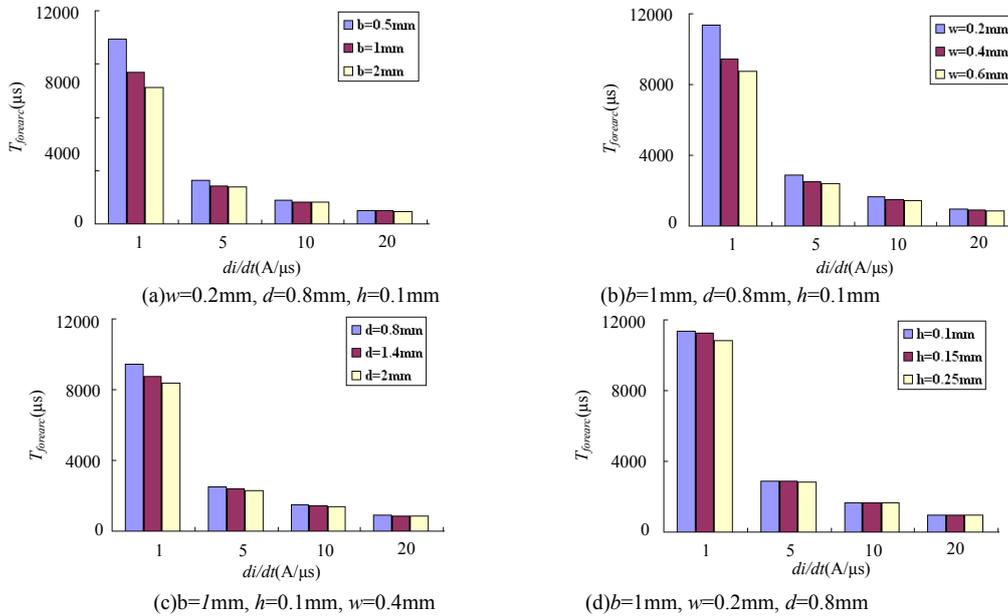


Figure 5. Simulation of pre-arcing time

The simulation results suggest:

- When the  $di/dt$  is lower than  $5A/\mu s$ , the pre-arcing time decreases with the increase of  $b$  and  $w$ , the  $d$  and  $h$  have less influence on the pre-arcing time;

- When the  $di/dt$  is higher than  $10A/\mu s$ , the influence of parametric variation on the pre-arcing time can be ignored, the pre-arcing time is only determined by the sectional area of the notches.

According to the application and the requirement of the arc-trigger, the  $di/dt$  is generally higher than  $10A/\mu s$ , the temperature rise is only considered in design. The arc-trigger with thin fuse link, slender notch, small aperture and narrow gap has low temperature rise and available high current density.

## 5. Design of Prototype

Tab.1 shows the structural parameters of the 2000A arc-trigger, which contains 50 notches. The cold resistant is  $23\mu\Omega$  and the current density of the notches is  $2000 A/mm^2$ .

Table.1 Parameters of 2000A arc-trigger

| h     | w     | d     | b   |
|-------|-------|-------|-----|
| 0.1mm | 0.2mm | 0.8mm | 1mm |

Fig.6 shows the relationship between the pre-arcing time and the  $di/dt$  of fault current from the simulation. The pre-arcing time decreases rapidly with the increase of the  $di/dt$ . when the  $di/dt$  is  $20A/\mu s$ , the pre-arcing time is about  $700\mu s$ .

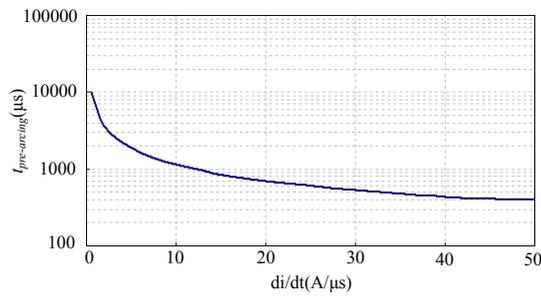
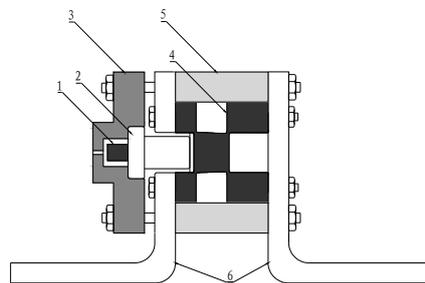


Figure 6. Relationship between  $T_{pre-arcing}$  and  $di/dt$

Fig.7 shows the Structure of high speed isolator, during the normal operation, the full load current is flowing through the conductor and the connecting terminals. After a fault occurs, the exploder is triggered to drive the piston, and then the conductor is cut off by the piston. It takes only  $110\mu s$  from triggering to breaking [15].

The high speed isolator is not arc-extinguishing. The fault current must be commutated to the quenching fuse. The basic requirements for the quenching fuse are a lowest possible impedance to shorten the commutating time, and an adequate pre-arcing  $I^2t$  to ensure good dielectric recovery of the high speed isolator. A  $250A/640V$  DC fuse is selected in the prototype. The inductance is  $0.2\mu H$ , the resistance is  $0.35m\Omega$ , and the pre-arcing  $I^2t$  is  $75kA^2s$



1 exploder 2 piston 3 cylinder 4 conductor 5 enclosure 6 connecting terminals

Figure 7. Structure of high speed isolator

## 6. Test of Prototype

A  $2000A/640V$  prototype is developed for testing, which is shown in Fig.8.



Figure 8. 2000A/640V prototype

### 6.1 Temperature rise test

The ambient temperature is 25°C. The hot resistance is 36μΩ and the temperature rise of the connecting terminals is 61K and 50K. The power consumption is only 144W at rated condition.

### 6.2 Current limiting test

Fig.9 shows the current limiting test circuit, in which  $S$  is the test source of the experiment station. The test parameters can be adjusted by modify the  $L_I$  and  $R_I$ .

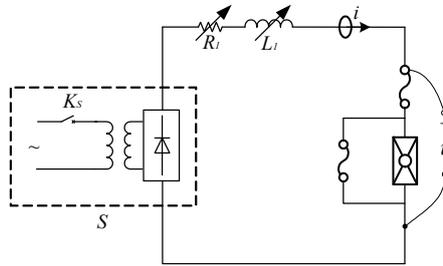


Figure 9. Current-limiting test circuit

Fig.10 shows the test waveforms. A prospective short-circuit current of 100kA is limited to 19kA. The arc-trigger blew out at 700μs ( $t_1$ ) and the arc voltage is about 70V. The high speed isolator is cut after 110μs at  $t_2$  and the arc voltage rise to 120V. The commutation time is about 20μs. The quenching fuse melts at 1.1ms ( $t_4$ ) and the peak arc voltage is 1380V. The total clearing time is 1.85ms ( $t_5$ ) and the melting  $I^2t$  is 115kA<sup>2</sup>s.

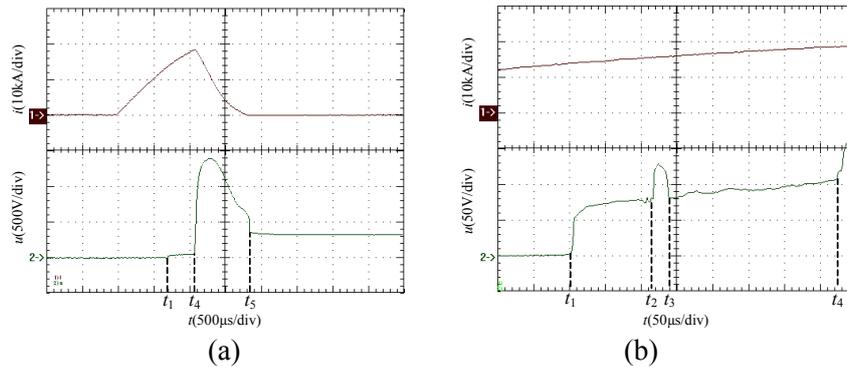


Figure 10. Waveforms of current-limiting tests

For comparison purposes, a 2000A/640V fast fuse is tested in the same condition, which has a peak let-through current=55kA and the melting  $I^2t=3230kA^2s$ . The AHCLF has a remarkable speed of interruption and current limiting performance which fast fuse cannot equal.

## 7. Conclusions

The key technologies of the AHCLF have been studied by simulations and experiments for application in high-current occasions. The main conclusions are:

- The simulation results indicate that the arc-trigger with thin fuse link, slender notch, small aperture and narrow gap has low temperature rise and available high current density;

- When the  $di/dt$  is low, the pre-arcing time decreases with the increase of the width of the gap  $b$ . and the width of the notch  $w$ . When the  $di/dt$  is high, the pre-arcing time is only determined by the sectional area of the notches.
- Based on the motioned results, a 2000A/640V AHCLF prototype has been developed for temperature rise and current limiting tests. The test results indicate that the AHCLF has low consumption and good current limiting performance. The melting  $I^2t$  is only 1/28 of the fast fuse with the same specifications.

## 8. References

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