論 文
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Empirical Modeling on the Breaking Characteristics of Power Current Limited Fuse

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Abstract – In this paper the modeling of interrupting characteristics of a high voltage current limiting fuse to be used in a power distribution system is introduced. In order to reduce the level of energy which can be absorbed by equipment during fault current flow, a high voltage current limiting fuse can generate a high voltage at the fuse terminals. Consequently it is necessary to model and analyze precisely the voltage and current variation during a CL fuse action. The characteristics of CL fuse operation modeled by electrical components have been performed with less than 6 [%] errors. So the fuse designer or manufacturer can estimate the characteristics of CL fuse operation by using this modeling. The Electro Magnetic Transient Program (EMTP) is used to develop the modeling.

Key Words : Modeling, CL Fuses, X/R, Power Factor, Arcing Energy, Fault Current, EMTP

1. Introduction

The prospective fault current caused by line to line or line to ground faults has increased significantly in recent years because power system capacity has increased. This has generated situations where fault current has exceeded the interrupting rating of the protection system. To interrupt these fault currents, a breaker, a cut out switch and a CL fuse have been used in series in the distribution line. But the breaker needs a minimum time of four cycles to interrupt the fault current and the C.O.S. needs a minimum time over a half cycle. So when the fault is generated faster current interruption is required to limit energy inflow. The CL fuse is suitable for interrupting in this case. It can limit the prospective current to less than a quarter cycle after the fault and then clear the fault totally within less than a half cycle. To develop the CL fuse, research investigating the characteristics of fuse operation before testing has been done with computer simulation.

Although there is a method which uses programming language to analyze the interrupting characteristics, it is not for beginner. So in this paper, the method of modeling for a CL fuse is suggested and is used to know the variation of fault energy when the making switch angle and the circuit condition(X/R) are varied.

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2. Operating characteristic of CL fuse

A fuse is a part of the distribution line before a fault, but when the fault occurs the fuse is operated by the short circuit current. The fuse element senses the fault current and melts and arcs and the arc plasma is absorbed in the filler. The fulgurite created by the arc rapidly increases the resistance of the fuse element. Because of this resistance the phase difference of current and voltage is small. If the fault is not cleared, unfortunately the body of the fuse or the tank of the transformer can explode. So before the fault energy reaches an explosive level it has to be cleared. CL fuses limit the fault energy, I^2t, more effectively than conventional breakers or non limiting fuses[1].

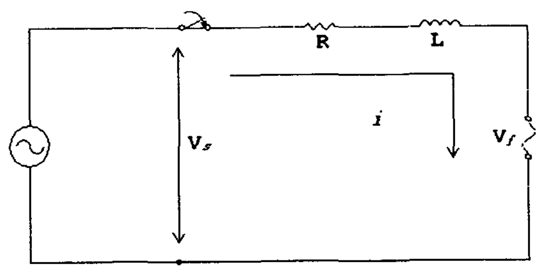


Fig. 1 Diagram for explaining a fuse's operating

In Fig. 1, before the fuse element is melted the instantaneous current and voltage are related by equation (1).

$$V_s = i(R+r) + L\frac{di}{dt} \quad (1)$$

At that time, the resistance of the fuse compared with the line resistance can be ignored. But after the fuse element melts, its resistance becomes much greater than before and we have:

$$V_s = i(r) + L\frac{di}{dt} \quad (2)$$

In this case: $I = \int \frac{V_s - V_f}{L}$ (3)

Where V_s is source voltage, R is a system resistance, r is fuse resistance, ir is fuse terminal voltage, and L is inductance.

The slope of current is positive and then increases because the instantaneous V_f is nearly zero when the fault current flows at $t=0$. However, the terminal voltage of the fuse rises after the fuse melts and arcs. And when both the system voltage and the terminal voltage of fuse become equal, $\frac{di}{dt}=0$ at that point, the current is limited. After that the fuse voltage exceeds the system voltage. As a result the slope of current becomes negative and then zero. At this time, the terminal voltage is represented by the equation (4).

$$V_s = V_s + L\frac{di}{dt} \quad (4)$$

The arc voltage, V_f is higher than the system voltage V_s because V_f is the sum of the gradient term and V_s. The current flow then decreases, and at that time, if the slope is constant, $L\frac{di}{dt}$ becomes a constant. The fuse voltage which is the sum of the system voltage and $L\frac{di}{dt}$ changes with the phase difference becoming zero at the end. And then after $L\frac{di}{dt}$ is zero, the fuse voltage becomes the same as the system voltage[2].

3. Parameters for modeling

The main characteristic is to limit the fault current and the limiting effect after melting is proportional to the fuse terminal voltage. Thus, the higher V_f, the faster fault current is decreased. The operation of the ideal fuse is when the current is instantly interrupted when the arc forms. But if the fault current is interrupted very rapidly, the $\frac{di}{dt}$ of the fault current becomes very large and the $L\frac{di}{dt}$ can exceed the system voltage.

Such a high voltage can damage other equipment items which are connected to the system. Therefore the maximum fuse voltage is controlled to a level beneath the system voltage to prevent damage to other equipment. So the only method to develop the efficiency of a fuse is to keep the fuse voltage under the maximum voltage which can damage other equipment, until the fault current falls to zero.

The fuse voltage waveform is dependent on the way in which the arc plasma resistance is controlled when the fault current is interrupted. In this paper, to analyze the CL fuse with the voltage varied by the arc plasma, four parameters are considered as shown in Fig. 2 below.

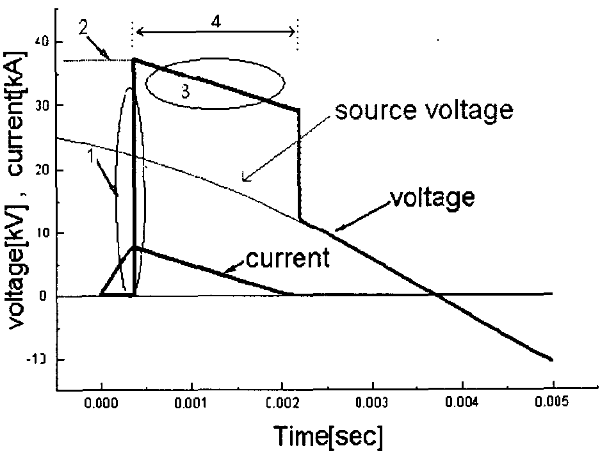


Fig. 2 Operation of the ideal CL fuse.

The first parameter is the risetime, (1), when the voltage reaches the maximum at the terminal, as in Fig. 2. The second is the maximum voltage (2) at the fuse terminal. The third is the unique decreasing characteristic of the voltage (3) until the fault current goes to zero. The fourth is the time period (4) when the fuse voltage is kept above the source voltage.

4. CL fuse's modeling

The CL fuse is modeled using these four parameters. Firstly, the melting point is determined by the joule heat energy which is $\int i^2 r dt$ without any heat sink and that energy is input as a constant value decided by the experiment. Secondly, after melting, the risetime of the terminal voltage can be changed by the circuit conditions. Also the rising voltage is represented by the capacitor charging voltage. It takes some time in the real fuse for the voltage to rise very sharply as the state varies from solid to vapor.

The start point of the triangular wave is not the current limiting point. It is in fact the melting point when the voltage reaches the peak voltage with the triangular wave. Although after melting finishes and then the element starts to cut off, some small current flows due to the remnant ionization. So the charging voltage is then rising continuously.

The risetime and voltage are calculated by equation (5)

$$C = \frac{i_{mean} \times t_m}{v_{\max}} \tag{5}$$

C : Equivalent capacitor

t_m: Risetime

i_{mean}: Average value of the current flow during the voltage rise

$v_{\max}$: Maximum voltage at the terminal.

In the third and fourth step, the voltage and the decreasing current stage are simulated using the arrester's characteristic in EMTP. The modeled circuit is shown in Fig. 3.

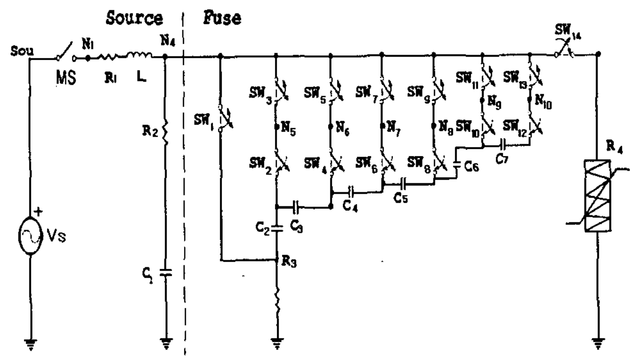


Fig. 3 The modeled CL fuse

The operation of the modeled fuse is explained as below. The left part of the middle solid line is the power source and the other part is the modeled fuse. In Fig. 3, when the MS (Making Switch) is closed between the node sou and N_1 the prospective fault current flows through R_3. The melting time can be determined from the total Joule energy. If the power source current is high, the energy of melting will be a constant value. Then the melting is unaffected by another external influence.

The power used in this model is applied to the melting fuse element during the first quarter cycle, so the constant melting energy is thus decided. As a result, after a time required for the melting energy to be passed, the closed switch, SW_1 is opened and, at the same time, the SW_2 is closed. The initial rising value of voltage at the fuse terminal is calculated by the C_2. If the fuse voltage reaches the value which is already decided at the C_2, the closed switch SW_3 is opened and the SW_4 is closed at the same time. By a series of processes such as this, if the voltage reaches the value which is already decided at C_7, the closed SW_{13} is opened and the SW_{14} is closed, so the non linear resistance R_4 operates for simulation. The parameter's values were decided by the experimental waveforms. In this circuit, the values of V_s, L, R_1 were already known and R_3, $C_2 - C_7$, R_4 and $SW_1 - SW_{14}$ are parameters for the fuse operation. The t_m, which is related to the risetime is simulated by the capacitor, $C_2 - C_7$ which is decided by the experiment. In Fig. 4, the flowchart explains the calculation process of the CL fuse.

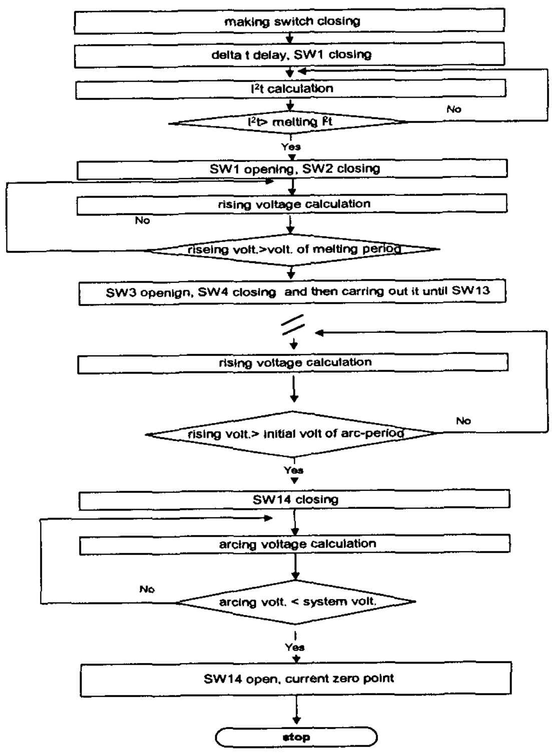
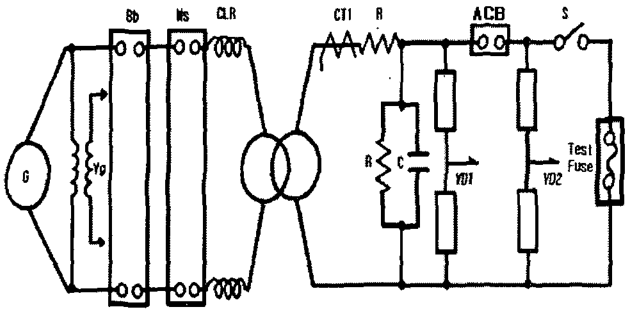


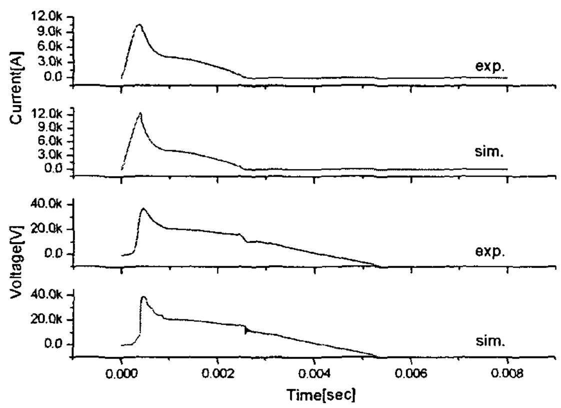
Fig. 4 Calculating Process for the modeled CL fuse

5. RESULTS AND APPLICATIONS

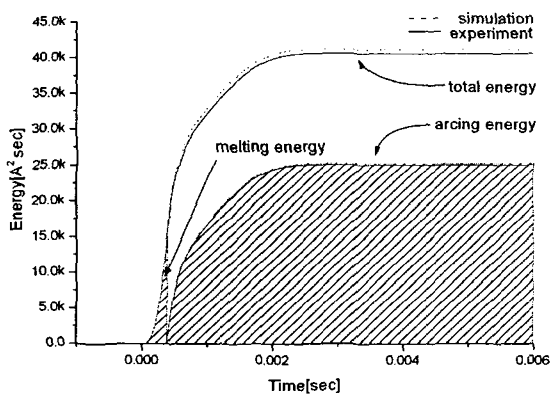
5.1 Comparison of actual tests and the simulation



G : short-circuit generator Vg : generator
Bb : back-up breaker Ms: making switch
CLR: current limiting reactor
CT1 : current transformer VD1, 2 : voltage divider
(a) Test schematic diragram of short-circuit generator



(b) Current and voltage waveform comparison between the experiment and the simulation



(c) Melting, arcing and total energy comparison between the experiment and the simulation

Fig. 5 Comparisons between the experiment results and the simulation of CL fuse at $\theta = 90°$

Fig. 5(a) shows the arrangement of a typical short-circuit generator and in Fig. 5(b), the voltage and current waveforms from the tests and the simulated waveforms are compared for the power source 15.5[kV], the rated current, 15[A], the fault current, 50[kA] and the system frequency, 60[Hz].

The maximum test voltage, exp. is 37.9[kV], and the simulated voltage, sim. is 38.3[kV]. So the difference is about 1[%]. The tested maximum current, exp. is 11.7[kA], and the simulated current, sim. is 12.3[kV]. So the difference in this case is about 5[%]. Also the melting (pre arcing) energy, the arcing energy and total energy (melting energy + arcing energy) are shown in Fig. 5(c) and the agreement of experiment and simulation is better than 5[%]. As a result we can see that the developed modeling of the fuse can be applied to accurately analyze the CL fuse characteristics.

5.2 Voltage and current characteristics variation with X/R and the making angle

The X/R ratio of the fault is important because it determines the peak asymmetrical fault current as follows.

$$I = I_0(\sin[\arctan(X/R) - \theta] \cdot \exp[-2\pi/(X/R)] + \sin[2\pi t + \theta - \arctan(X/R)])) \qquad (6)$$

The higher the X/R ratio, the higher the asymmetrical peak current. These high fault currents can cause magnetic forces and insulation damage. The actual waveform of the asymmetrical fault current is hard to predict because it depends on the time instant on the voltage cycle waveform that the fault occurs. In addition, the performance of the CL fuse depends on both the X/R ratio and the time of arc initiation because, after melting, the activation of the arc can be affected by the voltage level at the fuse terminal. For this reason, the fuse performance dependence on the X/R ratio and making angle must satisfy standard specifications[4,5].

For X/R ratios of 5 and 30, the simulated fuse current and voltage waveforms are shown in Fig. 6 for 15.5[kV], 50[kA], and $\theta = 90°$, using the simulated fuse model.

The peak of the asymmetrical fault current is decreased 4 times when the X/R ratio increases 6 times. The slope of current also varies as the peak current varies and this means that the initiation of melting or arcing can also be varied.

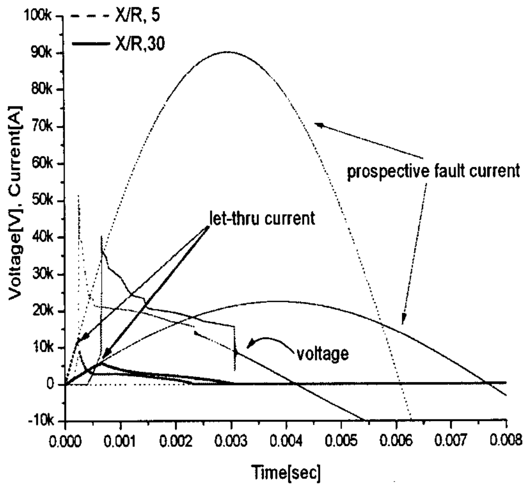


Fig. 6 Current and voltage variation with the X/R of the CL fuse at $\theta = 90°$, under test conditions of 15.5[kV], 50[kA].

When the making angle is 90 degrees, the angle of arc initiation is 5.3(≒0.24ms) degrees for X/R = 5 and 13(≒0.6ms) degrees for X/R = 30. Thus the difference in angle of arc initiation is 7.7 degrees. This is because the slope of current at X/R = 5 is smaller than at 30 and to melt the fuse element takes a longer time. Moreover the peak let through current is 12[kA] for X/R =5 and 5.8[kA] for X/R = 30. Also, the time to complete interruption is 2.3[ms] for X/R = 5 and 3[ms] for X/R = 30.

As a result, the larger the X/R ratio, the longer the arcing time. The current and voltage is simulated as the V-I characteristics of non linear resistance after arc initiation. From the V-I characteristics the higher voltage the higher the current flow. So in case of X/R = 30 it takes more time because the voltage is smaller than in the other case after the start of arcing and at the end the current becomes zero when the fuse voltage is 15.5[kV]. The main problem is the prediction of the characteristics during arcing. The fuse designer wants to be able to predict the fuse characteristics during the arcing period.

5.3 Arc energy variation with X/R ratio and making angle

The X/R ratio and the making angle are included in the simulation of the arcing period. Reference is made to the items in the interrupting performance tests in the IEEE Standard C37.41 "Design tests for high voltage fuses" and the Standard KS C 4612 "Current limiting fuses" to simulate the faults which can be generated in the field with 15.5[kV], 50[kA] for the fuse rating 20[A].

The activation of the arc in the CL fuse is analyzed with X/R ratio varied from 15 to 30 and the making angle varied from 0 to 180 degrees.

The arcing energy variation with making angle for various X/R is shown in Fig. 7. The actual test and simulation results are compared there. The test result, the bold solid line, is taken from reference [3] at 15.8[kV] and 20[kA] for 100[A], but the rating of the fuse is different. There is a problem with the different ratings as to how to estimate the way that the characteristics can be compared.

However both the actual test and the simulation show a similar tendency. As a result, there are some differences of the arcing energy with the same tendency for all of the X/R ratios and making angles within 0-60 degrees and 140-180 degrees. But there is only a slight difference during the 60-130 degree range. So the fuse designer needs to consider X/R during the 60-130 degrees range when they test to develop fuses. In addition when the making angle is within 20-40 degrees, the arcing energy is highest, however within 120-130 degrees it is smallest. The reason is the time of arc ignition. After melting, if the system voltage is rising the arcing of fuse could be more intense, so the arc energy can be increased.

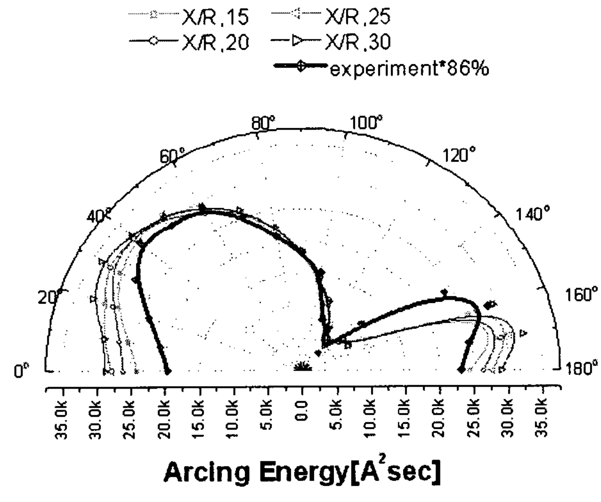


Fig. 7 Arcing energy comparison of test and simulation results and dependence on making angle and X/R ratio.

6. CONCLUSION

A fuse model based on experimental results have been developed. This model consists of switches using TACS and elements of EMTP and can be used to calculate CL fuse performance for a variety of fault conditions. In this paper, actual test results and simulation results agree to within 6[%].

Using this model, the characteristics of the CL fuse can be estimated with varying X/Rs and varying making angles. As a result both the actual test and the simulation results show similar tendencies and there is exact agreement of arcing energy for all X/R ratios and the range 60-130 degrees. When the making angle is within 20-40 degrees, the arcing energy is the maximum, while within 120-130 degrees it is a minimum.

Although this empirical model has inherent limitations, it is nevertheless a valuable tool for designers since it reveals the influence of the fuse operation characteristics on the fault energy into the apparatus to be protected, as well as reducing the number of test and development costs.

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