FUSE MODEL FOR OVER-CURRENT PROTECTION SIMULATION OF DC DISTRIBUTION SYSTEMS

MODÈLÈ DE FUSIBLE POUR LA SIMULATION DES DISPOSITIFS DE PROTECTION CONTRE LA SURINTENSITÉ DES SYSTÈMES DISTRIBUTEURS DE COURANT CONTINU

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Résumé
L'utilisation d'un outil de simulation assistée par ordinateur peut grandement faciliter la conception et l'analyse des dispositifs de protection contre la surintensité des systèmes distributeurs de courant continu utilisés en télécommunications. La présente communication fait le point sur le développement pour le logiciel SPICE d'un modèle de fusible permettant de représenter de manière exacte les paramètres caractéristiques des fusibles. Ce modèle de fusible peut également être adapté pour permettre la représentation du fonctionnement de disjoncteurs.

Abstract
The design and analysis of over-current protection for telecommunication DC power systems can be greatly assisted by the use of a computer-aided simulation tool. This paper reports on the development of a fuse model for SPICE derived software that can accurately represent characteristic fuse parameters. The fuse model can also be adapted to represent the operation of circuit breakers.

1. Introduction

The design and analysis of over-current protection for telecommunication DC power systems can be greatly assisted by the use of a computer-aided simulation tool. However, a simulation is only as accurate as the component models and element values used to represent the real world. This paper reports on the development of a fuse model that can accurately represent fuse characteristics. The fuse model can also be adapted to represent the operation of circuit breakers.

The performance of over-current protection devices significantly affects both the reliability and safety of the DC power system. Voltage excursions resulting from the operation of a fuse during a short circuit can cause electronic equipment malfunction due to over-voltage, and disrupt service due to under-voltage. Poor discrimination between protection devices can cause upstream device operation, resulting in major interruption to service.

The rapid advancement of both computing power and analogue circuit simulation programs derived from SPICE software provide a user-friendly environment for over-current protection design and analysis. This environment is advantageous as telecommunications power distribution systems are often large and complex, and developing an equivalent circuit model for a power system is not a trivial task.

The analysis of DC distribution systems using computer simulation has been shown to provide fair agreement between simulated and experimental results [1,2,3]. However, the fuse models developed have not been able to accurately represent fuse characteristics. Typical parameters for a fuse operating in a circuit with a given time constant and prospective current are rated current $\mathbf{i_r}$, peak current $\mathbf{i_p}$, pre-arcing time $\mathbf{t_p}$, arcing time $\mathbf{t_a}$, total operating time $\mathbf{t_t} = \mathbf{t_p} + \mathbf{t_a}$, pre-arcing i²t $\mathbf{(i^2t)_p}$, arcing i²t $\mathbf{(i^2t)_a}$ and total operating i²t $\mathbf{(i^2t)_t} = \mathbf{(i^2t)_p} + \mathbf{(i^2t)_a}$. Figure 1 illustrates some of these parameters. The prospective current for a circuit is the maximum current that would be reached if the fuse did not operate.

The i²t or current-squared time rating is a commonly used fuse characteristic when operating current levels are much higher that the rated fuse current $\mathbf{i_r}$. The circuit time constant defines the ratio **L/R**, where **L** and **R** are the effective circuit inductance and resistance components in series with the fuse and energy source.

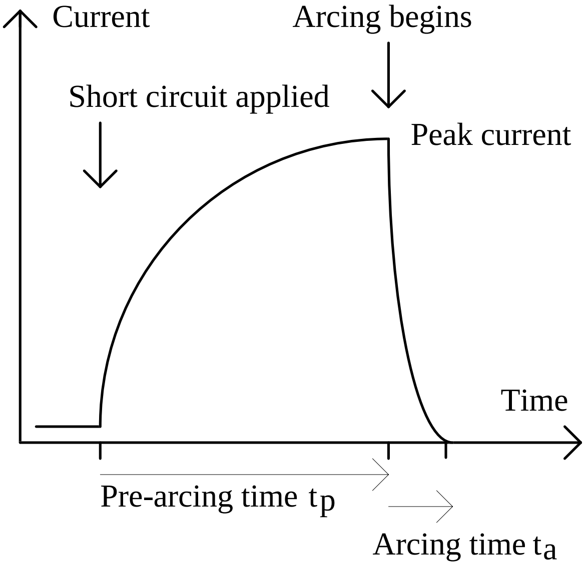

Figure 1. Some typical fuse parameters.

A fuse model is developed in Section 2 and model validation is undertaken in Section 3. Section 4 discusses the development of other DC power system component models for application to the analysis of over-current protection, and the paper is summarised in Section 5.

2. Fuse Model

The fuse model described in this paper implements two modelling functions from SPICE derived circuit simulation software; analogue switches and analogue behavioural modelling (ABM). The analogue switch has an output resistance which is controlled by either an input current or voltage. For example, when the input voltage is above 1V the switch is on (low resistance), and when below 0V the switch is off (high resistance), with a transition region occurring when the input is between 0 and 1V. ABM can describe a circuits operation using equations or tables. For instance, an output current can be generated that is equal to an input current squared.

The fuse model, shown in Figure 2, comprises a current controlled switch **Wfuse**, a voltage controlled voltage source **Efuse**, a voltage controlled switch **Sfuse**, and a current controlled current source **Gfuse**. The model functions by generating a current in **Gfuse** that is equal to the fuse current squared $\mathbf{i_f}^2$, and using this current to charge the capacitor **Cfuse**. The voltage developed across **Cfuse** is proportional to i²t and is used to operate **Sfuse**. The switch **Wfuse** only allows current to charge **Cfuse** when the fuse current $\mathbf{i_f}$ is above the fuse rated current $\mathbf{i_r}$. The voltage source **Efuse** operates as a non-linear resistor, modelling the rise in fuse resistance with current due to heating effects. The resistor **Rb** models the affects of fuse thermal loss by dissipating the voltage across **Cfuse**. Resistor **Ra** provides a current path for **Gfuse** when **Wfuse** is in an open state, and the RC network **Rc**/**Cc** provides a small time delay to ensure one-way operation of the switch **Sfuse**.

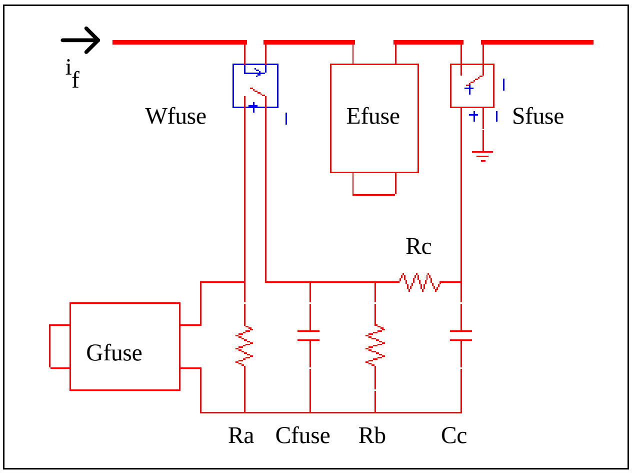

Figure 2. Fuse model.

The model accurately represents the following four fuse characteristics: 1) rated current, under which the fuse will not operate; 2) pre-arcing i²t, after which time the fuse will start to operate by limiting current; 3) arcing i²t, after which time the fuse current has reduced to zero; and 4) resistance increase with current, which includes the affects of thermal loss. The expressions describing the fuse model are now presented and have been developed for the commercial software PSpice.

Rated Current The current controlled switch **Wfuse** starts to turn on when the fuse current exceeds rated current $\mathbf{i_r}$, and is fully on when the fuse current reaches 110% of $\mathbf{i_r}$. The model expression for **Wfuse** is,

.model name iswitch(ION=1.1 $\mathbf{i_r}$, IOFF=$\mathbf{i_r}$)

Pre-arcing i²t The voltage developed across **Cfuse** is,

$$v_{Cfuse} = \int_0^t (i_f)^2\,dt \equiv \mathbf{i^2t} \qquad \text{, where } \mathbf{i_f > i_r}$$

By making the capacitor **Cfuse** value equal to $\mathbf{(i^2t)_p}$, in A²s, the voltage developed across **Cfuse** at the end of the pre-arcing time is normalised to 1V. When the voltage across **Cfuse** reaches 1V the voltage controlled switch **Sfuse** starts to turn off, and is fully off when the voltage reaches 1.2V. The model expression for the switch **Sfuse** is,

.model name vswitch (VON=1V VOFF=1.2V)

The **Rc**/**Cc** network introduces a small time delay to ensure one-way operation of the switch, and the delay can typically be minimised to an insignificant time of less than 0.1msec.

Arcing i²t The time duration $\mathbf{t_a}$ for the current to reduce to zero after the onset of arcing can be modelled by the turn-off characteristic of the switch **Sfuse**. Varying the transition range of the switch **Sfuse** controlling voltage (VOFF-VON) adjusts the arcing time $\mathbf{t_a}$ and hence the arcing i²t, $\mathbf{(i^2t)_a}$.

Resistance Increase and Thermal Loss During the application of a fault current, the fuse resistance increases with current level as the temperature of the fuse element increases towards the melting point. The resistance increase and resulting voltage drop across the fuse can be substantial. If the fault current is reduced before the i²t level reaches the pre-arcing level $\mathbf{(i^2t)_p}$, then the fuse element cools and resistance reduces back to the nominal resistance at ambient temperature $\mathbf{R_F}$.

The fuse resistance is modelled by a combination of the constant resistance of the switch **Sfuse**, and the non-linear resistance of the voltage source **Efuse**. The model expression for the switch **Sfuse** including resistance is,

.model name vswitch (RON=$\mathbf{R_F}$ VON=1V VOFF=1.2V)

The ABM model expression for the voltage source **Efuse** is,

Efuse <+node> <-node> value = { $\mathbf{i_f}$ * $\mathbf{v_{Cfuse}}$ * ($\mathbf{R_f}$ - $\mathbf{R_F}$)}

where $\mathbf{i_f}$ is the fuse current, $\mathbf{v_{Cfuse}}$ is the voltage across the capacitor **Cfuse**, and $\mathbf{R_f}$ is a fuse parameter equal to the fuse resistance at the end of the pre-arcing time.

The thermal loss of the fuse element is modelled by the resistor **Rb**, which discharges the voltage across capacitor **Cfuse**. Reducing the value of **Rb** increases the thermal loss, returning the fuse to its pre-fault state in a faster time.

Parameter Acquisition The parameters $\mathbf{i_r}$, $\mathbf{(i^2t)_p}$, $\mathbf{t_p}$, $\mathbf{i_p}$, $\mathbf{(i^2t)_a}$ and $\mathbf{t_a}$ are readily obtained from manufacturer's data for the fuse operating in a circuit with a given time constant and prospective current.

The nominal resistance of the fuse $\mathbf{R_F}$ at ambient temperature can be measured using a 4 terminal milliohm meter or measured in a suitable test circuit, as described in the next section. A measurement of the fuse resistance $\mathbf{R_f}$ taken at the end of the pre-arcing time can be made using the test circuit described in the next section.

The inclusion of resistor **Rb** in the model is optional, as it does not affect fuse operation during a fault leading to fuse operation in a short duration. The affect of **Rb** is significant only for low levels of fault current or where repetitive fault currents occur with the individual fault level below $\mathbf{(i^2t)_p}$.

Circuit Breaker Adaptation The fuse model can be used without modification to represent the operation of circuit breakers, however certain circuit breaker characteristics can only be included by adapting the fuse model. For example, to include the characteristics of minimum operating time, and other special current-time responses, may require the use of ABM using a look-up table.

3. Model Validation

Simulated results using the fuse model are compared with measured results in this section. The 32A HRC fuse from GEC Alsthom, type TIA32, was used in a high current test circuit for the measured results. The source voltage, prospective current and time constant of the test circuit are typical of the conditions existing in a high-ohmic distribution (HOD) feed of a telecommunications exchange.

The test circuit contained four 12V 35Ah Gates valve-regulated batteries, a Sprecher & Schuh 3 phase 90A contactor, a 100A/100mV 1% shunt, a 24µH 6mohm air-cored inductor, a 35mohm low-inductance resistor and the fuse under test. The three phase terminals of the contactor were connected in parallel and the contactor was manually actuated to eliminate contact bounce. The batteries were in good condition and fully charged. The test circuit has a time constant L/R = 0.3ms and a prospective current of about 660A.

The measured fuse current and voltage waveforms are shown in Figure 3. Measured parameters are $\mathbf{t_p}$=10.3ms, $\mathbf{t_a}$=0.8ms, $\mathbf{i_p}$ = 660A, and peak arc voltage = 74V. To obtain the fuse resistance $\mathbf{R_F}$ and $\mathbf{R_f}$, the fuse voltage was measured in detail during the pre-arcing period as shown in Figure 4. The fuse voltage at the start of the pre-arcing period is about 1.5V when the fuse current reaches the peak level of 660A, giving $\mathbf{R_F} \cong$ 2.3mohm. The fuse voltage at the end of the pre-arcing period is about 4V when the fuse current is 620A, giving $\mathbf{R_f} \cong$ 6.5mohm.

The simulated fuse current and voltage waveforms are shown in Figure 5. The fuse model parameters used were $\mathbf{i_r}$= 32A, $\mathbf{(i^2t)_p}$= 3,284A²s (manufacturer's data), VOFF = 1.32V and the measured values of $\mathbf{R_F}$ and $\mathbf{R_f}$. The simulated test circuit resistance was adjusted to 72.5mohm to obtain a peak current of 660A; this resistance represents the sum of the battery internal resistance, the inductor parasitic resistance, the contactor resistance and the 35mohm low-inductance resistor. The switch **Sfuse** controlling voltage VOFF was adjusted to 1.32V to obtain an arcing time of about 0.8ms and a peak arc voltage of 75V.

The simulated waveforms in Figure 5 show very good correlation with the measured waveforms in Figure 3. The simulated waveforms are shown in detail in Figure 6 to clearly show the increasing voltage drop across the fuse during the pre-arcing period, and the slight reduction in peak current during the pre-arcing period.

The main region of error in the simulated waveforms is during the transition between pre-arcing and arcing periods. The measured results show an abrupt transition, whereas the simulated results are smoother due to the turn-off characteristic of the switch **Sfuse**.

This section has shown the very good correlation between simulated and measured results of a fuse operating in a test circuit when using the fuse model developed in Section 2. Parameter acquisition for the fuse model has been shown to be simple and effective , using data from the manufacturer and results from a basic test circuit.

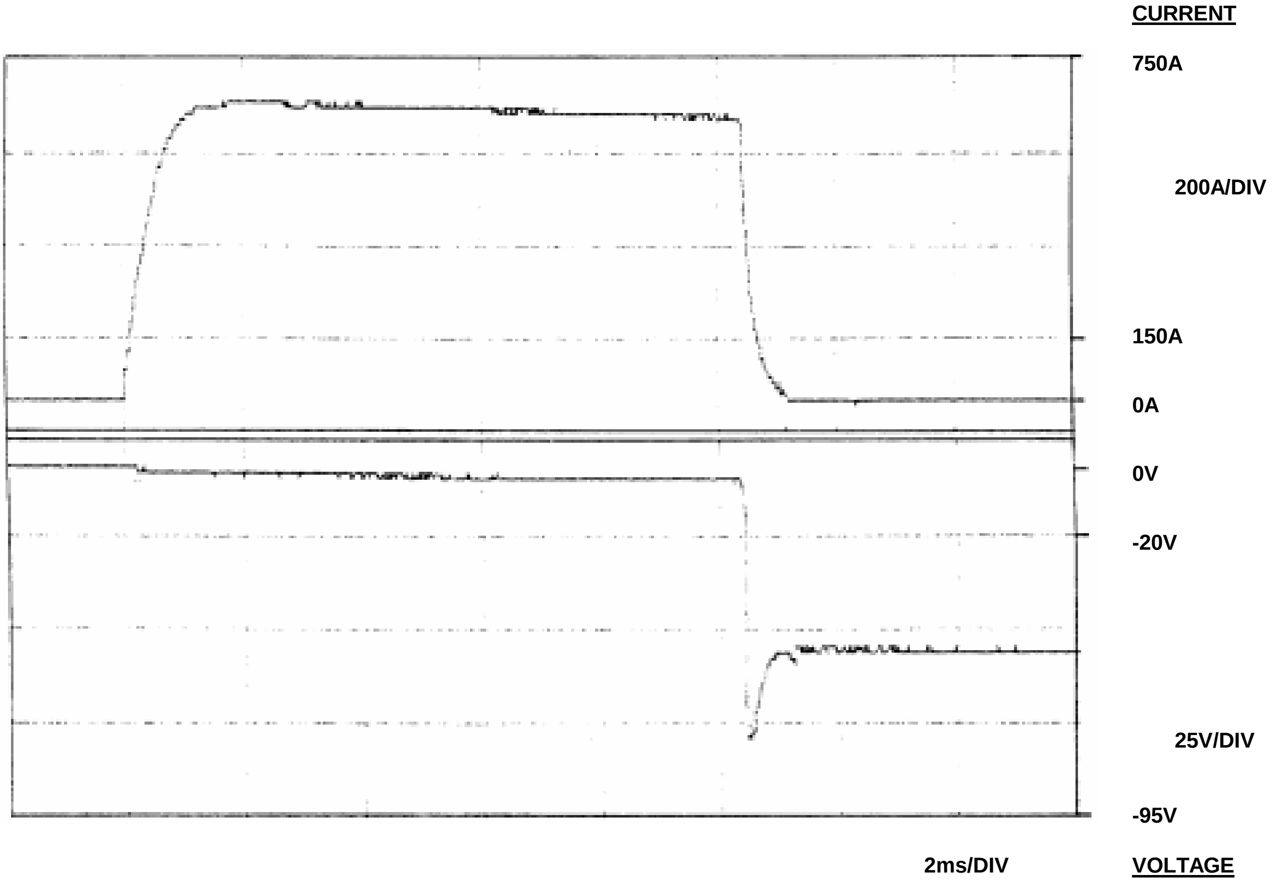

Figure 3. Measured fuse current and voltage waveforms.

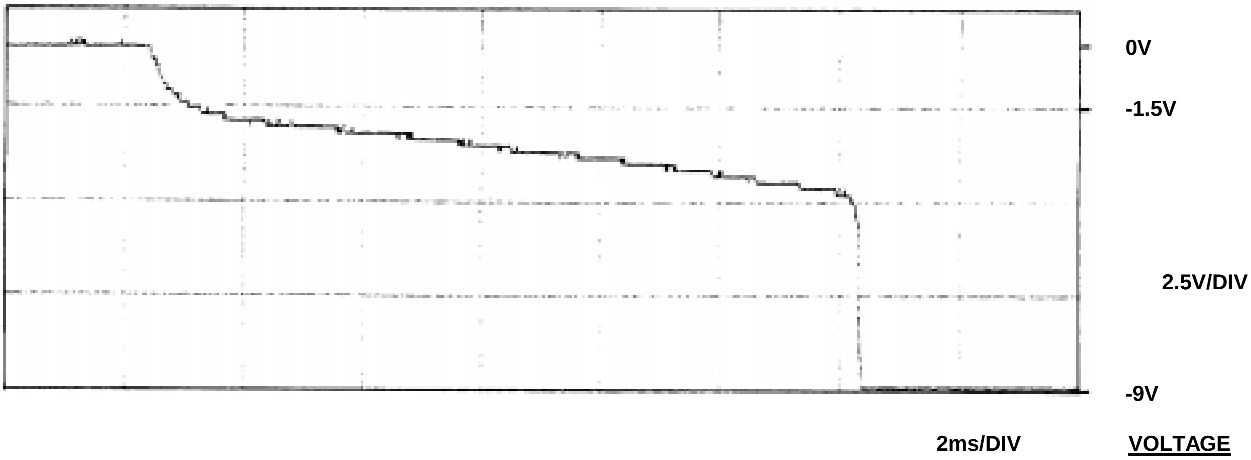

Figure 4. Measured fuse voltage waveform during pre-arcing period.

4. Application of Modelling to Distribution System Analysis

The application of simulation techniques to the analysis of over-current protection for telecommunications DC power systems is a complex task. The typical distribution system contains many elements, of which the fuse is but one non-linear device. The major power system components can be modelled to provide good correlation between simulated and measured results in an exchange environment [1-4], however many of the component models require further development to accurately represent their transient behaviour. This section briefly discusses the inadequacies of component models presently applied to distribution system analysis.

Battery Model The battery is typically modelled by a constant voltage source and parasitic series resistance and inductance. Short circuit battery currents have been shown [5] to remain constant over a short time duration (up to 10ms) but to have reduced significantly for a duration exceeding a few seconds, due mainly to diffusion polarisation. This effect could be modelled by a current-time dependent resistor using ABM.

Battery impedance measuring equipment is now readily available, allowing simple direct measurements to be made of parasitic resistance and inductance on a battery string, rather than using manufacturers' specifications for resistance and physical geometry for inductance.

Bus Bar Model Bus bar is made of rectangular copper section, and typically connects the rectifier and battery components of a central power system to the exchange equipment distribution cubicles. The bus has both positive and negative conductors which run in parallel at little separation.

We have found that the practical application of many `inductance formulae' give significant errors when applied to bus bars. However Schering [6] provides a graph of inductance curves that shows very good correlation with measurements made by Cher and Bryant [7] on typical sized exchange bus bars.

Distribution Cable Model Distribution cable is typically used to connect exchange equipment placed in racks with the power system distribution cubicles. The cables are typically run in close proximity to each other over a significant portion of their length, introducing mutual inductance effects between separate feeds as modelled by [1].

Some exchange architectures common the earth potential cable of each feed at both the distribution cubicle end and the equipment load end. This significantly lowers both the parasitic resistance and inductance values of the earth potential cable.

Inductor Model The parasitic inductance associated with any power system component displays real world high frequency losses, however a simulated inductor only obeys the equation $v=L\,\partial i/\partial t$. High levels of $\partial i/\partial t$ can be generated when a fault closes a low-impedance loop around either a battery or a large capacitor, or when a fuse subsequently opens the loop. This can occur for example, with faults close to capacitors placed in the distribution cubicles or in the equipment racks.

Significant errors in the simulated levels for voltage spikes developed across inductors can therefore occur whenever high $\partial i/\partial t$ levels exist, unless the inductor model includes high frequency effects.

5. Conclusion

This paper has reported on the development of a fuse model for SPICE derived software using analogue switch and analogue behavioural modelling (ABM) functions. The fuse model can also be used to represent the operation of circuit breakers.

The fuse model has been validated against measured results from a fuse operating in a test circuit under conditions typically existing in a high-ohmic distribution (HOD) feed of a telecommunications exchange. The inadequacies of other component models applied to the analysis of DC distribution systems has been discussed.

In summary, the use of accurate component models will allow the benefits of computer aided design (CAD) to be applied to the design and analysis of over-current protection for telecommunication DC power systems.

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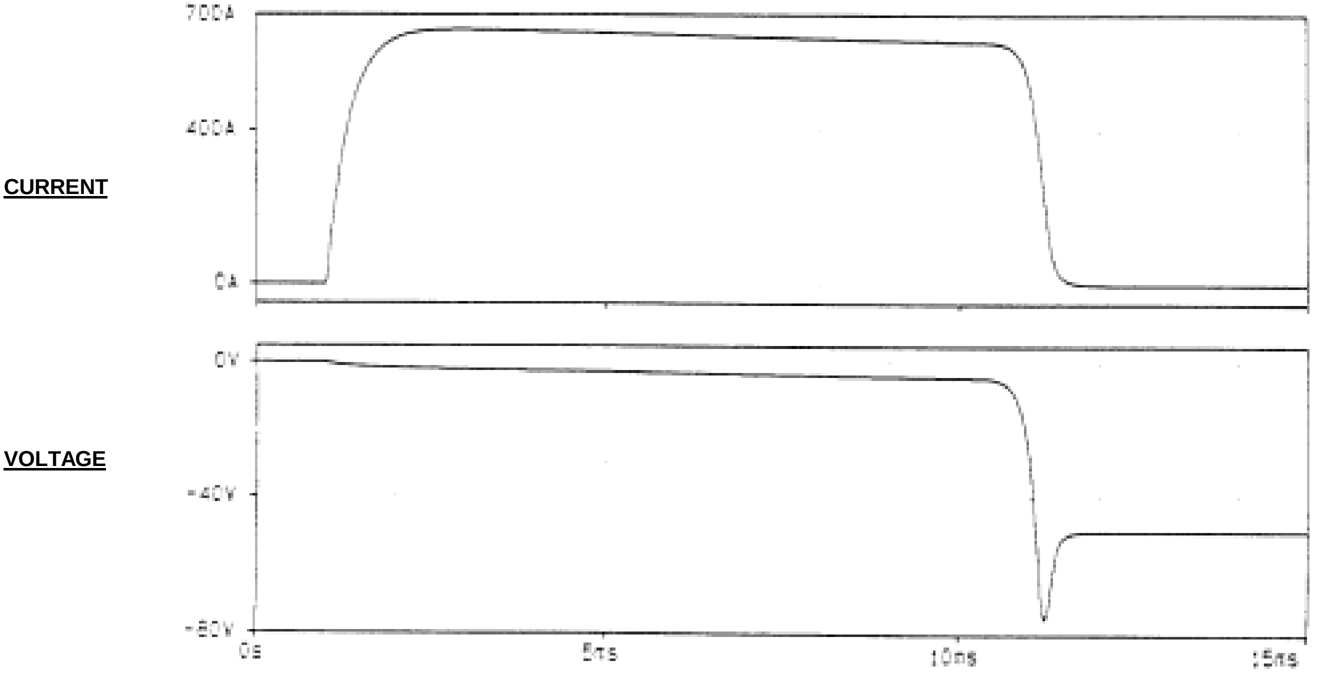

Figure 5. Simulated fuse current and voltage waveforms.

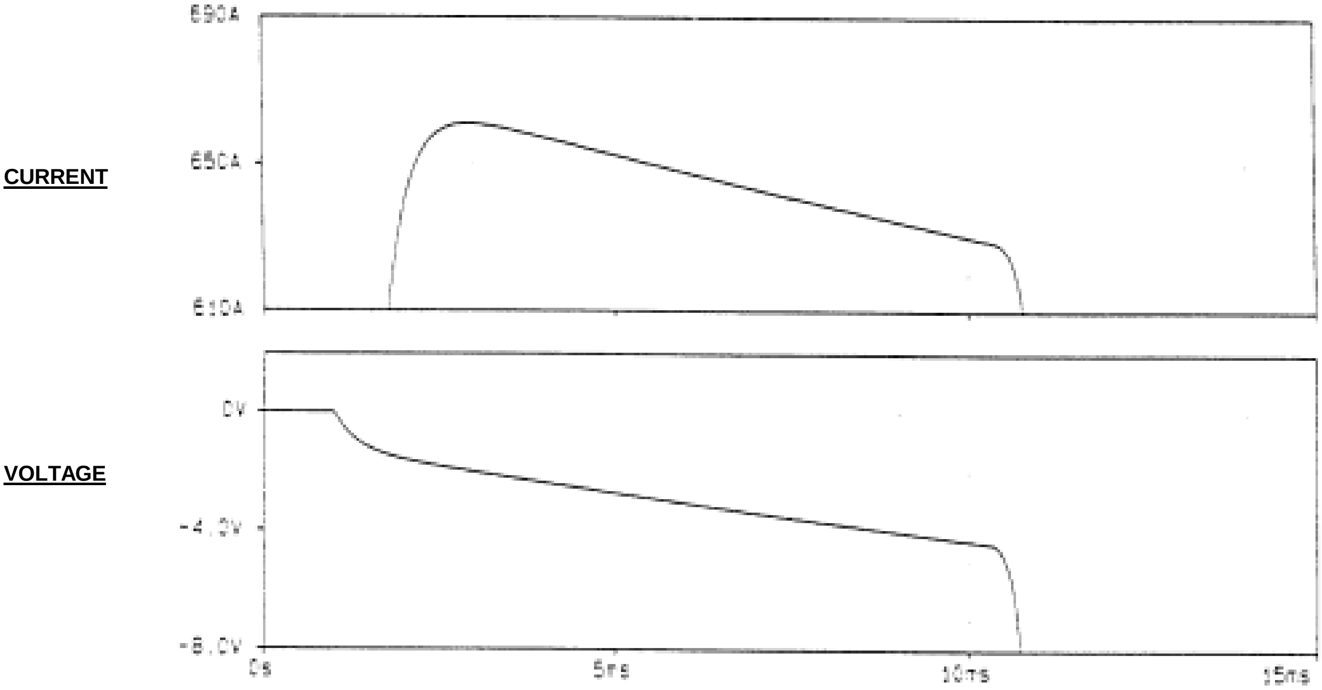

Figure 6. Simulated fuse current and voltage waveforms showing detail during the pre-arcing period.