BEHAVIOUR OF ELECTRIC FUSES IN AUTOMOTIVE SYSTEMS UNDER INTERMITTENT FAULT

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Abstract: This paper deals with the behaviour of electric fuses in automotive systems when intermittent faults occur. In this case the fuse intervention time cannot be predicted by means of manufacture fuse characteristic only but a more general dynamic model of fuse behaviour is needed. Here, a simple dynamic thermal model able to take into account this kind of fault is proposed and numerical and experimental tests are presented.

I. INTRODUCTION

Fuses for automotive systems are mainly used in order to protect electric power distribution network against short-circuiting and overloading. The most critical situations occur when fault current is comparable with the rating of the fuse; furthermore, the presence of an intermittent fault can also influence fuse intervention time; such a fault can be produced by an intermittent contact. The waveform of operating time versus fault current frequency of a stated fault current value is expected to increase monotonically in spite of some results found in literature [1] which predicted the existence of a range of critical fault frequencies avoiding fuse current interruption. These last results, based on experimental tests, require an accurate and a satisfactory validation.

The paper deals with the behaviour of fuses for automotive applications under the above critical conditions, which cannot be directly predicted by means of technical data given by manufacturers. Therefore, experimental verification were conducted, in order to identify a fuse model, both under step and intermittent input current condition. The model includes the circuit equations and the fuse thermal equations deducing model parameters from the above-mentioned experimental results. The thermal model is implemented by means of equivalence of thermal and electrical systems solved through a SPICE solver for electric circuits.

Finally, a parametric analysis, for different amplitude and frequency of the input current, has been performed and compared with experimental results.

II. TIME-CURRENT CHARACTERISTIC

II.1 Experimental Measurements

In order to perform the experimental measurements, the equipment sketched in Fig.1 is used.
The main components of the circuit are:

- DC supply: 12V
- Electronic power switch
- Current amplitude and frequency controller
- Shunt and Oscilloscope
- Automotive 10A Fuse

In particular, the current controller imposes a certain constant amplitude with changes of series circuit impedance; moreover, through the electronic power switch it sets the intermittent condition at the requested frequency and duty-cycle, controlling the rise and fall times of the current waveform.

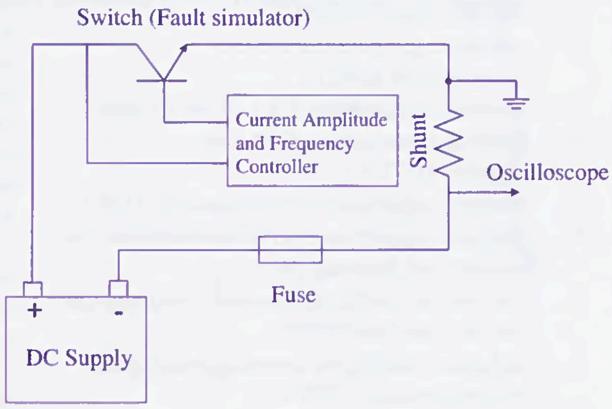

Fig. 1. Measurement equipment

II.2 Fuse Model Identification

In order to perform the simulation of the fuse behaviour in presence of an intermittent fault, an identification process of the fuse model based on time-current characteristics has to be conducted.

The fuse model presented in this paper is electro-thermal, and it is implemented by means of equivalence of thermal and electrical systems through a SPICE solver for electric circuits.

The component is represented by a bipole in which the relationship between voltage and current is dependent on fuse element and housing's temperatures with respect to the external ambient. These temperatures are function of electric power dissipated on the fuse element. The model is then based on the following equations:

a) electrical equation:

$$V = R_0 I[1+(T_1-T_0)\alpha] \tag{1}$$

b) thermal equations:

$$R_0 I^2 [1+(T_1-T_0)\alpha] = C_1\frac{dT_1}{dt}+K_{ci}(T_1-T_2) \tag{2}$$

$$K_{ci}(T_1-T_2)=C_2\frac{dT_2}{dt}+K_{ie}(T_2-T_a)^{esp}+ K_{irr}(T_{2k}{}^4-T_{ak}{}^4) \tag{3}$$

where:

- V voltage at fuse element nodes [V]
- I current through the fuse [A]
- R_0 fuse element resistance [Ω]
- T_1 fuse element temperature [°C]
- T_2 housing temperature [°C]
- T_a ambient temperature [°C]
- T_0 reference temperature for the measurement of R_0 [°C]
- T_{ik} absolute temperature [°K] of an element
- C_1 thermal capacitance of the fuse element [J / °C]
- C_2 thermal capacitance of the housing [J/°C]
- K_{ci} thermal conduction coefficient between fuse element and housing [W/°C]
- K_{ie} convection coefficient between housing and external ambient [W/°C]
- K_{irr} radiation coefficient between housing and external ambient [W/°K^4]
- α resistivity thermal coefficient for copper ($\alpha = 3.757e\text{-}3$ 1/°C)
- *esp* convection exponent

The electrical equation represents the electrical behaviour of the fuse element, in terms of a resistance linearly dependent on the difference between T_1 and T_0. The thermal equations can be interpreted as follows:

1. the thermal flux generated on the fuse element is distributed as power increasing fuse element temperature and power transmitted to the housing by conduction.
2. the power transmitted to the housing is transferred to the external ambient by convection and radiation.

This model does not take into account the thermal exchange with the contacts, supposing to consider a very large value for their thermal capacitance. Besides, in the computation of thermal flux, only the fuse element resistance is considered, in order to be closer to the manufacturer's experimental data, conducted in almost ideal and contact-free conditions. The circuit representation of the model equations is depicted in Fig.2.

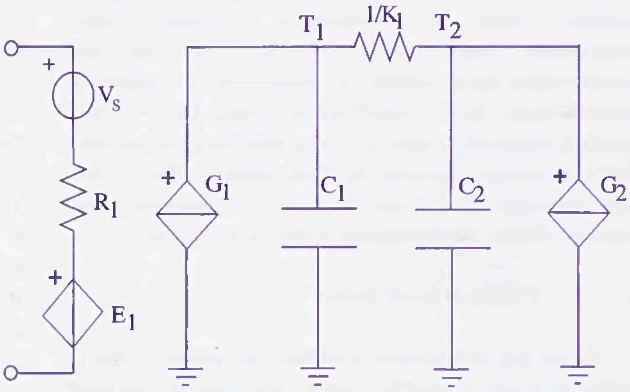

Fig. 2. The circuit model of the fuse

A bipole including the series of a resistance R_1 and a controlled voltage source E_1 implement the electrical equation. The independent source with null value V_s is a current sensor. The controlled current source G_1 is the equivalent representation of the thermal flux, whose value is the dissipated power on the electric bipole. The resistance $1/K_1$ represents the thermal conductance between the fuse element and the housing, whose thermal capacitances are respectively indicated by C_1 and C_2. The controlled current source G_2 is the representation of convection and radiation phenomena of thermal exchange between housing and external ambient.

The identification of model parameters consists in a fitting procedure whose the target is to minimize the root mean square error between the time-current characteristic calculated and the one provided by data manifacturers, for a certain set of currents. This procedure is implemented in the solver MATLAB, and is based on a specialized routine, that accepts a scalar valued function F(X) and an initial guess X_0 for the vector variable X. It returns a vector X_1 that is a local minimizer of F(X) near the starting vector X_0. In this case X is the vector of the model parameters, and F(X) is a suitable norm of the vector difference between the calculated curve and the manifacturer's one.

As can be seen in Fig.3, there is a good link between the experimental characteristics, defined by a maximum and a minimum curve, and the calculated ones, provided at two different temperatures in order to take into account the external temperature excursion during the measurements.

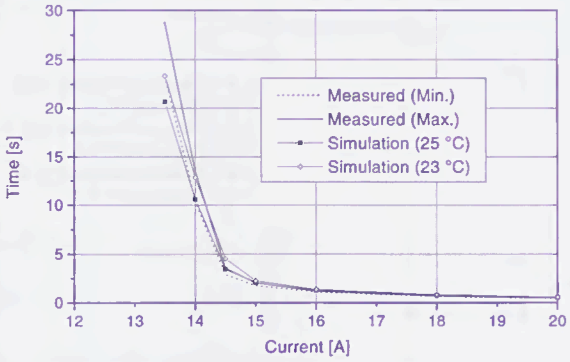

Fig. 3. Fuse time-current characteristic under step constant current

III. INTERMITTENT FAULT BEHAVIOUR

III.1 Experimental Measurements

The measurements were conducted on a 10A ATO Blade Fuse designed by LITTELFUSE. The ATO Blade Fuse is a family currently used on almost all car, trucks, buses and off the road vehicles world-wide.

The single wire used in the experiment is a 1mm^2 cross section of automotive low-voltage cable.

The simulation of the intermittent short circuit requires a stepwise current with different values of amplitude and frequency. The controller depicted in Fig.1 sets these current parameters. In particular, the values chosen for the peak of the stepwise current were 20, 22.5 and 25A. The frequency values were fixed to 10, 50, 100 and 200 Hz, and in each test the duty-cycle was assumed to be 0.5 In Fig.4 an experimental survey of the circuit current, is represented.

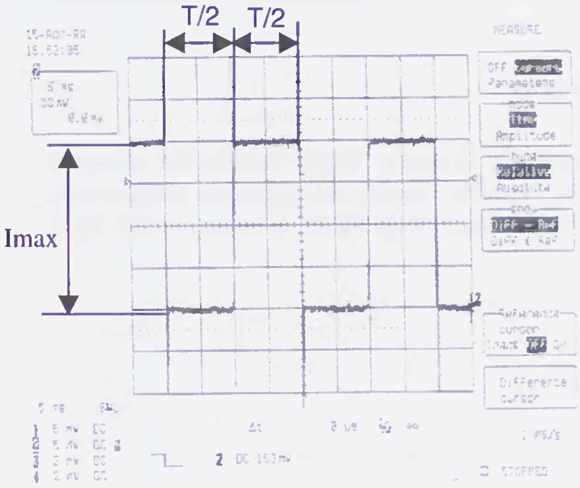

Fig. 4. Supply current during intermittent fault analysis.

At a fixed frequency and for a certain peak current value, a number up to 11 measurements was carried on, in order to take into account the statistic variance in the fuse behaviour.

III.2 System Model Identification

In order to simulate the whole electrical system, the circuit represented in Fig.5 has been implemented in the SPICE solver.

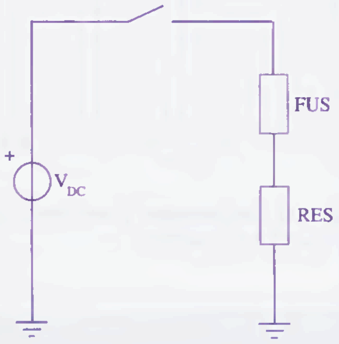

Fig. 5. The equivalent circuit of the whole electrical system

This is an equivalent circuit, that involves a constant DC source, an ideal switch to produce the intermittent current, the fuse model identified basing on the time-current characteristics, and an electro-thermal macro-model of the remaining part of the circuit.

In Fig.6 the electro-thermal macro-model of the part of the circuit including wires and terminations, is presented.

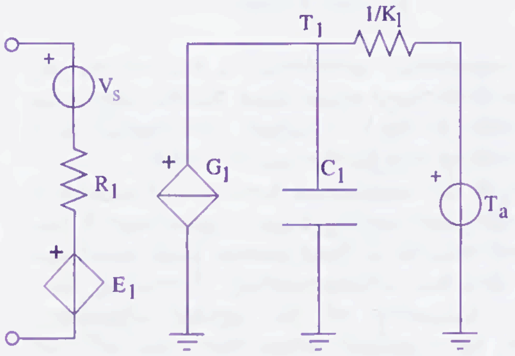

Fig. 6. The circuit model of the remaining part of the circuit

The series including the resistance R_1 and the controlled voltage source E_1, in which a certain amount of power is generated, represent the electrical part of the model. The thermal flux, represented by the controlled current source G_1, is flowing to the external ambient through the thermal conductance K_1; the capacitor C_1

represents the thermal capacitance of the electrical part considered.

In Fig.7 and Fig.8, simulated waveforms of intermittent current (Imax=22.5A) and fuse element temperature are represented for f=10 Hz and f=50 Hz.

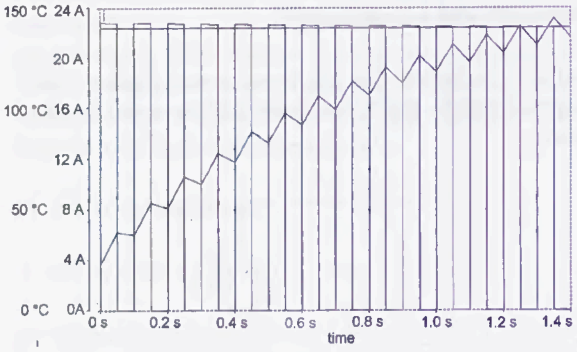

Fig. 7. Current and temperature waveforms for I=22.5A, f=10Hz

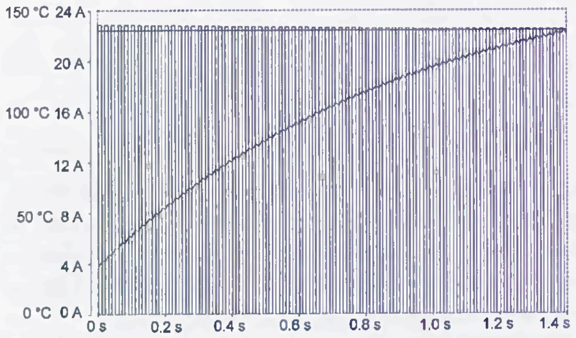

Fig. 8. Current and temperature waveforms for I=22.5A, f=50Hz

The temperature waveforms in the two curves have almost the same mean value, but the amplitude of the curve in Fig.7 is higher, contributing to a smaller melting time for the case of f=10 Hz.

In Fig.9, the comparison between the measured and the computed melting times, is presented. It can be noticed that, for a fixed current peak value, the melting time has a monotonically increasing flow with the frequency of the applied waveform. Moreover, the calculated values share quiet well the measured data, since for each couple current-frequency considered, the melting time computed is included in the range of the experimental data.

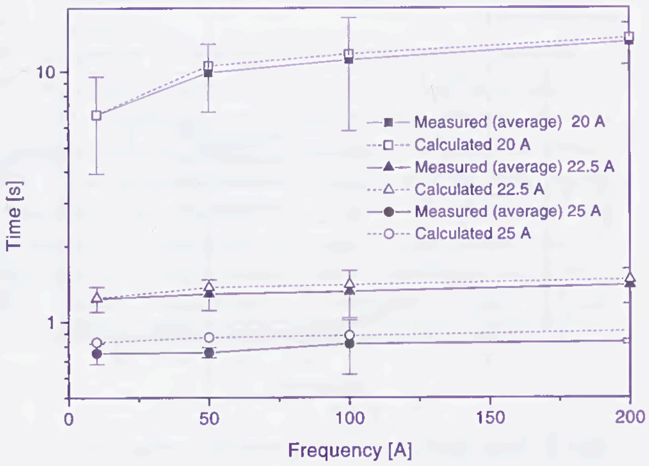

Fig. 9. Computed and measured melting times vs. current frequency

IV. CONCLUSIONS

In this paper, the behaviour of electric fuses in automotive systems under intermittent fault is examined. The condition of an intermittent short-circuit has been reproduced by supplying a pulse-wise current to a 10A ATO Blade Fuse.

A parametric analysis has been conducted; the range of current amplitude has extended from 20 to 25A, and the supplied frequency from 10 to 200Hz. Unlike the results of a typical case-study in literature [1], the present analysis has revealed a monotonically increasing behaviour of melting time with frequency of the input current.

ACKNOWLEDGEMENT

The authors wish to thank Mr. F. Quarona (Politecnico di Torino) for his support in experimental parts of this paper.

REFERENCES

[1] J. Suzuki, Y. Tamura, Japan Automobile Research Institute, "Ignition Process of Intermittent Short-Circuit on Modeled Automobile Wires", Copyright 1996 SAE, Inc.

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