EVALUATION OF THERMAL AND ELECTRICAL BEHAVIOUR OF FUSES IN CASE OF PARALLELING AND/OR HIGH FREQUENCIES

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Abstract : The calculation of the right fuse for a power semiconductor equipment is requiring more and more sophisticated calculations and simulations. Due to new semiconductors like IGBT/IGCT, fuses are undergoing high current duty cycles, high frequencies and are required by end users for longer life durations and lower I^2t.

In order to face these new requests and to understand how the fuses behave, we have developped a method which allows to evaluate thermal and electrical parameters.

This method consists in a coupling between two simple models for fuses and their surroundings.

First is a thermal model, including thermal resistances, capacitances and generators. This model takes into account fuse itself with its connections, and also heat generated by semiconductor and surrounding. The parameters for the thermal characteristics of the fuse have been expressed in a very simple way.

Second is a simulation of the circuit, using HOER and LOWE's formula [1] in order to evaluate electrical resistance, self and mutual inductances for each component of the circuit. A so-called InCa software [2] is used in this way.

Finally both models are coupled in a solver-software which gives temperature of each component and current in each conductor. The results are used for the choice ot the fuse, in addition with consideration of I^2t for protection and duty-cycles for life-duration.

An example of modelisation is presented. A specific customer application solved by this modelisation is also presented.

1. Introduction : The choice of a fuse depends on its thermal and electrical surrounding, and on electrical protection (I^2t, cut-off voltage...).

The multiplication of high frequency static converters leads to take care to high frequency effects on fuses. Numerical methods exists to solve electromagnetism- and thermal-equations. But such models are difficult to use because they require a lot of parameters such as thermal conductivity or emissivity values. The goal of our study is to have simple tools which permit to describe both thermal and electrical behaviors of the fuse. The model we need must :

- be very simple to use,
- allow to solve a lot of systems.

The build-up of those models answers to the necessity of help for fuses-design and research of solutions for customers specific applications.

Firstlty,. we will describe the thermal model, its structure with an example. Secondly, the electrical modeling will be presented. And then an example of actual application will be shown.

2. Thermal modelisation:

The general method needs parameters in order to take into account the temperature effects on the fuse derating [3]. Nowadays, numerical models based on the finite-differences resolution method [4] have been developed. But those models require data such as thermal conductivity, thermal constants values which are never well known or at least difficult to get.

The presented thermal model allows the calculation of the temperature for each element of the fuse : the copper terminals, the ceramic body and the fuse element, with the thermal and electrical characteristics of the fuse (see figure n°1). Instead of using a numerical method, we use a « global view » of the fuse, by describing thermal exchanges between its elements.

The following figures explain this global view.

Keywords : thermal design, device modelisation, high frequency power converters, diagnostics.

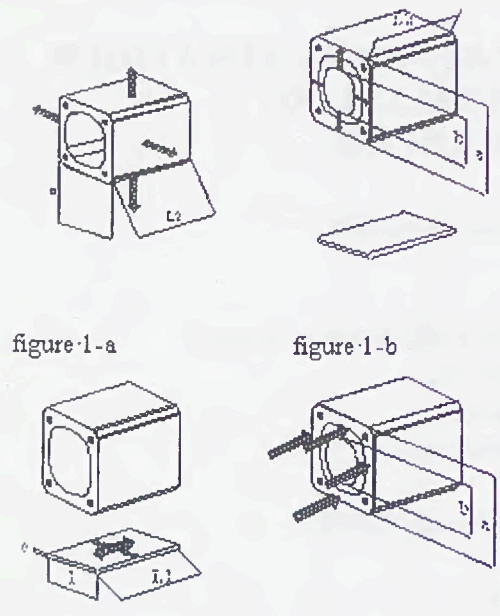

figure 1-a figure 1-b

figure 1-c figure 1-d

figure n°1

We can see the different exchange paths of the heat, and so the associated equivalent components. This method permits to reduce the number of parameters of the model, and to have very simple equations. In order to calculate the temperature we used the well known electro-thermal analogy. The model involves resistors, capacitors and current generator. Each components value is linked with very simple parameterized equations to the fuse geometry and to the material used (ceramic, silver, copper...). A statistic analysis based on tests-data allows to calculate the parameters of the model.
The integration of this model in an electrical solver (Simplorer [5], or Spice) permits to investigate several kinds of simulation, depending on the criteria to be optimized or on the effect to be underlined. By using this model, we can obtain several characteristics for a given fuse and its surrounding such as :
- Imax = f (surrounding...),
- Link size= f (Imax, surrounding...),
- Cooling = f (Imax, geometry).

An illustration of a characteristic calculated with this model is shown on the figure n°3. This graph shows the evolution of the losses in a fuse, versus the evolution of the electrical current. The resolution was made for different normalized conditions (of surrounding temperature, links size). The values were normalized in relation to the nominal electrical current of the fuse. The following figure describes the geometrical disposition of the fuse in the case C2 of simulation.

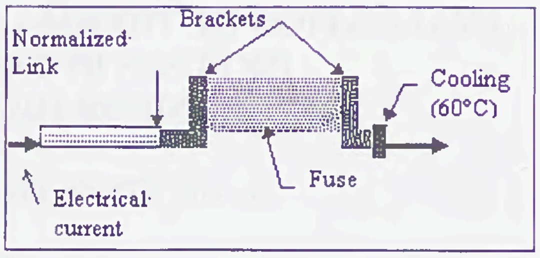

figure n°2.

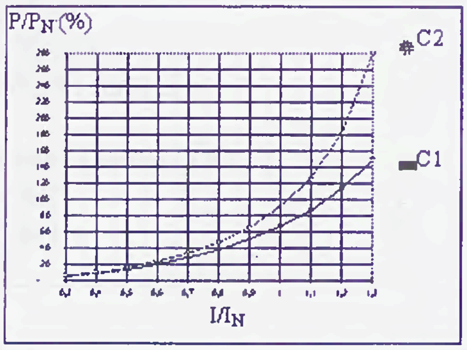

figure n°3 : example of curve performed with th thermal model.

Conditions of resolution of the lasts characteristics :

- ambient temperature = 30°C

	left terminal	right terminal
C1	Temp= 60°C	Temp= 60°C
C2	Temp= 60°C	normalized link (figure n°2)

figure n°4.

The easiness to calculate the model parameter and the use of an electrical solver permit to get those characteristics very quickly. This can be made without building a new model for each application, thanks to the solver composed of two coupled solvers : an electrical solver (based on Spice), and a state graph solver (based on the « Réseaux de Pétri » [6]).The coupling of those solvers, permits to adapt the model to any electrical application including fuse. So, it allows to predict the fuse-derating, when fuses are subjected to specific surrounding and cooling conditions.

The robustness of this model comes from the method of calculation of its parameters. More precise models could be done but our purpose is not to know the volumic distribution of temperature. The aim is to have an easy tool in order to estimate the global thermal behavior of fuses. This tool must be as simple as possible in order to be use with the electrical model for frequency-effects.

Keywords : thermal design, device modelisation, high frequency power converters, diagnostics.

3. *Electrical circuit simulation:*

As it was explained in the preceding paragraph, the choice of a fuse depends on its thermal surrounding, but not only. The evolution of power semiconductors leads to fast operatings in electrical circuits, with high current variations (and induced overvoltages) and high frequency values. It is difficult to estimate the current distribution in an electrical circuit. Measurements are also difficult to carry out. Building of a model able to solve electromagnetism equations is possible on a simple structure, but difficult on a complex one. The goal is to have simple and adaptive models . We decided to use a software which solves electromagnetism equation and gives the equivalent electrical circuit of a structure.

On a first point of view, the electrical circuit simulation considers the fuse as an « equivalent inductor » added to an existing application : the overvoltage caused by high current commutation must be limited. So the fuse inductance value must be as low as possible. As fuse works under high frequencies, the interaction between fuses and their surrounding must be taken into account. Two electromagnetic effects are involved : skin and proximity effects.

The first one depends on the frequency and can be expressed as :

$$\delta = \sqrt{\frac{2}{\omega.\sigma.\mu}} \qquad (1)$$

where : - δ is the skin depth
- ω is the pulsation $\omega=2.\pi.f$
- μ is the magnetic permeability
- σ is the electrical conductivity of the metal

and leads to unequal current distribution in a conductor (see figure n°5). The second effect (proximity effect) is caused by induced current between conductors by mutual effect (due to eddy current [1]).

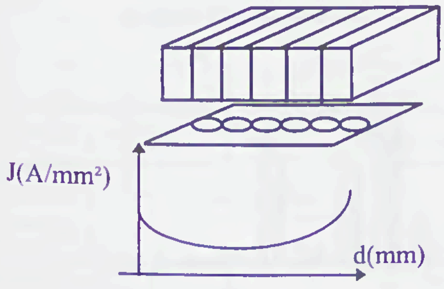

figure n°5.

The result of those interactions is an unsharing between parallel conductors (for example).

The following figure presents the effect of frequency on the current sharing between three parallel conductors. The total current is 450A. At frequencies higher than 40Hz, the unbalanced is important.

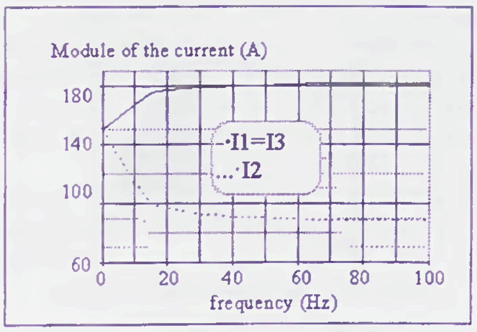

figure n°6 : Distribution of the current as a function of frequency [7]

The principle of the resolution used is based on the PEC[1] method [2]. From a geometrical description of a structure, a dedicated software calculates an electrical equivalent circuit, involving resistors, self inductors and mutual inductors.

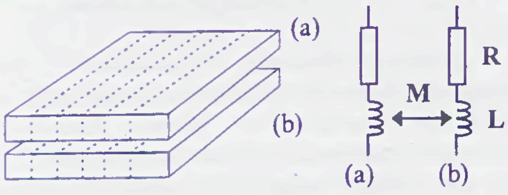

figure n°7.

After calculation, we get, , a matrix equation, describing the circuit, with the impedance matrix Z :

$$\left[\bar{V}\right] = \left[\bar{Z}\right].\left[\bar{I}\right] = \begin{bmatrix} R_1 + jL_1\omega & M_{12} \\ M_{21} & R_2 + jL_2\omega \end{bmatrix} . \begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \end{bmatrix} \qquad (2)$$

Because we use an electrical software, with the equivalent net-list file of the geometry, we can calculate the current distribution in the entire structure, and the interaction between the different elements.

The example of a coupled resolution (electro / thermal) is presented in the following section. It shows the advantage of using coupled simulation of electrical and thermal models. The study of the electrical behavior permits to know the exact value of the electrical current flowing across the fuse, and then to predict the global thermal behavior of the fuse.

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4. An example of a coupled resolution : We received a claim from a customer because fuses were subjected to a quick ageing and failure. Abnormal ageings were noticed in a power factor corrector device by a customer, specifically on the same electrical line wire. The aim of this study was to find the reason why fuses were ageing rapidly, and to find a replacement solution. One possible origin of this trouble may be a high value inductance of a coil, close to the two parallel fuses.

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[1] PEC : Partial Equivalent Circuit.

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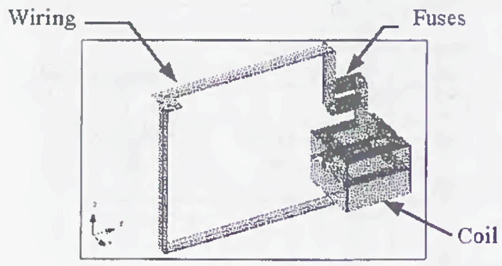

figure n°8 : InCa modelised structure

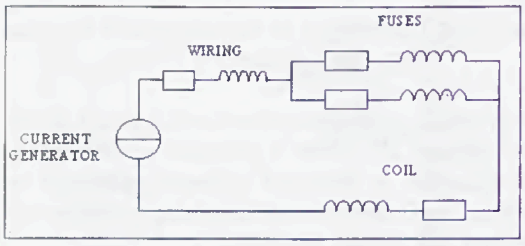

figure n°9 :Equivalent electrical circuit

The electrical simulation demonstrated the influence of this coil on the fuses, and how it derated the characteristics of the fuses. A geometrical modelisation of the wiring (figure n°8), using the software called InCa coupled with an electrical software gives the global electrical equivalent circuit on the structure (figure n°9.

Several resolutions for different frequencies show the evolution of interactions between the different elements. For frequencies from 50 Hz to 10kHz, the changes of impedances (self- and mutual-inductances are very low). The following calculations were made for a frequency of 1kHz. The first result of this resolution is an unequal current sharing into fuses elements.

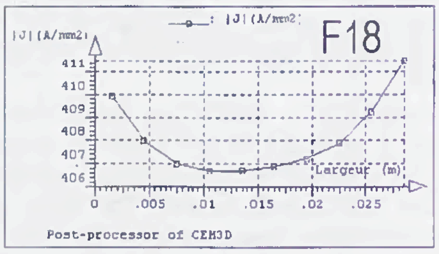

figure n°10 : Current density sharing on the width for different fuses elements.

Using the equivalent electrical circuit with an electrical software (such as Spice), with the actual current waveforms, we get the current sharing into the two fuses.

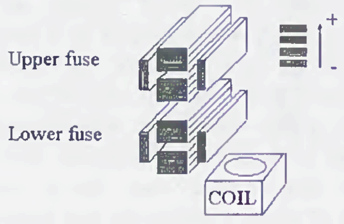

figure n°11 : synthesis of the results.

The total current across the fuses is unequaly shared into each fuse-element. For a total current equal to 100A, the upper fuse supports 45A as the lower supports 55A (figure n°12).

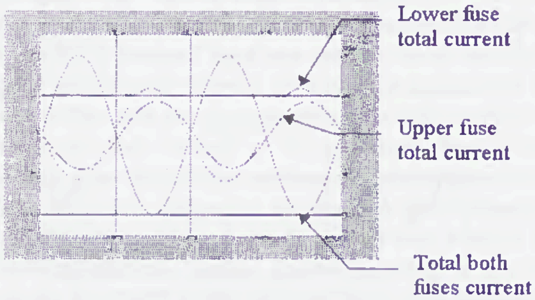

figure n°12.

And, inside a fuse (made of 8 elements), one can support 10A while another one is only flown by 1A as shown in figure n°12. The effect of the coil on the fuse is then well demonstrated.

The next step was the study of different fuses orientations, in order to find the right fuse with the best disposition. The following figures present some modelised structures.

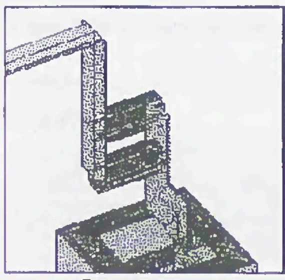

figure n°13.

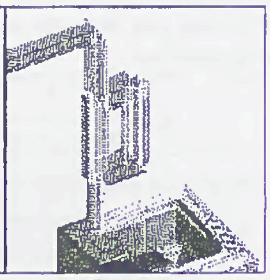

figure n°14.

More precise results of the current sharing between fuses and into a fuse are presented on figure n°15 for the geometrical disposition n°2 (figure n°14).

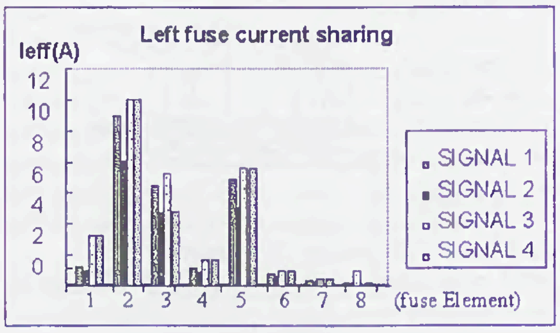

figure n°15.

Those results were performed for different electrical current waveforms (depending of the working operation of the device).

The damage of characteristics due to the coil for the parallel fuses is then well precise. All the combined currents lead to an unequal current sharing between

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fuses, and also inner fuse elements, leading to a thermal unequal heating of the different fuse elements. The result of this is mechanical stresses, whose on/off cycling leads to metallurgical-fatigue phenomenon and then to the derating of the fuse [8]. The final result can be an abnormal fuse blowing.

Research of the best solution : Changing the two paralleled fuses by a bigger one allows to minimize the proximity effect on the coil. An appropriated disposition of the fuse was determinated. The following figure n°16 shows the replacement solution proposed to our customer.

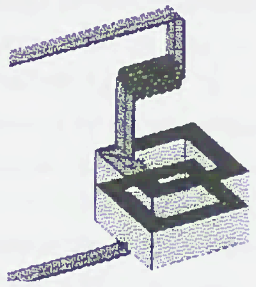

figure n° 16.

5. Conclusion

The use of coupled models allows to give quick and precise answers to specific problems, in the choice of a fuse and in its geometrical location in an electrical circuit. The global view of our thermal model permits to adapt it easily to a lot of structures. The electro/thermal resolution permits to study interactions between a fuse and its surrounding.

The principle of the solving method is explained by the following figure .

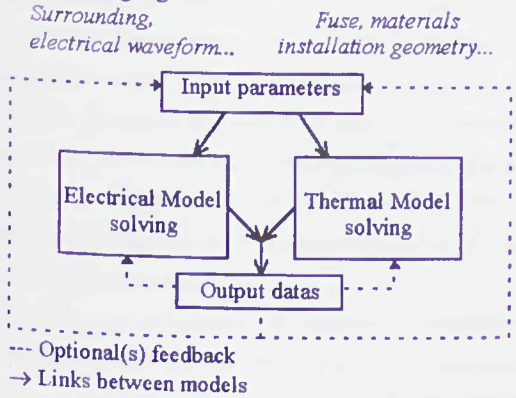

figure n°17.

Each parameter can be fixed or calculated; feedback between input(s) and output(s) can be made in order to optimize parameters (for example the cooling, the links size). Single or mixed resolution(s) can also be performed.

We have now simple tools to work on the Electro-Thermal and Electromagnetism Compatibility of fuse. We have also the possibility to simulate structures in order to optimize the choice of the fuses and eventually their design.

Thanks to those models, the global behavior of fuses is precise, and the interactions of both electrical and thermal surroundings are easily understood.

6. References :

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