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CURRENT EVALUATION INSIDE A POWER FUSE

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ABSTRACT
Power electronics components are protected using power fuses. It is a very well-known phenomenon that fuses for semi-conductors are subjected to thermal fatigue and fuses-manufacturers developed rules for a good determination of the protection. But with new semi-conductor-switches, such as IGBTB, the operational frequencies are very high (1 to 20 kHz) and it becomes necessary to understand what happens and to reconsider the behavior of the fuses in order to foresee what will happen in the field. An electrical modeling of power double body fuses is proposed in this article in order to evaluate global current and current density inside these components. The aim is to conclude on the design of these components or on their use in power structures.

KEY WORDS
PEEC method, Parasitic inductance, Current evaluation, Power Fuses

1. Introduction

Since frequency range of power semi-conductors increases, the constraints on fuses whose behavior is well known for low frequency can lead to their prematurely destruction. Indeed thermal fatigue phenomenon has to be studied [1].
So several assumptions can be made about this problem :

- The electrical environment of the fuses can introduces unbalances,
- Fuses have internal electromagnetic effects not yet underlined.

The first assumption is difficult to analyze because it depends on the application. So in this article we have focused the study on the analysis of the fuses themselves in order to know if there is an internal effect or not. Only skin and proximity effects inside are understudy. In fact, with the modeling process presented in this article it will be possible that the user of fuses gives the complete geometry of the structure in order to evaluate the impact of the environment of the fuses.

After a short presentation of the investigated structure in the following part, a model and the modeling method are shortly explained.

In part IV, application to the studied structure is detailed. In order to separate phenomenon, a first modeling has been made taking into account only the fuses and the with the connection between them. To complete the analysis, an harmonic study has evaluated the impact of the shape of the current inside the power components [2].

2. The Studied Structure

Today, the switch function of power structures is realized using several components in parallel. This problem of aging of fuses is reinforced when the number of parallel components is high, for example one common situation is from six to ten components in parallel.

The investigated structure is a double-body fuse connected in series with the components. In this article the study will focus on the fuse conduction.

Figure 1 shows the fuse inside. It is constituted by two fuses of sixteen thin plates each. These plates are usually called "fuse elements". For better understanding, half of the elements have been drawn on figure 1. The two fuses are connected in parallel so in fact there are thirty-two thin fuse elements connected in parallel.

The geometrical position of the fuses is different as it is shown on figure 1.

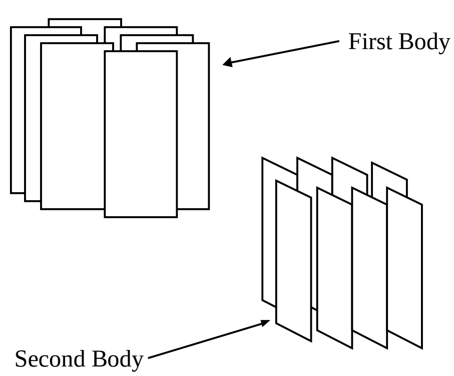


Fig. 1 : Inside the double body fuse

The modeled structure is presented on Figure 2.

The double body fuse is connected to a voltage source via a copper sheet for one side and for the other side all the elements are connected in parallel to the same potential.

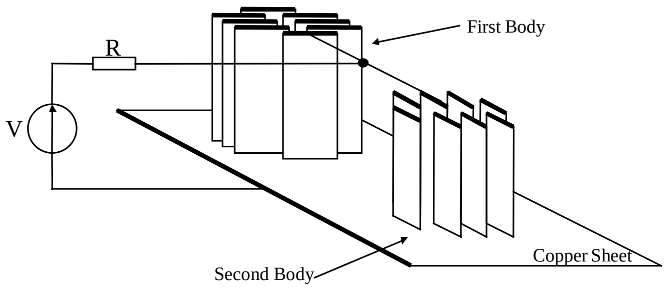


Fig. 2: The Electrical structure which is modeled

Indeed, in this kind of applications, currents are the most important values not voltages. So the resistance R is chosen so that current inside the structure is imposed by the load and not by the connections via their electrical intrinsic characteristics.

The electrical conditions are :

- a global current of 2000 A,
- a 50 Hz frequency voltage source.

3. Modeling Method and Model

The objective of the study is to evaluate the current inside each fuse and also the current density in each fuse element of each fuse.

For this purpose, an equivalent electrical circuit of fuse is determined. This is achieved using PEEC method which has been successfully used in other cases [3-5].

Thanks to this kind of model it will be possible to help the designer to know what happens inside the two fuses bodies in parallel and to analyze the frequency effect on the sharing of current between each of them. Hence some choices can be easier made such as the number of elements in parallel or the way to connect the fuses (their position). In order to separate phenomena, only the fuses have been modeled. This is necessary to better know their behavior and analyze possible currents unbalances. Even though, the designer of fuses doesn’t know anything about the cabling of the fuses and their use in power structures, it is not possible to take into account the electrical environment of the fuses. And moreover, in a second step of the modeling, the electrical equivalent circuit of fuses can help the user of fuses to optimize the cabling. Then he will be able to improve his structure and avoid some working problems.

The modeling method consists in associating to each elementary conductor such as the thin plates of the fuses an electrical equivalent circuit with lumped parameters. So the designer of the structure can directly use this very simple model. Several modeling methods exist to solve the Maxwell's electromagnetic equations. They can be divided into two classes:

- local numerical methods which are based on finite elements or finite differences. They consist in solving locally the Maxwell's equations.
- global methods : the method of moments which is a numerical method and the PEEC (Partial Element Equivalent Circuit) method which is an analytical method.

In order to replace each conductor by an electrical circuit as presented before, we will use the last method. With PEEC modeling, each thin plate is characterized by an L-R equivalent circuit. All these circuits are coupled with mutual inductance. And using a very simple meshing of the conductors [6], it is possible to take into account the frequency effect.

The electrical equivalent circuit of the investigated structure is presented on figure 3.

Then a simple electrical system has to be solved in order to obtain current in each thin plate and global current inside the fuse.

Note that this electrical solving involves complex numbers matrix since the phase shift of the current is not zero.

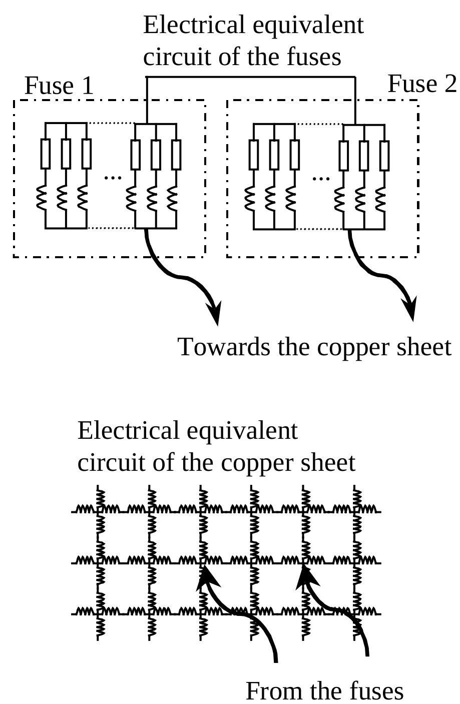


Fig.3 : Electrical equivalent circuit of the studied structure

4. Analysis of the Electrical Equivalent Circuit

In this part, the results are presented for the investigated structure. Several studies have been undertaken according the complexity of the adopted model. All models have been established at 50 Hz.

- First only fuses have been modeled in order to conclude on the current distribution between them. This leads to consider only the thirty two fuses elements.
- Then fuses are connected together using a copper sheet. This is a fuse function like commercialized packages. Since the electrical modeling of cabling has been introduced in the model, it is possible to estimate the impact of the way of cabling on current distribution inside the fuses.
- If we want to also take into account the environment of fuses, the designer has to give the converter geometry.
- Nevertheless, it is possible to analyze the influence of the frequency because since fuses are connected to power semi-conductors, current wave shapes can present quasi-vertical fronts, with very high di/dt. For that reason , we decided to study the specific case of the square signal shape. An harmonic study has been undertaken in order to evaluate the impact of such a signal with a high harmonic content.

4.1 Modeling without the copper sheet

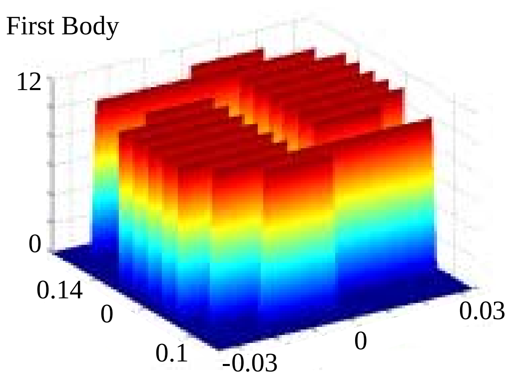
A first modeling has been made without the copper sheet, and the results are presented on table 1.

The global current in each part of the double body fuse is the same. No current unbalance exists.

TABLE I
VALUES OF CURRENT PER FUSE

	Module in A	Phase in °
First Body	1000	-8,9E-5
Second Body	1000	1,8E-5
Total	2000	-3,6E-5

On figure 4, the current distribution is presented. No skin effect and no proximity effect is detected. Global current is well distributed inside the fuse. Each thin plate is flown by the same current.



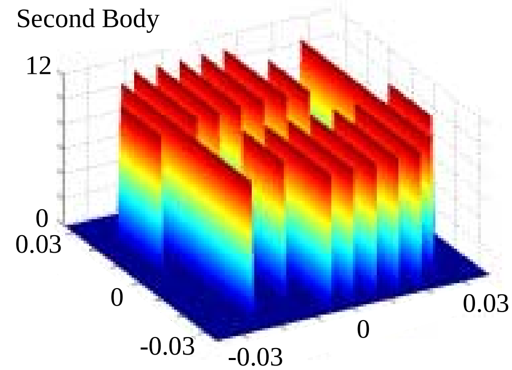


Fig.4 : Current Density inside the fuses in 10^6 A/m²

So the fuses themselves are not the cause of electrical unbalance.

4.2 Modeling with the copper sheet

If the modeling takes into account the copper sheet to associate the two fuses in parallel, the results for the global current of each fuse are presented in table 2.

TABLE II
VALUES OF CURRENT PER FUSE

	Module in A	Phase in °
First Body	1073	2,26
Second Body	929	-2,6
Total	2000	-1,5E-4

In this case a real unbalance between currents appears. This is directly linked to the way current is led to fuses (the copper sheet). So the cabling near the fuses is very important.

As for the first modeling, the current distribution inside each fuse is evaluated. The current density inside the copper sheet is also calculated. Figures 5 and 6 show the results.

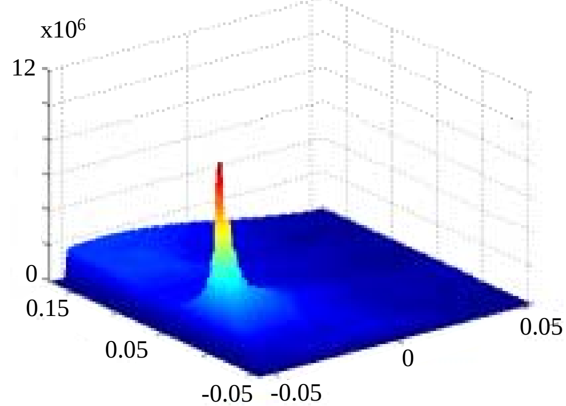


Fig. 5: Current density inside the copper sheet in A/m²

On figure 5, we can see that the smaller impedance track is preferred that is why there is a current peak in the sheet.

Not only the global current is not the same according the fuse as shown on table 2 but also inside each fuse the different thin plates are not flown by the same current. Figure 6 shows a real unbalance.

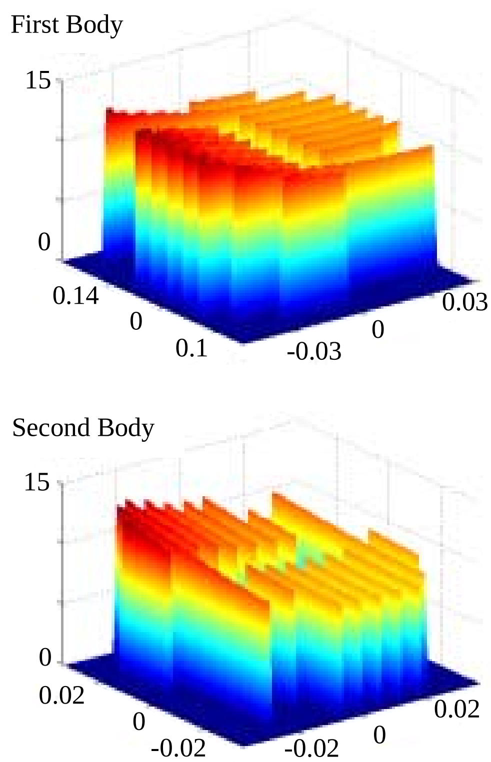


Fig. 6 : Current density inside the fuses in 10^6 A/m²

4.3 Harmonic analysis

An harmonic analysis has been undertaken in order to evaluate the influence of the shape of the current signal which is not a pure sine wave.

In order not to investigate the phenomenon only, this analysis has been made without the copper sheet.

The switches are on during a third of the period in normal working conditions. For the investigated structure, period is twenty milliseconds. If the current in the load is supposed to be constant, the current shape into the fuse is presented on figure 7.

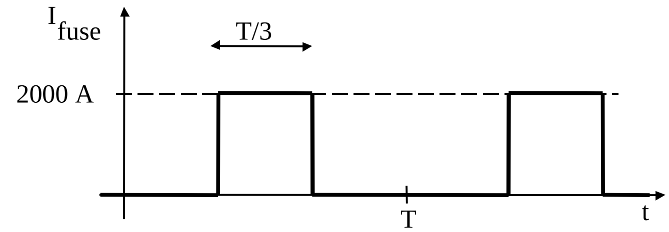


Fig. 7: Theoretical shape of current inside fuses

In fact, the electrical equivalent circuit of figure 3 leads to solve a complex electrical system (1).

$$[U(\omega)] = [Z(\omega)]\ [I(\omega)] \quad (1)$$

(1) has been solved for the different harmonic frequencies of the signal. This analysis has been made till the harmonic number 11. Then using these results the time domain current has been evaluated. Figure 8 shows the simulated current inside the double body fuse.

Then on figure 9, the Fourier decomposition of the current inside the fuse is shown without the continuous value.

In Table III the value of each current harmonic is given for the two fuses.

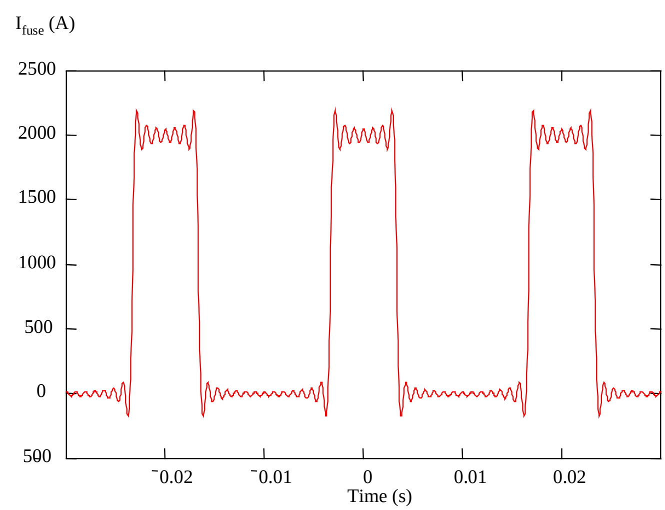


Fig. 8 : Current inside the fuse evaluated using the 11 first harmonic

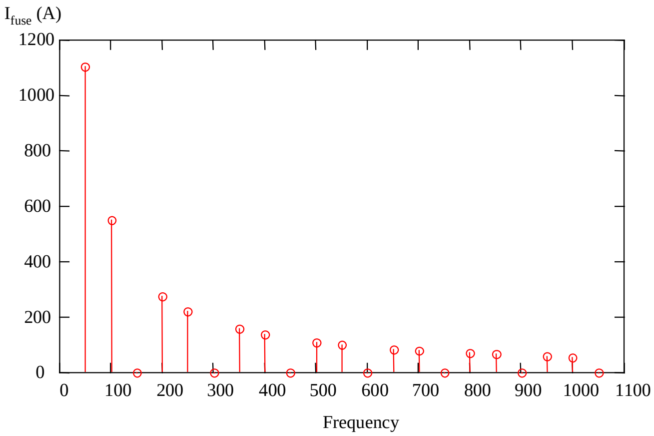


Fig. 9 : Spectrum of current inside the fuse

TABLE III
VALUES OF EACH HARMONIC CURRENT PER FUSE

Frequency (Hz)	Harmonic	Current (A)		
		Up Fuse	Low Fuse	Total
Continuous		333,6	333	666,6
50	1	552	551	1103
100	2	276,2	275	551,3
150	3	0	0	0
200	4	139	136,6	275,6
250	5	111,7	108,9	220,5
300	6	0	0	0
350	7	80	77	157
400	8	70,4	67,4	137,8
450	9	0	0	0
500	10	56,4	53,8	110,2
550	11	51,3	48,9	100,2

This table shows that the harmonics are not responsible of current unbalances between the two elements of the double body fuse.

For high frequencies, there are differences but their values are too small compared to the first harmonics to be involved in some bad workings.

So one conclusion of the harmonic analysis is to say that the great part of current unbalance between the two fuses is due to the way the fuses are connected together.

5. Conclusion

In this article, the modeling of a double body fuse is proposed in order to identify the cause of an electrical unbalance experimentally observed.

The modeling method leads to an electrical equivalent circuit. Even if there are special conditions of use and also high frequency electromagnetic effects, it is possible thanks to established models to analyze the sharing of global current between fuses in parallel, the current distribution into the elements of each fuse or their current density. The results can also be exploited in frequency or time domain.

Since the current unbalance is limited when only fuses are modeled, the modeling of the complete converter considering the fuses as simple conductors can be undertaken. This is possible if geometry of cabling is known because the evaluation of the electrical model relies on geometrical parameters of the structure.

Finally using this modeling process it will be possible to optimize the choice of fuse, the cabling of each element of the converter, …

The study has shown that the fuses themselves are not at the origin of the problem but they can be involved in unbalance-phenomena due to the geometry of the converter. It's the reason why, we should advise to consider their electrical environment and the way they are connected have to be involved in the modeling process and often they are sufficient to create an electrical unbalance.

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