Optimal design of inductors - transformers associated to converters for railway application

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Abstract — Nowadays, power converters in railway domain are more and more compact and powerful. This progress is due to the use of fast efficient components, working at high frequency like IGBT. But this evolution generates many harmonics losses in different components as inductors or transformers, and complicates their design. In addition, for the design stage, acoustics comfort is an increasingly important factor. Hence, it is necessary to develop multi-physic models in order to integrate different phenomena as the PWM effects, the temperature, and the noise. These models are coupled to an optimization tool in order to define the design rules of passive components: inductors or transformers coupled with inductor for the railway application.

I. Introduction

Even if some well-known finite element analysis tools can compute the magnetic components characteristics, their coupling can be tedious and their computational time is usually prohibitive, particularly in an optimization process. It's necessary to develop fast models with a good compromise between the accuracy of field calculations.

The aim of this paper is to optimize the design of magnetic components in order to minimize their masse, losses and acoustic noises. To achieve this goal, a multi-physical model is used, based on nodal models to keep a good ratio between accuracy and time computation. Firstly, response surfaces are computed to observe the influence of design variables on objective functions. Thanks to response surfaces, it is possible to extract the most influent variables on objective functions so that it permits to reduce the number of variables for the optimization process. In the last part concerns the use of optimization algorithm to optimize design.

II. Multi-Physics Modeling

Magnetic components, such as transformers and industrial inductors, bring into play a vast range of physical domains, such as electromagnetic, thermal and, in a lesser way, acoustic. All those physical phenomena interact onto each other, in a more or less strong way. Hence, any design process has to be taken into consideration by a multi-physical point of view. As an illustration, a synthesis of the different physical domains and their interactions between each other is shown Fig.1. The voltage and current spectrums are imposed.

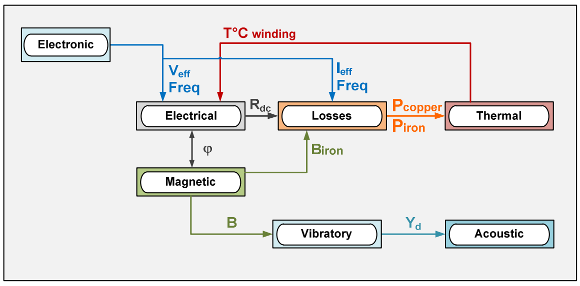

Fig. 1. Multi-physic problem with physical couplings

A. Losses model

The losses models are analytical. The Iron losses are based on Steinmetz equation. Eddy currents losses in magnetic core are computed for each harmonic current.

In the case of winding losses, proximity and skin effects are taking into account using Dowell model [1]. For each layer of copper, the DC resistance and a supplementary losses factor (AC effects) are determined. The DC resistance is computed thanks to Bezier curves equations.

B. Thermal model

A 3D nodal approach has been chosen for thermal simulation to allow the observation of local phenomena as hot spot contrary to analytical model which gives only average temperature [2]. The specifications of the model are the ability to estimate temperature in each layer of winding along the core, the magnetic core and the air ducts according to their size and position. The model takes account of conductivity and convection phenomena. Thermal tests have been done on some component to validate the model [3].

C. Vibro-Acoustic model

A spring mass model could be made by considering the two columns of the core as beams [4]. Hence, those beams can be discretized in N elemental harmonic oscillators. This model has been validated on classic beams made of pure material (like iron for example) coupled to a mass at the end of the chain. The results have been compared with finite elements simulations [4].

III. General Optimal Design

This part will be illustrated with the optimization of a DC inductor (4.5mH - 180A). Many parameters are currently fixed in the study as:

- Winding material : copper
- Winding insulation: Nomex 414
- Core material: M5X
- Conductor shape: rectangular or foil
- Total duck size: 12 mm

Once the different models finalized and assembled into a single "coupled model", it becomes possible to study the variations of the main variables representing for example, the good compromise between mass, temperature, losses and vibrations.

A. *Sensitivity study and significant factors*

The privileged tool employed is the Experimental Design Method [5] It is used to determine significant factors on the response values (screening tests).

Three factors are studied: the induction (B), the number of the coils (Ns), the current density (J); and two responses: the weight (kg), and the losses (W) (fig. 2)

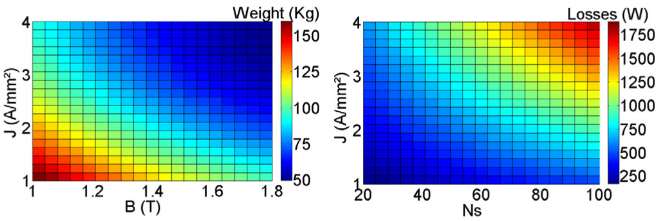

Fig. 2. Response values for the design of a DC inductor

The figure 2 shows the big influence of the 3 parameters on the 2 objective functions. It illustrates also the compromise between weight and losses with the density current variable.

As same it appears that it is important to maximize the induction value. This example concerns DC component so that increasing induction doesn't increase core losses. On the contrary, the number of spires needs to be reduced because the current is fixed, so that increasing the number of spires only increase copper losses.

Other design variables (size and place of air ducts, kind of insulation materials etc.) and response functions (vibration level, resonant frequencies, price etc.) will be tested and integrated in the full paper.

B. *Optimization algorithm*

The optimization step is done using genetic algorithms (NSGAII) [6] to find the good compromise between the weight and the losses according to some constraints as the acoustic noise level and the hot spot temperature. NSGAII is often used in electromagnetic problem due to its good ability to find global optimum with a quick convergence.

In this optimization, some others parameters are fixed:

- Induction level : 1.5T
- Number of air ducts: 1

The algorithm tries to minimize objective functions by modifying some design variables:

- Number of layers
- Number of turns
- Geometrical factor form of magnetic core
- Geometrical factor form of copper

Another Important constraint is the need of having full layer of copper. The number of turns needs to be a multiple of the number of layers. The other design variables are directly determinate and the air duct is placed at the middle of the winding. Results of optimization are exposed in fig3.

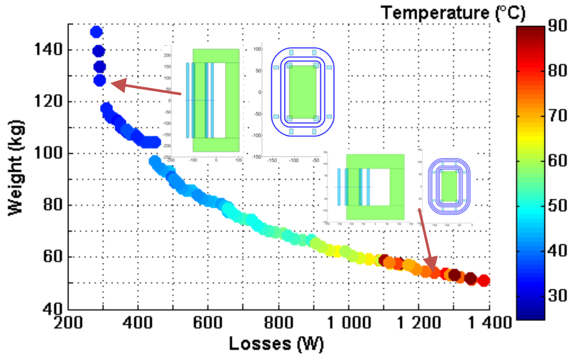

Fig. 3. Compromise between weight and losses for the DC inductor design

IV. CONCLUSION

Multi-physics modeling is realized by nodal models, which enable the possibility of taking into account local phenomena. In addition, the most important advantage is the computation time, especially in the case of coupling in a multi-physic design process.

The multi-objective optimization is done using NSGAII, an algorithm well adapted for the multi-physic model. The optimization process offers different geometric configurations of the machine that best satisfy the objectives while considering the imposed constraints.

In the full paper, we will detail the study of an AC three phase inductor, including high frequency effects. Moreover some other design variables which were previously fixed will be added to the optimization process. Design configuration obtained will be shown and explained.

V. REFERENCES

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