Multi-physics Design Rules of Permanent Magnet Synchronous Machine with Lumped Models

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Abstract — The design of dynamic behavior of electrical machines involves several fields of physics, such as electromagnetism, electronic, mechanic, thermal but also acoustic. A prohibitive computational time is required when using a coupled numerical approach such as finite element analysis. Hence, it is necessary to develop fast models that offer a good compromise between accuracy and computing time. The multi-physics lumped models which are applied to an inverter-fed permanent magnet synchronous machine (PMSM) are used. These models are coupled and totally parameterized in order to optimize the machine for traction application. Particle swarm optimization (PSO) allows us to obtain some general tendencies and different design rules. The objective is to provide a decision-making tool for PMSM design. In this summary, the study will focus on noise and torque.

I. Introduction

The PMSM is used for traction (variable speed and high power) and is supplied by an inverter. The permanent magnets are located on the surface. The first part presents four different lumped models: electronic, electric, magnetic and thermal and two analytical models: mechanic and vibro-acoustic [1] of PMSM. All physical phenomena interact among each other with weak or strong coupling. In the second part, an optimization algorithm (PSO) allows us to find an ensemble of optimal points. The optimization objectives highlighted are the maximization of average torque and minimization of electromagnetic noise while considering torque ripple. A sensitivity analysis of the solutions proposed by the Pareto front is used to complete the selection process by checking the robustness of the design of a few points.

II. Multi-physics Models

Different lumped models are defined for each physical domain. These topologies are chosen according to geometrical considerations and based on knowledge of the general direction of electrical, magnetic and thermal flux in the PMSM. The flux path is decomposed into elements in which we consider flux conservation. Each element is associated with a value (1) that expresses the capability of this element to be able to withstand electrical, magnetic or thermal flux circulation in PMSM.

$$R = \int_0^l \frac{\tau(x) \times dx}{S(x)} \qquad (2)$$

τ: Electrical, magnetic or thermal conductivity of material;
S, l: Section and length of flux tube considered;

Other elements such as inductors (end-windings effect, etc.), capacitors (transient of temperature, etc.) and sources are used to take into account different phenomena. The computation of these elements is completely parameterized.

A software implementation of these multi-physics models allows an automatic parameterized network generation. These different systems are expressed in a matrix form with the classical Kirchhoff's laws and are solved using numerical tools.

First, the electrical part uses classical circuit and is directly linked to the electronic model via the switching cells. The magnetic circuit is modeled by a permeance network [2]-[3] that takes into account saturation and movement. Further, a nodal network is used to estimate the variation of the performances due to temperature.

The expression for *electromechanical torque* of the machine is given in (3), applied to the air-gap area. It depends directly on the quantities of the magnetic model.

$$\Gamma_{em} = \sum_{u,v} \frac{\partial \Lambda g_{u,v}}{\partial \theta} \times \frac{\Delta \varepsilon g_{u,v}{}^2}{2} \qquad (4)$$

Λg: Air-gap permeance; Δε: Magnetomotive forces;
u: Stator tooth; v: Rotor pole; θ: Rotor position;

For the vibratory model, we differentiate two parts. For the natural part, the frequencies and modes of the stator are determined by an analytical approach [1]. For the exciting part, the distribution of Maxwell forces in the air-gap is decomposed in two-dimensional FFT according to the order and the frequency. The resonance phenomena may occur if spatial deformations of the two previous parts coincide at the same frequencies and involve significant level of noise.

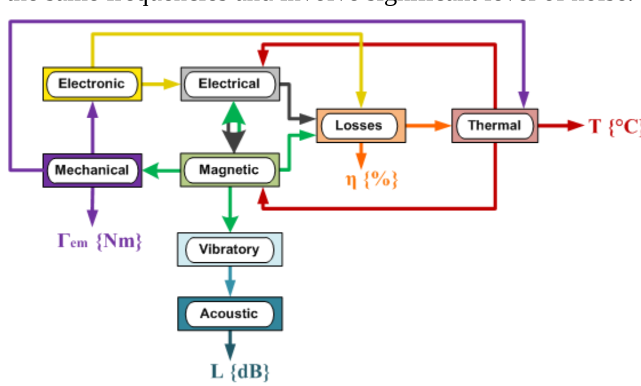

Fig. 1. Global multi-physic model and couplings

Fig.1. presents the global model along with the couplings. Electrical and magnetic models are considered in the same equation system and are computed at the same step. Input parameters for different models are: geometric,

electrical, material characteristics and PWM strategies. The output variables are: noise (L), torque (Γ_{em}) and local temperatures (T) , as well as mass, cost, and efficiency (η).

The validation of electromotive force and cogging torque is presented in [4]. The flux densities in the air-gap according to space and time are essential because they directly influence torque and noise of the PMSM and they are compared with finite element software. In the full paper, different results will be detailed and compared with experimental measurement such as noise.

III. Optimization

We have developed fast multi-physics models with a good compromise between accuracy and computing time .In order to optimize our machine for traction applications, the models are coupled to an optimization tool.

The optimization step is done using *Particle Swarm Optimization* (PSO), a population-based stochastic algorithm, which has proven to give a good balance between accuracy and computation time. The low number of model evaluations requested by this algorithm is of great interest in the case of multi-physics models [5]. In comparison to other stochastic algorithms: genetic algorithm (GA) or differential evolution (DE), the PSO has shown a faster convergence capability and stability [6].

PSO involves the experience of a number of individuals (also known as particles) in order to find the optimal solution. In the case of multi-objective optimizations a Pareto front of viable solutions is obtained which gives the best compromise between the objective functions. A number of improvements have been made in order to insure a quick convergence while avoiding being trapped in local-optima regions: fitness assignment that takes into consideration constraint violations, custom-chosen guides for each particle, border-conscious particles, etc.

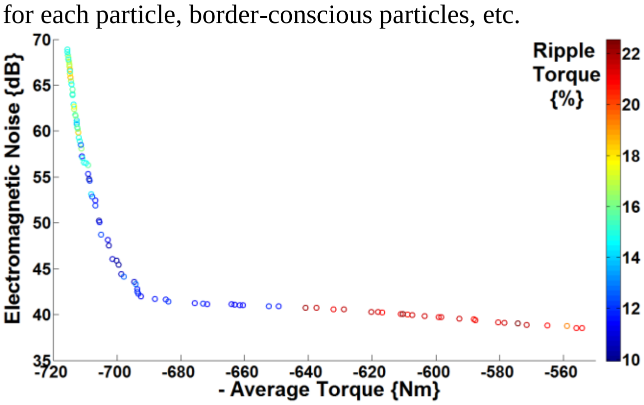

Fig. 2. Compromise between average torque and electromagnetic noise versus ripple torque (%)

The objective functions of the optimization problem are the average torque and electromagnetic noise, while torque ripple, weight and price are considered as constraints. Ripple torque is expressed as a percentage of average torque. The input parameters are all geometric: slot and magnet openings, as well as stator yoke, air-gap and magnet heights. These parameters do not influence the global volume which is kept constant throughout the process.

On the Pareto front (Fig.2.), we can observe that there is no obvious correlation between ripple torque and electromagnetic noise in the machine as detailed in [7]. The ripple torque has the maximum values for low noise, and it also depends on the machine's speed.

In addition, with a number of different Pareto fronts for different speeds, we have validated a few points using the robust design technique: experimental design. This process is necessary in order to explore the sensitivity of the optimal design. This part will be detailed in the full paper.

IV. Conclusion

Multi-physics modeling is realized by lumped models, which take into account complex geometries and enable the possibility of taking into account local phenomena (local saturation, eddy currents, demagnetization, etc.). Compared to finite elements models, the lumped models allow an easy coupling between multi-physics models and non-science models like: environmental, cost, etc. 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 PSO, an algorithm that insures a quick and accurate convergence towards the optimal solutions. 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 a complete study of PMSM for different speeds with different objective functions: noise, ripple torque, average torque, mass, cost and efficiency, and with more input parameters, for example: teeth and pole numbers. Design rules will be highlighted, particularly the compromise between noise, torque and temperature.

V. References

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