Multi-Physic Analysis of Electrical Machines: Hybrid Electro-Magneto-Aero-Thermal Modeling

Abstract**—**In this paper, a multi-physic approach allowing the accurate analysis of electrical machines is presented. This original approach exploits a generalized nonlinear adaptive magnetic equivalent circuit (MEC), a dynamic hysteresis model and an aero-thermal model. The model coupling has been applied to a radial-flux interior permanent-magnet synchronous machine (PMSM) dedicated to automotive applications. The influence of the MEC discretization on the iron loss calculation and the electromagnetic and thermal performances of the machine has been analyzed.

Keywords**—**Aero-thermal modeling, electromagnetic systems, hysteresis, iron losses, magnetic equivalent circuit, model coupling.

In the multi-physic and optimal design context of electrical machines, an original and accurate methodology is proposed and applied to a radial-flux interior permanent-magnet synchronous machine (PMSM) dedicated to automotive applications. This approach is based on an iterative coupling between a generalized nonlinear adaptive magnetic equivalent circuit (MEC), a dynamic hysteresis model and an aero-thermal model of the machine. To do so, different steps have been achieved:

1) The development of a 2-D/quasi 3-D generalized nonlinear adaptive MEC (using a mesh-based formulation) allowing the calculation of the magnetic state of the machine. This allows reducing computation time in comparison with the finite-element (FE) simulations, while providing quite similar results with a sufficient discretization;
2) The experimental characterization of the non-oriented SiFe grade constituting the machine and the modeling of its magnetic behavior. The Loss Surface (LS) hysteresis model of the SiFe alloy has been built and checked against experimental data. In almost cases, the model reproduces the magnetic behavior of the material within 10 %;
3) Once the model of the SiFe steels is established and validated, it was implemented in the FE Flux software of Altair (ex. Cedrat) as a post-processing module for the iron loss computation in the machine. Nowadays, the iron loss prediction using the LS model is implemented in Flux for a number of common non-oriented electrical steels;
4) The use of the MEC to evaluate the time evolution of the flux density in each element of the machine and then, the LS model for the evaluation of the iron losses in each element of the MEC. Indeed, in a recent previous work, a coupling between a nonlinear adaptive MEC and the LS model has been established. This original approach allows the computation of the iron losses from the magnetic flux density waveforms of the MEC. The obtained results on the same machine investigated here have been compared with those made retrospectively in the Flux software. The comparisons confirmed the validity of the approach;
5) The development of a 3-D aero-thermal model of the PMSM using the thermal lumped parameters method, which allows fast and accurate determination of the temperature distribution in its different constitutive parts by taking into account the aeraulic behavior of the machine and the power loss distribution;
6) The last step consists of coupling the MEC and the LS model with the aero-thermal model, made in Matlab® script. Based on an iterative algorithm, and starting from an initial state, the aero-thermal model evaluates the temperature in the different parts of the machine (stator teeth, stator yoke, stator teeth-tips, magnet, winding, winding heads…). The latter requires as inputs the following coupling variables: the copper losses (in the winding, winding heads) and the magnet losses, provided by the MEC and the iron losses in the different parts of the machine calculated from the MEC waveforms by the LS model. A criterion ΔT_C of 0.1°C was defined to reach the convergence of the procedure.

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