MULTI-PHYSICS DRIVE CYCLE PERFORMANCE COMPUTATION OF ELECTRIC MACHINES USING FEA

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Abstract

This works explores the modelling and computational challenges of finite element based electromagnetic-thermal coupled drive cycle performance analysis. Two laboratory scale motors are used as application cases: a 70 W 7000 rpm permanent magnet synchronous motor (PMSM) and a 4.4 kW 1430 rpm induction motor (IM). Multi-physics computations are performed for each individual operating point of the drive cycle, including a 2D electromagnetic finite element model directly coupled with a 3D thermal finite element model.

1 Introduction

Drive cycles are commonly used to evaluate the fuel consumption and emission of a vehicle [1], [2]. Drive cycle analysis within given small laboratory settings is not only challenging but the torque- and power-requirements of the real application can often not be met. However, it is possible to simulate the real drive cycles within the laboratory environment by the use of down-scaling, and thereby mimic the drive cycle performance of a real drive to a certain degree [3], [4], [5].

Modelling and simulation of electric machines for drive cycle scenarios is a computational challenge in itself. Use of both electromagnetic and thermal Finite Element Analysis (FEA) models and performing multi-physics coupled simulations is expected to increase computational accuracy but comes at the cost of time [6], [7]. By integrating multiple physical domains: electromagnetic, thermal, and mechanical, this approach offers a comprehensive simulation of how electric machines perform under different drive cycles. By simulating selected physical phenomena such as electromagnetic losses, heat generation and heat dissipation, detailed insight into a given machine's performance can be obtained. Such analysis at a particular motor operating point (OP) or a combination of a few points is very common and is a standard practice. However, understanding the complete drive cycle performance already during a machine's design stage itself has not been realized at large. Motor efficiency maps are commonly computed during the design stage, and used as look up tables to analyse the drive cycle performance scenarios. However, as these maps are created using steady-state motor OPs and/or at constant operating temperature, not much is known on the accuracy with which the drive cycle performance can be simulated, as this represents a dynamic operating scenario [8], [9].

This paper investigates the coupled magneto-thermal simulation of down-scaled drive cycles for two different laboratory motors using the FEA software JMAG [10]. It also highlights the model setup and computational challenges that come with such analyses.

2 Model Setup and Simulations

For the electromagnetic-thermal simulation of the drive cycle, a 2D electromagnetic model and a 3D thermal model of each of the motors are utilized. It is very complex to implement the full motor control system in a commercial software like JMAG, i.e., simulating both drive cycle torque and speed points simultaneously. This means, either the speed points or the corresponding torque points at a given time are used as input, and based on the model definition, the corresponding torque or speed points are simulated. To address this challenge, an alternative workflow is adopted as shown in Fig.1.

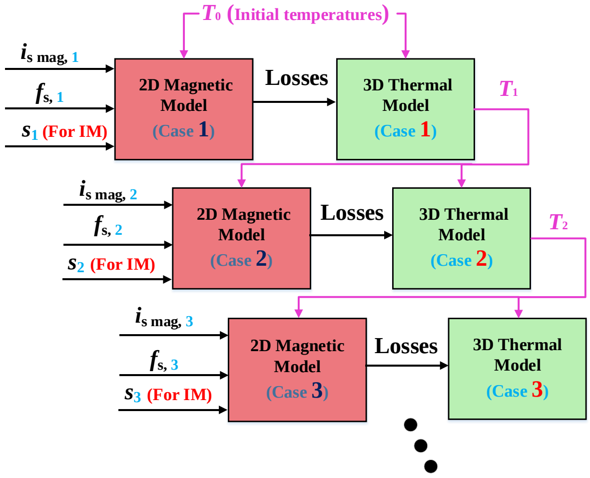

Fig. 1: Workflow of the electromagnetic-thermal FEA analysis.

Initially, all drive cycle OPs were analysed using an analytic motor model in MATLAB/Simulink. For example, for the IM, rotor field-oriented control (RFOC) was applied, while maximum torque per ampere (MTPA) was utilized for the PMSM to determine key parameters needed to achieve the desired speed and torque. The motor parameters included the stator current magnitude ($i_{s\,mag}$), stator frequency (f_s), and slip for the induction motor (s). The calculated parameters are then used as inputs to the electromagnetic model in JMAG, where both motors are supplied with a current source to achieve the specified torque reference. To integrate the 2D electromagnetic model with the 3D thermal model, a Python script was employed to facilitate automatic communication and data exchange between the two models.

At each OP, the electromagnetic simulation computes the motor losses, including stator and rotor copper and iron losses, which are used as input to the thermal model. The thermal model is executed in time steps corresponding to the time step of the drive cycle, generating updated temperatures for motor components. These temperatures are then fed back into the electromagnetic model to adjust temperature-dependent properties, such as the resistances, realizing the multi-physical approach and increasing the accuracy of the simulation results. Additionally, the updated temperatures serve as the initial conditions for the thermal model at the next OP. This iterative process is repeated for all drive cycle points, effectively capturing the dynamic interaction between electromagnetic and the thermal phenomena.

3 Analysis Results

The preliminary analysis results comprise a direct coupled electro-thermal simulation of a down-scaled drive cycle using FEA electromagnetic models and thermal models. The down-scaled WLTP drive cycle performance results for both motors are shown in Fig. 2. The preliminary results show the anticipated behaviours for both motors.

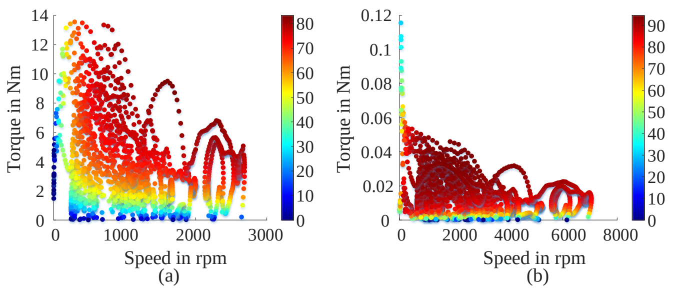

Fig. 2: Efficiency plots of down-scaled WLTP derived from coupled magneto-thermal FEA for: (a) IM, (b) PMSM.

4 Conclusion and Future Works

This study investigates the multi-physics electromagnettic-thermal coupled drive cycle simulation for two distinct electric machines at a laboratory scale, highlighting the modelling and simulation challenges inherent in such complex systems. A Python-scripted workflow integrating JMAG simulations is introduced, complemented by analytical results derived from MATLAB/Simulink. The full paper will expand upon these findings through direct laboratory drive cycle measurements of both motors.

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