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DATA-DRIVEN SIMULATION OF TRACTION ELECTRICAL MACHINES: A MODELLING STRATEGY FOR MULTI-PHYSICS DATASET GENERATION

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The design of traction electrical motors faces increasing challenges in satisfying requests for higher efficiency, speed, torque and cost reduction. Furthermore, the design of new machines must deal with the interaction of multiple physical domains, including electromagnetic, thermal, and structural aspects, leading to high computational costs. The adoption of surrogate data-driven models can significantly accelerate the optimized design of traction electrical machines. To this end, we propose a modelling strategy for the multi-physics dataset generation to build a benchmark for data-driven simulations.

Keywords:
electrical machines,
data-driven methods,
multi-objective optimization,
multi-physics analysis,
V-shaped motor

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I Introduction

The design of traction electrical motors must face new and difficult tasks, as the demands for performance in terms of efficiency, maximum speed, torque, and cost are always higher. An effective design procedure requires a multi-physical approach to address the interaction between different physical domains, such as electromagnetic, thermal, structural, and acoustic. In addition, the design problem goals often contrast each other:

- Maximizing the torque value requires higher current values, leading to higher power losses and, consequently, higher operating temperatures.
- Maximizing the rotating speed value increases the mechanical stresses on the rotor.

These examples highlight the multi-physical and multi-criteria nature of the traction electrical motor design. The multi-physical analysis can be addressed with the interaction of different analysis codes by transferring forcing terms and material operating points from one to another. These multi-physical analysis tasks are often performed in an optimization algorithm, resulting in considerable computational costs for the design procedure. However, the capabilities shown by the adoption of computational intelligence in engineering design problems help improve computational efficiency for the electrical motor design process [1-3].

Adopting a data-driven approach for the design of traction electrical motors requires defining a dataset of multi-physical solution outputs obtained by finite elements analysis codes. The obtained dataset is adopted to train the data-driven model, which can be used to surrogate the output of the traditional multi-physical analysis approach in a multi-objective optimization process framework. Our goal is to produce suitable data based on multi-physical simulations, providing a benchmark for comparing and testing the accuracy and computational efficiency of different data-driven approaches.

II Case Study

Among different possible motor configurations, a V-shaped Internal Permanent Magnet (IPM) configuration is chosen as a reference. Its geometry is described uniquely by well-defined rules, as are its material characteristics in all the physical domains involved. The encumbrance of the motor (stator outer radius and axial length) is fixed. Supply conditions and circuit data are provided.

The structure will be modelled mainly in its two-dimensional cross-section. The geometric cross-section is defined by the main aspects that can influence performance. In addition, the two-dimensional mesh is created with a suitable number of elements and a distribution that is able to return a sufficient degree of accuracy in all physical domains involved. In the following, the main hypotheses considered for each physical domain:

- Electromagnetic domain: the nonlinear magnetostatic analysis is based on the two-dimensional mesh with material nonlinearities considered at a given reference temperature. Even under magnetostatic formulation, several relative positions between rotor and stator ("snapshots") will be considered, enabling the evaluation of quantities like torque ripple, the magnetic induction waveform within iron, etc. In addition, other machine parameters, like no-load voltage, operating inductance value, etc., could also be added to the results dataset.
- Structural domain: the analysis starts from the two-dimensional mesh of the rotor, considering the maximum rotational speed at a given reference temperature. In particular, the following simplifying hypotheses will be considered:
  - the permanent magnet is constrained on the external contact with the slot, and no relative movement is allowed (no sliding between slot and magnet). The permanent magnet is not constrained on its internal side, giving rise to a worst-case scenario;
  - stresses related to the interference between the rotor core and the shaft are neglected.
- Thermal domain: in this case, the two-dimensional representation is not sufficient as axial thermal flow is crucial. Starting from the cross-section mesh, a three-dimensional domain will be created, and suitable boundary conditions, compatible with a water jacket cooling and potted end winding regions, will be applied to terminate the domain in the axial direction. In addition, the following considerations will be included:
  - In the first version of the dataset (iron and magnet losses neglected), the thermal case will be evaluated in the overload (peak performance)

condition by a thermal transient limited to the test time period of 10 s. It must be remarked that, in these conditions, the contribution of the copper losses is largely dominant over the iron ones, so they could be, in a first attempt, neglected;

- a wire winding is considered so that a homogenized material (copper + slot liner) will be adopted, while a layer of insulation between winding and slot is set;
- heat transfer at the air gap will be considered at the base rotational speed (corner speed).

III Workflow of the dataset-generating procedure

The workflow of the procedure that will build the results dataset is presented in Fig.1 and is made by the following steps:

- Definition of the parametric construction of the motor. All parameters are real-valued, and their number is p. The following physical conditions are valid for all analyses: rotational speed n_0, reference temperature for magnetic material characteristics, supply current phase angle;
- generation of N points belonging to the $\mathcal{R}^p$ space by means of an unstructured and hierarchical quasi-random sampling of the parameters hypercube, $k = 1, \ldots, N$ [4];
- generation of the motor geometry on the basis of $\mathbf{x_k}$ by means of SyR-e package [5];
- creation of the corresponding two-dimensional FEMM mesh through LUA scripting [6];
- starting by the two-dimensional triangular mesh, the analyses are performed by dedicated Matlab functions sharing the same triangular mesh and data about materials:
    - electromagnetic: calling the two-dimensional nonlinear solver FEMM, iterating on the relative position of stator and rotor to get the torque ripple. Results: T torque, TR torque ripple, PF power factor, efficiency;
    - structural: applying the elasto-static formulation, present in Matlab PDEsolver [7], on the rotor mesh with centrifugal loads at maximum

rotation speed. Result: maximum value of the von Mises or equivalent tensile stress;

  – thermal: applying a procedure based on the extrusion of two-dimensional mesh with the application of suitable boundary conditions on axial ends. Losses, both in copper slots and in iron, are evaluated by the electromagnetic model and are here used as forcing terms. Results: maximum value of temperature in steady state;

– collection of all results in a dataset containing: for each k^{th} configuration the values of the parameters $\mathbf{x_k}$ and of results $\mathbf{R_k}$.

The complete dataset will be made available to other research groups to compare their results. Details about the diffusion of the dataset and of collection of results will be given at the Symposium.

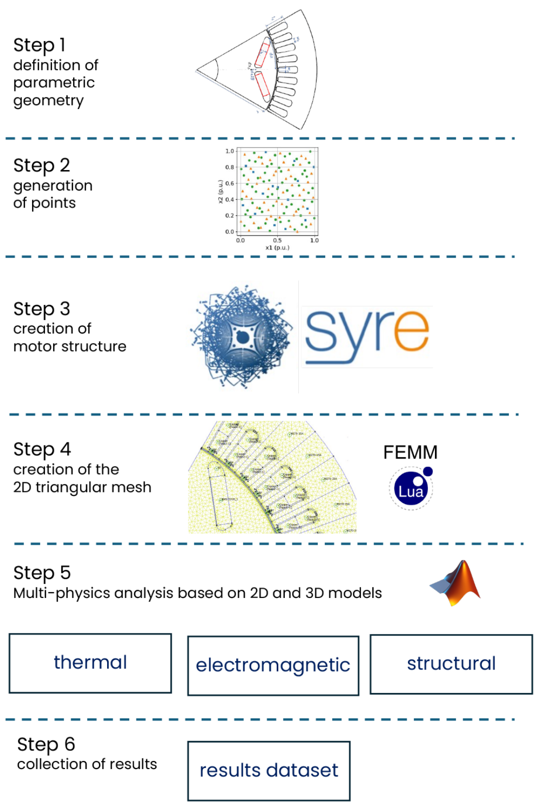

Figure 1: Workflow generating the results dataset.

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