Reduced Order Modelling for Electromagnetic Force Calculation in Electrical Machines

B. Mohamodhosen, C. Riley, D. Ilea

SIMULIA Opera, Dassault Systèmes UK Ltd., Kidlington, UK
Bilquis.mohamodhosen@3ds.com

Keywords: Design of Experiments, Permanent Magnet Motor, Radial and Tangential Force Calculation, Reduced Order Modelling, Response Surface Methodology

Abstract

This paper presents a Reduced Order Model (ROM) workflow to calculate the radial and tangential forces required for Noise, Vibration and Harshness analysis on the stator teeth of an electrical machine over a selected operating range. The workflow is applied to a permanent magnet synchronous motor Finite Element (FE) model, and a Design of Experiments is used to generate the sample points to create the ROM via Response Surface Methodology. The results from the ROM and FE model are analysed and compared for consistency and accuracy, for different operating points.

1 Introduction

Reduced Order Modelling (ROM) is a technique used to reduce the computational complexity of mathematical models in numerical solutions by producing an equivalent model with a lower fidelity that still retains the required accuracy. In this paper, we demonstrate a workflow to create a ROM to determine the radial and tangential forces acting on the stator of an electrical machine over a selected operating range, at different torques and speeds. These forces are further used for Noise, Vibration and Harshness (NVH) analysis, which is not covered in this paper.

In the first section following the introduction, we present the electrical machine used. In the second section, the ROM workflow is introduced, including the numerical tools used. In the third and fourth section, the ROM is used to determine the forces at different operating points. Lastly, the results are compared and validated.

2 Permanent Magnet Synchronous Motor Model

The Permanent Magnet Synchronous Motor (PMSM) shown in Fig. 1 is used, and one pair of poles out of the 5 pairs is modelled. The 3-phase 60 slots/10 poles motor has a nominal torque of 125 Nm and nominal speed of 10000 rpm.

The radial and tangential forces calculated in the stator teeth are subsequently exported to the NVH software for analysis [1] [2]. The ROM must therefore capture the behaviour of the forces over a selected range of operation, and be able to reproduce them for any torque or speed within that range.

The model was created using SIMULIA Opera®, an electromagnetic simulation software product within the Dassault Systèmes SIMULIA brand portfolio. The model building, solving and post-processing stages have been fully automated using Python.

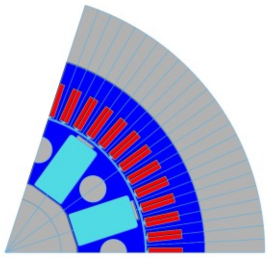

Fig. 1. 2D model of Permanent Magnet Synchronous Motor (1/5th of the full 360° model)

3. Reduced Order Model Workflow Creation

To capture the behaviour of the forces within the selected range, a number of operating points have to be simulated to create a mathematical model from the sample points. We use SIMULIA Isight®, a product within the same portfolio that allows creation of automated processes and exploration of the design space. Opera and Isight are coupled so that the FE model can be run for each sample point, and the information extracted from these runs are used by the Response Surface Methodology (RSM) algorithm to create the ROM.

To generate a good distribution of sample points over the selected range, the Optimal Latin Hypercube Sampling (OLHS) is used. We have used 500 sample points, which showed a suitable accuracy for the purpose. Once the FE model is solved for all points, RSM is used to interpolate the data, and create a smooth response surface. A meta-model in the form of a polynomial expression is then created using the least squares regression method to find the best fit for the output parameters w.r.t the input parameters. Fig. 2 illustrates the creation of the ROM. Consequently, it is used to find the radial and tangential forces for each point within the selected range.

The inputs and outputs must be correctly parameterized in the workflow. The desired operating range is prescribed by the variation of the speed N, and direct and quadrature currents I_d and I_q over a certain range of values, as given in (1)-(3). The outputs from the DoE are the torque, and the radial and tangential forces acting on the stator teeth, as given in (4)-(6).

The average torque, and radial and tangential forces are calculated over one pole pair. This results in an array of values for each force. However, to use the force signal in an efficient way, we decompose it into its Fourier terms, and use them as outputs. Once we have the Fourier terms for each signal, they can be used to reconstruct the forces. This has the benefit of making the creation of the ROM through RSM much easier and faster.

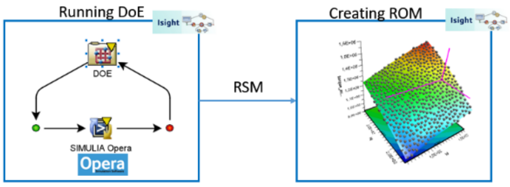

Fig. 2. Workflow to create Reduced Order Model

$$-162 \leq I_d \leq -62 \quad (1)$$
$$176 \leq I_q \leq 276 \quad (2)$$
$$0 \leq N \leq 10000 \quad (3)$$
$$T = h(I_d, I_q, N) \quad (4)$$
$$F_r = f(I_d, I_q) \quad (5)$$
$$F_t = g(I_d, I_q) \quad (6)$$

4. Creating the Reduced Order Model

A cubic polynomial is used to build the meta-model, which is sufficiently adequate in this case. A cross-validation error analysis is also done to minimize error between main and ROM data.

Each output (radial & tangential forces) is represented by its Fourier terms up to the 4th harmonic order, and therefore we have 9 terms for each output force: 4 cosine terms (a_1-a_4), 4 sine terms (b_1-b_4) and 1 dc term. The expression for each one of these 9 Fourier terms ($\boldsymbol{f}_{x_n}$) is in the form of (7),

$$f_{x_n} = K + a.I_d + b.I_q + c.I_d^2 + d.I_q^2 + e.I_d.I_q + f.I_d^3 + g.I_q^3 \quad (7)$$

where coefficients a-g and K are determined by Isight's RSM for each output, *x* is either radial or tangential, and *n* is the sine/cosine term and harmonic order, e.g. a_2 is the cosine term of 2nd harmonic order. Note that (7) does not include any terms for speed *N* as we do not look at the dynamic effects of induced currents in the model.

5. Using the Reduced Order Model

Practically speaking, the user must be able to find the radial and tangential forces by inputting the torque (*T*) and speed (*N*) rather than I_d and I_q values. Hence, an additional step is required, as depicted in Fig. 3.

To find the values of I_d and I_q for the desired torque and speed, a Nonlinear Sequential Quadratic Programming algorithm is used to solve the optimization problem defined in (8). This is shown in the first section of Fig. 3.

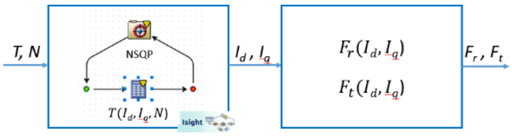

Fig. 3. Using the ROM with Torque *T* and Speed *N*

$$\min \left\{ \sqrt{(I_d^2 + I_q^2)} \right\}$$

Subject to:

$$h(T, N, I_d, I_q) = 0$$
$$-162 \leq I_d \leq -62 \quad (8)$$
$$176 \leq I_q \leq 276$$

Once I_d and I_q are known for the operating point, the second section of Fig. 3 can be used to calculate the forces by using the ROM created in section 4.

6. Validating the Results

We want to find the radial and tangential forces at $T = 129\ Nm$ and $N = 3000\ rpm$. Using the method in Fig. 3; we find the values: $I_d = -138.9$, $I_q = 219.6$. We then use the ROM created in Fig. 2 to get the radial and tangential forces. Fig. 4 compares the radial force from the FE model and ROM; a good match between the Fourier reconstructions can be seen (green and grey curves). More results will be presented in the final paper.

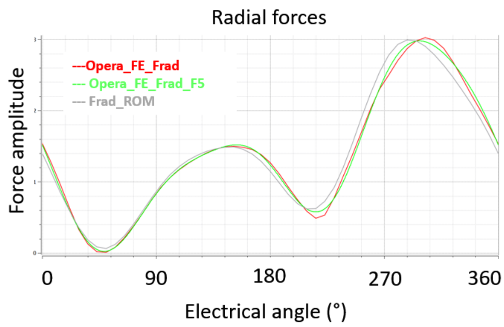

Fig. 4. Radial forces from FE model and ROM

Acknowledgements

This work was carried out within the EDISON project, funded by Innovate UK, which is part of the UK Research and Innovation national funding agency investing in science and research in the UK.

References

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