The Role of Temperature-dependent Material Properties in Optimizing the Design of Permanent Magnet Motors

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The effects of temperature-dependent material properties, including those of silicon steel and permanent magnet materials, on the design process of inverter-fed permanent magnet motors are investigated in this work. The magnetization curves of the materials are measured experimentally at different temperatures and imported into a finite element package. Then, a statistical study of an integrated motor-drive system consisting of an interior permanent magnet motor connected to a space vector modulated inverter is performed by assigning four different temperatures and building a design space of various objectives including the integrated system efficiency, the speed limits, the motor start-up quality, the torque ripple, the total harmonic distortion and the power factor as the geometrical dimensions are varied. The results reveal that incorporating the realistic material properties into the design process is essential. Moreover, different motor-drive performances have totally different variation rates as the material properties are changed. Some of them, such as the starting torque, increase while others, such as the total harmonic distortion, decrease upon increasing the motor temperature.

***Index Terms*—Design optimization, inverter, permanent magnet motor, temperature, material properties**

I. Introduction

Electrical machines consist of materials including silicon steel, permanent magnets (PM) and copper. The electrical and magnetic properties of these materials change with the operating temperature. The variations of these properties also affect the performance of machines. Therefore, incorporating the effects into the simulation process is critical for precise machine sizing. Sometimes, the transient thermal behavior of machines is analyzed using analytical or numerical approaches [1]- [3]. Although this is a promising way of dealing with a performance analysis process, it usually suffers from the lack of a proper knowledge of the effect of temperature variation on material properties including the magnetization curves. However, previous studies clearly show the importance of taking the temperature-dependent properties into account [4]. Thus, this work aims at incorporating the mentioned properties into a detailed design process of an inverter-fed interior permanent magnet motor (IPM) and performing a statistical study of the motor-drive performances at four operating temperatures, each distributed uniformly over the motor components. It is basically an analysis at different pre-defined temperatures using the material properties and the loss curves at those operating temperatures. So, the major assumption is to have the temperature distributed uniformly over the motor components. Otherwise, a transient thermal analysis which is time-consuming, especially in the case of a relatively large number of samples (12000 in this study), is required.

II. Simulation process

Fig. 1 illustrates the simulation process by means of which the following aspects are handled.

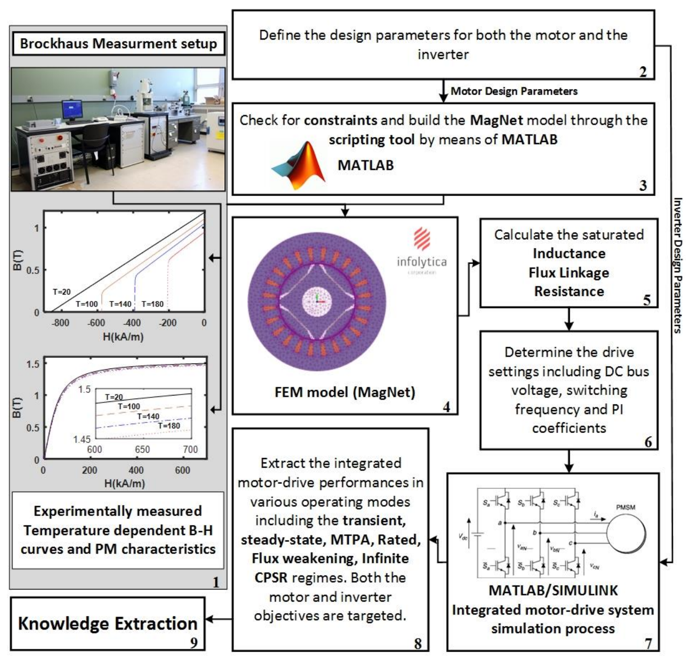

Fig. 1. Simulation process of inverter-fed permanent magnet motors

1. Importing the temperature-dependent material properties, those of the silicon steel (35WW300) and the PM (NdFeB), into the MagNet package [5]. The properties are measured at the temperatures 20°C, 100°C, 140°C and 180°C using the setup developed by the Brockhaus company.
2. Defining the design parameters along with the corresponding ranges using MATLAB.
3. Exporting the motor dimensions and materials to MagNet using MATLAB.

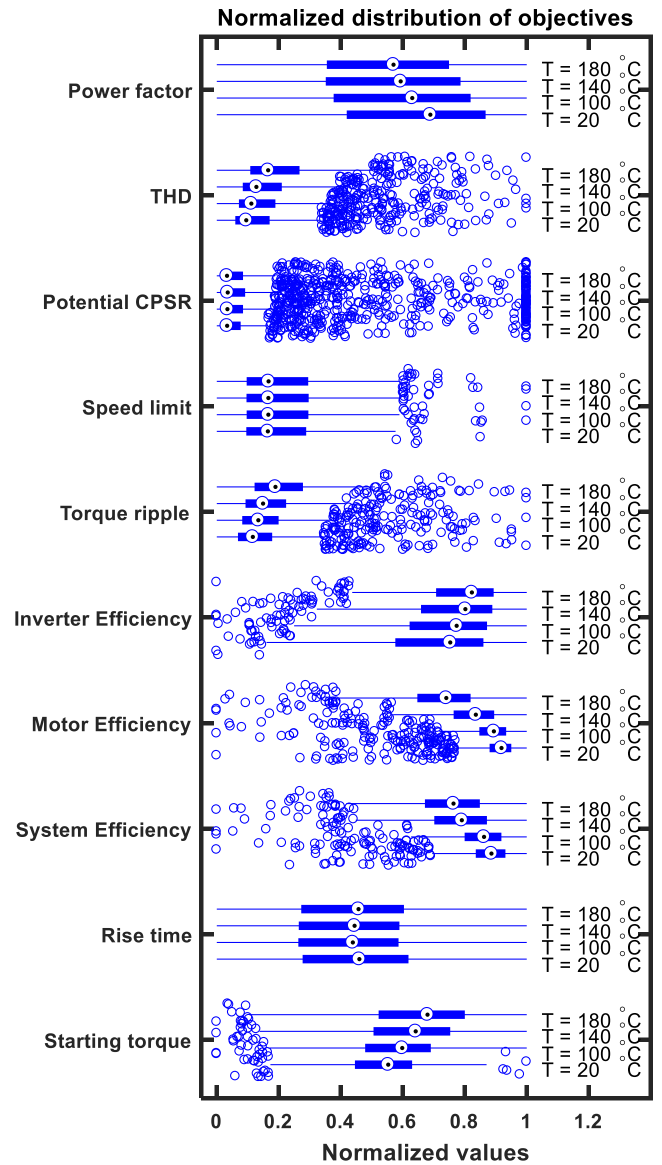

Fig. 2. Distribution of the motor-drive performances at different temperatures

4. Constructing the motor model using MagNet and computing the operational inductances, the flux linkage, and the resistances.
5. Passing the obtained values to MATLAB.
6. Adjusting the integrated motor-drive system parameters in SIMULINK.
7. Running the motor-drive system simulation using SIMULINK.
8. Extracting the performances in the transient, rated and flux weakening operations.
9. Providing the design knowledge.

III. Results

Fig. 2 shows the results of the simulation process applied to four different temperatures: 20, 100, 140 and 180 degrees celsius distributed uniformly over the motor components. The distribution of the motor-drive performances is obtained by simulating 3000 designs at each investigated temperature. The performances are normalized to a unity range using the technique discussed in [6]. Some of the features extracted using the average values of the distributions, shown by white circles in Fig. 2, are:

- The motor power factor has a decreasing trend as the temperature increases.
- The total harmonic distortion (THD) has an increasing trend.
- The CPSR which is a measure of the motor quality in the flux weakening operation is almost fixed.
- The efficiency of the motor is in accordance with the integrated system efficiency while the inverter efficiency variation reveals a different trend to that of the temperature variation.
- The rate of increase of the motor rise-time is smaller than that of the starting torque.
- The speed-limit defines the maximum available motor speed normalized with respect to the rated speed regarding the DC bus voltage. In the simulation process, the DC bus voltage and the switching frequency are set to 400V and 12KHz, respectively. This will be further discussed in the full version of the paper.

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