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Selective rotor assembly using fuzzy logic in the production of electric drives

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Abstract

The growing sector of sustainable mobility requires an increasing number of electric drives for automobiles, thus increasing the need for their efficient mass production. In current production scenarios, End-Of-Line (EOL) inspection is applied to determine the quality of the assembled final product. The work presented in this paper is developed in the project MuProD, which aims at developing an innovative quality control system to change the current concept of EOL quality control. The case under investigation is the production of electric drives where the rotor is composed of several magnetized stacks. The magnetic properties of each stack differ due to variations of the single magnets and the magnetization process itself. In addition, handling of the magnets within the production line may cause cracks that decrease the strength of the magnetic field. This paper proposes a new solution for deviation compensation in the production of electric drives by selective assembly based on a crisp classification and a Mamdani style fuzzy inference system. The magnetic field of each stack is measured after the magnetization stage, yielding a discrete space-resolved magnetic profile. This magnetic profile is transformed into another feature space through a combination of feature selection and feature extraction to reduce the dimension. Based on these new features, the stacks can be classified into crisp sets. In the second part, an appropriate fuzzy rule base for the matching of the stacks is developed to obtain a uniform magnetic field of the rotor. By applying this assembly strategy, the rotor and consequently the final motor reaches desired quality targets although deviations in the single stacks are present. The benefits of the approach are validated within an industrial context.

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Keywords: Assembly; Fuzzy logic; Drive; Selecvtive assembly; Feedforward Control

1. Introduction

The increasing need for electric drives in the automotive sector requires an efficient mass production, considering that optimized methods and machines from current production lines for combustion engines cannot be transferred to electric drive production directly. The challenges of the electric drives production and strategies to overcome them are part of the research carried out in the European funded project MuProD, while the focus is on the rotor magnetization and assembly [1]. A previous work presented selective and sequential assembly concepts for this kind of electric drives [2]. This paper extends the concept of selective assembly by combining it with fuzzy logic in order to choose the optimal combination of rotor stacks for compensating deviations in the magnetic field.

Section 1 of this paper introduces briefly the production line, the composition of the electric drive and the space-resolved measurement developed within MuProD. Furthermore, it provides a literature review about selective assembly and fuzzy logic. The features of a rotor stack and feature reduction are discussed in Section 2. Section 3 describes the fuzzy system, its components and experimental results. A brief summary and outlook is given in Section 4.

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1.1. Electric Drives Production

The assembly line of electric drives is composed of two main branches, respectively dedicated to the assembly and magnetization of the rotor and to the production of the stator. The focus of the MuProD activity is the rotor line. In detail, this line is composed of seven main stages, dedicated to the following operations M_i:

- M_1: loading of the stacks on the pallet.
- $M_{2,1}$,$M_{2,2}$: assembly of the magnets on the stacks.
- M_3: stack magnetization and total flux measurement.
- M_4: heating station.
- M_5: rotor assembly machine.
- M_6: rotor balancing station.
- M_7: rotor marking station.

After assembling the rotor and the stator, the completed motor undergoes the EOL inspection. At this stage, motor characteristics as well as customer requirements such as torque, speed, etc. are tested. Though some of the previously carried out production stages already include subordinated testing steps, defects due to chain-linking or super positioning of errors are only detected at the EOL inspection. Since failures in the magnetic circle have a considerable effect on the performance of the whole electric machine, a continuous high quality of the permanent magnet rotor is necessary.

1.2. Composition of the Rotor

In the production line a number P_{total} of different rotors p can be manufactured, with $p = 1, \ldots, P_{total}$. One rotor p is composed of S_P laminated rotor stacks, which is the size of the batch of stacks to be assembled. The part is called stack, as it consists of several metal sheets that are stacked. Each stack contains M_P magnets, where M_P is an even number as positive and negative poles alternate. In order to apply optimization methods to find the optimal assembling policy, the rotor is represented as a two dimensional matrix (Fig. 1), where the rows represent the stacks and each matrix element m_{ij} stands for one magnet (column i, row j). Columns of the matrix contain magnets of the same polarity. Consequently the matrix dimension is S_P x M_P. By definition, odd indexes stand for positive and even indexes for negative polarity of the corresponding magnet.

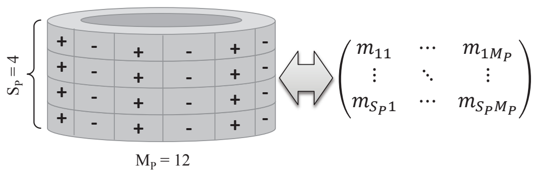

Fig. 1. Rotor consisting of $S_P = 4$ stacks and $M_P = 12$ magnets (matrix dimension is 4x12).

Due to variability of the magnetization process and the material properties, the magnetization of the magnets differs from the target value. Additionally, handling of the magnets within the production line can cause cracks and decrease the strength of the magnetic field. In order to increase the motor quality, a uniform magnetic field must be achieved for the complete rotor.

1.3. Space-resolved Measurement

In the current production line, the stack undergoes a total flux measurement after the magnetization process stage, resulting in one cumulative value for each stack. This value indicates whether the corresponding stack is outside a tolerance band and to be classified as defect. However, the magnet(s) responsible for causing this deviation cannot be identified. Within MuProD, a new space-resolved inspection strategy was developed. A hall sensor is located next to the rotating stack yielding a space-resolved (0°-360°) distribution of the magnetic field $B(\varphi)$ with φ=0…2Π (Fig. 2, left). For the optimization method described in this paper, this high-resolution signal is transformed, so that we obtain one value per magnet m_{ij} resulting in the discrete signal $B(k)$ with k=1,…,24 (Fig. 2, right). The value $B(k)$ is an indicator for the magnetic strength of the corresponding magnet k.

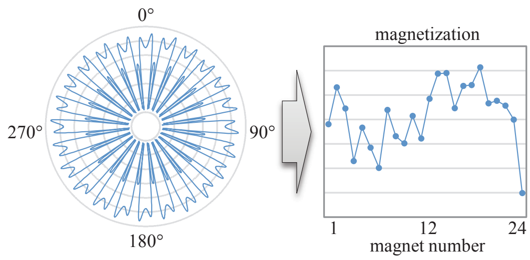

Fig. 2. Space-resolved magnetization measurement $B(\varphi)$ of one rotor stack (left) and the resulting discrete signal $B(k)$ (right).

1.4. Literature Review

State of the art quality control in the production of electric drives is the end of line (EOL) inspection [2]. This means that the defect is detected at the final inspection stage [3]. The main drawback of EOL inspection is the late and off-line inspection at the final stage of the manufacturing chain, where already all possible defects of the production chain have been accumulated. Thus, a defective workpiece is machined wasting time, money and energy resources for creating a final product, which is out of tolerances and has to be recycled or scrapped. Therefore, methods for feedforward control are considered in order to