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Quality-oriented design of rotor assembly strategies for electric drive production systems

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Abstract

Electric mobility is an emerging industrial sector that requires innovative quality control methods as common manufacturing and testing methods of combustion engines cannot be transferred directly to electric motors. This paper presents new solutions for the quantitative evaluation of quality-oriented rotor assembly strategies in electric drive production systems. The proposed methods assist the analysis of productivity and quality performance of two different assembly strategies namely selective assembly and sequential assembly. The impacts of these approaches are validated within a real industrial context, where state of the art quality and process control technologies show strong limitations. Experimental results have shown that the application of the proposed strategies yield a significant improvement in the production rate of conforming parts of the system. Moreover, the general applicability of these approaches to similar industrial problems encourages their adoption for defect reduction and elimination thus paving the way to zero-defect manufacturing paradigm.

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Keywords: Product Quality; Defect elimination; Electric drive assembly strategy;

1. Introduction

The growing demand for individual transportation yields an increasing number of cars worldwide. In order to reduce emissions of the current car fleet the trend is going towards zero-emission vehicles using electric drives [1]. The transportation sector can increase its energy efficiency by changing the travel behavior and the vehicle fleet, with respect to the amount of cars and the technology used [2]. Substituting the current car fleet by electric vehicles can drastically decrease local and greenhouse gas emissions [3,4]. Current studies show the huge potential of electric drives replacing combustion engines (petrol and diesel), starting with medium-sized cars [2,5]. This trend requires moving from small and medium lot sizes to mass production of electric drives in the automotive sector for hybrid and purely electric vehicles. However, methods and strategies used in production of conventional combustion engines cannot be transferred directly to the production of electric drives. Therefore, new approaches that guarantee output quality of electrical motors are needed. The project *MuProD*,[6] funded by the European Union, develops methods for increasing the quality of electric drives while decreasing the amount of scrap parts in multi-stage production systems moving towards zero-defect manufacturing.

This paper proposes downstream compensation methods applied to the production of rotors for electrical motors, and evaluates their effect on the overall system level performance taking into account system yield, production rates, and work in progress. The proposed methods are validated in an industrial context using real data obtained from Bosch production system. Section 2 describes the process chain of the production system. Section 3 introduces two new assembly strategies and compares them with the existing practice. In Section 4, the system level analysis is introduced and Section 5 presents the system level performance achieved under these strategies.

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2. System Description

In this section, Bosch electrical motor production line is considered. The rotor of an electrical motor consists of S_P stacks. Each stack consists of M_P magnets radially arranged on a circular steel ring. By piling several stacks together, rotors of different torque can be produced with the same cross-section. The production line is composed of two main branches, namely rotor assembly and stator production (Fig. 1). Light blue squares represent processing stages, red squares inspection stages and circles buffers for temporarily storing in-process inventory. In this paper, the focus of our analysis is the rotor line that is composed of seven main stages:

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

After the motor is assembled, it undergoes a final quality control at the end of line (EOL) inspection station. Two key quality features are inspected. First, the overall magnetic moment of the motor should be within a tolerance limit of 4% from the target value. Secondly, the motor should be free from significant cogging and vibration. The main drawback of the current inspection is that it is performed at the final stage of the manufacturing line, where defects cannot be corrected [7]. Consequently, a defective motor has to be recycled or scrapped. Therefore, feedforward control methods are considered for downstream compensation of deviations generated at previous process stages [7].

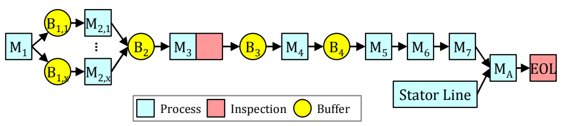

Fig. 1. Multi-stage production system for electric drives.

3. Rotor assembly strategies for defect reduction

3.1. Current Assembly policy

In the current configuration, there are no inspections before the end of the line. This limits the application of quality-oriented assembly strategies. For this reason assembly process is based on the order in which stacks arrive from the previous stage. Thus, output quality of the assembled rotor can be considered as a process that is only influenced by the quality of input stacks. Experiments under this policy show that the output quality of a rotor is a function of the cumulative randomness that arises from the individual stacks.

3.2. Selective assembly

Selective assembly strategy allows the assembly of high precision products from low precision components at the cost of increasing the complexity of the system management. In this case the goal is to implement this strategy at the assembly station (M_5). Two key quality features are considered under selective assembly. The first applies selective assembly based on the total magnetic flux measurement of stacks. The second approach targets the uniformity of the magnetic profile of the rotor using fuzzy inference system. Both approaches rely on a space-resolved measurement at M_3.

Total flux: Currently, if the measured overall magnetic moment of the motor deviates more than 4% from the target value, the motor is considered defective. This quantity is directly related to the total magnetic flux of the rotor which is again a function of total magnetic flux of individual stacks. Therefore the goal of selective assembly policy is to guarantee a rotor with a total magnetic flux close to the target value by selecting stacks from predefined classes. In this case, space-resolved inspection is used to measure of the total magnetic flux intensity of each stack at M_3. Measured stacks are sorted into two classes depending on the measured total magnetic flux. The buffer sizes for the two classes are identical and equal to half the size of the original buffer in the current configuration. Then, the assembly machine only couples stacks with high flux with stacks with low flux intensity. This combination allows the sum of the total magnetic flux of the rotor to be close to the specified target value compared to the current configuration.

A discrete event simulation is developed implementing selective assembly strategy based on the total flux of the rotor at the assembly station. For the sake of brevity, we directly discuss the output quality distribution of the rotor from the simulation (Fig. 2). In this analysis an equivalent lower and upper specification limits are defined based on data collected from the current system. Defect rate that is generated under the selective assembly with two classes is reduced to 2%, compared to 10% in the current configuration. These figures are strictly limited to the assembly station in isolation; the system level analysis using these results is treated in section 5.

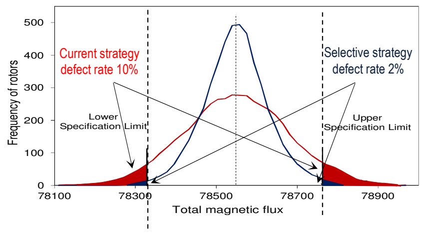

Fig. 2. Comparison of defect rates based on total magnetic flux.

Fuzzy logic using space-resolved inspection: In this section, selective assembly based on a fuzzy inference system (FIS) is explained. The goal is to reduce variation of the output field intensity and cogging of the motor. More details can be found in a previous paper [9]. From the space-resolved measurement in M_3, discrete magnetizations values of the 24 magnets in the laminated stacks are calculated. Efficient compression of the features enhances comprehension of the data set and enables generalizing upon the stack [9,10]. This reduction strategy consists of two steps, feature selection and extraction. First, magnets within a tolerance band are neglected. Second, new features are created based on the

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