Proactive Quality Control System for Defect Reduction in the Production of Electric Drives

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***Abstract*—State of the art in multi-stage production systems is End-Of-Line (EOL) quality control. The main drawback of EOL inspection is the 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. To overcome this drawback it is necessary to create solutions to reduce either defect generation or defect propagation. This paper focusses on the second approach, which aims at repairing defective workpieces by adapting consecutive process parameters in a multi-stage production system (downstream repair). By applying this concept to the production of electrical drives for power train applications, the effort needed for EOL testing can be reduced by shifting testing steps into the previous process chain. The currently used total flux measurement of laminated steel stacks is replaced by a space-resolved measurement. This permits the identification and local allocation of deviations in the magnetic field due to defective or weak magnets. The downstream repair strategy solves an optimization problem in order to compensate deviations in the magnetic field of single laminated steel stacks by adapting the assembly stage. Therefore, a tailored theoretical model is deduced out of the recorded data, which considers the position and the orientation of the laminated steel stack on the rotor. Two repair strategies are discussed within this paper, namely sequential and selective assembly. In the proper assembling sequence, the laminated steel stacks are then assembled on the rotor according to the optimal assembling policy. Thus deviations of the laminated steel stacks are compensated.**

***Keywords*—downstream repair, end-of-line inspection, selective assembly, sequential assembly**

I. Introduction

As state of the art quality control methods, Six Sigma and SPC are commonly used in the mass production of electric drives. Their main drawback is being End-Of-Line (EOL) methods, as they are based on off-line inspection of defective products, usually carried out at the final stage of the manufacturing chain [2]. At this stage of the process, all possible defects of the production chain have been accumulated. If a defect is detected at the last stage of the production chain, time consuming rework has to be performed or the product has to be scrapped. In this case, the already consumed machining time, material and energy has been wasted. To overcome this drawback it is necessary to create solutions to avoid the defect generation or to immediately react to the detected defects, without having to wait until the final stage of the manufacturing chain [5]. In this paper, the activities devoted to tackle this challenge and the preliminary results of the EU funded project MuProD are presented. In detail, it will be shown that by introducing a newly designed in-line workpiece inspection technology, various in-line workpiece repair strategies can be successfully implemented [1][3].

The paper is organized as follows: in the next section the product, the process and the production system under analysis are described. In section 3, the newly designed and implemented in-line inspection station is shown. In section 4, the two proposed workpiece repair strategies are explained and preliminary results are presented. Finally, conclusions and future research activities are discussed in section 5.

A. Composition of the Rotor

The state of the art Integrated Motor Generator (IMG) is a water cooled, permanent magnet excited synchronous machine with an inner rotor, as shown in Fig. 1. The rotor of the IMG consists of a cylindrical rotor carrier and laminated steel stacks. Each steel stack is provided with interior mounted permanent magnets. Those magnetic steel stacks are assembled to the rotor carrier under consideration of a defined interlocking angle. Due to this axial interlocking, effects like harmonics, cogging etc. can be reduced [4].

Fig. 1. Integrated Motor Generator IMG (Bosch).

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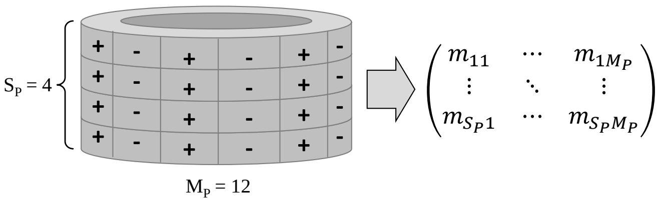

Fig. 2. Rotor consisting of S_P = 4 stacks and M_P = 12 magnets (matrix dimensions 4x12).

In the production line a number P of different rotors p can be manufactured, with p = 1, …, P. One rotor p is composed of S_P laminated rotor stacks, which can be seen as the size of the batch of stacks to be assembled. At the same time, each stack itself consists of M_P magnets. 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. 2), 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.

B. Current Production Line

The current production process for electric drives is represented in Fig. 3, where light grey squares ($M_\#$) represent processing stages, dark grey squares represent inspection stages and circles represent buffers for temporarily storing in-process inventory. The assembly line is composed of two main branches, respectively dedicated to the assembly and magnetization of the rotor and to the production of the stator. The main 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_1: loading of the stacks on the pallet.
- $M_{2,1}$,$M_{2,2}$: assembly of the magnets on the stacks. The station is composed of a pick and place system for positioning the magnets in their locations. Moreover, the glue is dispensed at the interfaces between the magnets and the stacks surface. Finally, the glue is thermally treated in a single oven.
- M_3: Stack magnetization process and total flux measurement.
- M_4: heating station. A rotating table moves the stacks into a heating chamber in order to prepare the stacks for the next assembly operation. Indeed the assembly principle is based on mechanical interference. Since it has several stack positions, it could be used as a sequence decoupling stage.
- M_5: assembly machine. The required number of stacks is taken from the heating station and a pile of stacks in the z direction of the machine is formed by mounting each stack on the central shaft. This represents the core of the rotor. In the current production line, the angle between the rotor stacks is fixed and cannot be adapted by the operators.
- 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 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. To overcome these problems a new space resolved measurement strategy of the magnetic field of each single stack is required.

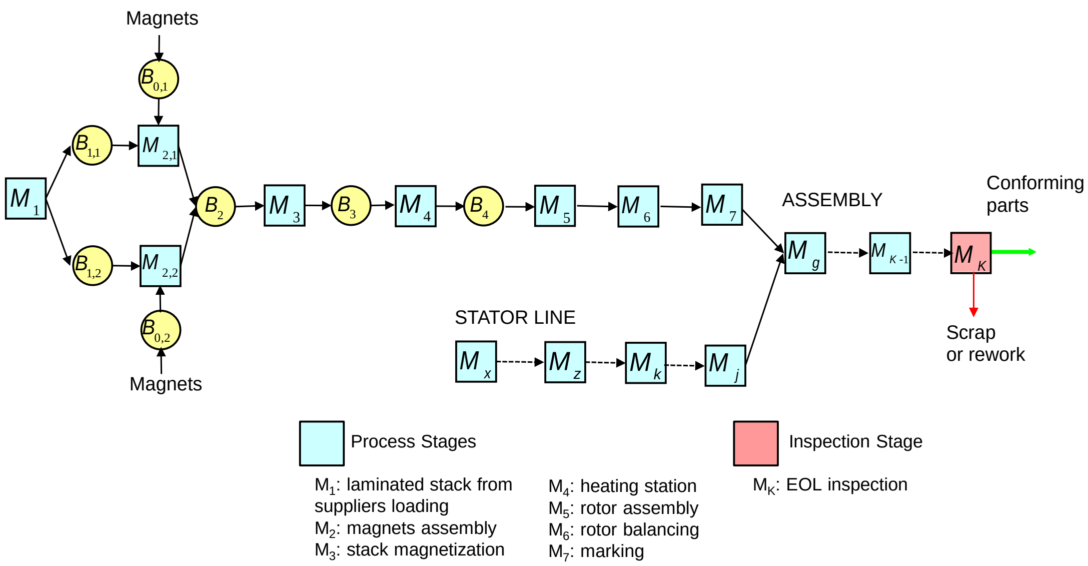

Fig. 3. Current production line for electric drives with EOL inspection.

II. Space Resolved Measurement

The magnetization process of the rotor is a crucial process, as the performance of the whole motor depends on it. The current set up of the magnetizing device allows a fast in-process measurement of the magnetization result. Therefore, this process is equipped with a measurement coil which measures the magnetic field of the rotor when it is removed from the magnetization device. However, due to physical effects and residual magnetism, measurement results fluctuate. Furthermore, because of the setup of the magnetizing and measurement coils within the magnetizing device, a space-resolved measurement is not possible (only integrated values of the ‘magnetic moment’ of the entire steel stack are obtained). Therefore, the result of the measurement can only be interpreted as a total magnetic flux over the whole steel stack.

To overcome this drawback a new space resolved measurement method including a test bench is developed as part of the MuProD project (Fig. 4). The main idea is to obtain measurements which are correlated to the angular position of each specific magnet on each single laminated steel stack. Technically, the rotor stack is measured while rotating with rotational speed ω. The resulting continuous magnetic field intensity for a rotation angle θ is called $B_{s,q}(\theta)$. Due to the sampling rate only a limited number of measurements will be taken during one rotation (typically several thousands). Taking into consideration the nominal position of each magnet, a discrete magnetic field intensity $B_{s,q}(m)$ for magnet $m=1,..,M_p$ and stack $s=1,..,S_p$ can be calculated.

A preliminary test bench for the space resolved measurement has been set up as it is shown in Fig. 4. It consists of a controlled rotary axis with the attached pneumatically self-centering three jaw chuck as well as the mechanical axis for positioning of the inductive sensor.

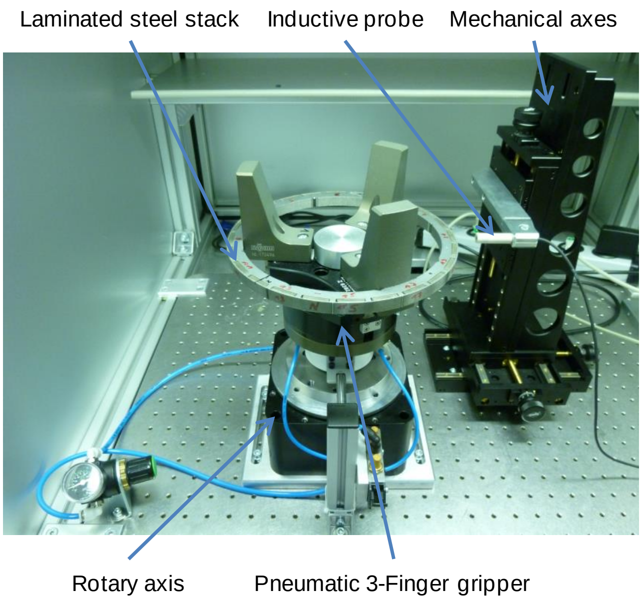

Fig. 4. Main components of the preliminaty test bench for space resolved measuring of the magnetic field.

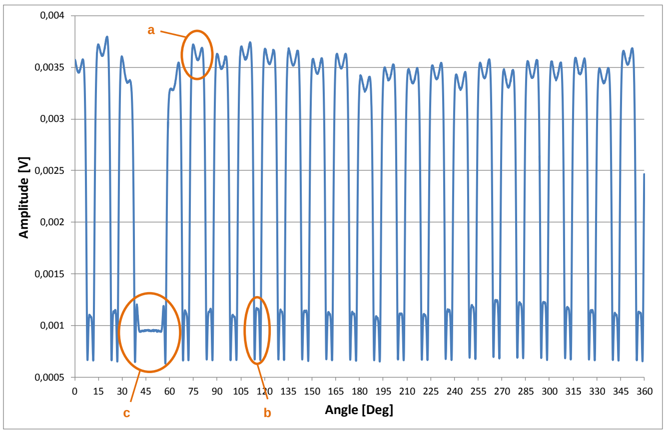

Fig. 5. Space resolved measurement of the magnetic field of a laminated steel stack with an artificial defect (here sensor output in V).

First experiments have been carried out using laminated steel stacks with different types of artificially induced defects. Fig. 5 illustrates the results of an experiment, in which a laminated steel stack with a defined magnetic failure was used. Analyzing the data, it is possible to verify the detectability of the defect by the sensor. Moreover, this information has been used to investigate the deviation in the sensor signal generated by different common defect types. With regard to those experiments, the magnetic flux over the magnets (a) as well as the interactions in between the transitional zones (b) can be clearly detected and correlated to the circumference of the laminated steel stack. Effects of missing or defective magnets are also detected (c) (see Fig. 5).

III. Repair Strategies

As deviations in the magnetic field of single rotor stacks were created in the previous process stages, the goal is to compensate those deviations by applying an optimal strategy π^{opt} in the downstream assembly stage, where a number S_P of laminated steel stacks is assembled to form one rotor of type p. Two possible downstream repair methods are investigated, namely sequential assembly (see section III.A) and selective assembly (see section III.B).

A. Sequential assembly

A batch of S_P laminated steel stacks is produced, stored in a buffer (with size S_p) and inspected, so that S_P magnetic profiles are available. The aim of this approach is to impose an angular misalignment α between the stacks with respect to a reference axis in order to gain uniformity and reduce variability of the output field intensity. The entity of this misalignment, namely the elements of the vector α, has to be computed by an optimization algorithm. The optimization problem is the minimization of a dispersion metrics calculated between the magnetic field intensity of the rotor. According to the representation of the rotor as a matrix the aim is to change α in order to compensate the deviations in the corresponding column. Values of vector α are integers indicating the shift of a magnet pair (two magnets) to the right in the same row. After $M_P/2$ shifting operations the stack reaches its starting position.

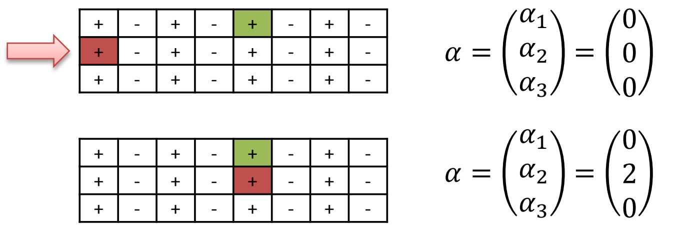

Fig. 6. Stack number two is shifted to the right in order to compensate the weak magnet at position one by the stronger magnet at position 5 of the first stack.

In order to avoid redundant permutations the first stack is not shifted and can be seen as reference for the shifting operations of the remaining S_p-1 stacks. An example of such a shifting operation is given in Fig. 6. During the execution phase, this optimization algorithm has to be executed for each specific batch of S_P stacks to be assembled in order to compute the specific assembly policy. Therefore, the computational time directly interferes with the cycle time and should be minimized. The number of possible permutations π^{all} is growing exponentially with the number of stacks:

$$\pi^{all} = \binom{M_P}{2}^{S_P - 1} \tag{1}$$

To reduce the computational effort and consequently the negative influence on the production cycle time, the value of π^{all} has to be decreased. However, the reduction of possible assembly combinations can affect the quality of the proposed assembly strategy π^{opt} in a negative way when the global minimum is removed so that the optimization algorithm yields only a local minimum. Two strategies are considered for reducing the number of combinations. The first approach is to consider only stacks with magnets out of tolerances in order to decrease the exponent of π^{all}. This implies that the number of stacks with magnets within tolerances S_{Ptol} is not considered in the optimization problem, reducing the number of possible combinations to:

$$\pi^{all} = \binom{M_P}{2}^{S_P - S_{Ptol} - 1} \tag{2}$$

This reduction strategy requires an algorithm for classifying the stacks into two groups, namely defective and not defective rotor stacks. The classification depends on the choice of the upper and lower limits of the magnetic field and affects the quality of proposed assembly strategies.

The second approach aims at reducing π^{all} by consideration of the most relevant magnets of the stacks within one batch. It can be seen as preprocessing the batch and finding dependencies before applying the procedure described above. In a first step the most relevant deviation has to be identified together with possible compensations.

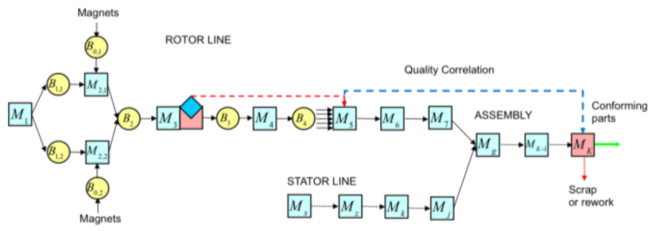

Fig. 7. Reconfigured line including on-line inspection and new sequential proactive assembly strategy.

The values of the vector α are fixed for the stack which causes the major deviation and for the stacks used for its compensation. If S_{Prep} stacks are involved the preprocessing requires the following number of possible permutations:

$$\pi^{prep} = \binom{M_P}{2}^{S_{Prep} - 1} \tag{3}$$

Then, the final optimization needs to find the optimum out of

$$\pi^{final} = \binom{M_P}{2}^{S_P - S_{Prep} - 1} \tag{4}$$

possibilities. Therefore, the final number of combinations is:

$$\pi^{all} = \pi^{prep} + \pi^{final} = \binom{M_P}{2}^{S_{Prep} - 1} + \binom{M_P}{2}^{S_P - S_{Prep} - 1} \tag{5}$$

In order to generate the optimal assembly strategy $\pi^{opt} = \alpha$, the information regarding the field profile of each single stack has to be available upfront for the entire lot to be assembled. This poses challenges on the production logistics of the system that need to be addressed. Indeed, it is not possible to place one stack in the assembly machine before all the other stacks in the lot have been magnetized and measured. In other words, the assembly process becomes a full batch process. Fig. 7 shows how the sequential assembly strategy interferes with the production line presented earlier.

B. Selective assembly

Selective assembly systems are found in several manufacturing contexts, above all automotive and mechanical components manufacturing, where the tolerances imposed on the assembled product are much tighter than the tolerance imposed on the sub-components. Selective assembly consists in measuring the key quality characteristics of each sub-component and sorting the components into bins according to the measurement outcome (sorting policy). In order to improve the product quality, the assembly station is allowed to assemble components only according to assigned component bins' matching (assembly and matching policy). By employing selective assembly, high precision assemblies can be produced from low precision components, at the cost of increasing the complexity of the system management, the work-in-progress and of decreasing the production rate of the system. Therefore, an integrated quality and production logistics analysis of this system is needed to correctly and profitably manage such trade-off.

Selective assembly is applied to the case under analysis as follows. Depending on the space resolved magnetic field measurement of each stack, clusters of stacks are formed and the stacks are temporarily stored in class-dependent buffers. Since the magnetization process is uncontrolled, queues are formed. An optimization algorithm is developed for

- generating the optimal sorting or binning policy (π^{binning}),
- generating the optimal matching policy (π^{matching}) and
- generating the optimal assembly policy (π^{assembly})

in order to reach a stable rotor field. This optimization algorithm is executed only once and off-line for generating the optimal selective assembly plan. On the contrary, during the process execution phase, the assembly strategy is kept constant. Therefore, the computational time does not interfere with the cycle time, since the optimization algorithm has to be launched only once. If compared with the sequential assembly, this approach is faster to be implemented but requires clustering. Fig. 8 shows how the selective assembly strategy can be included into the production line of electric drives.

Preliminary modeling investigations carried out in MuProD have proved that this approach can be particularly promising for the case under analysis. For example, in Fig. 9 the possible impact of selective assembly on the main system performance as a function of the buffer sizes is shown. The selective assembly strategy proves to be detrimental for the total throughput of the system, but beneficial for the effective throughput of the system, since more high quality assemblies are produced. Moreover, the Work in Progress is positively affected by the selective assembly practice. Therefore, this policy seems to be beneficial for the case under analysis.

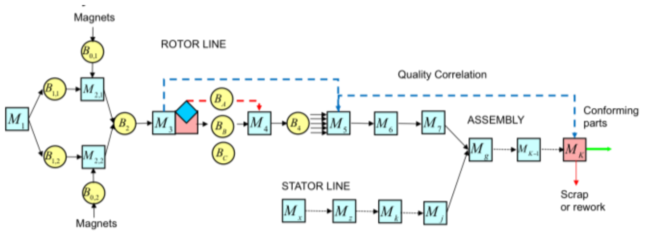

Fig. 8. Reconfigured line including on-line inspection and new selective assembly strategy.

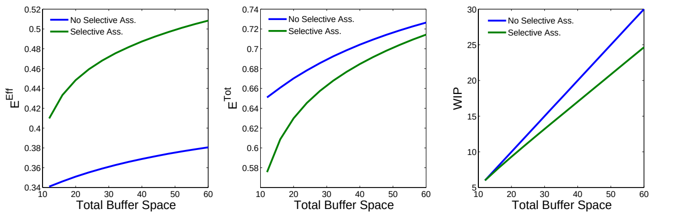

Fig. 9. Impact of the selective assembly strategy on the system performance. E^{Tot} is the total throughput of both conforming and non-conforming assemblies, E^{Eff} is the effective throughput of only conforming assemblies, WIP is the work in progress.

IV. Conclusion

In order to avoid the drawbacks of commonly used EOL inspections, an alternative repair strategy, namely downstream repair, was presented. Defects in the laminated steel stack, which cause deviations of the magnetic field, are detected in-line and repaired in the downstream assembly process. As this approach requires knowledge about the magnetic field of each single magnet, a new measurement station was developed. By carrying out first experiments, the possibility of gathering space resolved measurements in-line could be verified. It was shown that deviations in the magnetization of single magnets are detected by this device. However, for verifying the optimization results and for gaining more detailed insights about the magnetization process effect on the stack, further experiments have to be conducted. In detail, a DOE approach will be performed to investigate the effect of the eccentricity of the steel stack, the position of the sensor and the strategies executed while combining several laminated steel stacks in the assembly stage of the production line.

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References

[1] P. Nyhuis, G. Reinhart, and E. Abele, “Wandlungsfähige Produktionssysteme”, PZH Produktionstechnisches Zentrum, 2008.

[2] C. Staudter, J. Mollenhauer, R. Renata, O. Roenpage, C. von Hugo, A. Hamalides, “Design for Six Sigma + LeanToolset”, Berlin, Heidelberg, Springer, 2009.

[3] A. Kampker, P. Burggräf, Nee, C., “Strategic fit: Overview of cost, quality and scalability impact on the added value network in electric engine production”, 2nd WGP Annual Assembly, 2012.

[4] M. Scheidt, “Entwurfskriterien für permanenterregte Synchronmaschinen in Zahnspulentechnik unter Berücksichtigung der Zusatzverluste”, Kaiserslautern: Shaker Verlag, 2009.

[5] T. Schlick, G. Hertel, B. Hagemann, E. Maiser, M. Kramer, “Zukunftsfeld Elektromobilität”, Studie, RolandBerger, 2011.