Data analysis in the production process of electrical drive systems

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Abstract—**In a classical production process of electrical machines, the individual components are usually regarded as mechanical components. In this case, the process monitoring is performed accordingly. Due to the complex physical principles prevailing in electrical machines, manufacturing tolerances in the production process of each component can have a decisive influence on the operating behavior of electrical drive systems. Particularly in the case of magnetically highly utilized electrical machines, non-linear operational material characteristics prevail, which necessitates the observation of electromagnetic relevant properties of the stator and rotor components. Furthermore, this means that it is not sufficient to observe individual quality features during production; rather, a deduction of the operating behavior of the electrical machine based on the manufactured components is desired. A possible approach to this goal is presented in this paper. The benefit of an increased collection of measurement data in a generic production process is shown.**

I. INTRODUCTION

Highly utilized electric machines, as commonly used in electromobility, are particularly sensitive to asymmetries in the magnetic circuit. The consequences are, among other things, acoustic conspicuities [1], [2], cogging torques [3], [4], inadequate set-torque accuracy [5], and higher losses [6], [7]. Depending on the degree of asymmetry, the machine does not meet its predefined specifications. In an unfavorable case, an inadequate machine is detected as late as in the final application. In this case, the technological value added has been completed. High follow-up costs are required to remedy the deficiencies.

One way to address this problem is a comprehensive End-of-Line (EoL) test of each electric motor in order to recognize rejects before dispatch. This procedure can achieve good results, but requires very fast test cycles for the electric drive, which can not be achieved easily according to the current state of the art. A good addition to the EoL test is the simulation of the machine behavior. Variation simulations can help to determine the effects of production or material deviations and make a diagnosis of abnormalities in the production chain of an electrical machine possible. In this way, process fluctuations can be selectively localized and also predicted in the sense of predictive maintenance. By processing such data in a cloud, measurements from several production sites can be included in the analysis. A further increase in the recognition accuracy is made possible by determining the production and material quality before and after each production step. By simulation and self-learning algorithms, the behavior of the finished machine can be estimated during its production. This knowledge can be used to detect possible disturbances in an early stage of the production. It may even be possible to compensate for these effects by appropriately parameterizing the machine control in the control unit or inverter. This minimizes rejects and a more robust production may be achieved. A tolerance expansion of the production process may be possible, which can lead to a significant cost saving.

This paper gives an overview, how the manufacturing process of an electrical machine can affect the properties of the magnetic circuit and therefore the overall characteristics of the produced drive. Furthermore, a suggestion is presented how data mining within the production can help to improve the quality, decrease rejects, and create more robust designs with respect to manufacturing influences and tolerances. In which way an improvement of the torque accuracy of electric drives becomes possible using manufacturing process data or EoL tests is shown afterwards.

II. THE MAGNETIC CIRCUIT OF THE ELECTRICAL MACHINE

Besides the geometrical aspects the production process of an electrical drive has also to consider magnetic parameter of the machines's components. The magnetic behavior is crucial for the overall drive performance. Even small deviations in geometry, material characteristic, or other production based influences may affect the drive to become reject due to high losses, loudness or low efficiency for example. In Fig. 1 an exploded view of a permanent magnet synchronous machine is shown (main components). The magnetic circuit comprises the following parts:

- winding system
- stator stack
- rotor stack
- permanent magnets for the excitation flux.

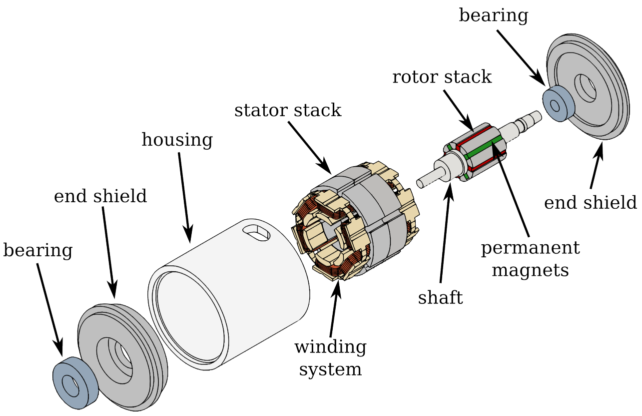


Fig. 1: Exploded view of permanent magnet synchronous machine.

The overall motor performance is closely linked to the properties of these components. Due to varying parameter and manufacturing influences the performance may be affected in such a way that the motor becomes a scrap part. Even small deviations from the ideal case make the magnetic circuit to become asymmetric. This shall be emphasized by two examples. In Fig. 2 a common magnetic deviation based on variation in the induction of a permanent magnet is shown. The flux density of the magnetic circuit is represented by a gray scaled color gradient. The darker the color the higher the flux density is. An ideal magnetized machine is shown in the upper half of the figure. In the lower half the circuit with a lower magnetization of one magnet is illustrated. The right part of the stator yoke shows a nonzero flux density contrary to the ideal magnetized machine, whereas the left part of the yoke shows no difference. As a result the machine has a lower overall excitation flux linkage, a higher cogging torque with additional harmonic orders and may tend to acoustic inadequacy.

The second example demonstrates how soft magnetic iron material of the stacks is influenced by the production process. In Fig. 3 the upper half shows the flux density distribution of the ideal circuit again. In the lower half the flux distribution due to material degradation by producing the lamination of the stator and rotor stack is presented. The underlying manufacturing process can be punching/mechanical cutting for high volume production or laser/waterjet cutting for small volumes. The concentration of the flux in the middle of yoke and teeth is conspicuous. This effect is based on the deterioration of the magnetic permeability and therefore rising magnetic resistance in proximity to the sheets outline [8]. One result is a dip in the overall excitation flux linkage again. Furthermore, the saturation behavior represented by the electrical inductance and the iron losses are impaired [6]. Relevant drive characteristic that are associated with the magnetic circuit are:

- efficiency/losses
- torque accuracy
- cogging/ripple torque
- amplitude and harmonics of the back emf
- acoustic behavior
- thermal aspects
- power/torque density
- life expectancy
- etc.

For that reason a quality management of a motor production has to include the magnetic properties and their dependency to the manufacturing process.

III. MONITORING OF MAGNETICALLY RELEVANT PROPERTIES IN THE MANUFACTURING PROCESS OF ELECTRICAL MACHINES

Consequently, a generic production chain with the capability of monitoring the magnetic behavior of the important components of the electric motor is presented. In contrast to classical manufacturing processes, additional measurement quantities are defined.

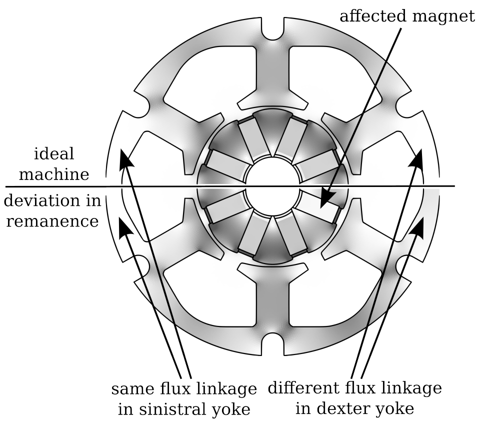


Fig. 2: Flux distribution in ideal machine compared to machine with magnetization deviation.

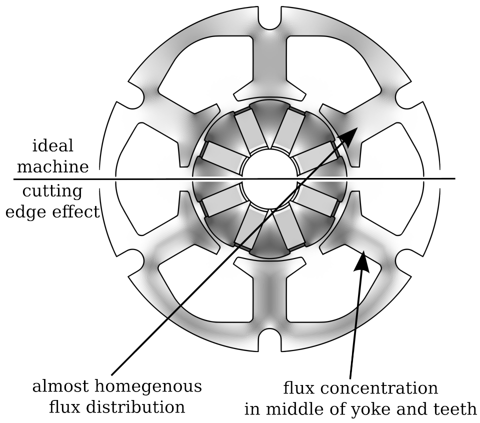
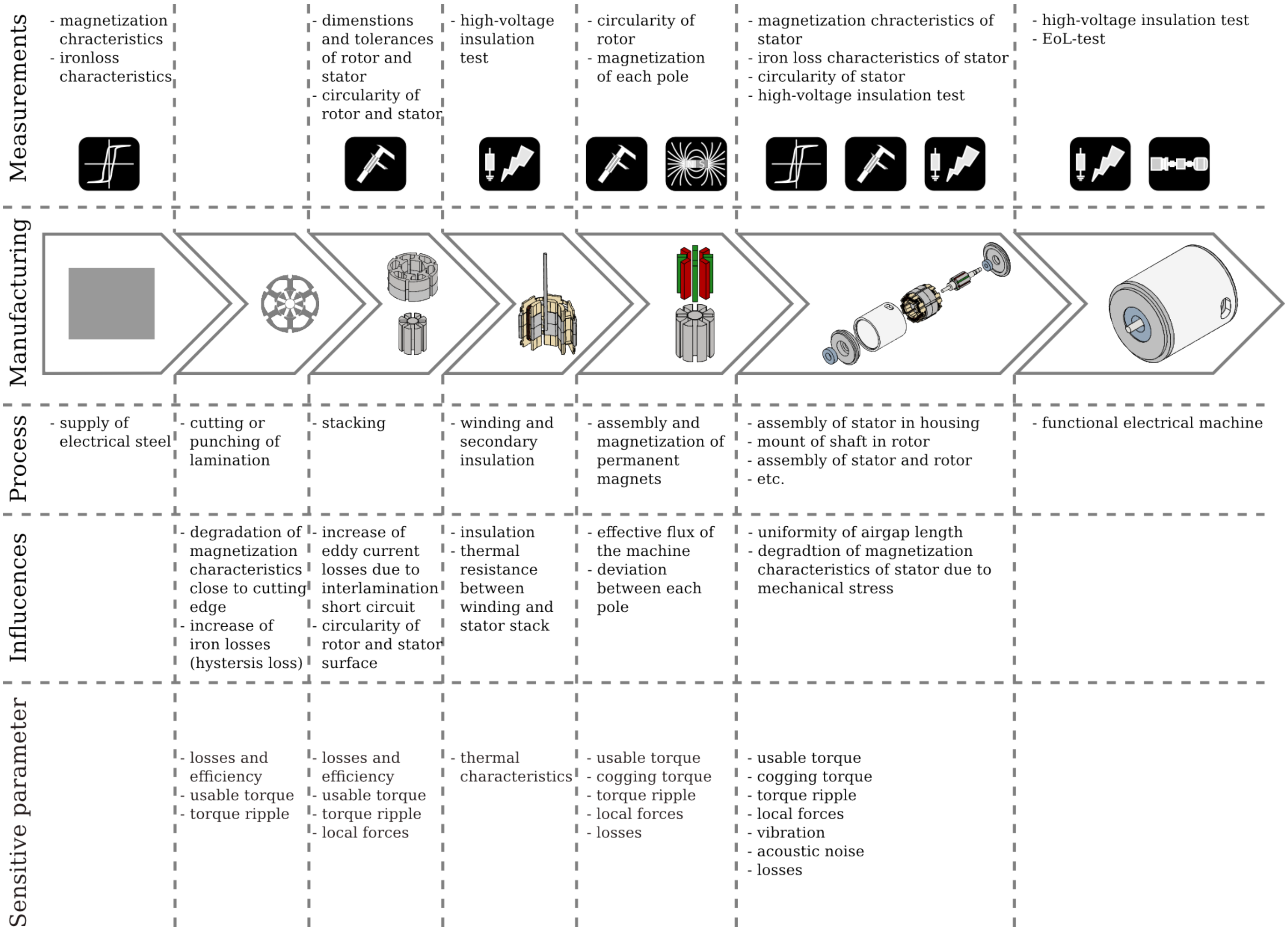


Fig. 3: Flux distribution in ideal machine compared to machine with cutting edge induced material degradation.



Measurements	- magnetization chracteristics - ironloss characteristics		- dimenstions and tolerances of rotor and stator - circularity of rotor and stator	- high-voltage insulation test	- circularity of rotor - magnetization of each pole	- magnetization chracteristics of stator - iron loss characteristics of stator - circularity of stator - high-voltage insulation test	- high-voltage insulation test - EoL-test
Manufacturing							
Process	- supply of electrical steel	- cutting or punching of lamination	- stacking	- winding and secondary insulation	- assembly and magnetization of permanent magnets	- assembly of stator in housing - mount of shaft in rotor - assembly of stator and rotor - etc.	- functional electrical machine
Influcences		- degradation of magnetization characteristics close to cutting edge - increase of iron losses (hystersis loss)	- increase of eddy current losses due to interlamination short circuit - circularity of rotor and stator surface	- insulation - thermal resistance between winding and stator stack	- effective flux of the machine - deviation between each pole	- uniformity of airgap length - degradtion of magnetization characteristics of stator due to mechanical stress	
Sensitive parameter		- losses and efficiency - usable torque - torque ripple	- losses and efficiency - usable torque - torque ripple - local forces	- thermal characteristics	- usable torque - cogging torque - torque ripple - local forces - losses	- usable torque - cogging torque - torque ripple - local forces - vibration - acoustic noise - losses	

Fig. 4: Exploded view of permanent magnet synchronous machine.

The relevant steps in the production process, the desired measurements, the magnetic relevant influences and the sensitive operational parameter are summarized in Fig. 4.

In particular, electromagnetically relevant components are stator stack with its winding and rotor stack with e.g. permanent magnets. The production chain starts with the production of the individual stator and rotor lamination. The lamination is usually produced with a stamping process. This process introduces local mechanical stresses which can strongly influence the magnetization characteristics and loss behavior of the electrical steel. In a next step, the individual iron sheets are packaged into stacks. In this step, electrically conductive connections are formed between the individual sheets and the loss behavior compared to the raw material is further impaired. In addition to influencing the material properties tolerances in the geometry of the individual packets occur. Therefore, measurements of the input material properties, stack material properties and stack geometry are desired quantities to be measured.

The stator is equipped with its insulation and winding system. This step is particularly critical for the later operability and safety of the machine. At least the dielectric strength of the insulation system has to be examined.

In a further step, the wound stator stack is joined into the housing. This step introduces mechanical stresses locally and may lead to degradation of the magnetic material and deviations of the geometry compared to the design, especially in the air gap. After this step, a characterization of the magnetic material, a measurement of the inner contour, and a test of insulation system is performed.

In the case of the rotor, permanent magnets are magnetized and inserted to the rotor stack ([9]). The magnetization can either be done before or after the mounting process. The excitation of the rotor has a significant influence on the operating behavior of the drive. The torque that can be generated and the losses occurring during operation are influenced by average magnetization. Non-uniform magnetization of the magnets cause torque ripples and increased radial forces. This may lead to unwanted acoustic characteristics in the target application. Representing the most sensitive parameter for the operational

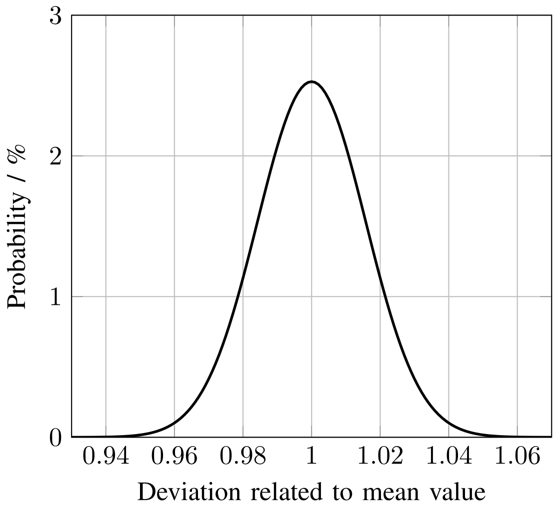


Fig. 5: pdf of the deviation of permanent magnet magnetization.

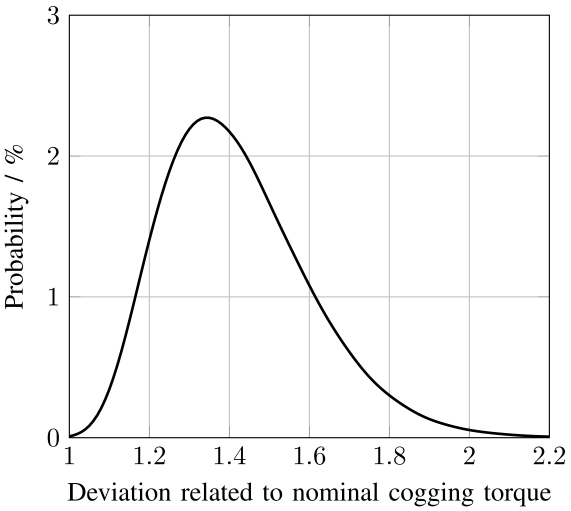


Fig. 6: pdf of the deviation of cogging torque.

behavior of the electrical machine, the magnetization of each magnetic pole as well as the geometry of the rotor is measured.

IV. QUALITY IMPROVEMENT BY PRODUCTION DATA ANALYSIS

The common approach for detecting rejects is the review of manufactured parts after a production process and compare them with the desired values. If an actual value is outside a preliminary defined range of tolerance, the element is rejected accordingly. This practice generally works well for geometric data, since construction elements may not fit together if a dimension is beyond tolerance limits. In case of magnetic tolerances the effect is not as obvious. The correlation between deviations and the overall machine behavior cannot be exactly determined without appropriate analysis tools, which is illustrated in the following example.

For an examination of permanent magnet variations magnetization measurements of 150 identical magnets of a single supplier in a special test facility [10] are performed. The probability distribution function (pdf) shows a normal distribution as shown in Fig. 5.

To study, in which way this distribution affects the motor, one has to take the number of required magnets for one motor into account, because:

a) there is a statistical balancing
b) the distribution leads to local effects in the magnetic circuit.

For the analysis the desired quality criterion has to be defined. If, for example, the maximum torque is of interest, the overall magnetization is to consider. For a machine with eight magnets the standard deviation of the input pdf is then reduced by $1/\sqrt{8}$ due to a) (only approximation due to non-linearities), still following the normal distribution. The measurement within a production process consists of an iron core with a probe winding in which the magnetized rotor is rotated. Based on several previously performed variation simulations it is possible to predict the change in the maximum torque with respect to the measurement result. This procedure follows the *inverse problem* approach.

Another relevant parameter is the cogging torque. In this case, not the overall magnetization is essential but the distribution mentioned in b). A prediction for the machine's behavior now has to take the circumferential and axial magnetization distribution into account. The required measurement is more extensive in this case. A hall sensor array as described in [11], [12] might be used. Then, however, even if the magnetization is fully identified, a behavior prediction is difficult, hence the inverse problem grows arbitrary especially if additional geometric deviations are considered as well. A pdf of 10^5 simulations with randomly distributed magnetization and eccentricity is shown in Fig. 6. The magnetic calculation is similarly done as described in [13], [14]. The underlying magnetization distribution is identical to the pdf in Fig. 5. The eccentricity distribution is based on results of a previous study [15]. For this approach the data base has to be known in advance with a sufficient accuracy.

A more feasible approach is to utilize all available measurement data of design process, the series start-up and EoL-tests instead of extensive preliminary analysis. Especially, the series start-up is expedient because within this process many tests are performed and time constraints are not as high as in the later series production. The proposed procedure is illustrated in Fig. 7. For the behavior prediction all process information are gathered and utilized for data mining algorithms [16]. With the results an analysis is performed for every constructed components and decision for rejection is made. If a construction part is close to tolerance limits a full test on the test bench

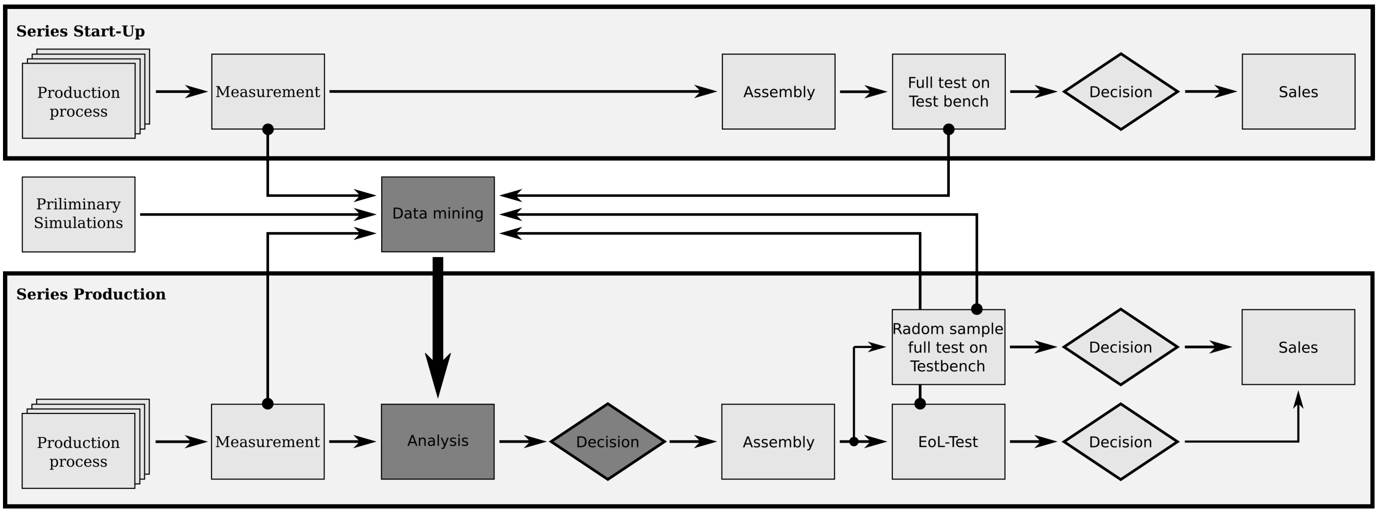


Fig. 7: Schematic diagram data acquisition and use in series production.

can be triggered automatically to ensure reject detection and check for possible process imperfections. This tests also helps for further improvement of the analysis algorithms and even process monitoring and predictive maintenance are possible [17]. Furthermore, with the acquired data the motor designer can be supported to develop designs that are robust with respect to critical production steps [18], [19], [20]. With the possibility of the Internet Of Things ”IoT” and cloud based computing the data analysis has not to be located at the production plant. This is very useful if more production sites are involved. An use-case for a drive parametrization based on production data is described in the next section.

V. USAGE OF PROCESS DATA FOR DRIVE PARAMETRIZATION

The operating point dependent flux linkage is a very important magnitude for the torque development of the electrical machine [21]. Since high utilized synchronous machines commonly have an interior magnet design, the flux linkage is strongly non-linear with respect to the machine current and affected by rotor temperature additionally. For that reason, the control of the machine has to be parameterized with non-linear control tables. These tables can be generated by use of magnetic field analysis or measurements. The latter approach is elaborate but results in more accurate data. Generally, generic control tables are created, that are used for all produced drives. In case of production deviations this leads to a fluctuating torque accuracy [5]. In Fig. 8 the measured torque deviations of a lower limit machine with 5.5 % lower excitation flux is shown. Especially in the high torque region the relative error is significant. To limit those deviations narrower tolerances in the magnetization could be demanded, which generally cause higher production cost. However, if the flux development of the machine is known, the control table can be adjusted to fit to the machine. With such an individualized control the torque error is reduced below 1 % in the entire operation area. Furthermore, the efficiency of the motor is increased, especially at high speeds, since less field weakening current is required. This is illustrated in Fig. 9.

Control parameter are stored in the electronics of the drive, i.e. the inverter. Thus, if an individualized control is used, the parameter have to be adjusted for the connected motor. This can be done by using electronic type plates, that can be stored in the position feedback system of the motor. But this feedback systems are very expensive if compared to the commonly used resolvers. Therefore, it is suggested to save the motor parameter in a database and program the control by IoT. To identify the motor a bar code can be used.

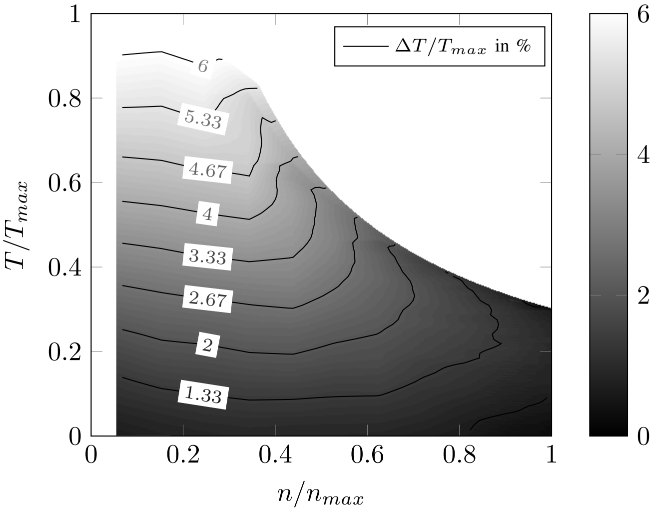


Fig. 8: Torque deviation of lower limit machine with generic control table.

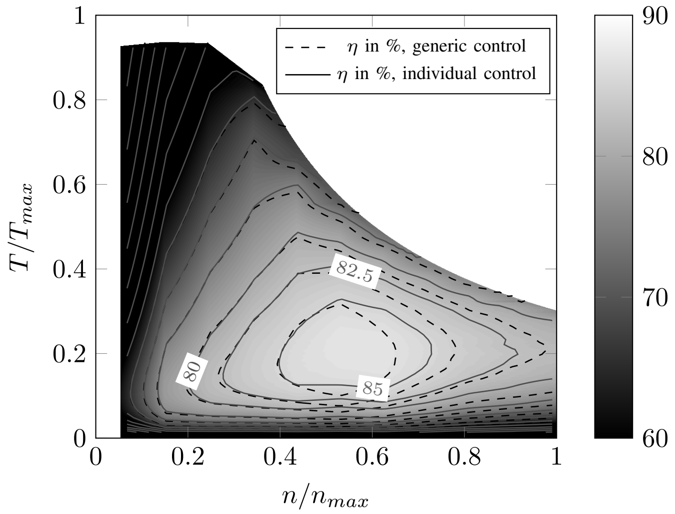


Fig. 9: Efficency map of lower limit machine with generic and individualized control.

The identification of the flux linkage has to be done for every motor. It is possible to run every machine on the EoL-test bench. But even if smart identification methods are used, the measurement will take up to ten minutes. A reduction of this time becomes possible if the magnetization, the stator and rotor stack parameter and the geometry are known. Then, only a few operating points have to be investigated and a full characterization of the flux linkage can be done in seconds.

VI. CONCLUSION

The paper shows why the magnetic properties of an electrical machine have to be taken into account for the manufacturing process. It is explained that not only summarized magnitudes like the overall magnetization of a permanent magnet rotor are significant for the drive behavior but also local effects within the magnetic circuit. Derived from that it is shown how production-accompanying measurements can help for improvement of quality and saving cost. By using data mining algorithms extensive EoL-Tests can be reduced to a minimum. Furthermore, the data can be used for parametrization of the machine's control in the final application compensating possible production induced effects.

REFERENCES

[1] J. L. Besnerais, "Effect of lamination asymmetries on magnetic vibrations and acoustic noise in synchronous machines," in *2015 18th International Conference on Electrical Machines and Systems (ICEMS)*, Oct 2015, pp. 1729–1733.

[2] D. J. Kim, H. J. Kim, J. P. Hong, and C. J. Park, "Estimation of acoustic noise and vibration in an induction machine considering rotor eccentricity," *IEEE Transactions on Magnetics*, vol. 50, no. 2, pp. 857–860, Feb 2014.

[3] G. W. Cho, W. S. Lee, I. H. Kang, J. G. Ha, H. W. Kim, W. S. Son, D. H. Song, M. K. Song, and G. T. Kim, "The stabilization of cogging torque variation by manufacturing tolerances," in *2016 IEEE Conference on Electromagnetic Field Computation (CEFC)*, Nov 2016, pp. 1–6.

[4] S. Zhang, E. Carraro, N. Bianchi, K. Wang, and K. Vervaeke, "Industrial-scale motor cogging torque control for a high-volume motor manufacturing," in *2015 IEEE International Electric Machines Drives Conference (IEMDC)*, May 2015, pp. 1235–1241.

[5] M. Ott and J. Böcker, "Sensitivity analysis on production tolerances for electric drive systems in automotive application," in *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*, Sept 2016, pp. 1–10.

[6] G. von Pfingsten, S. Steentjes, A. Thul, T. Herold, and K. Hameyer, "Soft magnetic material degradation due to manufacturing process: A comparison of measurements and numerical simulations," in *17th International Conference on Electrical Machines and Systems (ICEMS) 2014*. Hangzhou, China: IEEE, October 2014, pp. 2018–2024. [Online]. Available: http://134.130.107.200/uploads/bibliotest/2014GvPSoft.pdf

[7] M. Hofmann, H. Naumoski, U. Herr, and H. G. Herzog, "Magnetic properties of electrical steel sheets in respect of cutting: Micromagnetic analysis and macromagnetic modeling," *IEEE Transactions on Magnetics*, vol. 52, no. 2, pp. 1–14, Feb 2016.

[8] S. Elfgen, S. Steentjes, S. Böhmer, D. Franck, and K. Hameyer, "Influences of material degradation due to laser cutting on the operating behaviour of PMSM using a continuous local material model," in *2016 XXII International Conference on Electrical Machines (ICEM)*. Lausanne, Switzerland: IEEE, September 2016, pp. 1835–1840.

[9] A. Mahr, A. Meyer, B. Hofmann, M. Masuch, and J. Franke, "Innovative developments for automated assembly and fixation of integrated permanent magnets in rotors of synchronous machines," in *2015 5th International Electric Drives Production Conference (EDPC)*, Sept 2015, pp. 1–6.

[10] P. Offermann, I. Coenen, D. Franck, and K. Hameyer, "Magnet deviation measurements and their consideration in electromagnetic field simulation," in *15th International IGTE Symposium on Numerical Field Calculation in Electrical Engineering, IGTE 2012*. Graz, Austria: TU Graz, September 2012, pp. 305–309.

[11] S. Abersfelder, A. Meyer, A. Heyder, M. Thanner, and J. Franke, "Prediction of electric motor performance by in-line testing of permanent excited rotors," in *EDPC, 6th International Electric Drives Production Conference*, November 2016, pp. 80–85.

[12] A. Meyer, A. Heyder, M. Brela, N. Urban, J. Sparrer, and J. Franke, "Fully automated rotor inspection apparatus with high flexibility for permanent magnet synchronous motors using an improved hall sensor line array," in *2015 5th International Electric Drives Production Conference (EDPC)*, Sept 2015, pp. 1–5.

[13] S. Gerber and R. J. Wang, "Statistical analysis of cogging torque considering various manufacturing imperfections," in *2016 XXII International Conference on Electrical Machines (ICEM)*, Sept 2016, pp. 2066–2072.

[14] M. Schroder, D. Franck, and K. Hameyer, "Analytical modeling of manufacturing tolerances for surface mounted permanent magnet synchronous machines," in *2015 IEEE International Electric Machines Drives Conference (IEMDC)*, May 2015, pp. 1138–1144.

[15] A. Ruf, M. Schröder, A. K. Putri, R. Konrad, D. Franck, and K. Hameyer, "Analysis and determination of mechanical bearing load caused by unbalanced magnetic pull," *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 35, no. 2, pp. 728–743, March 2016.

[16] S. Abersfelder, A. Heyder, and J. Franke, "Optimization of a servo motor manufacturing value stream by use of industrie 4.0," in *2015 5th International Electric Drives Production Conference (EDPC)*, Sept 2015, pp. 1–5.

[17] C. P. Gatica, M. Koester, T. Gaukstern, E. Berlin, and M. Meyer, "An industrial analytics approach to predictive maintenance for machinery applications," in *2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA)*, Sept 2016, pp. 1–4.

[18] Y.-K. Kim, J.-P. Hong, and J. Hur, "Torque characteristic analysis considering the manufacturing tolerance for electric machine by stochastic response surface method," *IEEE Transactions on Industry Applications*, vol. 39, no. 3, pp. 713–719, May 2003.

[19] I. Coenen, M. Herranz Gracia, and K. Hameyer, "Influence and evaluation of non-ideal manufacturing process on the cogging torque of a permanent magnet excited synchronous machine," *COMPEL*, vol. 30, no. 3, pp. 876–884, 2011.

[20] G. Lei, J. G. Zhu, Y. G. Guo, J. F. Hu, W. Xu, and K. R. Shao, "Robust design optimization of pm-smc motors for six sigma quality manufacturing," *IEEE Transactions on Magnetics*, vol. 49, no. 7, pp. 3953–3956, July 2013.

[21] T. Herold, D. Franck, E. Lange, and K. Hameyer, "Extension of a D-Q Model of a Permanent Magnet Excited Synchronous Machine by Including Saturation, Cross-Coupling and Slotting Effects," in *International Electric Machines and Drives Conference, IEMDC 2011*, Niagara Falls, Ontario, Canada, May 2011, pp. CD–ROM.