Statistical evaluation of manufacturing tolerances in electrical machines by simulation and measurement

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Abstract—**The characteristics of electrical machines are influenced by the manufacturing process. It is therefore important to test the compliance of the required specifications as a first instance of monitoring. In order to develop a reliable end-of-line test it is essential to determine the statistical spread caused by manufacturing tolerances. This paper presents a statistical evaluation of the influences of non-ideal manufacturing. Simulation and measurement are being applied and compared.**

I. INTRODUCTION

Condition monitoring of electrical drives is important to meet the high requirements on its reliability [1]. Faults are expected to be detected earliest possible to prevent downtime of electrical devices which may cause delays and financial losses [2]. In the first instance of diagnostics an end-of-line test is necessary to check whether the produced machines comply with their specifications. The observance of tolerance ranges during manufacturing is important because of the parasitic effects in electrical machines such as torque ripple and radiated audible noise. These are strongly influenced by non-ideal manufacturing [3]. Furthermore the end-of-line test is helpful to record the reference data used to train the monitoring system.

For development of a reliable end-of-line test it is relevant to consider the statistical spread within one series of machines. This is essential in order to determine certain levels for which an overstepping would mean the rejection of the machine during the test.

Studying the influence of manufacturing tolerances is most commonly achieved by simulation [4], [5]. The distribution of the machine's parameters can be determined by use of stochastic approaches [6]. The benefit of applying simulation instead of measurement is less effort considering a sufficiently large number of experiments for a reliable analysis. There are approaches to intentionally construct tolerances in built prototypes [7]. But this is very difficult to realize because different effects have to be separated to interpret the results.

This work aims to determine the statistical spread for a permanent magnet excited machine using simulation and measurement. For the simulation, relevant deviations are considered and their stochastic distribution is assumed. The results are compared to measurements where a number of prototype samples is tested. For these prototypes the actual existing deviations are unknown. The measurement results are statistically analyzed in order to verify whether the applied approaches in simulation provide significant findings.

II. MONITORING OF ELECTRICAL MACHINES

Fault diagnostics of electrical machines is intensively being studied [8]. Monitoring the machine's behavior is important in order to ensure a high reliability of electrical devices on account of the increased automation of engineering processes. There is a huge number of monitoring techniques [1] using different physical quantities such as temperature, mechanical vibration, current or magnetic flux. Widely used and reliable methods are current and vibration monitoring [9].

In this work a monitoring system focusing electrical quantities such as current and voltage is considered. This non-invasive approach offers the advantage that no additional sensors have to be applied. The proposed system considers three stages of monitoring: starting from the testing subsequent to the manufacturing (end-of-line), to the tests at the first-time operation, to the monitoring of the continuous operation (Fig. 1). The main purpose of the first stage is to test whether the motor under study complies with its specifications. In addition, the reference data can be recorded in order to train the monitoring systems. During the following steps, faults shall be detected by comparing the current monitored condition and the reference condition.

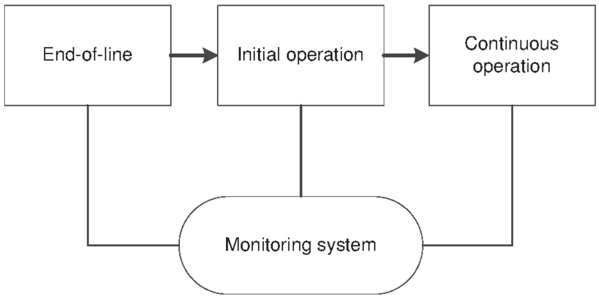

Fig. 1. Monitoring system.

This study is focused on the described first stage of monitoring. By determination of the statistical spread the basis

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for the development of a reliable end-of-line test is provided. The most often proposed setup for end-of-line tests includes back-EMF monitoring [17], [11]. Therefore, the following evaluation is performed regarding the back-EMF but can also be assigned to other measured quantities.

The motor under study is a three-phase permanent magnet synchronous machine (PMSM) in a sub-fractional-horsepower range. It presents six stator slots and a tooth-coil winding system. It has four pole pairs p meaning eight magnets at the rotor which are arranged in a spoke-type configuration [12].

III. EFFECTS OF MANUFACTURING IMPERFECTIONS

The manufacturing process of electrical drives contains a series of fabrication steps from the production and processing of materials to the molding and joining of components through to the assembling of the finished machine. None of theses steps is ideal. Deviations occur, for instance caused by positioning inaccuracy of the tools. These deviations can result in an unwanted behavior of the electrical machine. Undesired parasitic effects such as torque ripples and radiated audible noise may be increased [3], [13].

The commonly occuring tolerances for PMSMs are:

1) Variance of magnetization [14];
2) Rotor eccentricity [15];
3) Asymmetries of stator winding system, e.g. varying number of turns.

In [16] it has been shown that the back-EMF waveform balances rotor eccentricities in case of a common neutral point of the windings. Given that the studied machine presents a common neutral point, this fault is excluded for this statistical evaluation of back-EMF.

Asymmetries of the winding system can be inspected by measuring the phase-to-phase resistances. The variation in the studied machines is detected to be smaller than 0.5%. Therefore, this fault can be neglected as well.

The most significant tolerances in permanent magnet machines are variations of the magnet's magnetization. Especially cogging torque is strongly influenced by the magnet's quality as shown in [19]. Deviations in magnetization cause an asymmetric distribution of the flux-density at the air gap of the machine. This leads to new harmonic orders of cogging torque. The same applies for the back-EMF which also depends on the flux-density. The back-EMF U_i is the induced voltage at no load condition (open circuit). For a coil with w numbers of turns U_i is defined as follows:

$$U_i = -w\frac{d\phi}{dt} = -w\frac{d}{dt}(\iint \vec{B}d\vec{A}). \tag{1}$$

For the ideal faultless case where the air gap field is symmetric, the appearing orders in the back-EMF spectrum are determined by the winding arrangement [17]. For a three phase winding, these harmonic orders are:

$$\nu = 6g \pm 1 \,\text{with}\, g \in \mathbb{N}. \tag{2}$$

In case of rotor faults such as magnetization errors, new harmonic orders appear. For the studied machine these new orders can be expressed by:

$$\nu_{rf} = 1 \pm \frac{2k}{p} \,\text{with}\, k \in \mathbb{N}. \tag{3}$$

Thereby, the coil configuration of the studied machine is considered [18] in which one phase contains two coils which are displaced by $180°$. Thereof, it can be deduced that only even numbers ($2k$) appear in the back-EMF spectrum.

One example of influences in back-EMF caused by magnetization faults is shown in Fig. 2. Here, variations of the remanence flux-density B_R are assumed and the back-EMF is calculated by applying Finite Element Analysis. The resulting spectrum calculated by discrete Fourier transform yields the new harmonic orders corresponding to (3).

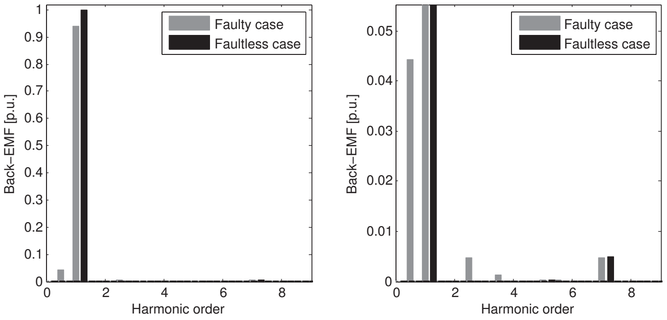

Fig. 2. Back-EMF spectrum assuming magnetization fault.

The appearance of these new orders itself does not indicate whether the tested machine is faulty and should be rejected. It only signifies an asymmetric distribution of flux-density which can also be caused by deviations within the allowed tolerance range. As no manufactured machine is ideal and presents a precise symmetric magnetic field, such orders will always appear in measurements. Therefore, it is essential to determine the level for which overstepping reliably indicates a faulty machine and leads to its rejection.

IV. STATISTICAL EVALUATION

The aim of this study is to determine the statistical spread within a series of manufactured machines. Simulations and measurements are performed. The comparison of both approaches shall proof whether the assumptions applied for the simulation provide proper results or not.

A. Simulation

To calculate the back-EMF, a two-dimensional time-stepping Finite Element Analysis (FEA) is applied. No-load operation at a certain speed is assumed and the voltage is calculated by use of the time derivative of the magnetic flux, as in equation (1).

In order to determine the influence of magnetization faults on the back-EMF characteristic, a stochastic analysis is applied as presented in [19]. From the data sheet of the permanent magnet material used, it is known that there is a tolerance range of $\pm 1.5\%$ concerning the remanence flux density B_R.

The probability distribution of B_R is unknown and assumed to be Gaussian distributed here. A standard deviation of 3σ equal to 1.5% of the nominal value is considered. For each magnet a random normally distributed value of B_R is generated in such a way that a series of random fault cases is created which back-EMF will be calculated by applying FEA.

B. Measurement

Fig. 3 shows the applied setup for measuring back-EMF. The motor under test is driven under open-circuit conditions. A flywheel is employed between drive and motor under test to damp possible influences of the drive. The data acquisition is performed via an oscilloscope.

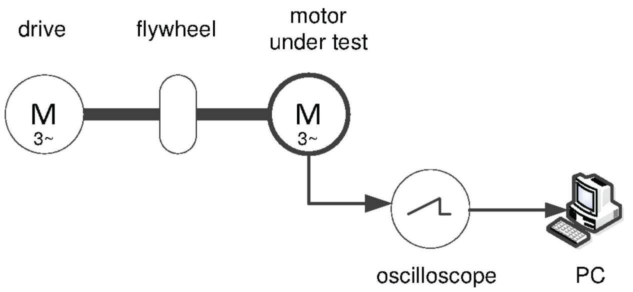

Fig. 3. Measurement setup.

In order to exclude measurement errors the experiments are repeated three times. Thereby, the reproducibility of the measurements is being confirmed.

C. Results

From a statistical point of view a huge number of experiments is reasonable in order to gain statistically robust results. For this study a number of 20 prototypes of the studied motor are available for the measurements. Therefore, the number of experiments is limited to 20. For reasons of comparability this number is considered for simulations as well. However, by applying simulation a larger amount of experiments could be realized with less effort.

The measured prototypes are newly manufactured, unused and fully functional. The allowed tolerance ranges of the manufacturing process are known, but the real existing deviations present in the machines are unidentified.

In the following the measured and simulated back-EMF characteristics are analyzed using the discrete Fourier transform. Particular frequency orders are evaluated.

1) Evaluation of first harmonic order: The fundamental component of the back-EMF is an indicator for the overall magnetization status of the machine. The measured first order is therefore used for parameterization of the ideal FEA model. Thus, the resulting first order obtained by measuring the 20 prototypes is evaluated in form of a histogram (Fig. 4). Based on this results, the magnets material properties (B_R) within the model are adjusted in such a way, that simulated value of first order and mean value of measured first order match.

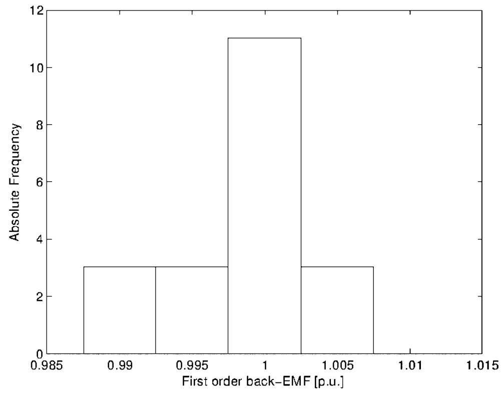

Fig. 4. Histogram of measured back-EMF: first order.

In this way it is verified that FEA simulation and measurement are based upon the same reference point. When considering the magnetization tolerances by use of stochastic analysis the distribution of simulated first order of back-EMF can be evaluated as shown in Fig. 5.

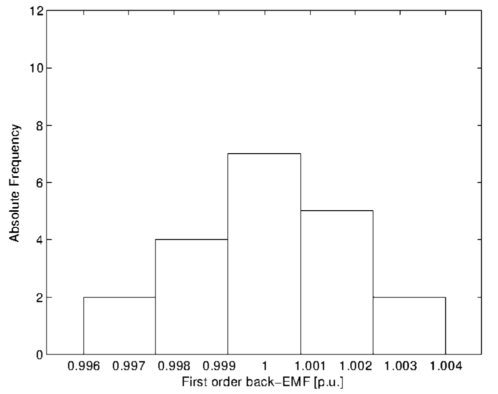

Fig. 5. Histogram of simulated back-EMF: first order.

It becomes apparent that the spread of the first harmonic order is small in both kind of experiments. This indicates the robustness of the studied machine. For comparison the distributions are interpolated as shown in Fig. 6. The distribution obtained by the simulation shows a larger variance when compared to the measured results. This was expected, as the simulation model is an approximation and not an exact replication of the real machine. Some inputs of the model are subjected to idealization, for instance the soft magnetic material properties. Furthermore, measurements are always subjected to inaccuracy of the measurement devices. The simulated distribution is close to the Gaussian distribution owed by the assumed input distribution.

2) Evaluation of orders indicating faults: In case of faults new harmonic orders appear in the back-EMF spectrum according to (3). For the studied machine the order number $\nu = 0.5$ is influenced in particular. It is a promising char-

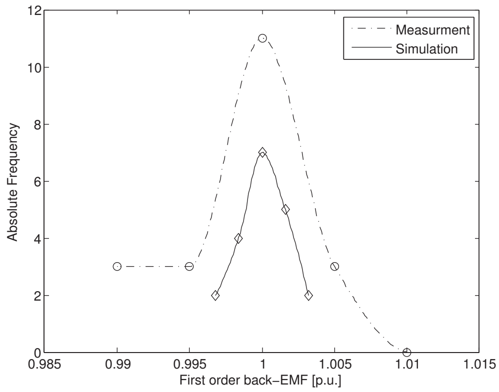

Fig. 6. Interpolated distribution of simulated back-EMF: first order.

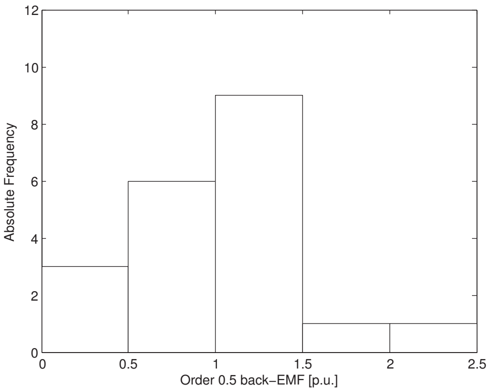

Fig. 8. Histogram of simulated back-EMF: order 0.5.

acteristic for fault diagnostics and its behavior influenced by tolerances is evaluated here. Fig. 7 shows the histogram of this order obtained by measurements.

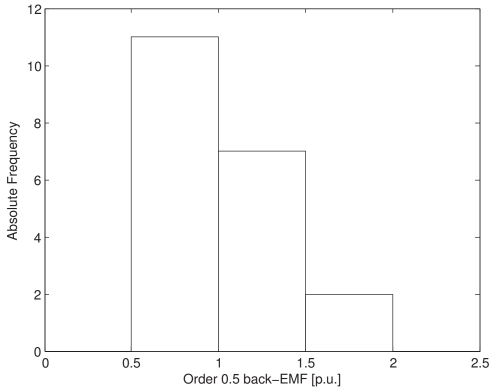

Fig. 7. Histogram of measured back-EMF: order 0.5.

The simulated results for $\nu = 0.5$ are shown in Fig. 8. For the ideal case the value of this order would be equal to zero. Therefore the presented values are related to the mean value.

The interpolated distributions are presented in Fig. 9. Similarly to the first order of the back-EMF, the simulated results are close to the Gaussian distribution. The amount of the influence is similar.

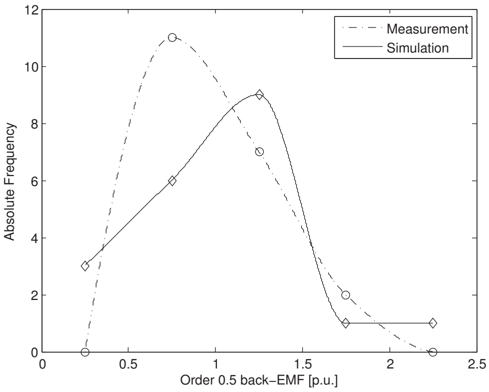

Fig. 9. Interpolated distribution of simulated back-EMF: order 0.5.

3) Summary of results: This analysis shows that the value of variance is similar in simulation and measurements. Despite the difference in the form of distribution, it can be concluded that the applied simulation is helpful to describe the influence of tolerances and leads to reasonable findings. The results confirm the significance of the magnetization tolerances. The studied machine shows a robust behavior in back-EMF towards tolerances.

V. CURRENT MONITORING

Current monitoring is an alternative to realize an end-of-line test. It can be implemented in such a way, that the motor under study is being connected to the inverter without any mechanical coupling to a drive. A start-up of the motor up to a certain speed is performed and the current is measured at various speeds. This method is beneficial due to its time- and cost-saving setup. When compared to the back-EMF setup, less hardware is required.

In the case of faults, the harmonic orders can be derived analogously to the back-EMF and will appear according to equation (3). Ampere's law reveals the general relation between electrical current I and magnetic flux density B:

$$\mu_0 \cdot I = \oint_S \vec{B} d\vec{s}. \quad (4)$$

In practice, the current may additionally be affected by the control system and by the inverter supply. These impacts have to be considered in order to avoid a wrong interpretation of the measured signals.

The proposed procedure is tested with one prototype. The measured current is analyzed by use of the short-time Fourier transform (STFT). This yields the spectrum including the frequency distribution versus speed of the non-stationary current signal. The results are presented in Fig. 10. The value of current is represented by a color range, where light colors mean a high and dark colors a low value. It can be seen that the harmonic orders are the same as for the back-EMF. Especially, the order number $\nu = 0.5$ is apparent.

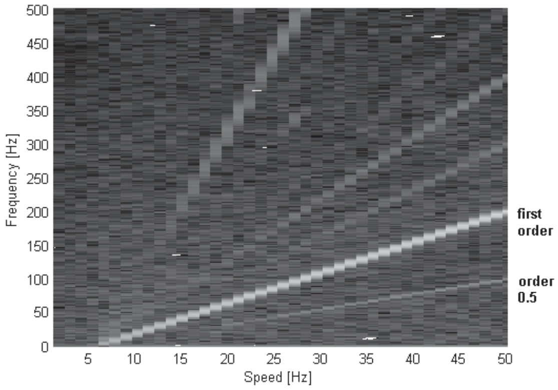

Fig. 10. Measured current spectrum.

Monitoring of the stator current to realize the end-of-line test approves to be a promising approach for future work. The time- and cost-saving setup is beneficial in the case that impacts caused by the control system or the inverter supply can be localized.

VI. CONCLUSION

This paper presents the statistical evaluation of manufacturing tolerances for a PMSM. The statistical spread in the back-EMF characteristic caused by a non-ideal manufacturing process is determined by applying simulation and measurement. This information is helpful for the development of an end-of-line test. Performing the applied evaluation, the values of the limiting qualities can be defined which have to be satisfied during the test. Non-compliance of this limits means the rejection of the tested machine.

By comparison with measurement it shows that the applied stochastic simulation approach is valid to describe the influences caused by tolerances. The benefit of simulation in contrast to measurements is less effort in realizing a sufficiently large number of experiments in order to achieve statistically firm results. The described evaluation confirms the applicability of simulation in order to get reasonable results concerning non-ideal manufacturing.

The results of this study contribute to the development of a reliable monitoring system. These are valuable for the realization of the first stage of a monitoring process which is crucial in order to train a diagnostic system to end up in a reliable detection of the machine's health status.

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