



Evaluating the influence of manufacturing tolerances in permanent magnet synchronous machines

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Abstract

Purpose – Manufacturing tolerances can result in an unwanted behavior of electrical machines. A quality control of machines subsequent to manufacturing is therefore required in order to test whether the machines comply with its specifications. This paper aims to describe the consideration of rotor tolerances due to non-ideal manufacturing processes.

Design/methodology/approach – Various fault scenarios are studied employing numerical field simulations focusing the influence of rotor tolerances on current and back-EMF of the studied machine.

Findings – This analysis shows that electrical quantities are applicable to realize tolerance diagnosis by evaluating the influence of non-ideal manufactured rotor components on the back-EMF and current characteristics of the studied machine.

Practical implications – This study provides an approach how to estimate the influence of the manufacturing tolerances for realization of a reliable quality control. This is useful to ensure a high reliability of the manufactured machines.

Originality/value – This paper gives a close insight on how to investigate non-ideal manufacturing and in particular its influence on the stator current.

Keywords Electrical machines, Finite element analysis (FEA), Manufacturing tolerances, Quality control, Electrical equipment

Paper type Research paper

1. Introduction

The reliability of electrical drives (Nandi *et al.*, 2005) is an important aspect to ensure a high availability. In industrial applications, permanent magnet excited synchronous machines (PMSM) are widely employed as they offer advantages in efficiency and power density. However, especially the rotor of PMSMs is susceptible to tolerances caused during mass production. Variations from the ideal machine influence its operational behavior (Gasparin *et al.*, 2009). Therefore, it is important to verify the machine's quality prior to its installation.

Reliable and widely used diagnostic methods are vibration and current monitoring (Tavner *et al.*, 2008). In this study, electrical quantities are focused because this offers the advantage that no additional sensors need to be installed (le Roux *et al.*, 2007).

1.1 Proposed monitoring setup

The most often proposed end-of-line test is back-EMF monitoring (Casadei *et al.*, 2009; Flach *et al.*, 2011). Figure 1 shows a possible setup for its realization. Here, the motor



under test is driven under open-circuit conditions. For attenuation of the drive's influence, a flywheel is employed between drive and motor under test.

This approach presents a non invasive monitoring method being beneficial for diagnosis. However, such a setup is very expensive. It is cost-expensive because a drive is required and a certain device is needed to damp possible influences of the drive. Above all, it is time-expensive due to the fact that the motor under test is mechanically coupled to the drive. This is not an efficient solution when a large number of machines needs to be tested during mass production.

In this study, an additional approach is investigated where the current is being monitored. The corresponding setup is shown in Figure 2. Here, a start-up of the motor up to a certain speed is performed in such a way that the current is measured at various speeds. The benefit of this method is its time- and cost-saving setup. When compared to the back-EMF setup, less hardware is needed. No mechanical coupling to a drive is required, simply the motor is connected to the inverter.

However, for evaluating the current, it needs to be considered that the current is a controlled quantity. Impacts caused by the control system or the inverter supply might lead to misinterpretation of the results.

In the following, the back-EMF and current characteristic of a PMSM is determined. In order to study various fault scenarios, numerical field calculation is employed considering tolerance affected rotor components. The aim is to evaluate the influence of such tolerances to be able to determine distinguishing characteristics. This information can be helpful to develop an appropriate end-of-line test and to reveal which of the proposed setups is most qualified.

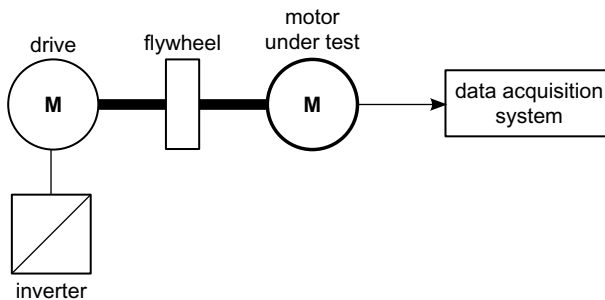


Figure 1. Back-EMF monitoring setup

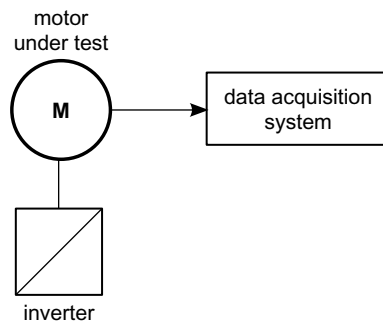


Figure 2. Current monitoring setup

2. Motor under study

The machine studied within this work is a three-phase permanent magnet synchronous machine in sub-fractional-horsepower range with tooth-coil winding system. It presents six stator slots and four pole pairs p . The eight magnets of the rotor are arranged in a spoke configuration as shown in Figure 3.

3. Influence of rotor tolerances

During the manufacturing process material dependant failures, geometrical or shape deviations may occur. Such tolerances influence the machine's behavior. For instance, increased torque ripples are caused (Heins *et al.*, 2011).

The considered tolerances within this paper concern the magnet's material and its dimensions. The magnetization faults are shown Figure 4. Possible deviations affect the magnitude of the remanence flux density B_R and the angle β of the magnetization direction. Further examples of rotor tolerances, not considered within this study, would be a displacement of the magnet and rotor eccentricity.

3.1 Theoretical analysis

Within this study, the influence of rotor tolerances onto electrical signals is focused. According to Casadei *et al.* (2009), for non-ideal rotor components new fractional harmonic orders n_{rf} are expected to appear in the back-EMF spectrum which are a function of the pole pair number p :

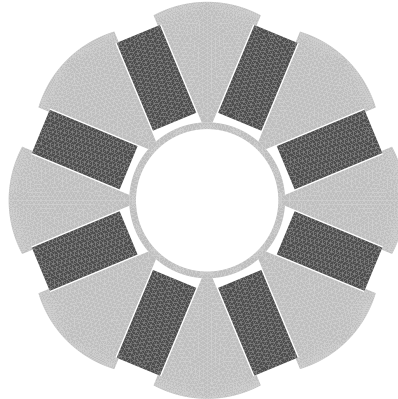


Figure 3.
Motor under study: spoke
type rotor construction

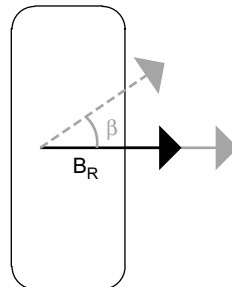


Figure 4.
Magnetization faults

$$n_{rf} = 1 \pm \frac{k}{p} \text{ with } k \in \mathbb{N}. \quad (1)$$

In the following, this relation shall be approved and specialized for the certain machine investigated.

The back-EMF V_i is the induced voltage at no load condition (open circuit). For a coil with w numbers of turns V_i is defined as follows:

$$V_i = -w \frac{d\phi}{dt} = -w \frac{d}{dt} \left(\iint \vec{B} d\vec{A} \right). \quad (2)$$

Applied to a machine's winding, it means that the back-EMF in one coil of the winding is determined by the air gap flux density B . Therefore, the back-EMF presents the same harmonic orders which appear in the spectrum of the flux density. The latter will be considered for an order analysis.

The magnetic flux density at the air gap of the machine is a rotating wave which is a function of relative position at the air gap α and time t (Cameron *et al.*, 1986). It is given as the product of the magnetomotive force Θ (MMF) and the air gap permeance Λ :

$$B(\alpha, t) = \Theta(\alpha, t) \cdot \Lambda(\alpha, t). \quad (3)$$

The functions of permeance, magnetomotive force and flux density can generally be represented by a series of space and time harmonics (Ebrahimi *et al.*, 2009):

$$\Lambda(\alpha, t) = \sum_{y_l, z_l} \Lambda_{y_l, z_l} \cdot \cos(y_l \cdot \alpha - z_l \cdot t), \quad (4)$$

$$\Theta(\alpha, t) = \sum_{y_t, z_t} \Theta_{y_t, z_t} \cdot \cos(y_t \cdot \alpha - z_t \cdot t), \quad (5)$$

$$B(\alpha, t) = \sum_{y_b, z_b} B_{y_b, z_b} \cdot \cos(y_b \cdot \alpha - z_b \cdot t). \quad (6)$$

At this, ω_1 is the supplying angular frequency. For reasons of illustration the phase angle is neglected.

For derivation of the fractional harmonic orders caused by non-ideal rotor components only the rotor fundamental component of the MMF is considered, meaning $y_t = p$ and $z_t = \omega_1$. Furthermore, a constant air gap width is considered, meaning $y_l = 0$ and $z_l = 0$. For the faultless case, this implies:

$$B_p(\alpha, t) = B_{p, \omega_1} \cdot \cos(p \cdot \alpha - \omega_1 \cdot t). \quad (7)$$

The above-mentioned rotor tolerances lead to an asymmetrical distribution of the air gap field. With the described approach, this means a modulation of the MMF caused by the rotor magnets. New space and time harmonics k with $k \in \mathbb{N}$ appear resulting in the following expression for the flux density considering non-ideal rotor components:

$$B_{rf}(\alpha, t) = \sum_k B_k \cdot \cos((p \pm k) \cdot \alpha - (\omega_1 \pm k\omega_m) \cdot t). \quad (8)$$

Here, ω_m is the rotational speed with $\omega_m = \omega_1/p$. Hence, B_{rf} can be expressed as follows:

$$B_{rf}(\alpha, t) = \sum_k B_k \cdot \cos \left((p \pm k) \cdot \alpha - \left(1 \pm \frac{k}{p} \right) \cdot \omega_1 t \right). \quad (9)$$

This expression indicates the new fractional harmonic orders appearing in the spectrum of the flux density and equally in the back-EMF spectrum due to deviations at the machine's rotor as predicted in expression (1). However, it is only valid considering one single coil (Urresty *et al.*, 2012). Deriving the harmonics for one phase, the coil configuration needs to be considered. One phase of the investigated machine contains two coils which are displaced by 180° .

According to equation (9) the back-EMF of the first coil in one phase assuming faulty rotor components can be determined as follows:

$$V_{irf1}(\alpha, t) = \sum_k V_{ik} \cdot \cos \left((p \pm k) \cdot 0^\circ - \left(1 \pm \frac{k}{p} \right) \cdot \omega_1 t \right). \quad (10)$$

Similarly, the back-EMF of the second coil in the same phase is:

$$V_{irf2}(\alpha, t) = \sum_k V_{ik} \cdot \cos \left((p \pm k) \cdot 180^\circ - \left(1 \pm \frac{k}{p} \right) \cdot \omega_1 t \right). \quad (11)$$

The resulting back-EMF V_{irfph} for one phase can be determined by the superposition of the two coils:

$$V_{irfph} = V_{irf1} + V_{irf2} = \sum_k V_{ik} \cos \left(\left(1 \pm \frac{k}{p} \right) \omega_1 t \right) \cdot [1 + \cos((p \pm k) \cdot 180^\circ)]. \quad (12)$$

For odd numbers $(p \pm k)$, equation (12) is equal to zero. With $p = 4$ it is obvious that only even numbers of k appear in the back-EMF spectrum.

Finally, equation (1) can be specialized for the analyzed machine, indicating the fractional harmonic orders appearing in the spectrum of back-EMF in case of non-ideal rotor components:

$$n'_{rf} = 1 \pm \frac{2k'}{p} \quad \text{with } k' \in \mathbb{N}. \quad (13)$$

For the faultless case where the air gap field is symmetrical, the appearing orders are determined by the winding arrangement (Casadei *et al.*, 2009). Considering a three phase winding, these harmonic orders are:

$$n = 6m \pm 1 \quad \text{with } m \in \mathbb{N}. \quad (14)$$

The mentioned fractional harmonic orders caused by faults appear in addition to equation (14).

For the current, the harmonic orders can be derived analogously. Ampere's law reveals the general relation between electrical current I and magnetic flux density B :

$$\mu_0 \cdot I = \oint_S \vec{B} d\vec{s}. \quad (15)$$

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

4. Methodology

To determine the influence of the rotor tolerances onto the back-EMF and current characteristic, numerical field simulations are used. Reliable analysis requires a sufficiently large number of experiments which means less effort performing with simulation instead of measurements. In addition, the interpretation of measurement results is difficult within this context, as for a certain prototype the real existing deviations are unknown. The intentional construction of tolerances is very difficult to realize.

4.1 Finite element analysis

To calculate the back-EMF, a two-dimensional time-stepping finite element analysis (FEA) is applied. No-load operation at a speed of 3,000 rpm is assumed and the voltage is calculated by use of the time derivative of the magnetic flux linking the stator coils.

For analysis, a discrete Fourier transform (DFT) is performed which yields the spectrum of back-EMF as shown in Figure 5. For the ideal faultless case with symmetrical air gap field, harmonic orders appear according to equation (14).

4.1.1 *Parameterization by statistical measurements.* For parameterization of the FEA model, a statistical verification is performed. The back-EMF is measured for ten prototypes of the machine analyzed by use of DFT. The first order of back-EMF of each pro-type is evaluated in form of a histogram shown in Figure 6. Based on this results, the magnets' material properties (B_R) within the model are adjusted in order that simulated value of first order and mean value of measured first order agree.

4.2 Extended d-q model

A d-q model is a common way to describe the PMSM's dynamical behavior considering the control system. Here, the application of such a model is studied to calculate the current. Since the common d-q model only takes the fundamental wave into account, it is

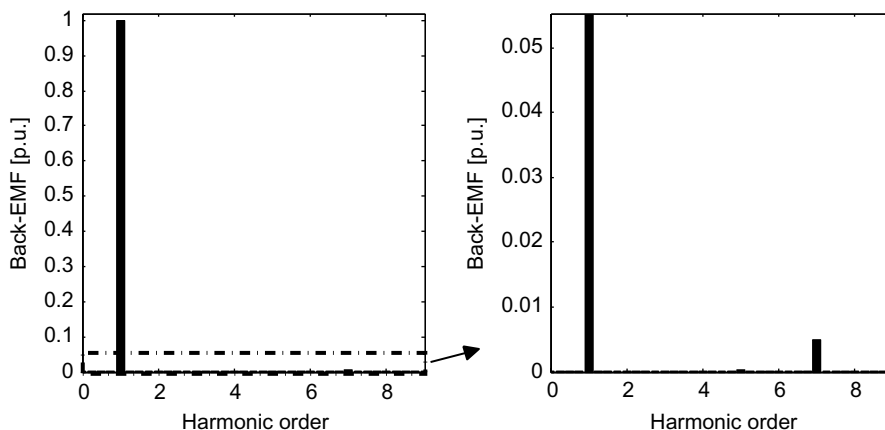


Figure 5. Back-EMF spectrum assuming faultless case

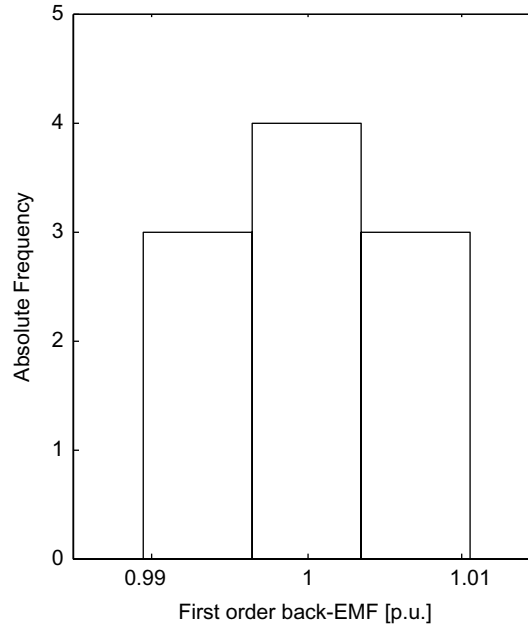


Figure 6.
Measured back-EMF
histogram

not able to consider non-ideal behavior such as local defects studied within this work. Hence, the extended d-q model presented in Herold *et al.* (2011) is applied to calculate the current. Here, the approach is the division of the overall flux into the current and the excitation based fluxes. The elements of the resulting extended equations, such as inductances, excitation flux and torque, are extracted by use of FEA.

In the following, a start-up of the machine from zero to 3,000 rpm is simulated and the stator current is analyzed by use of a short-time Fourier transform (STFT). This yields the spectrum including the frequency distribution over time of the non-stationary current signal. Figure 7 shows the result for the faultless case. 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.

Here, sine-wave excitation is assumed. With the presented model it is also possible to simulate inverter operation. However, modeling the inverter leads to a computationally expensive model. Figure 8 shows the result for the faultless case assuming inverter supply. Due to the high intensity of computation it is illustrated with lower resolution. Besides the main harmonic orders some new orders appear. However, these do not interfere with the orders which are expected to appear corresponding to equation (13) due to tolerances. Therefore, inverter supply is not considered within this study because of the computational costs.

5. Simulation results

To develop a reliable end-of-line check, the most common and important fault modes should be captured. In the following, different approaches are applied to simulate

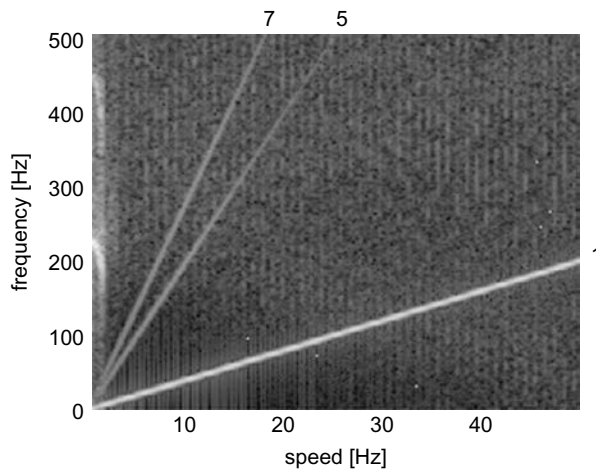


Figure 7.
Current spectrum
assuming faultless case

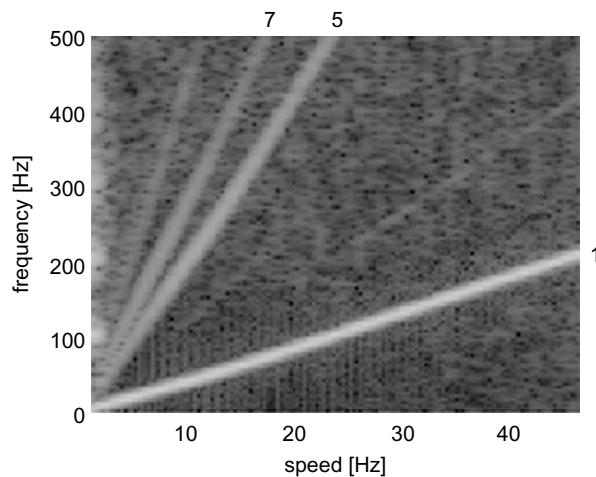


Figure 8.
Current spectrum
assuming faultless case
and inverter supply

various fault scenarios. The choice of the corresponding approach depends on the particular fault, the prior knowledge of the fault and the available data.

5.1 Worst-case analysis

For PMSMs cogging torque is an undesired effect as it leads to rotational oscillations of the drive train. Cogging torque is strongly influence by deviations caused by the manufacturing process (Gasparin *et al.*, 2009; Heins *et al.*, 2011). However, measuring cogging torque is very time- and cost-expensive (Schlensok *et al.*, 2007) and therefore no appropriate method for an end-of-line control. In the following it shall be studied how back-EMF and current are influenced at a faulty machine presenting a high value of cogging torque due to magnetization faults.

Considering a deviation in the magnitude of the magnets' remanence flux density B_R , the amount of variation of cogging torque is depending on which and how many permanent magnets are affected. In Coenen *et al.* (2012) design-of-experiments is applied to find out the worst-case configuration of magnetization faults concerning cogging torque. Applied to the studied machine, the configuration shown in Figure 9 shows the highest value of peak-to-peak cogging torque. Thereby, the filled magnets represent the ones that are defective. Considering a deviation at B_R of -10 percent, the value of cogging torque is about seven-times higher compared to the reference value of the ideal machine.

Figures 10 and 11 show the results for back-EMF and current in case of the described worst-case magnetization fault.

The spectra show new fractional harmonic orders, especially $n'_{ff} = 0.5$ and $n'_{ff} = 2.5$ are apparent according to equation (1). Compared to the faultless case the first harmonic order is reduced.

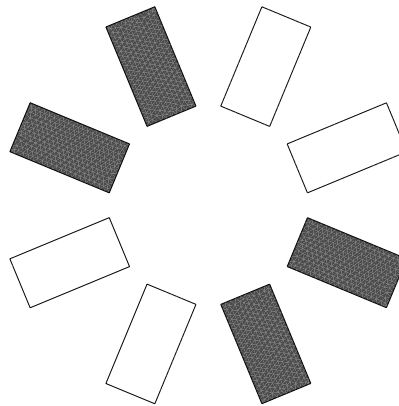


Figure 9.
Worst-case configuration
of magnetization faults

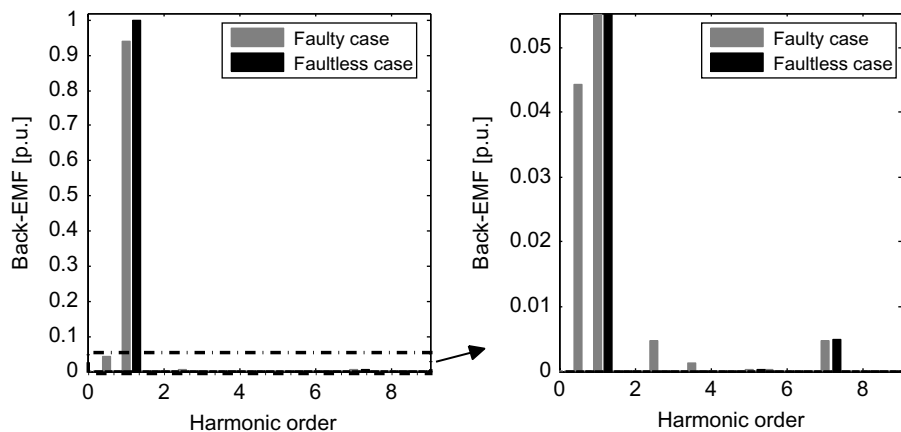


Figure 10.
Back-EMF spectrum
assuming worst-case
magnetization fault

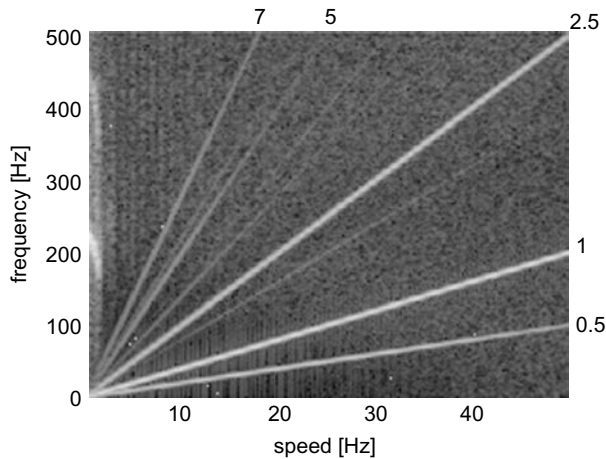


Figure 11. Current spectrum assuming worst-case magnetization fault

5.2 Sample cases

For the studied machine the height of the magnet can vary between 97 and 100 percent of its desired value and the width can vary by ± 1.5 percent. The dimensions of some sample magnets have been measured which are used as input data for this approach. None of the measured dimensions exceed the allowed tolerance range. Five cases are created where every magnet is subjected to the given tolerances. Figures 12 and 13 exemplarily show the back-EMF and current spectrum of one faulty case. The first harmonic order is reduced compared to the faultless case and the new ordinal numbers appear corresponding to equation (13).

When compared to the results from the worst-case magnetization fault studied in 5.1, one can see that the influence of deviations at the magnets' dimensions within the allowed tolerance range is not significant. The spectra show the same specific characteristics but less amounts. For all five studied cases the simulated spectra do not differ considerably from the faultless case.

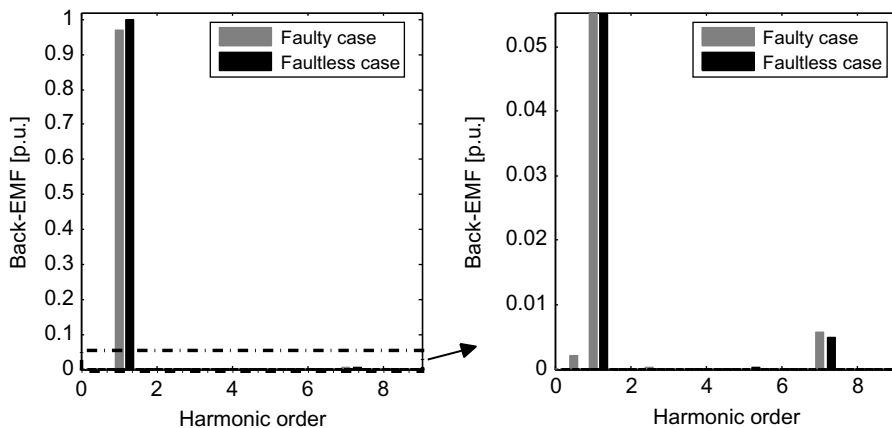
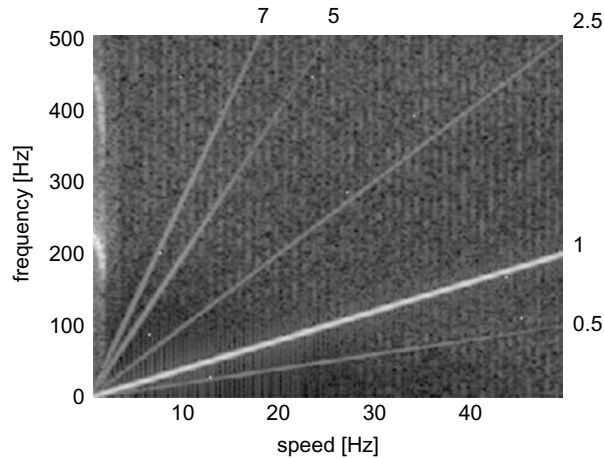


Figure 12. Back-EMF spectrum assuming faulty magnet dimensions

Figure 13.
Current spectrum
assuming faulty magnet
dimensions



5.3 Stochastic analysis

In Coenen *et al.* (2011) the influence of varying qualities of the permanent magnet has been investigated applying a stochastic analysis. This is applied here to compare the influences of deviations in the magnetization magnitude and magnetization direction. Overall, 60 failure configurations are studied. For 20 cases the remanence flux density B_R is assumed to be Gaussian distributed with a standard deviation of 3σ equal to 10 percent of the nominal value. For 20 other cases the magnetization direction is also assumed to be normally distributed with a standard deviation of 5° . The other 20 cases present both kind of deviations. Applying FEA, cogging torque and back-EMF are calculated and evaluated employing histograms.

The distribution of the first harmonic order of the back-EMF is shown in Figure 14. It shows the range in which the back-EMF is influenced because of the different magnetization deviations.

It can be seen that the influence of the deviations concerning the magnetization direction is very small. The magnitude fault is prevailing. This is to be expected for the studied machine as it presents interior magnets.

The same analysis is performed for the peak-to-peak cogging torque, which is shown in Figure 15. Again it can be concluded that the influence of magnetization direction is small when compared to the deviation in magnitude as the corresponding distribution shows.

Generally, magnetization faults influence cogging torque and back-EMF characteristic simultaneously (Kim *et al.*, 2006). For both quantities new fractional harmonic orders arise depending on the caused asymmetry in the air gap field. Based on the presented studies, it becomes apparent that the influence of magnetization tolerances on cogging torque is more significant as on back-EMF. This means, that on the one hand the machine's behavior is strongly influenced in general. But on the other hand, as a cogging torque test is excluded for an end-of-line concept, it implies high functional requirement of the measurement devices to detect faults by use of back-EMF analysis. This shows the importance of an influence analysis such as presented in this study. It is required to study the impact of tolerances to be able to separate it towards measurement inaccuracy.

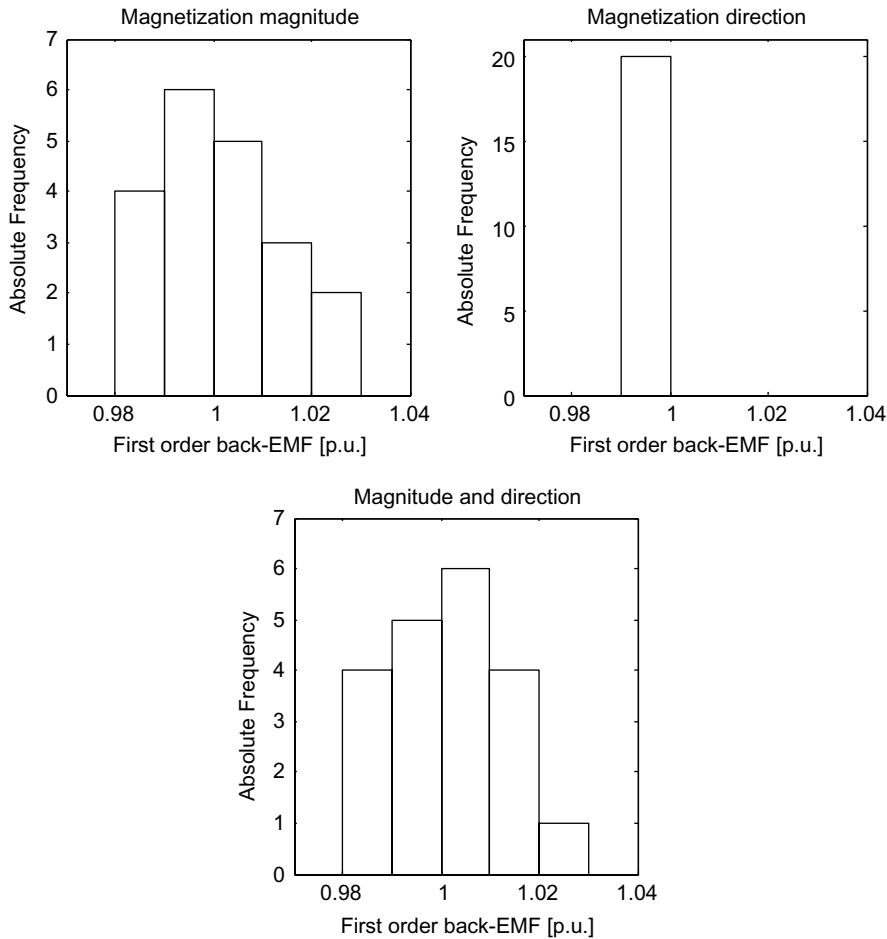


Figure 14. Back-EMF histogram considering magnetization faults

6. Conclusion

In this work, the influence of non-ideal manufactured rotor components of a PMSM on its back-EMF and current characteristic is studied. It has been shown that electrical quantities are applicable to realize tolerance diagnosis. Especially the stator current approves to be a promising approach due to its time- and cost-saving setup. The fractional harmonic orders caused by rotor faults are derived within a theoretical analysis and confirmed by the simulation results.

An end-of-line check could be realized in such a way that all machines presenting a certain level in these specific characteristics are rejected. With the presented methods, the range of these distinguishing characteristics can be evaluated to detect the corresponding levels for rejection. At this, measurement accuracy should be taken into account.

Comparing the different rotor tolerances, all present the same characteristics but with different amounts depending on the fault's intensity and arrangement. As a feedback for manufacturing, a differentiation of various tolerances would be gainful but cannot be

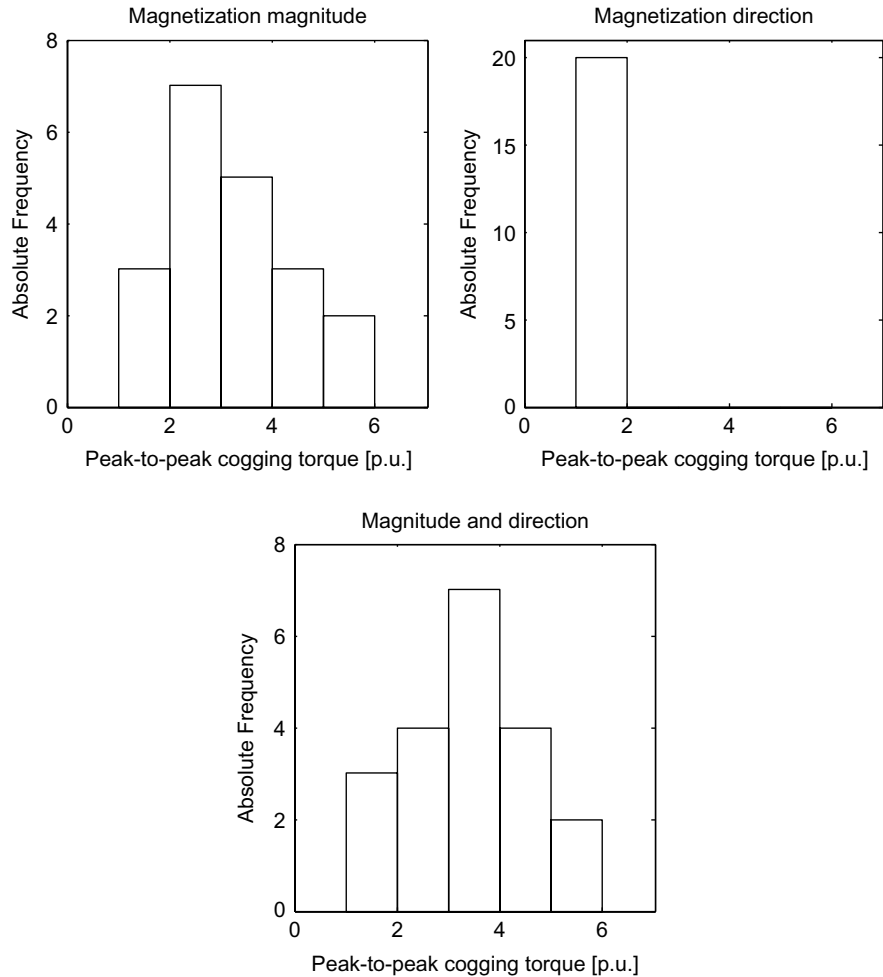


Figure 15.
Cogging torque
histogram considering
magnetization faults

achieved with the presented analysis. However, the focus of the end-of-line check is to verify the machines' quality which can be realized by the suggested approach. The results of this study evince to be valuable for application of an accurate quality control for PMSMs finally improving its reliability.

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