

Analysis of the Influence of Static and Dynamic Eccentricity on Back EMF of a Permanent Magnet Synchronous Motor

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Abstract

In this paper the measurement results that represent the back electromotive force (EMF) of a small drive permanent magnet synchronous machine (PMSM) are proposed. The focus is on the comparison between three mechanical configurations: the original one and a setup with static and dynamic eccentricity. Additionally, the influence of compensating currents is considered due to the circuitry of the windings belonging to one phase. This leads to quite similar gradients of back EMF in all three mechanical configurations.

The PMSM consists of an external rotor, has a pole pair number of 4 and a mechanical output power of 240 W. Each electric phase consists of four windings. Two of them are serial connected and both serial connections are parallel connected. If the partial back EMF at one winding is not equal to the back EMF at windings of the same phase, compensating currents will occur and will counteract the partial back EMF. This happens especially in case of static and dynamic eccentricity. In these cases the air gap length as well as the partial back EMF depend besides on the position also on the angle between the rotor and the stator of the machine.

To analyse the back EMF at several operating points, a machine test bench is set up. In order to measure the partial back EMF, the machine is equipped with additional stator windings. Furthermore, the parallel connections of the windings are disconnected and the pins are led through the machine's package. On the one hand, it is possible to leave the connection open-circuited to avoid compensating currents. On the other hand, the connection can be restored using an amperemeter, which enables a measurement of the intensity of the compensating currents at different operating points. Due to mechanical modifications on the machine it is possible to analyse the specific influence of static and dynamic eccentricity.

1 Introduction

The detailed analysis of the influence of mechanical tolerances on the electric behaviour of a machine has advantages in many applications. A cheaper manufacture of machines could lead to more unwanted mechanical variance between single motor samples. If it's possible to estimate their low effect on the machine's general properties, e.g. the electric characteristic, all produced samples can be run without limitation.

Intentionally installed mechanical tolerances can bring another use. If these modifications cause a defined electric behaviour, it could be possible, for example, to get sensorless information about the rotor's position by measuring the back EMF.

In this paper the influence of static and dynamic eccentricity on back EMF of a permanent magnet synchronous motor is analysed.

In the first section the machine and its different mechanical configurations are presented. The second section explains the test bench and the additional measuring methods. The last section points out the measuring results and the comparison between the three mechanical setups.

2 The Permanent Magnet Synchronous Machine (PMSM)

2.1 The unmodified machine

The considered three-phase PMSM is used as an electronically commutated brushless DC-motor in the application of a motor cooling fan. It has a mechanical output power of 240 W and its maximum string voltage is 12.7 V. It has a pole pair number of 4, hence, the stator consists of twelve single tooth windings. Furthermore, it has as essential feature an external rotor with eight surface mounted permanent magnet poles. The machine's structure is shown in Figure 1 as a matter of principle. The air gap length between rotor and stator is $l_{\text{gap}} = 0.8 \text{ mm}$.

The electric connection of the stator's windings is shown in Figure 2. Every electric string between two connecting terminals consists of four windings. Each two of them are serial connected and both serial connections are parallel connected. The three strings set up a delta connection.

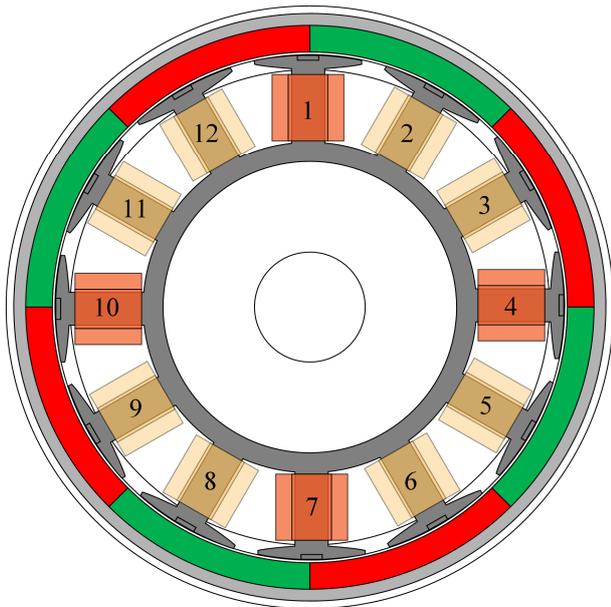


Figure 1 Structure of the considered PMSM as a matter of principle

2.2 Two types of eccentricity

In addition to the original mechanical configuration of the machine, two types of eccentricity are researched: the static and the dynamic eccentricity [1].

In case of static eccentricity the center of the stator is shifted $\Delta l = 0.2 \text{ mm}$ from the rotation axis, which is the center of the rotor at once. Therefore all windings have different air gap lengths which stay constant during a mechanical rotation. The smallest air gap length at winding 9 is $l_{\text{gap } 9} = 0.6 \text{ mm}$, the largest one at winding 3 is $l_{\text{gap } 3} = 1.0 \text{ mm}$. The schematic of static eccentricity is depicted in Figure 3. To figure out the eccentricity, the air gap length is not drawn to scale. The cross in the middle of the rotor symbolizes the rotation axis.

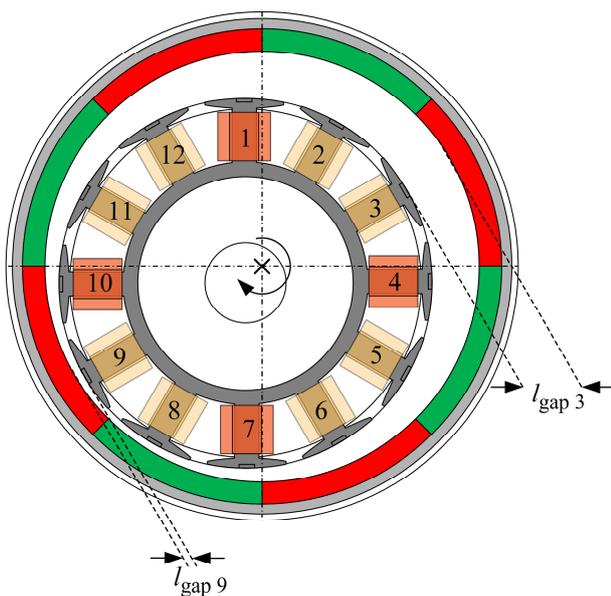


Figure 3 Schematic of static eccentricity

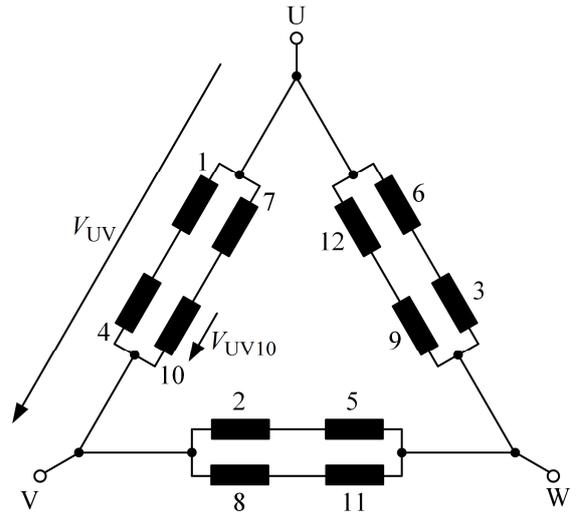


Figure 2 Electric connection of the stator's windings

In case of dynamic eccentricity the center of the rotor is shifted $\Delta l = 0.2 \text{ mm}$ from the rotation axis, which is the center of the stator at once. Therefore all windings have different air gap lengths, which vary according to the position of the rotor between the minimum air gap length $l_{\text{gap, min}} = 0.6 \text{ mm}$ and the maximum air gap length $l_{\text{gap, max}} = 1.0 \text{ mm}$. The schematic of dynamic eccentricity is depicted in Figure 4. The cross in the middle of the stator also symbolizes the rotation axis.

The unmodified setup and both types of eccentricity can be adjusted in the considered PMSM. So it's possible to compare the back EMF of all three mechanical configurations while analysing the same motor with equal parameters like for example the magnetization of rotor's permanent magnets.

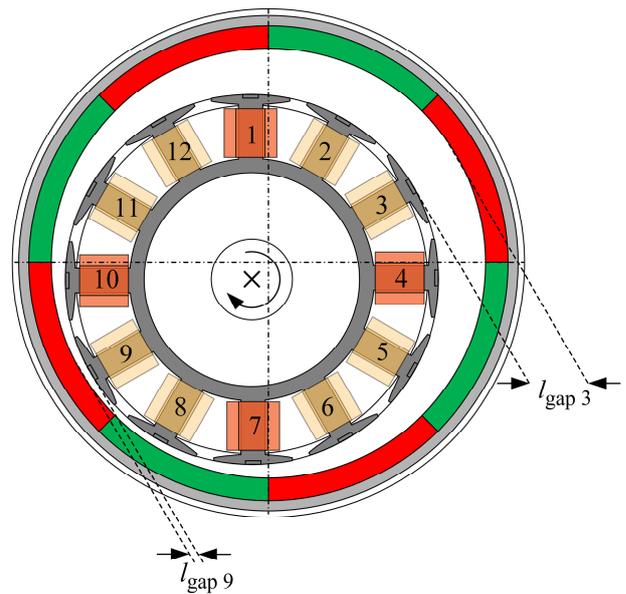


Figure 4 Schematic of dynamic eccentricity

3 The test bench

3.1 Mechanical setup

To analyse the back EMF at several operating points a machine test bench is set up. The device under test is coupled to an asynchronous load machine which is connected to an external inverter. The load machine is speed controlled. So it's possible to regulate the rotational frequency and measure the device under test's back EMF. In addition to record the rotational speed a rotary encoder with built in torque sensor is also integrated. The test bench is shown in Figure 5.

3.2 Electric setup

When the machines rotate with a definite rotational speed, the back EMF of a whole string can be measured between two responding connecting terminals.

For more detailed analysis the partial back EMF at every single winding has to be measured, too. Therefore a second measure winding is wound on every stator tooth. The equivalent circuit of the string UV and its measure windings is shown in Figure 6.

The stator's main windings and the additional measure windings build a transformer. Neglecting the stray flux of these transformers, the partial back EMF at one tooth can be calculated from the measured voltage at the measure windings and the ratio of turns of the stator windings N_{stat} and turns of the measure windings N_{meas} . The partial back EMF V_{UV10} at winding 10, for example, can be calculated with equation (1).

$$V_{UV10} = \frac{N_{stat}}{N_{meas}} \cdot V'_{UV10} \quad (1)$$

Another modification in the device under test is the opportunity to avoid possibly occurring compensating currents inside a string. If the sum of partial back EMF at two serial connected windings is higher than the partial back EMF at the ones which are parallel connected to them, the voltage difference effects a compensating current. The compensating current in the string UV is exemplarily represented in Figure 7.

To avoid the compensating currents, the parallel connections of the windings are disconnected and the pins are led

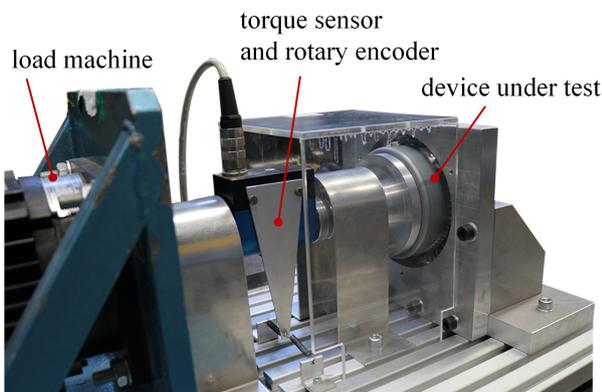


Figure 5 Machine test bench

through the machine's package. However, on the one hand, it is possible to leave the connection open-circuited to avoid compensating currents. The equivalent circuit of this operating mode is depicted in Figure 8. The voltage difference $V_{UU'}$ between the connecting terminal U of the machine and the new connecting terminal U' corresponds to the difference between the partial back EMF, which induces the compensating currents.

On the other hand, the connection can be restored to get the original electric setup of the machine, which allows the occurring of compensating currents. Reconnecting the two pins by using an amperemeter enables a measurement of the intensity of these currents at different operating points.

The following measurement results also show a comparison between these two setups to illustrate the influence of compensating currents.

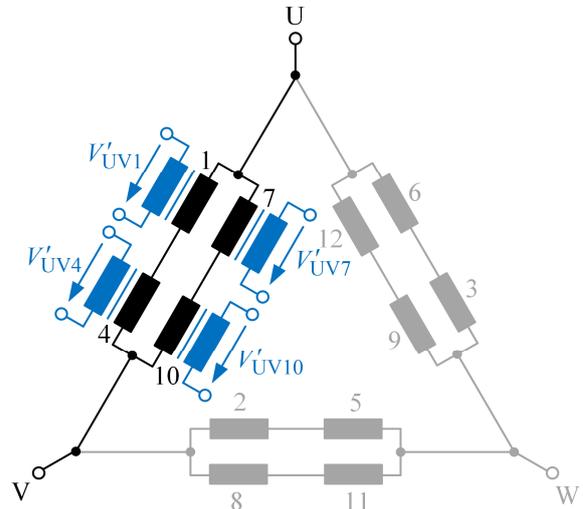


Figure 6 Equivalent circuit of the measure windings

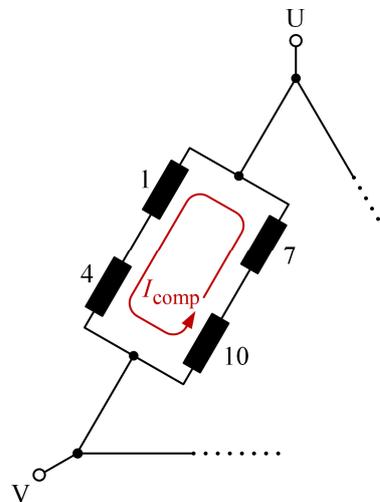


Figure 7 Compensating current in string UV

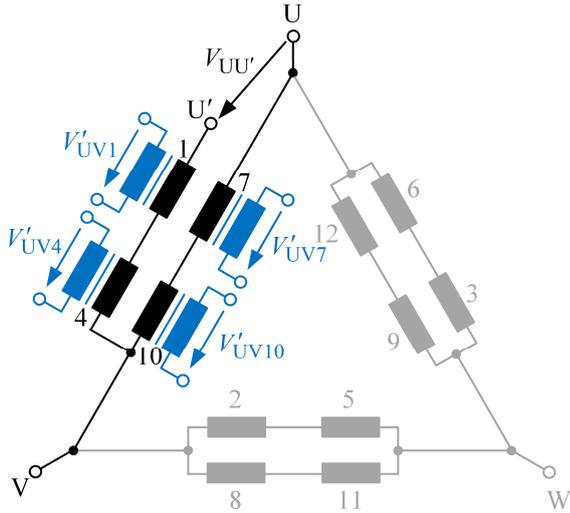


Figure 8 Setup to avoid compensating currents by opening the parallel circuit

4 Measurement results

The following measurement results are all recorded at the same rotational speed. They are presented in a normed way not to draw conclusions on the surveyed machine. To point out the characteristics of the results only the measurement of string UV is exhibited. Each colour belongs to one mechanical configuration, which has been described in section 2. Black belongs to the original configuration, blue to the setup with static eccentricity and red to the configuration with dynamic eccentricity.

4.1 Back EMF without compensating currents

To avoid compensating currents the parallel connection of the string UV is disconnected as it has been presented in section 3.2 respectively in Figure 8.

In Figure 9a the measured plot of back EMF V_{UV} between the connecting terminals U and V against the rotor's mechanical angle φ_{mech} is shown. In Figure 9b a zoomed view of Figure 9a is depicted. Caused by the pole pair number of 4, four electric periods occur within one mechanical turn.

The first conspicuousness is a small drop at the peaks of the curve. In detail it's an overlay of the fifth harmonic of the fundamental. The fifth harmonic with remarkable magnitude is caused by the structure of the rotor. The rotor's eight magnetic poles are magnetized on only five segments of permanent magnet material. Little gaps between the five segments effectuate the remarkable content of the fifth harmonic in all the mechanical configurations. Due to the fact, that the main topic of this paper is the analysis of influence of eccentricity, it doesn't go into the fifth harmonic in detail.

A detailed view of the back EMF without compensating currents points out that the setup with static eccentricity induces back EMF with highest amplitudes. The reason

for that is, that the windings 7 and 10, which are responsible for the back EMF V_{UV} in this configuration, have the smallest air gap length.

With a constant number of turns in a winding the absolute value of back EMF is proportional to the derivative of magnetic flux [2]. A smaller air gap length reduces the magnetic resistance and increases the magnetic flux and consequently its derivative. So a smaller air gap causes a higher back EMF.

The back EMF of the setup with dynamic eccentricity is the first half turn smaller and the second half turn higher than the back EMF of the original setup. It reflects the state of the air gap length. For the first half turn of the rotor the variable air gap lengths at windings 7 and 10 are smaller than the air gap length in original configuration, for the following half turn they are larger. However, it has to be mentioned that there are only minor differences between the back EMF curves of the three mechanical configurations.

The same behaviour can be found in the partial back EMF at single windings. Exemplarily the partial back EMF V_{UV10} at winding 10 is depicted in Figures 10a and 10b.

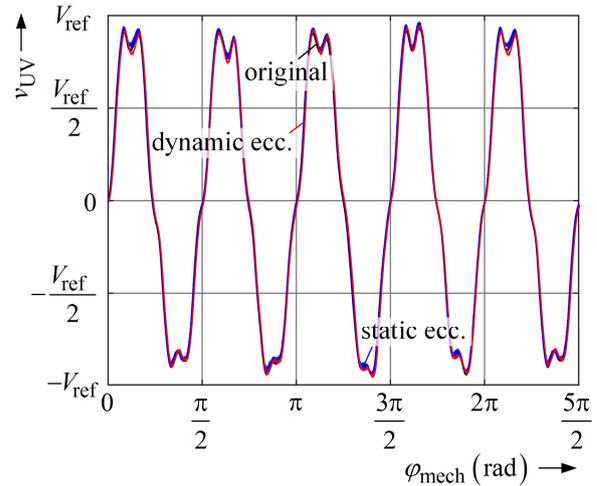


Figure 9a Back EMF V_{UV} without compensating currents

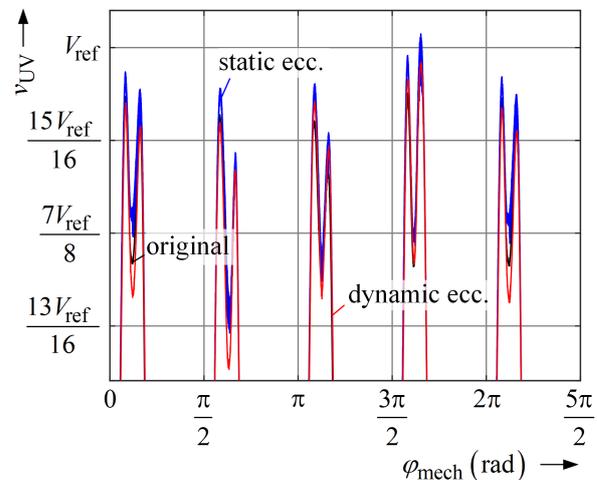


Figure 9b Zoomed view of back EMF V_{UV} without compensating currents

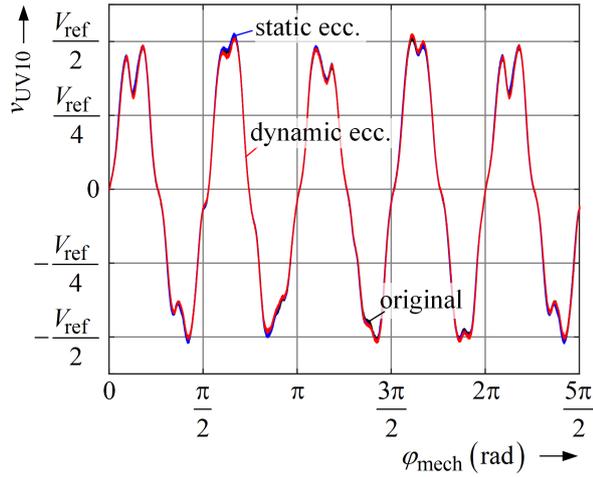


Figure 10a Partial back EMF V_{UV10} at winding 10 without compensating currents

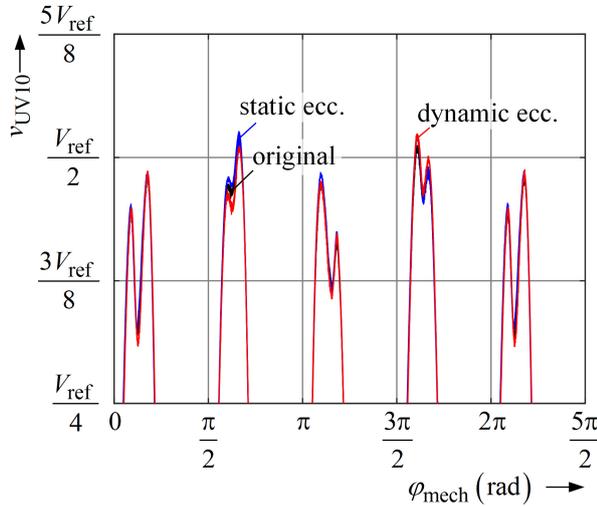


Figure 10b Zoomed view of partial back EMF V_{UV10} at winding 10 without compensating currents

Especially the changing amplitudes in dynamic eccentricity configuration can be observed in comparison to the original configuration.

To point out the different partial back EMF in partial strings of the parallel connection, the voltage between the connecting terminal U of the machine and the new connecting terminal U' is measured. The results are presented in Figure 11. Some amplitudes of the voltage $V_{UU'}$ reach peak values up to 20 % of the reference voltage V_{ref} , which also appears in original configuration. There is evidence to suggest that the influence of the asymmetry of rotor's magnetization has a stronger influence on the back EMF and on the compensating currents than some kind of eccentricity.

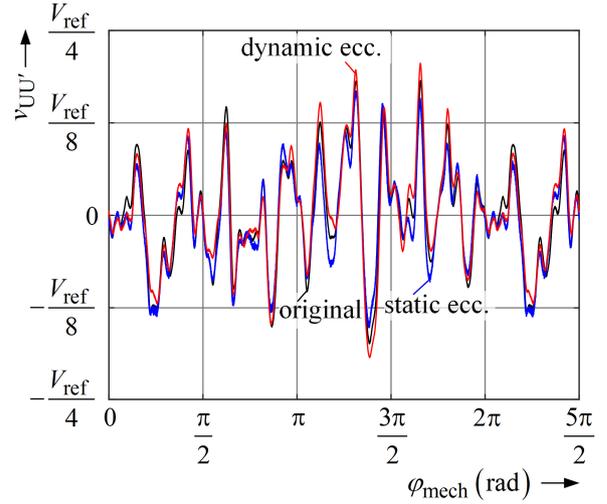


Figure 11 Voltage $V_{UU'}$ between the connecting terminals U and U'

4.2 Back EMF with compensating currents

To analyse the back EMF in original configuration the connecting terminals U and U' are short-circuited by an amperemeter to record the compensating currents. In Figure 12a the measured plot of back EMF V_{UV} between the connecting terminals U and V against the rotor's mechanical angle ϕ_{mech} is shown. In Figure 12b a zoomed view of Figure 12a is depicted.

In comparison to the back EMF without compensating currents the influence of eccentricity is less. All three curves differ only in a few points. The reason for this is the occurrence of compensating currents. As seen in Figure 11, it exists a relevant voltage difference between the two parallel connected pairs of windings. This voltage difference drives the compensating currents which are only limited by the ohmic resistance and the inductance of the windings. The compensating current counteracts the different partial back EMF and effects same sums of partial back EMF at parallel connected pairs of windings.

In Figure 13 the trend of the compensating current i_{comp} is depicted.

Thus it appears that the intensity of compensating currents in different mechanical configuration varies appreciably. In setups with static or dynamic eccentricity voltage differences between two parallel connected pairs of windings reach temporarily higher values. Hence, a higher compensating current is generated, which counteracts these differences. Consequently, the differences in the back EMF of a string seem to disappear.

All in all, a configuration with static and dynamic eccentricity has not that influence on back EMF because of occurring compensating currents which neutralize the different partial back EMF resulting from eccentricity.

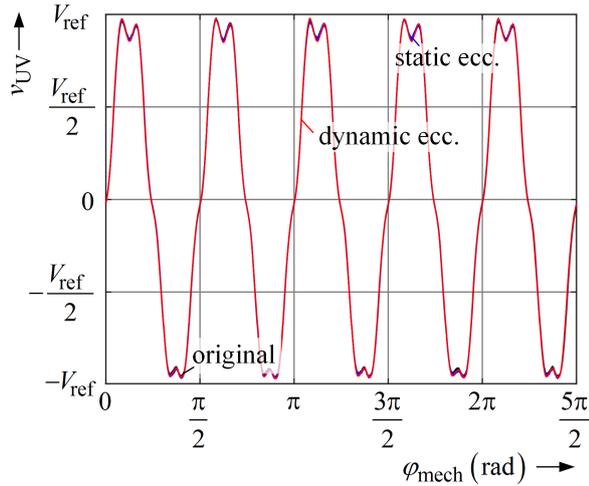


Figure 12a Back EMF V_{UV} with compensating currents

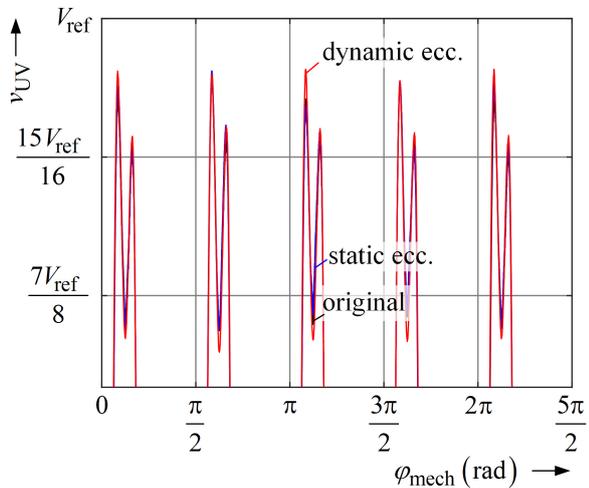


Figure 12b Zoomed view of back EMF V_{UV} with compensating currents

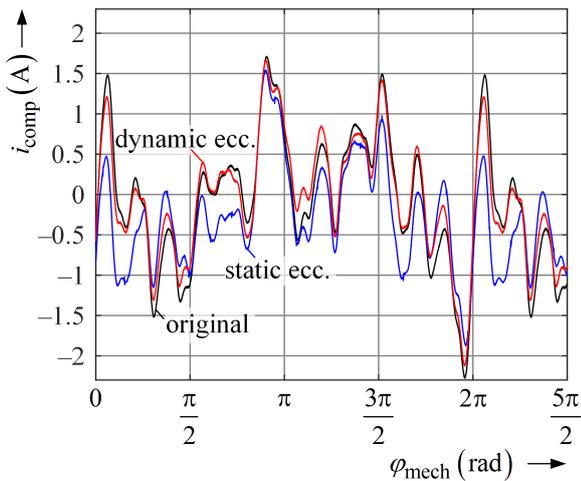


Figure 13 Compensating current i_{comp}

5 Conclusion

Within this paper the back EMF under the influence of static and dynamic eccentricity is compared to the original configuration. For the surveyed machine it has been shown that the influence of the asymmetry of rotor's magnetization has more influence on the back EMF than the influence of eccentricity. If the partial back EMF at single windings are different caused by motor's geometry or a setup of eccentricity, compensating currents inside the parallel-connected partial strings will occur, which counteract the different partial voltages.

If the parallel-connection is disconnected and the compensating currents are suppressed, the differences in the back EMF of the three presented mechanical configurations are clearer than with compensating currents.

The first section describes the mechanic and electric structure of the surveyed machine. Also the two types of eccentricities are explained.

The second section introduces into the test bench to analyse the back EMF. To measure the partial back EMF at single windings and avoid the occurrence of compensating currents some electric modifications are brought into the device under test machine.

In the last section the measurement results of back EMF and partial back EMF with and without compensating currents are presented and interpreted. Furthermore a curve of the compensating current is shown.

6 Literature

- [1] Mahmoud, H.: Bianchi, N.: Comparison between Synchronous Machines with Eccentricity: Reluctance and Permanent Magnets, International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Italy: Anacapri, June 2016
- [2] Binder, Andreas: Elektrische Maschinen und Antriebe, Springer-Verlag, 2012