Influence on Unbalanced Magnetic Pull

Henning Kasten [a], Christian Redemann [b]

[a] Levitec GmbH, 35633 Lahnau, Germany, henning.kasten@levitec.de
[b] Levitec GmbH, 35633 Lahnau, Germany, christian.redemann@levitec.de

***Abstract*— This article describes the effects of the unbalanced magnetic pull and the opportunities to suppress asymmetries of the air gap field.**

I. INTRODUCTION

Today, high speed drives are often realized with magnetic bearings. One of the main challenges of developing and building-up such machines is the rotor dynamics. Unbalanced magnetic pull, UMP, and eccentric air gap fields occur when the rotor is not perfectly symmetrically built or centered in the stator [1]. The disadvantages of this phenomenon are:

- Reducing of the rotor eigen frequency
- Additional noise and vibrations
- Higher currents in the coils of the magnetic bearings to compensate the additional forces.

It is possible to use specific windings, which suppress eccentric fields and undesired parasitic forces. Such windings are not new [2, 3]. Many large machines have been constructed with these windings. The strands of such windings are divided in many parallel connected winding parts. Unsymmetrically fields cause balancing currents, which reduce the eccentric fields but also increase the additional winding losses. This paper shows ways to reduce the UMP with specific windings and shows FEM aided forces and loss calculations. With the results the characteristics of these specific windings with parallel connected paths can be evaluated.

II. TYPES OF AIR GAP ECCENTRICITIES

Figure 1 above shows an ideal cylindrically symmetrical rotor, which is not perfectly centered. This circumstance will create a static eccentricity. The most minimal air gap length is at a position that will not change when the machine works. At this location the smallest magnetic reluctance and the highest values of the magnetic induction appear. Therefore, the deformed air gap field causes a constant force in the direction to the smallest air gap length. Production tolerances cause the static eccentricity. Furthermore, some applications have eccentric rotors to reach better grinding surfaces [4]. Unsymmetrical end windings and anisotropic stacks cause also static eccentricities but their magnitudes are very small. Figure 1 bottom shows another case. It is called dynamic eccentricity. The axis of the shaft is exactly placed in the stator hole. However, the rotor surface turns eccentrically to the shaft. As a result the minimal air gap length will turn around. Such rough rotors are not manufactured. But magnet material variations also cause dynamic eccentricity. To reach small eccentricity fields the rotor must be very exactly mounted. That causes high effort. In some applications this cannot be reached. Furthermore the rotor magnets must not have tolerances. In general, these tolerances produce the highest amount of eccentric fields.

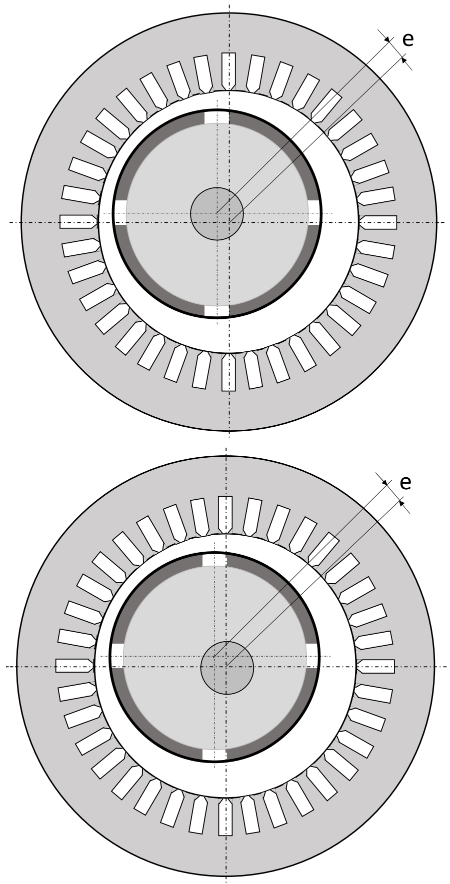

Figure 1. Static eccentricity (top) and dynamic eccentricity (bottom)

III. ROTOR MEASUREMENT

Figure 2 shows magnetic fields of electric machines with very different magnet heights. In spite of the high difference, the 2-pole machine has a symmetrical air gap field. The nature of the magnetic flux $\left(\operatorname{div}\vec{B}=0\right)$ explains this phenomenon. The fluxes of both poles must be equal. Therefore, 2-pole machines are insensitive to magnet asymmetries. The shown 4-pole machine has more degrees of freedom. The smallest rotor pole has the smallest flux and the highest rotor magnet causes the highest flux. This effect will also appear in motors with higher number of poles. To reach symmetrical fluxes it is necessary to use magnets with very small tolerances or to measure and adjust the finished rotor. Figure 3 shows an instrument for rotors with surface mounted permanent magnets. If the rotor turns, the field can be measured along the circumference in 6 positions.

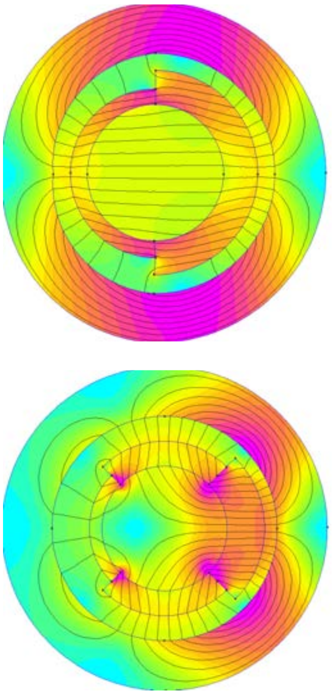

Figure 2. Magnetic fields of a 2-pole machine (top) and a 4-pole machine (bottom)

If the rotor length is greater than 50 mm, the rotor magnets will be divided in many segments to reduce the eddy current losses. Such rotors are built up with 50 or more magnet segments. However, to measure and select high numbers of magnets needs extra time and therefore is more expensive.

IV. Harmonics of the Eccentric Fields

Every real air gap field can be described by the theory of harmonics. Every single harmonic with an integer order number cannot create eccentric fields or resultant forces between stator and rotor. Eccentric field will be created by many harmonics with different order numbers. Figure 4 shows an eccentric field that is caused by two harmonics. The difference of both order numbers is only one. This small difference is typical for all eccentric fields. The most significant harmonics in machines with p pole pairs have the order numbers:

$$\nu = p \pm 1\,. \qquad (1)$$

They are also called eccentric harmonics. Both harmonics have the same magnitudes.

An exception are machins with only 2 poles ($p = 1$). In this case (1) is not to be used. The eccentric field of these rotors is created by harmonics with the order numbers $\nu = p = 1$ and $\nu = p + 1 = 2$.

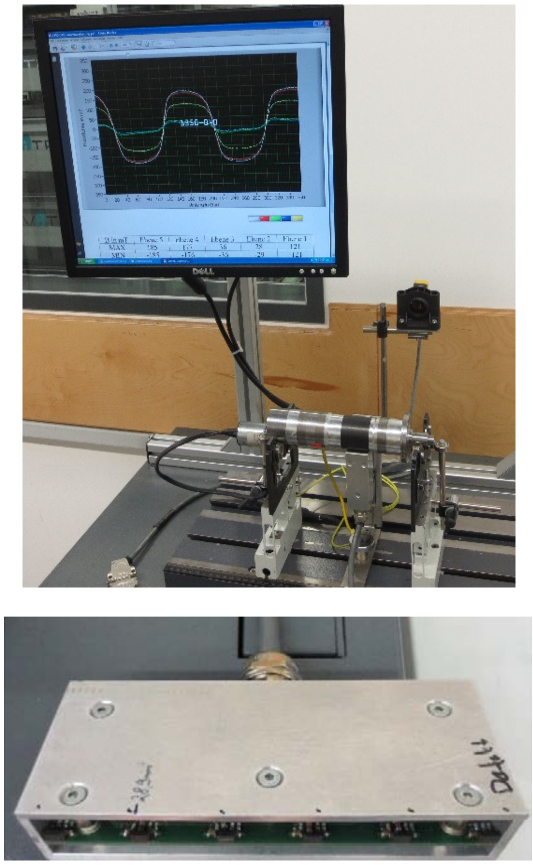

Figure 3. Automatic measuring machine for rotor magnets and an additional sensor for larger machines (bottom)

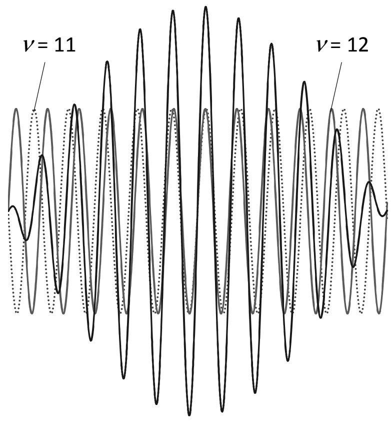

Figure 4. Superposition of two harmonics

V. Windings with Parallel Paths

Windings with parallel paths can help to reduce the asymmetries of the air gap field. On the other hand, additional circulating currents cause higher winding losses.

A. *Parallel Paths with diametric arranged coils*

At first only one phase of a 4-pole winding is analyzed. The number of slots per pole and phase is only one (Figure 5). The voltage u of one a current-carrying coil amounts:

$$u_c = Ri + w_c \frac{d\Phi_c}{dt}. \quad (2)$$

In electric machines, especially in those, which work with high speeds, the ohmic voltage drop can be neglected. For that reason, same magnetic fluxes Φ_c must pass in both parallel connected coils. The symmetry of both fluxes is achieved by an additional circulating current. This current increases the flux in one of both coils and decreases the flux in the other coil. Nevertheless, because of the stray flux Φ_σ the similar coil fluxes are different to the fluxes in the air gap Φ_δ. These three fluxes must fulfill the following equation:

$$\Phi_c = \Phi_\delta + \Phi_\sigma . \quad (3)$$

Accordingly small stray fluxes are essential to reach an air gap field with small eccentricity. Instead of the in (3) used fluxes it is also possible to handle this equation with inductances. With small stray inductivities a very symmetrical air gap field can be reached. Nevertheless, because of the additional circulating currents higher winding currents and losses will also occur.

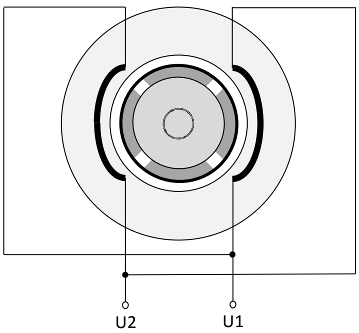

Figure 5. A single phase of a 4-pole Machine with parallel paths

A good suppression of eccentricity fields will be achieved by connecting all diametric placed coils parallel. This claim can be fulfilled with all two-shift windings and one-shift windings that have an even number of pole pairs.

B. One-shift windings with an uneven number of pole pairs

Figure 6 gives an example for this case. It can be seen an illustration of one phase of a 6-pole one-shift winding. In this case the suppression of the eccentricity is more obscured. The explanation will be given with the eccentric harmonics. The harmonics with the 2nd and 4th order numbers cause mainly the eccentric field. The three parallel connected coils induce voltages that are $\nu\,120°$ phase shifted to one another. The main field ($\nu = 3$) causes voltages that are in phase, wherefore the circulating current does not occur. But the eccentric harmonics generate phase shifted voltages by 120° degrees. The voltage that drives circulating currents averages:

$$U_2 = U_{c,2}(1 - e^{j240°}) = 1.732 U_{c,2}$$
$$U_4 = U_{c,4}(1 - e^{j120°}) = 1.732 U_{c,4} . \quad (4)$$

It is obvious, that this harmonics cause a high current in the shorted circuit. This current suppresses the eccentric harmonics and thereby the asymmetries in the air gap field.

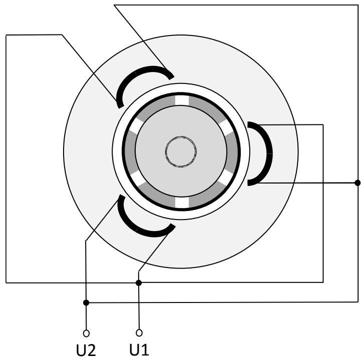

Figure 6. A single phase of a 6-pole one-shift winding

C. Windings with a higher number of slots per pole and phase

Figure 7 left shows two paths with many in series connected coils in a group. This connection causes only symmetrical fluxes of both groups. The coil fluxes do not have same values. Therefore the suppression of the eccentric fields is weaker than when only on coil per group is used. The suppression can be strengthened by using additional junctions, which are shown in figure 7 mid and right. Because only the additional circulating currents will pass through the junctions, the cross sections may be dimensioned smaller.

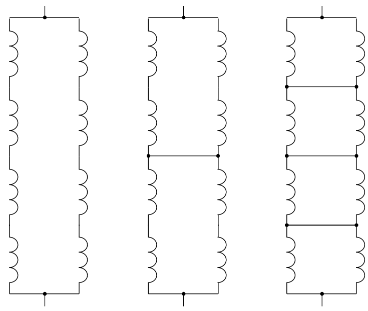
Figure 7. Phase with two parallel paths: without any additional junctions and additional junctions

VI. Favorable Number of Slots in Cage Rotors

With asynchronous machines it is possible to reach peripheral speeds greater than 200 m/s [3, 5]. The used rotors are very symmetrical. However, the rotor losses and the high harmonic content of such rotors are detrimental. A rotor with an even number of slots produces harmonics with uneven order numbers. Three phase windings show the same behavior. A superposition with two waves shown in figure 4 is not possible. Therefore rotors with an even number of slots cannot generate eccentric fields by the harmonic content. Rotors with an uneven number of rotor slots create harmonics with even order numbers. For that reason, such rotors can produce eccentric fields. But the advantage of this slot numbers is avoiding oscillating torques. By using uneven slot numbers, the rules in (5) should be adhered to.

$$N_2 \neq N_1 \pm 1 \cap N_2 \neq N_1 \pm (2p \pm 1). \quad (5)$$

N_1 stands for the number of stator slots and N_2 for the number of rotor slots.

VII. Calculation of forces and currents

The force calculation is important to know the bearing forces and to estimate the decrease of the rotor eigen frequency. Furthermore, suppressing of eccentric fields of particular windings can be determined. A description of an analytical way is too complex for this paper. In brief, an FEM-aided calculation should be given. At first, the machine will be examined without any winding currents. Abnormalities can be observed by changing the material properties and displacing the rotor position. Figure 8 shows a 2D-simulation with an eccentric placed rotor. The most of FEM software programs are able to determine the force between stator and rotor. [4] describes the effects of such forces and the influence of the critical speed. To determine the magnitudes of the eccentric harmonics, one rotor pole should be placed symmetrical to the smallest air gap length. The radial components of the air gap field at the smallest air gap length and in the opposite can be ascertained with the functions of the FEM program. Both calculated flux densities are local maximums of the fundamental wave. The difference is caused by the eccentricity. Therefore, the determined inductions are named with $\hat{B}_{\min}$ and $\hat{B}_{\max}$. The magnitudes of the most important eccentric harmonics can be calculated:

$$\hat{B}_{p\pm1} = \frac{\hat{B}_{max} - \hat{B}_{min}}{4}. \quad (6)$$

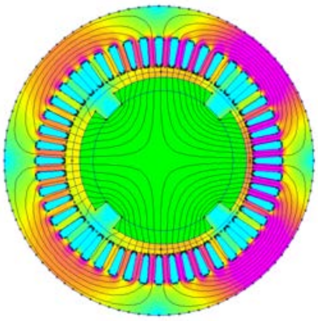

Figure 8. Magnetic field calculation with static eccentricity

In the next step the effect of windings with parallel paths can be calculated iteratively. Figure 9 shows the FEM calculation with the additional current. In this position and moment the circulating currents of the other phases are zero. Figure 10 shows the difference of the flux linkages of both groups and the resultant force in addition to the circulating current. The force is 8.2 kN/m without the circulating current. By using parallel phases the flux difference will be almost zero and the force is reduced by 4.4 kN/m.

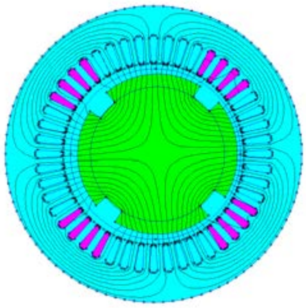

Figure 9. Field of the rotor and of the circulating current

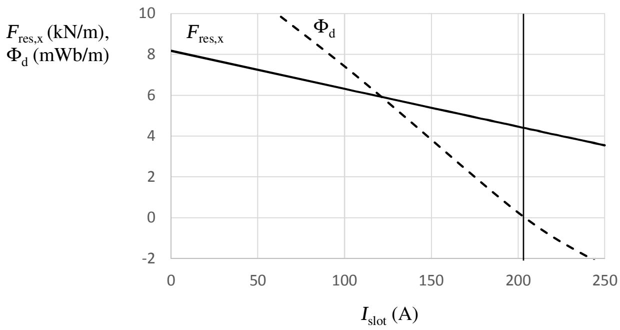

Figure 10. Resultant forces and flux difference as a function of circulating current

VIII. Conclusions

The paper has shown the disadvantages of unsymmetrical manufactured high speed machines with magnetic bearings. The eccentric air gap field was described with two harmonics, which can be suppressed with specific shown windings. Furthermore, ways have been shown to calculate with 2D-FEM forces and currents that are caused by the eccentricity.

References

[1] M. Wallin, "Measurement and modelling of unbalanced magnetic pull in hydropower generators", Uppsala University, 2013

[2] K.-H, Ketteler, "Über die Wirkung von parallelen Ankerzweigen auf das Oberfeldverhalten von Käfigläufern", Hannover University, 1983

[3] G. Müller, K. Vogt, B. Ponick, "Berechnung elektrischer Maschinen", Weinheim: Wiley-VCH, 2008

[4] SKF, "Von der Produktneuheit zur bewährten Lösung", EVOLUTION, 2003

[5] Huppunen, J, "High-speed solid-rotor induction machine – electromagnetic calculation and design" PhD thesis, Lappeenranta University of Technology, Finland, 2004