Sum-flux rotor position sensor with self-balancing magnetic bearing concept

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***Abstract*—Rotor position sensing is a key feature for successful operation for magnetic bearings. A position sensing concept based on the induction principle, embedded in a symmetrical multi-phase system may provide many interesting features. The knowledge of the electrical system's phase angle, combined with a conductive sensing coil as the only additional physical component, the principle allows detecting the radial rotor offset and can be used for providing self-balancing magnetic bearing functionality. The paper is aimed at clearly demonstrating the concept and is not meant as an actual magnetic bearing design.**

I. Introduction and idea

The reasons for not using distinct rotor displacement sensors in magnetic bearings or bearingless drives are numerous, ranging from robustness to system safety, system simplicity or costs. Many approaches for sensorless control of magnetic bearings can be found in the literature. Most are either based on an observer principle [1], estimating the rotor position from measured coil voltages or currents, or on the injection of high frequency current components [2], [3] or PWM current ripple usage [4], allowing inductance and, thus, position measurement.

In all of these works, the electromagnetic field variation is captured and fed into a signal treatment process of varying complexity. The present work focuses on a different position sensor concept, not strictly representing a sensorless principle, but also avoiding the disadvantages of classical position sensors. At the foundation of this work is the idea of using electromagnetic fields as an instrument of information since a magnetically conductive body will influence the field as it moves within it. This effect can be well used in symmetrical multi-phase systems. In an ideal situation, e.g. with a centered rotor, the flux components provoked by each phase cancel out, but any violation of the position symmetry generates a signal indicative of the magnitude and phase of this violation.

This principle has been introduced for a symmetric three-phase system in [5]. However, significant flaws are linked with the axially arranged flux detection concept of that work, shown in Fig. 1. The present work presents a novel detection method of the sum-flux using a circumferential sensing coil in Section II. For this purpose, a concept system is presented which allows to demonstrate the functionality of the principle

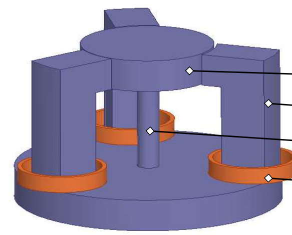

Figure 1. Concept of sum-flux detection in [5] with a sensor pin carrying a dedicated flux sensor.

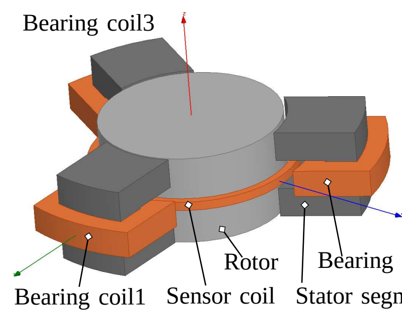

Figure 2. Concept demonstration system: 3-phase, 3-segment magnetic bearing

through finite element simulations. Section III then discusses the potential of using the gained information for self-balancing a magnetic bearing system. It needs to be clarified that especially for this self-sensing concept, the demonstration of the principle is in the focus - the presented designs are not yet aimed at an actual bearing prototype. Accordingly, the concluding Section IV is reserved for discussing the flaws of the concept and for giving an outlook to future work.

II. Sensing concept

A. Demonstration model

As a first example, we will consider the rather simple case of a primitive magnetic bearing without permanent magnets and with a magnetically conductive steel rotor. A symmetrical three-phase excitation is linked to the star-connected bearing coils wound around three dedicated stator segments. Additionally, a novel circumferential sensing coil is introduced in the stator, marked in Fig. 2. This sensing coil links with the flux components $\Phi(i)$ provoked by each of the three currents i_1, i_2, i_3 through the bearing coils.

For all conducted finite element simulations, the model assumes non-linear ferromagnetic properties of standard M400-50A electric steel for the rotor and the bearing cores and standard copper for all windings. However, only dimensionless signals will be used for the explanation of the working principle.

The bearing segments have been placed so that coil 1 coincides with the x-axis of the fixed coordinate system, coil 2 and coil 3 are displaced for $120°$ and $240°$ mechanically, respectively.

B. Functionality

As long as the rotor remains in the central position, the inductances of the bearing coils are identical and the fluxes through the rotor, and thus through the sensing coil, compensate one another. Therefore, zero voltage is induced in the sensing coil. However, when the rotor is radially displaced from the center, the symmetry of the system is violated, the flux components no longer compensate one another and a voltage dependent on the coil current frequency ω_{el} and the direction φ_{mech} and amplitude $\hat{\varepsilon}$ of the rotor excentricity is induced in the sensing coil. For the present considerations, we assume that the rotor position change happens at a frequency much below that of the electrical three-phase system. Therefore, the sensing coil will experience an induced voltage $V_{sense}(t)$ equivalent to

$$V_{sense}(t) = \frac{d\Psi_{sum}(t)}{dt} \tag{1}$$

with the linked sum flux

$$\Psi_{sum}(t) = \sum_{j=1}^{3} (N_j \Phi_j(t)) \tag{2}$$

being the sum of the momentary coil flux values $\Phi_{1..3}(t)$ multiplied with the number of winding turns $N_{1..3}$. This flux detection method provides high robustness compared to temperature-sensitive and mechanically delicate sensors. Additionally, one of the flaws of the axial sum-flux detection principle presented in [5] which introduced axial instability and sensitivity to axial rotor motion can be fixed with this concept.

C. Signal interpretation

Applying symmetrical three-phase currents to the three bearing coils, we can assume identical amplitude and an electrical angle φ_{el} of $120°$ between the phases as visible in Figure 3.

Three distinct situations for the sum-flux are shown in Figure 4, for the centered rotor, the statically displaced rotor in x-direction, and for the statically displaced rotor in y-direction. While the centered and x-displaced situation seem very intuitive, the y-displaced scenario is already less so. The phase shift is not that of the mechanical angle ($\varphi_{mech} = 90°$)

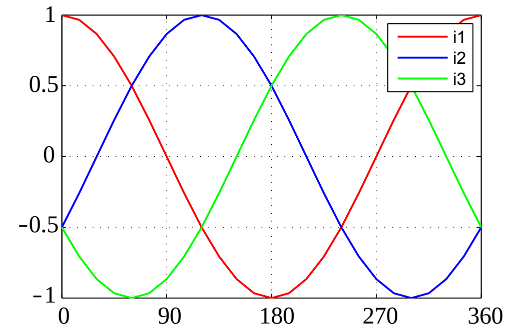

Figure 3. Normalized currents in three-phase system for non-deflected rotor.

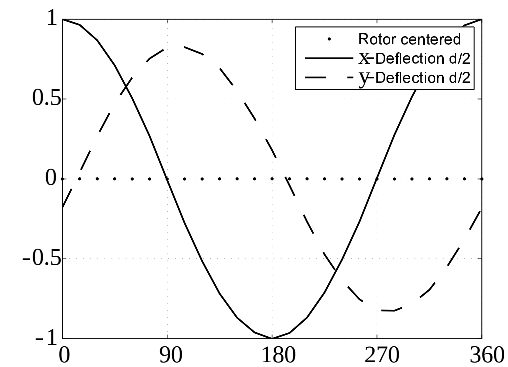

Figure 4. Normalized sum-flux through sensing coil in three distinct situations for an excentricity of half the air gap width.

and additionally, the amplitude of the sum-flux is smaller than in the case of the x-displacement.

The effect on the detected sum-flux can be seen more clearly in an orbit plot in Figure 5. The plot shows two types of curves which shall be interpreted in detail.

a) Synchronous orbit: For this scenario, the rotor has a fixed excentricity ε given in a certain fraction of the air gap d and a variable value of φ_{mech} which changes synchronous to the electrical angle φ_{el}. This means that the rotor travels around the stator bore or the touchdown bearings with the vector of the electric field - a situation which would occurr due to the attractive forces between rotor and stator if the electrical field frequency and the inertia of the rotor are sufficiently low. While this is not a very realistic case, it shows how the orbit deformes from a circular shape for small deflections to a more triangular shape for larger values of ε. This is linked to the nonlinear dependency between the air gap and the resulting inductance which can easily be seen in the calculation of the effective permeability

$$\mu_{eff} = \frac{\mu_{ideal}}{\frac{d}{l_{iron}}\mu_{ideal} + 1} \tag{3}$$

from the ideal permeability μ_{ideal} of an iron core when an air gap with the length d is introduced in the iron-path with a length of l_{iron}. It becomes clear that for rather small

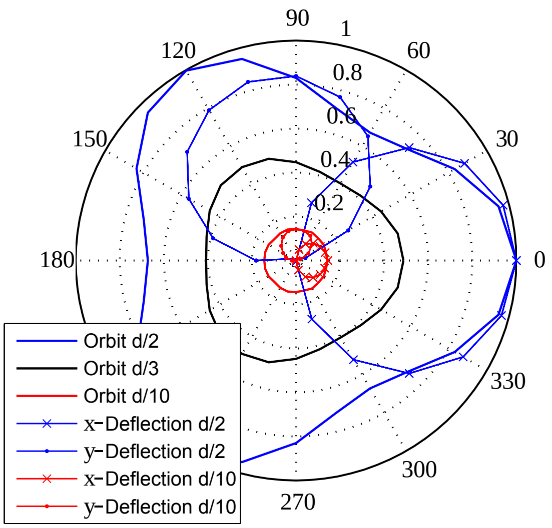

Figure 5. Normalized sum-flux through the sensing coil over φ_{el} in degree in case of an orbit synchronous to the electrical system ($\varphi_{mech} = \varphi_{el}$) and two stationary rotor deflections in x- and y-direction (i.e. $\varphi_{mech} = 0°$ or $90°$, respectively) for different excentricity values in fractions of the air gap d.

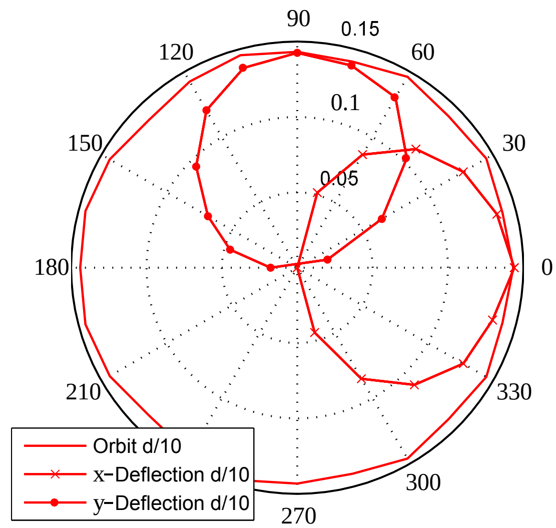

Figure 6. Zoom of Figure 5 showing the sum-flux over φ_{el} in degree in synchronous orbit, x- and y-deflection (i.e. $\varphi_{mech} = 0°$ or $90°$, respectively) for $\varepsilon = \frac{d}{10}$.

deflections, as e.g. for $\frac{1}{10}$ of the air gap width in Figure 6, the inductance change is independent of the deflection angle.

b) Static excentricity: The second scenario is a static deflection of the rotor with fixed values for both, ε and φ_{mech}. For the case of a sufficiently high field frequency or very high rotor inertia, the rotor position can be assumed to be quasi-static over one electrical period. In other words, the moving rotor position is a sequence of static excentricity positions. The resulting sum-flux curves for two dedicated situations marked as x-deflection and y-deflection are plotted in Figure 5 and Figure 6 for a full rotation of the electric field vector. Both, the diameter difference of the resulting circles and the non-intuitive angular orientation of the y-deflected rotor in case of a large deflection $\varepsilon = \frac{d}{2}$ are identical to the sum-flux in Figure 4. However, Figure 6 clearly shows that this distortion is not true for the linear case when the deflections are small.

Now the actual target outcome of this sensor principle becomes visible: The vector to the center point of the circle for the static deflection indicates the amplitude and direction of the rotor position.

D. Disturbance forces

Until now, the main effect on a rotor, centered in three bearing coils which are driven by a symmetric three-phase system without any position control at all ever has stayed unmentioned. Of course, unwanted attractive forces towards the bearing teeth when the respective coil is energized (regardless of the current direction) will act on the rotor. Figure 7 shows the orbit plot of these forces. For the sake of comparability, the plot is not dimensionless but shows the forces in Newton when an exemplary current amplitude of $\hat{i} = 500AWdg$, a rotor diameter of $dro = 30mm$, and an air gap of $d = 1mm$

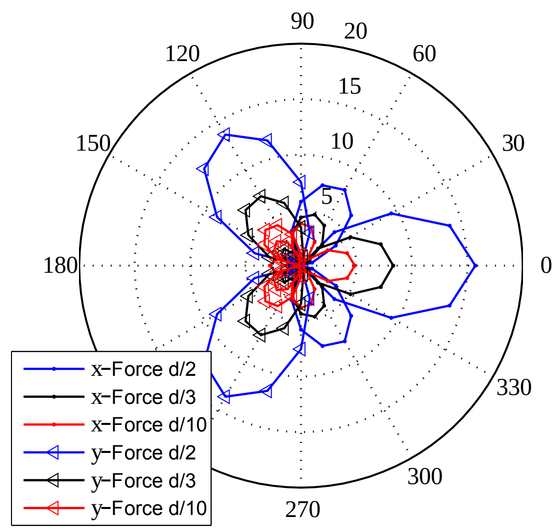

Figure 7. Disturbance forces in Newton in x- and y-direction over φ_{el} in degree in synchronous orbit for different excentricity values in fractions of the air gap d.

are chosen. These values shall only serve to provide better comparability, no actual bearing design is intended.

E. Opposing coil concept

With three bearing coils located along its circumference, there is a circulating force acting on the rotor. Of course, this behavior is highly undesirable for any realization concept. Therefore, a concept with six bearing coils as shown in Figure 8, where two opposing coils with opposite winding sense are connected to the same phase of the electrical three-phase system, can be envisioned.

Several advantages can be gained from this approach:

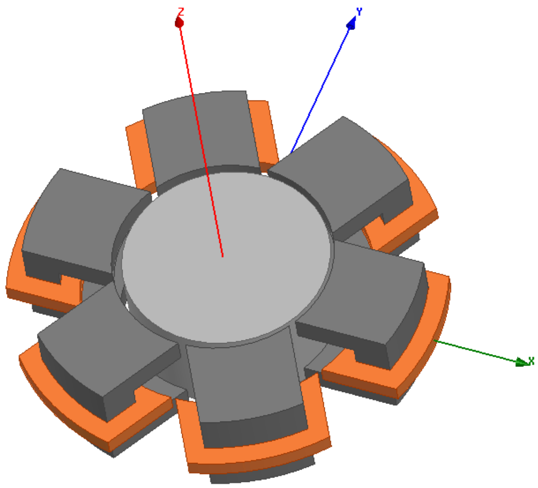

Figure 8. Concept with six bearing coils, opposite coils are wound with in opposing sense and are connected to same phase.

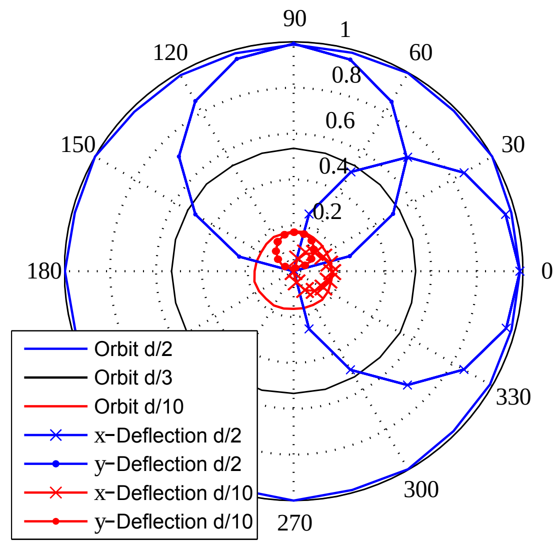

Figure 9. 6-coil sum-flux through the sensing coil over φ_{el} in degree in case of an orbit synchronous to the electrical system ($\varphi_{mech} = \varphi_{el}$) and two stationary rotor deflections in x- and y-direction (i.e. $\varphi_{mech} = 0°$ or $90°$, respectively) for different excentricity values in fractions of the air gap d.

- The attractive forces on the rotor due to the coil currents cancel out for the centered rotor and are greatly reduced for the excentric rotor.
- The opposite coils lead to a differential principle of one increasing inductance, providing a certain flux direction on one side, and one decreasing inductance, providing flux in the opposite direction on the other side. This cancels the non linearity effects due to the air gap dependency of the inductance.

Figure 9 shows the sum-flux orbit plot for this new six-coil concept. It becomes clear immediately, that the gained flexibility concerning linearity of the sensing method is of great value. Even for the large deflection of $\varepsilon = \frac{d}{2}$, the center point vector information indicates the amplitude and direction of the rotor position and there is no distortion of the signals regardless of the direction and amplitude of deflection.

As expected, the radial force on the rotor in the system with oppositely placed coils is greatly reduced. The same MMF was applied as in the three-coil design, now the $500AWdg$ are distributed to each of the the two opposite coil pairs, respectively.

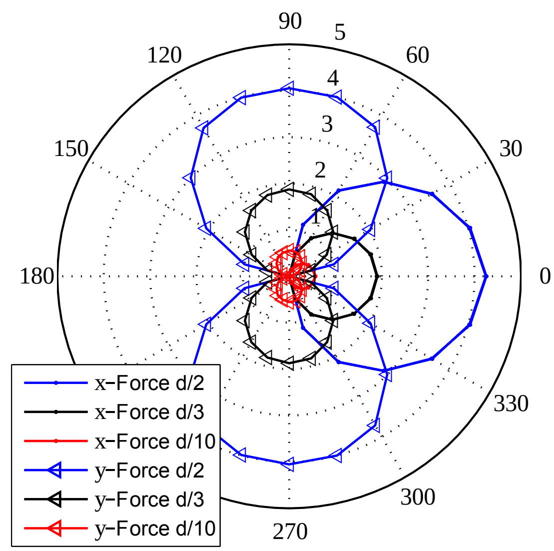

Figure 10. Disturbance forces in x- and y-direction on the rotor in Newton over φ_{el} in degree in synchronous orbit for different excentricity values in fractions of the air gap d for the 6-coil system.

III. Future Application to Self-Balancing

Magnetic bearing systems are known for being demanding concerning the necessary software and hardware. The previous section demonstrated a possible sensor concept which may serve as a thermally robust and mechanically simple sensor principle. However, the output of the discussed sum-flux sensing coil could also be used for the creation of radial forces when attached to the star point of the mentioned three-phase system.

Similar approaches of utilizing the star-point connection for magnetic bearings or bearingless drives are known from the literature. The authors of [6] propose a bearingless motor with radial passive suspension and one active magnetic bearing in axial direction which is actuated by controlling a common-mode current in the three-phase motor system.

Another work presented recently in [7] takes a different approach by using a three-phase active magnetic bearing. Additional motor torque for the single-phase motor of that study is provided by connecting the motor winding to star-point and dc-link center and by controlling the magnetic bearing currents accordingly.

Both works focus on reducing the number of required semiconductors in the power electronic circuit, specifically targeting three phase systems due to the high availability and low prices for three-phase inverters on the market.

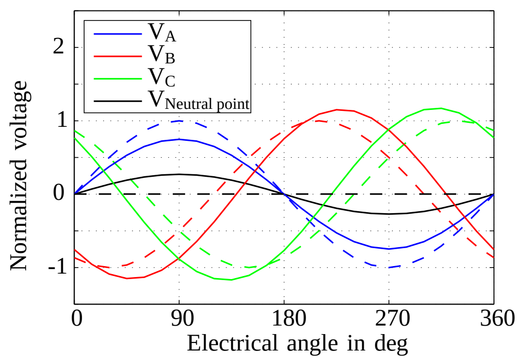

Figure 11. Principle of neutral point shift for reducing e.g. phase A voltage compared to non-shifted voltages (dashed)

Due to the potential sensing principle presented in this work, the authors dare to reflect a more drastic method of reducing the power electronic requirements which has been presented in [8] and [5]. Of course, the information gained by the induced voltage in the sensing coil presented in Section II can be used through sampling, filtering and applying it for controlling the bearing currents in a digital control cycle. It can, however, be amplified and applied directly to the neutral point of the star-connected bearing coils. The basic idea is that in a situation where the rotor is displaced towards one stator segment, the induced voltage in the sensing coil will be in phase with the phase voltage which provokes the current through that stator segment's coil. Adding the induced voltage to the neutral point will, thus, reduce the amplitude of that phase voltage and, therefore, decrease the force on the rotor in that direction. Due to the increase of the other coils' currents, a stabilizing force is generated.

Even though considerable effort is necessary to determine its feasibility, it could be considered as a very fascinating idea to construct a self-balancing bearing without the need for additional control, simply being connected to a symmetrical electrical multi-phase system such as the three-phase electrical grid. Of course, the question is legitimate why such an analog, reduced complexity system should be envisioned in a time when computational control power increases and cost and volume of switching power electronic circuits are strongly decreasing. Nevertheless, scientific discussion about such a concept may bring forward improvement for today's state of the art and may advance the search for very low cost or very robust magnetic bearing solutions.

IV. Concept Flaws and Potential Solutions

As mentioned in the introduction, this work focuses on the explanation of a concept with a very simple model in order to open it for discussion. This basic model still shows significant flaws:

- The self-balancing concept in its basic design lacks damping as only the direct value of displacement is taken into account when creating the corrective forces.
- For reasons of simplicity, there are no permanent magnets in the demonstration system. This lack of bias magnetization will entail high losses if significant bearing forces are to be created. However, for large rotors or for systems in thermally demanding environments, this could be an acceptable solution.
- The envisioned self-balancing concept depends on the fact that due to the neutral point shift, the rotor is less attracted to the stator on the side where he is too close, and more attracted to the opposite side. This is plausible for the three-coil concept shown in Figure 2. For the six-coil concept of Figure 8, however, this would not work without modifications, since the coil current on both sides of the rotor will be either weakened or strengthened as each pair of opposite coils are connected to the same phase.
- One possible solution to this could be to not hard-wire the two opposite coils but rather use two separated, star-connected systems which are both connected to the same three-phase supply system but of which the neutral point could be controlled individually. In such a scenario, the induced voltage of the sensing coil would be added with different sign to the two neutral points: This would e.g. lower the voltage of coil 1 in system 1 but increase the voltage of coil 1 in system 2. With system 2 being mechanically rotated about $180°$ with respect to system 1, this would increase the current on one side and decrease it on the other side. Even with all practical questions set aside, this theoretical concept will require significant future work.
- The stator segments are oriented in an axial direction, allowing the sensing coil to be wound cylindrically and still link with all stator segments. This means the bearing flux will travel axially through the rotor, making classical axial lamination obsolete and even detrimental for the permeability value of the stack. One remedy could be the use of a powder core rotor which provides high electric resistance in all directions but would cause strong mechanical limitations for the rotor due to the brittleness of these sintered materials. Additional non-cylindrical coil shapes are equally possible and would allow concepts without axial flux components.

V. Acknowledgment

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