On the Direct Use of Electromagnetic Field Information for Magnetic Rotor Position Control

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***Abstract*—This article describes a simple principle for obtaining information about the radial rotor position and later on shows how this information can be used to stabilize the rotor deflection in a magnetically levitated system. It is important to notice that the considered demonstration system was designed in a way the discussed effects are clearly noticeable. It is not meant to be a design proposal for an actual motor.**

I. Introduction

There are not many inventions that have had such a profound impact on human technology as the invention of the wheel. One of these rare exceptions is the invention of a rotating electromagnetic field, that significantly shaped the industrial world as we know it today. Unlike the case of the wheel, the process of creating the concept and finding a practical application of the rotating electromagnetic field took a relatively short period of about one decade, from 1882 to 1891, and is connected to a small group of brilliant scientists and inventors. The first in this group is the Serbian inventor Nikola Tesla, who in February of 1882 had a vision of a rotating electromagnetic field as a result of the interaction of poly-phase alternating currents, and later developed many of its important practical applications. The other two were the Italian Galileo Ferraris, and the Russian/Polish engineer and inventor Mikhail Dolivo-Dobrovolski who in 1891 at the International Electrotechnical Exhibition triumphantly demonstrated the possibilities of generating, transmitting and practically using poly-phase electrical currents. Not surprisingly, the main interest and research efforts for newly discovered theoretical concepts were focused on the areas of energetics in the final years of the 19th century. Essentially, human society was still in the very beginning of its information stage, and poly-phase signals, as well as the resulting rotating electromagnetic field, were considered predominantly as a means of efficient creation, distribution and consumption of energy. However, as we can see it now, they have much more intrinsic properties, important specifically for the exchange of information signals. These properties with their basic principles of work and a potential use for the area of magnetic levitation are the subject of the present work.

II. Rotating electromagnetic field as a source of information

While the primary purpose of rotating electromagnetic fields is the brushless delivery of energy to and from rotors of electric motors and generators, this field can perform one more very important function – to serve as an instrument of information exchange between the parts of electromechanical devices. By its very nature, a rotating electromagnetic field presents a radar-like, permanent monitor of the position of the rotor and its relative position with regard to other components - the stator, its poles and windings, etc. And, while a perfect poly-phase system is completely symmetrical and balanced, any violation of this symmetry will result in a disbalanced signal containing information about the source and nature of this disbalance. This basic fact has been used for detecting the rotor position in several publications. The authors of [1], [2], [3] inject additional high frequency voltage and current components for detecting the current rise as a function of the coil inductances and thus, of the rotor position. With sophisticated signal treatment, this so called sensorless principle was used to levitate the rotor of a magnetic bearing. Another example can be found in [4] and later by different authors in a very similar publication [5], where the axial position of a magnetically levitated blood pump was detected using Hall sensors which measured the electromagnetic field, distorted by the rotor deflection. Also most existing eddy current sensors, for which countless examples exist in literature and on the market, could be put into the group of devices which actively generate an electromagnetic field which is altered due to the rotor position. This change is detected by the passive sensor part and is then used in order to obtain the rotor position.

All the examples mentioned above have in common that the electromagnetic field variation is captured and fed into a signal treatment process of varying complexity. Looking at a very basic field configuration, we can, however, notice an extremely natural form of phase and amplitude of the harmonic signals as we will shown in the following sections. The principles are based on the findings described in [6] and [7]. The following paragraphs will demonstrate the method when applied to a demo structure for a 3D-FE simulation.

A. Demonstration system

Before diving off into the description of an actual prototype, we want to point out that the present structure is not meant to constitute an actual motor or bearing design but rather to allow a 3D-FE simulation, demonstrating the very simple and natural way of obtaining radial rotor position information from the electromagnetic field. For this simulation, the following

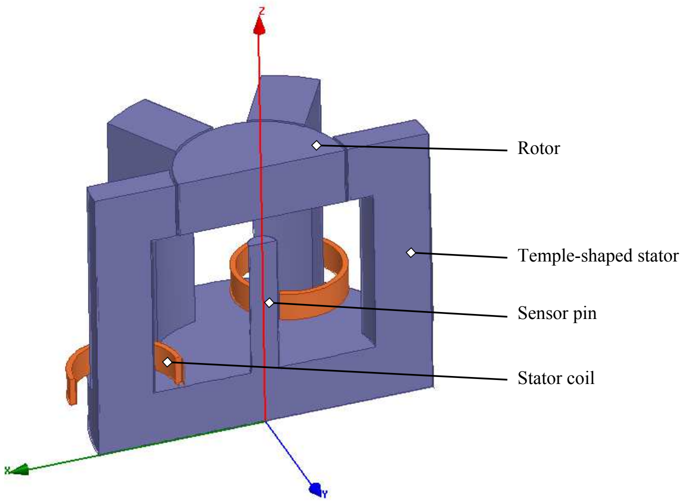

Figure 1. Simulated structure for showing the rotor position dependent electromagnetic field

assumptions were made:

- All magnetically conducting parts in both, the rotor and the stator of the used structure are considered as ideal magnetic conductors - saturation effects are not being taken into account.
- The axial rotor stabilization is not considered, the focus of this investigation is on the radial position information.
- All dimensions are chosen arbitrarily, they do not follow any design for an actual drive but shall be suitable for the 3D-FE simulation, demonstrating the mentioned effects.
- The resulting absolute values for flux densities, forces or other physical characteristics are not meant for designing an actual drive but have to be seen as relative indicators for the described phenomena.

Let us suppose a rotating, symmetric 3-phase, star-connected electrical system where each phase drives its current through one coil, being wound as a concentrated coil around one single stator tooth. The 6 teeth of which only 3 carry windings are located at a mechanical angle of 60° and are formed in a temple motor-style in order to provide sufficient space for all components. One of the special features of the demonstration system is a sensor pin located below the rotor. This pin has a large air gap to the rotor in order to keep the axial force influence to a minimum. A small but proportional part of the sum flux in the rotor will flow through this sensor pin. Together with an iron rotor disk, the motor topology of the system shown in Figure 1 resembles an induction machine principle.

B. Flux distribution

For the most simple case, let us assume sinusoidal currents $I_1(t)$, $I_2(t)$ and $I_3(t)$ of identical amplitude in the three phases, having an electrical phase shift of 120° to each other. The coils are placed such that coil 1 has its center at the x-axis of the Cartesian coordinate system marked in Figure 1. The remaining two coils are positioned at 120° and 240° in mathematically positive sense. The flux generated by the phase currents passes through the stator tooth, the rotor, the remaining teeth and the stator base plate functioning as a yoke. In the case of a completely centered rotor disk, no flux is conducted in the thin sensor pin which is located below the rotor disk since the sum of the coil flux components

$$\Phi_1(I_1) + \Phi_2(I_2) + \Phi_3(I_3) = 0 \quad (1)$$

is equal to zero. This fully symmetric situation can now be disturbed by a radial shift of the rotor which shall be investigated in three different scenarios.

1) *Centered position* (S0)
2) *Eccentric axis* (S1): The rotor is displaced radially and keeps on rotating about its (now displaced) axis of geometry. With the arbitrarily chosen values, the rotor is e.g. shifted towards coil 1 for half the air gap width δ. This means that the displacement vector in cylinder coordinates r, φ and z is

$$S1_{shift} = \begin{bmatrix} \frac{\delta}{2} \\ 0 \\ 0 \end{bmatrix}. \quad (2)$$

3) *Axis orbit* (S2): The axis of rotation is displaced from the center of geometry which means that the axis of geometry will describe a circular orbit as the rotor spins about its axis of rotation. For the simulation, the rotating displacement vector has a length of $\frac{\delta}{2}$ and was chosen to rotate at the same rate as the electrical phase vector but with a mechanical phase of $\varphi_{mech} = \varphi_{el} - 90°$, making the displacement vector

$$S2_{shift} = \begin{bmatrix} \frac{\delta}{2} \\ \varphi_{el} - 90° \\ 0 \end{bmatrix}. \quad (3)$$

This means that the rotor would come as close as $\frac{\delta}{2}$ to the stator tooth 1 (carrying coil 1) at the moment when the electrical phase angle is 90°, creating an identical situation point for both eccentricity scenarios.

The cross section through the entire structure at half the height of the sensor pin is given in Figure 2. Due to the shift of the rotor in x-direction in S1, the inductance value of coil 1 rises, the sum of all flux components is no longer equal to zero according to (1) and a proportional flux component can be found flowing in the sensor pin[1]. Figure 3 shows the mean flux density values in z-direction over the cross section of the sensor pin at half of its the vertical height for all scenarios S0, S1 and S2. As it could be expected, there is no sum flux for S0, there is sinusoidal sum flux for S1 and there is a sum flux showing a constant offset value and three times increased frequency for S2.

[1]At this point we want to recall that the dimensions and the air gap of the sensor pin was chosen arbitrarily. Any kind of real application would have to design this flux path in accordance to the flux sensor topology and its flux sensing range and resolution.

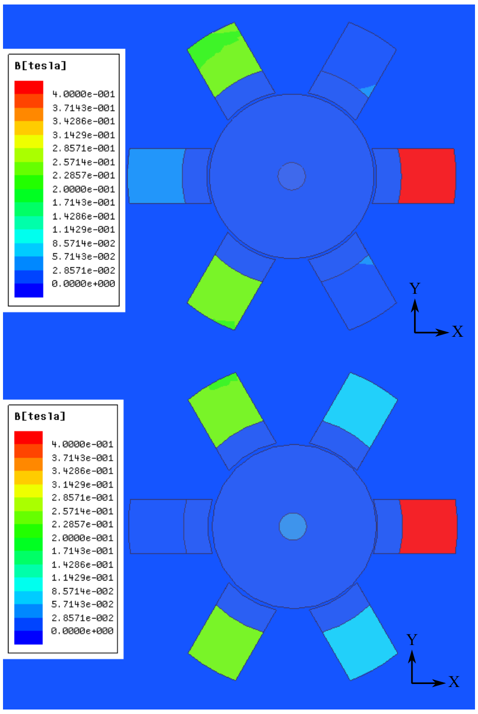

Figure 2. Flux distribution in a horizontal cross section at half the height of the sensor pin for a centered rotor S0 (top) and an eccentric rotor in S1 (bottom). The bottom figure is generally true for S1 and can additionally be interpreted as S2 at an electrical phase angle of 90°.

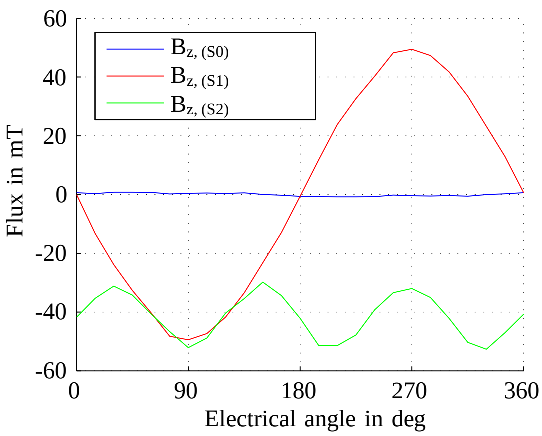

Figure 3. Mean flux density in positive z-direction in the central sensor pin over the electrical angle for different eccentricity situations

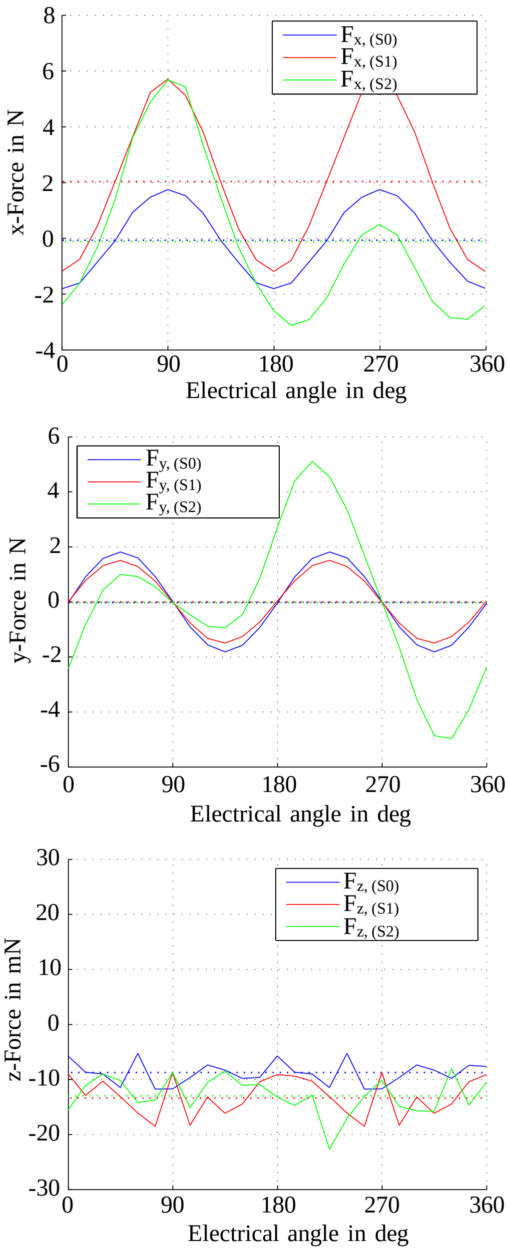

Figure 4. Forces distributions and mean force values acting on the rotor, given in Cartesian stator coordinates. Each component (x-forces on top, y-forces in the middle, z-forces on the bottom) was evaluated for all scenarios S0, S1 and S2.

C. Resulting reluctance force

The radial reluctance forces between the stator teeth and the rotor are identical in amplitude for all three air gap regions between the rotor and one of the coil-carrying stator teeth in case of the centered rotor. This is, of course, due to equal air gap flux density and equal geometric dimensions in the air gaps. The forces also have the same phase shift as the coil currents, leading to a rotating force vector acting on the rotor disk.

Shifting the rotor by applying the two eccentricity scenarios S1 and S2 will result in a changed force vector. Figure 4 shows the force distribution and the mean force values over one electric period. As the rotor was moved in positive x-axis direction (equivalent to the mechanical angle of $\varphi_{mech} = 0°$), the x-force orbit in S1 is also shifted to more positive values in this direction. The mean value reflects this simple correspondence clearly. For S2 with its orbiting axis, the force vector changes its amplitude over the electric angle but, as for the centered rotor, has a mean value of zero. The mentioned identical situation for the two eccentricity scenarios S1 and S2 can be seen at the identical curve height at an electrical angle of 90°.

Concerning the y-forces on the rotor, the force in S1 is almost identical to the case with centered rotor position except

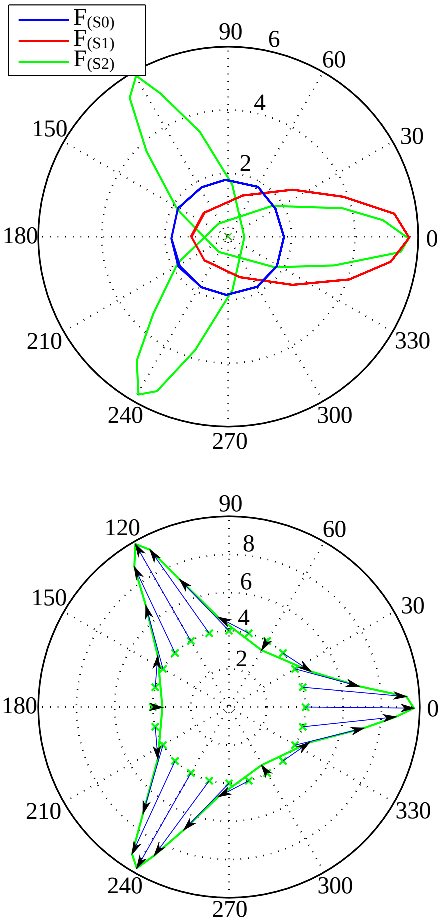

Figure 5. The cylindrical coordinate system offers a more natural way of seeing the occurring force orbits in newtons with their mechanical angle in degrees as the electric angle rotates for one period (top). Scenario S2 is shown again (bottom) with an arbitrarily chosen offset in order to reflect the changing rotor center position marked by the crosses and the corresponding force vector.

for the slightly smaller amplitude. Even if this is not the case for S2, the mean y-force for all scenarios is equally zero.

The z-force which is also displayed in Figure 4 is slightly negative due to the attractive reluctance force between rotor and sensor pin but the values are by far below the x- and y-forces and close to the simulation resolution, making them negligible for the moment.

Using the cylindrical coordinate system as shown in Figure 5 offers a direct view on the presented circumstances. The given angle scale refers to the mechanical force angle φ_{mech}. A vector pointing in direction of $\varphi_{mech} = 0$ is aligned with the positive x-axis as defined in Figure 2. The fact that the electrical angle φ_{el} is not directly visible may be irritating but must be kept in mind.

While the depicted force orbit for S0 is a circle and the one for S1 has elliptical shape, the curve of the force orbit in S2 is not very intuitive. Only when looked at with a certain offset shown in the bottom part of Figure 5, the characteristic becomes more clear. This offset is added for helping to relate the rotor center position (marked with 'x' tags) to the forces occurring in that position. Its value was chosen arbitrarily but was maintained constant for both, Figure 5 and Figure 8.

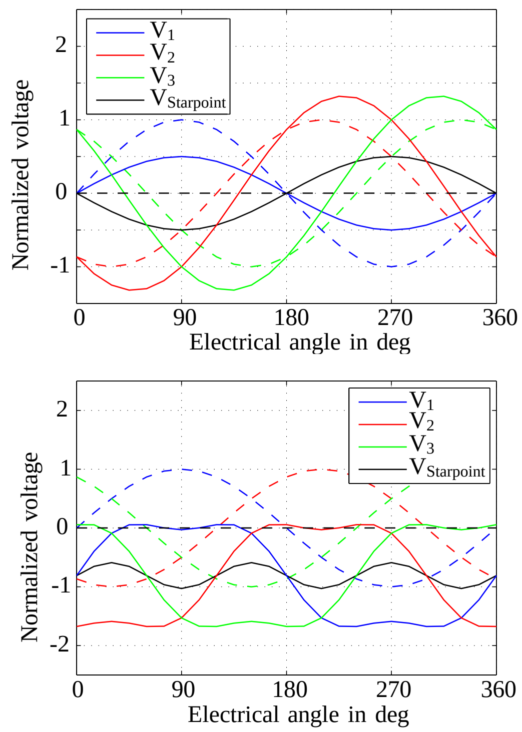

Figure 6. Symmetric 3-phase system (dotted lines) with star-point modulated according to flux in eccentricity situation S1 (top) and S2 (bottom) and resulting phase voltages (solid lines). All values are referenced to the peak value of the symmetric voltages.

III. Application of the gained information

In the sensorless motor control techniques referenced in the beginning of section II which are also applied in most eddy current sensors, certain parameters of the altered magnetic field are captured and treated in a signal processing part in order to extract the values of interest. Here, we want to show a much more straightforward approach by directly using the phase and amplitude information of the field through the central sensor pin, measured by one sensor (different sensor systems may be applied) in order to control the star point of the electrical system. Figure 6 shows the voltage traces of an original symmetric 3-phase system in dashed lines. Additionally, the resulting unsymmetrical phase and star point voltages are drawn in solid lines when the star-point of the system is modulated as shown in the black curve. In this case, the height of the star-point voltage is proportional to the flux value shown in Figure 3 for the eccentricity situation S1 and S2 with an arbitrarily chosen but constant ratio of amplification. The resulting currents in the stator coils increase or decrease the radial forces on the rotor.

As shown in Figure 7, these forces tend to correct the rotor eccentricity in case S1 by decreasing the current amplitude in the coil which the rotor is shifted towards. At the angle of $90°$ for instance, there is still a slightly attractive force (positive x-value) which would further deflect the rotor from its central position but the mean x-force over one electrical period is negative, thus stabilizing the rotor. For S2, the mean force is still zero which is necessary in order not to add a constant offset

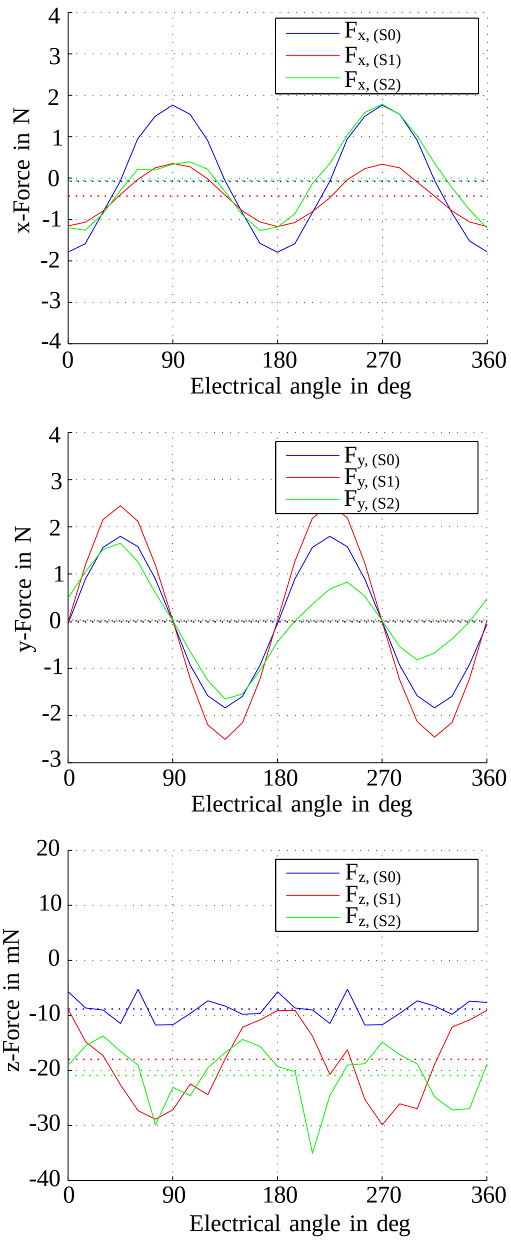

Figure 7. Forces distributions and mean force values acting on the rotor, when phase voltages are shaped by star-point modulation according to the measured sensor pin flux. Each component (x-forces on top, y-forces in the middle, z-forces on the bottom) was evaluated for all scenarios S0, S1 and S2.

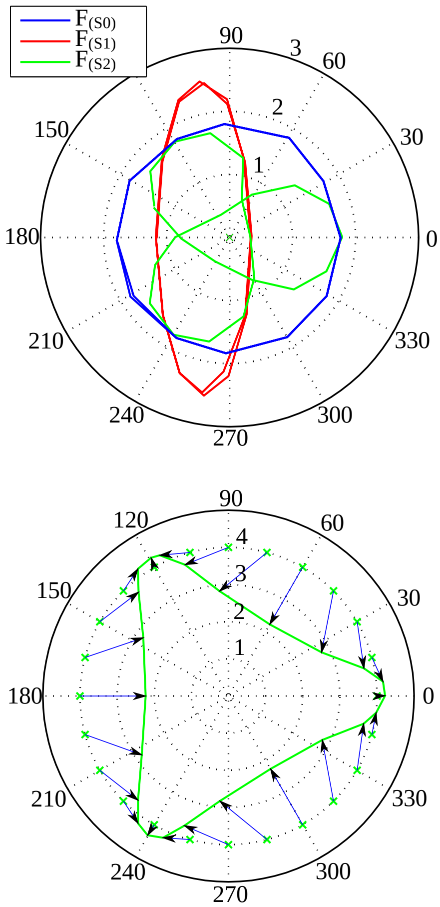

Figure 8. The cylindrical coordinate system with forces in newtons over the mechanical angle in degrees again offers a different view, showing clearly the stabilizing forces in cases S1 and S2. As for the Figure 5, scenario S2 (bottom) is shown with the arbitrarily chosen, but constant offset shown above in order to reflect the changing rotor center position marked by the crosses and the corresponding force vector.

like in S1 to the rotating displacement vector. Generally, the occurring z-forces shown in Figure 7 have increased slightly relative to Figure 4 but still range in a negligible magnitude.

Finally, let us again take a look at the picture in cylindrical coordinates, shown in Figure 8. In the image on top, the force ellipse of scenario S1 has deformed significantly in comparison to the constant star-point situation of Figure 5. The orbit clearly shows how the forces on the rotor would correct the rotor offset by acting towards a mechanical angle of 180° instead of pulling the rotor more towards 0°. As above, the force orbit of scenario S2 is difficult to interpret which is why it is drawn again with the same offset value as in Figure 5. The resulting force orbit and especially, the sketched force vectors, show how the rotor is moved back towards the center in almost every position except for the moments when the rotor axis is closest to one of the coil carrying stator teeth. This force amplitude, however, is only a result of the chosen amplification of the measured flux for modulating the star-point. It can basically be increased to much higher levels, thus providing much more aggressive stabilization forces.

IV. Discussion

When thinking of using the presented principles, several more or less severe limitations for practical use come up.

- Flux measurement is a delicate operation and e.g. Hall sensors which are able to measure flux with no or very little phase delay are unfortunately not very stable over temperature. Even if a homogeneous temperature distribution over the entire motor is assumed, the changing temperature and thus, the changing flux sensitivity would have to be compensated in order not to directly influence the actively created radial force amplitude. Another problem for the flux measurement is a possible axial deflection. As this would change the axial air gap, any axial movement would have severe influence on the measured sensor pin flux level in the demonstration system. A more sophisticated system of measuring this component could resolve the issue.

- Irregularities in the magnetic circuit in one of the teeth, e.g. due to rolling, punching or other manufacturing processes or material characteristics can easily result in a permanent shift of the central target position for the presented rotor position control.
- The flux sensor information was only used to influence the motor voltage proportionally, here. For an actual radial levitation control, of course also the derivative value would have to be taken into account in order to provide damping.
- The stability of the axial degree of freedom needs to be investigated thoroughly in order not to create unstable behavior due to the attractive reluctance forces between rotor and sensor pin.
- There are no permanent magnets in the presented demonstration system. This means that for the resting rotor or rather, for the case of the electric system being shut down, there will be no rotor position detection due to the missing sensor flux and also no stabilizing force of any kind on the rotor. Even if the electric system is up and running, the necessary field frequency would have to be well above the radial resonance frequency of a magnetically stabilized system so the rotor would not be severely deflected synchronously to the rotating flux vector.

V. Conclusion

The presented paper shows, how the electromagnetic field is influenced by the radial rotor position. For this reason, a disk shaped demonstration system was designed and simulated, using idealized materials and conditions. The information gained from the simple amplitude measurement of the flux in the sensor pin, together with the detailed knowledge about the three-phase system, allows a statement about the rotor orbit in both, amplitude and phase. This information can be expressed by e.g. digital signal processing or it can be used directly to modulate the star-point of the three-phase system driving the motor. It has been demonstrated that this modulation changes the phase currents in a way which makes them produce stabilizing radial forces acting on the rotor in the two essential eccentricity situations with constant and rotating deflection vector, respectively. The proposed method is essentially different from most eddy current sensors and sensorless techniques as it uses no digital signal treatment but merely amplifies the measured flux signal and, thus, retains its valuable phase and proportional amplitude information. As this work focuses on the demonstration of the principle, several more or less severe constraints for bearingless motor operation have not been considered here, however, the mentioned obstacles could probably be overcome in a sophisticated drive design. One may expect that the general considerations presented in this paper will result in significant improvement of the characteristics of the devices and systems mentioned in [6], [7].

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