Design Aspects and Test Results of a High Speed Bearingless Drive

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Abstract—Following the trend towards smaller drives operating at increased speeds, the present work examines the suitability of bearingless drives for high speed operation. With rising rotational frequency, the requirements for the drive components differ significantly from a design specification for low speeds. Therefore, the design of the stator, rotor and winding system is described in detail. In order to verify the conducted analytical and FE calculations, a laboratory prototype was constructed reaching - to the knowledge of the authors - a world record speed for bearingless drives of 115,000 rpm. Eventually, measurements showing specific losses and operational behavior of the drive are presented.

I. INTRODUCTION

As modern drives increase in power density, there is a clear trend towards smaller drives being operated at higher speeds. The lifetime limits of conventional bearings are quickly reached, therefore, different bearing methods are investigated. One alternative is provided by bearingless drives – a magnetic bearing being fully integrated into the motor unit, using only one common stator iron. Additionally, one common winding system can be used for both torque generation and bearing force creation. The necessary currents are no longer physically separated but are superposed, which shifts the complexity from the mechanical to the electrical system. These very compact drives offer all typical advantages of magnetic bearings such as significantly prolonged mechanical lifetime, possibility of hermetic sealing of the rotor from its environment or low bearing power losses at high speeds. Additionally, they can be run without lubrication due to the absence of mechanical friction.

In the last decade, bearingless drives have found their way into applications such as pumps or fans for delicate media like blood or sensitive chemicals [1]-[7]. Also, new applications for chemical process chambers [9]-[11] are planned. However, these products all operate in relatively low speed regions of up to 15 krpm as shown in Fig. 1. So do, to the knowledge of the authors, most bearingless drives in scientific research.

Therefore, the suitability for reaching high speeds remained unclear. This paper deals with the necessary design steps to push bearingless drives to speed regions beyond 100 krpm. The first part focuses on the special requirements of the individual drive components in order to be able to create and support high speeds. The respective design solutions for rotor, stator and winding system are presented. These design aspects have been considered in a laboratory prototype setting – to the knowledge of the authors – a speed world record for bearingless drives of 115 krpm. Experimental results and measurements conducted at this prototype are shown in the last section.

II. DRIVE TOPOLOGY

For magnetically levitating a body, two criteria have to be fulfilled. On the one hand, the absence of forces acting on the body in its resting position is a necessary condition and can be expressed as

$$ F(x_0, y_0, z_0) = 0. \quad (1) $$

On the other hand, the force gradient in each direction of the 3-dimensional space needs to be negative, which is a sufficient condition. In terms of potential energy, this describes a minimum energy state, written with $E_p$ for the potential energy as

$$ \frac{\partial F}{\partial x} = -\frac{\partial^2 E_p}{\partial x^2} < 0, \quad \frac{\partial F}{\partial y} = -\frac{\partial^2 E_p}{\partial y^2} < 0, \quad \frac{\partial F}{\partial z} = -\frac{\partial^2 E_p}{\partial z^2} < 0. \quad (2) $$

It is important to remark, that it is also necessary but not sufficient that the sum of the terms in (2), written as

![Fig. 1: Map of bearingless drives, data from [1]-[11]](image-url)

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\[ \nabla \cdot F = -\Delta E_p < 0 \quad , \] (3)
is negative.
The magnetic force density in a constant magnetic field is
\[ F = \frac{1}{2} \left( \frac{\mu - 1}{\mu} \right) \nabla B^2 \] (4)
where \( B \) stands for the magnetic flux density and \( \mu \) denotes the relative permeability of the respective material. Inserting (4) in (3) yields the force divergence
\[ \nabla \cdot F = \frac{1}{2} \left( \frac{\mu - 1}{\mu} \right) \Delta B^2 \] . (5)
Additionally, it can be shown that \( \Delta B^2 > 0 \) [13]. Thus, when moving a body out a zero-force point where (1) is fulfilled, the force divergence can not be negative unless diamagnetic or superconducting materials with \( \mu < 1 \) are considered. This conflicts with the necessary condition in (3), rendering levitation in a constant magnetic field without further stabilizing forces impossible. This basic relationship has first been published by Earnshaw in a different context in 1842 [12] and was later interpreted for the magnetic field by Braunbeck in 1939 [13]. For small deflections of the said body from its stable position, the force gradient described above can be interpreted as linear stiffnesses in the three dimensional coordinates
\[ F = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & c_z \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} . \] (6)
Together with (3) it becomes evident that due to
\[ \nabla \cdot F = c_{x\omega} + c_{y\omega} + c_{z\omega} < 0 \] (7)
at least one degree of freedom disposes of a negative stiffness component and therefore needs to be stabilized actively.
The compact bearingless drive presented uses no other bearing unit than the integrated motor-bearing and therefore, disposes of only one bearing point. Hence, a long rotor shaft turning about its minor axis of inertia and being supported at only one – either active or passive – central bearing point would not be suitable. A flat disc rotor, however, spins about its major axis of inertia and can be operated with one radial bearing unit, only.
The choice of stabilizing the radial deflections actively seems preferable, because together with the axial degree of freedom, also the tilt deflections are stabilized passively. This would not be the case for a radial passive, axial active magnetic bearing system with only one bearing point. In Fig. 2, it is clearly visible that only the displacements in radial direction must be controlled actively by the bearingless drive unit. Therefore, all degrees of freedom except for the motor rotation are constrained. Also, the axial construction space above and below the rotor stays available with the chosen topology.

![Fig. 2: Disc drive with passive stabilization forces in axial and tilt direction](image)

In addition to allowing a compact bearing design, the flat disc has a higher polar moment of inertia compared to elongate rotors with equivalent mass. This increases the angular momentum \( L(\omega) \) at a certain speed and yields the disc rotor less prone to disturbance torques \( \Delta L \) which cause a nutation whirl [14]. The resulting nutation cone angle
\[ \epsilon = \frac{\Delta L}{L(\omega)} \] (8)
therefore also decreases with rising angular speed \( \omega \).

### III. Stator design

A crucial difference to motors with separated magnetic bearings concerning stator design arises from the joint motor-bearing-functionality. As for conventional magnetic bearings, high air gap flux density is necessary in order to produce the required bearing forces. Unlike in those systems, this air gap field cannot be designed as a homopolar field which is independent of the rotor angle, since the alternating field is necessary for the motor functionality. Having an air gap field that varies with the rotor angle means, however, that the stator iron is permeated by a strong oscillating magnetic field. Therefore, the field related hysteresis and eddy current losses in the stator are of critical importance, especially at high rotational speeds. Hysteresis losses per volume can be characterized as
\[ p_h = f(A_h, \omega) \] (9)
where \( A_h \) denotes the area enclosed by the hysteresis curve which reflects the losses caused by the reorientation of the magnetic domains. Further, \( \omega \) stands for the angular frequency of the considered field harmonic.

Eddy current losses per volume depend on
\[ p_e = f(\sigma, B^2, \omega^2) \] (10)
with $\sigma$ being the electric conductivity and $B$ being the magnetic flux density. The linear and quadratic influence of $\omega$ and $B$ in (9) and (10), respectively, demonstrates the severity of this conceptual disadvantage of bearingless drives described above. The following measures can help to confine the occurring stator losses.

1. **Slotless Stator Topology**

Stator teeth reduce the magnetic resistance by shortening the air gap length. They are typically the zones of highest flux concentration up to the saturation flux density of the used material. Additionally, the transition from air to stator tooth provokes higher field harmonics, distorting the sinusoidal field. Both effects cause increased iron losses especially at high speeds and therefore, a slotless design with an air gap winding has been chosen. For high speed permanent magnet machines, [16] shows that a significant loss reduction can be achieved by this topology. Even though the comparison between slotted and slotless designs was conducted for machines with conventional bearings, the same principles of loss reduction apply to the present bearingless drive.

In combination with a diametrically magnetized rotor, the non-slotted stator also leads to a purely sinusoid magnetic air gap field. Of course, such an air gap winding accounts for high magnetic air gaps and thus, low bearing stiffness. Basically, this reduces the passive stiffnesses in axial and tilt direction and renders the rotor more prone to occurring disturbance forces. On the other hand, the negative and thus instable radial stiffness decreases as well which makes it easier for the active magnetic bearing to levitate the rotor out of its resting position at start-up. Additionally, the bearing control becomes less susceptible to sensor imprecision and noise because the resulting disturbance forces due to small deflections can easier be overcome by the active stabilization. Overall, lower stiffnesses do not necessarily have to be considered an undesirable property of a magnetic bearing.

2. **Stator Material**

Despite the slotless topology, the maximum stator flux density with the chosen rotor magnet still amount to an amplitude of above 1 Tesla, as shown in Fig. 3. This field strength together with the demanded rotor speeds require careful selection of the used stator material.

In order to reduce losses, the material should dispose of a narrow hysteresis curve, since the enclosed surface of the curve is proportional to the losses, rising linearly with increasing machine speed. Additionally, electric conductivity in the direction of occurring eddy currents should be as low as possible in order to constrain the related losses, which increase quadratically over the applied frequency. This can either be achieved by laminating the stator core or by using sintered Soft Magnetic Composites (SMC). The ferromagnetic grains in their powder structure are separated by an insulating layer, yielding very low electric conductivity. This would also allow 3D-flux paths since, unlike in laminated iron cores, the internal currents are blocked in every direction. The main disadvantage of these sinter materials is the low relative permeability with typical values below $10^3$ and their poor mechanical stress resistivity.

For the presented bearingless drive, two different stators have been tested, one laminated core made of low-loss nickel-iron sheets, the other one crafted out of a block of SMC material.

![Fig. 3: Flux densities in rotor, air gap and stator](image)

**IV. Winding Layout**

For stabilizing the rotor, the bearing reaction following rotor displacements must be sufficiently quick. Therefore, the electrical time constant of the winding must be significantly smaller than the mechanical time constant of the unstable radial rotor suspension. If the electrical system is designed to be 10 times as fast, the winding inductance $L$ must satisfy

$$L \leq \frac{M_{\text{Rotor}}}{c_{\text{rad}}} \cdot \frac{R}{10}$$

where $c_{\text{rad}}$, $M_{\text{Rotor}}$ and $R$ denote the angle dependent radial stiffness, the rotor mass and the winding resistance, respectively. Estimating the winding length and thus, the copper resistance, and taking the present rotor stiffness into account, the inductance must not exceed 50µH. In addition to the loss reduction mentioned in section III, this demand calls for a non-slotted design with an air gap winding.

In order to control the two radial bearing forces and the motor torque independently, three degrees of freedom are necessary in the winding system. If single-phase characteristic is to be avoided, i.e., if the motor should be able to exert torque in every angular rotor position, another degree of freedom is needed. Therefore, five phases constitute the minimum number of phases for a star connected winding system in order to fulfill the above demands with the present drive unit [15].

The winding was manufactured in a toroid form around the stator core. In order to obtain air coil characteristic, the two coils connected to form one phase were wound in opposing
winding directions so their flux in the stator is canceled. A detailed description of the used winding scheme, as well as the foregoing design steps including the comparison of full pitch, reduced pitch and concentrated coils was published in [17].

V. Rotor

1. Magnetic properties

A diametrically magnetized, two-pole permanent magnet ring is used as the rotor. Therefore, the electrical and mechanical rotational speeds are equal. Since the magnetic air gap is very large due to the slotless design, high power density sintered neodyme-iron-boron (NdFeB) magnet material is used to achieve sufficiently high air gap flux density for the magnetic bearing. An inner back iron ring reduces the magnetic resistance in the flux path and thus minimizes the necessary volume of expensive magnet material. Its width was optimized using 3D FE simulation so that the hollow inner region is field-free.

2. Analytical stress calculation

Sintered NdFeB is a very brittle material with low yield strength. This would limit the field of operation due to the occurring centrifugal forces acting on the rotor. Therefore, a retaining sleeve supports the magnet ring. Following Timoshenko’s stress calculation for rotating discs in [18], the rotor is modeled as a thin ring undergoing the stress due to a perfectly symmetric rotation about the axis perpendicular to the plane of the disc. Isotropic elasticity as well as symmetry of the cylinder along the rotation axis are presumed. Due to this symmetric form, shear stress can be omitted. At a certain angular frequency \( \omega \), the radial and tangential stresses as well as the radial displacement can be calculated as a function of the radius \( r \) for both magnet and surrounding retaining sleeve.

\[
\sigma_{\text{Mises}} = \sqrt{(\sigma_r^2 + \sigma_{\text{tang}}^2 - \sigma_{\text{rad}} \cdot \sigma_{\text{tang}})} \quad (12)
\]

in order to develop an estimation of the maximum endurable angular speed. In Fig. 4, the occurring stress components and the von Mises comparison stress are shown for a fixed angular speed of 100krpm. Three rotors with sleeves out of carbon fiber, hot work ferromagnetic and high-strength nonmagnetic steel have been realized. The operational results are presented in the measurement section.

VI. Practical Results

As mentioned above, a prototype of the designed bearingless disc drive has been built. Fig. 5 shows both, the 3D model and the actual constructed drive. Due to the modular design, different rotors and stators can be tested without completely dismantling the prototype.

Fig. 5: Design scheme and laboratory prototype

1. Operational behavior

The drive is connected to the controller unit which integrates power electronics, sensor signal treatment and the controlling DSP circuit running the non-linear control scheme. The most critical system parameter during operation is the radial deflection which must be kept below 0.5mm by the bearing forces at all times in order to avoid collision of the rotor with the touchdown bearing. Even though usually, neither bearing nor rotor are damaged in case of such a collision, the resulting disturbance forces may be to big for continuing stable operation. In Fig. 6, the cracking of the magnet ring due to high centrifugal forces is clearly visible as a peak in the rotor position trace as the rotor spins beyond 100krpm. Also, the crossing of the critical frequencies below 10krpm can be identified clearly by the high rotor deflection values.

The second critical parameter also shown in the same figure is the stator current level. Its maximum value is defined by the emergency shutdown threshold of the power electronics circuit. As the drive currents increase, a small radial deflection is more and more likely to provoke a current peak which finally exceeds the limit and makes the power circuit shut down. This is the worst case scenario because it leads to the rotor crashing into the touchdown bearing without any magnetic bearing support.

A third limiting parameter shown in Fig. 6 is the total

Fig. 4: Stress distribution for an unbandaged rotor

The resulting values can be used to calculate the von Mises comparison stress.
power consumption. It rises steadily with increasing rotor speed and reflects the necessary bearing power and the occurring losses such as windage losses and stator iron losses. According to the total power consumption of the system, no appreciable difference between the SMC and the nickel-iron stator could be noticed. However, the stator losses have to be quantified in detail before a verdict about the suitability of each material can be given since small differences in the air gap diameter or the winding system might distort the measurement during operation.

2. Stator losses

The latter can be divided into hysteresis and eddy current losses. At the real prototype, however, it is impossible to distinguish these losses during operation. Therefore, a test rig has been constructed where the rotor can be mechanically positioned in its operating position and driven by a separate machine. By inserting a stator without windings and measuring the power transferred from the spinning rotor to the stator, the total iron losses can be determined. Fig. 7 shows the resulting values for both stator cores which were mentioned in section II. Since there is no remarkable difference, both materials are considered as suitable.

The measurement result seems quite astonishing, since the hysteresis losses with sintered SMC material are typically much higher than with nickel-iron. Therefore, the total losses at low frequency were expected to be higher than for the sheet material. Only at increasing frequency and thus increasing eddy current losses, the sintered core was expected to provoke less losses than the laminated core.

3. Mechanical rotor stability

The diagnosis of the rotor bandage quality also proves to be difficult because the stresses in either magnet or sleeve cannot be measured during operation. The only possibility to evaluate the mechanical properties of a rotor is to increase the speed until material failure occurs.

<table>
<thead>
<tr>
<th>Rotor type</th>
<th>Maximum speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbandaged rotor</td>
<td>72krpm</td>
</tr>
<tr>
<td>Rotor with 0.5mm CFK bandage</td>
<td>96krpm</td>
</tr>
<tr>
<td>Rotor with 0.5mm hot work steel</td>
<td>115krpm</td>
</tr>
</tbody>
</table>

Tab. 1: Attained speed limits for different rotor types

Table 1 shows the maximum speeds attained with different rotors. If the magnet reaches its stress limit before the sleeve
does, the magnet will crack but the rotor might just continue to spin if the occurring unbalance is small enough. If the sleeve fails first, the brittle magnet ring is no longer supported and will also be destroyed. Fig. 8 shows two burst sleeves fail first, the brittle magnet ring is no longer to spin if the occurring unbalance is small enough. If the rotors with a 0.5mm CFK bandage and a 0.5mm hot work steel sleeve, respectively.

VII. CONCLUSION

The suitability of bearingless drives for high speed operation up to and beyond 100krpm has been demonstrated. The special demands to be considered during the design process have been described and have turned out to be attainable with state of the art techniques. Frequency dependent losses become an increasing challenge and need to be further reduced. Especially stator losses which rise quadratically with frequency due to eddy current effects need to be constrained. The limiting factor for further increasing the rotational speeds, however, is the mechanical strength of the rotor materials. The brittle magnet material in the rotor needs to be supported mechanically by a retaining sleeve.

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