

Setup with two Self-Sensing Magnetic Bearings using Differential 3-Active INFORM

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Abstract—This paper describes how a rotor with two radial self-sensing Hybrid Magnetic Bearings (HMB) with a novel self-sensing method is set up.

Replacing position sensors with low cost alternatives currently is a broad field of research as it allows to decrease costs significantly. First the adapted version of the INFORM method in use is described in detail, explaining the advantages compared to the classic INFORM. Next the results of a 3D electro-magnetic finite element simulation are shown. The simulation was used to find an optimal geometry concerning the mutually exclusive goals of maximising bearing force and sensitivity / linearity of the INFORM method.

Finally the simulation results are compared to measurements on the prototype.

I. INTRODUCTION

The Department of Electrical Drives and Machines at the Technical University of Vienna has already tested and proofed the applicability of the so called INFORM method for self-sensing magnetic bearings in previous prototypes [1][2]. The new prototype introduced in this paper uses a differential measuring approach, which increases the signal to noise ratio significantly compared to the classical INFORM approach. Further it is the first prototype set up with two radial self-sensing HMB based on INFORM.

II. THE INFORM METHOD

A. Operating principle

The so called INFORM method (Indirect Flux Detection by Online Reactance Measurement) was originally developed for the rotor position detection of synchronous drives [3] and is well known for the sensorless control of synchronous drive applications. It relies on measuring the position by high frequency voltage injection pulses. If the iron path and leakage fluxes are neglected, then the coil inductance is solely dependent on the air-gap between rotor and stator. Assuming a three pole stator arranged in Y-shape, then the coil inductance can be calculated from:

$$L(x)|_{y=0} = \frac{\mu_0 N^2 A}{\frac{3}{2} \left(l_0 - \frac{x}{2} \right)} \quad (1)$$

with the number of coil turns N , the air gap area A , the nominal air gap length l_0 and the displacement x at

$y = 0$. If the inductances of the three coils are known, the 2D radial displacement (x,y) can be calculated. The following paragraph describes how these inductances are obtained.

B. 3-Active INFORM

The classic INFORM measure sequence stops the current-control-loop in determined time steps to inject the needed high frequency voltage pulses [4]. The cycles in between this voltage pulses is used by the current controller to adjust the winding current using a classical pulse width modulation. This intercepting behaviour limits the position sampling rate and consequently causes a low bandwidth of the position controller. This is especially critical in an originally unstable system like a magnetic bearing with a constant bias flux. Therefore the so called 3-Active INFORM was introduced to increase the INFORM sampling rate.

The pulse sequence is produced according to [5], which is a combination of three active test voltage space phasors, approximating arbitrary voltage space phasors within a certain limit. Hence, INFORM measurement information and desired space phasors according to current control can be realized at the same time. Figure 1 illustrates two example voltage space vectors. The zero-voltage space vector u_0 is generated if all

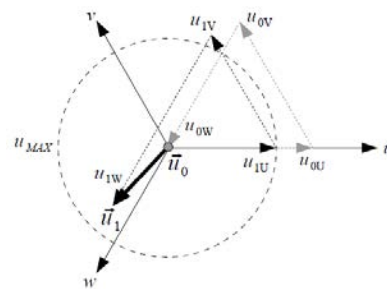


Figure 1. Two voltage space phasors examples u_0 and u_1 in 3-Active PWM modus

three ON-times are equal. If the ON-times differ from each other, a voltage space vector is generated, in this example u_1 . Due to the sequence pattern, a positive voltage in U, V or W direction is applied on the bearings coils at every moment which allows the evaluate the position after each current control cycle. The corresponding voltage and current curves

for one cycle are shown in figure 2.

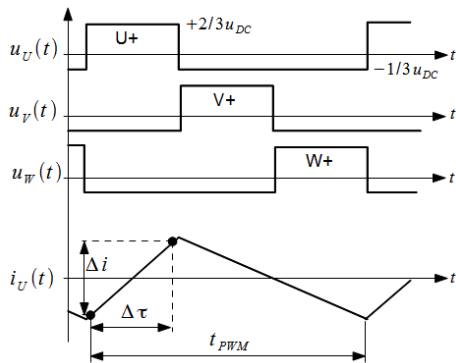


Figure 2. Voltage and current curves in 3-Active PWM modus

Using equation 2, the coil inductance can be calculated out of the known dc link voltage and the measured current slope ($r_s = 0\Omega$).

$$u = L \cdot \frac{di(t)}{dt} \rightarrow L = u \cdot \frac{\Delta\tau}{\Delta i} \quad (2)$$

When the coil inductances are known the position can be calculated using calculation rules basing upon the mathematical model described in [5].

Downside of the 3-Active PWM pattern is a loss in the applicable voltage, as there is a minimum ON-time required for each phase. This typically limits the voltage space phasor magnitude to a maximum of 25% of the direct current link voltage.

C. Differential 3-Active INFORM

The 3-Active INFORM increases the sample rate a lot compared to the classical INFORM, as the position can be detected in every current control cycle. Beside the smaller available voltage space phasor magnitude, another downside is the small amplitude of the injected current ripple compared to the nominal current of the magnetic bearing. If the current slope now is measured with the ADC-input for the working current, the resolution is considerably low, as the ripple magnitude is usually about one tenth of the nominal current. The solution is a differential approach which has been introduced by [6]. The in this prototype used variant consists of a stator with six poles, where the differential winding current of two opposite poles is measured. The differential current is proportional to the inductance difference and thereby also to the displacement. As the rotor is displaced in y-direction, the inductance of the upper coil is bigger. The corresponding currents for one 3-Active PWM cycle are shown in figure 3. The differential current is measured with a transformer where the two coil-wires are wound in different directions on the primary side. The secondary side is terminated with a small resistance. The resulting voltage signal is converted in an separate ADC input of the IC. This allows to measure the current ripple independently from the working current with full available resolution. Figure 4 shows the schematic circuit for one pole-pair. The

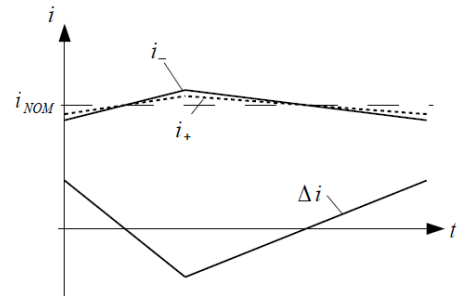


Figure 3. Current slopes in two opposite coils at displacement

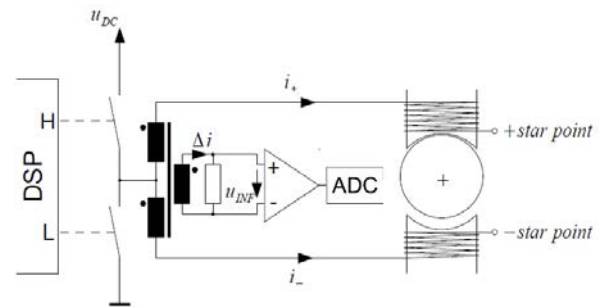


Figure 4. Schematic measurement circuit for the differential INFORM method

differential approach increases the signal to noise ration (SNR) significantly. Figure 5 shows the position detection in three different positions. The corresponding standard

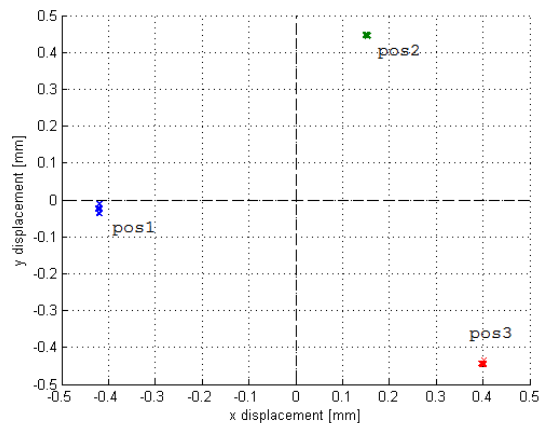


Figure 5. Position detection with differential 3-Active INFORM measurement

deviations of the position measurement are given in table I.

Table I
STANDARD DEVIATION OF THE POSITION MEASUREMENT WITHIN THE THREE POSITIONS (RADIAL AIR GAP = 0.8MM)

position	x-direction	y-direction
pos1	0.812 μm	1.992 μm
pos2	1.350 μm	0.7937 μm
pos3	1.276 μm	0.9097 μm

A noise of approx. $1\mu\text{m}$ at an air gap of 0.8mm is at

the class of accuracy of sensors and facilitates high dynamic control algorithms. At this resolution, the noise of the ADC chain becomes a considerable factor, making it necessary to also focus on electromagnetic compatibility and print design. Figure 6 shows the measured position and velocity estimated by a Kalman filter at a step of the target position (PD position controller). The curves prove the high SNR. This allows a stiff

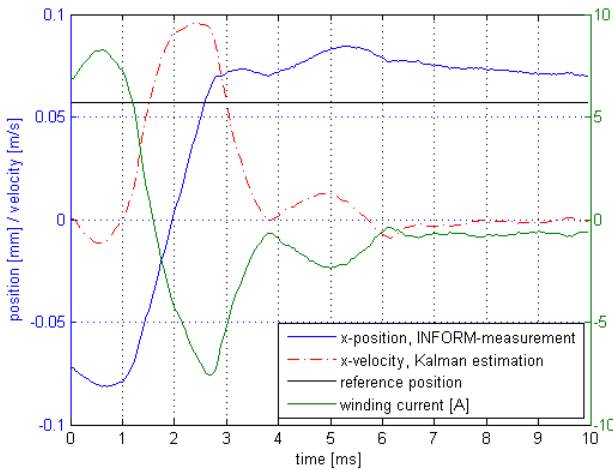


Figure 6. Step response of a change in x-direction

control and thus a quick change of position. Interestingly the position first changes to the opposite direction for a bit. One possible explanation could be the influence of the winding current on the position measurement. Further investigations will be done on that effect.

III. DESIGN AND CONSTRUCTION

A. General requirements

The basic parameters like outer diameter and nominal voltage were chosen by the given electrical drive and voltage inverter. In order to be able to use three phase inverter from the field of electrical drives and therefore reduce costs, the number of phases was chosen with three. It was shown in [7] that magnetic bearings can be realized through three poles arranged in Y-shape. As this prototype uses a differential approach, the number of poles was chosen to be six. Further operating costs can be sunk when using permanent magnets for bias flux as shown in [8]. So this prototypes uses HMBs with permanent magnets to create a homo-polar bias flux.

The air gap was chosen as a compromise between available bearing force and the available accuracy of production. The general parameters are listed in table II.

B. Bearing force

To find the optimal distribution of copper and iron for the given outer diameter, a static-electromagnetic 3D finite element model was created. Optimization goals were maximising the bearing force while ensuring a good sensitivity and linearity for the INFORM method. Hence primary bottlenecks for the magnetic flux have to be avoided

Table II
BASIC PARAMETERS OF THE PROTOTYPE

Parameter	Value
Outer bearing diameter	120 mm
Air gap	0.8 mm
Mass of rotor	0.8 kg
Bearing force	20 N
Number of poles	6

and a good balance between space for iron for the guidance of the magnetic flux and space for copper to conduct the current has to be found.

The simulation of the final configuration (figure 7) shows that the centering force decreases with an increasing displacement. This is due to leakage fluxes that can not be influenced by the control current and the negative stiffness due to the bias flux. Compared to figure 7, the measured bearing

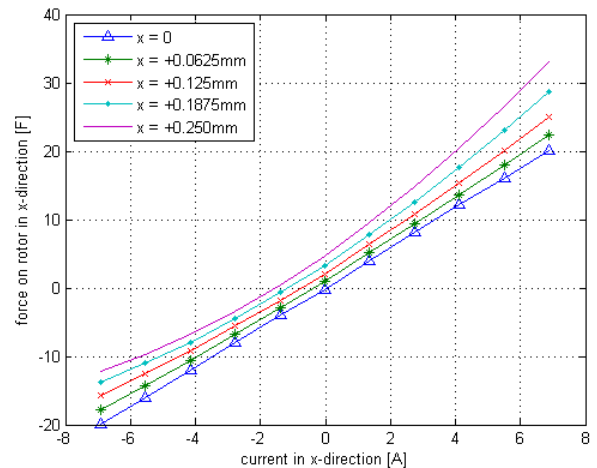


Figure 7. Simulated bearing force over winding current and y-displacement

force is shown in figure 8 Possible cause for the difference between the simulation and the measurement are not exact model parameters which are especially hard to obtain for the laminated iron.

Second reason could be the ripple current of the 3-active INFORM measurement. As the reluctance force is a quadratic function of the magnetic flux, the ripple could cause a higher force. Further investigations will be done on that topic.

C. The prototype

Figure 9 shows the current state of the prototype. It consists of a rotor supported by two independent HMB in radial direction. In axial direction the rotor is supported passive, as the energetic minimum of the magnetic field is in the centred position. The inverter was originally designed for a conventional electrical drive application. The only adaptation necessary was the adjustment of the voltage and current measurement range, and the gain of the additionally ADC

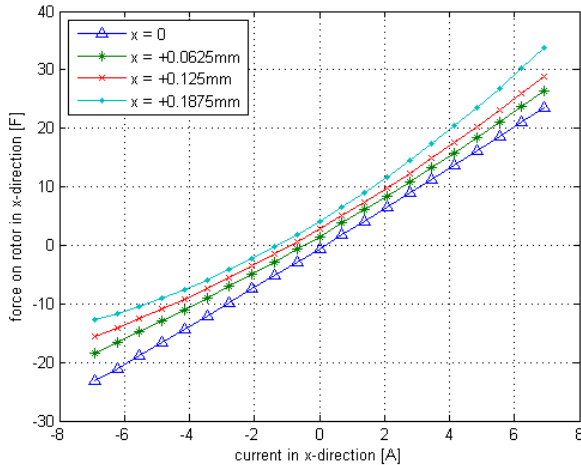


Figure 8. Measured bearing force over winding current and y-displacement

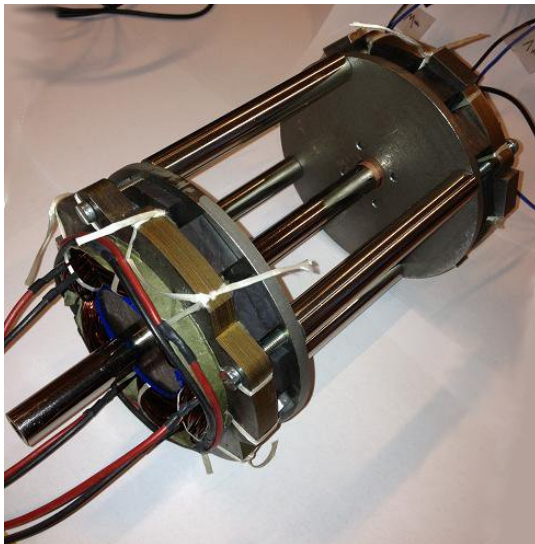


Figure 9. Prototype with two self-sensing HMBs

inputs for the differential current signal. The rest remained the same, which proves the ability of the presented self-sensing method for being realized with conventional 3-phase inverters.

IV. CONCLUSION

Throughout different measurements, the differential 3-Active INFORM proved to oppose a big improvement compared to the classical INFORM method [4]. Downside of the presented method is the influence of saturation in the iron path on the position detection. This limits the available bearing force, as the control-currents need to be limited. More intense investigations on methods to compensate these influence on the accuracy of the implemented self-sensing method should be done.

Upside is the good resolution and the high bandwidth. At this level of accuracy the noise of the whole ADC-chain becomes a considerable factor. Especially the short distance between the measure transformer and the ADC input

of the inverters controller, help reducing the ADC-chain noise.

Summarized it can be said that this first results show that this self sensing method is promising way and worth to be further investigated.

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