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TEST BENCH FOR THREE PHASE PERMANENT MAGNET BIASED RADIAL AMBS WITH A SENSORLESS CONTROL STRATEGY BASED ON INFORM METHOD

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ABSTRACT

In this paper a test bench for permanent magnet biased radial Active Magnetic Bearing (AMB) with respect to a sensorless control strategy based on INFORM method is presented. The purpose of this Hybrid Magnetic Bearing (HMB) prototype is to research the capability of the INFORM method for sensorless control of HMBs. The well known INFORM method for sensorless control of Permanent Magnet Synchronous Motors (PMSM) is adapted for the HMB and also described in principle. For the test bench a three phase MOSFET inverter was build up. First measurement results of the INFORM capability are presented.

INTRODUCTION

Self-sensing (sensorless) controlled active magnetic bearings (AMB) have been field of interest for many years [1]-[3]. In this paper the INFORM method will be used for sensorless control of a permanent magnet biased hybrid magnetic bearing. A sensorless control strategy avoids normally used external position sensors (e.g. eddy current sensors) and reduces the costs of the HMB system. The HMB was designed in respect to different properties. INFORM capability was realized by using a three coil AMB. High Forces at low currents are achieved by biasing with permanent magnets [4]. To reduce iron losses at high speed revolution a homopolar configuration was used. Other known three coil HMBs (e.g. [5]) have heteropolar rotor magnetization. The implementation as a three coil HMB allows using a traditional three phase power inverter which has reduced losses and costs compared to standard AMBs with four power amplifiers.

THE INFORM METHOD

The classical INFORM method (Indirect Flux Detection by Online Reactance Measurement) is well known for rotor position detection of Permanent Magnet Sychronous Motors [6]. Typically different reactances in d- and q- axis either based on geometry or saturation effects can be measured. The INFORM method is a voltage injection method and can also be used in AMBs for measurement of the inductances for position detection in sensorless control mode. The INFORM method uses the control coils themselves for position detection. Therefore the coil inductances need to be depended on rotor displacement. The nominal inductance at centered rotor depends on the number of turns N of the winding, the area of the pole A_P and the nominal air gap δ_0.

$$L_0 = \frac{\mu_0 N^2 A_P}{\frac{3}{2}\delta_0} \tag{1}$$

By displacement x_1 of the rotor in direction of the first coil (x direction-figure 2), the inductance of the coil gets

$$L_1 = \frac{\mu_0 N^2 A_P}{\frac{3}{2}\left(\delta_0 - \frac{x_1}{2}\right)} \tag{2}$$

The relative value of the coil inductance l_1 yields the relation between the inductance and displacement of the rotor

$$l_1 = \frac{L_1}{L_0} = \frac{\delta_0}{\delta_0 - \frac{x_1}{2}} \tag{3}$$

The complex displacement phasor $\underline{x}$ is built by combining the three spatial displacements x_1, x_2 and x_3 in each coil direction as follows:

$$\underline{x} = \frac{2}{3}\left(x_1 e^{j0} + x_2 e^{j\frac{2\pi}{3}} + x_3 e^{j\frac{4\pi}{3}} \right). \tag{4}$$

This leads to

$$\underline{x} = \frac{2}{3}\left(\frac{-2\delta_0}{l_1} e^{j0} + \frac{-2\delta_0}{l_2} e^{j\frac{2\pi}{3}} + \frac{-2\delta_0}{l_3} e^{j\frac{4\pi}{3}} \right). \qquad (5)$$

The coil inductances l_1, l_2 and l_3 can be determined by measuring the current reaction on voltage excitation in time domain. E.g. the current slope Δi_1 caused by a space phasor $\underline{u}=e^{j0}$ is measured within a fixed time step $\Delta\tau$, and same is done for phase 2 and 3. By combination of these three current measurements caused by three INFORM sequences the complex value

$$\underline{c} = \frac{2}{3}\left(\Delta i_1 e^{j0} + \Delta i_2 e^{j\frac{2\pi}{3}} + \Delta i_3 e^{j\frac{4\pi}{3}} \right) \qquad (6)$$

similar to the complex INFORM value $\underline{c}_{INFORM}$ [6] is build. Finally, the rotor position can be calculated as

$$\underline{x} = -2 \cdot \underline{c} \qquad (7)$$

The current slopes Δi_1, Δi_2, Δi_3 depend on the DC link voltage u_{DC}, the coil inductance and the measuring time interval $\Delta\tau$. In a typical INFORM sequence as shown in figure 1, the slope is measured in positive and negative direction. Hence the combined current slope is

$$\Delta i_1 = \Delta i_{11} - \Delta i_{21} \qquad (8)$$

and the time step yields

$$\Delta\tau = \Delta\tau_1 + \Delta\tau_2 . \qquad (9)$$

The INFORM sequence is cyclically implemented in each phase (U,V,W,U,V,W…) and interrupts the current controller (PWM modus) at certain time steps.

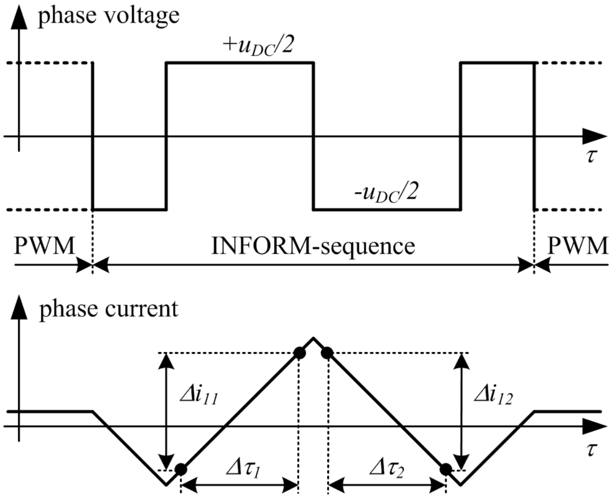

FIGURE 1: Typical INFORM sequence with phase voltage and phase current over time.

THE HYBRID RADIAL AMB SYSTEM

In figure 2 the basic structure of the realized HMB is given. The bias flux can be generated either by ferrite or NdFeB permanent magnets which are magnetized in center direction. In order to adjust the magnitude of the magnetic bias flux it is possible to change the number as well as the spatial distribution of the magnets(figure 3). The bias flux path is built by the stator yoke, the laminated steel sheets, the solid rotor and both stator yoke plates on each side. In order to reduce the volume of the HMB prototype the iron length is split in three parts. In the first implementation the full iron length is used. The control flux path is built only by the laminated steel sheets and the rotor. Three concentrated coils in star connection are used to generate the control flux.

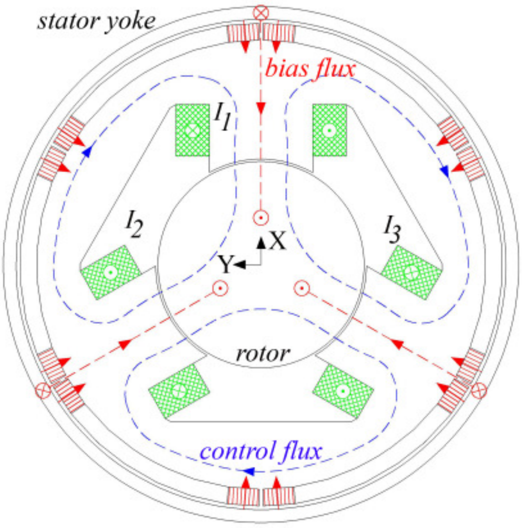

FIGURE 2: Principle of the realized HMB system.

In figure 3 the geometry of the laminated steel for the stator is shown. The permanent magnets for flux biasing are placed at the borders of the metal sheets. The advantage of this structure is a homopolar magnetisation of the rotor and yields less iron losses at high angular velocity. Two rotor types (solid steel and laminated steel) are available for investigations. To verify the quality of the INFORM method, the rotor displacement can be measured by two eddy current sensors (bandwidth 80kHz, measurement range 2mm) in X- and Y-direction. The typical data of the HMB prototype are given in table 1. The second bearing of the shaft is implemented as classical ball bearing.

TABLE 1: Characteristic data of the realized HMB prototype (with NdFeB-Magnets)

Outer diameter	190mm
Total length	140mm
Rotor diameter	80mm
Nominal airgap	1.0mm
Pole area	2233 mm^2
Turns of the winding	20
Nominal coil inductance	0.75 mH
Nominal radial force	750N

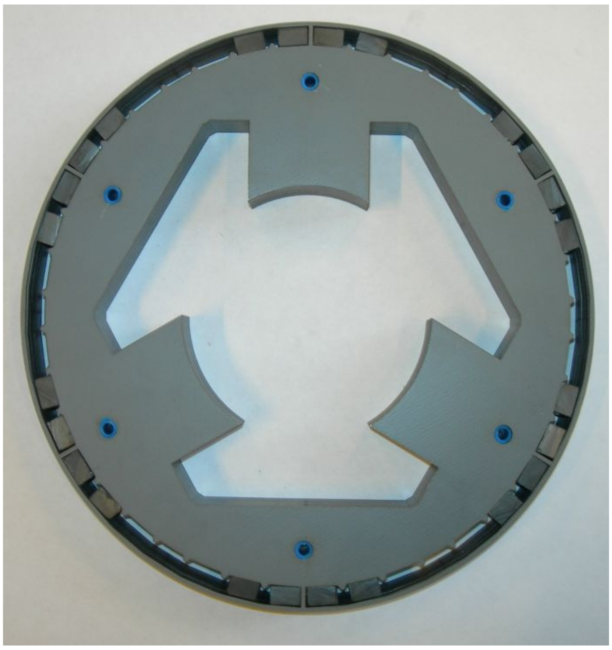

FIGURE 3: **L**aminated steel sheets of the three phase radial HMB with permanent magnets (ferrite magnets) shown without stator yoke

POWER AMPLIFIER

The power amplifier is realized as a classical three phase MOSFET voltage inverter controlled by a Digital Signal Processor (TMS320F2812). The DSP clock is 150MHz and allows implementation of complex time triggered control structures with high sample rates. This inverter was designed with respect to high switching frequency and offers the possibility of current measurement by using current transducers and shunts in each phase for comparison. A phase voltage measurement in each phase is also implemented.

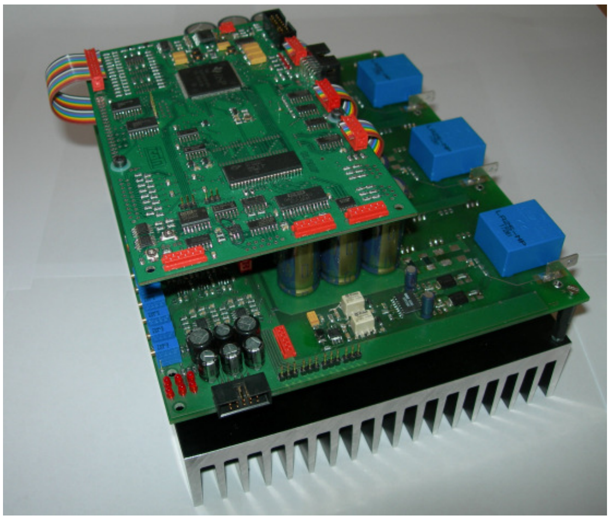

FIGURE 4: Prototype of the developed three phase high frequency voltage inverter of the HMB test stand.

TABLE 2: Characteristic data of the used three phase voltage inverter

Type of power switches	MOSFET
Switching frequency max.	50 kHz
DC Link voltage max.	200V
Continous phase current max.	25 A
Peak phase current max.	40 A

SIMULATION RESULTS

To verify the mathematical model of the used three coil HMB a 3D-Finite Element Model (FEM) simulation was done with MSC/EMAS. Such FEM simulations allow simple variation of parameters like e.g. bias flux and its influence on the HMB parameters as well as the identification of the INFORM quality.

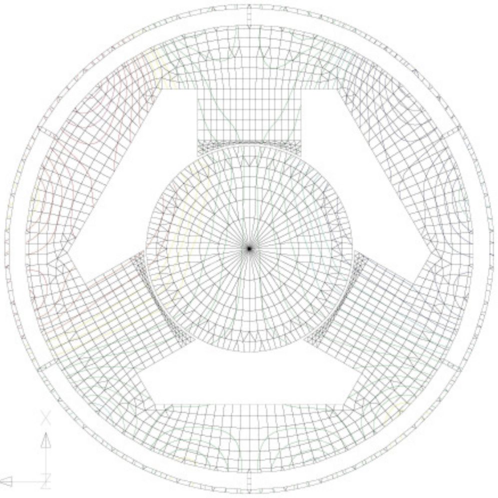

FIGURE 5: Generated mesh of the FEM model with z-component of the magnetic vector potential at i_X = -10A, 12 ferrite magnets (shown without stator yoke)

MEASUREMENT RESULTS

A basic INFORM sequence (figure 1) was implemented in the DSP control structure. Figure 6 shows the phase current within a typical INFORM voltage sequence in u-direction. In figure 7 position measurement by INFORM method is given at four fixed rotor positions (table 3). At each position 1000 INFORM measurements (always U,V,W) are analyzed and printed in the picture. No levitation is implemented in this case. To verify first INFORM-measurements during levitation, a sensor-based position control with classical PID controller in X and Y direction was developed. For compensation of rotor mass a bias current i_x =6A was measured during levitation in centered position (HMB with 12 ferrite magnets). By increasing the magnetic bias flux (change number or type of magnets) the bias current changes and can be optimized.

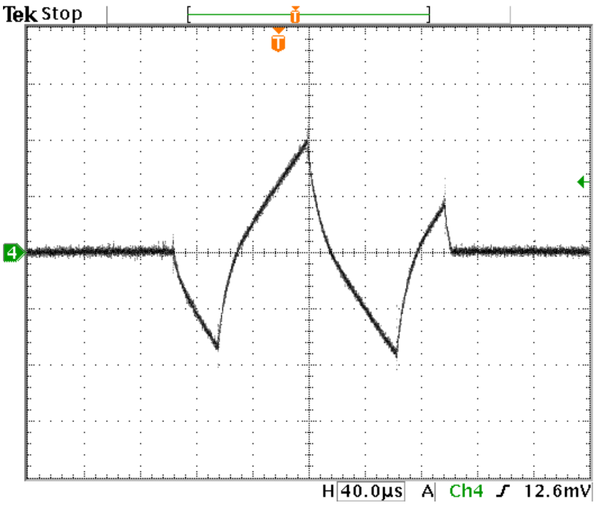

FIGURE 6: Current signal in phase 1 of the INFORM measurement for rotor position detection (current signal at 5A/div, 90V DC link voltage, solid steel rotor)

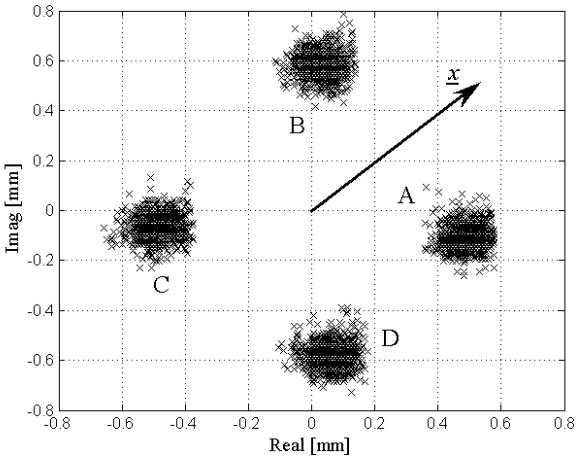

FIGURE 7: Rotor position detection at fixed rotor positions with half airgap displacement (1000 measurements at each position)

TABLE 3: INFORM measurements at fixed rotor positions (half airgap displacement)

Fixed rotor positon	$\underline{X}=X+jY$
A	0.5mm + j0
B	0 + j0.5mm
C	-0.5mm + j0
D	0 - j0.5mm

For further investigations in sensor controlled levitation, INFORM measurement sequences are activated. The implementation of the INFORM sequence interrupts the current controller and yields fast current disturbances which have no influence on levitation. First the dependence in X direction is considered. Therefore the position set point is changed by a ramp function. Figure 8 shows a displacement from x =-0,4mm to centered position (lift up process). It can be seen, that a monotonous INFORM signal (=Re{$\underline{x}$}) is measured. Furthermore a nonlinear behavior due to the nonlinearity of position dependent inductances is recognized as expected. The measurement result of a move down process (form center to x=-0,4mm) is given in figure 9 and shows similar behavior.

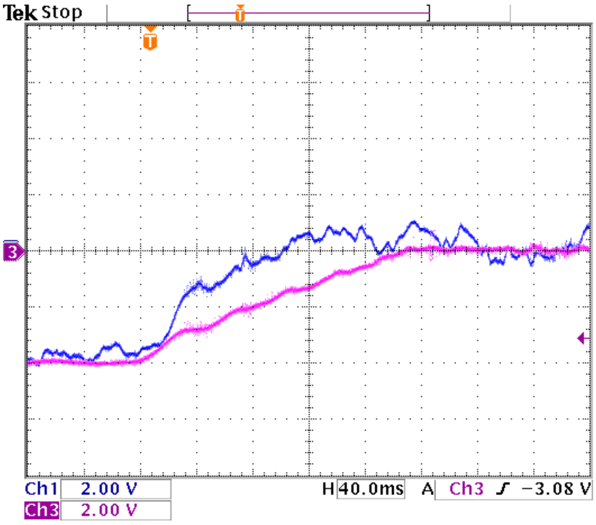

FIGURE 8: Rotor displacement from x = -0,4mm to center position during sensor based levitation - Ch1: sensorless INFORM signal, Ch3: sensor signal

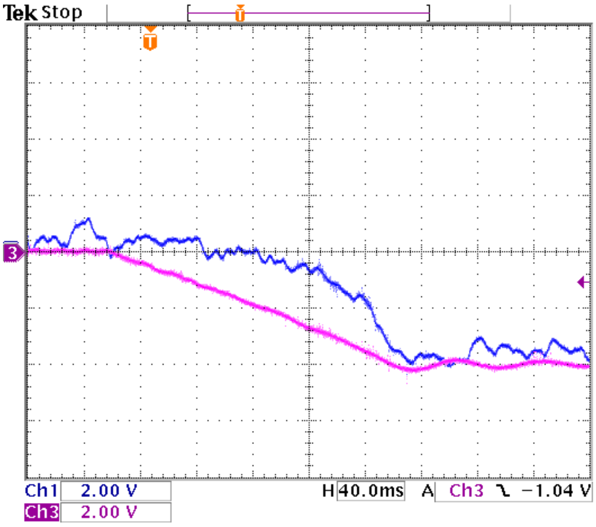

FIGURE 9: Rotor displacement center position to x = -0,4mm during sensor based levitation - Ch1: sensorless INFORM signal, Ch3: sensor signal

Also displacements in Y direction are considered and measurement results are shown in figure 10 and figure 11. A position shift from right to left during levitation with active INFORM measurement is given in figure 10. Again the sensorless signal shows monotonous behaviour. The same measurement is done from left to right side (figure 11) and yields similar results

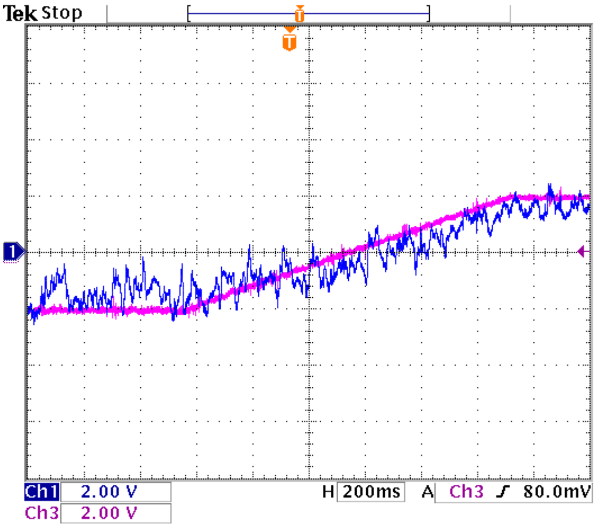

FIGURE 10: Rotor displacement from y = -0,2mm to y=0,2mm during sensor based levitation - Ch1: sensorless INFORM signal, Ch3: sensor signal

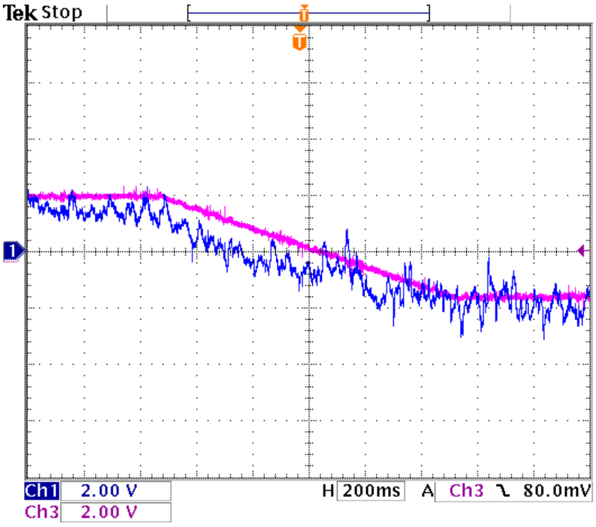

FIGURE 11: Rotor displacement from y = 0,2mm to y= -0,2mm during sensor based levitation - Ch1: sensorless INFORM signal, Ch3: sensor signal

CONCLUSIONS AND OUTLOOK

A test stand to investigate the behavior of the INFORM method for sensorless control of hybrid magnetic bearings was manufactured. The INFORM method uses the control coils themselves for rotor position detection. First measurements of INFORM capability were presented without control and during sensor controlled mode. Optimization of the HMB prototype to improve INFORM behaviour can be done by varying different parameters like bias flux, turns of the windings, iron length and rotor type. The realized three phase high frequency voltage is also prepared for improving INFORM quality. The present measurements confirm a proper function of the INFORM method. Further investigations will be done with respect to INFORM optimization by varying the HMB parameters as well as the INFORM procedure and implementation of a sensorless controlled HMB. Measurements of power consumption with the goal of minimisation will also be done. Finally a low cost active magnetic bearing system based on a sensorless control strategy with INFORM method and a simple three phase inverter will be realized.

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