The 15th International Symposium on Magnetic Bearings, August 3-6, 2016, Mojiko Hotel, Kitakyushu, Japan

ISMB15

New Results on the Robustness of Self-Sensing Magnetic Bearings

Markus HUTTERER[*], Matthias HOFER[*] and Manfred SCHRÖDL[*]
[*] Vienna University of Technology
Guhausstrae 25, 1040 Vienna, Austria
E-mail: markus.hutterer@tuwien.ac.at

Abstract

This paper shows the design and new results of a self-sensing homopolar active magnetic bearing (AMB). The considered magnetic bearing provides the bias flux using permanent magnets. Only the control flux for the stabilization of the system is provided by electro-magnets. This so called hybrid magnetic bearing (HMB) minimizes the energy losses and shows a high linearity. Therefore, this structure is a good choice for industrial applications which uses position sensors for closing the control loop. However, the self-sensing control of such bearing types require a position dependent inductance. Many homopolar structures share the same flux at two opposite poles and the coils of these poles are connected in serial. Hence, the inductance is almost independent of the rotor position. The proposed bearing type shows a way where also a hybrid homopolar magnetic bearing can be controlled without external position sensors. The self-sensing method is based on inductance measurement by applying voltage pulses to the system. The current slope is measured directly using an induction ring. A differential evaluation of the current slopes increases the position dependent part of the signal and decreases the errors due to eddy currents and the leakage flux. The last part of the paper shows the measured sensitivity function of the system at standstill and rotational speed.

Key words : Self-sensing, homopolar, robustness, current slope

1. Introduction

Active Magnetic bearings (AMBs) exhibit several attractive advantages compared to conventional bearing systems, such as no friction losses, wearless, the ability of long-term high speed running, and the possibility to infect the mechanical properties [Schweitzer, 2009]. But active magnetic bearings are unstable for open loop operations and for a stable levitation a position information of the rotor is required to close the loop using a position controller. To get this position information typically position sensors are used. But in the last years also self-sensing strategies are developed. The aim of this self-sensing techniques is to use the actuator itself as a position sensor. Thus, an external sensor is avoided and a cost reduction and a redundant position information of the system is achieved. Therefore, self-sensing or respectively sensorless technologies for AMBs have been field of research for many years with the target to reach the same performance as sensor based systems. One of these different methods is the INFORM (Indirect Flux detection by Online Reactance Measurement) method, which is described in [Hofer, 2013] and [Nenning, 2014]. [Hofer, 2015] developed a ”fully” self-sensing AMB-system. ”Fully” in this context means that the magnetic bearing and the electrical drive is controlled using self-sensing techniques. The theoretical paper [Morse 1998] shows a very severe robustness limit for self-sensing magnetic bearings. Therefore, it seems to be not possible to design and control a self-sensing magnetic bearing which fulfills the requirements of industrial applications. However, [Maslen, 2004] extended this theory to the time varying nature of switching ripple systems. With this extension the norm bound of the sensitivity function is in a range where the industrial requirements can be fulfilled. In [Schammas, 2005] a sensitivity function was shown, where the highest peak is at about 3.5 what is near the requested maximum value of 3. To show the suitability of self-sensing magnetic bearing this paper describes a 4-DOF AMB System which rusn at 6000 rpm and has the highest peak of the sensitivity function below 3. The INFORM method is used to estimate the position of the rotor.

The contributions of this paper can be summarized as follows:

- A novel self-sensing strategy is developed, which uses induction rings for measuring the current slope directly. This method provides an accurate position estimation and reduces the required computing power of the digital signal processor.

- A homo polar magnetic bearing structure is evaluated in the sense of linearity and self-sensing performance.

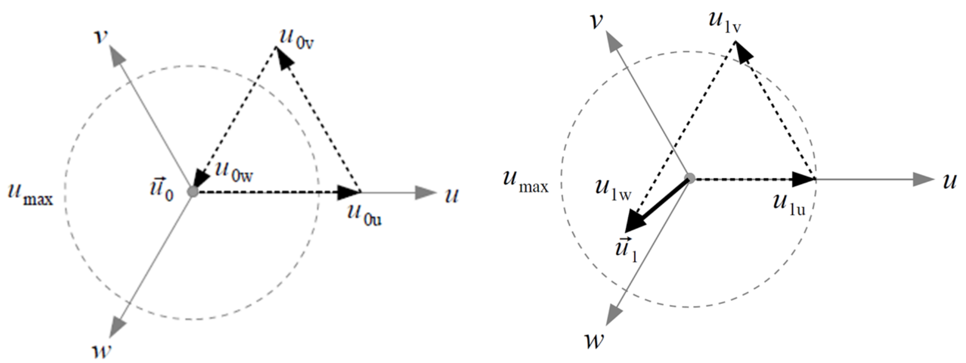
2. Current Slope measurement using a modified PWM

The INFORM method is based on the position dependence of the reluctance of the system. For explanation the basic physically effect the iron path and the leakage flux is neglected. Therefore, the inductance depends on the air-gap between rotor and stator. The inductance of a magnetic bearing can be calculated by:

$$L(x) = \frac{\mu_0 N^2 A}{2(l_0 - x)} \tag{1}$$

with the number of coil windings N, the air-gap surface A, the nominal air-gap length l_0 and the displacement x.

To determine the inductance, voltage pulses are applied on the system and in contrast to [Schammass, 2005] the current slopes are measured and not the first harmonic. By using the current slopes directly, the estimation of the distance gets independent of the duty cycle. This theory was extended for three phase bearing structures, to use this method on the prototype. There are two different INFORM methods which can applied on the AMB system. The first is the classical INFORM, which is known from the sensorless control of AC Machines [Schroedl, 1996]. This procedure stops the current control in equidistant time steps and injects defined voltage pulses. This stopping of the current control limits the sampling rate of the control structure, what is of course very critical for open loop unstable systems. To overcome this problem, the 3-Active INFORM PWM pattern for three phase systems was developed. This method uses a special PWM sequence, where the duty cycle is always higher than zero. Therefore the position can be measured in every PWM cycle. If the current controller has a zero as output the PWM sequence corresponds with Fig.1(a) and for a resulting voltage u_1 with Fig.1(b).



(a) voltage space phasor for no resulting current

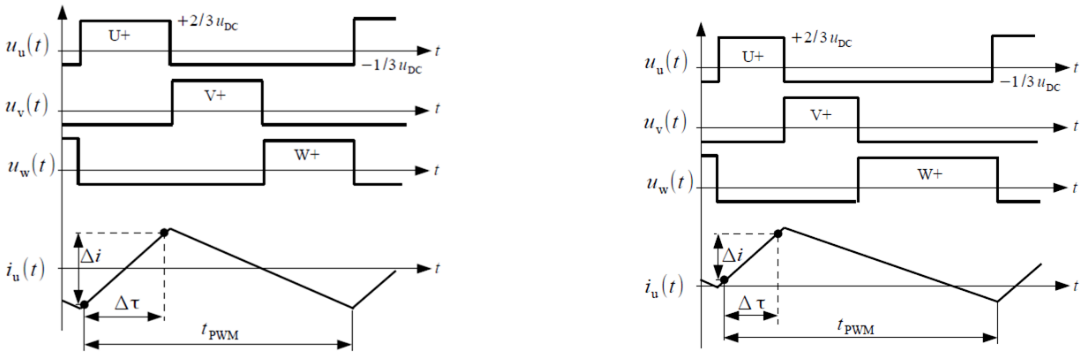
(b) voltage space phasor for a resulting current

Fig. 1 3-Active INFORM space phasors

Fig.2 shows the corresponding voltage and current curves of the 3-Active INFORM method. However, a drawback of this method is a higher limit of the maximum achievable voltage space phasor, due to the required minimum duty-cycle of the INFORM method for slope evaluation.

3. Homopolar structure of the prototype

Fig.3(a) illustrates the cross-section of the proposed magnetic bearing extended with magnetic flux lines. For simplification only the bias and control flux lines of the one axis is shown. The bias flux is provided by permanent magnets and is closed in the axial dimension. The direction of the bias flux shows from every pole to the center. Therefore a fixed point on a spinning rotor lies always in a magnetic flux of the same direction. This is a big advantage compared to hetero-polar bearings, where the direction of the magnetic flux is different for different poles. Hence, the hetero-polar structure has higher iron losses for a spinning rotor compared to the homo-polar magnetic bearing. Also the linearity of the magnetic force is better, because two opposite coils share nearly the same flux. To motivate the usage of the proposed homo-polar



(a) $u(t)$ and $i(t)$ for no resulting current

(b) $u(t)$ and $i(t)$ for a resulting current

Fig. 2 3-Active INFORM voltage and current curves

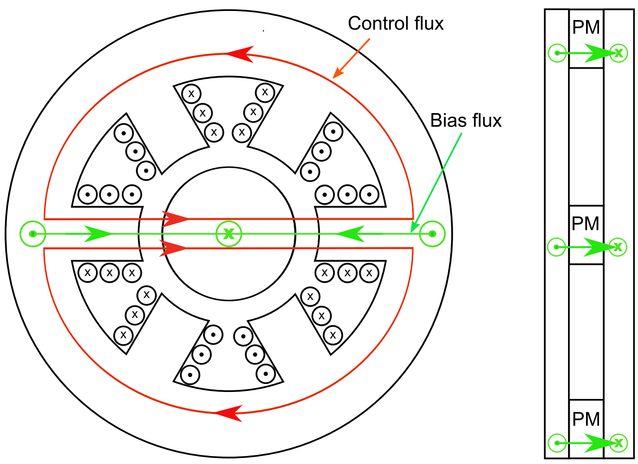


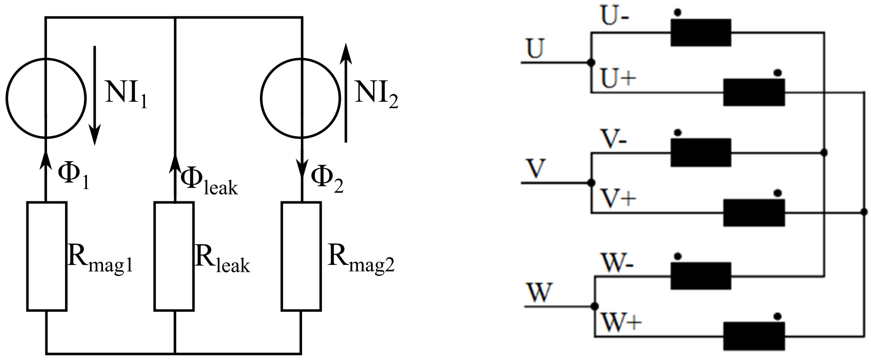
Fig. 3 Cross-section of the proposed magnetic bearing

structure only one dimension of the bearing is treated. The equations of the magnetic circuit for the control flux according to Fig.4 are (saturation effects are neglected):

$$\begin{aligned} N(I_1 + I_2) &= \Phi_1 R_{mag1} + \Phi_2 R_{mag2} \\ NI_2 &= \Phi_2 R_{mag2} + \Phi_{leak} R_{leak} \\ 0 &= \Phi_1 - \Phi_2 + \Phi_{leak} \end{aligned} \quad (2)$$

For a well developed system R_{leak} is much greater than $R_{mag1} + R_{mag2}$ and therefore $\Phi_1 \approx \Phi_2$. Using this assumption, from the first row of equation (2) can be concluded, that the flux $\Phi_1 \approx \Phi_2$ depends on the sum of the currents $I_1 + I_2$ and on the sum of the reluctances $R_{mag1} + R_{mag2}$. The reluctances R_{mag1} and R_{mag2} are both dependent on the displacement of the rotor. However, the sum of the reluctances $R_{mag1} + R_{mag2}$ is independent of the rotor displacement. Thus, the control flux only depends on the current and not on the rotor displacement. In contrast, many hetero-polar magnetic bearings in industry application have a significant dependence on the rotor position. Because the control flux only depends on the sum of the currents, it is not necessary to connect the coils serial. In Fig.4(b) the coils are switched parallel with different winding directions. This parallel structure is used, because for a serial connection no rotor displacement dependency in the currents can be observed. But the proposed homopolar structure will not work, if only the control flux is used, because the resulting force is proportional to the square of the flux density. Therefore, the system is extended with a bias magnetisation provided by permanent magnets (PM). This bias flux shows for every pole to the center of the bearing. If the control flux and the bias flux is superposed the flux at one side of the rotor increases and decreases on the other side dependent on the current. Thus, a resulting force in the desired direction can be achieved.

The bias flux density dependent on the rotor displacement can be seen in Fig.5(a), where B_{l1PM} and B_{l2PM} describes the flux densities in the air-gap for a permanent magnet pre-magnetisation and B_{l1CL} and B_{l2CL} describes the flux densities in the air-gap for a electro-magnet pre-magnetisation of a hetero-polar bearing. The simulation is done without considering a saturation effect. Therefore, the electric biased fluxes will saturate if the rotor is near the gap boarders for real systems.

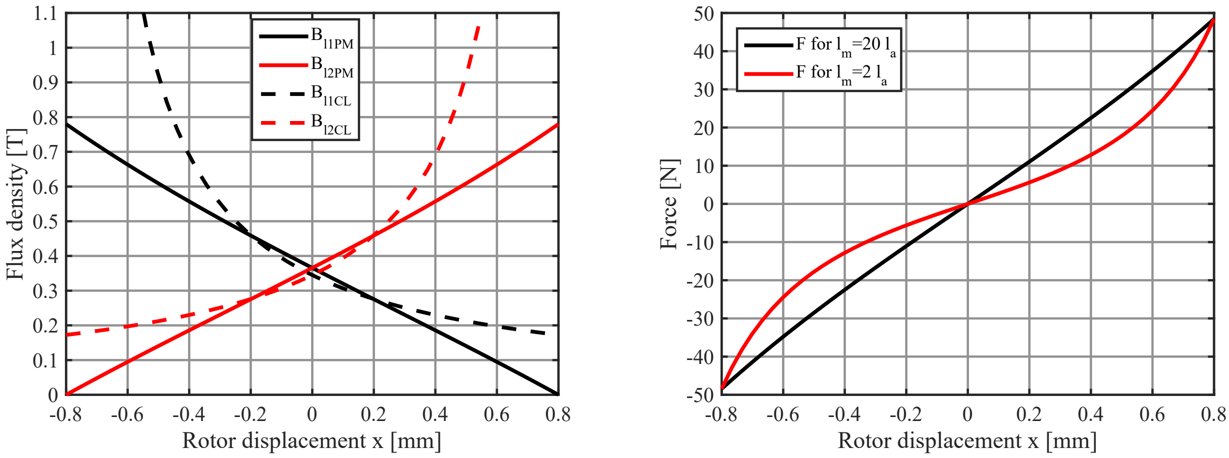


(a) Magnetic circuit of the control flux of a one dimensional homopolar magnetic bearing

(b) Connection of the coils

Fig. 4 3-Active INFORM voltage and current curves

However, with the permanent magnet pre-magnetisation the flux densities are below the saturation for the whole operating range of the bearing. Also the linearity of the permanent magnet pre-magnetisation is significantly better compared to the electrical pre-magnetisation. Many hetero polar magnetic bearings with electrical pre-magnetisation have a problem with a "sticking effect" if the rotor is near the boarder, because of a fast increasing flux density. This problem is mainly solved by a well designed permanent magnet pre-magnetisation.



(a) Bias flux dependent on the rotor displacement

(b) Resulting force dependent on the rotor displacement

Fig. 5 3-Active INFORM voltage and current curves

With the following equation the resulting force can be calculated in x-direction:

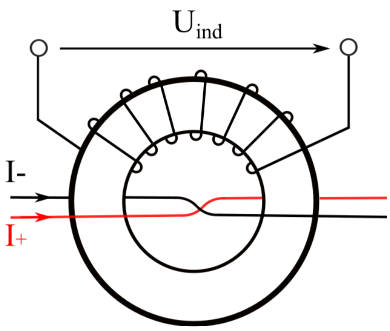
$$F(x) = \frac{A}{2\mu_0}\left((B_{l1PM} + B_{el})^2 - (B_{l1PM} - B_{el})^2\right) = \frac{A}{2\mu_0}\left(B_{l1PM}^2 - B_{l1PM}^2 + 2\,B_{el}\,(B_{l1PM} + B_{l2PM})\right) \qquad (3)$$

with the flux density caused by the coils B_{el} according to equation (2) and the surface area of the pole A. The most significant dependency of the rotor displacement is shown in the differences of the squared bias fluxes $B_{l1PM}^2 - B_{l1PM}^2$ compared to the additional term $B_{l1PM}^2 + B_{l1PM}^2$. Using this assumption the linear dependence to the sum of the currents can be stated by the term $2\,B_{el}\,(B_{l1PM} + B_{l2PM})$. The dependence of the resulting force to the rotor displacement x can be seen in Fig.5(b). For a well designed system the dependency on x is nearly linear. However, if the length of the permanent magnet is to low compared to the air-gap ($l_m = 2\,l_a$) the dependency will get non-linear. But this linear behavior is based on the equality of the control fluxes at both pole areas. Therefore, the linearity is only guaranteed in the one dimensional case. If also the other poles are considered this assumption cannot be full-filled in all cases and the non-linear behavior will increase.

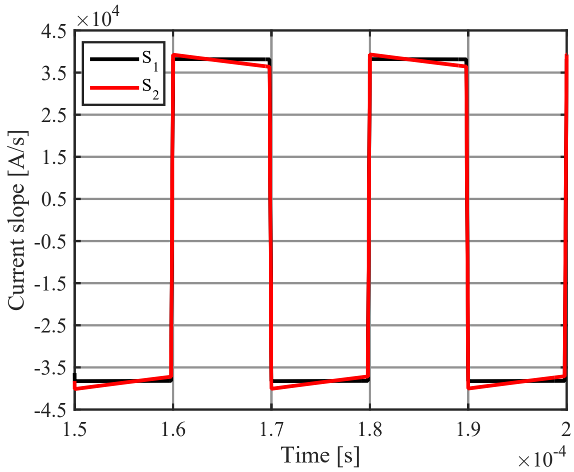
4. Differential measurement of the current slopes on the prototype

The state of the art technology often uses the measured current for the current controller to calculate the gradient. In common magnetic bearing systems, the current ripple is below 10 % of the rating current [Nenning, 2014-2]. Therefore the resolution of the current slope detection is also only 10 %. To solve that problem, in this paper a differential approach is used. The 6-pole structure has always two poles which are 180 °shifted. For the evaluation of the rotor position the difference of the current slopes of both poles is measured. Therefore an induction ring according to Fig.6(a) is used. The currents of the negative and the positive coil enters the induction area in opposite direction and a voltage U_{ind} is inducted in the measuring coil which is proportional to the difference of the current slopes. Because the sum of the currents slopes are almost rotor position independent, the difference of the current slopes is used instead. The advantages of the differential measurement of the current slopes can be summarized as follows:

- The voltage U_{ind} on the DSP is nearly proportional to the rotor displacement. Therefore no numerical differentiation is required. This fact simplifies the evaluation on the DSP and the computation time is reduced.
- Because the transfer function of the measuring coil can be modelled as differentiator in the required frequency range, the lower frequency signal caused by the actuating current is suppressed compared to the higher frequency measuring current.



(a) Direct Measurement of the current slope using an induction ring



(b) Dependence of the current slopes on the leakage flux R_{leak}

Fig. 6 Direct measurement of the current slopes

To proof the position dependency of the difference current equation (2) in combination with Faraday's law

$$U(t) = N\frac{d\Phi}{dt} + R_c\, I(t) \tag{4}$$

yields:

$$\dot{I}_{diff} = \frac{(2\, A\, R_c\, R_{leak}\, \mu_0 + R_c\, \delta_0)\,(I_2 - I_1) + (R_c\, x)\,(I_2 + I_1) + 2\, U\, x}{\mu_0\, A\, N^2} \tag{5}$$

with the difference of the current slopes I_{diff} the coil resistance R_c, the nominal air gap δ_0, the currents I_1 and I_2 the surface of the air-gap A and the applied AMB coil voltage U. Because the current of two opposite coils has the same direction, the first term of equation (**??**) is decreased by the differential approach. Thus also the current dependence of the position estimation is decreased. The second term which makes the equation non-linear and couples the position and the current is increased. This fact is a problem for low sampling rates and high resulting current ripples. The big advantage of this method is the increasing of the proportional dependence by a factor two compared to the evaluation of the poles independently. For the evaluation of the current slopes the currents in both coils differ dependent on the rotor position. This condition requires also different fluxes in the coils. To full fill this requirements a leakage flux R_{leak} is necessary and always there in real systems. However, this leakage flux should be high enough for minimizing the error of the position estimation. But for the linearity of the force generation, the leakage flux has to be as low as possible. Therefore a design trade-off has to be chosen for the magnetic bearing system. Fig. 6(b) shows the current slopes for two different values of the leakage flux R_{leak}, where S_1 demonstrate the current slope for R_{leak} is equal to the reluctance of one air gap for $x = 0$ and S_2 for R_{leak} is 100 time the reluctance of the simulation of S_1 . The current slope has also a sufficient quality for the higher leakage reluctance. This fact can be used for designing the geometry of an homo-polar magnetic bearing with a defined leakage flux.

5. Experimental results

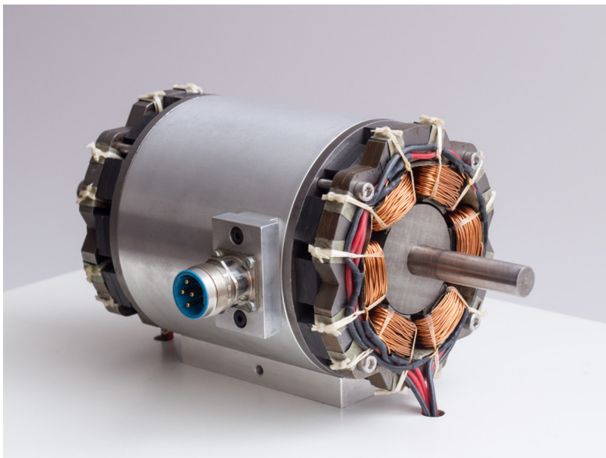
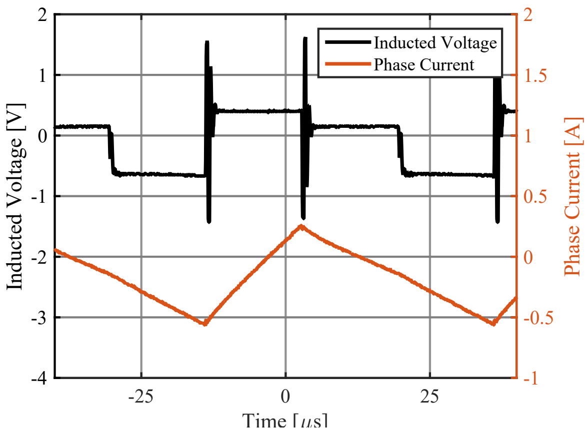
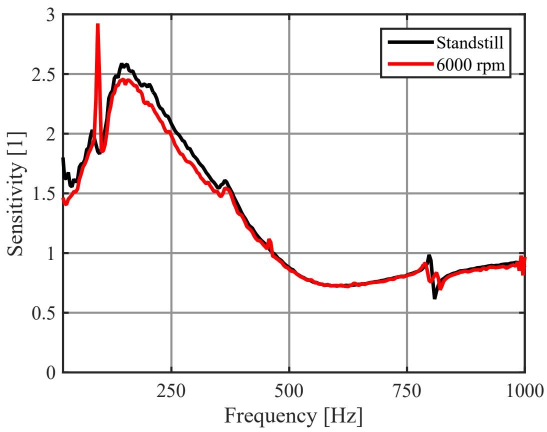


Fig. 7 4-DOF Magnetic bearing prototype



(a) Measured current slopes using the induction ring



(b) Sensitivity function of the magnetic bearing prototype

Fig. 8 Experimental results of the proposed method

This section gives experimental results of the proposed method tested on the prototype from Fig.7. The mechanical air-gap of the magnetic bearing is 500 μm. The prototype is based on the proposed homopolar structure. The rotor is driven by a synchronous reluctance motor. The advantage of this propulsion is that the radial forces caused by the motor is only present, if the motor coils are supplied. Therefore, the magnetic bearing can first center the rotor before the motor controller is switched on. Because of the weak polar moment of inertia and the symmetry of the rotor, a 4-DOF decentralized PID controller is used for the stabilization of the position. The axial direction is stabilized passively by the resulting reluctance forces caused by the radial magnetic fluxes, if the rotor is deflected in the axial direction.

Fig.8(a) shows the inducted voltage and the currents ripple of the U-phase for a general position. The high peaks at the switching points are caused by the almost unsteadily transitions. The measured inducted voltage is not decreasing during one measuring cycle compared to Fig.6(b). For the input of the position controller only the inducted voltage of the positive slope is used, because the cross coupling to the other axis is lower in that case. The inducted voltage in the $V+$ and $W+$ cycle is also different, because for a general position the current and voltage distribution in the $U+$ and $U-$ phase are different in both cases. Only for special rotor position (e.g. deflection only in the U direction) the inducted voltage will be the same for the $V+$ and $W+$ cycle.

To get a robustness measure of the purposed magnetic bearing control structure output sensitivity functions were measured. The norm ISO 14839-3 introduced an upper limit of the sensitivity to a factor of three. As it can be seen from Fig.8(b) this requirement is full-filled for the proposed self-sensing magnetic bearing. Because the rotor and the bearing are symmetric only one sensitivity function is measured, because the behavior of the other bearings are nearly the same. The function shows also nearly the same behavior for standstill and a rotational speed of 6000 rpm. This is only the case, because of the low gyroscopic effect. For industrial application the function for different speeds often differs very much, because of the non-linear coupling of the gyroscopic effect. Therefore more complex control structures are required. The peak at the sensitivity function for the rotating system is caused by the synchronous unbalance oscillation. However, this peak is an error of the sensitivity function, because it is not considered in the FFT (Fast Fourier Transformation) of the input signal.

6. CONCLUSIONS

This paper describes a novel structure and method for a selfsening magnetic bearing. The proposed method uses the current slopes caused by the PWM voltage pulses for estimation of the position. Therefore a method was developed, which ensures that the duty cycle is always higher than zero. In contrast to the state of the art modulation approaches, the proposed technique measures the current slope directly using an induction ring. The induction ring measures the difference of two opposite bearing slopes. This fact increases the estimation sensitivity and reduces the impact of the leakage flux. The magnetic bearing itself is designed in a homopolar way, where the bias magnetisation is provided by permanent magnets. Thus, the structure shows a almost linear behavior. The experimental results show that the proposed method provides a sensitivity function which full-fills the requirements for long term running industrial applications.

7. References

References

G. Schweitzer, Magnetic Bearings: Theory, Design, and Applications to Rotating Machinery, Springer Berlin, 2009.

M. Hofer, Design and Sensorless Position Control of a Permanent Magnet Biased Radial Active Magnetic Bearing, PhD thesis, Vienna, 2013.

T. Nenning, M. Hofer, M. Hutterer and M. Schrödl, Setup with two Self-Sensing Magnetic Bearings using Differential 3-active INFORM, 14th International Symposium on Magnetics Bearings, Linz, 2014.

T. Nenning, Comparison of current slope based position estimation of magnetic bearing systems (written in german), PhD thesis, Vienna, 2013.

M. Hofer, P. Ebermann and M. Schrödl, Fully position sensorless control of a magnetically levitated reluctance synchronous machine by three-phase active magnetic bearing, IEEE International Symposium for Electrical Drives, Sydney, 2015

N. Morse, R. Smith, B.Paden, and J. Antaki. Position sensed and self-sensing magnetic bearing configuration and associated robustness limitations. IEEE Conference on Decision and Control, 1998

E. Maslen, D.Montie and T. Iwasaki. Robustness of Selfsensing Magnetic Bearings using Amplifier Switching Ripple, Ninth International Symposium on Magnetic Bearings, Lexington 2004

A. Schammass, R. Herzog, P. Bühler and H. Bleuler, New results for Self-Sensing Active Magnetic Bearings Using Modulation Approach, IEEE Transaction on Control Systems Technology, Vol. 13, No.4, 2005

M. Schrödl, Sensorless Control of AC Machines at Low Speed and Standstill Based on the INFORM Method, IEEE Industry Application Conference, San Diego 1996.