DESIGN OF A LOW COST ACTIVE MAGNETIC BEARING

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ABSTRACT

An alternative design of a low cost magnetic bearing is presented in this paper. The main components are originaly used for electronic drives. The digital controller is realized with a DSP-controller, the power amplifier uses 3-phase IGBT modules. The reflective position sensors are designed for consumer applications. A special attention is paid on the magnetic core which is realized with 3 phase motor laminations. Advantages and disadvantages of these laminations are discussed. A method to calculate the losses is presented. Different winding schemes are discussed.

BASIC CONCEPT OF THE LOW COST MAGNETIC BEARING

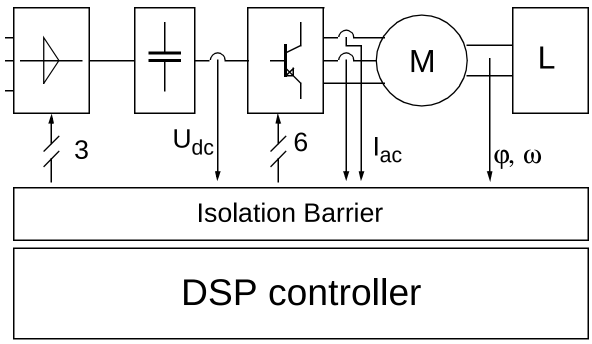

FIGURE 1: Block diagram of an electronic AC drive

The basic idea of this concept is to realize a complete model range for different load capacities and force dynamics by using standard components. A comparison of the block diagram of an electronic drive (fig. 1) with one of Active Magnetic Bearing (fig. 2) shows the affinity of both systems. Many components and techniques used for the industrial production of electronic drive trains can be used to realize low cost magnetic bearings. The rectifier together with an energy storage element generates a DC voltage. In some cases this DC voltage is controlled by 3 PWM outputs of the controller. 6 PWM outputs are needed to generate a 3 phase voltage. Two or three motor currents are measured and controlled. Speed and position of the load are controlled using sensor signals. However, there is enough performance for sensorless control with speed and position estimators.

The used controller hardware was originally designed for power converters. The acceptances and necessity of power converters for industrial applications as well as for consumer applications has increased rapidly.
To satisfy the requirements of the market, some manu-

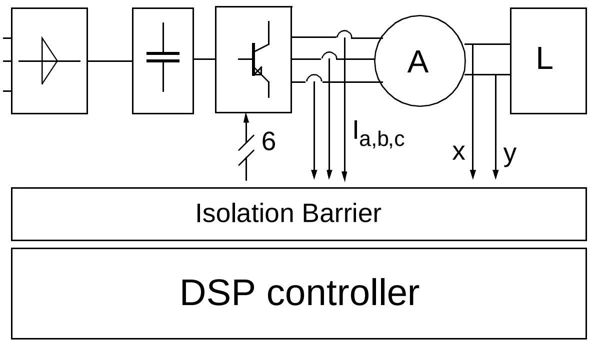

FIGURE 2: Block diagram of a 3 phase active magnetic bearing

facturers of semiconductors have developed high integrated devices, called DSP-controller who combine the integrability of micro controllers and the performance of digital signal processors. *Texas Instruments* was one of the first manufacturers of these controllers. Some main features of the selected TMS 320F240 are the 20MIPS fixed-point 16 bit CPU, on chip 16k flash ROM and the 544 words RAM and dual 10 bit ADC as well as 12 PWM channels. As fig. 1 shows, there is no need for a DAC device. The current is directly controlled by the PWM channels. Experiments with different actuators pointed out that the resolution of the PWM becomes to small if the inductivity of the magnetic circuit decreases. The dynamic of the magnetic circuit of an AMB is dominated by the first term of equation (1). The second term, describing the induction due to motion, dominates the dynamic of a motor at higher speeds. It is very small for magnetic bearings.The last therm caused by non linearity is small for AMBs.

$$E = \frac{d\Psi}{dt} = \frac{di}{dt}L(x,\ i) + i\left\{\frac{\partial}{\partial x}L(x,\ i)\cdot\ \frac{\partial x}{\partial t} + \frac{\partial}{\partial i}L(x,\ i)\cdot\ \frac{\partial i}{\partial t}\right\} \quad \textbf{(1)}$$

Thus, the resolution is good enough for electronic drives but an analog current controller has to be implemented, which is driven by an external DAC.
The idea of using power converters has already been presented some years ago. In [2] the authors describe a design using one 3 phase converter for an AMB without any modification. The presented low cost concept only uses the main components like rectifiers and power switches instead of the whole converter.
The power rectifiers are offered in a wide voltage and current range. Some are offered as modules with 4 diodes for single phase AC voltage or 6 diodes for 3 phases.

FIGURE 3: Stator windings of an 3 phase motor

Power switches can be realized in different techniques, depending on power and voltage range and the desired switching frequency. The Insulated Gate Bipolar Transistors (IGBT), which combines the advantages of field effect and bipolar transistors, has become more and more important in the last years. Switching frequencies of some 10kHz are not a problem any longer and costs have been cut down. As well as the rectifiers they are offered in modules with six transistors. A further development which offers a large scale integration is called intelligent IGBT module. Drivers and protection electronic for the transistors is integrated in this modules. Together with an isolation barrier to prevent destruction which can be realized by opto electronic couplers, these modules can directly be connected to the PWM outputs of the DSP controller.

STATOR LAMINATIONS

The stator laminations of the electromagnetic actuator can be realized with motor laminations. In [1] the authors present a design using rotor laminations of a DC motor. The preferred laminations for this solution are the stator laminations of 3 phase motors. Figure 3 shows the stator of such a motor with high pole number. .

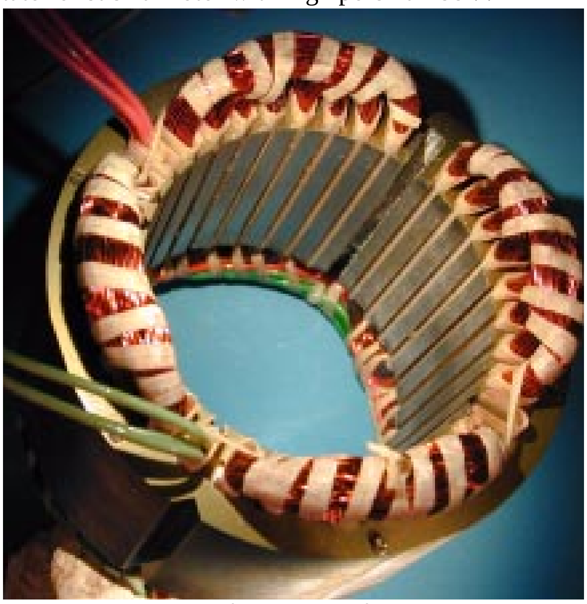

FIGURE 4: Picture of the stator of a 4 phase AMB

Figure 4 shows the laminations of a 3 phase AMB with IEC 6-8.70 laminations. The main advantage of these laminations is the wide range of size (outer diameter from 25 mm to more than 600 mm at various length), the standardisation and the low price. The price for an actuator with conventional laminations (two „U‘s“ per pole) with an outer diameter of about 200mm and a length of 50mm is 40 times as much as the price for the punched 3 phase motor laminations same size. Of course, the price for the conventional punched laminations would be as low as the 3 phase motor laminations but the cost for the

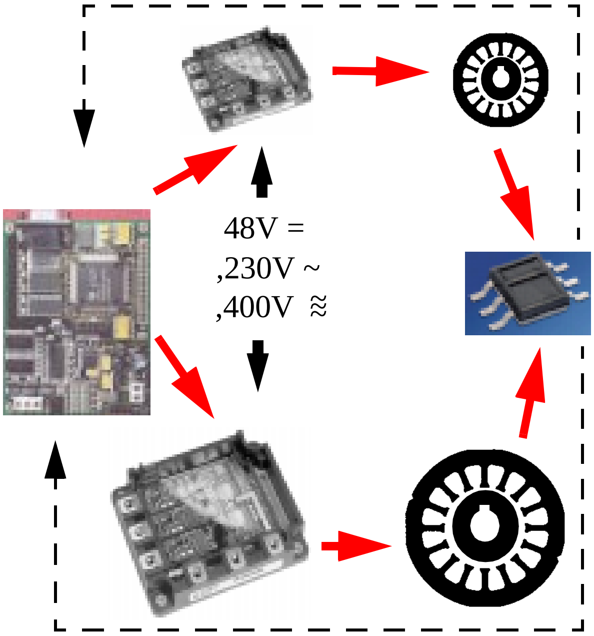

FIGURE 5: Modular concept of the low-cost bearing

punching tools are very high. Punching technology is only interesting for large quantities. 3 phase motor laminations are an alternative concept for batch production or prototypes because of the easy availability at low prices. Maybe there will be standardized laminations for switched reluctance motors in the future, which could be a better choice

ROTOR LAMINATIONS

The rotor laminations can neither be used from AC nor from DC or SR motors. All these laminations have sluts in different shapes. Round sections, originally made for single groove process, are also standardized and available in all corresponding stator diameters. The air gap between rotor and stator laminations is nearly zero. The desired air gap can be realized with a lathe or by grinding the laminations after assembling the shaft.

The standard material for 3 phase motor laminations is called V800-50. This is a synonym for silicon iron where 50 represents the thickness of the lamination in hundredth of a millimetre. The number after the V represents the core losses at a sinusoidal magnetic field with a frequency of 50 Hz and 1.5T. 800 means 8W/kg total core losses[1]. This material should be good enough for most of magnetic bearings applications. For heteropolar designs, a better material should be selected for the rotor laminations with regard of lower losses. For example V270-35 would be such a material. However, the reducing of losses is reached by reduction of the thickness and increasing the share of silicon [3]. This reduces the saturation flux density, because silicon is a non magnetic material.

The way of winding the coils and put them into the slots is the same for magnetic bearings and motors. Thus it is easy to find a manufacturer for the windings although only one or two stators are needed. The only difference are the narrow winding pitches for heteropolar magnetic bearings. The winding pitch is the number of slots surrounded by one winding. Winding pitches smaller than 4 should be avoided. Otherwise the end windings become very large. The narrow winding pitches cause slightly longer production times as for homopolar or 3 phase motors. The isolation classifications for the windings can also be used for most AMB applications. The most common maximum temperatures are 155 °C or 180°C.

CURRENT AND POSITION SENSOR

As fig. 2 shows, there are some sensors needed for the low cost bearing. Current sensors are used in power converters also. As power converters, the power amplifier for the AMB can work with DC voltages of 600 volts. In most application, the DC voltage is set to 325V or less to get lower noise levels. Low cost hall element current compensation transformers with a cut-off frequency of 30kHz are selected. The current range is switchable from 10A to 20 A. Ranges from 5A up to 60A are offered in the same package.

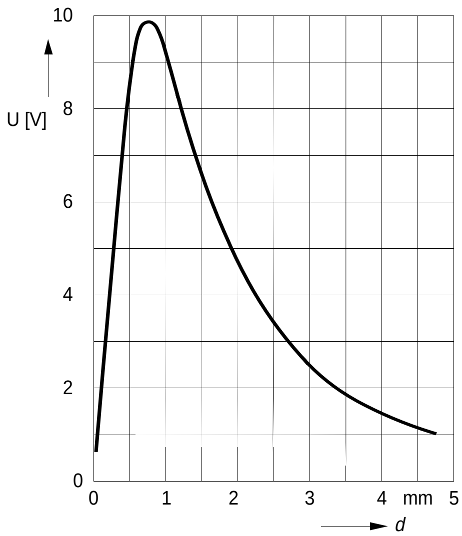

FIGURE 6: Output voltage versus distance

A typical application of the reflective interrupter position sensor is speed monitoring and regulation. If the maximum displacement of the rotor is smaller than 0.6mm, the sensor offers a nearly linear signal. For larger displacement, the right section of the curve shown

1. In [3], the authors introduce correction values for other waveforms.

in fig. 6 should be used. Differential signal processing of at least two sensors offers good linearization for displacements of 2 mm or larger and compensation of the temperature drift. The cut-off frequencies of the infrared Ga-As design are higher than 20kHz.

There are two problems using these sensors as displacement sensors in AMBs. The temperature operating range is rather low. The used design can operate between -40 and +85 °C. As fig. 7 shows, the sensor is directly integrated in the stator core to minimize the core to offer minimal mounting cost and colloncation. However, this means that the sensor temperature will nearly reach the final stator temperature.

The main problem are the high frequency noises generated by the optical non-homogeneity of the rotors surface when the rotor turns. An optical non-homogenous surface is detected as a displacement of the rotor. Figure 7 also shows, that there is not a single sensor but 3 or 5 in axial position. Thus, a mean value of the position is measured. Coating the rotor also reduces the noise level. Beyond it, a low order high pass filter improves signal quality.

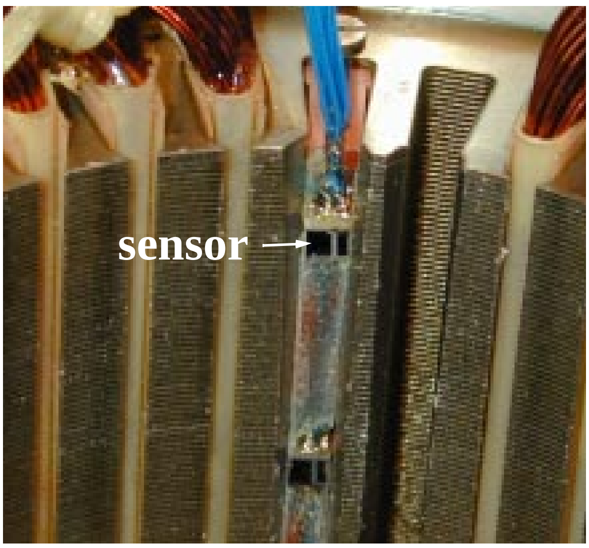

FIGURE 7: Implementation of the position sensors in a slot

ADVANTAGES OF THE IRON STATOR CORE

Laminations of a 3 phase motors allow different designs of AMBs. It is possible to realize heteropolar as well as homopolar bearings. Homopolar and heteropolar bearings using permanent magnets for magnetic bias and static force compensation based on ac motor laminations are described in [6]. As fig. 3 and fig. 4 show, it is possible to built 3 or 4 phase bearings as well as 6 or 8 pole systems with the same stator core. If a pole separation is not needed, 3 or 6 resp. 4 or 8 can be realized with one

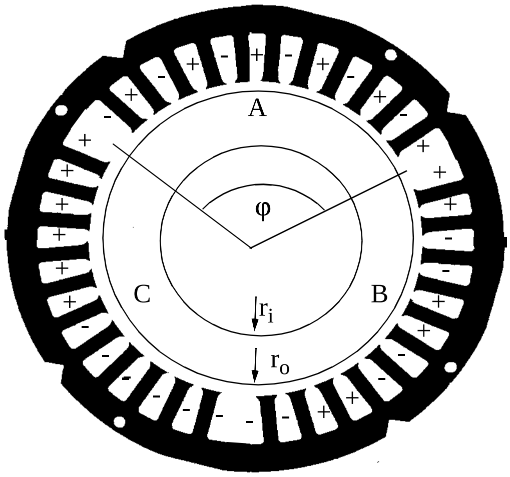

FIGURE 8: Possibleble winding shemes for a 3-pole AMB with IEC 80/6-8.80

switchable winding. It is also possible, to enlarge one pole of an axis, decreasing the other one, to offer higher lifting capability in one direction. A redundant design is also possible with the same laminations. Figure 10 shows the magnetic field of a 4 pole design. If separate windings are used to generate this field, there is still a resulting force if one ore two flux pathes are faulty.

As already mentioned, 3 phase IGBT- modules are used in the power amplifiers. The 4 pole arrangement can be realized with three power amplifiers, if one bias coil is used for all poles and an opposite winding direction of the control coils. If the coupling due to the flux linking is unacceptable, two modules are needed. In the following, some special effects of this kind of laminations are discussed.

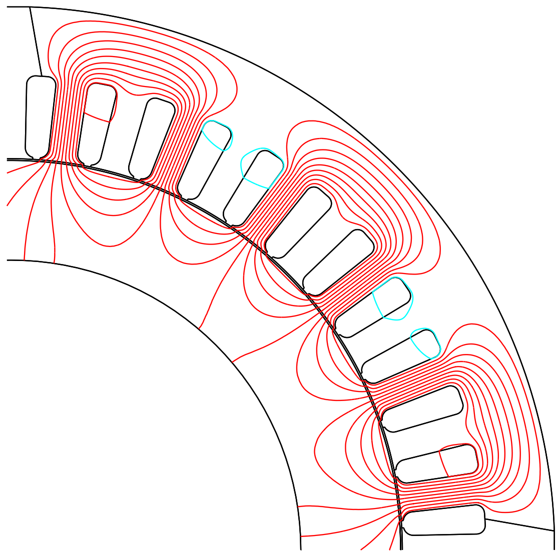

FIGURE 10: Three independent flux pathes of a 4 pole design

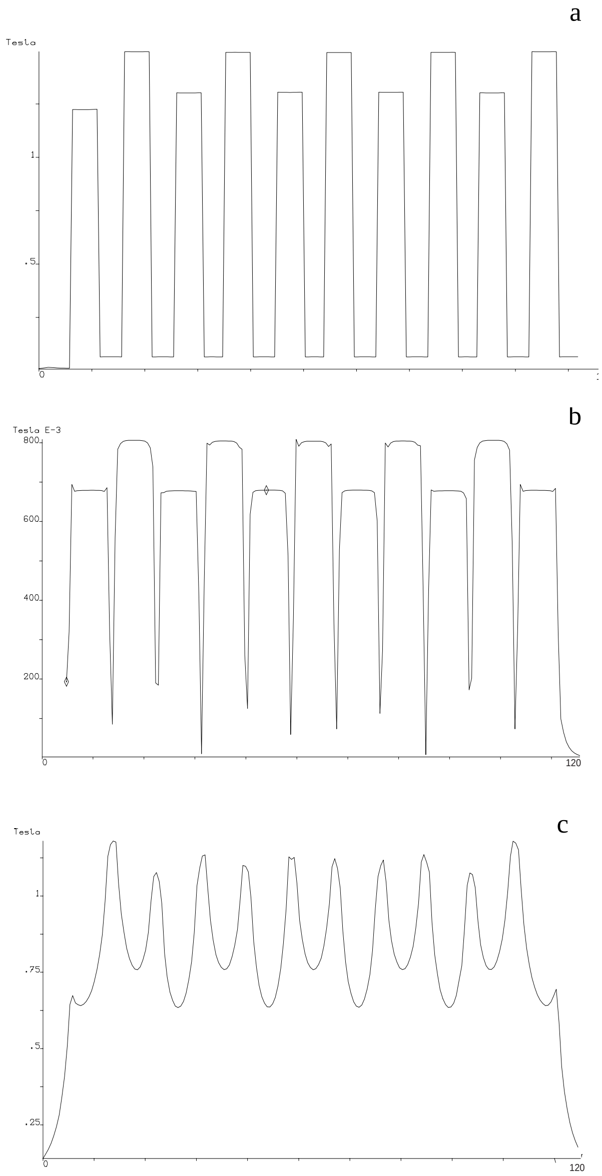

FIGURE 11: Value of the flux density in the middle of the stator slot (a), in the middle of the air gap, nominal position (b), 1mm below rotor surface (c)

MAGNETIC LOSSES IN THE ROTOR

Figure 8 shows different possible winding schemes for a 3 phase design.

In sector *A*, the direction of winding changes in every slot.Figure 11 shows the value lux density of *A*. In *B* it changes every two slots and in *C*, only one change of polarity is realized. All designs offer different forces and losses. In [4] and [8] the authors give a formula for the calculation of eddy current and hysteresis losses in thin[1] laminations as following.

$$P_e = c_e B^2 f^2 V \quad \textbf{(2)}$$

$$P_h = c_h f B^{1,6} V \quad \textbf{(3)}$$

where c_e and c_h are constants for geometry and material, *B* is the amplitude and *f* the frequency of the flux density, and *V* the volume of the iron. The influence of the magnetic field generated from the eddy currents themselves is neglected.

The flux density in the rotor is not constant in the whole volume. Beyond it, there are higher harmonics in the flux density. In [5], the authors show that some other constants can be introduced to minimize these influences. However these factors depend on the geometry and can not be used for motor laminations. When using motor laminations, the calculation becomes more difficult, because number and shapes of the poles differs. Thus, more correction factors are needed. If these factors are unknown, a calculation is possible with a time intensive transient finite element calculation of the magnetic circuit. Less precise is the calculation with the help of the static field distribution. If the maximum flux density is known for each radius of the rotor as shown in the eddy current losses are calculated by

$$P_e = \int_{r_i}^{r_o} \pi^3 l r \frac{\sigma \tau^2}{6} (B_{m(r)} f)^2 dr \quad \textbf{(4)}$$

$$P_h = k_h \cdot \int_{r_i}^{r_o} \pi l r f \cdot B^2_{m(r)} dr \quad \textbf{(5)}$$

l is lth axial length and r the radius of the rotor, τ the thickness of the laminations, ρ the specific conductivity of the material.

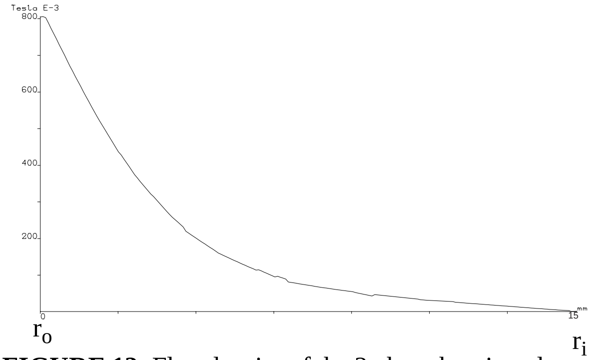

FIGURE 12: Flux density of the 3 phase bearing along the radius of the rotor (ro..ri)

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1. Thickness much more smaller than the penetration depth

The maximum flux density for sheme *A* is shown in fig. 12.The formulas will be verified in experiment and transient field calculation soon. Figure 13 compares the losses calculated with (4) and (5). Although the frequency in *A* is double as much as in *B*, the losses are less than twice as much. Due to the higher penetration depth of the flux in scheme *C* and the higher maximum flux density, the losses are not as low as expected

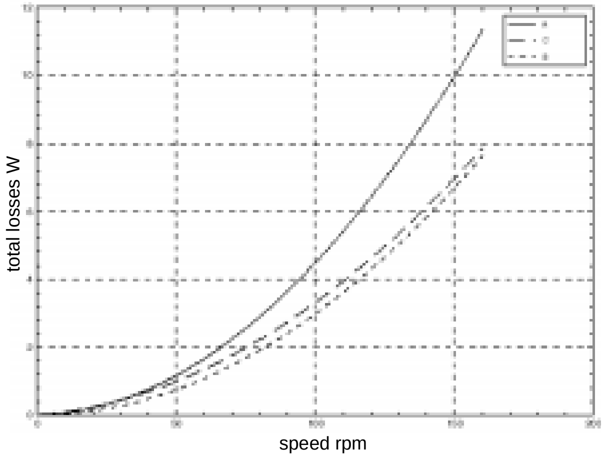

FIGURE 13: Total looses versus speed

FORCES

When electromagnetic actuators have to be designed, normally it is an iterative process to find out the optimum relation between the cross-section of iron and copper.

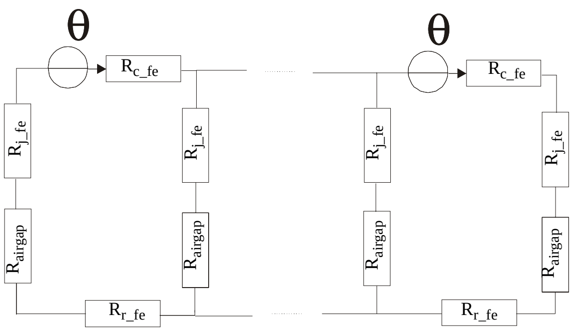

FIGURE 14: Simplified equivalent circuit diagram for two of 6 windings of scheme A in fig. 8

If the iron cross section is to small, saturation will appear, if there is to little winding space, the windings become to hot. There are some publications of design rules to optimize this relation for „u-shaped“ magnetic bearings. The advantage of 3 phase laminations is, that they already have an optimal design from this point of view. However, most of the 3 phase motors have a fan to cool the windings. Thus, a higher current density is possible in the windings. The cross section of iron is to large for AMBs. With a current density of 5 - 6 A/mm^2, typically 1.4 T are reached in the iron core, if the air gap is the same as it is for the accompanying 3 phase motor. Because of the „shoes“, this flux density is reduced to about 1.1 T in the air gap. Flux scattering can not be neglected. Thus, a first estimation of forces is possible.

A higher accuracy of force calculation is possible by solving the equations of the equivalent circuit. Because of the asymmetry in case of a centric rotor, the equivalent circuit can be solved easily..

TABLE 1: Force of one pole of IEC160/8.170 (Da=240mm, Di=160mm, ls=0.5mm, J=5A/mm^2)

Scheme	A	B	C
FE-calculation	6657 N	10245 N	13317
Network-calculation	7100	11340	14450

CONCLUSION

An alternative design of a low cost magnetic bearing is presented in this paper. The main components are originaly used for electronic drives. The digital controller is realized with a DSP-controller, the power amplifier uses 3-phase IGBT modules. The reflective position sensors are designed for consumer applications. A special attention is paid on the magnetic core which is realized with 3 phase motor laminations.

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