RADIAL ACTIVE MAGNETIC BEARING FOR OPERATION WITH A 3-PHASE POWER CONVERTER

Reto Schöb
Sulzer Electronics AG
Winterthur, Switzerland

Christian Redemann
Laboratory for Electrical Engineering Design (EEK)
Swiss Federal Institute of Technology
Zürich Switzerland

Thomas Gempp
Laboratory for Electrical Engineering Design (EEK)
Swiss Federal Institute of Technology
Zürich Switzerland

SUMMARY

In order to reduce costs, radial active magnetic bearings have been proposed which are formed by only three electromagnets. Unfortunately it is not possible to operate the three coils with a 3-phase power converter, since the sum of the coil currents does not equal zero. Three independent amplifier channels are needed for the control of this arrangement. In this paper, a radial magnetic bearing is proposed which can be operated by commercial 3-phase power amplifiers. By the use of an arrangement of bias coils, it is possible to make the sum of the three currents become zero. Some problems related to this bearing arrangement as well as their solutions are discussed and shown using the example of two prototype bearings.

MOTIVATION

In a radial active magnetic bearing, usually four independent electromagnets are arranged around the rotor. They are operated either by four unipolar power amplifiers or by two bipolar amplifiers. A simplification can be achieved by the arrangement of only 3 electromagnets. Such arrangements have been shown for example in [1] and [2]. In this case still three independent unipolar power amplifiers are needed for the control of one radial bearing. Unfortunately, it is not possible to operate the three coils with a 3-phase power converter. However, it would be very attractive to operate magnetic bearings with 3-phase power converters, mainly because of two reasons:

- 3-phase converters are used in huge quantities for electrical drives and are therefore available at very low prices. Today they are even cheaper than dc power amplifiers.
- Modern 3-phase servo amplifiers incorporate high performance digital processors like signal processors. These processors would offer enough calculation power for the control of active magnetic bearings. This means that a 3-phase servo amplifier could be easily transformed into a magnetic bearing controller merely by exchanging software.

THE NEW APPROACH

In this paper, a radial magnetic bearing is suggested which can be operated by 3-phase power amplifiers. Its basic principle is shown in figure 1. Figure 2 shows how the coils are connected to a 3-phase power converter.

There is one major point which has to be considered with the implementation of the bearing by using a 3-phase power converter. In a 3-phase system, the sum of the phase currents must equal zero. This is the case whether the winding coils are connected either in a star configuration with a floating start point or in a triangular configuration. It means that only two out of the three phase currents (i_u, i_v, i_w in figure 1) can be independently controlled. The third phase current equals the negative sum of the two others. At first glance this seems to be no problem for the radial bearing, since only two degrees of freedom should be controlled.

The equation system which shows the relationship between the magnet forces (F_u, F_v, F_w) and the resulting forces in the two directions x and y (F_x, F_y) is undetermined:

$$F_x = F_u - \frac{1}{2} F_v - \frac{1}{2} F_w \quad (1)$$

$$F_y = \frac{\sqrt{3}}{2} F_v - \frac{\sqrt{3}}{2} F_w \quad (2)$$

A further condition is possible, for example that the sum of all magnetic forces equals zero. If the magnetic forces were proportional to the winding currents, the bearing could easily be operated as a 3-phase system. However, this would mean that the electromagnets can generate attractive forces as well as repulsive forces, depending on the sign of the current. But since the magnetic forces are proportional to the power of two to the winding current, only attractive forces can be generated. A better idea is to let the sum of all magnetic forces and therefore the sum of the winding currents equal a constant, positive value. However, in this case the currents no longer form a 3-phase system and the windings cannot be driven by a 3-phase power converter.

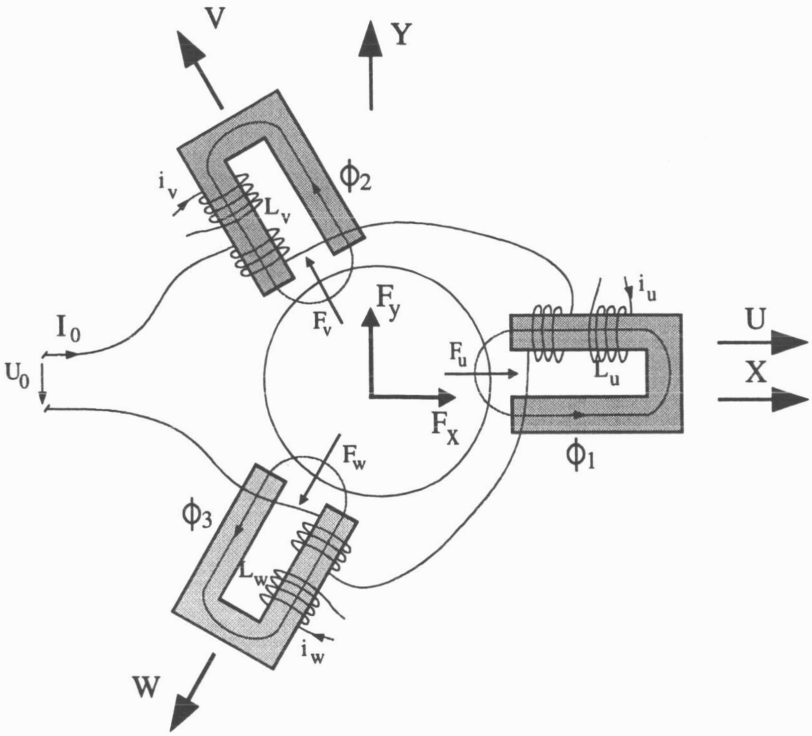

Figure 1. Functional principle of the radial magnetic bearing for 3-phase operation

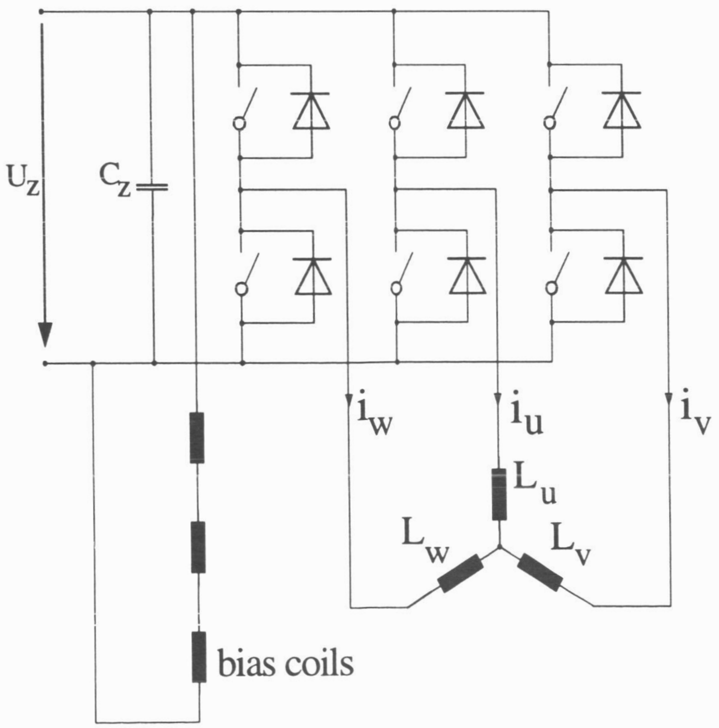

Figure 2. Connection of the bearing coils to the 3-phase power converter

The idea is now to generate a constant magnetomotive force in all of the three electromagnets by separate premagnetization coils which are connected in series directly to the dc link (see figures 1 and 2). The linearized equations for the magnet forces are then:

$$F_u = k\,(i_u + i_0) \tag{3}$$

$$F_v = k\,(i_v + i_0) \tag{4}$$

$$F_w = k\,(i_w + i_0) \tag{5}$$

If these equations are inserted in equations 1 and 2, it can be seen that the premagnetization current i_o disappears in the resulting force formulas.

$$\begin{aligned} F_x &= k\,((i_u + i_0) - \frac{1}{2}(i_v + i_0) - \frac{1}{2}(i_w + i_0)) \\ &= k\,(i_u - \frac{1}{2} i_v - \frac{1}{2} i_w) \end{aligned} \tag{6}$$

$$\begin{aligned} F_y &= k\frac{\sqrt{3}}{2}(i_v + i_0) - k\frac{\sqrt{3}}{2}(i_w + i_0) \\ &= k\frac{\sqrt{3}}{2} i_v - k\frac{\sqrt{3}}{2} i_w \end{aligned} \tag{7}$$

Now, the condition for a 3-phase system is applicable.

$$i_u + i_v + i_w = 0 \tag{8}$$

With equations 6, 7 and 8, the equations for the three phase currents with the forces F_x and F_y as parameters can be evaluated:

$$i_u = \frac{2}{3k} F_x \tag{9}$$

$$i_v = \frac{1}{3k}(-F_x + \sqrt{3}\,F_y) \tag{10}$$

$$i_w = \frac{1}{3k}(-F_x - \sqrt{3}\,F_y) \tag{11}$$

$$\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = \frac{2}{3k} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} F_x \\ F_y \end{bmatrix} \tag{12}$$

If the equation system is written in a matrix form (equation 12), it is obvious that the currents form a 3-phase system. They can be evaluated by a simple 2- to 3-phase transformation from the set-values (X_s and Y_s) of a position controller. The basic control scheme of the 3-phase bearing is shown in figure 3.

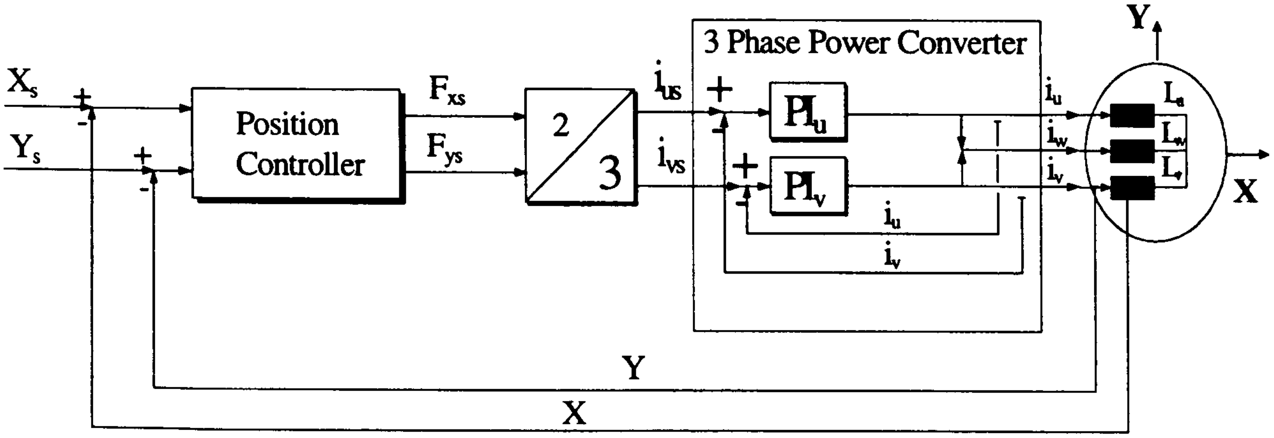

Figure 3. Control scheme of the 3-phase radial bearing

NONLINEARITY AND CROSS-COUPLING

The linear equations 6 and 7 are based on the assumption that the force changes are directly proportional to the changes in currents. However, this assumption is valid only for small changes of the current and as long as the rotor is placed in the center of the three electromagnets. In reality, the magnetic forces are proportional to the magnetomotive forces (which are dependent on the phase currents as well as on the premagnetization current) by the power of two. Also, they are inversely proportional to the power of two of the air gaps. These dependencies lead to a nonlinear behavior of the bearing forces for high currents as well as for large displacements of the rotor. Figure 4 shows the calculated displacement-force graph of a test bearing in X-direction. The figures 5 and 6 show current-force graphs of the same bearing for two different premagnetization currents and for several rotor positions. Effects of magnetic material saturation are not considered in these calculations. The graphs show that the linearity of the bearing becomes better with a higher premagnetization current, and worse with a rise of the displacement and the control current.

There are similar nonlinearities in all active magnetic bearings. A robust controller can handle them without problems. Several methods to compensate these nonlinearities have been proposed for example in [3] and [4]. However there are two differences between the behavior of 4-phase bearings and the discussed prototype bearing. One difference is the strong asymmetry related to the displacement as well as to the control current which are shown in the X-direction (Figures 4-6). However a robust controller can deal even with these asymmetries as long as there is no change of sign of the forces as shown in figure 5. Figures 7 and 8 show the displacement-force graphs and the current-force graphs of the prototype bearing in the Y-direction. What might be at first surprising is the fact that these graphs are perfectly symmetrical. They are fully comparable to a 4-phase bearing. The behavior of the bearing is completely different in the X-direction and in the Y-direction and it is much easier to find a stable controller for the Y-direction than for the X-direction. However, the asymmetry of the system could be easily compensated by nonlinear compensation with a look-up table.

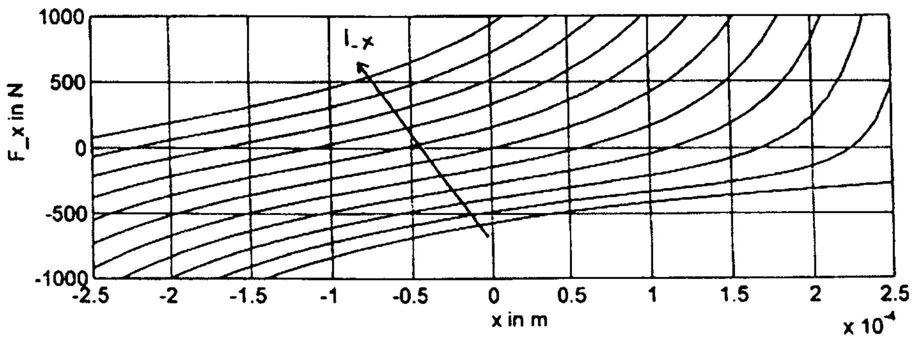

Figure 4. Calculated displacement-force graph of test bearing in X-direction

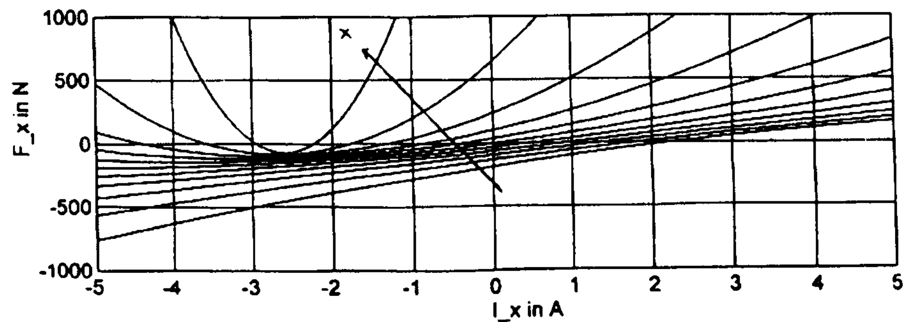

Figure 5. Current-force graph of test bearing in X-direction for premagnetization current of 3 A

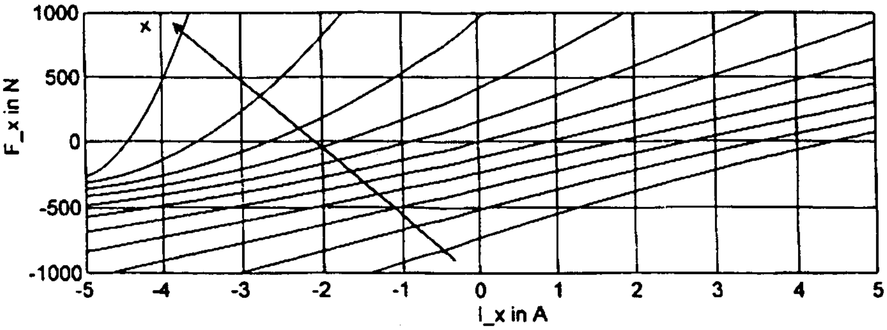

Figure 6. Current-force graph of test bearing in X-direction for premagnetization current of 6 A

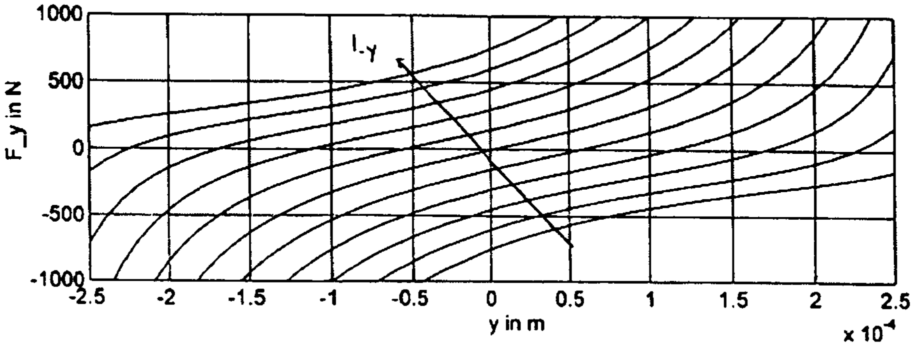

Figure 7. Displacement-force graph of test bearing in Y-direction

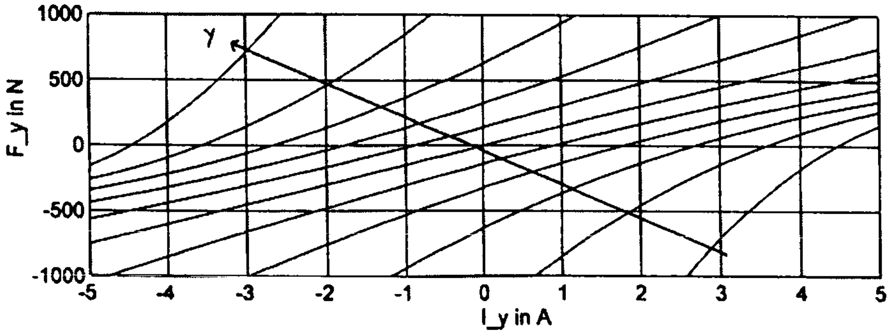

Figure 8. Current-force graph of test bearing in Y-direction

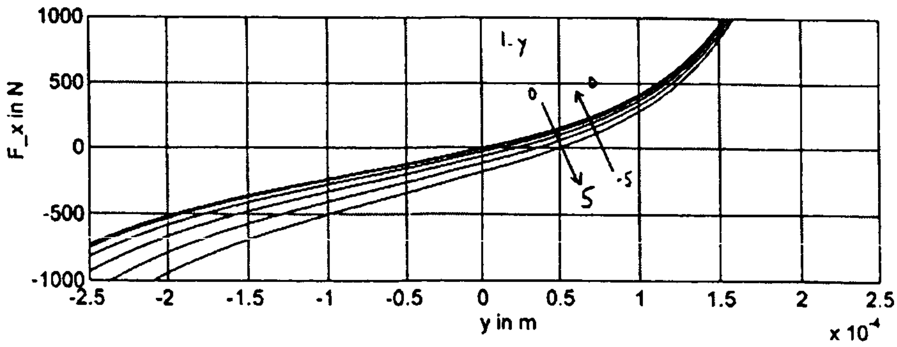

Figure 9. Cross-coupling from Y-current and Y-displacement to force in X-direction

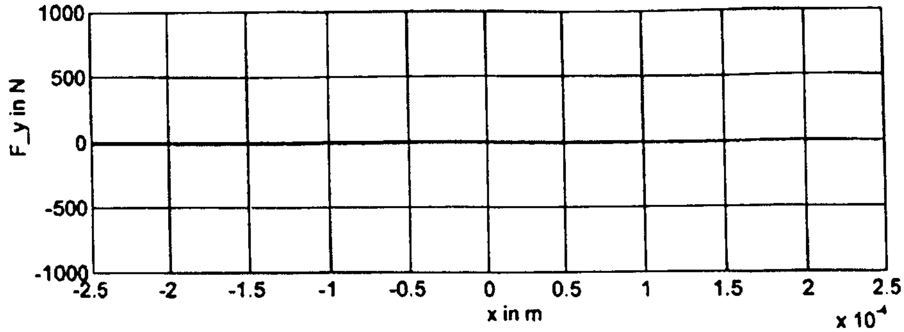

Figure 10. Cross-coupling from X-current and X-displacement to force in Y-direction

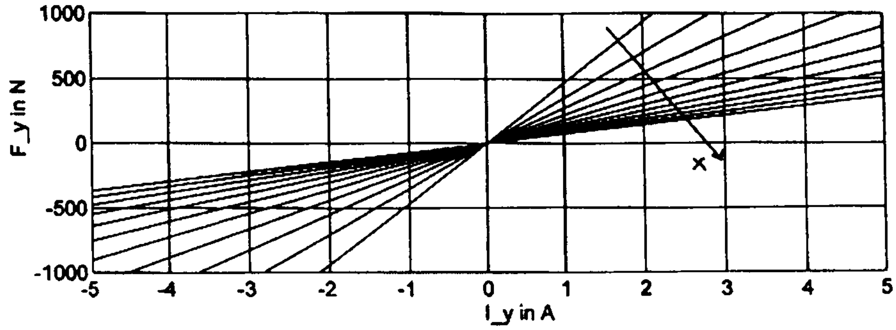

Figure 11. Dependence of current-force graphs in Y direction on X-current and X-displacement

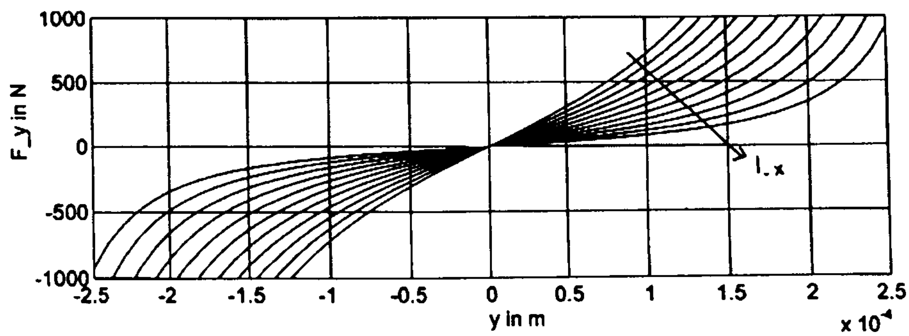

Figure 12. Dependence of displacement-force graphs in Y-direction on X-current and X-displacement

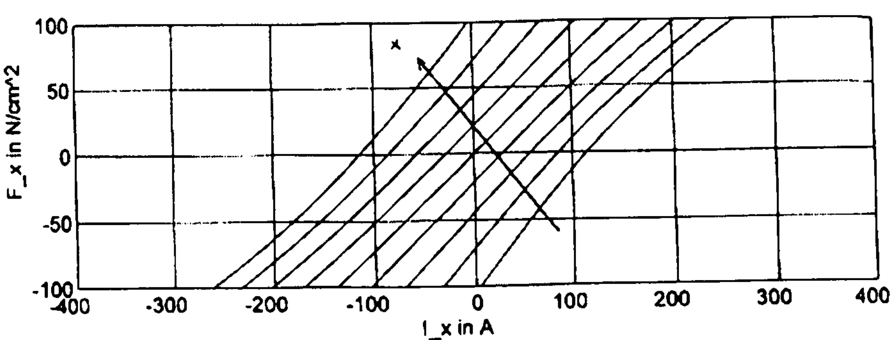

Figure 13. Calculated current-force graph for 3-phase/12-pole radial bearing

The main problem with the discussed arrangement is the fact that its asymmetry also leads to cross-coupling between the two bearing axes. Figure 9 shows the forces of the bearing in X-direction as a function of the displacement and the control current in Y-direction. In a symmetrical arrangement (4-phase bearing) without cross-coupling the force in X-direction would be fully independent of changes of control current and position in Y-direction. This means it would remain zero. Figure 9 shows however a high dependence mainly on the rotor position. There is no cross-coupling from X-axis to Y-axis as long as there is no Y-current or displacement (figure 10). However, there is an influence on the current-force slope k_{iy} as well as on the displacement-force slope k_{sy} which can be seen in figures 11 and 12.

The reason for the strong cross-coupling is the wrong assumption of a linear dependence between the magnetic forces in the electromagnets and the related control currents on which our model and the 3-2-phase transformation were based. For control of 4-phase bearings the same assumption is commonly made. But because of the geometrical symmetry of the magnet arrangement a nonlinearity does not lead to cross-coupling.

A simple solution for the problem would be an underlaid flux(force)-control of magnets. However, such a control scheme would require independent control of all three winding currents. It would not be compatible with a 3-phase system. A mathematical decoupling in a digital controller should be possible without the requirement of much calculation power by gain scheduling based on a look-up table. Here the drawback would be the necessity of a good knowledge of the system and a high sensitivity to parameter changes.

A 3-PHASE BEARING WITHOUT CROSS-COUPLING

A better solution to the problem of cross-coupling is the design of a symmetrical arrangement of the 3-phase system. One solution is the arrangement of six magnets around the rotor. In this case two opposite magnets are connected to the same phase of the 3-phase converter. The principle of this bearing is shown in figure 14. Figure 15 demonstrates a practical implementation of this bearing type in the form of a large outer rotor bearing. The load capacity of this bearing is 3000 N, the stator diameter is 350 mm and the air gap is 1.5 mm. Figure 13 displays the calculated current-force graph for this bearing. It is very linear and perfectly symmetrical to displacements. The 12-pole arrangement shows virtually no cross-coupling effects. For the large bearing the 12 poles are no disadvantage. However, for smaller bearings it would be an advantage to have fewer poles. Figure 16 shows a 6-pole bearing with a 3-phase winding and low cross-coupling. This type of bearing was designed and tested for the support of a linear slider (figure 17).

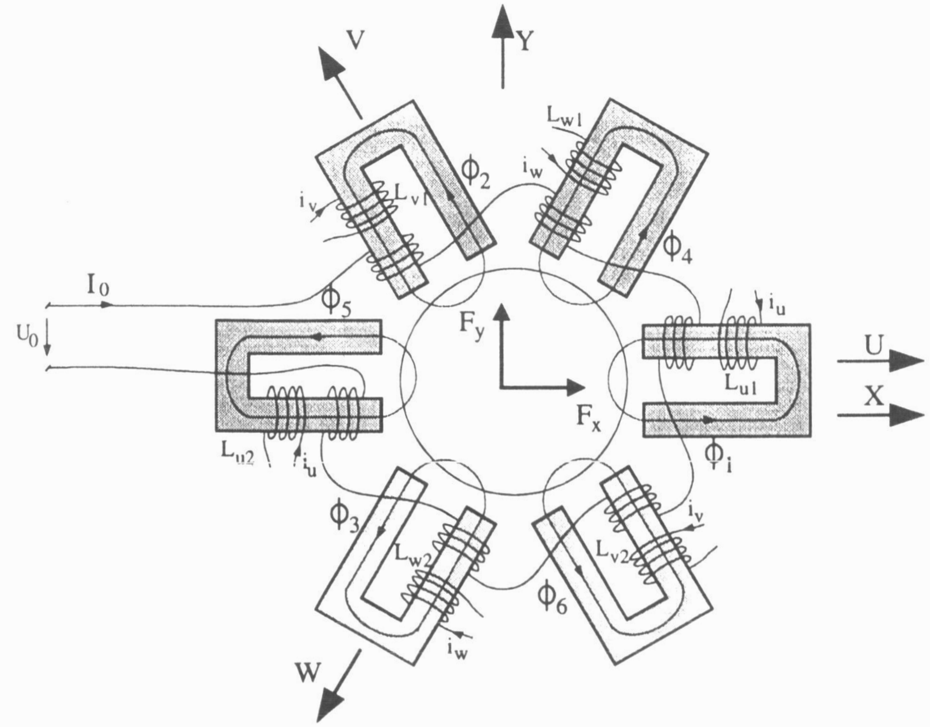

Figure 14. 3-phase radial bearing with reduced cross-coupling (12-pole arrangement)

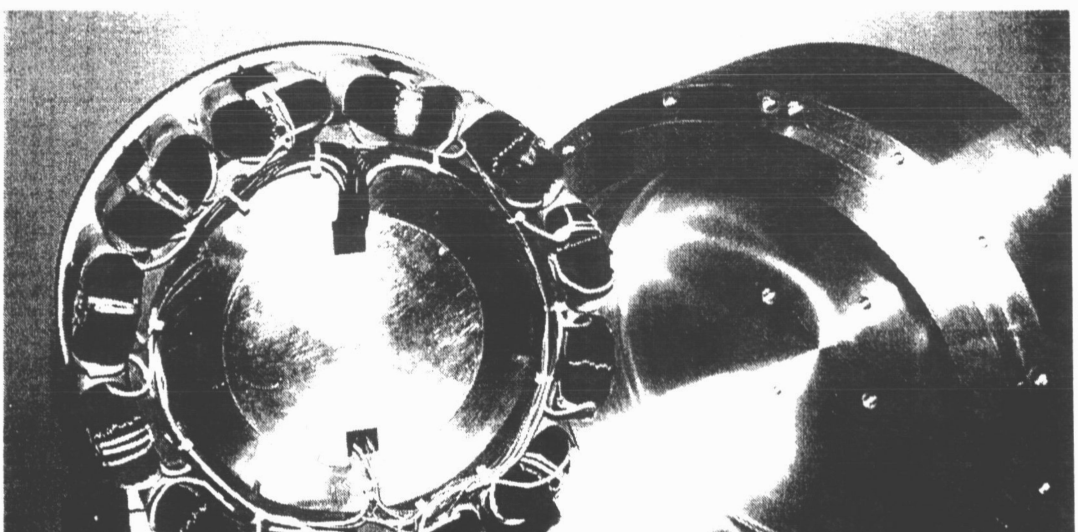

Figure 15. 3-phase/12-pole outer rotor type radial bearing with reduced cross-coupling

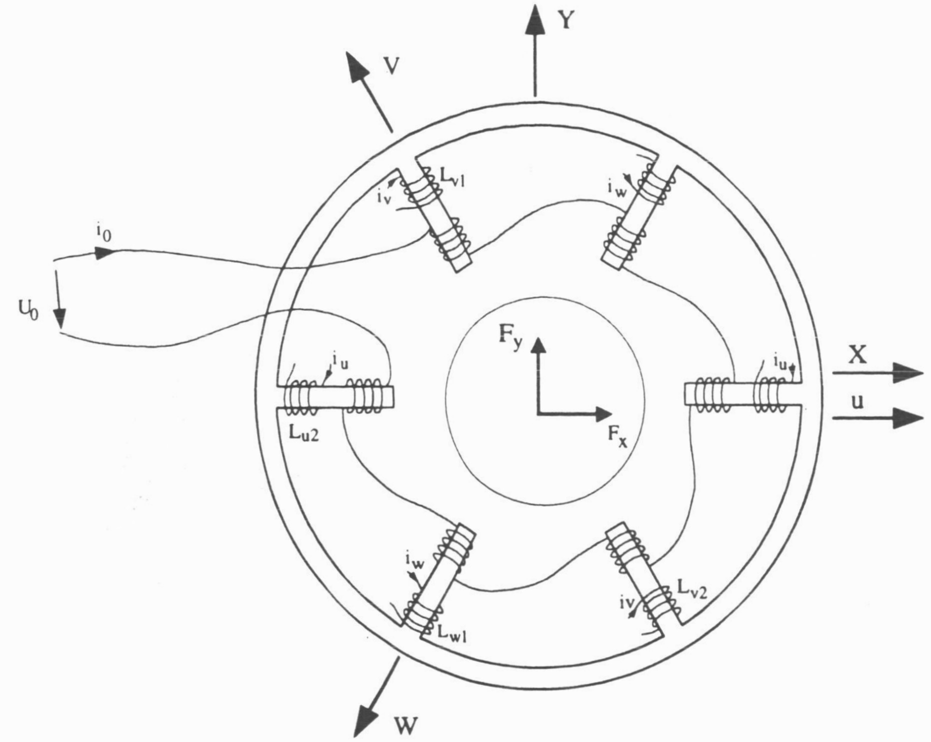

Figure 16. 3-phase radial bearing with reduced cross-coupling (6-pole arrangement)

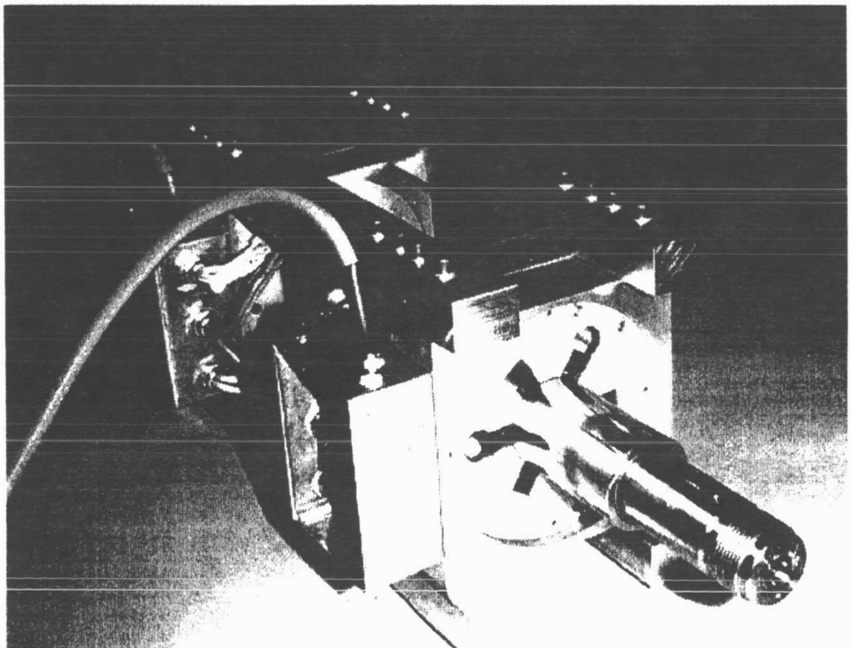

Figure 17. Linear slider supported by two 3-phase/6pole radial bearings

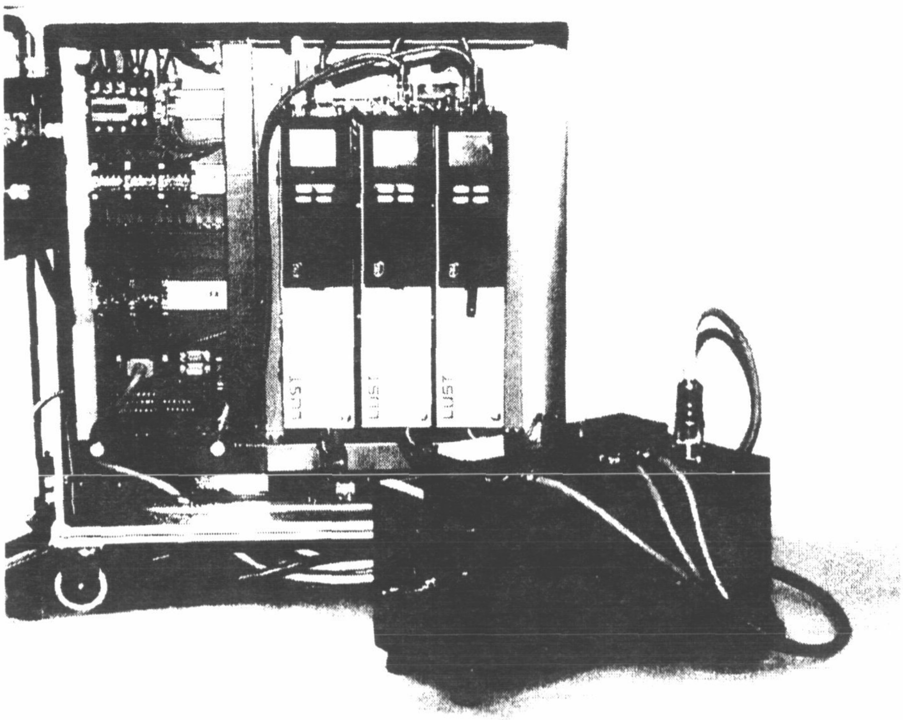

Figure 18. Magnetic bearing controller based on 3-phase servo amplifiers

CONTROL ELECTRONICS

Figure 18 shows a magnetic bearing controller for five spatial degrees of freedom. It is entirely based on commercial 3-phase servo amplifiers by LUST Drive Technology (MC7000 series). The only hardware modification of the 3kVA converters is an additional 2-channel sensor card (for the position sensing of the rotor) which is plugged into an extension slot. Everything else is accomplished by software. All control parameters are stored on a chip card and can be easily set. The controllers can exchange data by a high speed serial link. Several field bus interfaces are available for this system. The power range of the servo amplifiers starts at 1.4kVA and ends at 44 kVA.

ACKNOWLEDGEMENT

The project was supported by the Laboratory for Electrical Engineering Design (EEK) of the Swiss Federal Institute of Technology (ETH) in Zurich and the companies Sulzer Electronics AG., Winterthur (Switzerland) and Lust Antriebstechnik GmbH, Lahnau Germany.

REFERENCES

1. Ueyama, H.: EP O 612 928

2. Bühler, P. et al.: Digital Control for Low Cost Industrial AMB Applications, 5th Int. Symposium On Magnetic Bearings, Kanazawa, August 1996

3. Boeringer A.: DE 31 14 426 A1

4. Habermann, H.; and Brunet, M.: US 4,308,490