DEVELOPMENTS ON BEARINGLESS DRIVE TECHNOLOGY

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ABSTRACT

Meanwhile the bearingless motor technology offers a lot of mechanical and electrical design variants for various kinds of applications. A comparison of switched reluctance motor, asynchronous motor and permanent magnet motor technology shows advantages and disadvantages with regard to different technical requirements. Especially for small motor applications with large air gaps the permanent magnet motor is of great importance. This is confirmed by a comparison of electromagnetic and permanent-magnetic pole designs. Based on bearingless permanent magnet motors with integrated winding systems for levitation as well as torque generation reliability and fault-tolerant design studies are carried out. It is shown that with an appropriate motor design a failure of an arbitrary phase can be compensated by the motor itself. In such a case there is no need for failure detection in order to switch over to special auxiliary control algorithms. A further advantage of the integrated winding system is the high grade of copper utilization independent of the ratio of radial force and torque loads.

INTRODUCTION

Bearingless motors represent a very young motor technology. In the process of the ninetieth scientific researches increased in a considerable number of projects on international level /1/. Since that time a lot of technical progresses have been made in the development of bearingless motors which have led to the first industrial serial productions in the last years.

It has turned out that especially in the high-tech segment of the small motor market the bearingless motor technology can offer a technically and economically attractive alternative to conventional motor solutions. Particularly drive systems which require high quality standards concerning

- maintenance-free operation,
- long lifetime or
- sterile, pollution- and contamination-free transportation of fluids or gases

belong to the typical application areas of bearingless motors.

An essential prerequisite to the economical success in small motor applications will be - at least in the long term – a considerable reduction of production costs. Today, the mechanical part of the bearingless drive system together with the sensor and signal processor electronics are the main limiting cost factors for a fast spreading of this new technology.

In the co-operation of the 'Linz Center of Competence in Mechatronics' with the University of Linz and the industrial partner 'Levitronix GmbH' a lot of measures have been taken to bring the bearingless drive concepts more in line with the market requirements. Some of these developments and research results are presented in this paper.

SRM-, ASM- OR PMM - TECHNOLOGY?

As in conventional motor technologies all three of these bearingless motor principles have their legitimacy for small motor applications. But there are important restrictions which have to be regarded, when a selection is made.

The bearingless **Switched Reluctance Motor** is the most robust motor, especially appropriate for applications with high external impact or vibration forces, high temperatures or high mechanical or electrical overload conditions. As both the excitation and the armature fields are generated by the stator currents the air gap of such motors should be very small. Otherwise the reactive power of the motor will increase dramatically. For this reason the SRM is also well suited for and often used in bearingless micro systems. Figure 1 shows a torque-current diagram of the switched reluctance motor in comparison with a permanent magnet motor of approximately the same

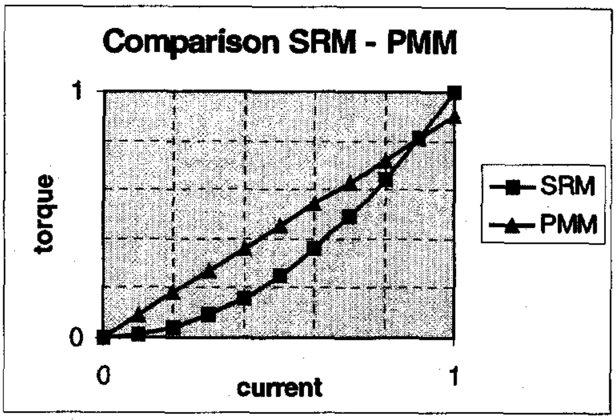

FIGURE 1: *Comparison of the torque characteristics of the bearingless switched reluctance motor and the permanent magnet motor*

nominal power. From the quadratic curve shape it becomes obvious that the SRM shows bad values in the part-load region and gets a better performance with increasing load. Another point which should be regarded in this context is the relatively high torque ripple in the commutation cycles. Therefore, in some torque-sensitive applications it may be necessary to apply special phase current shapes (s. Fig. 2) to reduce the disturbing torque ripple /2/.

In bearingless **<u>AS</u>ynchronous <u>M</u>otors** usually the torque ripple is not a relevant problem, especially when the winding slots of the rotor are skewed. But concerning the air gap similar construction rules as for the SRM have to be considered. Otherwise an increased reactive power consumption will significantly reduce the power factor of the bearingless machine. Pertaining to the torque performance it is possible to achieve linear characteristics comparable to synchronous machines if field oriented motor control is applied.

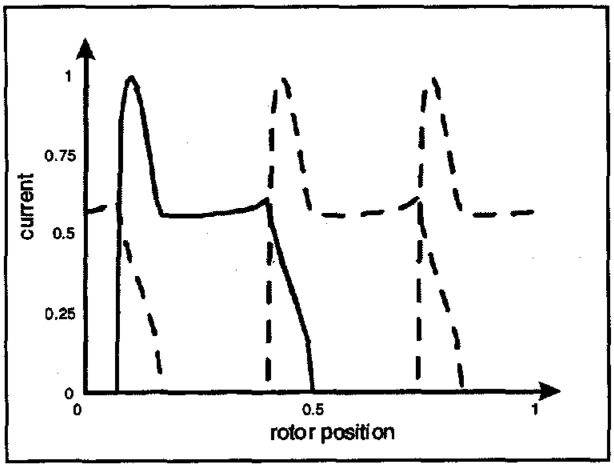

FIGURE 2: *Special angular dependent current curves for torque ripple reduction in SRM motors*

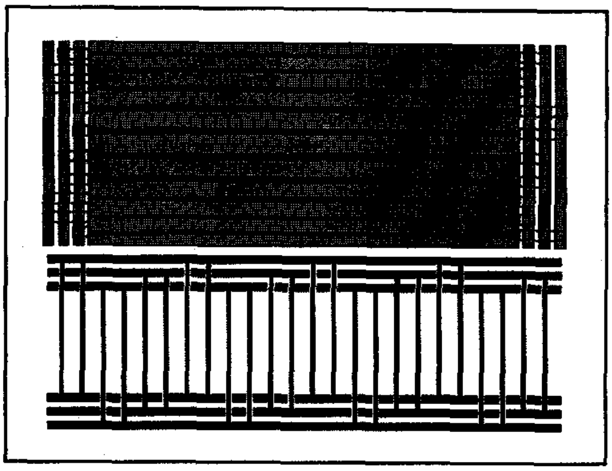

FIGURE 3: *Pole-selective winding scheme of a squirrel-cage rotor for bearingless motors with low interaction between motor and bearing operation*

Concerning the design of the rotor care has to be taken in the case of bearingless operation. With the generation of radial levitation forces additional voltages are induced in the rotating squirrel-cage rotor leading to disturbing eddy currents. Large brake torque values may be the result. To avoid this effect with bearingless asynchronous motors, special winding arrangements of the rotor are necessary /3/. An example for such a modified squirrel-cage rotor is shown in Figure 3. The n conductor bars are distributed to m phases, whereby each separate phase is connected on both sides to a cage ring which is isolated from the remaining rings. Due to the mechanically complex interconnecting in some cases the short-circuit coils are manufactured also in wound form. So far a technical low cost production of small bearingless asynchronous motors seems to be problematic. Therefore, larger industrial production numbers of small motors are not known yet.

While the bearingless switched reluctance and asynchronous motors turn out as extremely robust from the mechanical, thermal and electrical sight, bearingless **<u>P</u>ermanent <u>M</u>agnet <u>M</u>otors** have to be very carefully used in these points. The limiting values of the permanent magnet materials such as the mechanical and thermal strength or the demagnetizing characteristics are of great importance in the design process. However, contrary to the SRM and ASM the permanent magnet motors are suitable for applications with large air gaps and even under these conditions usually achieve high efficiencies. The following comparative consideration of electromagnetic and permanent-magnetic circuits will help to get a feeling for the differences in the pole sizes. On the assumption of equal air gaps the cross-sections of permanent-magnetic and electromagnetic field excitation poles are calculated at comparable magnetic flux values. Thereby, the permanent magnet material is operated in it's optimal operating point.

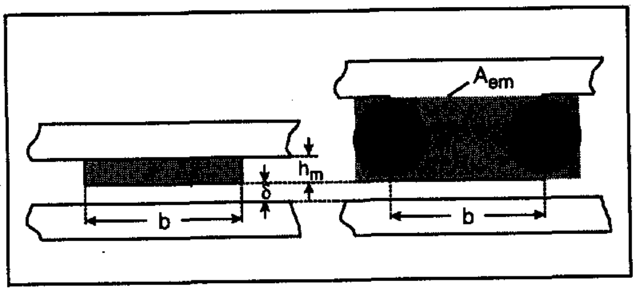

FIGURE 4: *Geometry of the permanent-magnetic and electromagnetic circuit*

In the following comparison, it is assumed that the coil arrangement has a circular cross-section (s. Figure 4). The reluctance of the ferromagnetic material will be negligible.

With Maxwell's equations

$$\oint_c H ds = 0, \quad (1)$$

$$\oint_A B dA = 0, \quad (2)$$

the relation

$$B_\delta = \mu_0 H_\delta \quad (3)$$

and the magnetization characteristic for rare-earth permanent magnet materials

$$B_m = B_r + \mu_0 \mu_r H_m \quad (4)$$

we can calculate the mean flux density

$$\overline{B}_\delta = \sigma_{pm} B_r \frac{1}{1 + \mu_r \frac{\delta}{h_m}} \quad (5)$$

for the permanent-magnetic pole arrangement of Figure 4. Thereby, $\overline{B}_\delta$ is defined as the ratio of the total pole flux and the air gap surface. With the leakage factor σ_{pm} also the flux leakage of the permanent-magnetic circuit is taken into account. From Equation (5) the necessary permanent magnet cross-section can be derived

$$A_{pm} = \frac{\mu_r b \, \delta}{(\sigma_{pm} \frac{B_r}{\overline{B}_\delta} - 1)}. \quad (6)$$

The calculation of the electromagnetic pole arrangement is based on the equation

$$\oint_c H ds = NI \quad (7)$$

and (3). Combining these equations we get the mean flux density

$$\overline{B}_\delta = \sigma_{em} \mu_0 \frac{NI}{\delta}. \quad (8)$$

In the previous equation σ_{em} denotes the flux leakage factor of the electromagnetic circuit and N·I the magneto-motive force of the pole.

The encasing cross-section of the electromagnetic pole is approximately given by

$$A_{em} \approx b \; 2r_{coil}, \quad (9)$$

respectively,

$$A_{em} \approx (b_{fe} + 4r_{coil}) \; 2r_{coil} \quad (10)$$

if the coil cross-section overlaps the ferromagnetic pole.

From the ratio of flux densities

$$\frac{B_{fe}}{\overline{B}_\delta} \approx \frac{b}{b_{fe}} \quad (11)$$

and the current density J_{co} in the copper cross-section

$$J_{co} = \frac{NI}{\pi \, r_{coil}^2 f_{coil}} \quad (12)$$

the encasing cross-section of the electromagnetic pole results in

$$A_{em} \approx 2 \; b \sqrt{\frac{\overline{B}_\delta \; \delta}{\pi \; \sigma_{em} \; f_{coil} \; \mu_0 \; J_{co}}} \quad (13)$$

respectively,

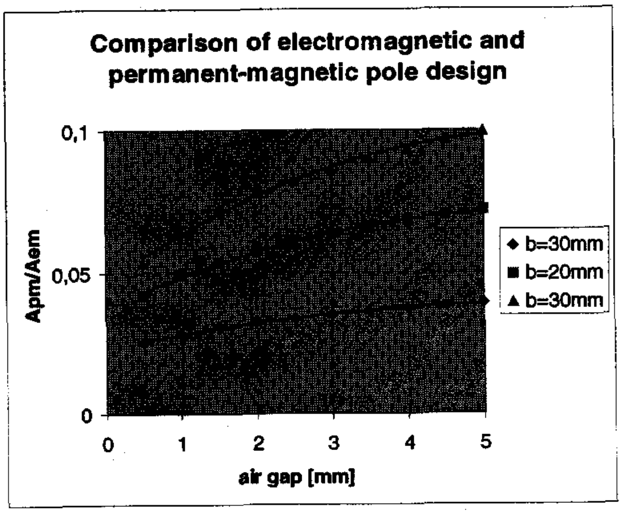

FIGURE 5: *Ratio of cross-sections of permanent-magnetic and electromagnetic pole arrangements in dependence on the air gap*

Assumptions: $B_r = 1.4T$, $\mu_r = 1.07$, $\overline{B}_\delta = 0.5B_r$, $B_{fe} = 1.4T$, $J_{co} = 8A/mm^2$, $f_{coil} = 0.5$

$$A_{em} \approx 2\left(b\frac{\overline{B}_\delta}{B_{fe}} + 4\sqrt{\frac{\overline{B}_\delta\ \delta}{\pi\ \sigma_{em}\ f_{coil}\ \mu_0\ J_{co}}} \right) \cdot \sqrt{\frac{\overline{B}_\delta\ \delta}{\pi\ \sigma_{em}\ f_{coil}\ \mu_0\ J_{co}}} \qquad (14)$$

in the case of overlapping coils.

In Equation (11) and (14) B_{fe} denotes the maximum flux density in the narrow part of the pole. J_{co} and f_{coil} define the current density in the wire and the winding factor of the coil.

Figure 5 presents the cross-section ratios A_{pm}/A_{em} computed for different air gaps. The flux leakage coefficients σ_{pm} and σ_{em} have been determined from Finite-Element calculations. By the selection $\overline{B}_\delta = 0.5B_r$ the permanent magnet is operated approximately at its maximum energy density.

In Figure 6 a scale size comparison between the permanent-magnetic and the electromagnetic pole arrangement is presented. It becomes evident that especially for large air gaps - as they arise e.g. in hermetically closed bearingless pumps - the use of high-energy permanent magnet materials leads to essential improvements concerning efficiency and motor volume.

RELIABILITY AND FAULT-TOLERANT DESIGN

The reliability of a drive system is close connected to the number of its elements and the robustness of these elements against mechanical, electrical and thermal disturbances or loads. Frequently an increase of the

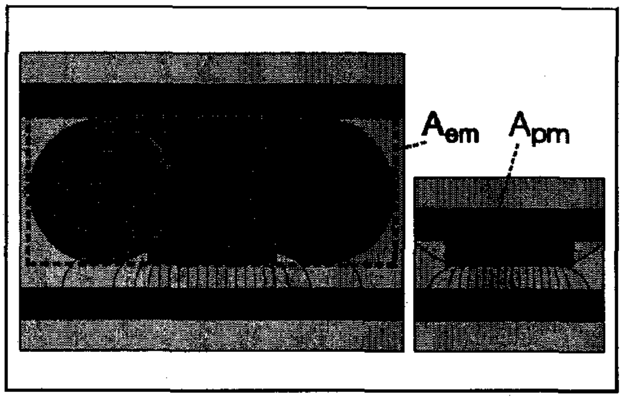

FIGURE 6: *Comparison of a permanent-magnetic and electromagnetic pole design with equal magnetic energy in the air gap (air gap: 4 mm, b=20 mm, B_r=1.4T, μ_r =1.07, $\overline{B}_\delta$ =0.5B_r, J_{co}= 8A/mm^2, f_{coil}=0.5)*

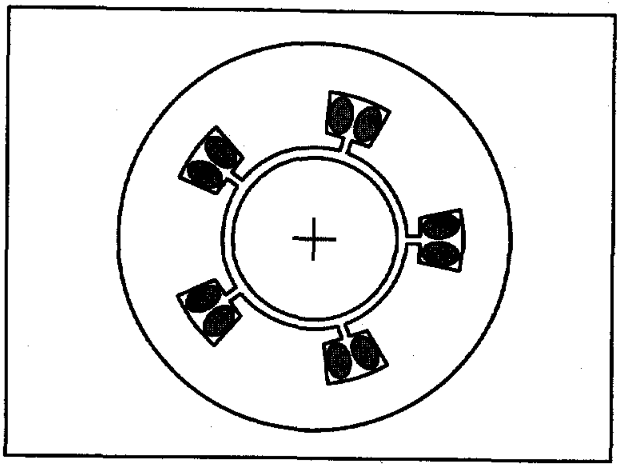

FIGURE 7: *Bearingless five-coil motor: a reduced 2x3-phase system with two rotary field control functions for levitation force as well as torque generation*

reliability is effected by redundant subsystems. On the motor and power electronic side this can take place, for example, by double winding and power converter systems with the disadvantage that the mechanical and electrical expenditure increases remarkably.

If - in the case of a failure - an operation with lower levitation force and torque performance is allowed, an auxiliary operation with a lower active phase number can be a cost reducing alternative. However, a basic condition is that arbitrary levitation force vectors as well as the motor torque still can be generated by the remaining stator windings.

Figure 7 shows an example of a bearingless permanent magnet motor with five concentrated coils. In contrary to four-coil arrangements /4/-/6/ it is possible to realize rotary fields for both levitation force and torque generation.

The levitation force and torque production of a five-coil bearingless permanent magnet motor can be generally described in linearized representation by

$$\begin{bmatrix} \mathbf{F}_r \\ T \end{bmatrix} = \begin{bmatrix} \mathbf{M}_a(\mathbf{x}_r, \varphi) \\ \mathbf{N}_a(\mathbf{x}_r, \varphi) \end{bmatrix} \mathbf{i}_5 + \begin{bmatrix} \mathbf{M}_b(\mathbf{x}_r, \varphi) \\ 0 \end{bmatrix}, \qquad (15)$$

with

$$\mathbf{M}_a(\mathbf{x}_r, \varphi) \in \mathbb{R}^{2x5}$$
$$\mathbf{M}_b(\mathbf{x}_r, \varphi) \in \mathbb{R}^{2x1} \qquad (16)$$
$$\mathbf{N}_a(\mathbf{x}_r, \varphi) \in \mathbb{R}^{1x5},$$

whereby following assignments are made: $\mathbf{F}_r$ levitation force vector, T torque, $\mathbf{x}_r$ position vector, φ rotor angle, $\mathbf{M}_a$, $\mathbf{M}_b$ and $\mathbf{N}_a$ position and angle dependent matrixes, $\mathbf{i}_5$ phase current vector. For the operation with a centrically positioned rotor the destabilizing permanent-magnetic force term $\mathbf{M}_b$

becomes negligible.

Basically, bearingless motor operation requires active control in three degrees of freedom. For the bearingless operation of the five-coil motor the following basic postulate can be defined

$$\text{rank}\begin{bmatrix} \mathbf{M}_a(\mathbf{x}_r,\varphi) \\ \mathbf{N}_a(\mathbf{x}_r,\varphi) \end{bmatrix} = 3 \,. \tag{17}$$

Equation (17) is valid for the described motor. Due to the special motor design the rank condition is still fulfilled even if one or two motor phases fail.

As example Figure 8 shows the orbit curves of a realized five-coil motor. Naturally, owing to the reduced levitation forces the auxiliary operation modes with four respectively three coils lead to larger orbit curves.

Thus, the proposed motor design offers a lot of advantages concerning system reliability:

- all coils generate levitation force as well as torque components
- all coils are geometrically and functionally equivalent so that it is irrelevant which coils fail
- a failure case doesn't require switching to special auxiliary current shapes or control algorithms and therefore,
- failure detection isn't necessary for auxiliary operation.

But Equation (17) doesn't include all possible motor configurations. Beside motors based on rotary fields there are also other bearingless motor designs which partly use alternating fields for operation. In this case the rank of the system matrix ($\mathbf{M}_a$, $\mathbf{N}_a$) and $\mathbf{M}_a$ is reduced by one as defined in the following equation

$$\text{rank}\begin{bmatrix} \mathbf{M}_a(\mathbf{x}_r,\varphi) \\ \mathbf{N}_a(\mathbf{x}_r,\varphi) \end{bmatrix} = \text{rank}(\mathbf{M}_a(\mathbf{x}_r,\varphi)) = 2 \,. \tag{18}$$

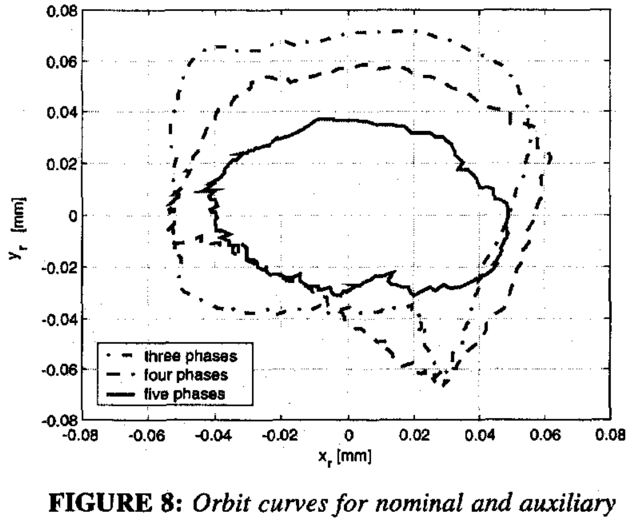

FIGURE 8: *Orbit curves for nominal and auxiliary operation modes with five, four and three phases*

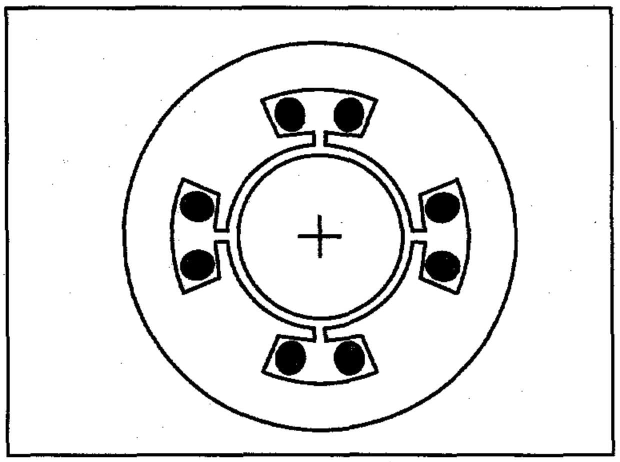

FIGURE 9: *Bearingless 4-coil motor: a motor with angle dependent electromagnetic torque gaps*

Under these conditions it isn't possible to generate the electromagnetic torque in all angular rotor positions. An example of a motor with such characteristics is shown in Figure 9.

For reliable start and running conditions it is necessary to compensate the lack of electromagnetic torque by an additional term N_b added to Equation (15)

$$\begin{bmatrix} \mathbf{F}_r \\ T \end{bmatrix} = \begin{bmatrix} \mathbf{M}_a(\mathbf{x}_r,\varphi) \\ \mathbf{N}_a(\mathbf{x}_r,\varphi) \end{bmatrix} \mathbf{i}_5 + \begin{bmatrix} \mathbf{M}_b(\mathbf{x}_r,\varphi) \\ N_b(\mathbf{x}_r,\varphi) \end{bmatrix} . \tag{19}$$

Generally, the values of N_b are influenced by the motor design. Various appropriate motor arrangements are possible in this context.

ONLINE ADAPTATION OF LEVITATION AND TORQUE CAPACITY

The previous motor designs with four, five or more phases have some remarkable features in common: they are equipped with concentrated windings and each winding is simultaneously fed with different current components responsible for the generation of two orthogonal force components and one torque component.

This makes it possible to vary the proportions of levitation force and torque components depending on the external load situations while using the whole coil cross-section each time. Therefore, e. g. in situations with low external radial forces almost the whole cross-section of the winding can be used for torque generation (s. Fig. 10a) whereas in cases with low external torque load almost the whole cross-section of the winding is available for the generation of levitation forces (s. Fig. 10b). This application-oriented mode of operation leads to an high utilization of the copper cross-section and also to good efficiency results (s. Figure 11). In contrast to the previous design variants in standard winding configurations the cross-sections for the magnetic bearing and the motor function are bound to separate

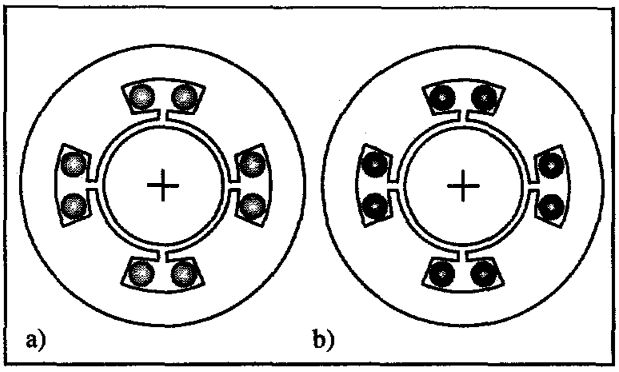

FIGURE 10: *Bearingless motor with variable levitation force (dark) and torque (light) proportions in the current distribution of the coil cross-sections*

windings.

CONCLUSIONS

In this paper some considerations are presented which are important for the selection and operation of bearingless motors. In a comparison of electromagnetic and permanent-magnetic pole designs it becomes evident, that in small motor applications permanent magnets are very important components to reduce the motor volume and to increase the motor efficiency significantly. Especially in applications with large air gaps other design variants are practically inefficient. Furthermore, reliability and fault-tolerant design aspects are analyzed and discussed. With the use of integrated windings, i.e. windings for torque as well as radial force generation, the failure of arbitrary phases can be compensated by the motor itself. Especially a five-phase configuration offers a lot of advantages in this respect.

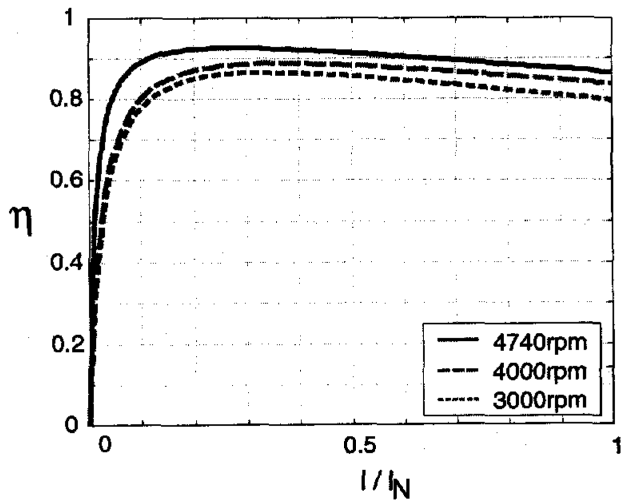

FIGURE 11: *Example for the efficiency performance of a bearingless motor at low radial load conditions (measurements)*

The efficiency of bearingless permanent magnet motors using rare-earth magnets reaches high values, particularly, when the whole winding cross-section can be variably used for the changing conditions in levitation and motor operation.

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FIGURE 12: *Bearingless motor in a pump application*