BASIC APPROACH FOR THE DESIGN OF BEARINGLESS MOTORS

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ABSTRACT

In this paper a basic approach for the design of bearingless motors is presented. The particularity is, that the rated values for radial force and power must be attained for the same air gap area. Starting from the known design of AC-machines the reduction of the utilization factor C by the radial force generation is considered. By an iterative sequence a reduction factor is varied until the rated values of output power and maximum radial force are reached.

INTRODUCTION

The principle of radial force generation of bearigless motors is to combine two winding sets with a difference in the pole pair number of one [1], [2]. By superposition of these two magnetic fields not only torque but also a radial force can be produced. Figure 1 shows the principle by means of a 4-pole motor winding (reluc-tance motor) and a 2-pole bearing winding.

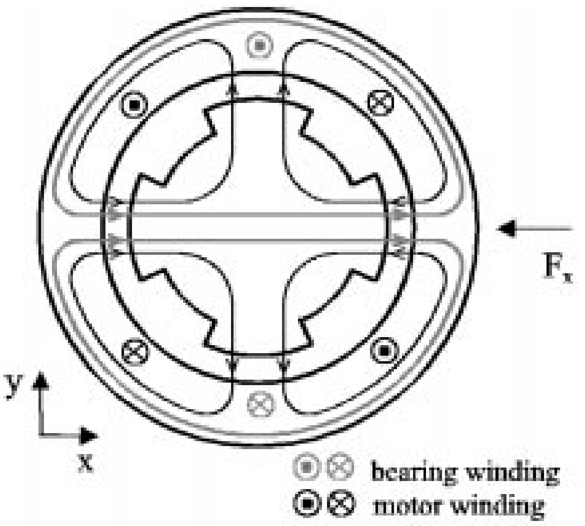

FIGURE 1: Principle of radial force generation

The motor magnetic field is illustrated with the black field lines and the additional field of the bearing winding with the gray field lines.
From the figure is cognizable, that on the right hand side the gray field lines are reverse to the motor magnetic field, while they have the same direction at the opossite rotor pole. In the result a radial force in negative x-direction is produced.
When we assume the magnetic circuit to be linear radial force generation has no influence on torque or motor power. But it is known, that this assumption does not comply with reality. For real machines there are some limits like saturation and heating [3].
That's why a synchronous torque and radial force generation reduces the motor power respectively increases the volume – but how much? Which dimensions are necessary to fulfill specific guidelines? A basic approach is presented in the next chapter and verfied with an example.

ESTIMATION OF THE MAIN DIMENSIONS

The estimation of the main dimensions is done according to the wellknown design of electrical machines [3]. The electromagnetic load of AC-machines is determined by the inner apparent power

$$P_i = \frac{\pi^2}{\sqrt{2}} \xi_1 A \hat{B}_1 D^2 l_i n_0 = C D^2 l_i n_0 \qquad (1)$$

with:
- ξ_1 winding factor
- A electric loading
- $\hat{B}_1$ amplitude of the air-gap induction (fundamental wave)
- C utilization factor; f(machine type, rated power, pole pair number, ...)

As equation (1) shows the utilization factor C contains the product of electric loading A and magnetic air gap induction. Only the mathematical form of the expression and the characteristical values of the air-gap induction and the electrical loading vary for different machines.

In bearingless motors are both torque and radial forces generated in one magnetic circuit. That means, the values of the maximum radial force and rated power must be reached for the same air gap area. Concerning the aspect of saturation the influence of the bearing system is clarified with figure 2.

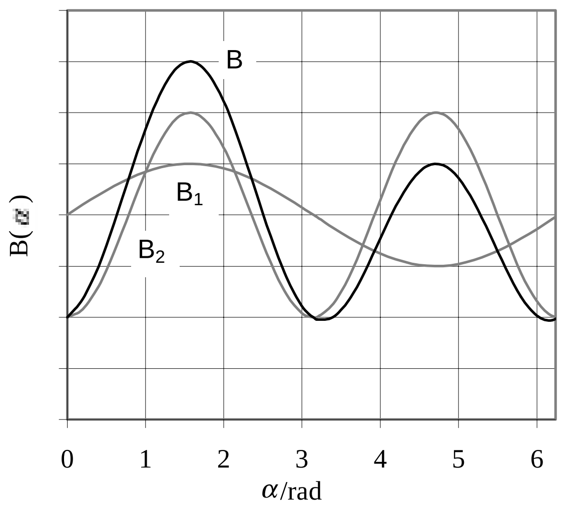

FIGURE 2: Superposition of the fundamental waves

The superposition of the fundamental waves can be written as [2]

$$B(\alpha) = \hat{B}_1 \cos(\alpha + \mu) + \hat{B}_2 \cos(2\alpha + \gamma) . \qquad (2)$$

In figure 2 the worst case is shown, that means the amplitudes of both induction fundamental waves have the same angular position.

By the enhancement of the amplitude the strong influence of saturation becomes clear.

For the further ventilations the air-gap induction of (1) is replaced by the magnetic loading according to

$$B_m = \frac{1}{\pi} \int_{\tau_p} B(\alpha) d\alpha . \qquad (3)$$

The main idea is now to divide the machine fictitious into the motor subsytem and the bearing subsystem.

For a first approach we asssume that the recommended values for the air-gap induction are the same as for the normal motor design. In case of the bearingless motor both systems, motor- and bearing system contribute to the induction. That means the guide value of B_m must be split conveniently on both systems in such a way, that the values for maximum radial force and the rated power are achieved. Starting from the guide value B_m follows

$$B_m = B_{mB} + B_{mM} \qquad (4)$$

with
- B_m magnetic loading - guide value
- B_{mB} magnetic loading - rate bearing
- B_{mM} magnetic loading - rate motor.

Figure 3 shows the sequence of the design in principle. Initial values are the rated power and speed and the required maximum radial force. For the windings it is advisable to chose the pole pair numbers one and two with respect to the stator frequencies.

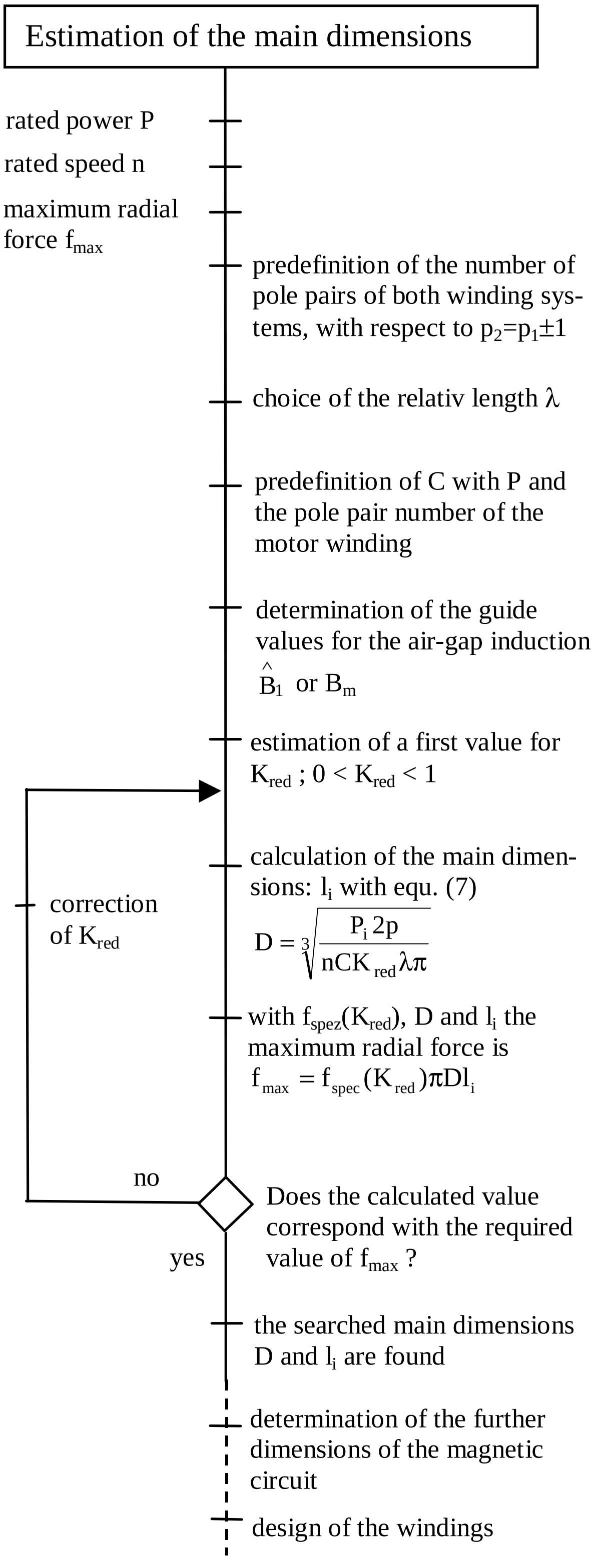

FIGURE 3: Design scheme

For the different AC-machines the utilization factor C is given as a function of the output power or power per pole. Thereby is assumed that the values of electric loading and magnetic air gap induction vary only a little with regard to the guide values. But if the subsystem motor is designed for a differing – lower – air-gap induction B_{mM}, the reduction of the utilization factor C must be considered

$$C_{red} = C \cdot (1 - \frac{B_{mB}}{B_m}) = C \cdot K_{red} \quad . \qquad (5)$$

The question is now, which value is to chose for the factor K_{red}, to obtain the requirements of torque and radial forces. There are two marginal cases:

$K_{red} = 1$ — that means $B_m = B_{mM}$, $B_{mB} = 0$, no rate of the air gap induction for the radial force generation, this is conform with the known motor design

$K_{red} = 0$ — that means the whole air-gap induction B_m is used for radial force generation, $B_m = B_{mL}$, $B_{mM} = 0$, no torque can be produced.

Because in the bearingless motor both torque and radial force should be generated, the reduction factor will range between $0 < K_{red} < 1$.

For the design according to figure 3 it is necessary to know the specific radial force $f_{spec}(K_{red})$. This value is not only depending on K_{red} but also on the machine type and size. Steady data can only result from the experience of realized machines. It is proposed to reference the available maximum force to the rotor surface.

$$f_{spec} = \frac{f_{max}(K_{red}, machine\ type\ ,\text{–}size)}{\pi D l_i} \qquad (6)$$

With the relative length λ

$$\lambda = \frac{l_i}{\tau_p} = \frac{2 p l_i}{D\pi} \qquad (7)$$

and equations (1), (3), (5) the required diameter for the firstly chosen K_{red} can be calculated

$$D = \sqrt[3]{\frac{P_i 2p}{nCK_{red}\lambda\pi}} \qquad (8)$$

and with (7) also l_i is found. Now from equation (6) the available maximum radial force, depending on K_{red} can be estimated. By comparison of the received value with the required value of f_{max} follows, if K_{red} has to be corrected upwards or downwards. This sequence is to iterate until the required value of f_{max} is hit with sufficient precision. After that the further dimensions of the magnetic circuit and the windings have to be designed. But the aim of this investigations is the estimation of the main dimensions

VERIFICATION WITH AN EXAMPLE

The above design scheme discussed in principle will be verified now with an example. By means of a bearingless reluctance machine the force-current and the torque-current charcteristic are analysed, taking into account electromagnetic guide values.

Figure 4 shows a picture of the test machine. The motor is constructed in such a way, that only one shaft end is beared by electromagnetic forces while the other one is beared by ball bearings. That means the machine is not complete bearingless. But for the further investigations this fact is not meaningful.

FIGURE 4: Bearingless reluctance machine

In figure 5 the stator/rotor shape and the winding configuration are pictured. The stator core stack is from an asynchronous machine. The motor winding as well as the rotor core stack are 4-pole and the bearing winding is 2-pole.

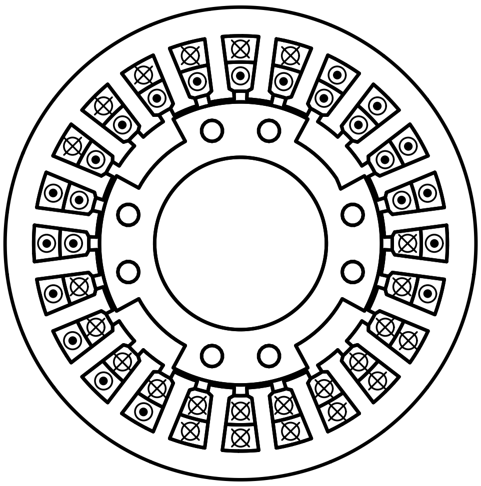

FIGURE 5: Stator/rotor shape, winding configuration

On base of the shown shape and winding configuration a FEM-model is built. The first calculations are made to find a practical electromagnetic operating point. To it the machine was used only as motor and the current in the motor winding i_2 was varied from 0 to 20A. The direct and quadrature current components i_{2d} and i_{2q} were always equal.

$$i_2 = \sqrt{i_{2d}^2 + i_{2q}^2} \qquad (9)$$

with $\quad i_{2d} = i_{2q}$

Torque of the reluctance machine is given by

$$M = \frac{3}{2} p(L_d - L_q) i_{2d} i_{2q} . \qquad (10)$$

Starting from zero picture 6 shows at first a quadratic rise of torque according to equation (10).

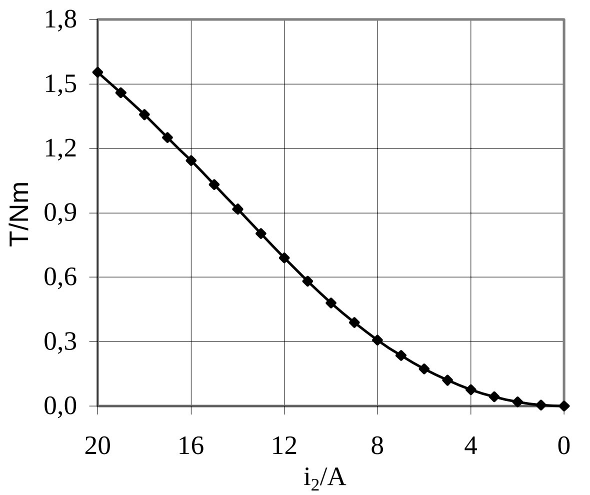

FIGURE 6: Motor torque as function of i_2 with (i_{2d}=i_{2q})

With a further increasing current the increase of torque becomes smaller and smaller, caused by magnetic saturation. The problem is now to find a operating point where the machine is good utilized and on the other hand the guide values for the electromagnetic load are observed. It is difficult to name guide values, they vary in a wide range depending on the machine type, machine size, cooling and so on.

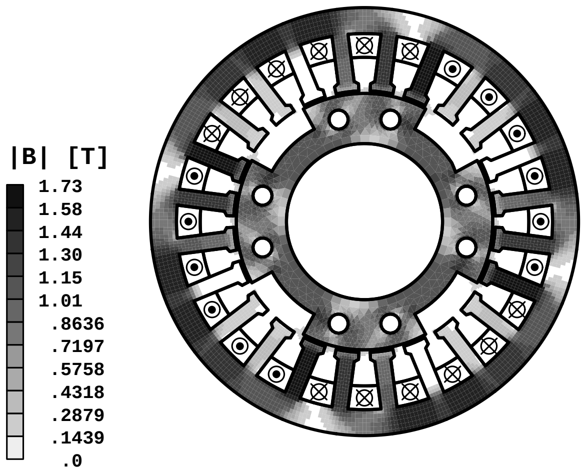

FIGURE 7: Flux density distribution

For the magnetic load we take the values from [3] for an asynchronous machine.

stator back:	1,3...1,65 T
rotor back:	0,4...1,6 T
teeth:	1,4...2,1 T
air gap.	0,4...0,65 T (B_m)

For a current vector of i_2*=14A* a flux density distribution according to figure 7 is yield. The maximum values of the flux intensity are rather midway of the guide values. Figure 8 shows the belonging flux distribution in the air gap of the machine.

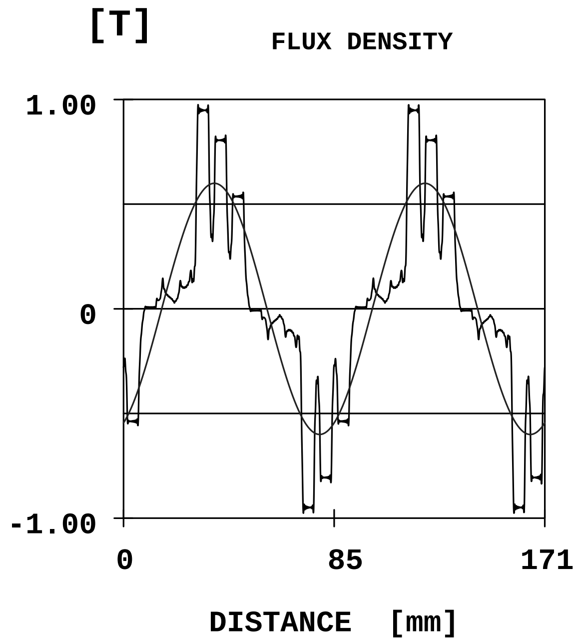

FIGURE 8: Flux density distribution in the air gap and fundamental wave

The maximum value is about 0,95T. The amplitude of the fundamental wave is 0,6T.
Converted to a medium flux density over the pole width the value is:

$$B_m = \frac{2}{\pi} \hat{B}_1 = 0{,}382T \qquad (11)$$

This is a quite low value regarding to the guide value. But since the rotor is not cylindrical (in relation to the asynchronous machine) the fundamental wave is respectively lower.
The electrical stress is characterized by the product of current density S and electric loading A. According to [3] this value should range between *A S = (100...350) (kA/m) (A/mm²)*, depending on the machine size and the cooling system. With the choosen current $i_2 = 14A$ the current density in the winding is $S = 8A/mm^2$, thereby is assumed that the whole slot space can be used for the motor winding – to find a proper electromagnetic operating point we consider the machine firstly only as motor.

With $A = \frac{mwI}{p\tau_p}$ (12)

and $\tau_p = \frac{D\pi}{2p}$, (13)

we get a electric loading of *A = 25kA/m*. With the current density a electrical stress of about *AS = 200 (kA/m) (A/mm²)* is found. Taking into account, that the machine is watercooled, the values for S, respectively AS are realistic. From the point of electromagnetical loading a maximum value of i_2 = 14A is suitable for this machine. This equals an amplitude of the m.m.f. fundamental of $\hat{\Theta}_{max} = 756\,A$.

When we now include the bearing system in our investigations, i.e. the additional 2-pole winding, this value will be the limit of the sum of the m.m.f. fundamentals.

$$\hat{\Theta}_{max} = 756\,A = \hat{\Theta}_{2\,max} + \hat{\Theta}_{1\,max} \quad (14)$$

It means the maximum value can only be split on both systems. Figure 9 and 10 show the torque and radial force characteristic regarding to equation (14).

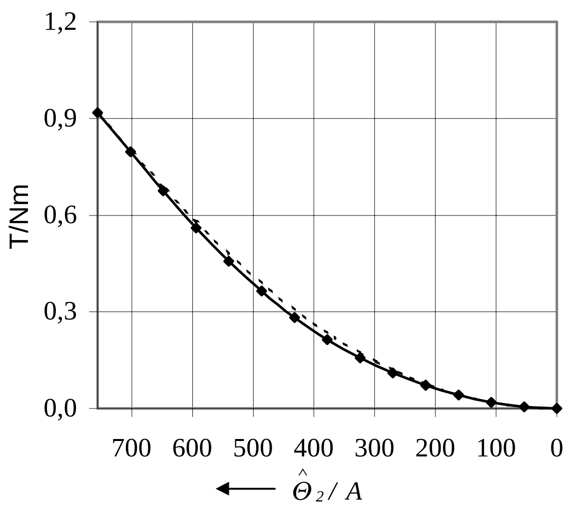

FIGURE 9: Torque at synchronous generated radial force

Let's make an example: we want to generate a radial force of 100N, thus an amplitude of the m.m.f. fundamental of 170A is required. According to (14) for torque generation remains a value of 586A, it equals about 0.55Nm. Any other combinations (operating points) are possible.

The dotted line in figure 9 corresponds to figure 6, i.e. without synchronous radial force generation, thats why this curve is a little above. The curve shape of figure 10 is explained as follows: to radial force generation the currents, respectively m.m.f.'s, of both winding sets contribute, they are multiplied [1], [2], [6]. When one of them is zero the resulting radial force is also zero and between this two points is a maximum.

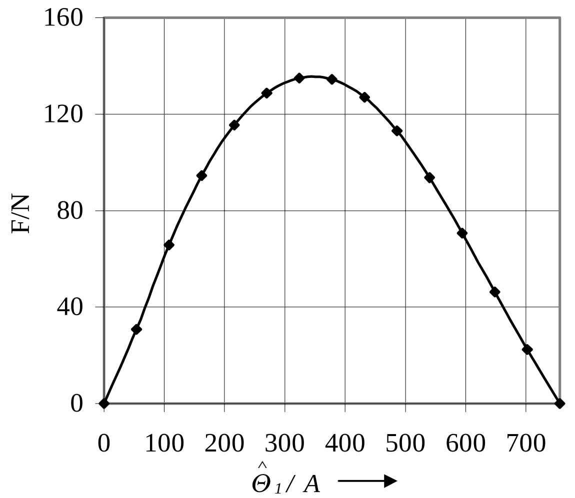

FIGURE 10: Radial force at synchronous generated torque

Figure 11 shows the torque reduction caused by synchronous radial force generation. The reduction factor is defined by

$$K_{red} = \frac{T}{T_{max}}, \quad (15)$$

where T_{max} is the torque when the machine is only used as motor.

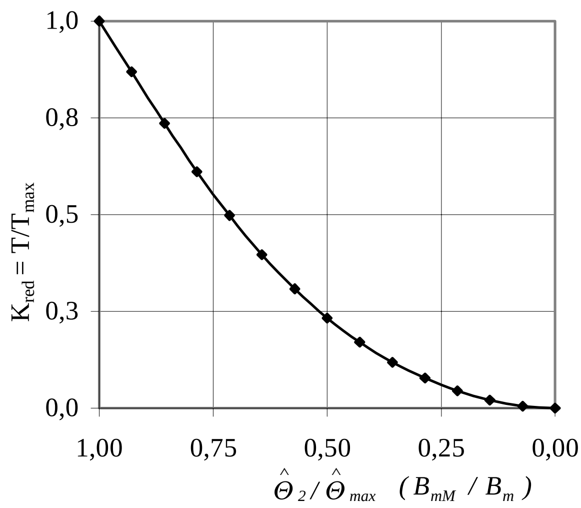

FIGURE 11: Torque reduction

In figure 12 the specific radial force is shown, on the basis of figure 10. Thereby the radial force is referenced to the whole rotor surface according to equation (6).

With K_{red} (figure 11) and f_{spec} (figure 12) it is possible to test the design scheme according to figure 3.

The initial values for the design are:

P_{mech}=1,5kW
n = 30 000min^{-1}
f_{max}=100N

These values are close to the parameters of the machine pictured in figure 4, if the proposed design scheme works in principle, the results should be near to the dimensions of our machine (D=55mm; l_i=45mm).

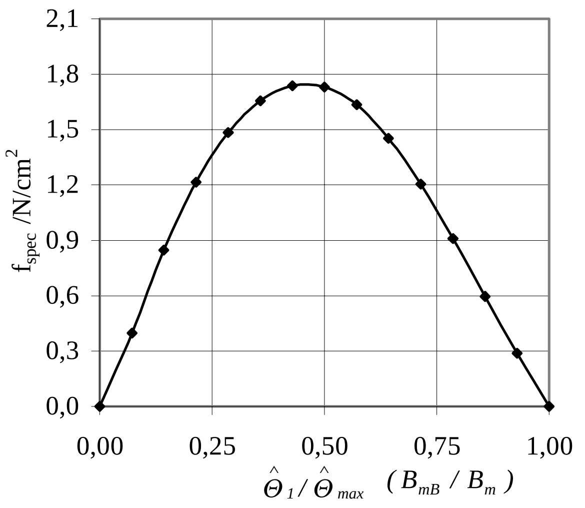

FIGURE 12: Specific radial force

For the motor winding we chose p=2 and for the bearing winding p=1. The combination of the pole pair numbers one and two is adviseable with respect to the required stator frequencies.
For the relative length we chose $\lambda=1$. The mechanical utilization factor of the test machine is $c_{mech}=0,42$ $(kWmin)/(m^3)$, this is about one third of a same size asynchronous machine.
The problem is now to chose a value for K_{red}, it equals the question how much is the motor power reduced by radial force generation. Lets take at random $K_{red}= 0,5$. As the starting point is the mechanical power for the estimation of the diameter equation (16) is used instead of (8).

$$D = \sqrt{\frac{P_{mech} 2p}{nc_{mech} K_{red} \lambda \pi}} \qquad (16)$$

It yields D=0,067m and with (6) $l_i=0,053m$. From figure 11 with $K_{red}=0,5$ follows $\hat{\Theta}_2 / \hat{\Theta}_{max} = 0,7$ and with (14), divided by Θ_{max}, for $\hat{\Theta}_1 / \hat{\Theta}_{max} = 0,3$ is yield. With it from figure 13 follows $f_{spec}=1,5N/cm^2$. Now the available radial force can be estimated according to (6). We get $f = f_{max}=167N$. The comparison with the desired value indicates, that K_{red} has to be corrected downwards, a value of $K_{red}=0,7$ appears to be suitable.
If we do the calculation again $D=0,06m$; $l_i=0,047m$ and $f = f_{max}=106N$ results. That means the initial value is hit with sufficient precision and the main dimension are found. However after the estimation of the further dimension of the magnetic circuit and the design of the windings FEM-calculations should be done to check and if necessary to correct the first design. It is also to check if the mechanical stress of the rotor at the maximum speed is within acceptable limits. Else the diameter has to be corrected (with λ).

QUESTIONS LEFT, OPTIONS, IMPROVEMENTS

Many aspects of the design of bearingless motors are not or only partly discussed. Some of them should be at least mentioned.
The principle of the proposed design scheme is applicable also to other types of bearingless motors, such as asynchronous or PM-synchronous machines. But the verification is done with a reluctance motor. The problem in general is, that the found values for $K_{red}(B_{mB}/B_m)$ and $f_{spec}(B_{mB}/B_m)$ are in fact only correct for our special machine – or for reluctance machines with similar size. For an application of the proposed design scheme to machines with distinct different dimensions or other motor types it is necessary to estimate the data $K_{red}(B_{mB}/B_m)$ and $f_{spec}(B_{mB}/B_m)$. FEM-programs can be proper ficilities. But in fact only measurements and the experience of many different bearingless machines can deliver universal reference points.
Different appendages and assumptions are necessary to be discussed and modified when the design is applied to other motor types.
Concerning the estimation of the several dimensions of the stator and rotor shape (back heigth and so on) differences to the normal motor design are expected – further investigations are necessary.

CONCLUSIONS

With the presented design sequence a way to determine the main dimensions of bearingless AC-machines is shown in principle. It shall primarily be used to find an approximate estimation of the main dimensions of the magnetic circuit. By the experience of realized bearingless motors the design will be further improved and completed.

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