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Design of an BLDC drive with iron core to improve the efficiency of Ventricular Assist Devices

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Abstract — Single sided Brushless DC (BLDC) drives with axial flux have the advantage of a flat design and high torque. This makes them a good choice for operating less invasive implantable Ventricular Assist Devices (VADs), which can be applied for the therapy of cardio vascular diseases. The disadvantage of such drives is the occurrence of high axial forces. In order to avoid axial forces some VAD drives have air gap windings. Their torque generation completely relies on magnetic stray fluxes. Therefore an increase in efficiency is expected when using iron teeth with single tooth windings. As iron losses have to be considered now, a study is performed to identify the key parameters for iron and copper losses. From this study an efficient VAD drive design is deduced.

I. INTRODUCTION

In industrialized countries cardio vascular diseases are the major cause of death. When drug based therapies fails and there is no donor organ available for a heart transplant, a mechanic circulatory system is required. If some pumping capabilities remain, the native heart can be unloaded with a Ventricular Assist Device (VAD). By connecting the VAD with a ventricle of the human heart, it can ensure a sufficient perfusion of the systemic or pulmonary blood circuit. Further blood damage must be limited to allow for a VAD operation.

There are three major reasons for blood damage. Thrombus formation can be related to contact with non biocompatible surfaces or stagnation of the blood flow. Hemolysis is mostly caused by too high shear forces of the VAD's pump system. Overheating of the blood yields its denaturation, which is irreversible for a temperature higher than 42 ˚C. As the electric losses inside the drive system are the main reason for overheating, they have to be limited.

For a less invasive implantation a small dimensioned VAD is required. As single sided BLDC drives have the advantage of a compact design, they are applied in some VADs, e.g. in the DuraHeart [1] or Worldheart [2]. The disadvantage of such drive systems are high axial forces, which are solved by applying air gap windings in [1]. In this way the torque generation completely relies on stray flux, which results in high copper losses. When applying iron teeth with single tooth windings a higher efficiency is expected due to a higher magnetic flux density. But this modification yields higher axial forces and additional iron losses. After introducing the drive system a study is performed to identify the key parameters for copper and iron losses.

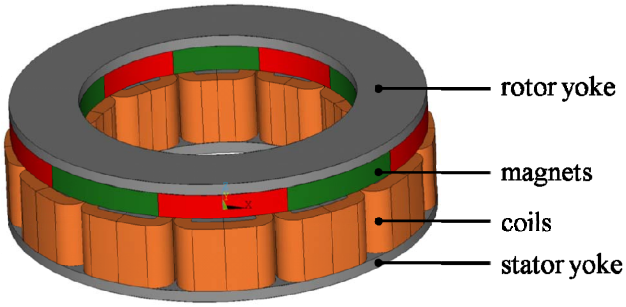

Fig. 1: BLDC drive.

II. DRIVE DESIGN

Fig. 1 shows the drive design of the studied BLDC motor. The rotor consists of an iron disc with 10 mounted alternating axially magnetized neodymium iron boron (NdFeB) magnets. Their remanent flux density amounts to 1.36 T at a temperature of 40 ˚C. 12 coils are attached to the stator iron. Each coil is wounded with rectangular copper wire. In this a copper fill factor of 60 % is achieved. Both, the rotor and the stator yoke are made of the soft magnetic iron 9S20K. Due to construction reasons the yokes are solid and not laminated. For the design an air gap of 0.8 mm is applied. The rotor is levitated by a combination of hydrodynamic and permanent magnet bearings. This hybrid bearing is not discussed in more detail here, but the general design approach is described in [4].

The drive system operates a VAD, which is designed for a long term full support of the left ventricle. From a clinical point of view this requires a system which can guarantee a perfusion of up to 7l of blood per minute against a mean systemic pressure of 100 mmHg. CAD simulations of the pump system of the VAD, showed that a speed of 2500 rpm and a torque of 12 mNm is required to achieve the desired perfusion. According to

$$T_{out} = \frac{P_{out}}{2 \cdot \pi \cdot n_N},$$

the mechanical output power Pout of the drive can be derived from the output torque Tout and the pump speed n to 3.14 W. In order to avoid blood damage the input power of the drive system needs to be limited to 5W. From this constraint, the required efficiency can be calculated. The design objectives including the drives dimensions are collected in

Table **1**.

Table 1: Drive Design Parameters.

design objectives	Prototype
nominal speed	2500 rpm
nominal torque	12 mNm
max. axial force	50 N
stator height	6 mm
outer diameter	38 mm
inner diameter	24

III. METHOD

The losses in electric machines can be classified as mechanical losses, iron losses and copper losses. As in [5] the objective of this parameter study is to balance the axial forces and to keep the resulting as low as possible. While in [5] soft magnetic material has been studied, this time the drive design itself is studied, e.g. the shape or height of the stator teeth. Before introducing the simulation results the applied calculation chain is explained.

The disadvantage of single sided BLDC drives is the occurrence of axial forces, which have to be compensated by the drives bearing system. According to

$$\vec{F}_{axial} = \frac{B^2 \cdot A}{2 \cdot \mu_0} \cdot \vec{e}_{axial}. \tag{2}$$

the axial force $\vec{F}_{axial}$ depends on the magnetic induction B, the cross section area A of the stator teeth and the permeability of the vacuum μ_0. As the stator teeth area is known from the drive design only the magnetic induction inside the virtual air gap has to be determined. Because the relative permeability μ_r of air and NdFeB is 1, the virtual air gap is calculated by the sum of the air gap height and the permanent magnet height. In total the virtual air gap amounts to 3.3 mm, which is about 30 % of the drive height. For this reason Finite Element (FE) simulations are applied to determine the distribution of the magnetic induction inside the air gap.

For the calculation of the resulting losses inside the drive, the previously mentioned loss mechanisms are considered. Mechanical losses are related to air friction of the shaft and load currents, which can not be measured directly. For this reasons they are approximated to 2 % of the output power of the drive as proposed in [6].

In literature [3], [7] iron losses are defined as the sum of hysteresis and eddy current losses. When changing the direction of the magnetization inside the soft magnetic material such as the stator, energy is consumed for the adjustment of the Weiss domains. This adjustment results in heat losses, which are proportional to the area enclosed by the materials hysteresis curve.

$$P_{hy} = \sigma_{hy} \cdot k_{hy} \cdot \frac{f}{50Hz} \cdot \left(\frac{B}{1T}\right)^2 \tag{3}$$

As stated in the equation above, the hysteresis losses are linear dependent to the operation frequency f and are increasing with the square of the magnetic induction B. While the factor σ_{hy} adjusts the frequency to 50 Hz and the magnetic induction to 1T, the second factor k_{hy} considers effects caused by the handling of the core material.

The rotating magnetic field induces eddy currents in the stator teeth. On one hand this yields eddy current losses, on the other hand the driving torque is reduced. This effect is caused by the torque component related to the eddy currents, which opposes the driving torque. Analytically, these eddy current losses can be calculated by

$$P_{ed} = \sigma_{ed} \cdot k_{ed} \cdot \left(\frac{f}{50Hz}\right)^2 \cdot \left(\frac{B}{1T}\right)^2. \tag{4}$$

Besides the power of the frequency term, this equation is formally identical to equation 3. Further the k-values in both equations differ from each other. Methods for determining theses values are explained in [8].

In a first step the driving torque can be deduced from the tangential force component inside the drive, which is given by the Lorentz force equation

$$\vec{F}_{\tan} = I \cdot (\vec{l} \times \vec{B}) \cdot \vec{e}_{\tan}. \tag{5}$$

The second term in this equation is the cross product of the magnetic induction B and active wire length l. When multiplying the result with the coil current I the tangential force is obtained. The output torque is linked to the radial force by the average rotor diameter. Equations 2 to 5 all rely on the magnetic induction B. The aforementioned large air gap, saturation effects in the rotor backiron as well as in the tips of the stator teeth, requires a numerical Finite Element Analysis to determine the distribution of the magnetic induction. For these simulations a transient solver from the iMoose solver package [9], developed at the Institute of Electrical Machines of the RWTH Aachen University, was applied, considering the quasi transient movement of the rotor. Besides the coil currents all other variables of equations 2 to 5 are defined by the drive design and can therefore be considered to be constant for each drive model. Therefore the required coil supply is a function of the torque requirement. By this way, the torque can be directly linked to the copper and eddy losses. The calculation of the copper losses requires three steps including two FEM simulations. First, the cogging torque has to be determined, which is dependent on the relative position between the permanent magnets in the rotor and the stator teeths. In the next simulation, the coils are supplied with a constant current linkage θ of 50A. In order to determine the torque, generated by the current linkage, the cogging torque

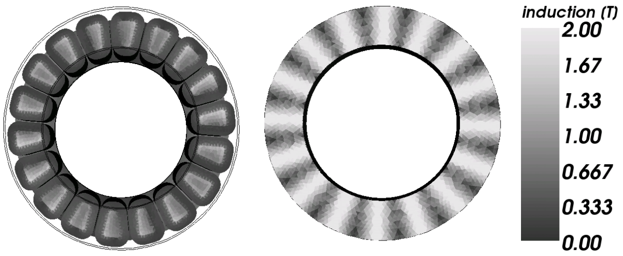

Fig. 2: saturation in the BLDC drive.

has to be substracted from the simulated torque. As a six step commutation is applied for the control of the drive, the following equation applies:

$$T_{out} \propto \theta_R \theta_S \sin(\varepsilon) \tag{6}$$

In this equation the generated torque T is a function of the rotor θ_R and stator θ_S current linkages and the sine of the angle ε between them. Due to its permanent magnet excitation, θ_R is constant and ε is always 90 degree. Therefore, the required stator current linkage for generating the required driving torque of 12mNm can be obtained by

$$\Theta_S = \frac{12mNm}{T_{out} - T_{ed}} \cdot 50A. \tag{7}$$

The cogging torque is already considered in T_{out}, while the opposing torque component T_{ed} caused by the eddy currents yields an increased current supply for generating the required output torque of the drive. In the next step, the resulting copper losses are calculated according to

$$P_{co} = \frac{2}{3} \cdot n_c \cdot \theta_S^{\,2} \cdot \rho_{cp} \cdot \frac{l}{A \cdot CF} \cdot \left(1 + \alpha_{co} \cdot \left(T - T_{20}\right)\right) \tag{8}$$

In this equation the factor $2/3$ considers the six step commutation control of the drive, where only two out of three phases are supplied at the same time. The copper fill factor CF is assumed to be 60% and θ_S represents the current linkage in the coils supplying two third of the n_c coils of the drive. The resistance of one coil is calculated by its resistivity ρ_{cp} at room temperature, its wire length l and its cross sectional area A. In order to obtain the resistance at an assumed stator and rotor backiron temperature T of 45°C, the last term of equation 7, containing the temperature coefficent α_{co} for copper and the room temperature T_{20}, is required.

Finally, the resulting efficiency η is calculated by the quotient of the output power P_{out} and the sum of the resulting losses and the generated output power.

$$\eta = \frac{P_{out}}{P_{out} + 0.02P_{out} + P_{hy} + P_{ed} + P_{co}}. \tag{9}$$

IV. RESULTS

The introduced computation chain is applied to the drive design parameters stator tooth height and winding thickness. In Fig. 3 the electric losses in dependence of the stator tooth height is presented. When not considering the iron losses P_i the copper losses reach their minimum at a stator tooth height of 5 mm and amount to about 200 mW. In this case the stator tooth height equals the height of the coils in the stator. So the reason for the decrease of the copper losses is that the magnetic induction inside the coils rises due to the soft magnetic iron.

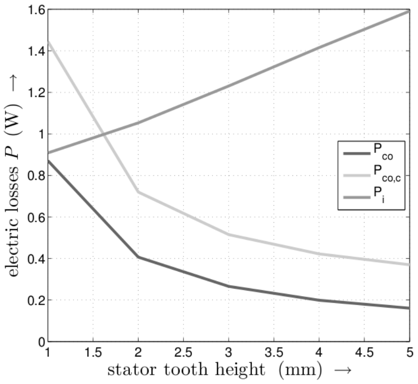

Fig. 3: electric losses vs. stator tooth height.

But according to equations 3 and 4, the iron losses rise when increasing the soft magnetic iron volume. This behavior is shown by the graph named P_i, which has its minimum at a stator tooth height of 1mm. As the induced eddy current counteract the driving torque, the coil supply in the stator has to be increased to yield the operation torque. For this reason the copper losses are increased when compensating the effect of the eddy current. In Fig. 3 this is shown by the characteristic $P_{co,c}$.

When comparing the resulting drive efficiency with (η) and without (η_{co}) considering the iron losses, the maximum difference between them amounts to 35% as shown in Fig. 4. . The maximum efficiency is about 64%, which is too low when considering the design constraints. Due to the axial flux direction inside the drive and its dimension a lamination of the stator is impossible. Further, SMC material is not considered here for reasons explained in more detail in the following Conclusion. In order to allow to compare different drive designs, the material applied in the simulation as well as the basic drive design will be kept. This results in a constant drive frequency and the k-factors as well as σ can be also regarded as constant. So the only way to reduce the iron losses is to modify the resulting magnetic induction B.

One option is to reduce the volume of the soft magnetic iron by increasing the winding thickness. As a result the outer radius of the stator teeth decreases and the active wire length increases. In Fig. 5 and 6, the winding thickness is increased in steps of 0.1 mm starting from 1.7 mm and ending at 3 mm. The reduced iron volume significantly contributes to lower

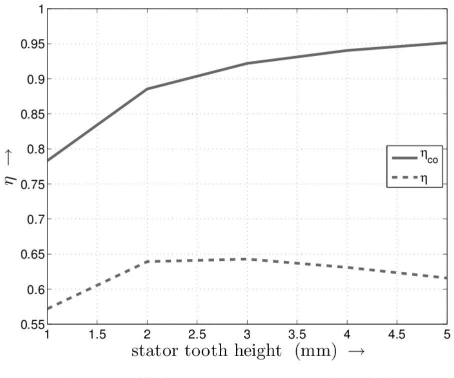

Fig. 4: efficiency vs. stator tooth height.

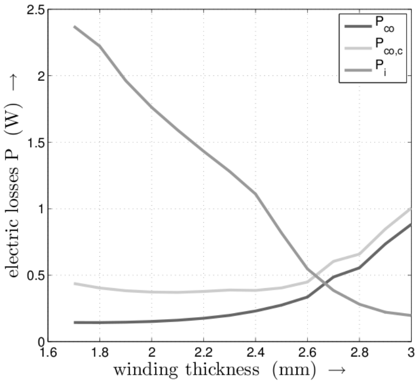

Fig. 5: electric losses vs. winding thickness.

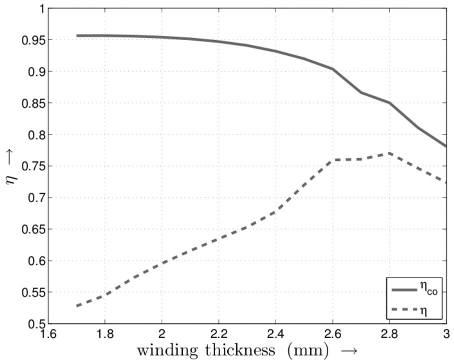

Fig. 6: efficiency vs. winding thickness.

iron losses. Until a thickness of 2.4 mm the copper losses only increase slightly. For this reason this maximum efficiency of about 75% is reached for a winding thickness of 2.8 mm.

As the drive parameters are interdependent of each other, the resulting efficiency is studied in Fig. 7, in dependence of the parameter stator tooth height and winding thickness. Both parameters have an impact on the copper and iron losses. The stator tooth height influences the distribution of the magnetic flux density inside the air gap. When increasing the winding thickness the surface area of the teeth is reduced. In this way the winding resistance is reduced, while the magnetic flux density rises. From the surface plot a maximum efficiency of 77% is obtained, which is slightly higher when only increasing the winding thickness. Further an excessive increase in the winding thickness yields deformated stator teeth and problems in the stability of the stator. For this reason the winding thickness has been limited to 2.5 mm in these simulations.

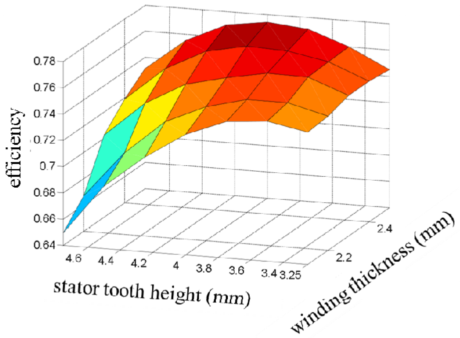

Fig. 7: efficiency vs. stator tooth heigh [mm] and winding thickness [mm].

Further drive parameter to reduce the are the shape and the remanent induction of the rotor magnets as well as the thicknesses of the rotor and stator backirons. As their influence was neglect able in comparison to the presented parameters, they are not presented here.

V. CONCLUSIONS

When studying drive parameters their impact on the electric losses can be identified. A good combination of these parameters yields a high efficient drive and axial force, which can be compensated by the motor's bearing system. As shown in Fig. 4 the efficiency of air gap windings yields an efficiency of approx. 55% for the introduced drive topology. In Ventricular Assist Devices single sided BLDC drives with air gap windings are often applied to yield a compact design and to avoid the drives disadvantage of axial forces. As demonstrated the efficiency of a drive with iron teeth and single tooth winding can be increased beyond 20% when compared to a drive of the same dimension and air gap windings.

SMC is a soft magnetic material consisting of iron particles with an insulating layer. For this reason they are well suited to reduce eddy current losses. On the other hand they yield an increase in the hysteresis losses. Additional the manufacturing with SMC material is more cost extensive. For these reasons SMC material has been excluded from this study.

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