Electromagnetic torque capabilities of axial-flux and radial-flux permanent-magnet machines

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Abstract— **This paper aims to evaluate capabilities of axial-flux and radial-flux permanent-magnet machines. The comparison is done exclusively from an electromagnetic point of view. The electromagnetic design comparison of conventional radial- flux and axial-flux topologies is carried out in view of traction drive applications.**

Index Terms—**Axial-flux permanent-magnet machine, radial-flux permanent-magnet machine, electromagnetic design comparison**

I. INTRODUCTION

The idea of comparing two different machines is a difficult task. Many researchers try to force the equality in comparison using subjective constraints. The end result is often that the constraints themselves favor one geometry over the other, leading to inconclusive results.

Small electronically-commutated (or brushless) axial-flux permanent-magnet (AFPM) machines have been under keen research interest in the last decade as an alternative to conventional radial-flux PM machines, particularly for low-speed direct-drive applications (e.g. wheel motors and wind generators), due to their advantages of flexible disk (pancake) shape, compact and rugged construction, adjustable flat (plane) airgap, high power density and high torque-to-weight ratio [1-3].

The paper presents a comparative analysis of electric motors with PM-excited radial, respectively axial, magnetic flux. The ability to develop the electromagnetic torque defines the comparison criterion. The analysis may serve for sizing / choosing small structures for electric traction and wind-power energy conversion applications.

The machines are compared in terms of electromagnetic torque and torque density capabilities with the overall volume, losses and flux density that are kept constants.

II. RADIAL-FLUX PERMANENT-MAGNET MACHINE

The design of a conventional three phase 6/18 RFPMM has been considered, leading to the configuration shown in Fig. 1.

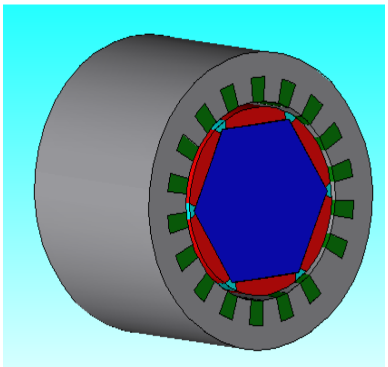

Fig. 1. Radial-flux permanent-magnet machine

For this machine the coils are wound around 18 stator teeth. The magnets are glued on the rotor skeleton.

The main advantage of the radial-flux machine is the standardized topology, which means lower production costs.

III. AXIAL-FLUX PERMANENT-MAGNET MACHINE

The simplest AFPM machine structure uses an annular, slotted (or slotless) stator, containing the radially-arranged armature windings, and a disk-rotor, carrying PMs that produce the axial flux. The AFPM machine has a larger diameter-to-active-length ratio compared to its radial-flux counterpart. As a consequence, when the number of poles increases, the AFPM-machine radial active part remains almost unchanged, while the axial length can decrease, so that the torque density increases.

The research work contained in this paper first refers to small brushless AFPM machines having surface- mounted NdFeB rotor-PMs and three-phase slotted-stator distributed armature windings, which are most suitable for low-speed direct-drive applications. The primary reasons are that, the fixture of external stators may be arranged easily, and the axial loading of bearings is rather small due to the internal rotor topology.

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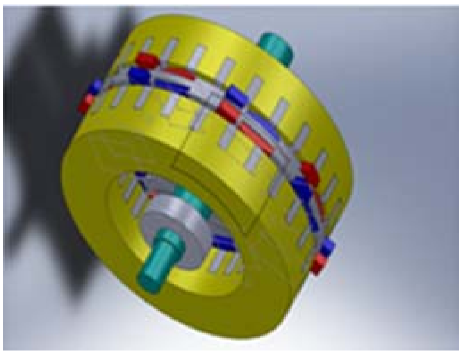


Fig. 2. Axial-flux permanent-magnet machine

Once with the advance in PM technology, the AFPM machine has born interest among the researchers in electric machines domain. The machines with axial airgap made the designers now to consider this solution a feasible one.

The AFPM machine considered in this paper [4] is a two-stators and one-rotor topology. The rotor with 4 pole-pairs is sandwiched between the two stators. The rated power is about 0.3 kW, and the rated rotational speed is 1500 rpm. The magnets are of high-energy NdFeB-type, and are glued on the solid-iron disc-rotor. The material of the stator core is a fully-processed electrical steel sheet M600-50A.

IV. COMPARATIVE ELECTROMAGNETIC DESIGN

Besides the technological and manufacturing differences, it seems interesting to compare AFPM and RFPM machines to understand when and where the first ones show potential advantages.

A general comparison of AFPM vs. RFPM machines is not possible due to the large number of possible technical solutions; thus the comparison is focused on two specific types of surface-mounted PM machines:

- the most common RFPM machine with one external stator and one internal rotor;
- the AFPM machine with two external stators and one internal rotor.

Both machines are compared in terms of electromagnetic torque and torque density for the same overall volume, losses and the flux density. The study is carried out in order to evaluate the comparative capabilities of both machines.

As explained in [5], the comparison between the machines is done using the 'sizing equations', which link the electromagnetic torque (T) to the active machine length (L) and the machine reference diameter (D):

$$T \sim D^2 \cdot L \tag{1}$$

Accordingly, one assumes that the elevation in temperature (ΔT) is due to Joule losses, and the heat transfer is only convective.

Thus, the heat transfer can be expressed as

$$\Delta\theta = \frac{RI^2}{hS_{ex}} , \tag{2}$$

where R is the electrical resistance of the stator winding, which takes into account also the effect of stator teeth, and $S_{ex} = \pi D \cdot L$ is the thermal exchange surface area.

By developing the expressions for R and S_{ex} in (2), the elevation in temperature is found to be constant if the current is proportional to the reference diameter :

$$I^2 = \frac{hS_{ex} \cdot \Delta\theta}{R} = const. \times D^2 \cdot \Delta\theta . \tag{3}$$

From classical equations of electric machine theory, the electromagnetic torque can be considered to be proportional to the useful airgap surface A_{gap} :

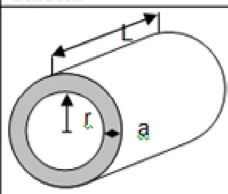
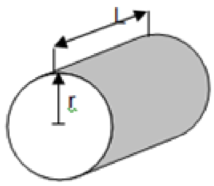
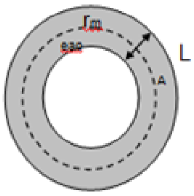
$$T \sim A_{gap} \tag{4}$$

The comparative geometry and electromagnetic torque expression for the RFPM and AFPM machines under study are given in Table I.

The ratio (K) in the torque expression depends only on the technology used to design the PM machines.

The width of the AFPM machine is supposed to be equal to $2a$. This corresponds to the double stator thickness of the RFPM machine, which is a quite realistic assumption.

Table I. Comparative geometry and electromagnetic torque expression for the RFPM and AFPM machines

	Radial	Axial
Bulk		
Area A_{gap} (m²)	 $A_R = 2\pi \cdot r \cdot L$	 $A_A = 2\pi \cdot r_{mean} \cdot L_A$
Volume (m³)	$V_R = \pi \cdot (r+a)^2 \cdot L$	$V_A = \pi \cdot \left(r_{mean} + \frac{L_A}{2}\right)^2 \cdot 2a$
Diameter (m)	$D_R = 2(r+a)$	$D_A = 2\left(r_{mean} + \frac{L_A}{2}\right)$
Width (m)	$W_R = L$	$W_A = 2a$
Torque (Nm)	$T_R = K \cdot 2\pi \cdot \left(\frac{D_R}{2} - a\right)^2 \cdot W_R$	$T_A = K \cdot 2\pi \cdot \left(\frac{D_A}{2} - \frac{L_A}{2}\right)^2 \cdot L_A$

Both AFPM and RFPM machines develop the same torque if they have the same airgap area, i.e. $A_R = A_A$.

The two machines are equivalent if they develop the same electromagnetic torque, and have the same bulk dimensions, i.e. $W_R=W_A$ and $D_R=D_A$.

From Table I, the following torque relation is introduced:

$$T_R = \alpha \cdot T_A \,, \qquad (6)$$

where α defines the torque ratio between the RFPM and AFPM machines. If α is bigger than 1, the RFPM machine structure is obviously preferred instead of an AFPM one.

From the same Table I, one may write :

$$L_A = \frac{D_A}{\beta} \qquad 3 < \beta \leq \infty \qquad (7)$$

where β represents the stack length in relation to the outer diameter for the AFPM machine structure. For machine building practical reasons, $\beta \geq 3$. If β equals 2, the inner diameter of the AFPM machine is null.

By introducing the torque expressions of Table I in (6), one obtains :

$$\left(\frac{D_R}{2} - a\right)^2 \cdot W_R = \alpha \cdot \left(\frac{D_A}{2} - \frac{L_A}{2}\right)^2 \cdot L_A \,. \qquad (8)$$

By considering (7) and the same bulk dimensions of both RFPM and AFPM machines (i.e. $W_R=W_A$ and $D_R=D_A$), (8) leads to

$$\frac{\alpha}{\beta}\left(\frac{\beta - 1}{\beta}\right)^2 x^3 - x^2 + 2x - 1 = 0 \qquad (9)$$

with the shape coefficient $x = \dfrac{D_A}{W_A} = \dfrac{D}{W}$.

An AFPM machine can be transformed around its mean radius into a RFPM machine. In such a transformation, the width is always two times smaller than the diameter, which means that $x \geq 3$.

In the particular case $\alpha = 1$, (9) becomes

$$(x-\beta)\left(x - \frac{\beta(2\beta-1) + \beta\sqrt{4\beta-3}}{2(\beta-1)^2}\right) \times \left(x - \frac{\beta(2\beta-1) - \beta\sqrt{4\beta-3}}{2(\beta-1)^2}\right) = 0. \qquad (10)$$

Equation (10) shows that an AFPM machine is equivalent to a RFPM one with the same bulk dimensions if the shape coefficient x is equal to β.

To be efficient, the AFPM machine must have a high diameter for a small width. For example, if $\beta=4$, the diameter must be, at least, four times higher than the width in order to have an AFPM machine structure instead of a RFPM one.

The expression of $\alpha\,(x, \beta)$ can be obtained from (9) as

$$\alpha(x,\beta) = \frac{(x-1)^2 \cdot \beta^3}{(\beta-1)^2 \cdot x^2} \qquad (11)$$

If $\alpha > 1$, RFPM machine is preferred, while if $\alpha < 1$, AFPM machine is better. The above equations do not allow the machine sizing, but gives the answer whether the designed AFPM or RFPM machine is well chosen with reference to its bulk dimensions.

Fig. 3 shows the evolution of α as a function of x and β. When $\alpha < 1$, at the bottom of the figure, an AFPM machine structure is a good choice, otherwise a classical RFPM one should be preferred.

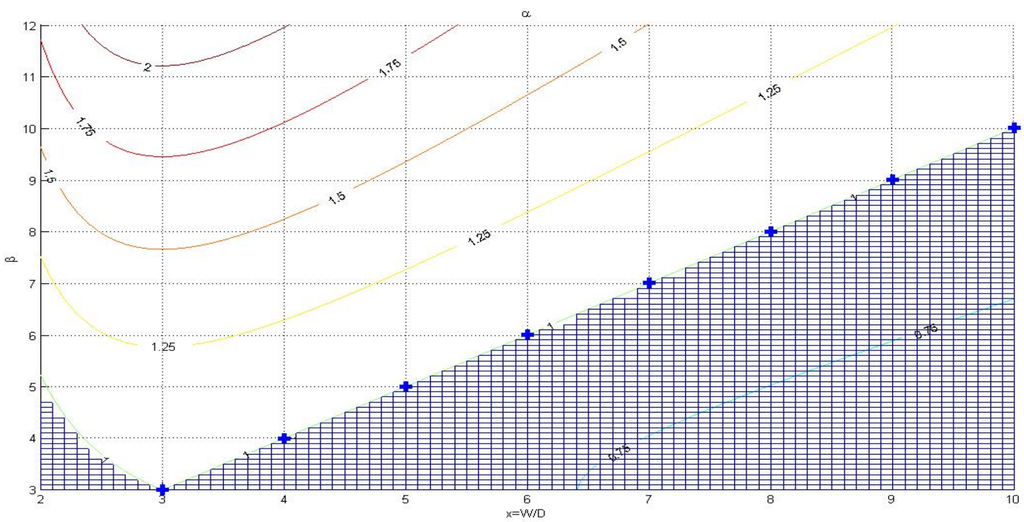


Fig. 3. Evolution of α as a function of x and β, for single airgap.

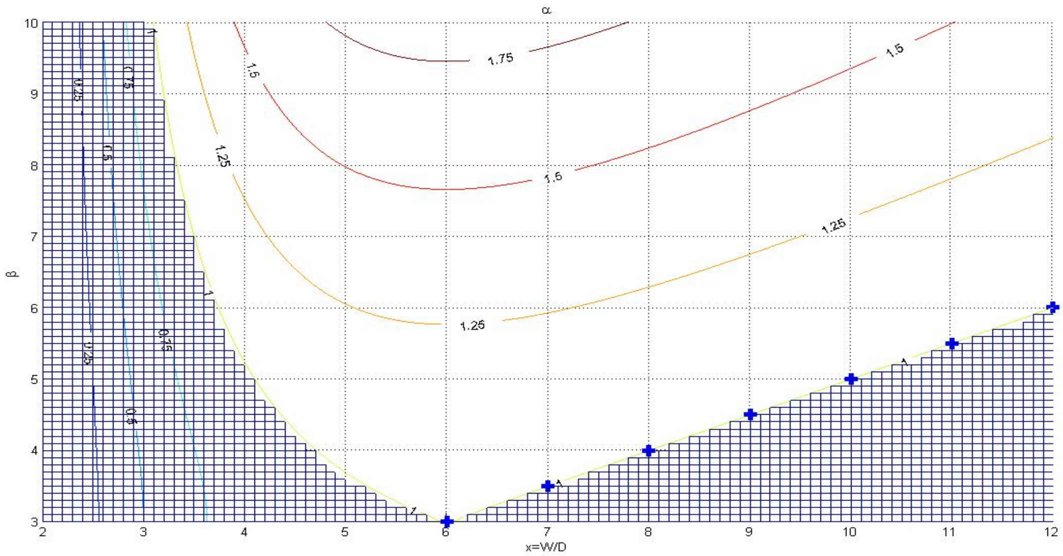


Fig. 4. Evolution of α as a function of x and β, for double airgap.

V. Conclusions

The reasoning process is similar if an AFPM machine with double airgap is studied; then, the width is $W_A = 4a$ and the electromagnetic torque becomes

$$T_A = 2K \cdot 2\pi \cdot \left(\frac{D_A}{2} - \frac{L_A}{2}\right)^2 \cdot L_A \qquad (12)$$

Equation (10) is simply multiplied by 2. Fig. 4 shows the evolution of α as a function of x and β, for this case. The domain for preferential choice of an AFPM machine is increased.

If in the above torque expressions, one considers the machine diameter at the third power instead of the second one, one obtains again $x = \beta$ as a solution of (10), what means that the electromagnetic torque is also proportional to $D^3 L$, as reported earlier in [3].

It must be emphasize that the other two solutions, x_2 and x_3, of equation (10) are always smaller than 3, and converge towards 1, as shown in Fig. 5.

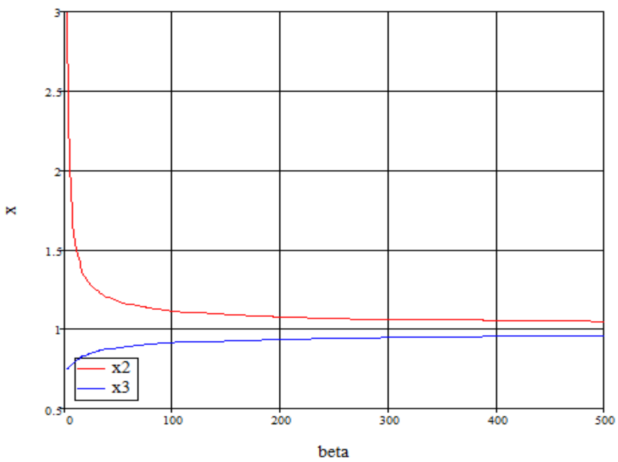


Fig. 5. Evolution of x_2 and x_3 as a function of β.

RFPM machines possess positive features for electric traction applications, such as simple structure, ruggedness, high torque density and wide-speed operation range. For a direct-drive topology, the AFPM machine provides higher torque-to-weight ratio, better heat removal, flexible compact shape and adjustable airgap, as compared to its RFPM counterpart.

The comparative electromagnetic design analysis developed in the paper for RFPM and AFPM machine topologies has shown that both are equivalent in torque and size, if the shape coefficient x is equal to the ratio β between the stack length to the outer diameter of the PM machine. Besides, there is a certain combination of coefficients x and β, for which the AFPM machine structure provides more torque capability than the classical RFPM one.

Since the PM machine output torque is proportional to the effective airgap area for constant electrical and magnetic loadings, the AFPM machine with double airgap reveals higher torque-to-weight ratio.

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