AXIAL AND RADIAL-FLUX PERMANENT MAGNET GENERATORS FOR DIRECT-DRIVE WIND TURBINES.

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ABSTRACT: The application of permanent magnet machines as direct-drive generators for wind turbines is considered. The Axial-Flux Permanent-Magnet (AFPM) machine with slots is compared to the Radial-Flux Permanent-Magnet (RFPM) machine, for this application. Using a computer-based design model, the two machine types are optimized with respect to the lowest Cost/Torque. Design optimization for maximum Torque/Volume is also investigated. The calculations show that the RFPM machine has lower Cost/Torque than the AFPM machine with slots, and lower torque/volume than the AFPM machine with slots.
Keywords: Generators, Direct Drive, Cost Analyses.

1. INTRODUCTION

The conventional electromechanical converter of a wind turbine is composed of a gearbox and an induction generator. A second alternative is to use a direct-drive generator with an AC/AC converter. The direct-drive solution eliminates the maintenance associated to the gearbox, and possibly increases the system reliability. The direct-drive system also provides a fully-variable speed system, which increases the power extracted from the wind, and increases the grid stability. Variable-speed can also be achieved with the gearbox system, if its induction generator is doubly-fed. Then, the induction generator must have a wound rotor connected to an AC/AC converter. The doubly-fed induction generator requires slip rings, which must be regularly inspected. The direct-drive solution eliminates both the inspection of slip rings, and the maintenance of the gearbox.

Even though many advantages arise from the use of a direct-drive system, the greatest majority of wind turbines sold today still contain a gearbox system. This can be explained by the cost of the actual direct-drive systems. A study presented in [1] indicates that direct-drive systems using a wound-rotor synchronous machine are substantially more expensive than the geared system. Discussions with a few wind turbine manufacturers also confirmed this idea, that direct-drive is still more expensive than the geared-drive system.

If a breakdown of the costs of a direct-drive wind turbine is made, it appears that the generator represents a significant part of the turbine cost. In [1], the wound-rotor synchronous generator studied represents 36% of the total turbine cost, with a rated power of 1.5 MW. The study of [1] is done with a wound-rotor synchronous generator. However, there is a possibility that other machine configurations could bring a lower generator cost. An interesting direction is the replacement of the rotor windings in the synchronous generator by permanent magnets. A study [2] shows that the mass of a radial-flux permanent magnets generator may be 2 times lower than that of a wound-rotor synchronous generator of the same diameter. The costs are also substantially reduced.

With respect to permanent magnet generators, some people in the wind turbine industry seem to think that further gains can be obtained if axially-oriented magnets are used in the generator, instead of radially-oriented magnets. In this paper, we compare the Axial-Flux Permanent Magnet (AFPM) machine with slots to the Radial-Flux Permanent Magnet (RFPM) machine. The study investigates if any substantial cost benefits can be obtained if the AFPM machine is used, instead of the RFPM machine.

This comparison is made on the basis of the total cost of active material divided by the rated torque of the machine. The designs of both the RFPM and AFPM machines are optimized, and the results show that RFPM generators still have a lower cost/torque than the AFPM machines with slots.

2. AXIAL AND RADIAL-FLUX PERMANENT MAGNET MACHINES

Permanent magnet machines allow a great deal of flexibility in their geometry. Among other possibilities, the permanent magnets on the rotor, can be either radially or axially oriented.

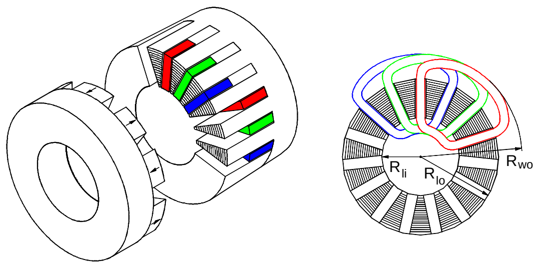

Figure 1: AFPM machine with slots

Figure 1 illustrates an AFPM machine with slots. It must be noted that the axial-flux machine can also be built without slots. The result is a TORUS machine, which has the advantage of easy construction, but the disadvantage of large air gaps and thick magnets. The resulting machine design appears to be about 2 times more costly than the RFPM machine of equivalent diameter [3]. In this paper, the TORUS machine is not analyzed further. Only the AFPM machine with slots will be considered.

The AFPM machine with slots is compared to the RFPM machine, which also has slots. The RFPM machine is shown in fig. 2.

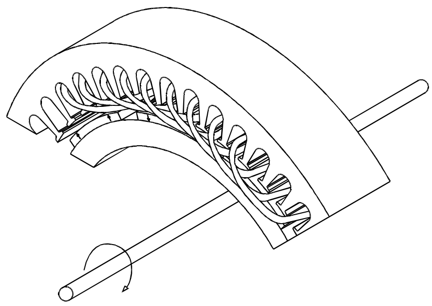

Figure 2: RFPM machine

3. OPTIMIZATION PROCESS AND CRITERIA

The comparison between the AFPM machine with slots and the RFPM machine is done as follows. First, a computer-based design model has been developed. Such a model allows a fast calculation of the machine design, its geometry, and its resulting performances. For a given outer diameter, the design program calculates 4320 different designs of AFPM machines with slots. Table I shows the parameters used in the design model.

Table I: AFPM Design parameters

DESIGN VARIABLES :

Radii ratio K_R	Between 0.4 and 0.9
Pole pitch at inner radius	Between 3.5 cm and 12 cm
Flux density B_g in the airgap	Between 0.5 and 0.95

DESIGN CONSTANTS :

Number of phases	3
Number of slots per pole	3
Slot depth	4 x slot width
Current density J	3.6 A/mm^2
Copper filling factor	0.62
Ratio of slot width over tooth width at inner radius	1.05 (constant for all designs)
Airgap thickness	0.1% of outside diameter
Number of conductors per slot	2
Permanent magnets used	Nd-Fe-B, 1.1 tesla
Phase angle between I and E	0 degree
Magnet width/ Pole pitch	0.7
Skewing factor	0.95
Thickness of the slot wedge	5 mm

The factor K_R in table I is defined by:

$$K_R = \frac{R_{li}}{R_{lo}}$$

where R_{li} and R_{lo} are shown in fig. 1. The optimization process has been conducted for several diameters: outer diameters between 1 m and 5 m have been considered. The diameters and rotational speeds are given in table II.

The diameter D_{out} used for the AFPM is the total machine diameter, including the end windings. It must be noted that in principle, there is no direct link between the turbine rotational speed and the generator outside diameter.

Table II: Outer diameters and corresponding rotational speeds used in the design calculations for AFPM and RFPM machines

D_{out} (m)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
N (rpm)	75	55	46	38	34	29	26	19

The rotational speeds of table II have been chosen by the authors, as reasonable values for a wind turbine, with respect to the obtained torque. The chosen speed is used for the comparison of efficiencies.

All 4320 designs of AFPM machines are different. For each design, the masses of copper, steel laminations and permanent magnets are calculated, and multiplied by a specific cost. The specific costs chosen for this study are 6 Euro/kg for steel and copper, and 40 Euro/kg for permanent magnets. These numbers include the cost of active material and some labor, but they remain approximations.

In the end, all designs of AFPM machine have different costs, torques and powers. The program identifies the AFPM design with the lowest cost/torque. The volume is also calculated for each of the 4320 designs, and the design with the highest ratio of torque/volume is identified.

In the optimization of the RFPM machine, a second computer-based model has been developed. For a given outer diameter and a given axial length, 432 different designs of the RFPM machine are calculated. Then, the axial length of the RFPM machine is adjusted to obtain the same torque rating as the optimized AFPM machine, and the optimization program is run once again. The masses, cost, torque, power and volume are obtained for each of the 432 designs. The cost/torque and torque/volume are obtained. Table II illustrates the design parameters used for the RFPM machine.

Table III: RFPM Design variables

Pole pitch	Between 3.5 cm and 12 cm
Flux density B_g in the airgap	Between 0.5 and 0.95

The design constants used for the RFPM are exactly the same as the ones used for the AFPM machine, and those are presented in table I. For the RFPM machine, D_{out} is also the outer diameter, and it includes the stator back iron.

For both AFPM and RFPM designs, saturation has been taken into account, by eliminating all designs with a tooth flux density higher than 1.9 T at no-load. In fact, this requirement is not so important, because all the designs with optimum cost/torque showed a tooth flux density in the vincinity of 1.5 T.

It should be noted here that cost/torque and torque/volume are used here as optimization criteria, instead of cost/power and power/volume. For low rotational speeds, a given machine with a given mass will have double power, if the rotational speed is doubled. Since we are dealing with wind turbines having different nominal speeds, the only way to compare direct-drive generators together is to use power P_{mech} divided by rotational speed N as a basis for comparison, instead of power. Since P_{mech} /N is proportional to torque, it is reasonable to use the torque T_{mech} as the basis for comparison.

4. RESULTS OF THE OPTIMIZATION PROCESS

4.1 Optimization of Cost/Torque

The AFPM machines presented here have been optimized for the lowest Cost/Torque possible. Table IV shows the resulting Cost/Torque for AFPM machines with outer diameters between 1 m and 5 m.

The optimization process is also applied to RFPM machines. The RFPM machine design with the lowest Cost/Torque is then obtained, and the results are shown in Table V.

It must be noted that the total axial length L_{tot} of the RFPM machine includes the end windings. In the calculation of torque/volume, the volume is also computed by considering the end windings.

Table IV: AFPM designs with the lowest Cost/torque, for several diameters

D_{out}	K_R	T_{nom}	Cost/ Torque	Torque density
(m)	-	(kNm)	Euro/ kNm	kNm/m^3
1.0	0.87	1.0	523	23
1.5	0.87	5.4	333	38
2.0	0.87	17.4	244	53
2.5	0.87	40.8	192	68
3.0	0.86	83.8	159	85
3.5	0.89	112.4	136	83
4.0	0.89	173.9	119	99
5.0	0.88	346.4	97	128

Table V: RFPM designs with the lowest Cost/torque, for several diameters

D_{out}	L_{tot}	T_{nom}	Cost/ Torque	Torque density
(m)	(m)	(kNm)	Euro/ kNm	kNm/m^3
1.0	0.13	1.0	476	11
1.5	0.19	5.8	295	18
2.0	0.24	17.9	218	24
2.5	0.29	40.9	172	29
3.0	0.34	84.0	139	35
3.5	0.34	112.4	121	35
4.0	0.37	175.1	105	38
5.0	0.42	345.3	85	42

For all diameters, the RFPM machine has a Cost/Torque 9 to 12 % lower than for the AFPM machine with slots.

4.2 Optimization of Torque/Volume

Table VI now presents the result of the optimization process, if the AFPM machine design with the highest torque/volume is chosen. An equivalent RFPM design is also derived, with the same diameter and nominal torque. The design is optimized for highest torque/volume. The results are presented in table VII.

For all diameters, the optimum ratio K_R for maximum Torque/Volume is about 0.66. Inspection of tables VI and VII readily indicates that much higher torque/volume may be obtained with the AFPM machine with slots. A ratio of 4.3 is observed for D_{out} = 5m. However, an AFPM machine K_R = 0.66 gives a much higher Cost/Torque than for the RFPM machine. For a 5 m-diameter AFPM machine, the Cost/Torque is 80% higher than for the RFPM machine.

Table VI: AFPM designs with the highest Torque/Volume, for several diameters

D_{out}	K_R	T_{nom}	Cost/ Torque	Torque density
(m)	-	(kNm)	Euro/ kNm	kNm/m^3
1.0	0.64	2.0	728	38
1.5	0.63	9.6	478	62
2.0	0.66	26.8	330	86
2.5	0.66	65.4	261	110
3.0	0.66	129.7	220	134
3.5	0.66	241.7	187	159
4.0	0.65	384.8	167	183
5.0	0.65	758.0	141	229

Table VII: RFPM designs with the highest Torque/Volume, for several diameters

D_{out}	L_{tot}	T_{nom}	Cost/ Torque	Torque density
(m)	(m)	(kNm)	Euro/ kNm	kNm/m^3
1.0	0.16	2.0	440	15
1.5	0.24	10.0	279	24
2.0	0.29	26.8	205	30
2.5	0.36	65.5	159	37
3.0	0.43	130.0	128	43
3.5	0.52	243.4	108	49
4.0	0.60	384.4	95	51
5.0	0.72	758.8	78	53

4.3 Effect of K_R on Cost/Torque, Torque/Volume and efficiency of the AFPM machines

Table IV showed that AFPM machines with slots obtain the lowest Cost/Torque when K_R ~ 0.88, for all the diameters investigated. Also, table VI shows that the highest Torque/Volume is obtained when K_R ~ 0.66, for all the diameters investigated. Fig. 3 shows the variation of cost/torque of AFPM machines, as a function of K_R, for an AFPM machine having an outer diameter of 5 m. Each point in fig. 3 represents a machine design, which is optimized for lowest cost/torque.

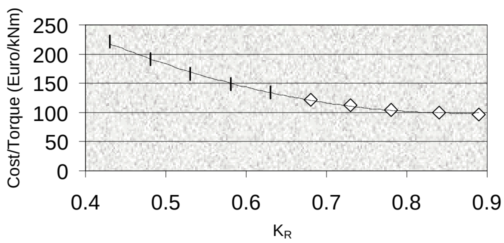

Figure 3: Cost/Torque of optimized AFPM designs, for a 5 meter-diameter machine vs K_R

The trend observed in fig. 3 for a 5 meter-diameter AFPM machine was also observed for all other diameters. The Cost/Torque decreases, as K_R gets closer to unity.

Fig. 4 shows the variation of torque density for AFPM machine designs. The outer diameter is 5 meter for each design, and each AFPM design is optimized for the highest torque/volume. Fig. 4 shows a maximum of the torque density curve, for K_R ~ 0.66. This was also observed for all the other diameters investigated.

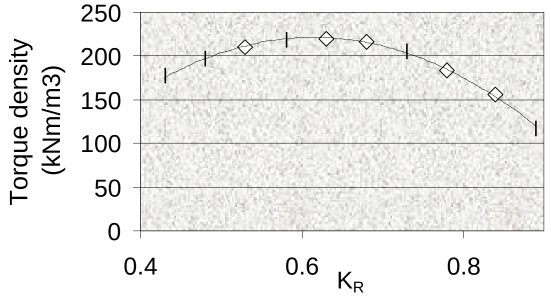

Figure 4: Torque/Volume of optimized AFPM designs, for a 5 meter-diameter machine vs K_R

Earlier, we stated that the cost of direct-drive generators should be decreased. Since cost is more important than volume, the ratio K_R should be made as high as possible. However, the efficiency must also be considered in the application. Fig. 5 shows the efficiency as a function of K_R.

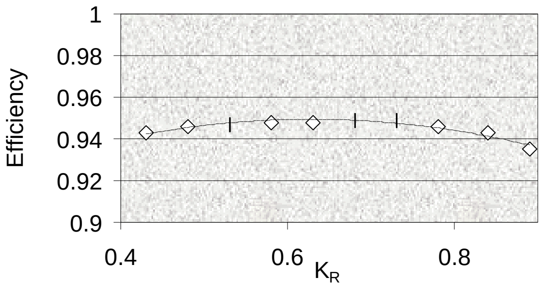

Figure 5: Efficiency of a 5 meter-diameter AFPM machine vs K_R.

In fig. 5, each point represents a machine design, where the optimization constraint was the lowest cost/torque. Inspection of figure 5 shows that increasing K_R near unity brings a significant decrease in efficiency. This is caused by the presence of copper losses in the end windings. For high values of K_R, the end windings become almost as long as the parts of the windings housed inside the slots. If efficiency is to be considered, the ratio K_R should not be made too high. A good trade-off between low cost/torque and acceptable efficiency is obtained for values of K_R between 0.75 and 0.80.

In table VIII, the AFPM design has been optimized with respect to the lowest Cost/Torque, while K_R has been set constant to 0.78. The optimization process is also applied to RFPM machines. The RFPM machine design with the lowest Cost/Torque is then obtained, and the results are shown in Table IX.

Table VIII: AFPM designs with the lowest Cost/torque, for several diameters and K_R = 0.78

D_{out}	T_{nom}	Cost/ Torque	Torque density	Eff.
(m)	(kNm)	Euro/ kNm	kNm/m^3	(%)
1.0	2.0	551	33	90.0
1.5	9.7	354	53	91.8
2.0	31.2	260	73	92.8
2.5	66.0	206	95	93.6
3.0	116	168	113	94.3
3.5	189	146	135	94.6
4.0	260	127	147	94.6
5.0	516	105	187	94.5

Table IX: RFPM designs with the lowest Cost/torque, for several diameters

D_{out}	T_{nom}	Cost/ Torque	Torque density	Eff
(m)	(kNm)	Euro/ kNm	kNm/m^3	(%)
1.0	2.0	434	16	90.0
1.5	9.8	280	24	91.3
2.0	31.2	201	32	92.7
2.5	65.9	158	37	93.3
3.0	116.2	130	41	94.3
3.5	188.8	111	44	94.6
4.0	259.8	99	45	94.9
5.0	515.4	81	48	94.7

The RFPM machines now have a Cost/Torque about 22% lower than the AFPM machines. The efficiency performances of the two machines are quite comparable.

5. CONCLUSION

This study investigated whether the AFPM machine with slots could give a cheaper direct-drive generator than the RFPM machine. For AFPM machines, the lowest Cost/Torque occurs at K_R = 0.88. However, the end windings create significant losses for high values of K_R. A good trade-off between high efficiency and low Cost/Torque was chosen as K_R = 0.78.

A comparison between the optimal Cost/Torque of the RFPM machine and that of the AFPM machine with slots was performed. The AFPM machine with slots with K_R = 0.78 gives a Cost/Torque about 22% higher than the RFPM machine of the same diameter and same nominal torque rating. For K_R = 0.88, the Cost/Torque of the AFPM machine with slots was still about 12% higher than the Cost/Torque of the RFPM machine.

The torques/volume of the two machine types have also been compared. The torque/volume of the AFPM machine with slots is 2 to 5 times higher than that of the RFPM machine. The main difference lies in the thickness of the AFPM machine, which is much shorter than for the RFPM machine.

In direct-drive generators, cost reduction is more important than the reduction of the total axial thickness. Based on the results presented herein, the RFPM machine still appears as a better choice for a direct-drive generator, than the AFPM machine with slots.

6. REFERENCES

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