Comparison of generator topologies for direct-drive wind turbines

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ABSTRACT

In direct-drive wind turbines, the generator outer diameter and cost must be reduced substantially to allow a higher penetration of direct-drive wind-turbines on the market. In this paper, different generator topologies are investigated. A comparison is carried out, on the basis of 60 different machine prototypes built or designed by numerous authors. Data for those machines is found in the scientific literature. The comparison is based on torque density and cost/torque. Only the machines active material is considered.

Keywords: Wind turbines, direct-drive, wind turbine generators, machine comparisons, generator cost.

1. INTRODUCTION

The comparison of machines of different topologies is a rather tricky task. Analytical derivation of the torque density and mass of active material is possible for every topology. Such a mathematical model, based on the geometrical parameters of each topology, must also take into consideration the thermal characteristics of the machines. Although thermal modeling of a geometry can be achieved, it is strongly dependent on the inactive material (support, enclosure) geometry, which are often variable, depending on the application.

Another method of comparing machine topologies, is to build (or design) a large number of prototypes, and obtain sufficient information to draw a general conclusion. This is the method used in this paper, except that no prototypes were built by the authors. All the data on machine prototypes are taken from the scientific literature, which is filled with examples of built prototypes.

This paper compares various machine topologies with the well known characteristics of the Radial Flux Permanent Magnet (RFPM) machine built with surface magnets.

The criteria used for comparison are torque density (torque per volume), and cost/torque. These two criteria are identified as being critical for the integration of direct-drive generators in wind turbines.

2. CRITERIA

The two criteria used for comparison are:

- Torque density (in kNm / m^3)
- Cost / torque (in ECU / kNm)

2.1. Torque density

Nowadays, direct-drive generators have large diameters, leading to transportation and installation problems. Also, the wind turbine nacelle must be redesigned completely. Direct-drive generators can be built with lower diameters. However, this increases their length substantially, especially at powers above 1 MW. Power density becomes a very important criterion.

It is possible to increase the power density of a given machine, only by increasing its rotational speed. Therefore, it is not possible to compare machines having different rotational speeds, by using power density. Torque density is chosen, because it is independent of the choice for any rotational speed. This is true only up to a certain speed, which is largely above the typical speeds found in wind turbines.

Torque density is defined as:

$$T_d = \frac{T}{(\pi d_o^2/4)L_a} \tag{1}$$

Where T is the machine nominal torque in kNm, T_d is the machine torque density in kNm/m^3, d_o is the stator outer diameter (active outer diameter only), and L_a is the machine total axial length (active length only including stator end windings).

Torque density is presented as a function of diameter. All machines can be stacked in their axial length. For a given diameter, the torque density and cost/torque is the same for any number of machines stacked in their axial length.

2.2. Cost/Torque

Generator cost is critical for the acceptance of direct-drive on the market. For a given power, the topology chosen should minimize the cost of active material. However, cost/power cannot be used to compare machines of different rotational speeds. Cost/torque must be used for the same reason as explained above. Producing more torque requires extra magnet thickness, extra conducting material, and extra iron, which all lead to an increase in cost.

However, it is difficult to obtain the cost for a machine from most authors. An estimation for cost was done from three assumptions:

A) Only active material is considered in costs. Manufacturing costs and costs for inactive material are not included.

B) Iron, copper and ferrite magnets have specific costs: 6 ECU / kg

C) Rare earth magnets have specific costs: 40 ECU / kg

3. MACHINE TOPOLOGIES INVESTIGATED

The study is carried out for various machine topologies. They are listed below. Some of them are not illustrated. Illustrations are provided in the accompanying reference.

The machine topologies covered in this study are:

A) Radial Flux Permanent Magnet (RFPM) machine with surface magnets [1][2][3][10], illustrated in figure 1.

B) Radial Flux Permanent Magnet (RFPM) with flux concentration (ferrite magnets)[9].

C) Axial Flux Permanent Magnet (AFPM) with air gap windings or “Torus” [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23], illustrated in figure 2.

D) Transverse Flux Permanent Magnet (TFPM), including 4 variants:

- with flux concentration; Weh variant [4], illustrated in figure 3.
- with flux concentration; Mitcham variant [8].
- Single-Sided Surface Magnets (SSSM) [5][7].
- Double-Sided Flux-concentrated (DSFC) [5][6], illustrated in figure 4.

E) Switched-Reluctance Machine (SRM) [27][28] [29].

F) Transverse Vernier Individual Hybrid Reluctance Machine (TVIHRM) [26].

G) Axial Flux Interior Permanent Magnet (AFIPM) (with slot windings) [10][11], illustrated in figure 5.

The data used for each topology was taken from previous work by different authors. For each above mentioned topology, the source of information is included in the accompanying reference.

Other topologies were also considered, but were not used in the comparison, due to the lack of sufficient optimized designs [24][25].

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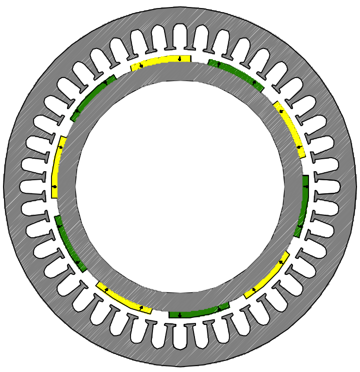

Fig. 1: Radial Flux Permanent Magnet (RFPM) machine with surface magnets

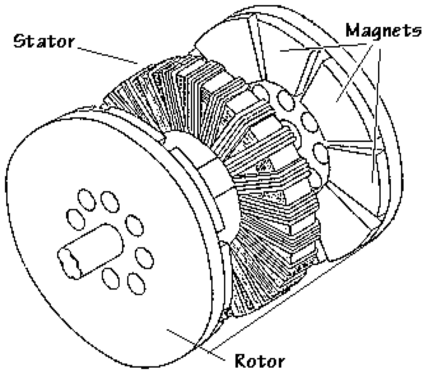

Fig. 2: Axial Flux Permanent Magnet (AFPM) machine with air gap windings or “Torus”

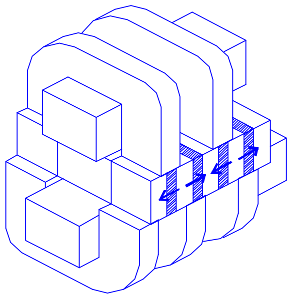

Fig. 3: Three (3) poles of a Transverse Flux Permanent Magnet (TFPM) machine with flux concentration; Weh variant

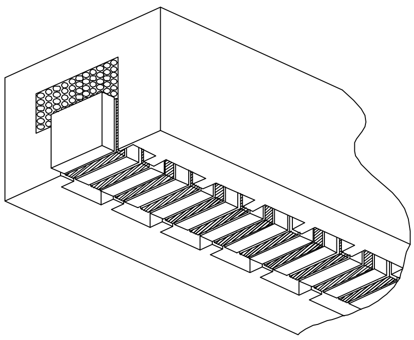

Fig. 4: Transverse Flux Permanent Magnet (TFPM) machine, Double-Sided Flux-concentrated (DSFC)

Most of the prototypes or designs considered were optimized designs, which makes it possible to compare machines together.

The induction machine is not included in the comparison, because induction generators used in direct-drive configuration require large number of poles and large diameters, which lead to high magnetizing currents. Their power factor and efficiency are low and their axial length must be increased substantially, in order to give acceptable performance (see design example in [29]).

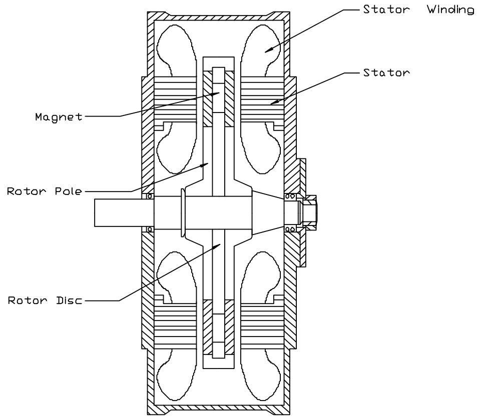

Fig. 5: Axial Flux Interior Permanent Magnet machine

4. RESULTS OF COLLECTED DATA

4.1. "Torus" machine vs RFPM machine with surface magnets

Figure 6 shows that machines built with the "Torus" topology give torque densities twice higher than the torque densities of the RFPM machine with surface magnets.

However, the air gap winding requires that thick magnets be placed on the rotor. Figure 7 shows that machines designed with the "Torus" topology have a cost/torque for active material twice the cost/torque for the RFPM topology with surface magnets, for any given diameter.

4.2. Transverse Flux Permanent Magnet (TFPM) vs RFPM machine with surface magnets

Figure 6 shows that TFPM machines can be built with 2 to 3 times the torque density of RFPM machines with surface magnets.

Contrary to the "Torus" machine, where double torque density was reached at the expense of twice the cost per torque, the TFPM machine can reach lower cost per torque than the RFPM machine with surface magnets. Figure 7 shows it is possible to build TFPM machines with about half the cost/torque of the RFPM machine with surface magnets.

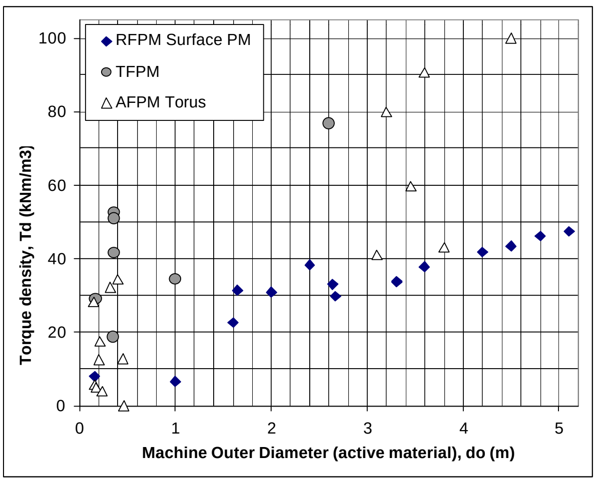

Fig. 6: Torque density for "Torus", TFPM and RFPM with surface magnets

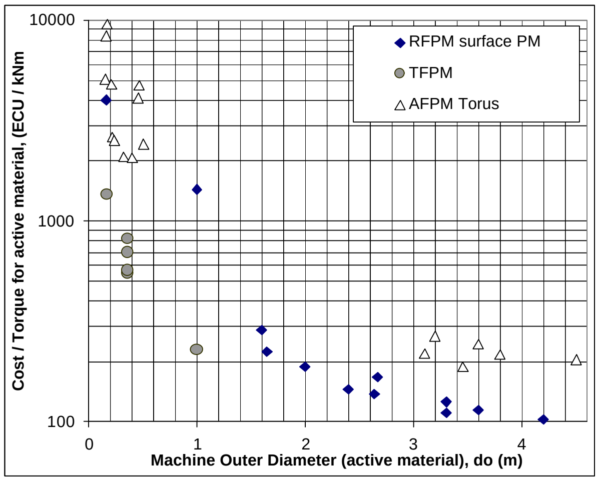

Fig. 7: Cost/torque for "Torus", TFPM and RFPM with surface magnets

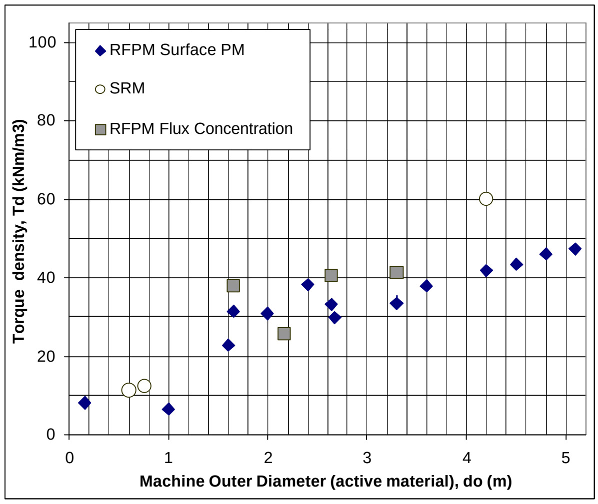

Fig. 8: Torque density for RFPM with flux concentration (and ferrite magnets), SRM and RFPM with NdFeB surface magnets.

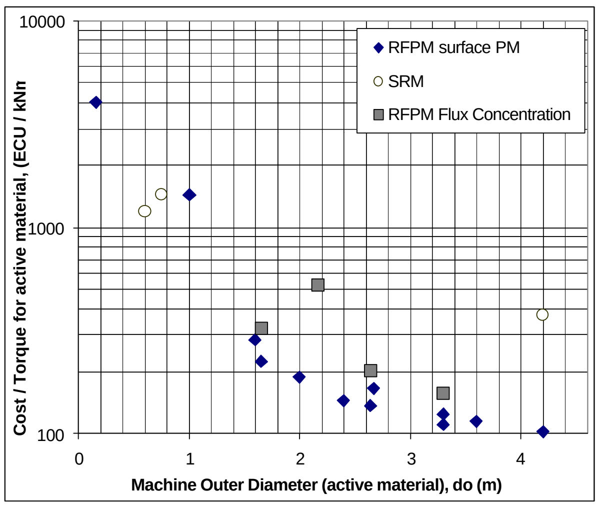

Fig. 9: Cost/torque for RFPM with flux concentration (and ferrite magnets), SRM and RFPM with NdFeB surface magnets

4.3. RFPM machine with Flux concentration vs RFPM machine with surface magnets

Figure 8 and figure 9 show that there is no real advantage in using RFPM machines with buried ferrite magnets (flux concentration structure).

Nearly equivalent torque densities are observed in the prototypes built, and similar (or even higher) costs/torque are observed.

With decreasing cost for rare earth magnets, the advantage of the RFPM machine used in flux concentration structure will become even less obvious.

4.4. Switched-Reluctance Machine(SRM)

Figure 8 and figure 9 show that SRM designs lead to torque density and cost/torque close to the values obtained for RFPM machines. In the case of the 4.2 m diameter machine designed by [29], a torque density 50% higher is obtained, at the expense of very high rotor mass, and therefore high cost/torque (4 times the cost/torque of the RFPM machine with surface magnets of equivalent diameter).

4.5. Axial Flux Interior Permanent Magnet (AFIPM) machine vs others

Only one built prototype of the AFIPM machine was reported [11]. A comparison with designs of other topologies with equivalent diameters is carried out in table 2. The prototype of the AFIPM machine shows characteristics close to those of the TFPM prototype. Both AFIPM and TFPM prototypes of table 2 show higher performance than RFPM and “Torus” machines built.

4.6. Transverse Vernier Individual Hybrid Reluctance Machine (TVIHRM) vs others

Only one optimized prototype of the TVIHRM was reported [26]. A comparison with other topologies of equivalent diameters is carried out in table 1. The prototype of the TVIHRM machine gives torque density much lower than the TFPM and “Torus” prototypes.

However, the cost/torque is lower than the cost/torque observed in the case of the “Torus” prototype of equivalent diameter. Also, the cost/torque of the TVIHRM prototype is higher than the cost/ torque for the TFPM prototype of equivalent diameter.

Topology	Diameter	Torque density	Approximate cost/Torque
	(m)	(kNm/m^3)	(ECU/kNm)
TVIHRM	0,40	9,1	1565
AFPM Torus - 1 stage	0,40	34,4	2063
TFPM DSFC	0,36	50,9	566

Table 1. Comparison of TVIHRM prototype with other machine topologies of equivalent diameter

Topology	Diameter	Torque density	Approximate cost/Torque
	(m)	(kNm/m^3)	(ECU/kNm)
AFIPM	0,17	26,1	1663
TFPM SSSM	0,17	28,9	1360
RFPM surface magnets	0,16	11,5	4021
“Torus” 1-stage	0,21	12,4	4777

Table 2. Comparison of AFIPM prototype with other machine topologies of equivalent diameters

5. CONCLUSION

Prototypes of RFPM machines built using ferrite magnets in flux concentration structure do not show superior characteristics over the RFPM machines built with surface magnets.

Machines built using the “Torus” topology gave twice the torque density of the RFPM machines with surface magnets. However, the large thickness of the magnets make the cost/torque of the “Torus” machines twice that of the RFPM machine with surface magnets.

It is possible to build machines with twice the torque density and half the cost/torque of the RFPM machine with surface magnets, by using the TFPM structure.

SR machines designed gave torque density and cost/torque equivalent to the RFPM machine with surface magnets. SR machines can be built with 50% higher torque density than RFPM machines, at the expense of 4 times the cost/torque.

The prototype of the AFIPM machine showed excellent characteristics, comparable to those of the TFPM prototype of equivalent diameter. Basically, the AFIPM is an axial flux machine with teeth, which requires less magnet material than the “Torus” topology.

The prototypes of the TVIHRM machine did not provide good torque density.

Although this study has no theoretical background, it gives indication from practical experience that two topologies must be considered to meet the target imposed by the wind turbine direct-drive application: lower diameters and lower material costs:

- TFPM machine
- AFIPM machine proposed by [11]

Finally, it must be noted that for all topologies analyzed, the larger the machine diameter, the higher the torque density and the lower the cost/torque.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] Grauers A., Carlson O., Hogberg A., Lundmark P., Johnsson M., Svenning S., “Test and Design Evaluation of a 20 kW Direct Driven PM Generator with a Frequency Converter”, European Wind Energy Conference, EWEA, 1997, p. 686

[2] Lampola P., Perho J., Vaananen J., “Analysis of a low speed PM Wind Generator connected to a frequency converter”, Proceedings of the International Conference on Electrical Machines, Vigo, Spain, 1996, p. 393

[3] Grauers A., “Design of Direct-driven Permanent-Magnet Generators for Wind Turbines”, PhD Thesis, 1996, Chalmers University, Goteborg, Sweden

[4] Weh H., “Directly-Driven Permanent-Magnet Excited Synchronous Generator for Variable Speed Operation”, European Community Wind Energy Conf., EWEA, 1988, p. 566

[5] Harris M. R., Pajooman G. H., Sharkh S.M.A., Mecrow B.C., “Comparison of Flux-Concentrated and Surface-Magnet Configurations of the VRPM (Transverse-Flux) machine”, Proceedings of the International Conference on Electrical Machines, 1998, p. 1119

[6] Mecrow B.C., Jack A.G., Maddison C.P., “PM Machines for High Torque, Low Speed Applications”, Proceedings of the International Conference on Electrical Machines, Vigo, Spain, p. 461

[7] Henneberger G., Bork M., “Development of a new Transverse flux motor”, Colloquium on New Topologies for PM Machines, IEE London 1997, Proceedings, p. 1/1

[8] Mitcham AJ., “Transverse Flux Motors for Electric Propulsion of Ships”, Colloquium on New Topologies for PM Machines, IEE London 1997, Proceedings, p. 3/1

[9] Spooner E., Williamson A.C., “Direct coupled, Permanent Magnet Generators for Wind Turbine”, Proceedings of IEE- Electric Power Applications, Vol 143, No. 1, Jan 96, p. 1

[10] Zhang Z., Profumo F., Tenconi A., “Axial-Flux versus Radial-Flux permanent-magnet motors”, Electromotion, vol. 3, 1996, p. 134

[11] Profumo F., Tenconi A., Zhang Z., Cavagnino A., “Novel Axial Flux Interior PM Synchronous Motor realized with Powdered Soft Magnetic Materials”, Proceedings of the Conference of the Industry Application Society, IEEE, 1998, p. 152

[12] Di Napoli A., Caricchi F., Crescimbini F., Noia G., “Design Criteria of a Low-Speed Axial-Flux PM Synchronous Machines”, International Conference on Evolution and Modern Aspects of Synchronous Machines, 1991, p. 1119

[13] Honorati O., Caricchi F., Crescimbini F., Noia G., “Gear-Less Wind Energy Conversion System Using an Axial Flux PM Synchronous Machine”, Proceedings of the European Wind Energy Conference, Amsterdam, EWEA, 1991, p. 814

[14] Lo Bianco G., Caricchi F., Crescimbini F., Honorati O., “Design of Gearless Wind Generator for Off-Shore Applications”, OWEMES, 1997, p. 365

[15] Caricchi F., Callea V., Crescimbini F., Solero L., Falchetta M., “Prototype of Variable-Speed, Direct-Drive generator for wind power exploitation in extremely cold climates”, Proceedings of the European Wind Energy Conference, Nice, EWEA, 1999, p. 821

[16] Caricchi F., Crescimbini F., Honorati O., Vivarelli R., “Prototype of a Wind-Turbine Directly-Coupled Axial-Flux PM Generator”,

[17] Caricchi F., Crescimbini F., Honorati O., “Modular AFPM for Ship propulsion drives”, Transactions on Energy Conversion, IEEE, Vol. 14, No. 3, Sept. 1999, p. 673

[18] Chalmers B. J., Wu W., Spooner E., “An Axial-Flux PM Generator For a Gearless Wind Energy System”, Transactions on Energy Conversion, IEEE, Vol 14, No.2, June 1999, p. 251

[19] Chalmers B. J., Spooner E., Honorati O., Crescimbini F., Caricchi F., “Compact PM Machines”, Electric Machines and Power Systems, Taylor & Francis, 1997, vol. 25, p.635

[20] Soderlund L., Koski A., Vihriala H., Eriksson J-T., Perala R., “Design of an Axial-Flux Permanent Magnet Wind Power Generator”, Proceedings of the Conference on Electrical Machines and Drives, IEE, 1997, p. 224

[21] Stiebler M., Okla O., “A Permanent-Magnet Toroid Wind-Generator”, Proceedings of the International Conference on Electrical Machines, 1992, p. 1043

[22] Spooner E., Chalmers B.J., ‘‘TORUS: A slotless, toroidal-stator, permanent-magnet generator”, Proceedings of the IEE-B, Nov. 1992, Vol. 139, No. 6, p. 497

[23] Spooner E., Williamson A.C., “PM Generators For Wind Power Application”, Proceedings of the International Conference on Electrical Machines, 1992, p. 1048

[24] Luo J., Qin D., Lipo T.A., Li S., Huang S., “Axial Flux Circumferential Current Permanent Magnet (AFCC) Machine”, Proceedings of the Conference of the Industry Application Society, IEEE, 1998, p. 144

[25] Muljadi E., Butterfield C.P., Wan Y-H: “Axial-Flux, Modular, PM Generator with a toroidal winding for wind turbine application”, Proceedings of the Conference of the Industry Application Society, IEEE, 1998, p. 174

[26] Hadjidj D., Miraoui A., Kauffmann J.M. “Optimization of a Transverse Vernier Individual Hybrid Reluctance Motor for an electrical wheel”, Proceedings of the International Conference on Electrical Machines, 1998, p. 1768

[27] Torrey D. “Variable-Reluctance Generators in Wind-Energy Systems”, Proceedings of the Power Electronics Specialists Conference, IEEE, 1993, p. 561

[28] Mueller M. A. “Design of Low Speed Reluctance Machines for Wind Energy Converters”, Proceedings of the Conference on Electrical Machines and Drives, IEE, 1999, p. 60

[29] De Haan S.W.H., Veltman A.T., Janousek J., Cerovsky Z., Mericka J., Pavelka J., Perina J., Petrasek F., “A high efficiency electrical conversion system with variable reluctance generator for variable speed wind turbine”, ECN report no. ECN-C--95-033, 1995