PM Wind Generator Topologies

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***Abstract*—The objective of this paper is to provide a comparison among permanent magnet (PM) wind generators of different topologies. Seven configurations are chosen for the comparison, consisting of both radial-flux and axial-flux machines. The comparison is done at seven power levels ranging from 1 to 200 kW. The basis for the comparison is discussed and implemented in detail in the design procedure. The criteria used for comparison are considered to be critical for the efficient deployment of PM wind generators. The design data are optimized and verified by finite-element analysis and commercial generator test results. For a given application, the results provide an indication of the best-suited machine.**

***Keywords*: Axial flux, outer rotor, permanent magnet, radial flux, wind generator.**

I. INTRODUCTION

To convert wind power into electricity, many types of generator concepts have been used and proposed, [1]. Most of the low-speed wind turbine generators presented are permanent-magnet (PM) machines. These have the advantages of high efficiency and reliability since there is no need of external excitation and conductor losses are removed from the rotor [2], [3].Basically, PM generators can be divided into radial-flux and axial-flux machines, according to the flux direction in the air gap. Transverse flux machines exist, but do not seem to have gained a foothold in wind power generation. The availability of modern high energy density magnet materials, such as NdFeB, has made it possible to design special topologies such as toothless stators with air gap windings[1],[2]. A comparison of generator topologies for direct-drive wind turbines has been carried out using torque density and costltorque with respect to the machine outer diameter as the criteria [4]. Sixty different machine prototypes are compared. However, the study lacks theoretical background and the data considered deal with different requirements and situations.

Comparison of machines of different topologies is a delicate task. An analytical approach for the derivation of torque density and mass of active material is possible for some topologies. but the application is limited. An effective way to compare machine topologies is to design a large number of prototypes and obtain sufficient information to draw general conclusions. This is the method used in this paper, and optimum design is considered for each prototype.

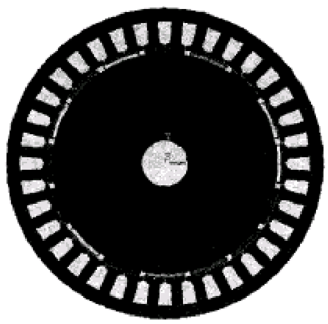

Fig. 1. Inner rotor radial flux construction

The machine topologies considered in this study include the conventional inner-rotor radial-flux construction, outer-rotor radial-flux construction, double-stator axial-flux construction, double rotor axial-flux construction, single-sided axial-flux constructions with force balance stator and force balance rotor, and Torus toothless axial-flux construction. All the compared machines are built with surface-mounted magnets (NdFeB) and grouped into two categories. One has direct-driven generators operating at low speeds of 50 or 100 rot/min; the other has the machines rotating at a high speed of 1200 rot/min, where gearboxes are needed. The criteria used for comparison are torque density, active material weight, outer radius, total length, total volume, and efficiency. These criteria are identified as being critical for the efficient deployment of generators in wind turbines.

The basis for the comparison is highlighted to make the comparison fair and reasonable. The design equations are verified by finite-element analysis and commercial generator test results.

II. MACHINE TOPOLOGIES INVESTIGATED

All the compared machines are three-phase synchronous generators.

A. Conventional Inner-Rotor Radial-Flux Machine This is kind of a typical radial-flux generator, as shown in Fig. 1, with the PM poles rotating inside the stationary armature windings. The stator is made up of electrical grade steel laminations with distributed windings. The rotor is cylindrical

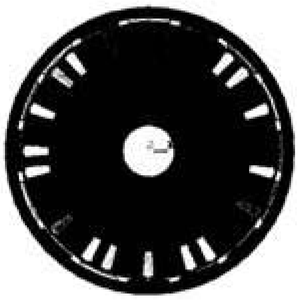

Fig. 2 Radial flux construction with outer rotor

in shape with a shaft on which the bearings are mounted. There are two magnets providing the magnetomotive force (MMF) required in a pair of poles, which can effectively resist the demagnetization caused by the armature reaction in a sudden short circuit. The air gap flux density is closely related to the magnet remanence and the magnet working point. It is difficult to get high air gap flux densities with low remanence magnets in this configuration.

B. Radial-Flux Machine With Outer Rotor As illustrated in Fig. 2, the wound stator in the outer- rotor configuration is stationary, located at the center of the machine, while the magnets are mounted evenly along the inner circumference of the rotating drum supported by front and rear bearings. The magnetic circuits are the same as those in the conventional inner-rotor radial-flux generator. But the blades of the wind turbine can be conveniently bolted to the front face of the drum to realize the direct coupling between the wind turbine and the PM generator. Because of the enlarged periphery of the outer-rotor drum, the multipole structure can be easily accommodated, and therefore the total length of the magnetic path is reduced. As the rotor is directly exposed to the wind, the cooling condition is improved for the magnets so that the resistance to high temperature demagnetization is enhanced.

C. Double-Stator Slotted Axial-Flux Machine The layout of this type of machine is shown in Fig. 3. The shape of the stator as well as the rotor resembles a pancake, and these machines are commonly referred to as pancake machines. The machine consists of two external stators and one inner rotor. The PMs are axially magnetized and are surface mounted or inset into a cut window on the rotor disc. In all axial flux machines, the rotor rotates relative to the stator with the flux crossing the air gap in the axial direction. The stator iron core is laminated in the radial direction and resembles concentric rings that have a constant slot width and tapered teeth.

D. Double Rotor Slotted Axial-Flux Machine This configuration is similar to that of the double-stator slotted axial-flux machine, except that there is one stator and two rotors. The stator is located in the middle of the two rotors and slotted on both sides. An iron flux path is neede rotor back of yoke, but the stator back yoke can be el and saved.

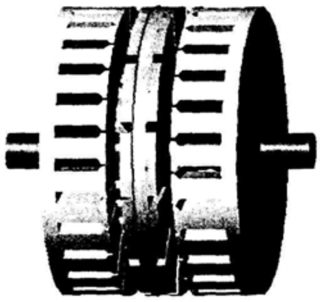

Fig. 3. Axial-flux construction with double stators.

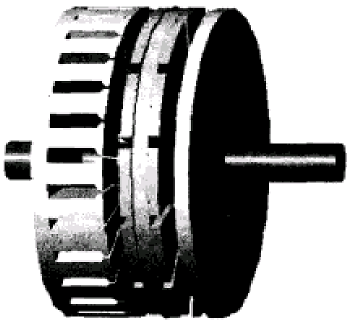

Fig. 4. Single-sided axial-flux machine with stator balance.

E. Single-Sided Axial-Flux Machine With Stator Balance This configuration is simple, as there is only one stator and one rotor. However, a large attractive force exists between the stator and the rotor.

To prevent the rotor from in the axial direction, a special thrust bearing must be used , which will make the construction more complicated. By adding an additional stator to the construction, an effective way is introduced in this paper to balance the attractive force, as shown in Fig. 4. On the opposite side of the rotor, PM poles are needed to produce the magnetic field necessary to induce the balance force. The stator is laminated, as the magnetic field oscillates, creating hysteresis and eddy-current losses.

F Single-Sided Axial-Flux Machine With Rotor Bale
This configuration is similar to the single-sided machine with stator balance, except that an additional mounted magnet is added to the construction instead balance. The stator yoke length should be extended to path for the magnetic field through which the balance be induced. An iron flux path is needed on the additional rotor back of yoke. Thus, this construction uses more materials than the stator balance construction.

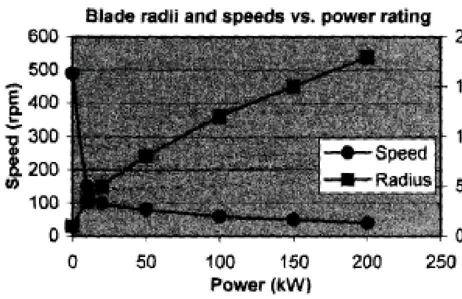

Fig. 5. Typical turbine blade radii and rated speed versus power rating

G. Axial-Flux Machine With Toroidal Winding
This kind of prototype generator has a simple construction and is often referred to as a Torus machine. It is a slotless double-sided axial flux PM disc-typed machine. The two rotor discs are made of mild steel and have surface-mounted PMs to produce an axially directed magnetic field in the machine air gaps. The machine stator comprises a slotless toroidally wound strip-iron core that carries a three-phase winding in a toroidal fashion by means of concentrated coils. The coils have a rectangular shape according to the core cross section. The active conductor lengths are the two radial portions facing the magnets, the polarities of which are arranged to induce additive electromotive forces (EMFs) around a stator coil.

III. BASIS FOR COMPARISON

In general, most modern three-bladed direct-drive horizontal axis wind turbines are designed to operate at maximum aerodynamic efficiency. The radius of the turbine blades and the rated speed can be determined as a function of the output power, as illustrated in Fig. *5.* To make the comparison fair and reasonable, several parameters are kept constant or changeable in a limited range. All the machines are designed using 220 V as the rated phase voltage, and the power factor is kept at 0.9, which is commonly used for wind generators. The following power ratings are chosen: 1, 10, 20, 50, 100, 150, and 200 kW for the output power. The rated speed is chosen to be 100 rot/min for machines below and equal 50 kW, and 50 rot/min for machines above 50 kW. These speeds are typical for direct-drive stand-alone generators. As large turbines have low speed, the designed rated speeds decrease with an increase in power rating. The 1200 rot/min machines with gearboxes are also designed for these configurations and have a design frequency output of 60 Hz. Since there exists large discrepancies in operating conditions between direct- drive stand-alone machines and grid-connected machines, the comparison will be made separately, divided into two groups.
The number of poles is fixed at 6 for l200 rot/min machines and will change according to the design requirements for low- speed machines. It is well known that the speed of a synchronous machine is closely related to the armature EMF frequency *f,* number of pole pairs p, and thus indirectly to the armature diameter *D* and the pole pitch r by the formula:

$$n = \frac{60f}{p} = \frac{120f\tau}{\pi D}$$

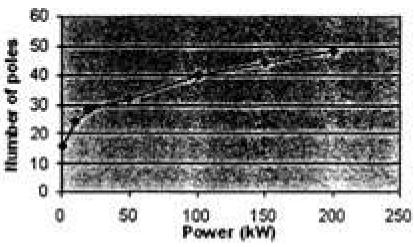

Fig. 6. Number of poles versus power rating.

Usually, the frequency for direct-drive wind generators is changeable within a fixed range of 10 to 60 Hz. It is evident from (1) that an effective way to have low speed is to increase the number of pole pairs. That requires, however, an increase of the armature diameter or reduction of the pole pitch or application of both these means. Enlargement of the armature diameter means enlargement of the overall volume and increase of the cost, which is undesirable. On the other hand, the pole pitch reduction meets the feasibility limit since the armature teeth become too narrow and the small slot width to depth ratio reduces the slot fill factor and increases slot leakage. Additionally, the short coil overhangs make single- layer winding almost unworkable and complicates a double- layer construction. Therefore, the number of poles must be chosen to match the design requirements. Fig. 6 shows the change in number of poles with respect to power ratings. The slot fill for all the slotted machines is kept constant with a very small variation for each of the power ratings. The slotless machines have different slot fills, but they are made consistent with the values obtained, for each of the different ratings. The slot fill is calculated with a fixed slot insulation thickness and using square cross-sectional wire even though the actual wire being used is circular.

The tooth and yoke flux densities are kept constant with some small variations of around 1.5 T for all the designs. This value allows better use of the lamination steel. The air gap flux density will change to obtain the optimum design. The air gaps are increased with an increase of the output power rating to accommodate the mechanical clearance, as larger output powers require larger stator and rotor diameters. The thickness of magnets is chosen to make the magnet working point far away from the knee point of the demagnetizing curve to prevent the magnets from demagnetization at all operating conditions, including sudden short circuits. It is also assumed that the machines are cooled adequately such that the temperature rise is not over the magnet temperature limit, which means forced cooling is required for larger output machines.

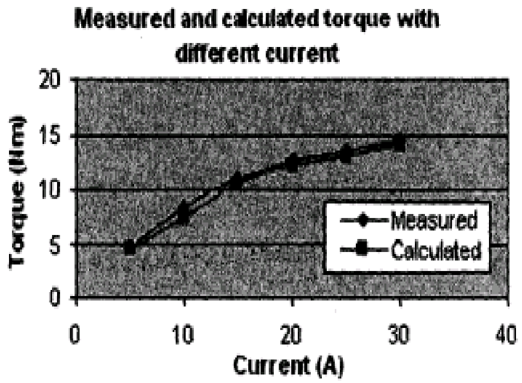

Fig. 7. Comparison of measured and calculated torque with different currents

The current density in the stator windings is kept constant at 4 x 106 A/m2 for all the designs. The three-phase windings are Y connected. As the power output gets larger, multiple strands of copper wire are used in the stator coil. In actuality, the number of strands is usually increased while decreasing the wire diameter so that forming the conductors in the slots and the end turns becomes easier. As the machines have multipole construction at low speed, fractional slot and short pitch windings have to be applied to decrease the harmonics.

The magnets used are sintered NdFeB for all the machines with remanence of 1.0 T and coercivity of 750 kA/m. These values correspond to the working temperature and the magnet temperature coefficients are considered in the designs.

The generator design is the result of the comprehensive application of machine theory, design and test knowledge, and experience. Many factors will influence the accuracy of the design. which make the design complicated and time consuming, especially for new and special constructions. Some factors may be derived analytically with the addition of experience to modify the coefficients. Other factors cannot be derived analytically. In those cases, numerical computation must be applied. In this paper, some critical coefficients, such as magnetic field waveform coefficient, leakage coefficient, and armature reaction coefficient, are first derived analytically and then numerically modified using the finite-element method (FEM). For example, the magnetic field waveform coefficient:

$$K_f = \frac{B_{\delta 1}}{B_\delta}$$

where *B* is the amplitude of air gap flux density and *B1* is the fundamental amplitude of air gap flux density. The waveform of the magnetic field in the air gap can be computed by FEM, and then Fourier analysis applied to obtain the fundamental amplitude. In this way, some curves and look-up tables are introduced by FEM computations to make the future design more convenient. All the designs are optimized to get the highest torque density and efficiency.

To verify the accuracy of the analytical model, two eperimental machines are designed first to provide benchmarks. One is the axial-flux PM servomotor with 16 poles, one two stators.

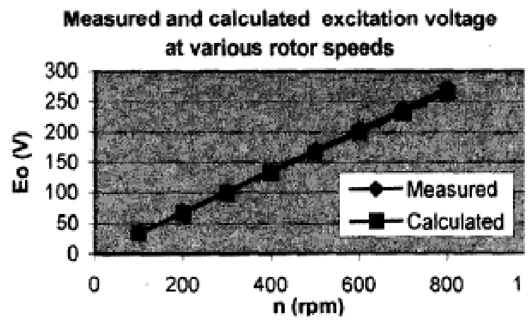

Fig. 8. Comparison of measured and calculated rms value of fundame excitation voltage at various rotor speeds.

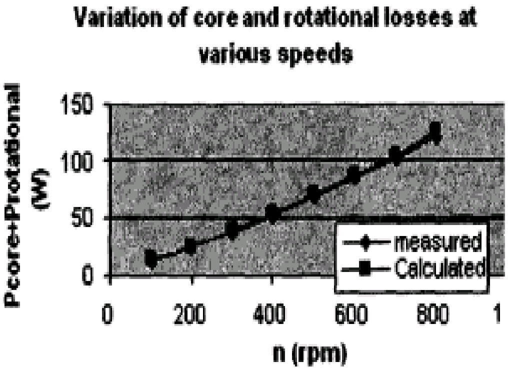

Fig. 9 Variation of core and rotational losses with speed

Fig.7 shows the designed and tested results. work proves that the magnetic circuit calculations with) flux configurations are accurate. Another is the conventional inner-rotor radial-flux E - generator with output power of 3.5 kW, 750 rot/min, 8 and 36 slots, which is a commercial product. The c"' of resulting rms value of the fundamental excitation between calculation and measurement is shown in Fig.8 and variation of calculated and measured core and rotational1 with speed is illustrated in Fig.9. From the results presented here, it can be seen agreement exists between calculated and measured which validates the design equations.

V. CONCLUSION

From the data presented in previous sections, it is inferred that axial-flux slotted machines have a smaller volume for a given power rating, making the power density very high. This is true for all the investigated power ratings. However, it should be mentioned that as the power rating increases and the outer radius becomes larger, the mechanical dynamic balance must be taken into consideration for axial-flux machines.

The two-sided axial-flux configuration is superior to the one- sided axial-flux configuration. However, one-sided constructions use less copper and have a lower conductor loss. This kind of construction is also simple in construction.

For all of the comparisons, the outer-rotor radial-flux construction is superior to the inner-rotor radial-flux construction. The former also has advantages such as ease of installation and cooling. Therefore, the outer-rotor construction is more suitable to be applied in wind energy systems.

The Torus construction is simple, and many researches have chosen this configuration. However, this construction requires more magnet weight because of the presence of the additional air gap for accommodating stator windings. As the power rating increases, both the air gap and air gap reluctance due to the magnet and winding become larger. Therefore, this construction is more suitable for low power rating wind generators.

For most of the comparisons, the low-speed constructions are superior to high-speed constructions, which means that multipole permanent magnet (PM) generators are preferred in the application of small gearless low-speed wind systems.

REFERENCES

[1] H. Silaghi and M. Silaghi "Variable-Speed Wind Generation System Using Permanent Magnet Synchronous Generator," Analele Universității din Oradea, Fascicola Electrotehnică, Sectiunea Stiinta Calculatoarelor si Sisteme de Control, Oradea 2006, pp. 118-123.

[2] E. Spooner and A. C. Williamson, "Direct coupled. permanent magnet generators for wind turbine applications," *Proc. IEE—Electe Power Appi.*. vol. 143, no. 1, pp. 1—8, Jan. 1996.

[3] L. Soderlund and J.-T. Eriksson. "A permanent-magnet generator for.wind power applications," *IEEE Trans. Magn.,* vol. 32. no. *4,* pp. 2389—2392, Jul. 1996.

[4] J. Chen, C. V. Nayar, and L. Xu, "Design and finite-element analysis of an Outer-rotor permanent-magnet generator for directly coupled wind turbines," *IEEE Trans. Magn.,* vol. 36, no. 5, pp. 3802—3809, Sep. 2000.