Slow-Speed Ring-Shaped Permanent Magnet Generator for Wind Applications

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***Abstract*- Department of Fundamentals of Electrical Engineering and Electrical Machines in Tallinn University of Technology has been researching the possibilities for using slow-speed ring-shaped permanent magnet generators in wind energy applications. Goliath Wind Ltd and my!Wind Ltd are the industrial partners for this project. There are different benefits and solutions for these generator types. This paper is describing different rotor solutions for slow-speed ring-shaped permanent magnet generators using different magnet types and presents also an overview of a finished 5 kW generator.**

I. Introduction

Nowadays world moves more and more towards energy generation from renewable sources. One of the resources that seems to have a vast potential in this field is wind energy. This is also the reason which has led to a development and optimization of wind generators.

Different generators are used in wind appliances. The oldest and the most used generator in wind energy is the induction machine [1]. However, this solution usually needs an implementation of a gearbox, which does not affect the reliability of the machines in a good way. To raise the efficiency of the machines, more attention is paid to directly driven wind applications. Permanent magnet machines are the ones most often used in directly driven windmills [2].

In this paper solutions of wind generators in which permanent magnets are used and that comply with basic requirements for design of wind generators have been researched. Those requirements are [3]:

- simple construction,
- light weight,
- low speed,
- high output power,
- variable-speed generation,
- low starting torque,
- low cost.

II. Permanent Magnets

Using permanent magnets in generators presents an opportunity to build energy efficient machines. This property has made them attractive to be used also in wind applications. Development of large industrial permanent magnet machines is still young and offers many different solutions.

One of the most important factors in the selection of permanent magnets is energy density. Fig. 1 shows the development of permanent magnets in time according to the raise in energy density.

Magnets made from rear earth elements have given a push forward in the development of permanent magnets. SmCo (Samarium-Cobalt) magnets have usually been too expensive to be used in generators. At the same time NdFeB (Neodymium-Iron-Boron) magnets are more favorable than SmCo magnets regarding energy density, but their long term problem has been their endurance of heat. However, in the last decade NdFeB magnets have evolved greatly in their endurance capability to heat and corrosion [3]. This makes them one of the most used magnetic materials in large electrical machines.

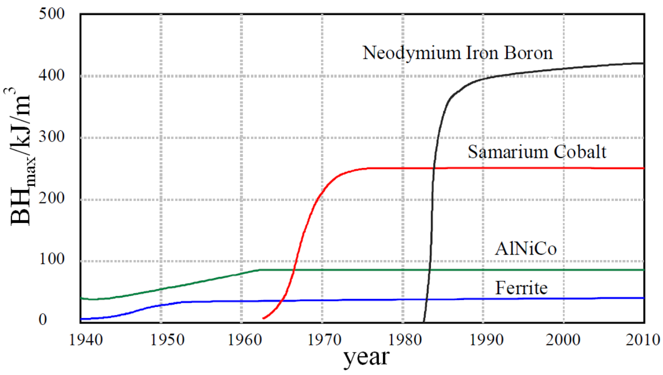

Fig. 1. Maximum energy product $(BH)_{max}$ development of permanent magnet materials.

Price of neodymium (Nd), used in NdFeB magnets, has been unsteady during the last decade. Consumption of rear earth elements has been rising due to their usage in wind generators and lately also in electric vehicle drives. Although, the supply with present consumption should be available for more than 1000 years [3] price of Nd has started to grow during the last decade. In 2011 Nd price made a sharp leap and grew almost five times (Fig. 2).

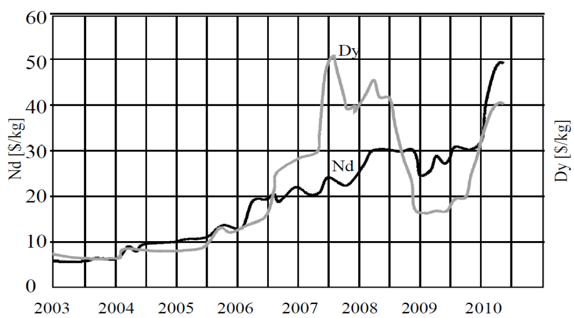

Fig. 2. Rear earth material price development over the years. Nd - neodymium, Dy – dysprosium.

China is one of the main producers of rear earth elements and also the main policymaker of Nd price. Although, building new mines outside China has already started, which should stabilize the market and make rear earth materials more available for consumers, proper exploitation of those mines could take years.

III. Selection of Generator Topology

Directly driven generators used in wind appliances are large, heavy and expensive compared to the generators used in windmills with gearboxes [4]. At the same time they are more reliable as there are less mechanical parts that are subjected to wear. Weight of directly driven wind application is relatively large, because standard generator solutions are used. These derive directly from slow-speed hydro generators. In the selection of generator topology one of the goals is to construct a generator as light as possible to be used in directly driven windmills.

Electrical part of the generator can be divided into active part and passive part. The generator active part consists of the electrical field source, which can be either an electromagnet or a permanent magnet and a coil, to which electrical energy is generated. Passive part is used for guiding the electrical field and getting high energy density in the air gap. Regarding specific weights, active and passive parts are almost equal – iron 7870 kg/m^3, copper 8940 kg/m^3 and NdFeB magnet 7500 kg/m^3. Half of the generator weight usually consists of passive part weight when electrical machines are considered. As passive part is needed only for guiding and amplifying of the magnetic field and is not directly needed for electricity generation, then theoretically it is not needed in the stator. When removed a considerable drop of magnetic field density in the air gap can be observed but usage of rear earth elements gives the possibility of still gaining at least 0.25 T field in the air gap [5]. This is enough to construct the electrical machine and gives the opportunity to build machines with large diameter and light weight. Resulting generator weighs 20-30% less than similar machines with iron cores and its efficiency is more than 90% [5].

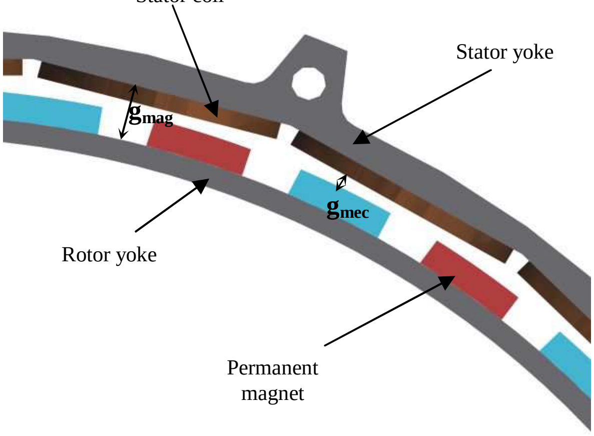

Fig. 3. Construction of the generator.

The initial construction in this study is a generator with iron-free stator [5]. However, it was concluded in previous studies that it makes sense to use back iron in the rotor. This solution has similar properties to the iron-free one, but it leads to a higher magnetic flux density in the air gap and is easier to build. It was concluded that the best solution for the generator that can be used in directly driven wind appliances is the construction shown on Fig. 3. This is a slotless permanent magnet three-phase generator.

This solution gives the possibility of building large diameter slow-speed rear earth magnet light weight machines that have a small startup torque. Small startup torque comes from the construction, because ferromagnetic surfaces of rotor and stator are practically even. This means that magnetic resistance in this machine regardless of the rotor position is the same and cogging torque does not emerge in this machine. Absence of cogging torque is very important, because in wind applications, the generator rotates most of the time having a very small torque comparing to the rated one. This means that cogging torque can cause unwanted changes in speed (vibrations) or even hinder the starting of the generator. Fig. 4 shows the graph of the torque affecting the wind generator. In that figure n_0 is the rotational speed for starting torque, n_1 is the rotational speed for main working torque and n_2 is the rotational speed at maximum torque which is considered to be rated torque at rated speed.

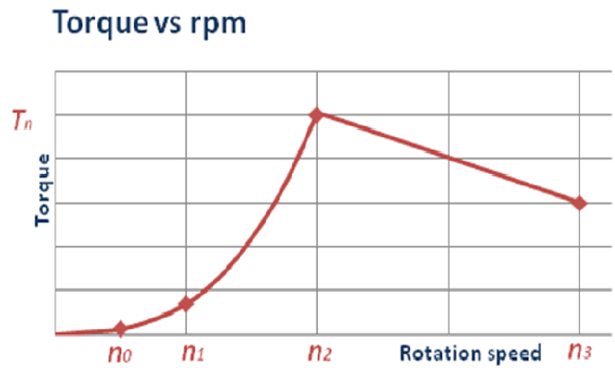

Fig. 4. Wind generator torque curve versus speed.

Additionally one of the advantages of this kind of a generator is the small self-inductance of the coil, according to the literature [6]. Small self-inductance is caused by a large magnetic air gap as both permanent magnet and the coil have practically the same permeability as air. As a result there will not be a large voltage drop in the terminals during loading of the generator.

IV. Machine Design

Generator was designed to be working for a 5 kW downwind windmill and was supposed to comply with fore described generator topology. In selection of permanent magnets energy density was taken into account. The largest energy density is in NdFeB magnets (Fig. 5), which were the ones selected for the first generator.

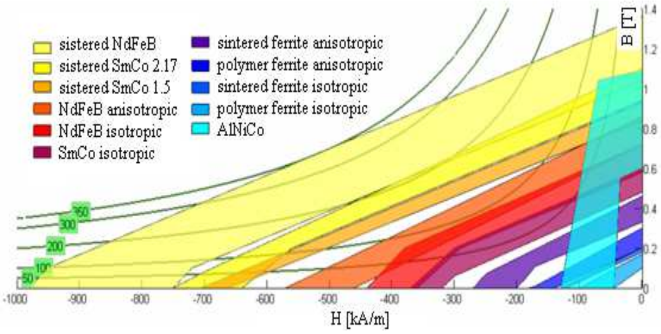

Fig. 5. Demagnetization curves of different magnetic materials.

As a result of the design process, a generator was constructed. Parameters of the generator are brought out in Table 1 and laboratory prototype of the generator is shown in Fig. 6.

TABLE I

NdFeB Generator Parameters

Power	5 kW
Rotational speed	230 rpm
Nominal voltage	340 Vac
Nominal current	8,5 Aac
Coils	24
Poles	40
Generator diameter	690 mm

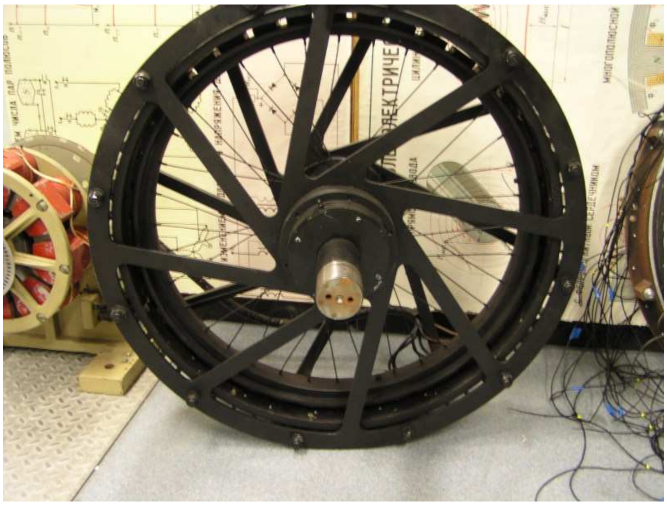

Fig. 6. Prototype machine with NdFeB magnets.

Tests were performed and comparison of the test results with the calculations can be seen in Fig. 7.

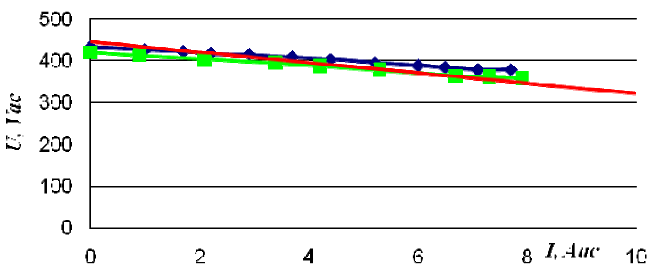

Fig. 7. NdFeB generator load characteristic. Blue and green line are measured lines and red is calculated

This generator is also used for testing in the downwind windmill shown in Fig. 8. Purpose of these tests is to develop a generator that can work in the grid.

Fig. 8. Prototype downwind windmill.

V. Possible Solutions Using Different Magnets

As the prices of NdFeB magnets have been raising significantly in year 2011, possibilities of using other magnetic materials in this generator have been researched. Firstly, other well used and energy dense rear earth SmCo magnet (Fig. 5) was studied. This material has slightly weaker magnetic parameters than NdFeB and this yields to the understanding that no major changes have to be done in the construction of the generator.

Magnetic density in the air gap of NdFeB generator was 0.66 T. To get the same density in SmCo machine, magnets must be slightly bigger in size. It was calculated that in order to get the same magnetic properties in SmCo machine as in NdFeB machine, thickness of the magnets must be raised 1.2 times. This means 1.12 times growth in generator weight.

Additionally low energy density magnetic materials were studied. If AlNiCo (Aluminum-Nickel-Cobalt) magnet is observed, it can be said that it is possible to get large Br with this material, but when the machine is loaded, the density of magnetic flux drops rapidly and there is a high risk of magnet demagnetization. Usage of such magnet in a generator is complicated and not desired.

As another possible solution, usage of ferrite magnets in the generator was studied. As energy density of ferrite magnets is small and their Br is low, it is almost impossible to gain a reasonably strong field in this generator using traditional layout of the magnets. To raise magnetic flux density in the air gap, special layout solutions of the magnets were researched. One of possibly sufficient solutions turned out to be the halbach array. In this solution radial magnets are fitted between the poles of the magnets, which help to guide the magnetic field in desired way (Fig. 9.).

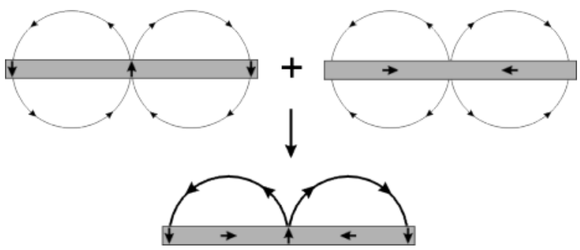

Fig. 9. Principle of halbach array.

This solution helps to significantly raise the magnetic flux density in the air gap and gives a realistic possibility of using ferrite magnets. One of the disadvantages of that solution is that compared to rear earth elements more magnetic material is needed for transporting the same amount of energy through the air gap. This raises the weight of the generator. At the same time ferrite magnets are considerably cheaper compared to rear earth magnets.

FEM (Finite-element method) analysis was performed on the ferrite machine. Picture of the magnetic field of this analysis is shown on Fig. 10. In this figure also the layout and field lines can be observed. It was found according to the analysis that with this solution it is possible to achieve magnetic flux density of 0.37 T in the air gap, which is 44% less than in case of rear earth materials. Due to this fact it is not only necessary to use more magnetic materials, but the generator also must be wider to achieve the same output parameters as in case of rear earth element machines. As ferrite is significantly cheaper than rear earth magnets, the price of the machine is still compatible with rear earth material machines.

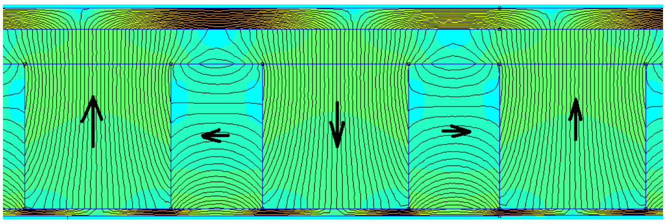

Fig. 10. FEM calculation results and permanent magnet magnetization direction.

Ferrite machine is being constructed at the moment. Half completed machine can be seen on Fig. 11. Main magnets are already placed, but halbach array magnets are missing in the figure.

VI. FUTURE WORK

Plans for future work are as follows:

- construct and test SmCo and ferrite machines,
- compare test results with calculated parameters,
- study the faults of this generator topology concentrating on air gap eccentricity due to rotor and stator eccentricity, elliptic stator and rotor bend,
- study of generator phase shift angle is desired.

VII. CONCLUSION

In this paper a new type of wind generator, the so called slotless directly driven permanent magnet machine is researched. Selection of different generator topologies and advantages of chosen topology are presented. Different magnetic materials and their possible use in this generator have been studied. As a result generators with three different magnetic materials have been chosen and constructed. Calculations show that although NdFeB magnet generator is the lightest in weight, price of this material is very high. This means that slightly heavier SmCo and significantly heavier ferrite machines are compatible with NdFeB machine.

Fig. 11. Prototype machine with ferrite magnets.

ACKNOWLEDGMENT

This paper is supported by the project “Analysis and improvement of analytical model of permanent magnet generator” in cooperation with companies Goliath Wind Ltd and my!Wind Ltd. This research work has been supported by Estonian Archimedes Foundation (project „Doctoral School of Energy and Geotechnology II“).

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