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LITERATURE REVIEW ON PERMANENT MAGNET GENERATORS DESIGN AND DYNAMIC BEHAVIOR

ABSTRACT

This paper is a literature review which describes the construction of state of the art of permanent magnet generators and motors constructing and discusses the current and possible application of these machines in industry. Permanent magnet machines are a well-know class of rotating and linear electric machines used for many years in industrial applications. A particular interest for permanent magnet generators is connected with wind mills, which seem to be becoming increasingly popular nowadays. Geared and direct-driven permanent magnet generators are described. A classification of direct-driven permanent magnet generators is given. Design aspects of permanent magnet generators are presented. Permanent magnet generators for wind turbines designs are highlighted. Dynamics and vibration problems of permanent magnet generators covered in literature are presented. The application of the Finite Element Method for mechanical problems solution in the field of permanent magnet generators is discussed.

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1. INTRODUCTION

According to the US Government statistics, the global electricity consumption in 2003 was 14781 TWh. The growth is rapid and the forecast for the year 2010 estimates the consumption to be 19045 TWh and for 2030 a remarkable 30116 TWh. Simultaneously, the prevention of climatic change is considered as one of the most important international goals in energy policy. In the future, CO_2-emissions should be smaller than today. This all seems to be impossible without the optimal usage of renewable natural resources in electricity production.

Electromechanical energy conversion employing generators and motors play a crucial role in energy consumption and production. For this reason, the improvement of efficiencies in generators and motors is important in the battle against climate change and increasing energy requirements. Permanent magnet technology represents a new enhanced area that can be used both in generators and motors. Electromechanical power conversion based on permanent magnet technology is inevitably when energy efficient solutions for generating and motoring are considered. Sophisticated energy conversion technologies with permanent magnets also make it possible to create a new conversion apparatus for competitive distributed energy technology. One example of such a development is the large direct driven windmill generators. In this particular application, the efficiency can be considerably improved by further studies of permanent magnet technology.

Permanent magnets have been used industrially since the invention of the first carbon steel permanent magnet materials in the beginning of the 20th century. Permanent magnet motors are a well-known class of rotating and linear electric machines used in both motoring and generating modes. Permanent magnet machines have been used for decades in applications where simplicity of structure and a low initial cost were of primary importance. More recently, permanent magnet machines have been applied to more demanding applications, primarily as the result of the availability of low-cost power electronic control devices and the improvement of permanent magnet characteristics. In general, modern permanent magnet machines are competitive both in performance and cost with many types of machines.

The term "permanent magnet machine" describes all electromagnetic energy conversion devices in which the magnetic excitation is supplied by a permanent magnet or several permanent magnets. The energy converters using permanent magnets include a variety of configurations, and such terms as motor, generator, alternator, stepper motor, linear motor, actuator, transducer, control motor, tachometer, brushless dc motor and many others are used to describe them. The stator of the machine (motor) is identical to the stator of a multiphase AC machine. However, the new component is the rotor, which in contrast to conventional rotors relies on permanent magnets as the source of excitation rather than an electric current in windings. The optimum rotor configuration, rotor electromagnetic and mechanical design, as well as the stator electromagnetic design must be matched to achieve a higher efficient machine of the desired load characteristics, high power factor, and high efficiency and performance [1].

A machine with a high torque/high power density and high efficiency at a low design operating speed can be considered for the direct-drive wind turbine application. The reason id a machine's ability to provide a significant reduction in the cost of converting wind derived mechanical power to electric power by eliminating the geared speed increaser, typically used into wind power applications. Its associated operation and maintenance costs are also relatively low. Low-speed, high-power direct-drive electric machines are not common in industry – their role is almost exclusively limited to extremely

large hydroelectric generators and special application low-speed high-torque motors. For this reason, the technology of low-speed, high-torque motors requires scrupulous evaluation in order to determine their suitability for a direct-drive wind turbine application [2].
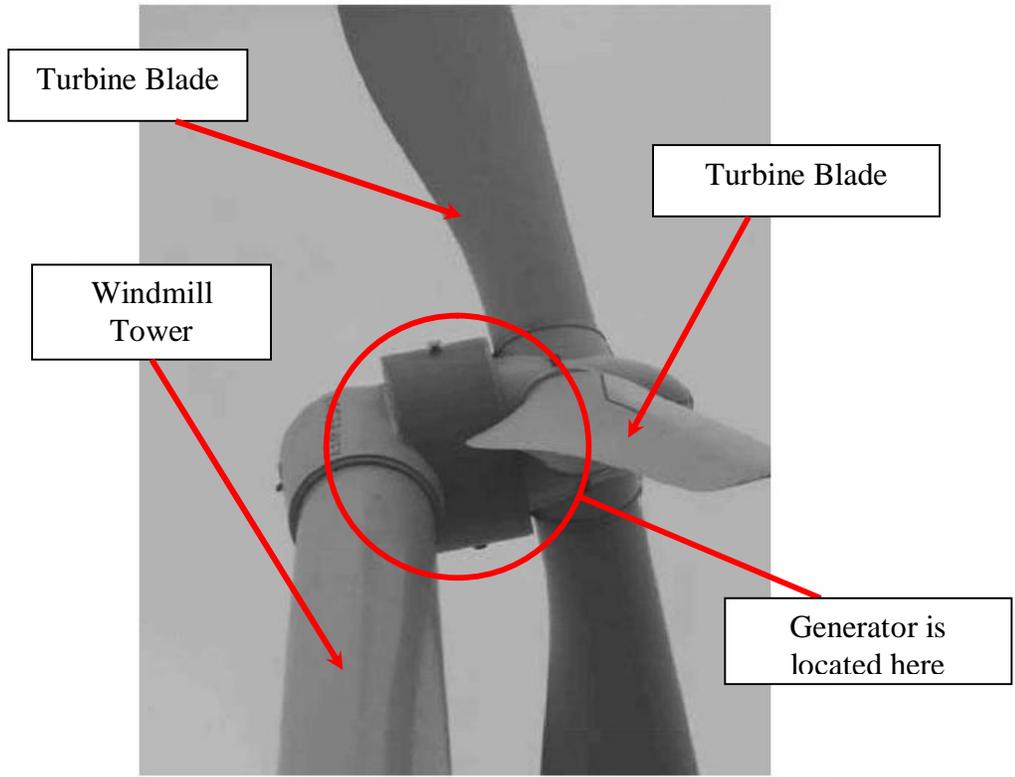

Fig. 1. Photo of a 1.5-MW direct-drive wind turbine with permanent magnet generator of Zephyros [3]

Electrical machines and generators can vary in height and weight significantly. While some of the generators are large, extremely heavy and can be installed only on or under the ground, others are compact and can be installed, for example, even at the top of a windmill – an illustration of such a generator is given in Fig. 1. Then the windmill tower is used as a supporter for the turbine and generator, and it can achieve a considerable height (see Fig. 2).

Electric machines, whether operating as motors or generators, are generally categorized as having either a radial or axial air gap while at least one machine type is a combination of both (i.e., transverse flux). The path that the air gap magnetic flux travels relative to the machine's rotor axis (i.e., axis of rotation) distinguishes the air gap type. In the axial air gap machine, this path is parallel to the rotor axis. Conversely, in the radial air gap machine, this path is radially outward from the rotor axis. Radial and axial air gap machines can be further categorized according to the type of electrical power supplied to them (for motor application) or generated by them (for generator application). This power is either the alternating current AC or the direct current DC. The excitation that creates the magnetic flux of these machines originates with either AC or DC power, except in the case of permanent magnet motors, where the excitation is provided by the permanent magnets themselves. Therefore, no external source of excitation is required [5]. A typical radial flux permanent magnet (RFPM) machine with surface magnets is illustrated in Fig. 3.

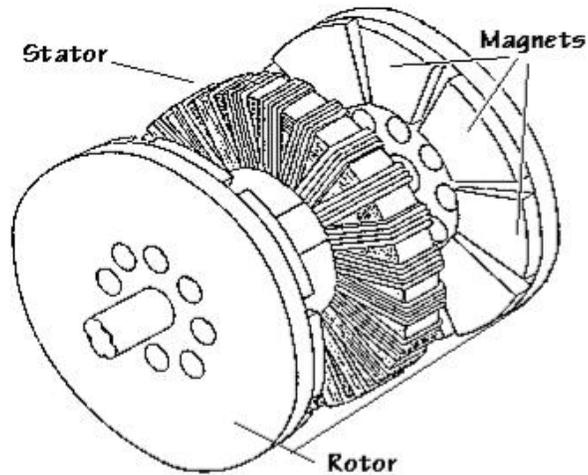Fig. 2. Photo of a windmill tower in comparison with a truck

Fig. 3. Axial Flux Permanent Magnet (AFPM) machine with air gap windings [4]

Large and fast motors with high requirements on power demand, control accuracy, system uptime, and lower life cycle costs have specified increasing demands on machine drives and have led to the need to

simplify those drives. Development of practical permanent magnet synchronous AC electric motor technology allows lower speed and higher torque output compared to a conventional AC induction motor. Using this technology, the number of mechanical drive components required in a number of machine applications can be reduced. In most cases, this technology permits the elimination of a gearbox, which results in that the mechanical drive is reduced to the coupling between the AC drive motor and the machine section. The savings in the required machine-side footprint can be significant. Conventional induction motor speed rates are normally about 900 to 1,800 RPM, which demands a gear reducer to match the motor speed rating and section speed requirement. The corresponding gearless speeds are typically from 300 to 600 RPM. AC permanent magnet motors have proven high performance and flexibility at very wide speed ranges, making the direct drive concept reasonable for most applications [6].

Direct-driven permanent magnet motors and generators can be divided into several groups. In the construction of such machines a certain number of problems may occur. Many problems are reviewed in scientific papers. The majority of problems deal with electrical or electro-mechanical parts of the structures while some papers describe and explain the problem of mechanical issue including static analysis, dynamics and vibration.

The objective of this paper is to the explain design and structural analysis of the state of the art of modern permanent magnet generators. The goal of this review is also to shed light on what has been done in recent years in the field of permanent magnet generator application in windmill turbines and vibration problems of permanent magnet generators components.

This review is divided in several sections. Section 2 deals with the classification of direct-driven permanent magnet generators. Section 3 introduces basic design features of permanent magnet generators and some specific problems which may occur while constructing a generator, such as attaching magnets to the shaft. Special attention is paid to permanent magnet generators of wind turbines, because this permanent magnet generator application seems to be one of the most interesting and wide-spread ones in the nearest future. For example, "the placing of wind turbines offshore is likely to lead to developments of the technology as far-reaching as those which turned the crude onshore machines of the early 1980's into the elegant giants of today. Cost drivers will differ offshore, with large projects of 50 MW+ and a premium on high reliability, efficient access and as much self-maintainability as possible" [7]. Since permanent magnet generators include rotating structures, Section 4 deals with dynamics behavior and vibration problems of permanent magnet machines. A way of calculating mechanical vibrations is represented, the finite element technique is introduced and it is explained that the finite element method is a useful tool to compute the magnetic field and mechanical deformation of a machine.

2. DIRECT-DRIVEN PERMANENT MAGNET GENERATORS CLASSIFICATION

The comparison of permanent magnet motors and generators of different topologies is a cumbersome task. The 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, should be accounted for when considering the thermal characteristics of the machines. Although thermal modeling of geometry can be achieved, it depends strongly on the geometry of inactive material (support, enclosure), which is often variable, depending on the application [6].

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As proposed in [6], the criteria used for comparison are torque density (kNm / m3), and cost/torque (ECU / kNm). These two criteria are identified as being critical for the integration of direct-drive generators in wind turbines.

Direct-driven generators normally have large diameters, leading to transportation and installation problems. It is also noteworthy that the use of direct-driven generators leads to the need to redesign the turbine nacelle completely. On the one hand, the direct-driven generators can be built with lower diameters. However, this increases their length substantially, especially at power rates above 1 MW. In the dimensioning of direct-driven generators, power density is an 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 the power density criterion. In these cases, torque density should be chosen, since it is independent of the rotational speed. This is a valid assumption, up to a certain speed level, which is considerably above the usual speeds employed in wind turbines. Torque density can be defined as:

$$T_d = \frac{T}{(\pi d_0^2 / 4) L_a} \qquad (2.1)$$

where T is the machine nominal torque in kNm, T_d is the machine torque density in kNm/m³, d_0 is the stator outer diameter (active outer diameter only), and L_a is the total axial length of the machine (active length only including stator end windings). In Equation 2.1, torque density is presented as a function of diameter.

Generator cost is critical for the acceptance of direct-driven machines on the market. For a given power, the topology chosen should minimize the cost of active material. For the optimization purposes, cost/torque should be used as explained above. Producing more torque requires extra magnet thickness, as well as extra conducting material and extra iron, which all can lead to an increase in cost.

The machine topologies covered in this study are:

A) Radial Flux Permanent Magnet (RFPM) machine with surface magnets, illustrated in Fig. 4;

B) Radial Flux Permanent Magnet (RFPM) with flux concentration (ferrite magnets), represented in Fig. 5;

C) Axial Flux Permanent Magnet (AFPM) with air gap windings or "TORUS";

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

- with flux concentration - Weh variant, represented in Fig. 6;

- with flux concentration - Mitcham variant, represented in Fig. 7;

- Single-Sided Surface Magnets (SSSM), depicted in Fig. 8;

- Double-Sided Flux-concentrated (DSFC), illustrated in Fig. 9;

E) Switched-Reluctance Machine (SRM), illustrated in Fig. 10;

F) Transverse Vernier Individual Hybrid Reluctance Machine (TVIHRM), given in Fig. 11;

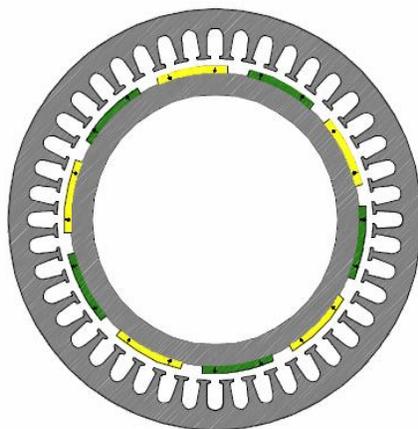G) Axial Flux Interior Permanent Magnet (AFIPM) (with slot windings), illustrated in Fig. 12.

Fig. 4. Radial Flux Permanent Magnet (RFPM) machine with surface magnets [5]
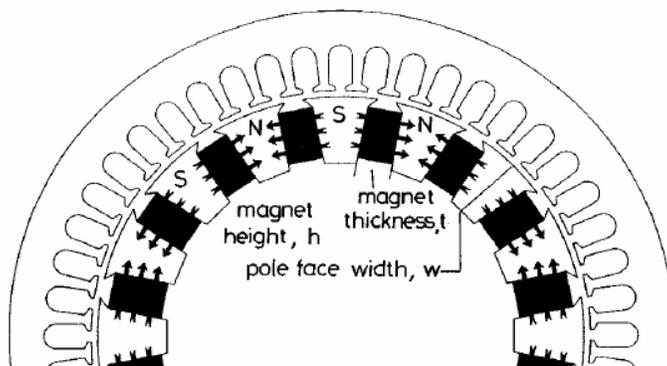
Fig. 5. Flux concentrating System for Radial Flux Permanent Magnet (RFPM)
machine with flux concentration [8]

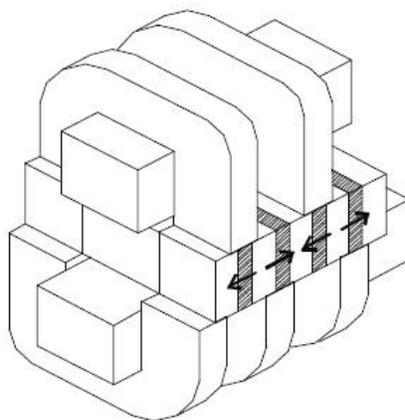Fig. 6. Three (3) poles of a Transverse Flux Permanent Magnet (TFPM) machine
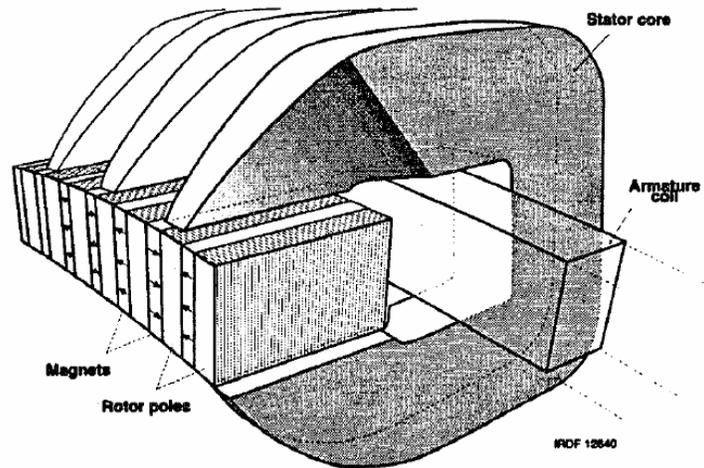with flux concentration - Weh variant [5]

Fig. 7. Three (3) poles of a Transverse Flux Permanent Magnet (TFPM) machine with flux concentration - Mitcham variant [9]
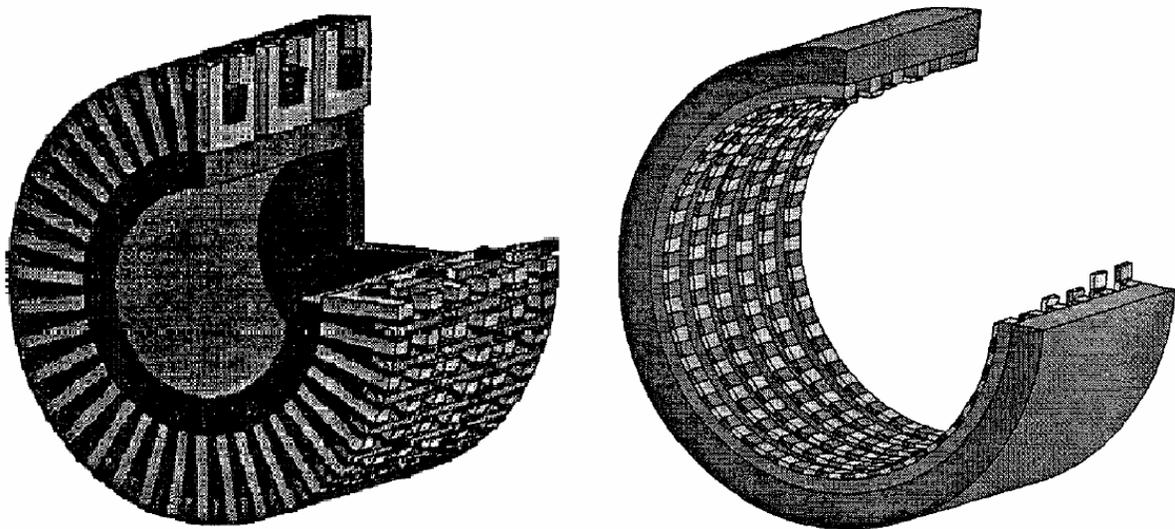

Fig. 8. Transverse Flux Permanent Magnet (TFPM), Single-Sided Surface Magnets (SSSM): Stator layout (left), Rotor layout (right) [10]
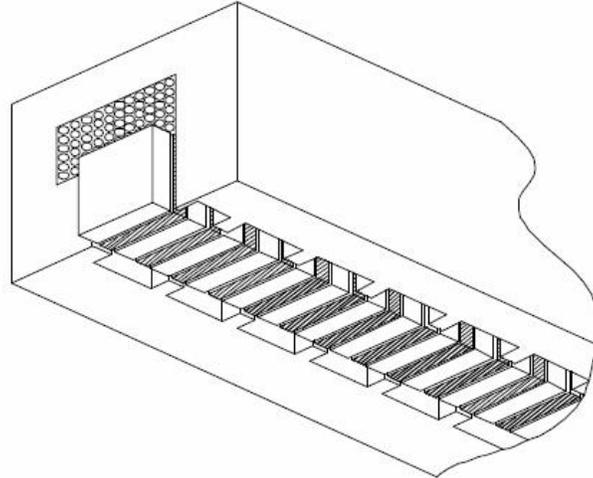
Fig. 9. Transverse Flux Permanent Magnet (TFPM) machine,
Double-Sided Flux-concentrated (DSFC) [5]
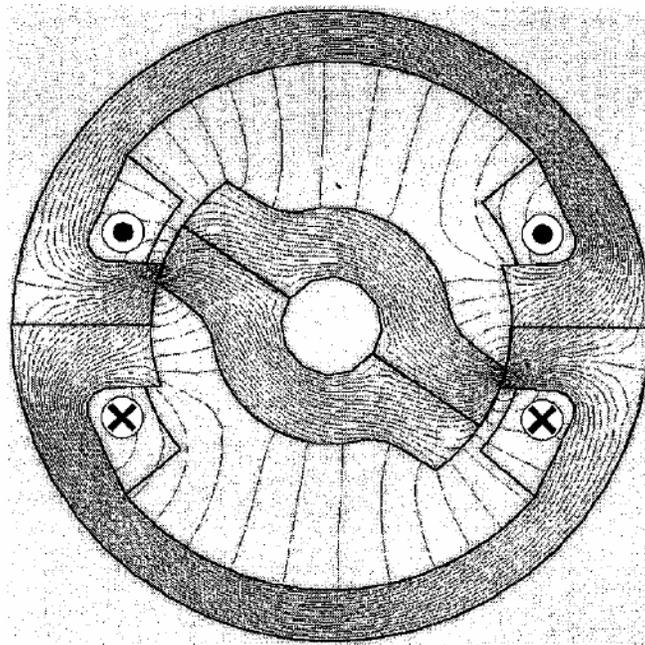
Fig. 10. Switched-Reluctance Machine (SRM) [11]

Also an induction machine could have been listed here. The reason why the induction machine is not included in the comparison is that induction generators used in direct-driven configuration require a large number of poles and large diameters, which may lead to high magnetizing currents. Their power factor and efficiency are low and their axial length must be increased substantially, in order to yield acceptable performance.

Data collection and comparison [6] give some significant information. Prototypes of RFPM machines built using ferrite magnets in the flux concentration structure do not show superior characteristics over the RFPM machines built with surface magnets. Machines built using the "TORUS" topology give twice the torque density of the RFPM machines with surface magnets. On the other hand, the large

thickness of the magnets used in "TORUS" machines make the cost/torque of these machines twice that of the RFPM machines with surface magnets. However, 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 machine design gives 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 four times the cost/torque. As the result of the research, the prototype of the AFIPM machine showed excellent characteristics, comparable to those of the TFPM prototype of an equivalent diameter. Basically, the AFIPM is an axial flux machine with teeth, which requires less magnet material than the "TORUS" construction. The prototypes of the TVIHRM machine did not provide good torque density.
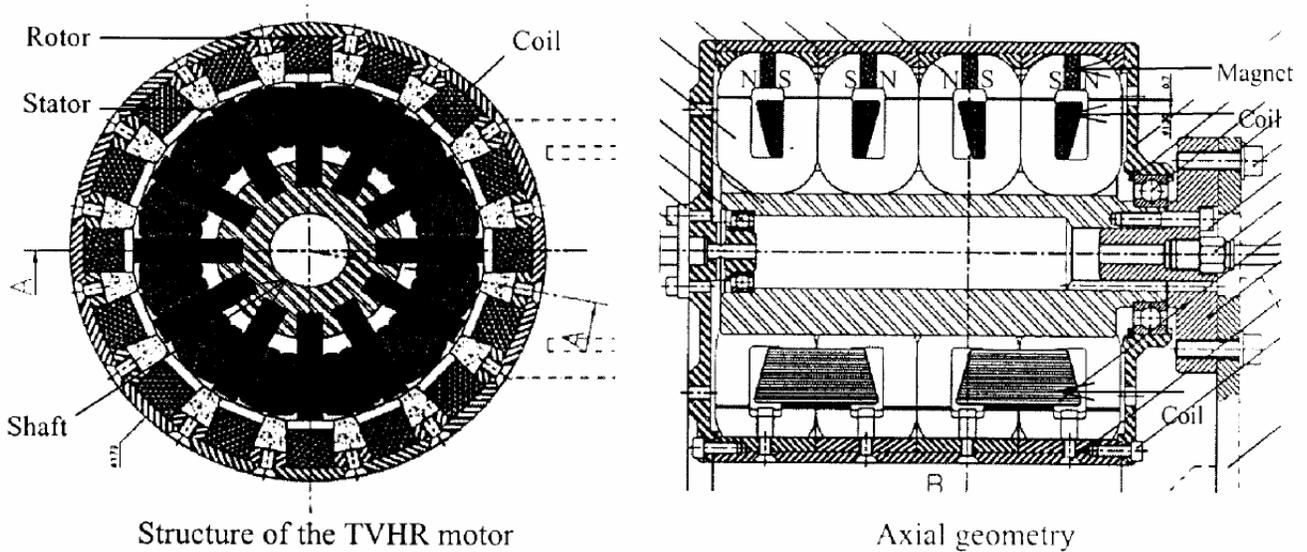

Fig. 11. Transverse Vernier Individual Hybrid Reluctance Machine (TVIHRM) [12]

Finally, an important feature must be noted: for all topologies analyzed in [6], the larger is the machine diameter, the higher is the torque density and the lower is the cost/torque. However, it should be mentioned that the weight of the machine increases with the increase of the diameter
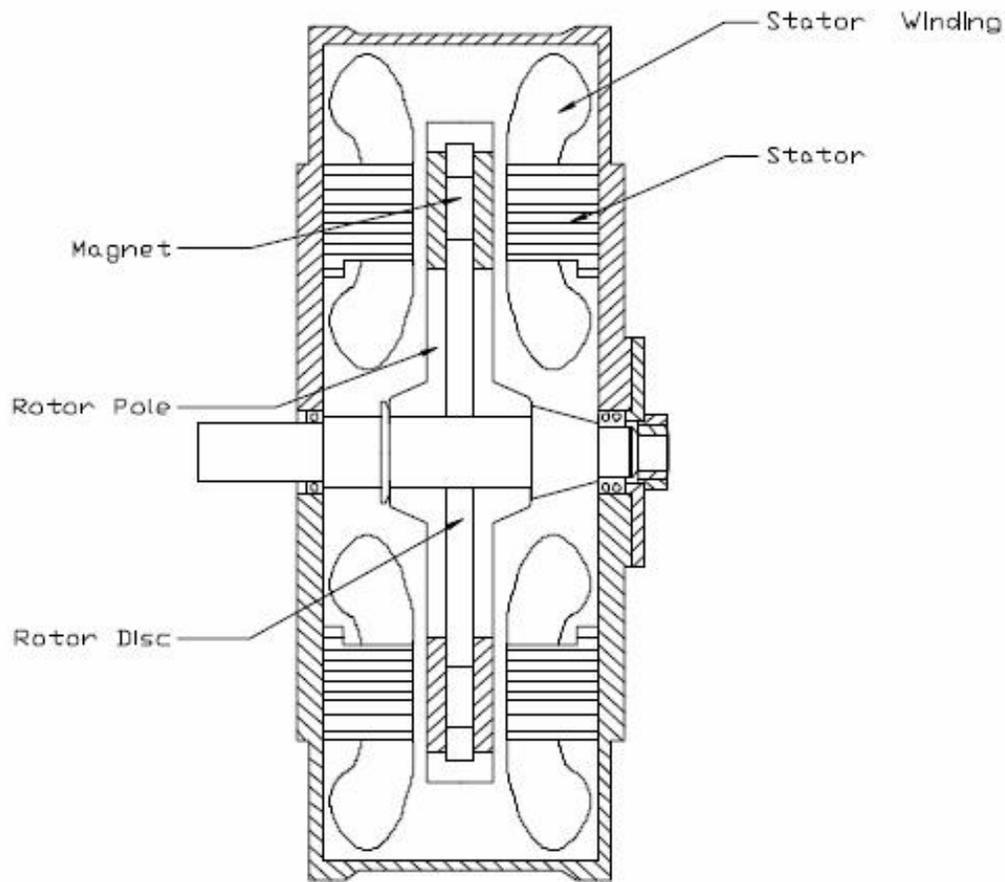
Fig. 12. Axial Flux Interior Permanent Magnet machine [5]

Due to the above-mentioned reasons, the 'TORUS' electrical machine provides simple as well as cheap and compact construction. As states [13], 'TORUS' is "a compact electrical machine particularly suitable for use as an engine-driven generator and which, when supplied via suitable switching circuits, can operate as a brushless DC motor to start the engine". The use of Neodymium-Iron-Boron permanent magnets gives good efficiency and small overall size and weight. Initially, 'TORUS' was developed for use as a portable generator, as it provides low voltage DC output. For portable generating equipment lightness and compactness are of immense importance. High efficiency is also crucial, since it influences the quantity of fuel which must be carried. In general, a machine which is designed to deliver high power from a small space must address the following features:

- High electric and magnetic loadings;

- Intensive cooling to remove the loss from the small volume;

- Low impedance to avoid pull-out.

'TORUS' makes use of sintered Neodymium-Iron-Boron for the magnets so that a high magnetic loading can be achieved. In fact, disc rotors of 'TORUS' act naturally as fans and, for this reason, good cooling of the stator winding is ensured even with in the case of high electric loading. Slotless winding can be used in 'TORUS'. This construction provides low values of the phase itself and mutual

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inductances because the magnetic gap is necessarily large and slot leakage is, of course, absent. Also, with high magnetic loading, it is possible to generate the required electro-magnetic flux (EMF) using a small number of winding turns so that the resistances and inductances are low. Accordingly, 'TORUS' is inherently light and compact. In addition, its mechanical configuration makes it well suited for integration with the engine to form a compact unit. The machine is short and thus it can be mounted directly on the engine output shaft, eliminating the need for separate bearings or couplings. In addition, it may operate as a brushless DC motor for starting the engine, making no need for the usual starter motor and gears.

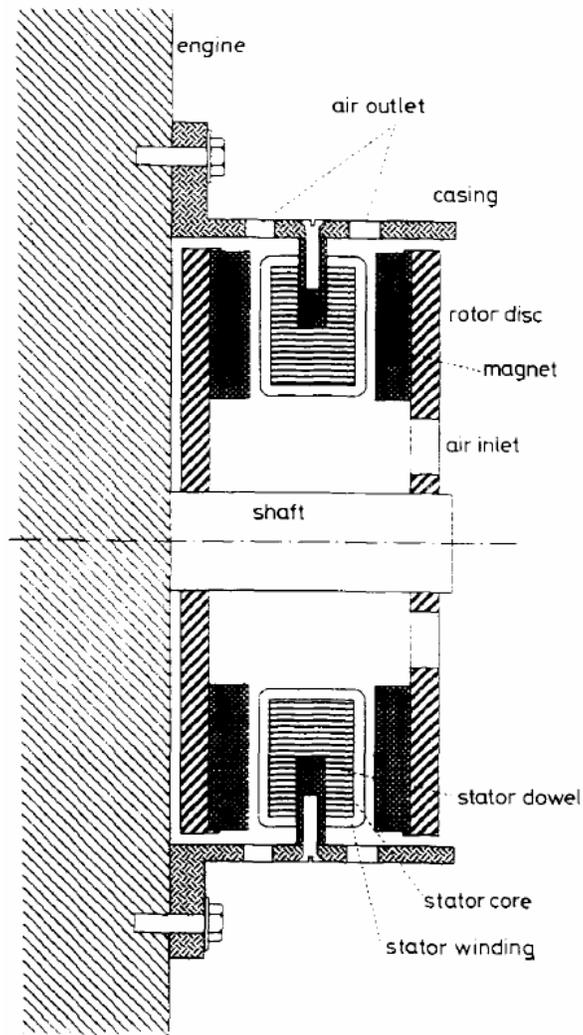Fig. 13. 'TORUS' machine cross-section [13]

The basic layout of the 'TORUS' machine is shown in Fig. 13. A simple toroidal strip-wound stator core carries a slotless toroidal winding. The rotor of the machine comprises two discs carrying axially polarized magnets. It is important to reiterate that the toroidal machine naturally generates a high-volume flow of cooling air through the active parts.

3. PERMANENT MAGNET GENERATOR DESIGN

Permanent magnet generators can be considered as complex machines and for this reason their mechanical design can be an antiviral task. Many scientific papers deal with design aspects and peculiarities of permanent magnet generators. This section highlights general methods and aspects of permanent magnet generators mechanical design.

3.1. Comparison of direct-driven and geared wind turbine generators

The two main types of generators are geared generators and direct-driven generators. Both concepts are widely used in industrial applications such as in wind turbines. Both concepts have advantages as well as drawbacks. In [3], the main aspects of generator design are highlighted with a comparison of five concepts of geared and direct-driven generators in wind turbine application. The concepts introduced concepts are the doubly-fed induction generator with a three-stage gearbox (DFIG3G), the direct-drive synchronous generator with electrical excitation (DDSG), the direct-drive permanent-magnet generator (DDPMG), the permanent magnet generator with a single stage gearbox (PMG1G) and the doubly-fed induction generator with a single-stage gearbox (DFIG1G).

The three most commonly used generator systems for wind turbines are the following [3]:

1) Until the late 1990s, most wind turbine manufacturers built constant-speed wind turbines with power levels below 1.5 MW using a multistage gearbox and a standard squirrel-cage induction generator directly connected to the grid.

2) Since the late 1990s, most wind turbine manufacturers have changed to variable speed wind turbines for power levels from roughly 1.5MW up, mainly in order to enable more flexible matching with requirements on audible noise, power quality and energy yield. A multistage gearbox, a relatively low-cost standard DFIG and a power electronic converter feeding the rotor winding with a power rating of approximately 30% of the rated power of the turbine have typically been used.

3) Since 1991, turbine manufacturers have proposed gearless generator systems with direct-driven generators, mainly to reduce failures in gearboxes and to decrease the quantity of maintenance problems. A power electronic converter for full-rated power is necessary for the grid connection. The low-speed high-torque generators and the fully rated converters for gearless wind turbines are usually expensive.

Most direct-driven turbines being implemented at the moment have synchronous generators with electrical excitation. For the increase in power levels and decrease in speeds, these direct-driven generators are becoming larger and increasingly expensive. Therefore, the use of a single-stage gearbox (with a gear ratio in the order of 6 or higher) and a permanent magnet generator has been proposed. This system, called the multibrid system, is illustrated in Fig. 14. On the one hand, the resulting system combines some of the disadvantages of both the geared and the direct-driven systems: the system has a gearbox and it has a special and therefore expensive generator and a fully rated converter. On the other hand, a significant decrease in the generator cost and an increase in generator efficiency can be obtained, particularly when compared to direct-driven systems.
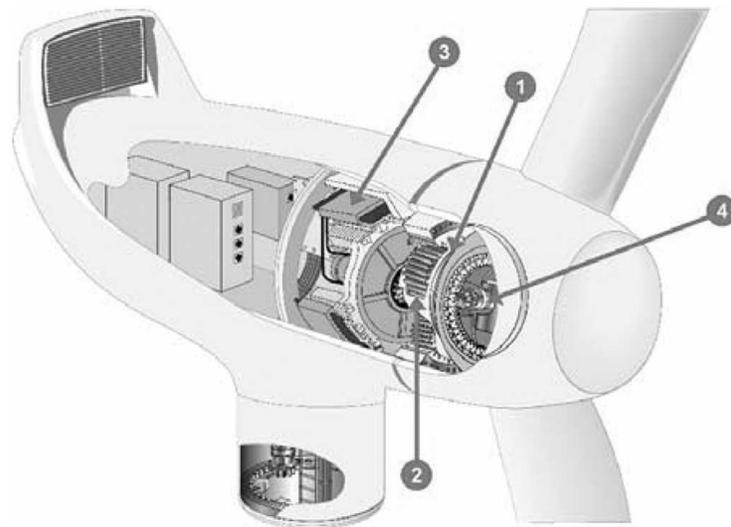
The rotor is combined to the power unit using a custom-made three-row roller bearing (1).
The roller bearing transfers the rotor loads directly to the main casing past the planetary gear and generator.
The single-stage planetary gear (2) increases the rotating speed from 8-25 rpm to 44-146 rpm.
The low speed permanent magnet generator (3) produces the electricity.
The rotational speed of rotor is controlled by three independent electric pitches (4).

Fig. 14. Sketch of the system with a single-stage gearbox [3]

It is noteworthy that a single-stage gearbox could be used in combination with a DFIG. Due to high generator torque and low rotation speed, the generator can be expected to have a large diameter and air gap leading to a high magnetizing current and high losses. However, the rating of the converter could be reduced to roughly 30%, giving an important benefit for cost and efficiency.

For both systems based on the single-stage gearbox, the use of gears leads to a significant reduction in the external dimensions, which makes it possible to install such a 3-MW wind turbine on locations that are currently limited from a logistic point of view to 1.5-MW turbines. To compare the five generator systems, a 3-MW, 15 rpm wind turbine is used. For this turbine, an approximate design of the generators is made to obtain indications of weight and cost.

The DFIG3G is the lightest, low cost solution with standard components, explaining why it is the most widely-used commercially. However, it has low energy efficiency due to the high losses in the gearbox. Because it is mainly built from standard components consisting of copper and iron, major improvements in performance or cost reductions cannot be expected.

The DDSG appears to be the heaviest and most expensive alternative.

The DDPMG generator is an attractive approach because the active material weight of the generator for the same air-gap diameter as of DDSG is nearly halved, while the energy efficiency is a few percent higher in comparison with DDSG. It has the highest energy yield. However, compared to the generator systems with a gearbox, it is more expensive. Further improvements to this generator system may be expected because the cost of permanent magnets and power electronics is decreasing and because further optimization and integration of the generator system is possible.

The GPM1G is an interesting approach, especially if this machine can also be used in other applications (for example, for ship propulsion) so that the development cost can be shared.

The DFIG1G seems the most efficient choice in terms of energy efficiency divided by cost. This is mainly due to the lower rating of the converter, which results in a reduction of the converter cost and the converter losses. However, this system may be overly complex to be widely attractive to manufacturers. Important design aspects for which further work is needed are reliability and availability. Needless to say that these are increasingly important issues for wind turbines, especially for offshore ones. Manufacturers supplying the DFIG3G use generator and converter components which are close to industrial standards, and thus benefit in standardization, cost and reliability. However, this system has components such as the gearbox and the brushes which may wear down [14].

3.2. Design of a direct-driven, low speed permanent magnet machine

In [15] it is concluded that a most promising permanent magnet machine field deals with direct-driven applications. The benefits of a direct-driven machine are produced by the elimination of the gear. As a consequence, the problems associated with the efficiency, oil maintenance and pollution, and positioning precision can be alleviated. A high torque density makes the direct drive solution effective in the applications where the gear speed ratio is small (2÷4). This is due to the fact that the mechanical loads are carried by a slightly oversized motor frame with respect to motor inertia leading to good dynamic characteristics and high efficiency. On the other hand, in low-speed, high-torque applications (gear speed ratio exceeding 10), high efficiency results in strong cost savings during the power drive life. The permanent magnet machine thus becomes a competitive solution despite a higher start-up cost.

In [15], attention is focused on "slow" machines, i.e. high torque (more than 10000 Nm) and low speed (less than 50 rpm) ones. In this application, the number of poles of a traditional permanent magnet becomes high, resulting in a ring-shaped machine. The concept of an optimal machine is associated with torque density and efficiency. In case the machine frame is constrained, optimization is associated with the maximization of efficiency. In case the given efficiency is focused on the size minimization, it is also important to consider the power factor as a necessary compromise with torque density in the optimization procedure. In order to simplify the formation of windings and overall assembly, and to avoid complicated anti-cogging measures (since torque smoothness is important at high torque and low speed), a Multi-Coil Brush-Less (MCBL) machine topology can be considered.

In short, for given mechanical specifications:

- the minimum size at rated power factor and efficiency, or

- the maximum efficiency at rated power factor and size

is pursued.

3.3. Permanent magnet generators for wind turbines design aspects

Wind energy can make a significant and increasing contribution to the electric utility networks since the wind power is a "green" and inexpensive source. However, as it was already stated, there are two problems which occur during wind power generator construction and which need to be solved: the first one is the unstable wind speed and the second one is the low rotating speed of the wind turbine due to the large diameter of the blades. In order to solve the problem of changeable wind speed, technologies to estimate the variable speed constant frequency have been developed. The conventional way to solve the second problem is using a gearbox to increase the rotor speed and reduce the generator size. Unfortunately, the gearbox generates vibration and noise, increases losses and needs lubrication as well

as regular maintenance [16]. As it was stated earlier, the gearbox increases the costs of the structure significantly.

Direct-driven variable speed permanent magnet wind power generators (PMWG) have recently received an increasing amount of attention. The reason for this is the reduced cost of the produced electric power made possible by the elimination of the gearbox and by the use of variable speed increasing the energy capture. Traditionally, the gearbox is required to increase the low rotational speed of the turbine (typically 20-40 rpm) up to a speed which is suitable for a common 4-pole generator (1500 rpm). The removal of the gearbox increases system efficiency and reduces its weight, losses and the need for maintenance. However, the low rotational speed causes a generator construction to have a large number of poles. Moreover, the generator must naturally be efficient and has a competitive cost. Due to the variable speed scheme a frequency converter is required to supply power to a grid.

Reference [16] states that the requirement of a large pole number can be met with permanent magnets which allow small pole pitch. A simple and effective generator structure can be constructed by the disc type axial flux configuration, the active parts of which are presented in Fig. 3. The stator is a toroidal wound from iron tape accommodating rectangular coils forming an air gap winding. Rotor discs with attached permanent magnets reside on both sides of the stator. In this paper, optimum design based on minimizing the sum of investment and energy loss costs for a 100 kW prototype generator is studied. The investment costs cover only the cost of the active part material while the manufacturing and structural costs are assumed to be constant over the dimensional range studied.

Some problems which occur during the construction of such a generator are highlighted below. Firstly, the turbine is allowed to rotate with variable speed, which means that the power and frequency of the generator vary constantly. Thus the generator must be designed not only for one specific operating speed but for the whole operating range determined by the wind speed distribution. Secondly, the magnets must be securely fastened against the tangential forces originating from operational torque. Gluing cannot be considered as a reliable method, since the thermal coefficients of magnet material and iron are different. The magnets can be fastened to the core by brass wedges between the magnet poles. This means that the magnets must be tapered, usually 10 degrees. Since the NdBFe cannot be machined, the tapering must be made during the manufacturing process. Practically, the wedges are in a static magnetic field such that no significant eddy currents are induced. Any axial movement and the deformation of the rotor structure must be securely prevented. A rigid rotor support structure can be achieved by coupling the discs together.

Finally, a common problem with permanent magnet machine construction is the assembly. In the present type of generator, however, the assembly of the magnets can be carried out piece by piece with all the iron parts already in their positions so that no strong forces are present at any stage of assembly.

In [17], modular construction is proposed to reduce PM generator assembly problems. As it is stated, radial-field, multipole, permanent magnet, synchronous machines may be used as direct-coupled generators for large grid-connected wind turbines. Power ratings from below 100 kW to more than 1 MW and pole numbers of 100 to 300 may be required. Modular construction reduces the detail design effort, and the number of drawings and tools needed. Module designs which can be used for a wide range of machines are presented [17]. The rotor modules use standard ferrite magnet blocks. The stator modules are simple E-cores each carrying a single rectangular coil. The arrangement eases the assembly of the magnetized parts and creates a machine with low reactances and high efficiency. A multipole permanent magnet rotor and proposed rotor modules are shown in Fig. 15 and Fig. 16, respectively.
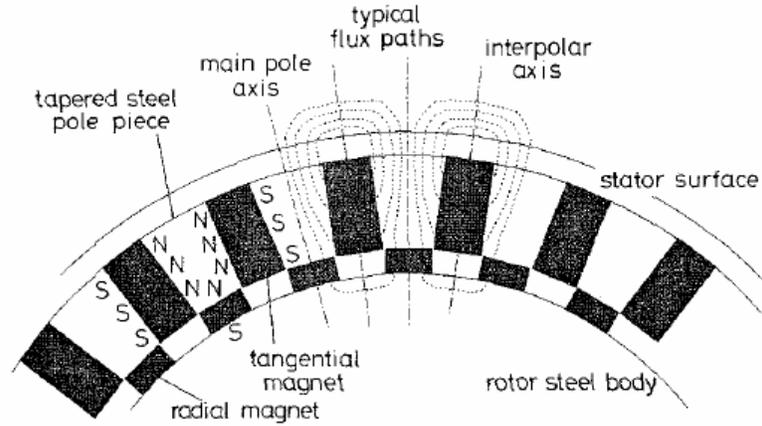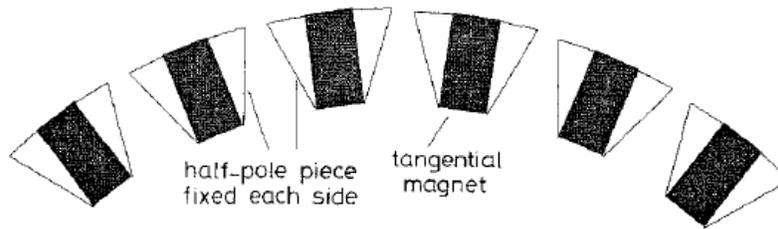
Fig. 15. Multipole permanent magnet rotor

Fig. 16. Proposed rotor modules

In [17], a laboratory machine was constructed for a test purpose. This machine was assembled from subassemblies, each comprising a tapered pole piece with a magnet fixed to each side and the bottom surface. The subassemblies correspond to the salient poles and field coils of a normal synchronous motor. It was found out that the flux density in the pole piece is low near the bottom. For this reason, it was suggested that material could be removed from that region. This would make it difficult to fit the tangential magnet beneath the pole piece as well as would introduce an additional flux leakage path. Although it would partially spoil the excellent magnetic features, they are not necessarily of tremendous value.

In order to achieve a gearless construction for the wind energy conversion system, a low speed multi-pole generator is required, and consequently, a large number of stator slots are needed to construct the multi-pole windings. In [16], a new winding structure with a large number of poles and low number of slots is adopted to solve the problem that the number of slots is normally larger than the number of poles for the conventional machine design. The design features of a direct-driven permanent magnet wind power generator (DPMIWG) with the rated power in the region of 10-50 kW, which can be either grid connected or stand alone to provide AC power to the users, is introduced in the paper.
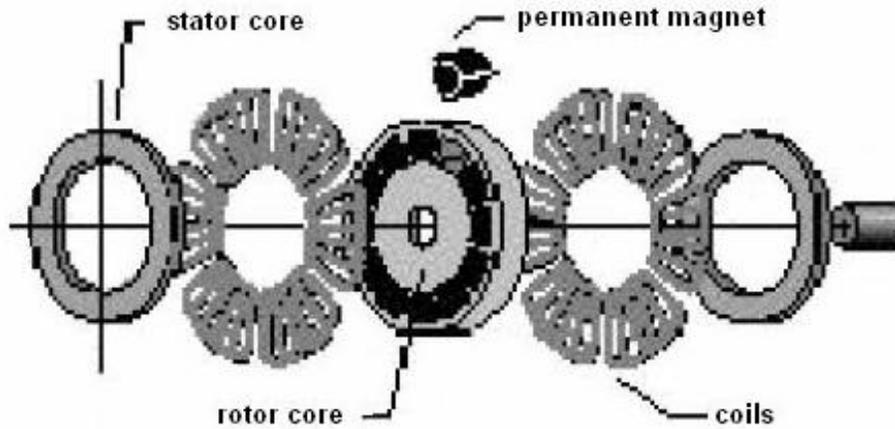
Fig. 17. Structure of axial flux PM machine [16]

In contrast to the long and thin structure of the high speed machine, the low speed machine usually has a short and thick structure that resamples a disc in order to use effectively the rotating speed of the rotor. Although the conventional synchronous and induction machines can be used, the permanent magnet machine is a favorite with the direct-driven wind generator due to its high efficiency and simple structure. There are mainly two structures of DPMWG: the axial flux machine as shown in Fig. 17, and the radial flux machine as shown in Fig. 18. The inner rotor or outer rotor structure can be used for these two kinds of permanent magnet generators.

It is important to mention that the choice of thickness for permanent magnets with radial magnetization is related to the requirement of protecting the magnets from demagnetization and generating the needed magnetic field of the air gap.
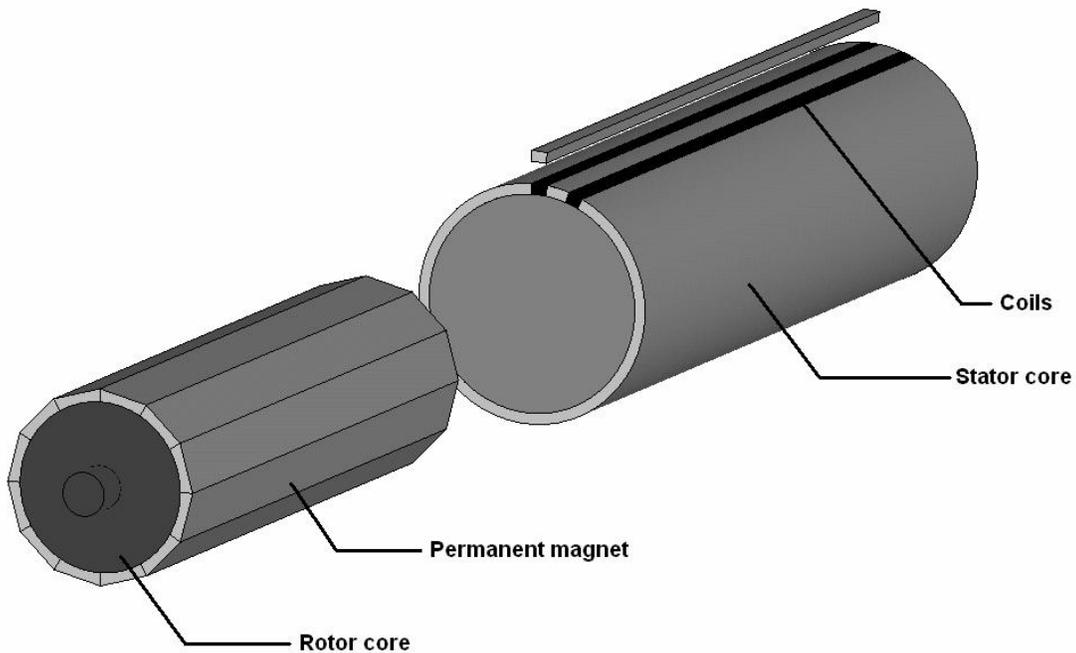

Fig. 18. Structure of the radial flux PM machine

As an example, a practical direct-driven low speed wind generator is drafted. The specifications of the wind generator are as follows [16]:

- Rated power 20 kW

- Rated speed 110 r/min

- Rated phase voltage 300 V

- Rated frequency > 35 Hz

The relationship between the rotor speed n, the number of pole pairs p and the frequency f for a synchronous generator can be expressed as

$$f = \frac{pn}{60},$$ (3.1)

Based on the frequency requirement, the number of pole pairs is chosen as 20, the corresponding frequency at the rated speed is 36.6 Hz.

The surface mounted NdFeB permanent magnet inner rotor structure is adopted in this example. The reason for this choice is not only the high power density and efficiency of the permanent magnet machine, but also the consideration that the surface mounted permanent magnet rotor is particularly suitable for the multipole rotor structure. The limited width of the stator tooth does not allow choosing a large number of slots. The fewer the number of the slots that are used, the more effective is the utilization of the stator core, and hence the stator winding is easier to build. In the example, 36 stator slots are taken in the design. Compared with the conventional design, the number of poles is increased from 32 to 40, and the number of slots is reduced from 72 to 36. The proposed structure of the rotor and stator is as represented in Fig. 19.
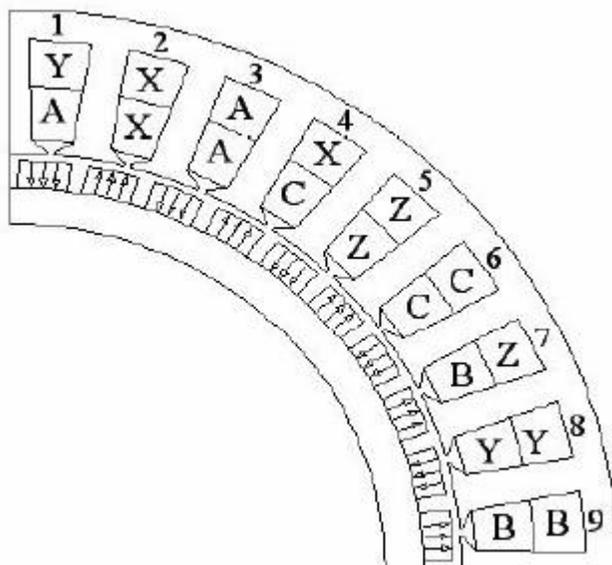

Fig. 19. Structure of stator and rotor for a low speed PM generator with 40 poles and 36 slots

How to design the multipole stator winding using fewer slots in the limited size of the stator core is an important issue for low speed generator design. The new design scheme of the direct-driven permanent magnet wind generator with a large number of poles and small number of slots is presented in [16]. The comparative study based on finite element analysis (FEA) for different numbers of poles and slots shows that the proposed design scheme offers efficient performance both for no load and rated load conditions. The design with fewer slots can reduce the flux density of stator teeth, and provide more room for housing the stator winding to increase the output power.

3.4. Examples of the solution of some specific permanent magnet generator design problems

Since a permanent magnet generator is a complicated structure, a number of specific problems occur when designing the machine compounds. Examples of such problems and their solution are considered in this section.

In many dynamoelectric machines, such as self-excited synchronous generators used in aircrafts, a permanent magnet generator is used as a source of excitation current and includes a circular permanent magnets secured to the shaft of the machine. However, a number of problems have been encountered in securing a permanent magnet to a rotating shaft, due primarily to the nature and behavior of the materials used for permanent magnets. For example, the materials used for permanent magnets, such as Alnico VI, tend to be brittle and in many cases have various metallurgical defects including excessive porosity. One approach to solve this problem has been to attach the magnet to the shaft by means of circumferential clamping. However, clamping the magnet to the shaft by this method can place excessive stress on the magnet. This may result in fractures during the operation of the generator. Another approach which has been suggested is to use an adhesive material to secure the magnet to the shaft. A significant disadvantage of this approach is caused by the temperature-sensitive nature of the adhesive, wherein the adhesive properties tend to fail at elevated temperatures, thus allowing the magnet to become disengaged from the shaft. In many applications, this is a serious consideration since generators, and aircraft generators in particular, are often required to function in high temperature environments. Perhaps one of the most significant problems with the adhesive method of attachment is the different thermal expansion rates of the steel shaft material and the permanent magnet material. For example, if the magnetic material has a coefficient of expansion greater than the material of the shaft, at high temperatures the magnetic material would tend to expand away from the shaft, thereby placing excessive strains on the adhesive material. On the other hand, if the magnetic material has a coefficient of expansion lower than that of the shaft material, the shaft would expand at a greater rate than the magnetic material at high temperatures. This will, in turn, place unacceptable tensile stress on the magnet, thereby significantly increasing the probability of fracturing the magnetic material [18].

In [18], it is suggested that an object of the invention is to provide a structure for retaining a circular permanent magnet on a rotating shaft. It is assumed that the shaft should be configured with a support portion having a shoulder. There should be a shouldered ring secured to the support portion of the shaft, efficient to axially retain the permanent magnet on the support portion. Also a securing member such as a pin or a key engaged with the magnet and the shaft to prevent the magnet from rotating (rotational slippage) with respect to the shaft should be installed.
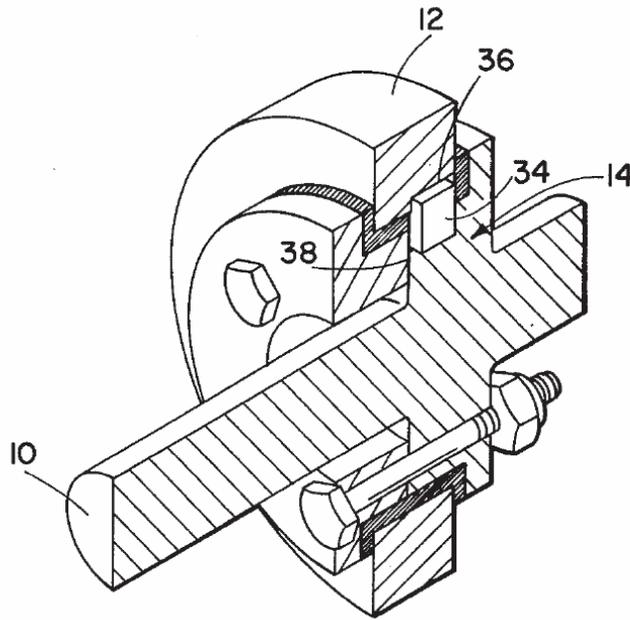
Fig. 20. Perspective on a structure for retaining a permanent magnet on a shaft

The invention structure is shown in Fig. 20. The magnet **12** is prevented from rotating with respect to the shaft **10** by means of a key **34** which is inserted in a keyway slot **36** configured out of the permanent magnet **12** and a keyway slot **38** configured out of the support portion **14** [18].

A flexible material is interposed between the supporting surface and the magnet in order to reduce vibration and motion of the magnet on the shaft. The innovation described in [18] has been patented.

A permanent magnet generator needs to have a rotor in its structure. The selection of a rotor material is also a significant aspect of an electrical machine design. The embedded radial permanent magnet design requires that a non-magnetic hub be used in order to generate the proper flux path during the operation. The material historically used for this component is stainless steel type 304 or 316 [18]. This material is selected because of its excellent machining characteristics and mechanical properties as well as reasonable costs. Alternate materials such as high-strength aluminum (6061-T4 or greater) can also be considered, but require analysis to assure that their mechanical properties along with the configuration selected are acceptable during normal operation. This consideration may require mechanical finite element models of the rotor assembly to be generated and analyzed to verify acceptance prior to use. The reduction of weight and cost makes the use of aluminum very attractive, but limits its interface with other materials when it comes to permanent attachment such as welding. Since only the outside cylinder is required to be nonmagnetic, the use of stainless steel allows the remaining hub components to be made out of standard steel and welded using bi-metallic weld procedures. This somewhat limits the material costs, but increases the labor cost due to some of the complexities caused by welding dissimilar metals. On the other hand, the use of aluminum also introduces another disadvantage, which is the need to use threaded inserts on all mechanical connections where fasteners are used. Overall, the selection of the material for the rotor hub is critical since it offers several advantages and disadvantages for both stainless steel and aluminum [2]. A detailed analysis of the design and considerations to manufacturing practices should be fulfilled prior to making the final decision.

4. DYNAMICS AND VIBRATION PROBLEMS OF PERMANENT MAGNET GENERATORS

Permanent magnet machines and generators include rotational compounds. For this reason, dynamics and vibration problems are of crucial consideration when a new machine is designed. Usually, wind turbines are connected to an electric generator with a low number of poles by means of a gear box to increase the shaft speed. When torque is applied to a shaft, it will distort storing strain energy. Due to applied torque or electrical load variations, this energy may transfer from the shaft into the electrical system and back, leading to an oscillation of a torsional mode. If this mode is not damped and no protective systems are provided, the shaft may be damaged [19]. Hence, the dynamic behavior of the structure should be carefully examined. However, practical experiments related to the mechanical resonance of the shaft may damage the shaft and the gear box. For this reason, analytical and/or numerical analysis such as the finite element approach is needed. A number of papers deal with permanent magnet generators dynamics and vibration problems. This section covers some examples of such problems highlighted in scientific publications.

In [20] a way to calculate mechanical vibrations of the stator and the case of the two dimensional modeling of electrical machines are presented. The mechanical vibrations are the result of magnetic forces acting on the surfaces of the stator.

The proceeding of the vibration calculation can be divided into three steps:

1. Finite Element Method (FEM) calculation of the magnetic field,

2. Local force density calculation and its Fourier decomposition,

3. Calculation of the dynamic displacements of the electrical machine's stator and case.

Mechanical computation using FEM is a frequently used analysis approach and, accordingly, it is described in detail below, as given in [20].

The finite element calculation of dynamic displacements is based on the principle of virtual work, which describes the minimum of the difference from the kinetic energy and the elastic potential of the whole structure. Using this principle, one gets the following system of equations:

$$\mathbf{M}\ddot{\mathbf{D}} + \mathbf{K}\mathbf{D} = \mathbf{R} , \qquad (4.1)$$

where $\mathbf{D}$ is the vector of node displacements, $\mathbf{M}$ is the global mass matrix including the information of inertia, $\mathbf{K}$ is the global stiffness matrix, describing the elastic features of the structure and the vector $\mathbf{R}$ includes the amplitudes of the exciting force densities. Because of the harmonic time dependence of the node displacements, one gets

$$\ddot{\mathbf{D}} = -\omega_{mech}^2 \cdot \mathbf{D} , \qquad (4.2)$$

where the ω_{mech} is the frequency of the harmonics.

Combined with Equation (4.1), it follows that

$$\left(\mathbf{K} - \omega_{mech}^2 \cdot \mathbf{M}\right) \cdot \mathbf{D} = \mathbf{R} . \qquad (4.3)$$

The models for both the magnetic and the mechanical computation can be accomplished using triangular elements. The mechanical finite element model considered in [20] is shown in Fig. 21. The model includes the stator and its case with 1100 nodes and 1776 elements. The two bore-holes have, as a result of the Dirichlet boundary conditions, constrained displacements.

Mechanical vibrations are computed using the considered model. As an example, one of the modes is presented in Fig. 22.
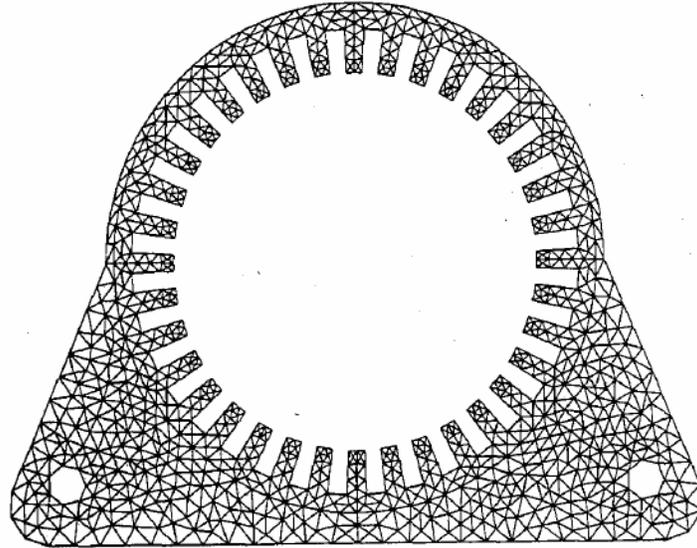

Fig. 21. Stator FE model

The magnetic field of the machine was also computed using Finite Element Analysis. It is concluded that the Finite Element Method is a useful tool to compute the magnetic field of the machine (Finite Element Method was used in [21] when an outer rotor direct drive permanent magnet generator was analyzed) and the mechanical deformation of the machine even in the case of time harmonic magnetic fields. The computed results of structure deformations show the importance of eigenvalue analysis.
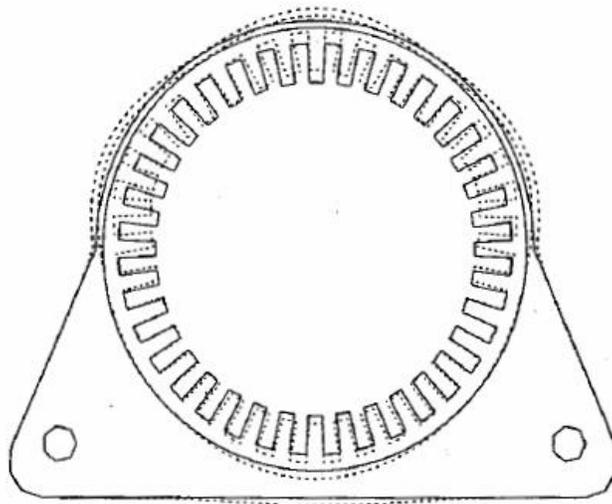

Fig. 22. Structure deformation at one of the modes which fundamental frequency is 7200 Hz

It is important to reiterate that a gearbox in a wind turbine brings weight and increases the device costs, demands regular maintenance, generates noise and incurs losses. Eliminating the gearbox would improve the attractiveness of wind generation. It is noteworthy that the direct connection of the generator to the wind turbine requires the generator to have a large number of poles. Both induction generators and wound-field synchronous generators of a high pole number must have a large diameter for efficient operation and are consequently very expensive. Permanent magnet excitation for synchronous machines allows a small pole pitch to be used and can yield cost-effective designs. However, the small pole pitch precludes the use of normal damper circuits which are necessary for stable operation. Instead of this approach, damping may be provided by mounting the stator in a manner which allows some degree of rotation and by transmitting the torque reaction through a spring-and-damper suspension. The principle of providing damping through compliant suspension of the generator was examined by Kirtley with respect to superconducting machines [22]. It was found out that such an arrangement gives greater damping than conventional damper windings and provides significantly improved control over generator oscillations during wind gusts, electrical transients and on synchronization.
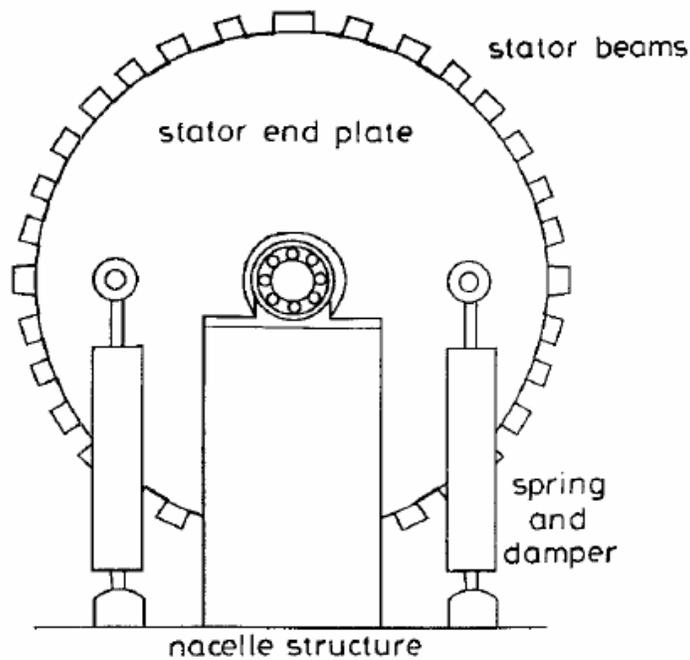

Fig. 23. Compliant mounting of the generator

In [23], the use of such a compliant stator mounting with a medium-sized wind turbine rated at 455kW is discussed. The scheme of the compliant stator mounting is represented in Fig. 23. The key features of the turbine and the method of modeling each part are outlined in the description of the simulation model development. The permanent magnet generator model is then used in order to investigate the behavior of the compliant mounting under synchronization and under subsequent changes in operating conditions. An eigenvalue technique is used to quantify the generator damping in conjunction with a full, nonlinear simulation to investigate the actual response of the generator. It is then concluded that generator performance can be improved with compliant mountings rather than with conventional damper windings, provided that the characteristics of the compliant mounting are tuned to the main parameters of the generator. A single value of spring stiffness and damping coefficient, if chosen correctly, will result in a generator with good dynamic performance over a wide range of operating

conditions. During the selection of the compliant mounting damping coefficient and stiffness, it is vital to ensure that the low frequency eigenvalue corresponds to the 1st mode operation (where the rotor and stator oscillate together against the power system with an undamped natural frequency of oscillation dependent on the stiffness of the stator compliant mounting). Required values of spring stiffness have been calculated.

5. CONCLUSION

Permanent magnet machines are a well-known and spreading class of rotating and linear electric machines used in both motoring and generating modes. Permanent magnet machines have been used for many years in applications where simplicity of structure and a low initial cost have been of primary importance. It is worth mentioning that, more recently, permanent magnet machines have been applied to more demanding applications, primarily as the result of the availability of low-cost power electronic control devices and the improvement of permanent magnet characteristics. In general, modern permanent magnet machines are competitive both in performance and cost with many types of machines.

Permanent magnet generators form a class of permanent magnet machines. Mainly, permanent magnet generators can be divided into two groups: geared machines and direct-driven machines. Currently, the tendency to eliminate the gearbox from the permanent magnet generator structure is increasing because the gearbox brings additional weight and costs, demands regular maintenance, generates noise and incurs losses. However, many problems may occur while constructing a new direct-driven permanent magnet generator design. A number of papers deal with the solution of these problems: design features and specialties, generator assembly complexity, dynamics behavior and vibration damping of generator compounds. This literature review covers some of such papers and highlights some efficient ways to solve the above-mentioned problems.

Today, the gearbox tends to be eliminated from permanent magnet generators. Although it helps in solving some problems such as overweight of the structure, gearbox compound damage, etc., many other design and manufacturing difficulties still remain. For example, fastening of the magnets is a critical issue, especially as gluing is not a reliable method. In this review, one of the suggested alternative methods is considered - the magnets can be fastened to the core by brass wedges between the magnet poles. Permanent magnet generator assembly is also an issue for discussion. A modular construction, which makes the assembly easier, is considered.

Also some specific problems of constructing permanent magnet generators were discussed. For example, the materials used for permanent magnets tend to be brittle and in many cases have various metallurgical defects, including excessive porosity. Two approaches to the solution of this problem were considered. One approach to this problem has been to attach the magnet to the shaft by means of circumferential clamping. Another approach has been to use an adhesive material to secure the magnet to the shaft. Advantages and disadvantages of both methods were highlighted.

Needless to say that dynamic and vibration problems of permanent magnet generators are issues of high importance. Wind turbines are often connected to an electric generator with a low number of poles by means of a gearbox to increase the shaft speed. When torque is applied to a shaft, the shaft starts twisting, storing potential energy. With input torque or electrical load variations, this energy can go from the shaft into the electrical system and back, oscillating in a torsional mode. If this mode is

damped not enough and there is no protective system acting at that moment, the shaft may be damaged. Hence, the dynamic behavior of a structure should be examined. FEM was used for dynamic behavior prediction. Basic concept of finite element calculation of dynamic displacement was highlighted. It was shown that FEM is a useful tool to compute both the magnetic field and the mechanical deformation of the machine.

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