Size Reduction of Permanent Magnet Generators for Wind Turbines with Higher Energy Density Permanent Magnets

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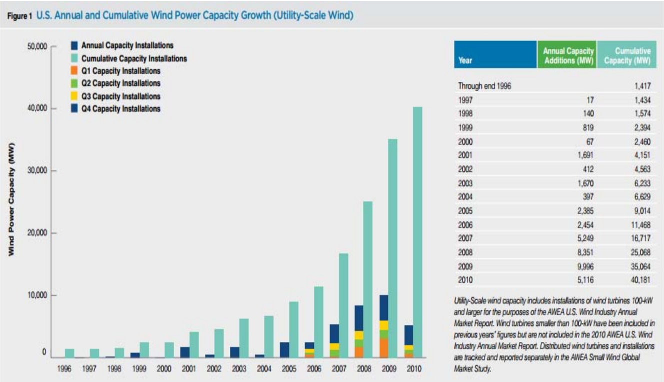
***Abstract*— Permanent magnet generators' (PMGs) dimensions scale with rated power due the sizing law for PMGs, which necessitates increased rotor volume to provide additional torque, preventing use of PMGs in large scale wind turbines. The use of higher energy density permanent magnets may offset the need to scale dimensions to achieve higher input torque. The properties of a permanent magnet necessary to achieve 25% reduction in dimensions in a 10MW wind turbine were calculated. A 29% increase in torque as a result of a 34% increase in the energy product of the permanent magnet is demonstrated.**

Keywords*— *permanent magnets, permanent magnet generators, wind energy

I. INTRODUCTION

Wind capacity in the United States has more than doubled since the inception of the wind industry as demonstrated in Fig. 1. Currently, the U.S has 60GW installed wind capacity; this translates to 3.6% of total electricity generation [1]. The U.S. Department of Energy has proposed that 20% of electricity generation in the U.S. should be obtained from wind by 2030 [2]. Clearly, wind turbines with higher power ratings are necessary to achieve this goal. These larger wind turbines, as well as offshore development, will allow access to faster, more sustainable winds necessary to provide more power.



Year	Annual Capacity Additions (MW)	Cumulative Capacity (MW)
Through end 1996		1,417
1997	17	1,434
1998	140	1,574
1999	819	2,394
2000	67	2,460
2001	1,691	4,151
2002	412	4,563
2003	1,670	6,233
2004	397	6,629
2005	2,385	9,014
2006	2,454	11,468
2007	5,249	16,717
2008	8,351	25,068
2009	9,996	35,064
2010	5,116	40,181

Utility-Scale wind capacity includes installations of wind turbines 100-kW and larger for the purposes of the AWEA U.S. Wind Industry Annual Market Report. Wind turbines smaller than 100-kW have been included in previous years' figures but are not included in the 2010 AWEA U.S. Wind Industry Annual Market Report. Distributed wind turbines and installations are tracked and reported separately in the AWEA Small Wind Global Market Study.

Fig. 1. U.S. annual and cumulative wind power capacity growth [1].

The majority of wind turbines currently employ doubly-fed induction generators (DFIG) to convert mechanical to electrical energy in the nacelle. DFIGs require a gearbox to increase the rotational speed of the shaft for efficient energy conversion. However, gearboxes are one of the most frequent causes of wind turbine failures and account for the greatest downtime [3], which results in a loss of profits for the wind farm. Gearbox failure significantly increases the operating and maintenance costs, requiring the use of expensive crane rentals [4]. Gearbox repair or replacement is even more challenging for offshore wind. It is desirable to eliminate the need for gearboxes in large scale wind turbines, especially for those that are offshore. Direct drive permanent magnet generators (PMGs) offer an alternate solution to DFIGs.

II. PERMANENT MAGNET GENERATORS

A. Fundamental Principles

In PMGs, the permanent magnets provide the magnetic flux necessary to induce a voltage in the stator windings by Faraday's law of induction. Permanent magnet properties such as coercivity, remanence and energy product are important parameters for PMG design. Coercivity is the ability of a permanent magnet to withstand demagnetization. Remanence is the magnetic flux density of the magnet after magnetization, representing the upper limit on flux density provided by the magnet. Finally, the energy product is defined as the maximum amount of energy stored in the magnet. The theoretical upper limit of energy product is given by

$$|BH|_{max} = B_r^2 / (4\mu_0\mu_r) \tag{1}$$

where B_r is the remanence, μ_0 is the permeability of free space and μ_r is the relative permeability. Magnetic permeability is a measure of the ease with which magnetic flux flows through a material. The energy product is the most widely quoted figure of merit for permanent magnets [5]. A combination of high remanence and high coercivity is desirable in permanent magnets.

Permanent magnets fall into four families: Alnico, ceramics or hard ferrites, SmCo and NdFeB magnets. NdFeB is the industry standard in PMGs for wind turbines because it has the highest energy product (up to 477.5kJ/m^3) [5]. The energy product is the energy density of the magnet, so less volume of NdFeB is required to provide a specified flux density than other permanent magnet materials. The weight of the nacelle is an important design consideration in wind turbines, so decreasing the weight of permanent magnets is desirable. However, it should be noted that NdFeB does have limitations on its operating temperature [5-6] because of its Curie temperature of 312° C, which effectively means that its highest practical operating temperature is about 170°C. Other permanent materials such as SmCo offer a higher operating temperature and coercivity; NdFeB is preferred for PMG wind turbine application due to its higher maximum energy product, high cost of Co and the relatively low price of Nd with respect to Sm [5-6].

B. *Sizing Law*

PMGs offer several advantages over DFIGs. In a direct drive configuration, PMGs eliminate the need for a gearbox; the generator shaft rotates at the same speed as the blade rotor. Also, PMGs are more efficient than DFIGs. However, in the literature there are conflicting claims regarding which generator is more cost effective [7]. For instance, PMGs require a full size power converter, while the power converter for a DFIG is rated at only one third of the stator power rating. Yet, DFIGs result in higher operation and maintenance costs due to gearbox failure.

The primary argument for DFIGs over PMGs is that at larger outputs DFIGs are smaller and less massive. To achieve 6000kNm of input torque, the drivetrain weight with a PMG is approximately twice that of with a DFIG [8]. PMG dimensions scale much more dramatically as input torque is increased. This is due to the sizing law for PMGs, which is given by

$$T = kD_r^2L \tag{2}$$

where T is torque, k is a sizing constant, D_r is the rotor diameter and L is the stack length [9-10]. Higher input torque is required to achieve larger power output as described by the familiar relation below

$$P = T\omega \tag{3}$$

where P is the power and ω is the rated speed of the generator. From equations (2) and (3) it is evident that the size of the PMG must increase to provide larger output power. This increases the weight of PMGs, prohibiting their application in large scale wind turbines. The turbine tower must support the entire weight of the nacelle and rotor hub, so large, massive PMGs are undesirable in wind turbine design.

However, the torque (and output power) may be increased by another means. The sizing constant k is given by

$$k = 1.74k_{w1}BA \tag{4}$$

where k_{w1} is the fundamental harmonic winding factor, B is the average flux density of the rotor surface and A is the electrical loading [9,11]. Currently, increasing the average flux density of the rotor surface is limited by the energy density of the permanent magnet. However, if the energy product of the permanent magnet could be increased, the average flux density of the rotor surface could also be increased, thereby increasing the sizing constant, torque, and ultimately the output power of the PMG. This would help offset the need for increasing the dimensions of the PMG. A 25% reduction in dimensions of a 10MW PMG is proposed to demonstrate proof of concept since this would have even greater weight saving implications (rotor volume would be reduced by 58%). The theoretical properties of a permanent magnet necessary to provide the same level of input torque for a 10MW PMG with the proposed reductions in dimensions are calculated analytically. The theoretical results are then verified through finite element analysis.

III. METHODOLOGY

Initially, a small scale 3.5kW PMG was designed, and then scaled to 10MW. General machine topology was chosen to reflect that of industry based on discussions with a member of corporate research at ABB. Such commercial PMGs are radial-flux with N35SH or N35UH grade NdFeB magnets in a surface mounted or inset permanent magnet topology. Inner and outer rotor topologies are both used. For direct drive configuration in large scale wind, outer rotor topology is preferential because it allows for reduction in stack length. However, for this investigation inner rotor topology was selected for ease of design.

A radial-flux, surface mounted 3.5kW PMG was designed. The dimensions of the PMG were based on the design of Abdel-Khalik *et al.* [12]. Only 4 magnetic poles were selected to minimize the number of common denominators between the pole and slot number, which is desirable to minimize cogging torque. M19 26 Ga non-oriented Si steel was selected for the rotor and stator laminations [13]. Finite element software, MotorSolve by Infolytica Corporation, aided in design and was used to characterize the instantaneous performance of the generator at varying rotor position. The effects of varying the energy product and permanent magnet geometry were investigated for the 3.5kW design. The hypothesis of this paper was tested for the 10MW design; the input and output power, torque and efficiency were averaged over all rotor positions.

TABLE I. GENERAL SPECIFICATIONS OF THE 3.5KW PMG DESIGN

Rated torque (Nm)	100
Rated speed (rpm)	333
# of phases	3
# of poles	4
# of slots	24
Outer rotor diameter (mm)	192
Inner rotor diameter (mm)	113
Outer stator diameter (mm)	348
Inner stator diameter (mm)	194
Stack length (mm)	348

A. Model Validation

A finite element model of the 3.5kW PMG was developed using MotorSolve. To validate the results, the air gap flux density was determined analytically and numerically. The analytical model was developed by Zhu [14] where the air gap flux density is given by

$$B_g(r,\theta) = \sum_{n=1,3,5\ldots}^{\infty} \frac{\mu_0 M_n}{\mu_r} \frac{np}{(np)^2-1} \left\{ \frac{(np-1)+2\left(\frac{R_r}{R_m}\right)^{np+1}-(np+1)\left(\frac{R_r}{R_m}\right)^{2np}}{\frac{\mu_r+1}{\mu_r}\left[1-\left(\frac{R_r}{R_s}\right)^{2np}\right]-\frac{\mu_r-1}{\mu_r}\left[\left(\frac{R_m}{R_s}\right)^{2np}-\left(\frac{R_r}{R_m}\right)^{2np}\right]} \right\} \cdot \left[\left(\frac{r}{R_s}\right)^{np-1}\left(\frac{R_m}{R_s}\right)^{np+1}+\left(\frac{R_m}{r}\right)^{np+1}\right]\cos(np\theta) \qquad (5)$$

$$M_n = \frac{2B_r\alpha_p}{\mu_0} \frac{\sin\left(\frac{n\pi\alpha_p}{2}\right)}{\frac{n\pi\alpha_p}{2}} \qquad (6)$$

where μ_0 = permeability of free space
M_n = magnetization
μ_r = relative permeability
p = number of pole pairs
R_s = inner radius of stator
R_m = radius of magnets = $R_s - g$
g = air gap length
R_r = outer radius of rotor = $R_m - h_m$
h_m = radial thickness of magnet
r = radius at which flux density is being calculated
B_r = remanence
α_p = magnet pole arc to pole pitch ratio.

The comparison between the analytical and numerical results indicates good agreement (Fig. 2). The fringing field which occurs in the numerical result is an effect due to the presence of stator slots, which the analytical model ignores. There is a discrepancy in the position of the air gap flux density curves. This indicates a difference in the location of the permanent magnets and will not affect the average values of torque, power and efficiency computed from the numerical model.

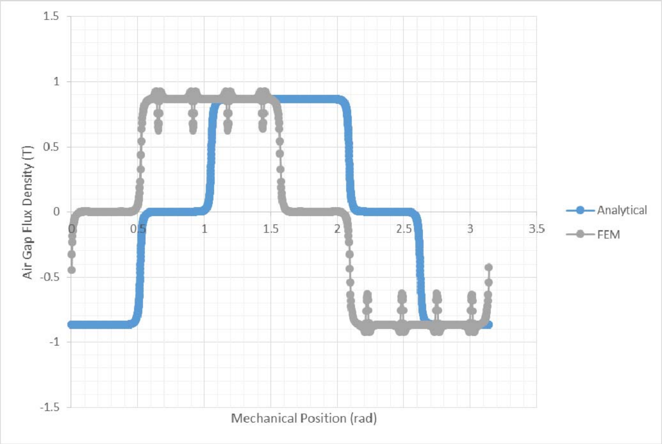


Fig. 2. Comparison of air gap flux density calculated with an analytical model and finite element model (FEM).

B. Scaling of PMG Design: 3.5kW to 10MW

The 3.5kW design was scaled to achieve a rated power of 10MW. NdFeB 48/11 grade magnets were selected to provide a high energy product. For the rated speed of 333rpm, a rated torque of 286,532Nm is required to achieve 10MW of power, as evident from equation (3). According to equation (2), each dimension must be scaled by 14.2 times to achieve this rated torque assuming the sizing constant *k* remains unchanged.

TABLE II. GENERAL SPECIFICATIONS OF THE 10MW PMG DESIGN WHERE DIMENSIONS OF THE 3.5KW DESIGN HAVE BEEN SCALED BY 14.2 TIMES (CASE 1)

Rated Torque (Nm)	286532
Outer rotor diameter (mm)	2726
Inner rotor diameter (mm)	1359
Outer stator diameter (mm)	4942
Inner stator diameter (mm)	2754
Stack length (mm)	4942

It has been hypothesized that the rated torque of the 10MW PMG design can be maintained when the dimensions are reduced by 25% if the energy product of the permanent magnet is increased. This will increase the average flux density of the rotor surface, and consequently the sizing constant *k*. The dimensions of the 10MW PMG design in Table II were reduced by 25% (Table III). To account for the resulting reduction in torque, the sizing constant *k* must increase by 2.37 times. The sizing constant will increase linearly with an increase in the average flux density of the rotor surface as described by equation (4). Assuming this flux density will scale linearly with an increase in energy product and the electrical load remains constant, the energy product must also scale by 2.37 times. This implies the remanence of the permanent magnet must be increased by 1.54 times, as evident from equation (1). The calculated theoretical remanence, relative permeability and upper limit on the energy product were calculated as shown below.

$$B_r = 1.54*1.39T = 2.14T$$

$$\mu_r = (B_r/H_c) / \mu_0 = 1.64035$$

$$|BH|_{max} = 553.9kJ/m^3$$

where H_c is the coercivity equal to 1,060,650A/m and μ_0 is $4\pi x10^{-7}$ H/m. The initial remanence and coercivity are that of NdFeB 48/11.

TABLE III. GENERAL SPECIFICATIONS OF THE 10MW PMG DESIGN WHERE DIMENSIONS OF THE DESIGN IN TABLE II HAVE BEEN REDUCED BY 25% (CASES 2-3)

Rated Torque (Nm)	286532
Outer rotor diameter (mm)	2045
Inner rotor diameter (mm)	1020
Outer stator diameter (mm)	3707
Inner stator diameter (mm)	2066
Stack length (mm)	3707

IV. RESULTS & DISCUSSION

A. *Variation of Energy Product*

For the 3.5kW design, the "grade" of NdFeB magnet was varied (i.e. the properties were altered) in order to understand the impact of the energy product on the performance of the generator. Four grades of NdFeB magnets were selected. For increased grade, the remanence, coercivity and energy product of the permanent magnet increased as demonstrated in Table IV. **The output power of the generator increased linearly with energy product**, assuming all other factors were held constant. This result is expected since more magnetic flux is available to excite the stator windings, inducing more voltage in the armature.

From Fig. 3, it is evident that **increased energy product also resulted in decreased efficiency**. This result is less intuitive, and perhaps even surprising. It is likely that for high energy product, stray field losses increased. Without optimization of the geometry of the permanent magnets, the flux density is not well focused. Variation of permanent magnet geometry or stator teeth geometry may reduce such losses. This is an important consideration if higher energy density permanent magnets are to be considered for future use. There is a tradeoff between efficiency and output power for increased energy product of the permanent magnets.

TABLE IV. Magnetic Properties of Various Grades of NdFeB Magnets.

	NdFeB 28/32	**NdFeB 34/22**	**NdFeB 40/15**	**NdFeB 48/11**
B_r **(T)**	1.08	1.19	1.29	1.39
H_c **(A/m)**	-815539	-894591	-971014	-1060650
μ_r	1.05554	1.06427	1.05474	1.03967
$\|BH\|_{max}$ **(kJ/m³)**	220.6	267.6	312.4	367.4

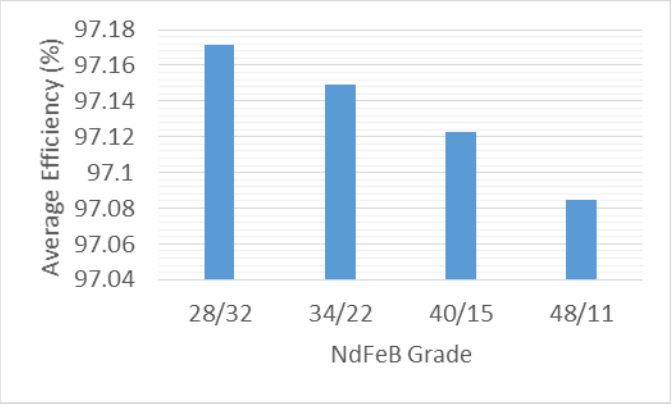


Fig. 3. Average efficiency of 3.5kW PMG with varying permanent magnet grades.

B. *Effects of Permanent Magnet Geometry*

The effects of varying magnet angle and magnet thickness were investigated. The magnet angle and magnet thickness were varied independently from their initial values of 60° and 5mm respectively; the change in each parameter resulted in equal change in volume.

Output power was observed to increase with magnet volume in general. This result is again intuitive. For larger permanent magnet volume, more flux is available for excitation of the stator windings. It is similar to the previous result in which more output power was produced due to higher energy product. In both cases, the strength of flux source increased.

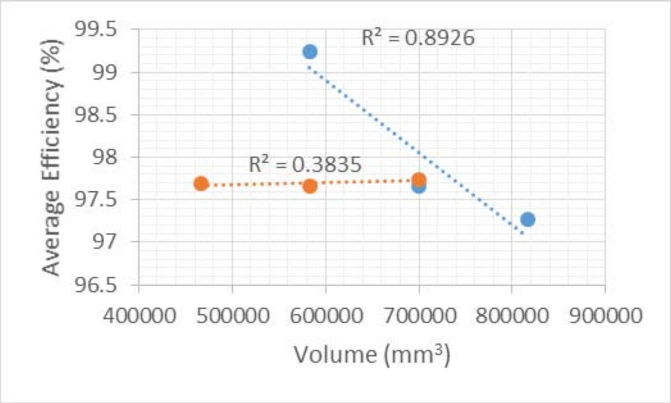


Fig. 4. Average efficiency of 3.5kW PMG with varying permanent magnet volume by change in magnet thickness (orange) and change in magnet angle (blue).

The efficiency was observed to decrease linearly with an increase in magnet angle (Fig. 4). This is consistent with the previous results in which efficiency decreased due to higher energy product. However, a linear trend was not observed between efficiency and increased magnet thickness as demonstrated by the poor linear fit in Fig. 4. Thus, efficiency is not related linearly to change in permanent magnet volume in general. This suggests that the geometry of the permanent magnet also contributes to the efficiency.

C. Sizing Law Investigation

The average input and output power, torque and efficiency of the three PMG cases were compared to determine the validity of the proposed hypothesis. Case 1 refers to the 10MW design presented in Table II in which only the dimensions of the 3.5kW PMG were scaled to achieve rated torque. Case 2 refers to a 25% reduction in dimensions (Table III) with no change in the permanent magnet properties. Case 3 refers to the 10MW design presented in Table III in which the remanence and energy product were increased to the values previously determined to achieve rated torque. Thus, case 1 and 3 should theoretically be able to provide the same rated torque. From Figs. 5 and 6, the reduction in average output power and torque in case 2 (compared to case 1) demonstrates the principle of the sizing law. It is apparent from Figs. 5 and 6 that rated power and rated torque were achieved for both cases 1 and 3. In case 3, the increased permanent magnet energy product was able to compensate for the lack of torque provided by the size of the PMG. Thus, the hypothesis has been validated.

The results suggest that ideally the permanent magnetic material would allow for a reduction in dimensions of 25%, translating to a reduction in rotor volume of 58%. It is also important to note that high efficiency of the PMG was maintained for reduced dimensions and increased energy product as shown in Fig. 7.

V. CONCLUSIONS

A 10MW PMG was designed by the simple process of scaling a 3.5kW PMG. The effects of varying design parameters such as permanent magnet volume, geometry and energy product were studied. Efficiency of PMGs seem to be dependent on the volume as well as the geometry of the permanent magnets. It was noticeable that an unexpected tradeoff exists between output power and efficiency when increasing the energy product of the permanent magnet for a given PMG design. It was demonstrated that the dimensions of the 10MW PMG can be reduced by 25% through increasing the energy product of the permanent magnet. This translates to a rotor volume reduction of 58%. The improvement of permanent magnetic materials in the form of increased energy product has significant implications for the future use of PMGs in large scale wind turbines.

VI. FUTURE WORK

By way of example, it has been proven that increased remanence and energy product of permanent magnets allow for reductions in the size of PMGs. However, there are many issues left to be addressed. In order for PMGs to compete with DFIGs in large scale wind turbine application, PMG size and mass must be reduced. Further size reduction is possible and should be aligned with industry objectives. The remanence represents the upper limit of achievable flux density supplied by the permanent magnet in the absence of an applied field. This value cannot exceed the saturation of the Si steel laminations in the rotor and stator. For M19 non-oriented Si steel laminations, saturation occurs at approximately 2.4T. Therefore, the remanence could be increased slightly, allowing for further reduction in the size of the PMG. The dimensions could also be reduced further through the use of outer rotor topology as previously discussed.

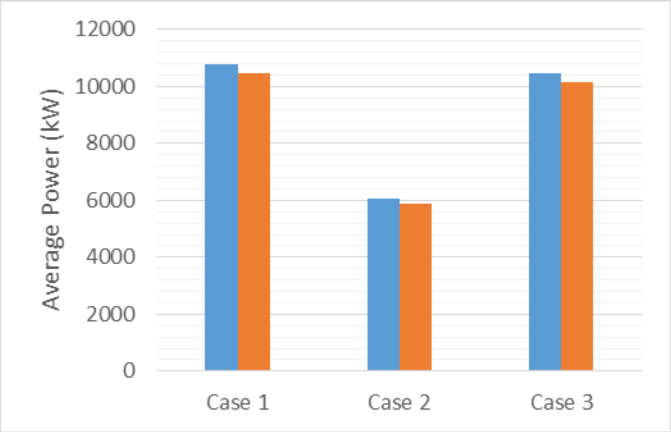


Fig. 5. Comparison of the average input power (blue) and output power (orange) of each PMG.

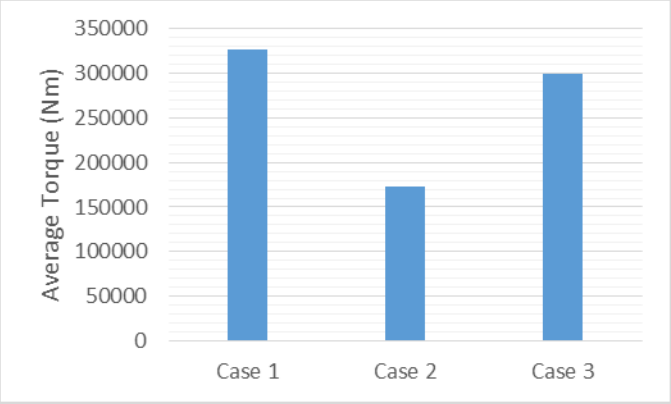


Fig. 6. Comparison of the average torque of each PMG.

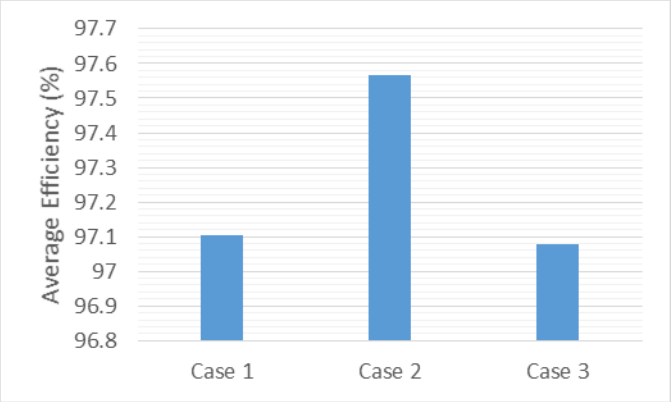


Fig. 7. Comparison of the average efficiency of each PMG.

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