IMPROVED COST OF ENERGY COMPARISON OF PERMANENT MAGNET GENERATORS FOR LARGE OFFSHORE WIND TURBINES

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Abstract:

This paper investigates geared and direct-drive permanent magnet generators for a typical offshore wind turbine, providing a detailed comparison of various wind turbine drivetrain configurations in order to minimise the Cost of Energy. The permanent magnet generator topologies considered include a direct-drive machine and single stage, two-stage or three-stage gearbox driven generators. The cost of energy calculations are based on initial capital costs, the costs of manufacture, installation, operations and maintenance, with particular focus on improved calculations of the annual energy yield with better availability estimations and gearbox loss modelling.

Keywords: Cost of energy, permanent magnet generator, direct-drive, gearbox, wind turbine.

1 Introduction

This paper builds on the work of Polinder *et al.* [1] and Bywaters *et al.* [2] but with an emphasis on a typical 6MW offshore wind turbine. This paper considers the four following generator topologies: the direct-drive permanent magnet generator (DDPMG), the permanent magnet generator with single stage gearbox (PMG1G), the permanent magnet generator with two-stage gearbox (PMG2G), and the permanent magnet generator with three-stage gearbox (PMG3G).

Offshore wind farm development has rapidly increased in the past few years. The issues and limitations present in onshore wind farm development, such as turbine size and noise production, are much less prevalent offshore, and combined with excellent wind resources offshore wind farms are becoming more attractive to developers on a global scale. However, the harsh sea environment poses several issues for developers such as installation and scheduled/unscheduled maintenance. Weather windows can be unpredictable and often too short to carry out significant repairs and so developing reliable and efficient wind turbines is of extreme importance. Large wind turbines (>5 MW) are now being manufactured to allow a fewer number of turbines to be installed in an offshore site whilst maintaining high energy yield. By reducing the number of installed turbines the service and repair requirements can be minimized.

Over the past few decades, wind turbine manufacturers have been exploring various drive train topologies ranging from multistage gearbox and induction generators to gearless direct-drive systems. With high emphasis on turbine reliability for modern offshore developments, some manufacturers are beginning to concentrate on using direct-drive generators which do not have a gearbox (eliminating gearbox related failures). Direct-drive technology might offer reduced maintenance cost and complexity and improved reliability [3]. However, these slow speed generators need to be large, able to deliver high torque and robust enough to cope with large forces that might be avoided by using a gearbox. Therefore, direct-drive machines tend to be large, heavy and are expensive.

With an aim to further enhance performance and reliability, manufacturers are also implementing permanent magnet (PM) systems into their turbines to eliminate excitation losses. Permanent magnet machines do not require additional power supply for the magnet field excitation and have higher efficiency and reliability [3] compared with electrically excited machines. Sizing and cost become significant issues with direct-drive PM configurations as generators may require very large diameters and so can be heavy and expensive which in turn can create transport and installation issues. As a result, turbine manufacturers have also been considering hybrid systems consisting of a permanent magnet generator and single-stage or 2-stage gearboxes. The gearbox and generator can either be separate or integrated together, for example the Multibrid systems – such as the AREVA M5000. Both approaches represent a compromise between high speed geared systems and direct-drive systems. Medium speed solutions require a smaller generator than a direct-drive generator.

In this paper the authors limit analysis and discussion to drivetrains with permanent magnet generators – which are currently the preferred solution for a majority of manufacturers of offshore wind turbines. The generator systems considered in this paper are as follows:

- DDPMG – Direct-drive permanent magnet generator
- PMG1G – Permanent magnet generator, single-stage gearbox
- PMG2G – Permanent magnet generator, two-stage gearbox
- PMG3G – Permanent magnet generator, three-stage gearbox

Whilst being cognisant of promising alternatives to the gearboxes (hydraulic and electromechanical gearboxes) and PM generators (DFIGs, brushless DFIGs and HTS generators), the authors want to address the question "which PM generator drivetrain delivers the lowest cost of energy offshore?" The variation in turbine designs suggests that different manufacturers have come to different conclusions.

The contribution of this paper is that it compares different permanent magnet generators on a cost of energy basis. The paper begins with a section on the modelling of the wind turbine, gearbox, converter and the generator. The details of the four different generator topologies are then described and their simulated performances are analysed which includes a sensitivity analysis. The paper concludes with a comparison of the four generator concepts and which configuration may offer the most economic cost of energy.

A baseline scenario is presented with typical drivetrain losses, costs and ratings. Using the same designs, further scenarios are investigated. In two scenarios the gearbox or the generator is replaced once in its lifetime for each of the drivetrains, and in another the cost of permanent magnets increases. These represent credible risks that drivetrain designers must consider.

2 Modelling Methodology

The design of the wind turbine and the generator configurations are based on approximations and values found in Polinder's paper [1]. The generator dimensions of the 3 MW wind turbine that form the basis of that study are scaled by the generator torque to maintain consistent comparisons for the 6 MW turbine considered in this paper. The geared generator concepts have their gear ratio design based on current manufacturers design and some limited optimisation. The costs of the generator configurations are based on the mass of materials used in each generator and material cost in Table 1. Other costs such as construction and the costs of the converter are scaled with an inflation rate of 2.4% p.a. [4] to be in accordance with the present day value.

Wind Turbine Characteristics	
Rated Grid Power (MW)	6
Rotor Diameter (m)	140
Rated Wind Speed (m/s)	11
Rated Speed (rpm)	12
Optimum Tip Speed Ratio	8
Maximum Aerodynamic Efficiency (%)	48
Mass density of air (kg/m^3)	1.225
Generator Material Characteristics	
Slot filling factor k_{sfil}	0.6
Remnant flux density of magnets B_{rm} (T)	1.2
Recoil permeability of the magnets μ_{rm}	1.06
Resistivity of copper at 120^{o}C ρ_{Cu} (μΩm)	0.025
Eddy-current losses in laminations at 1.5 T, 50 Hz P_{Fe0h} (W/kg)	0.5
Hysterisis losses in laminations at 1.5 T and 50 Hz P_{Fe0h} (W/kg)	2
Loss Modelling	
Maximum losses in a 6 MW VSI P_{convm} (kW)	180
Cost Modelling	
Single-stage gearbox (ratio 8) cost (kEuro)	672
Two-stage gearbox (ratio 40) cost (kEuro)	1170
Three-stage gearbox (ratio 100) cost (kEuro)	1330
Power electronics cost (Euro/kW)	40
Laminations cost (Euro/kg)	3
Copper cost (Euro/kg)	15
Permanent magnet cost (Euro/kg)	48
Rest of wind turbine cost (Euro)	6100

Table 1: Modelling Characteristics.

2.1 Wind Turbine Model

The comparison of the four generator systems was achieved through the simulation of a theoretical 6 MW wind turbine with a rated speed of 12 rpm. The aerodynamic power of a wind turbine is given by the following equation:

$$P = \frac{1}{2}\rho_{\text{air}}\pi r^2 v_{\text{w}}^3 C_{\text{p}}(\lambda,\theta) \tag{1}$$

where ρ_{air} is the mass density of air, r is the rotor radius of the wind turbine, v_{w} is the wind speed, and C_{p} is the power coefficient (or aerodynamic efficiency) which is a function of tip speed ratio λ and pitch angle θ. The Weibull distribution $p(v)$ that describes the variation in wind speed at a given site over a year is given in equation (2) below:

$$p(v) = \frac{k}{C}\left(\frac{v}{C}\right)^{k-1} \exp\left[-\left(\frac{v}{C}\right)^{k}\right] \qquad (2)$$

where k is the shape parameter, C is the scale parameter, and v is the wind speed.

The annual energy production (AEP) is calculated based on the Weibull probability distribution:

$$AEP = 8760 \int_{v_{\mathrm{i}}}^{v_{\mathrm{c}}} P_{\mathrm{grid}}(v)p(v)dv \qquad (3)$$

where v_{i} is the cut-in wind speed and v_{c} is the cut-out wind speed if the turbine.

The power curve and Weibull distribution of the turbine are shown in Figure 1. The cut-in wind speed is 4 m/s and the cut-out wind speed is 25 m/s with a rated power of 6 MW being attained at a wind speed of 11 m/s. The parameters for the Weibull distribution are based on a location in the North Sea with a mean wind speed of 9.8 m/s, a scale parameter of 10.8 and a shape parameter of 2.32.

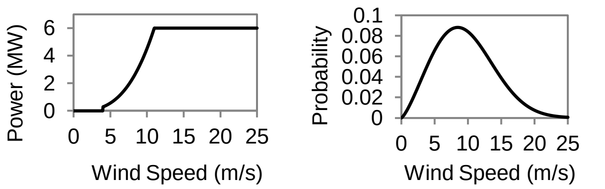

Figure 1. Power curve and Weibull distribution as a function of wind speed.

2.2 Gearbox Modelling

The cost of gearboxes is difficult to estimate given the variety in topologies and manufacturers. However Fingersh *et al.* give some useful expressions as a starting point [5].

Reference [5] gives an estimate of the cost (in €) of the single-stage gearbox following equation (4). In this case we use a gear ratio of 8.

$$\text{Gearbox Cost} = 74.1 \times (\text{Machine Rating})^{1.00} \qquad (4)$$

The ratio of the three-stage gearbox is chosen to be 100 and an estimate of the cost of the gearbox is given by [5]:

$$\text{Gearbox Cost} = 16.45 \times (Machine\ Rating)^{1.249} \qquad (5)$$

Cost functions for two-stage gearboxes are more difficult to find. In this case we assume an average of equations (4) and (5); this gives equation (6). In this study the gear ratio is chosen to be 40.

$$\text{Gearbox Cost} = 45 \times (\text{Machine Rating})^{1.12} \qquad (6)$$

In previous studies (e.g. [1], [6]) gearbox losses have been approximated based on an assumption that 1% of viscous losses per gearbox stage are reasonable. Reference [1] used x = 3% for a 3-stage gearbox and x=1.5% for a single-stage gearbox and scaled the loss using a ratio of actual rotational speed (n) to rated rotational speed (n_{rated}). P_{rated} is the wind turbine power:

$$P_{\text{Gearbox loss}}(n) = xP_{\mathrm{rated}}\frac{n}{n_{\mathrm{rated}}} \qquad (7)$$

The losses in an example 3-stage gearbox topology [7] were calculated according to equation (7). These are shown by the “Scaled 3% loss model” curve in Figure 2 for a 2.5MW turbine. A more sophisticated approach was then used to calculate the losses. ISO/TR 14179-1:2001 standards [8] specify likely losses for cooling requirements and where applied to the gear and bearing data from [6]. The losses from this method are given in Figure 2 by the “ISO method” curve. It shows that equation (7) can overestimate gearbox losses over the whole wind speed range and particularly at low-medium wind speeds.

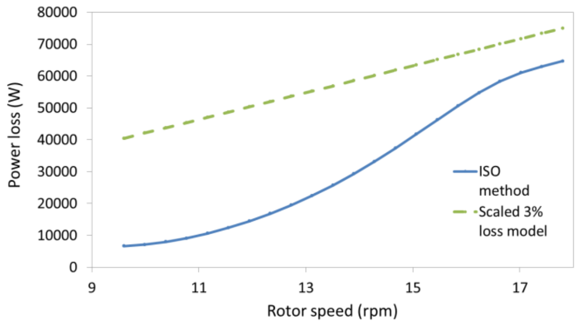

Figure 2. Comparison of gearbox loss models for a 2.5MW wind turbine

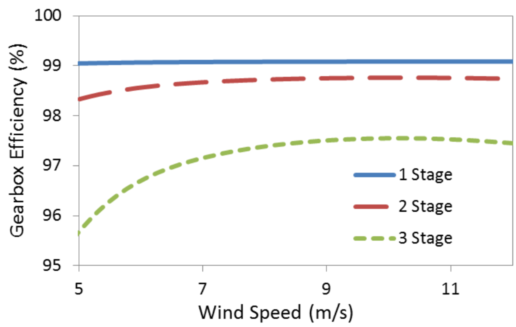

Figure 3: Gearbox efficiency curves used in this study

The data from [6] was used to calculate losses associated with the first, second and third stages of the gearbox. These losses were then scaled to the required gearbox sizes for this study. The gearbox efficiency curves for the chosen designs are presented in Figure 3.

2.3 Converter Modelling

In this study all of the drivetrains require a fully rated converter as permanent magnet generators are used.

Back-to-back power converters can be used as the interface between the turbine generator and the grid by implementing PWM (pulse width modulation) to ensure a steady sine-wave output from the variable speed operation of the turbine. The power converter consists of a series of IGBTs that make up a generator side converter, a grid side inverter, and a DC-link capacitor. The losses in the power converter are modeled using the following equation:

$$P_{\text{conv}} = \frac{P_{\text{convm}}}{31}\left(1 + 10\frac{I_{\text{s}}}{I_{\text{sm}}} + 5\frac{I_{\text{s}}^2}{I_{\text{sm}}^2} + 10\frac{I_{\text{g}}}{I_{\text{gm}}} + 5\frac{I_{\text{g}}^2}{I_{\text{gm}}^2}\right) \quad (8)$$

where P_{convm} is the dissipation in the converter at rated power (3% of the rated power of the converter), I_{s} is the generator side converter current, I_{sm} is the maximum generator side converter current, I_{g} is the grid side inverter current, I_{gm} is the maximum grid side inverter current [1].

2.4 Generator Modelling

Equivalent circuit models are used to compare the generators are described in [1]. The magnetized inductance of an AC machine is given by:

$$L_{sm} = \frac{6\mu_0 l_{\text{s}} r_{\text{s}} (k_{\text{w}} N_{\text{s}})^2}{p^2 g_{\text{eff}} \pi} \quad (9)$$

where l_{s} is the stack length in axial direction, r_{s} is the stator radius, N_{s} is the number of turns of the phase winding, k_{w} is the winding factor, p is the number of pole pairs, and g_{eff} is the effective air gap. The effective air gap is given by:

$$g_{eff} = k_{\text{sat}} k_{\text{Cs}} \left(g + \frac{l_{\text{m}}}{\mu_{\text{rm}}}\right) \quad (10)$$

where k_{sat} is a factor representing the reluctance of the iron in the magnetic circuit, k_{Cs} is the Carter factor for the stator slots, g is the mechanical air gap, μ_{rm} is the relative recoil permeability of the magnets, and l_{m} is the magnet length in the direction of the magnetization.

The flux density directly above a magnet in the air gap of a permanent magnet machine is calculated as:

$$\hat{B}_{\text{g}} = \frac{l_{\text{m}}}{\mu_{\text{rm}} g_{\text{eff}}} B_{\text{rm}} \frac{4}{\pi} \sin\left(\frac{\pi b_{\text{p}}}{2\tau_{\text{p}}}\right) \quad (11)$$

where B_{rm} is the remanent flux density of the magnets (1.2T), b_{p} is the magnet width and τ_{p} is the pole pitch.

The no-load voltage induced by the flux density in a stator winding is given by:

$$E_{\text{p}} = \sqrt{2} k_{\text{w}} N_{\text{s}} \omega_{\text{m}} r_{\text{s}} l_{\text{s}} \hat{B}_{\text{g}} \quad (12)$$

where ω_{m} is the mechanical angular speed of the rotor. The copper losses in the generator are calculated from the currents and resistances (I^2R losses). The specific iron losses are given by:

$$P_{\text{Fe}} = 2P_{\text{Fe0h}}\left(\frac{f_{\text{e}}}{f_0}\right)\left(\frac{\hat{B}_{\text{Fe}}}{\hat{B}_0}\right)^2 + 2P_{\text{Fe0e}}\left(\frac{f_{\text{e}}}{f_0}\right)^2\left(\frac{\hat{B}_{\text{Fe}}}{\hat{B}_0}\right)^2 \quad (13)$$

where f_{e} is the frequency of the field in the iron, P_{Fe0h} is the hysteresis loss per unit mass at the given angular frequency f_0 and flux density B_0, and P_{Fe0e} is the eddy current loss per unit mass.

2.5 Cost of Energy

The cost of energy (COE) [2] per MWh is the overall outcome of this study and is calculated using the following equation:

$$COE = \frac{(FCR \times ICC + AOM)}{AEP} \quad (14)$$

where *FCR* is the Fixed Charge Rate, *ICC* is the Initial Capital Cost of the turbine, *AOM* is the Annual Operation and Maintenance and *AEP* is the Annual Energy Production.

In this case *ICC* is made up of a fixed part which represents the rest of the wind turbine (common to all of the designs) and a part which equals the cost of the generator, any gearbox and the power converter.

AOM is calculated according to [5] which uses a cost/MWh energy produced ratio for calculating operation and maintenance costs. It ignores the effect of drivetrain choice of maintenance cost – unfortunately there is a lack of data that distinguishes operation and maintenance costs of different types of offshore wind turbine drivetrains.

AEP is calculated using the methods described in Section 2 as well as availability data given in Table

2. These availability figures are based on failure rates that are synthesised from various reliability studies and onshore mean time to repair modified to include extra downtime for offshore work and delays. For more details the reader is referred to the paper by Carroll [9].

3 Results

The results for all four designs are presented in Table 2. The following sections details the loss mechanisms and costs for each of the designs.

	DD PMG	**PMG 1G**	**PMG 2G**	**PMG 3G**
Generator Specifications				
Generator speed (rpm)	12	96	480	1200
Gearbox ratio	-	1:8	1:40	1:100
Stator radius r_s (m)	3.5	2.5	0.7	0.5
Stack length l_s (m)	1.5	0.4	0.8	0.9
Number of pole pairs p	100	54	10	3
Air gap g (mm)	7	5	1.4	1
Stator slot width b_{ss} (mm)	17	21	19	33
Stator tooth width b_{st} (mm)	20	27	23	40
Stator slot height h_{ss} (mm)	80	80	80	80
Stator yoke height h_{sy} (mm)	40	40	40	40
Rotor yoke height h_{ry} (mm)	40	40	40	40
Magnet height l_m (mm)	15	15	15	15
Magnet width b_p (mm)	87.5	116	178	417
Generator Parameters				
Main inductance L_m (mH)	8.3	1.9	3.7	8.3
Stator leakage inductance $L_{s\sigma}$ (mH)	10.4	1.3	0.9	0.4
Stator resistance R_s (mΩ)	181	32.5	20.9	12.1
Generator Material Weight (ton)				
Iron	30.6	6.4	3.3	2.8
Copper	6.6	2.0	1.0	1.1
PM	2.9	0.6	0.3	0.3
Total	40.1	9.0	4.6	4.2
Cost (kEuro)				
Generator active material	330	77	39	38
Generator construction	436	115	24	10
Gearbox	-	672	1170	1330
Generator system cost	767	864	1240	1380
Converter	283	283	283	283
Other wind turbine parts	6000	6000	6000	6000
Total cost of wind turbine	7050	7250	7520	7660
Annual Energy				
Copper losses (MWh)	1120	201	135	79
Iron losses (MWh)	151	242	243	529
Converter losses (MWh)	880	861	868	894
Gearbox losses (MWh)	0	314	779	879
Availability (%)	93.4	93.0	92.8	92.6
Total losses (MWh)	2150	1620	2030	2380
Energy yield (GWh)	28.0	28.6	28.3	28.2
Cost of Energy				
ICC (kEuro)	21400	22000	22800	23200
AOM (kEuro)	628	641	635	632
FCR	0.116	0.116	0.116	0.116
COE (Euro/MWh)	110.7	111.3	115.6	117.7

Table 2: Design details, costs and performance of 4 drivetrains

3.1 DDPMG

Overall this drivetrain gave the lowest Cost of Energy in the baseline study. The Siemens SWT-6.0 150 and Alstom Haliade turbines – although very different machines – fit into this category.

Results from the MATLAB model for the DDPMG are shown in Figure 4. The results shown include voltage and current levels, the wind turbine power curve, the system efficiency and losses. The system efficiency takes into account bearing and cable losses as well as generator and converter losses. In this case the generator diameter was restricted to 7m. The significant losses in the system result from high copper losses that account for over half of the total losses. This is due to the requirement that in order to produce a high torque there is a large number of coils. Availability is high: even though there are increased winding failures in the direct-drive generator, there is no downtime due to a gearbox.

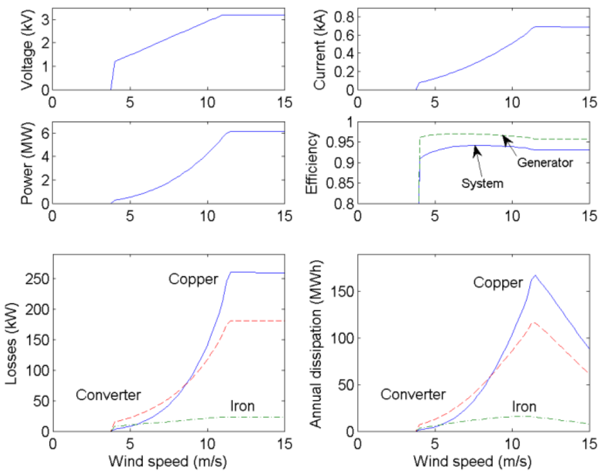

Figure 4: DDPMG Drivetrain Operation & Performance

3.2 PMG1G

This drivetrain a similar but slightly higher Cost of Energy than the direct-drive machine. Although it has a lower rating than the turbine discussed here, the AREVA M5000 would be a good exemplar of the single-stage PM generator drivetrain. Results are shown in Figure 5 and Table 2.

Because of its smaller torque rating the electrical machine is smaller and cheaper (in terms of materials and construction) than the direct-drive generator. The addition of the gearbox does make it more expensive (than the direct drive machine) from the view point of capital costs.

The real benefit of a PMG driven by a single-stage gearbox is the low losses with copper losses, iron losses and gearbox losses all being fairly balanced.

Although there is a gearbox – which means that there are failures and downtime over and above the direct-drive machine – there are less electrical failures because the generator is smaller. Offshore availability is very similar to the direct-drive machine.

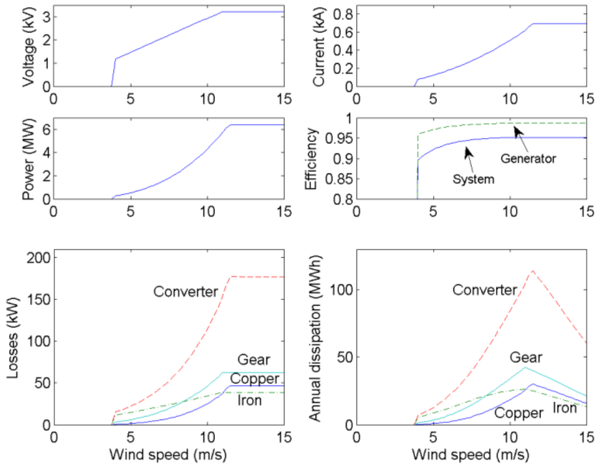

Figure 5: PMG1G Drivetrain Operation & Performance

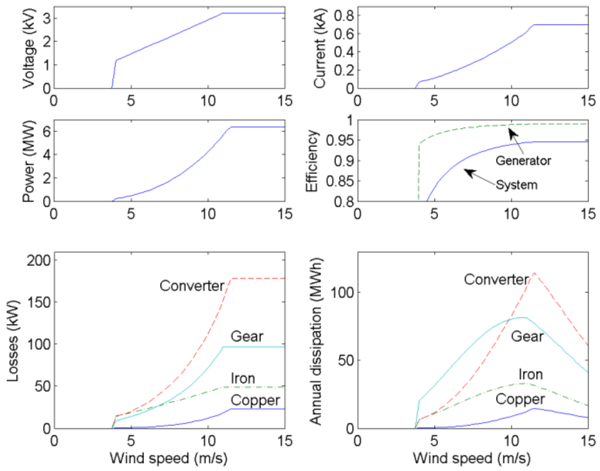

Figure 6: PMG2G Drivetrain Operation & Performance

3.3 PMG2G

The Gamesa G128-5.0 MW and Samsung S7.0-171 turbines adopt a 2-stage gearbox with a permanent magnet generator. Results are shown in Figure 6 and Table 2.

Here the Cost of Energy is higher than the direct-drive and PMG1G. Overall losses and costs are higher than the drivetrains with slower generators; availability is marginally worse because of the added failures in the gearbox when a second stage is added.

The generator size is considerably smaller than the single-stage gearbox design and so has reduced losses in the stator. This lightweight generator would also be advantageous to developers during installation procedures. However, due to having a two-stage gearbox, the gearbox losses become more significant and the gearbox itself is larger and more expensive.

3.4 PMG3G

The PMG driven by a 3-stage gearbox has not yet been a popular choice in the offshore wind market, although the leading generator manufacturers such as ABB and the Switch have high speed PMGs in the 5-7MW range. As one might expect, the generator is very compact, cheap and efficient. Unfortunately the increased losses, cost and downtime due to the additional gearbox stage give rise to a higher Cost of Energy than all of the other drivetrains. Results from the MATLAB model for the PMG with a 3-stage gearbox are shown in Figure 7 and Table 2. It might be attractive should the cost of permanent magnets become very high or if owners believe that they will have to replace many generators in their fleet.

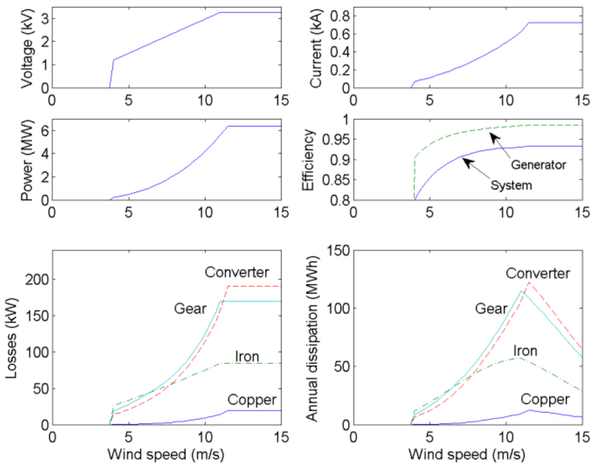

Figure 7: PMG3G Drivetrain Operation & Performance

4 Sensitivity Analysis

Once designed and in production, the Cost of Energy of an offshore wind turbine is somewhat dependent on future events such as material price changes and sub-assembly failure rates. In this section the model is used to look at the sensitivity to some of these factors.

	DD PMG	PMG 1G	PMG 2G	PMG 3G
COE (Euro/MWh)	110.7	111.3	115.6	117.7
COE: 1 gearbox replacement (Euro/MWh)	110.7	114.4	120.9	123.8
COE: 1 generator replacement (Euro/MWh)	114.0	112.2	115.9	117.8

Table 3: Sensitivity analysis for different scenarios

4.1 Gearbox and generator replacement scenarios

There have been some wind farms where there have been a significant number of gearbox replacements required. What happens to the cost of energy if there is one gearbox replacement per turbine over the lifetime of the wind farm? This can be modelled by modifying equation (14) and adding a replacement cost for one gearbox replacement or one generator replacement. Table 3 shows the change in cost of energy (from the baseline study in section 3). The increase in Cost of Energy for the geared drivetrains demonstrates gives a clearer advantage for the direct-drive machines.

On the other hand the geared drivetrains are less sensitive to the cost of having to replace a generator once in the wind turbine's life. Under this scenario it is the single-stage design which has the lowest Cost of Energy.

4.2 Permanent magnet cost increase scenario

The last scenario in this study looks at the sensitivity of Cost of Energy to changes in permanent magnet prices. Future changes in magnet costs mainly affect a portion of the generator part of the initial capital cost (*ICC*) component in equation (14). The baseline cost of the magnets is €48/kg; here the same baseline designs but with a scenario of €120/kg are also tested. Figure 8 shows these points. If all other factors are constant then the Cost of Energy changes linearly. The direct-drive design has the highest gradient, reflecting the high magnet content in lower speed, higher torque generators. One can interpret Figure 8 as showing that a future magnet cost change from €48/kg to €60/kg would make the permanent magnet generator with a single-stage gearbox more attractive than the direct-drive option.

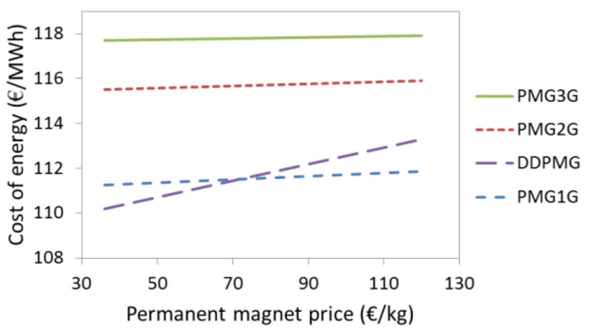

Figure 8: Sensitivity to change in permanent magnet price.

5 Discussion and Conclusions

This study provides a comparison between four different drivetrain configurations using permanent magnet generators. The drivetrains were modelled to assess which drivetrain configuration offers the lowest Cost of Energy solution for a large offshore wind turbine.

A direct-drive option can deliver the lowest Cost of Energy. This is shown in both the baseline study and when a gearbox replacement is required (for the other candidate designs). Permanent magnet generators have a limited track record in the wind industry (particularly offshore) and so the scenario of a generator replacement – once during the turbine's lifetime – is not unreasonable. Here the direct-drive generator is second best. Even under significant permanent magnet cost increases (i.e. ×2.5) this drivetrain fairs well, though once the magnet price increases above about €60/kg it is inferior to the single-stage gearbox machine.

Some potential disadvantages of the direct-drive generator have not been captured in this study: any increased wind turbine costs if the tower, foundation and installation costs increase because if increased top head mass is large; also changes in operation and maintenance costs which depend on the drivetrain. The availability has been based on onshore failure rate data in the absence of real operating data of offshore wind turbines with direct-drive PMGs.

In this study the diameter of the direct-drive generator was limited to 7m – this was assumed to be pragmatic in terms of transportation – and based on an air-cooled design. The optimisation consistently delivered designs at this limit which suggests that a large diameter machine would deliver an even lower Cost of Energy (by producing higher efficiency with the same amount of expensive active material). This is an opportunity for offshore wind turbines where transportation restrictions are not as strict as onshore.

The PMG1G performs well in terms of both energy yield and COE. The single stage gearbox concept outperforms the other gearbox designs, reinforcing the benefits of the "Multibrid" design. In the scenario with one gearbox replacement, there was a slightly bigger difference between the COE for the DDPMG and the PMG1G. For scenarios with a generator replacement or when the magnet cost increases by a reasonable amount this drivetrain delivers the lowest Cost of Energy.

This study did not define the amount of integration of generator and gearbox; it is possible that some highly integrated designs might lead to higher maintenance and replacement costs.

The higher speed generator drivetrains faired much worse under the baseline and other scenarios. Gearbox cost reductions below the assumed values predicted by equations (5) and (6) may help reduce Cost of Energy to more competitive levels under the combined scenarios of higher magnet costs and a generator replacements.

Acknowledgments

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