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How electrical machine and drivetrain design can influence Offshore Wind Cost of Energy

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***Abstract*— The selection, design and optimisation of torque speed conversion, generator and power electronics can have a profound impact on the Cost of Energy of wind turbines. Offshore wind is a challenging environment and the Cost of Energy is significantly higher than that found onshore. Because of these differences there are opportunities for new and innovative designs. This paper will explore the differences between onshore and offshore wind turbines and why it makes sense to spend more on the initial capital costs of this offshore equipment if it can deliver higher efficiency across the full operating range, lower failure rate, shorter mean time to repair and lower O&M costs. This discussion will be followed by a review of some promising technologies and how they might reduce the Cost of Energy of a typical offshore wind farm.**

Introduction

When designing power takeoff systems or powertrains for renewable energy, it can be difficult to know what design parameters are the most important: cost, efficiency, running costs, reliability or mass? This paper discusses an approach – using Cost of Energy – for balancing these competing parameters for the design of gearbox, generator and converter systems for offshore wind.

Offshore Wind Technology

The offshore wind sector is a fast growing industry. The demand is largely politically motivated: this energy source provides secure energy which does not produce any CO_2. Unfortunately it is expensive. Currently without economic support, offshore wind is unable to compete with onshore wind, despite the wind resource being stronger and more consistent and the planning process being more streamlined than onshore. 8GW of offshore wind turbines is connected to the grid in Europe, mainly in the North Sea. The current average distance to port is 32km. The mean water depth of these turbines is 22m [1]. The UK has plans for 32GW of offshore wind [2].

The trends in the offshore industry include:

- larger turbines – these make better use of expensive foundations.
- more turbines per wind farm – makes better use of expensive grid connection.
- sites that are further from shore and may need HVDC to export power (and not lose too much power in cable losses). Some of those locations have deeper water that requires more expensive foundations.

Fig. 1: In the Gunfleet Sands III demonstration project, two 6MW Siemens machines are being tested [3].

Why is the "Cost of Energy" of Offshore Wind so high?

From a simple engineering perspective we can appreciate why the cost of a unit of electricity from offshore wind energy may be higher than onshore wind. Fig. 1 shows a vessel which is used to install, repair and decommission 6MW turbines. These types of vessel can cost in the range of £100k a day to hire. Turbine foundations are much more expensive in the offshore environment as it any gird connection. A further set of challenges comes from any failure, typically offshore this leads to higher operations and maintenance costs and increased downtime. To examine this question further, it is necessary to consider the concept of levelised cost of energy in more detail.

COST OF ENERGY

Cost of Energy (*CoE*) attempts to give the cost of a unit of energy produced by a technology, based on all lifetime costs and all energy converted during the lifetime of the plant [4]. A simplified way of expressing this is,

$$CoE = \frac{(ICC \times FCR) + AOM}{AEP} \quad (1)$$

where *ICC* is the initial capital cost of the wind farm, *FCR* is the fixed charge rate (which represents the act of fairly spreading the costs across the lifetime of the plant), *AOM* is the annual operating and maintenance costs for a wind farm and AEP is the annual energy production of the wind farm.

Initial Capital Costs

The *ICC* depends on costs of the turbine, the drivetrain and generator cost, the costs of the rest of the wind farm, the cost of Balance of Plant, installation costs, manufacturing costs, an material costs.

Annual Operating and Maintenance Costs

AOM depends on failure rates, vessel hire costs and vessel requirements for failure modes, maintenance strategies, distance to port, wind and wave climate at wind farm, and the number of turbines

Annual Energy Production

AEP depends on wind resource, turbine power curve, number of turbines, drivetrain and generator efficiency, turbine availability (failure rates and repair rates).

Why a higher CoE than onshore wind?

There are a number of reasons:

- *ICC*. Installation, turbine, turbine equipment and wind farm costs are higher.
- *FCR*. Projects are riskier and financing costs are higher
- *AOM*. There are more failures, maintenance is more expensive offshore
- *AEP*. Although the wind resource may be better and more consistent, there are more failures and the repair rate is lower

STATE OF THE ART DRIVETRAIN AND GENERATORS

One can think about the design of wind turbines by the choice of the gearbox or its equivalent (to step up speed and step down torque, for use by the generator) and the choice of the generator. This can be seen in Fig. 2. The most successful design onshore is the DFIG and this has been proposed by a few companies. The largest manufacturers have turned their attention to PM generators either at a medium speed or in a direct drive configuration.

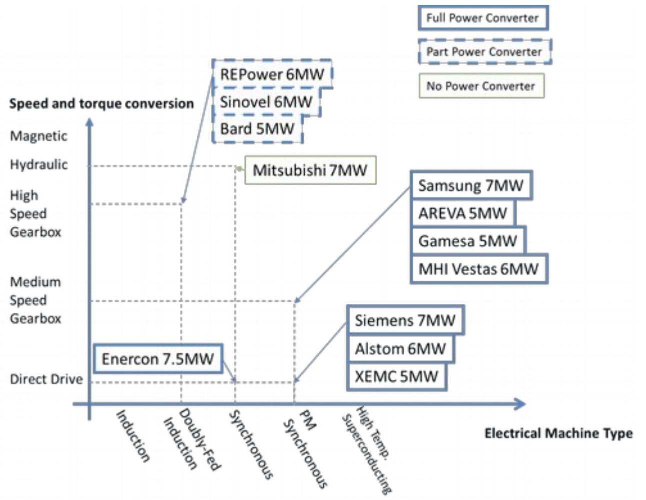

Fig. 2: Distinguishing large wind turbines by their drivetrain, generator and converter types.

What is the CoE for the State of the Art?

Data from [4] can be used with (1) to calculate the Cost of Energy for a baseline wind farm made up of 125×4MW wind turbines, each with a 3 stage gearbox drivetrain and a DFIG. The Cost of Energy for this baseline is £138.4/MWh. When assessing the contribution that the powertrain makes to this, it can be seen that:

- **11.8%** of the ***ICC*** is due to gearbox, generator and converter capital costs.
- **50%** of the ***AOM*** costs are due to the gearbox, generator and converter O&M costs.
- **4.6%** ***AEP*** is lost in the gearbox, generator and converter.
- The turbine is unavailable for **2%** of the time due to failures in the gearbox, generator and converter.

Table I shows some variation in capital costs for different generators for the same 3MW wind turbine. Some of this is based on the turbines in [5] otherwise costs are scaled based on results from [6]. PMGs are more expensive than DFIGs (because of material costs and assembly challenges) and cost increases with generator torque rating.

TABLE I. COSTS OF 3MW GENERATORS

Generator type	Cost of generator
High speed DFIG	£35-40,000
High speed PMG	£55-60,000
Medium speed PMG	£120-150,000
Direct drive PMG	£275-325,000

Fig. 3 shows some generic but indicative drivetrain and generator efficiency curves. These show that PMGs are more efficient than DFIGs/SCIGs because they have no rotor copper losses.

Lower speed drivetrains are more efficient – especially at lower power – because gearbox losses – and no load losses in particular – are less.

Direct-drive configurations are most efficient, almost until rated torque. There are no gearbox losses, but the machine is so large that copper and iron losses can be significant and so generator efficiency is less.

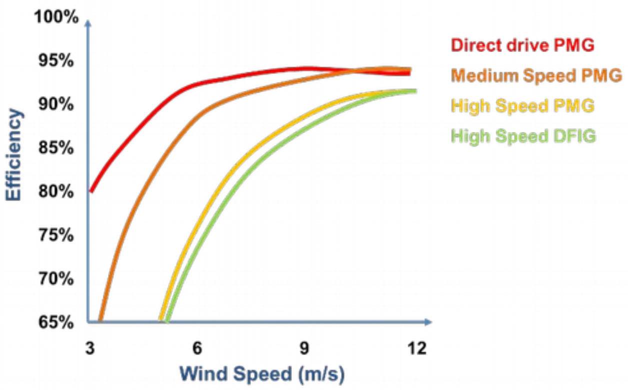

Fig. 3: Indicative drivetrain and generator efficiencies based on [7]

AN IDEAL WIND TURBINE DRIVETRAIN AND GENERATOR

It is useful to think about the Cost of Energy of a wind farm with turbines that have an idealised, unobtainable drivetrain and generator combination that minimses the *CoE* only by changing *ICC*, *AOM* and *AEP* directly affected by the gearbox, generator and converter technology. This then allows one to think about how much of the *CoE* can be influenced by the drivetrain and generator choice.

Such a hypothetical drivetrain and generator would cost £0 to manufacture and £0 to install. It would never fail or if it did the cost to repair would be £0. They would be 100% efficient (across all the power curve). They would never fail or if they did the time to repair would be 0 hours. Again, based on the data in the previous section the Cost of Energy for a wind turbine with this ideal drivetrain and generator would be £99.7/MWh (equivalent to a change of -28%).

HOW TO MAKE THE BIGGEST IMPACT ON COE

One can consider this difference between the baseline and the ideal as a 100% scale. Taking capital costs, running costs, losses and availability in turn and addressing them in isolation to other factors, we can see what the influence is on the CoE. This is shown in Fig. 5.

Setting *ICC* to 0 and keeping the rest of the baseline values constant, one finds a 27% influence. Note that *ICC* of the rest of the turbine and Balance of Plant are significant and unchanged.

With *AOM* set to 0 and keeping the rest of the baseline constant, a 60% influence is found. Gearbox, generator and power converter are about 50% of the overall O&M costs, whereas their capital costs are a small percentage of the *ICC*. *ICC* and O&M costs are similar order of magnitude, hence a big impact is seen here.

Finally reducing losses to 0 has a 16% influence and reducing the downtime to 0 has a 7% influence.

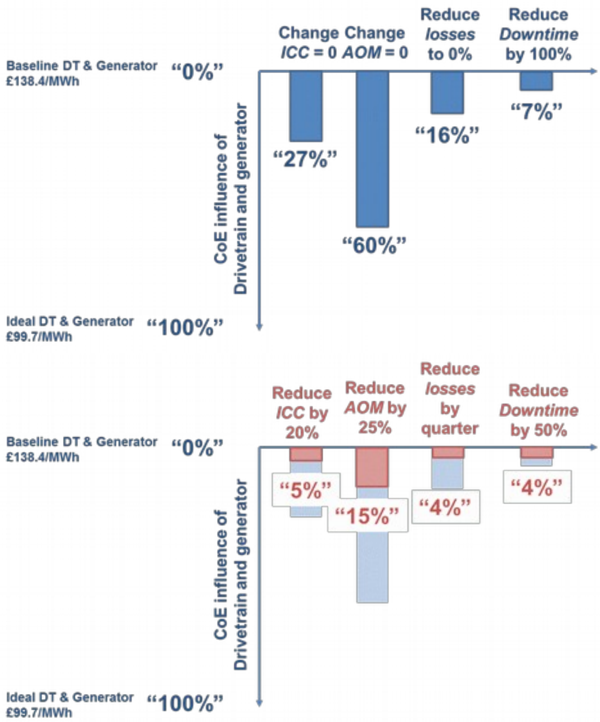

Fig. 6: CoE influence of drivetrain and generator design: *ICC*, *AOM*, losses and availability (plausible scenarios).

Of course those scenarios themselves are very extreme – and not feasible. Some new scenarios are shown in Fig. 6. These are themselves very stretching but are a bit more plausible. One can see that changes in *ICC* and efficiency improvements give similar influence. Reducing O&M costs and improving availability for the gearbox, generator and power converter often go hand-in-hand and together can bring about 20% influence.

The implication is that spending a bit more on capital cost of the drivetrain/generator to make a big impact on reliability and O&M costs is a good idea.

INTERESTING TECHNOLOGIES FOR LOW COST OF ENERGY

The analysis shows that technologies that reduce failure rates and/or reduce the costs and times associated with repair will likely have a big impact on Cost of Energy.

Permanent Magnet Generators

One example is the modular permanent magnet generators, such as those used by Siemens [8]. Modularity can allow failures in larger generators to be repaired more quickly and without recourse to heavy lift vessels.

Air-cored machines help avoid airgap closure in direct-drive machines (probably the most critical of failure modes). The lack of attraction between rotor and stator, also makes change out of stator modules much more plausible [9].

New DFIGs

So called brushless DFIGs have no brush gear and a smaller power converter [10]. This avoids one of the chief generator failure modes and allows the use of a smaller power converter (than fully rated) meaning that the failures are limited.

Alternatives to Gearboxes

Magnetic gearboxes with permanent magnet generators, e.g. those proposed by Magnomatics [11] are promising as they should removes mechanical contact and subsequent failure mechanisms from the process of converting low to high speed.

Modular hydraulic gearboxes with a directly grid connected synchronous machine, e.g. Artemis/Mitsubishi [12] allows a level of redundancy. Modularised hydraulic system allows repairs without large expensive vessels. These hydraulic systems do not have the low part load efficiency that have prevented their adoption in previous years. They make use of conventional grid-connected synchronous machines. This avoids power converters (with their high failure rates).

CONCLUSIONS

Cost of Energy is a useful way of framing design trade-offs for drivetrain and generator design in offshore wind. About 28% of the *CoE* for a typical wind farm can be directly attributed to the design of the gearbox, generator and converter. Technologies that concentrate on reducing failure rates, and reducing costs and time to repair will likely have the biggest impact on Cost of Energy.

REFERENCES

[1] European Wind Energy Association. "The European Offshore Wind Industry–Key Trends and Statistics 2014."

[2] Crown Estate, http://www.thecrownestate.co.uk/energy-and-infrastructure/offshore-wind-energy/our-portfolio/

[3] Siemens Press Picture PN201301-07, http://www.siemens.com/press/en/feature/2013/energy/2013-01-rotorblade.php

[4] Tegen, S., *et al.* "Cost of wind energy review." Golden, Colorado, National Renewable Energy Laboratory (NREL) (2010).

[5] Carroll, James, Alasdair McDonald, and David McMillan. "Reliability Comparison of Wind Turbines With DFIG and PMG Drive Trains." Energy conversion, IEEE transactions on 30.2 (2015): 663.

[6] Polinder, Henk, *et al.* "Comparison of direct-drive and geared generator concepts for wind turbines." Energy conversion, IEEE transactions on 21.3 (2006): 725-733.

[7] Zhang, Z., *et al.* “State of the Art in Generator Technology for Offshore Wind Energy Conversion Systems.” ‘11 IEMDC

[8] www.siemens.dk/windpower/

[9] http://www.boulderwindpower.com/

[10] http://www.windtechnologies.com/

[11] http://www.magnomatics.com/

[12] http://www.artemisip.com/