Comparison of Levelized Cost of Energy of superconducting direct drive generators for a 10 MW offshore wind turbine


Abstract—A method for comparing the Levelized Cost of Energy (LCoE) of different superconducting drive trains is introduced. The properties of a 10 MW MgB2 superconducting direct drive generator are presented in terms weight scaled to a turbine with a rotor diameter up to 280 m and the cost break down of the nacelle components. The partial load efficiency of the generator is evaluated for a constant cooling power of 0, 50 kW and 100 kW and the annual energy production is used to determine the impact on Levelized Cost of Energy.

Index Terms—Generators, Levelized Cost of Energy (LCoE), Superconductor, Wind Energy.

I. INTRODUCTION

Superconducting generators have been proposed as an enabling technology for large offshore wind turbines, because the torque density of the superconducting generator can offer more compact and lightweight machines[1]. This hypothesis has been investigated as a part of the INNWIND.EU project, where 10-20 MW offshore turbines, targeting 50 m water depths in the North Sea, are designed [2]. These designs involve the development of turbine rotors with diameters of up to 280 m, drive trains, and both fixed and floating offshore foundations, all with a 25 year lifetime. To compare different concepts, the Levelized Cost of Energy (LCoE) is determined from the capital and operational expenditure (CAPEX and OPEX) of the equipment divided by the annual energy production summed over the lifetime.

This paper presents the final design of the INNWIND.EU 10 MW MgB2 based superconducting direct drive generator, and the LCoE of the superconducting generator [3] is compared with the LCoE of a corresponding magnetic Pseudo Direct Drive (PDD) generator [4].

II. LEVELIZED COST OF ENERGY (LCOE)

A. Definition of LCoE with focus on generator

A method for comparing different energy producing technologies at the end of plant-life is to calculate the cost of the energy produced CoE by adding up all the costs C and divide with the total energy produced E, whereby CoE = C/E [€/MWh].

One would however often like to compare technologies before they are constructed in order to determine which of them will be the best investment [5]. This can be done by asking how much money should be reserved for a cost at the decision time \( t = 0 \) so in order to pay for the cost after \( i \) years \( c_i \). The initial amount is smaller, because alternative investments with an interest rate of \( w \) has to be considered until the year of payment, whereby \( c_i = c_0(1+w)^i \). The energy \( E_i \) produced during the years will result in an income \( i \) being proportional to the energy sales price \( s_i \), but the income from producing the energy \( E_i \) in year \( i \) is worth less at the beginning of the investment \( i_0, i \), because it takes time before it can be reinvested. Thus \( i_0 = E_i s_i (1/(1+w)^i) \). The ratio between all the costs and the income recalculated to the beginning of the investment then becomes:

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\[ LCoE = \frac{\sum_{i=0}^{LT} \frac{c_i}{(1+w)^i}}{\frac{1}{c_{LT}} \sum_{i=0}^{LT} E_i (1+w)^i} = \frac{1}{s_{LT}} \sum_{i=0}^{LT} \frac{c_i E_i}{(1+w)^i} = \frac{1}{s_{LT}} LCoE \]

where \(LT\) is the life time, \(c_i\) is the cost in year \(i\), \(w\) is the interest rate, \(E_i\) is the energy production in year \(i\), \(s_i\) is the energy sales price in year \(i\), \(s_{LT}\) is the energy price (assumed constant for all the years), and finally the Levelized Cost of Energy is denoted \(LCoE\). If different energy technologies are in the same market then \(s_{LT}\) can be assumed to be the same, whereby the technology with the lowest \(LCoE\) is the most favorable.

The above method can be used to compare the \(LCoE\) of superconducting wind turbine generators with other drive train technologies by making some simplifying assumptions. First the cost terms are split into the CAPital EXPediture (CAPEX) and the OPERational EXPenditure (OPEX), which will be denoted \(C_i\) and \(O_i\) for the cost of the equipment and running cost in year \(i\). The cost of the equipment is specified as the cost of the drive train \(C_D\) and the rest \(C_R\) of the turbine and foundation in case of an offshore turbine. These costs are payed at the beginning, whereas the operation cost \(o_i\) are assumed constant for every year and split into a drive train \(o_{D,i}\) and the remaining part \(o_{R,i}\). The \(LCoE\) can then be written as

\[ LCoE = \frac{C_D + o_{D} \cdot LT + \Delta C + o_{R} \cdot LT + \Delta O}{E_{LT}} = \frac{C_D + o_{D} \cdot LT + \Delta C + o_{R} \cdot LT + \Delta O}{E_{LT}} \]

where the Annual Energy Production (AEP) \(E_{LT}\) is assumed constant every year and the levelizing factor \(a\) is introduced as

\[ a = \frac{1}{E_{LT}} \sum_{i=0}^{LT} \frac{1}{(1+w)^i} \]

The two terms in equation (2) can be considered the CAPEX and the OPEX contributions to \(LCoE\).

An interest rate \(w = 5.75\%\) and a life time \(LT = 25\) years can be considered as constants resulting in \(a = 0.55\). The Annual Energy Production will depend on the wind resource characterized by a Weibull distribution and the losses of the drive trains. The cost of the drive train \(C_D\) can be found from the materials used in the design, but the operation expenditures are hard to determine before full scale demonstration of the superconducting generators have been evaluated. Thus the operation expenditures are assumed to be the level observed of other previous offshore wind turbines \(O/E_{LT} = 24\) €/MWh [11].

B. Sensitivity of \(LCoE\) to generator and turbine properties

One can determine the sensitivity of \(LCoE\) due to the parameters of eq. (2) by introducing variations

\[ \frac{\Delta LCoE}{LCoE_0} = \frac{\Delta E_{LT}}{E_{LT}} + \frac{\Delta E_{CAPEX}}{E_{CAPEX}} + \frac{\Delta E_{OPEX}}{E_{OPEX}} + \frac{\Delta C_D}{C_D} + \frac{\Delta C_R}{C_R} + \frac{\Delta O}{O} + \frac{\Delta LT}{LT_0} \]

where the \(\Delta E_{LT}/E_{LT}\) is the relative change of the annual energy production and similar for the other parameters. The ratios \(LCoE_{CAPEX}/LCoE_0\) and \(LCoE_{OPEX}/LCoE_0\) are estimated to be 0.72 and 0.28 respectively by using a cost of the turbine and foundations being \(C_R \sim 27\) M€ [6,7,11].

III. 10 MW MgB2 GENERATOR

A. Generator topology

A series of different MgB2 based superconducting generator topologies have been investigated by defining the different active materials of the pole and then varying the dimensions in order to obtain the torque of the 10 MW INNWIND.EU reference turbine and to optimize for the lowest \(LCoE\) [6,7]. The costs of the generators are calculated based on the assumed unit cost of the active materials, being 3 mm x 0.7 mm MgB2 tape with a copper strip from Columbus at a cost of 4 €/m [8], copper armature windings (15 €/kg), magnetic steel laminates (3 €/kg), and glass fiber (15 €/m). These unit costs represent the cost that the active material have in the final generator and include the profit of the manufacturing companies [9]. The conclusion from the investigations of [6,7] is that it is much easier to obtain the torque and low cost from the fully iron-cored MgB2 generator with the current properties of the MgB2 tapes, but at the expense of a higher active mass. In the INNWIND.EU project it was investigated if a cost reduction of the tower and foundations could be gained from a possible weight reduction of the superconducting generator, but it was found that reducing the tower top mass would shift a critical resonance of the tower and foundation closer to the blade passing excitation frequency, and thereby reduce the life time of the foundation [10]. Thus, the design philosophy for the INNWIND.EU MgB2 generator was changed from “light weight and not too expensive” to “cheap and not too heavy”. In terms of (2) this means that the cost of the rest of the structure \(C_R\) is not expected to change much with changes in the drive train mass.

B. Front mounted generator in nacelle

The optimized active materials of the MgB2 generators using the method of [6,7] where used to determine an appropriate aspect ratio of the 10 MW generator to be able to integrate the generator into a nacelle, where the generator is mounted in front of the turbine blades as shown in Fig. 1. This configuration has been denoted the king pin concept, because a static pin is going through the hub that is holding the 3 blades and is supported on both sides by roller bearings. It has been found that a \(D = 8.4\) m and \(L = 1.3\) m MgB2 generator seems to match the dimensions of the King-pin nacelle and the resulting weight of the generator is 286 tons.

Table I shows the main properties of the 10 MW MgB2 generator [11] and Fig. 2 shows the expected mass scaling of the generator, blade and nacelle as function of the turbine rotor diameter approaching \(D_{turbine} = 280\) m by using the scaling principles of [12]. The unit cost of the structural steel used for the nacelle is 3-4 €/kg.

C. Cryostats and cooling system

The choice of the iron-cored topology of the INNWIND.EU 10 MW MgB2 generator calls for a cryostat concept, where warm magnetic steel laminated poles go through the MgB2 racetrack coils. This concept has been investigated in the Su-
prapower project [13] and has been projected onto the INNWIND.EU generator by assuming that a similar heat load will be present. This has been used to estimate the cryocooler coldheads and compressors demand, whereby the cost of the cryogenics system has been determined [11]. It is found that about 15 coldheads will be needed to provide the cooling and a loss of 104 kW, corresponding to 1 % of the full rated power of the turbine, is needed to run the compressors. Fig. 3 shows the cost and mass break down of the nacelle components of the 10 MW MgB$_2$ generator layout, including the cryostat and compressor cost [11].

D. Efficiency of superconducting generator

The efficiency of the 10 MW MgB$_2$ superconducting generator has been determined from the joule losses in the armature windings, the hysteresis losses of the magnetic steel laminates, and the eddy current losses, all as function of the wind speed of the 10 MW INNWIND.EU reference turbine [6,7]. Appropriate power converters for the 10 MW generator have also been investigated [14] and the efficiency of the power converter is included in Fig. 4. The design Weibull wind distribution corresponding to an IEC class Ia wind resource having a mean wind speed of $v_{\text{ave}} = 10.0$ m/s and a shape parameter of $k = 2$ [15] is also shown. Thus one can then calculate the annual energy production of the 10 MW turbine using the mechanical power curve of the rotor blades $P_{\text{mech}}(v)$ [15] adjusted for the partial load efficiency $\varepsilon(v)$ and integrate that over the wind speed distribution

$$E_{t,C} = \int_{v_{\text{cut-in}}}^{v_{\text{cut-out}}} P_{\text{mech}}(v)\varepsilon(v)P_{\text{Weibull}}(v)\,dv$$

where $v_{\text{cut-in}} = 4$ m/s and $v_{\text{cut-out}} = 25$ m/s is giving the operational wind speed range. Once the wind speed reaches rated wind speed at $V_{\text{rated}} = 11.4$ m/s, the turbine blades are pitched and the turbine produces the rated power. Thus, above rated wind speed, the output is $P = 10$ MW.

IV. COMPARISON OF LCoE

Fig 4. shows the partial load efficiency of the 10 MW MgB$_2$ generator when including a constant cooling power of 0, 50 or 100 kW, as well as the 10 MW RBCO based direct drive and a magnetic Pseudo Direct Drive (PDD) of INNWIND.EU. The annual energy production of the different drive trains has been evaluated using (5) and the impact on LCoE from (4) is shown in table II. The pure annual energy production with no losses have been used as the baseline and the increase of LCoE is therefore with respect to a loss free drive train. By summing the drive train costs in Fig. 3 to $C_D = 2.6$ M€ including power converter, one can estimate the LCoE of the 10 MW MgB$_2$ generator using (2) to be

$$\text{LCoE} = \frac{2.6 \text{ M€} + 27 \text{ M€}}{0.55 \cdot 48.3 \text{ GWh} + 24 \text{ MWh}} = 68.6 \text{ €/MWh}$$

This estimate is however considerably higher than most recent LCoE levels for offshore wind around 40 €/MWh [17] and indicates that the material unit cost should be lowered in order to match absolute cost values. The impact of the cost of the different drive trains can in principle be done, but a challenge is how to ensure the same inclusion of manufacturing cost and profit. One can however determine the change of LCoE if the drive train cost $CD$ is reduced to half. From the second term of (4) one obtains

$$\frac{\text{LCoE}_{\text{CAPEX}}}{\text{LCoE}_0} = 0.72 \cdot \frac{\Delta C_D}{C_D} = 0.72 \cdot \frac{-1.3 \text{ M€}}{2.6 \text{ M€} + 27 \text{ M€}} = -3.2 \%$$

V. DISCUSSION

The analysis of the 10 MW MgB$_2$ generator shows that the constant power consumption of 100 kW of the cooling machines reduces the partial load efficiency of the turbine and effort to reduce the cooling power to about 50 kW will be needed and could reduce LCoE by about 0.6 %. It should however be noted that the Pseudo Direct Drive generator based on permanent magnets is more efficient than the superconducting drive train even when the cooling is neglected. Secondly it is seen that reducing the cost of the superconducting drive train to half can result in a reduction of the LCoE of about 3 %, which will also be needed to compete with the PDD.

VI. CONCLUSION

A method for comparing the levelized cost of energy of different superconducting drive trains have been used to indicate that the constant cooling loss of 100 kW of the 10 MW MgB$_2$ generator should be reduced to 50 kW in order to obtain a better partial load efficiency. Secondly a reduction of the drive train cost from 2.6 M€ to half would be beneficial. A reduction of LCoE of 0.6 % and about 3 % would result.
Fig. 2. Mass scaling of the main components of the front mounted MgB$_2$ superconducting direct drive generator as function of the turbine rotor diameter. The MgB$_2$ generator active materials mass (green) are added to the structural generator mass whereby the total generator mass (red) is obtained. By adding also the blade mass (blue) and the nacelle mass then the Rotor Nacelle Assembly (RNA) mass (black) is obtained. The RNA of the INNWIND.EU reference designs for $P = 10$ MW and 20 MW are shown (stars) as well as the RNA of the Vestas V-164 [16] and the total generator mass of a 10 MW permanent direct drive generator design by Polinder [9].

### TABLE I

<table>
<thead>
<tr>
<th>Power [MW]</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine rotor diameter [m]</td>
<td>178</td>
<td>252</td>
</tr>
<tr>
<td>Rated Speed [RPM]</td>
<td>9.65</td>
<td>7.13</td>
</tr>
<tr>
<td>Rated line-to-line voltage [V]</td>
<td>3300</td>
<td>6600</td>
</tr>
<tr>
<td>Specific electrical loading [kA/m]</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Field current density in coil (20 K) [A/mm$^2$]</td>
<td>111</td>
<td>115</td>
</tr>
<tr>
<td>Field current density in tape (20 K) [A/mm$^2$]</td>
<td>178</td>
<td>184</td>
</tr>
<tr>
<td>Stator outer diameter D, [m]</td>
<td>8.4</td>
<td>10.8</td>
</tr>
<tr>
<td>Number of phases m</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Slots per pole per phase q</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pole pitch $l_p$ [mm]</td>
<td>471</td>
<td>471</td>
</tr>
<tr>
<td>Number of pole pairs p</td>
<td>28</td>
<td>36</td>
</tr>
<tr>
<td>Frequency $f_e$ [Hz]</td>
<td>4.5</td>
<td>4.2</td>
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<tr>
<td>Axial stack length $L_s$ [m]</td>
<td>1.31</td>
<td>2.25</td>
</tr>
<tr>
<td>Shear stress $\sigma_t$ [kPa]</td>
<td>72.3</td>
<td>71.6</td>
</tr>
<tr>
<td>Normal stress $\sigma_r$ [kPa]</td>
<td>486</td>
<td>469</td>
</tr>
<tr>
<td>$D^2L_s$ [m$^3$]</td>
<td>92.4</td>
<td>262.4</td>
</tr>
<tr>
<td>Air gap length $g$ [mm]</td>
<td>8.4</td>
<td>10.8</td>
</tr>
<tr>
<td>MgB$_2$ field winding (incl. end) [ton]</td>
<td>0.32</td>
<td>0.52</td>
</tr>
<tr>
<td>Rotor iron mass [ton]</td>
<td>51.8</td>
<td>111.5</td>
</tr>
<tr>
<td>Cryostat mass [ton]</td>
<td>3.4</td>
<td>8.9</td>
</tr>
<tr>
<td>Stator iron mass [ton]</td>
<td>49.4</td>
<td>106.8</td>
</tr>
<tr>
<td>Copper mass (incl.-end) [ton]</td>
<td>13.1</td>
<td>24.3</td>
</tr>
<tr>
<td>Total rotor mass [ton]</td>
<td>55.5</td>
<td>120.4</td>
</tr>
<tr>
<td>Total stator mass [ton]</td>
<td>62.4</td>
<td>131.0</td>
</tr>
<tr>
<td>Total active mass [ton]</td>
<td>118</td>
<td>251</td>
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<tr>
<td>Structural mass [ton]</td>
<td>168</td>
<td>437</td>
</tr>
<tr>
<td>Total generator mass [ton]</td>
<td>286</td>
<td>688</td>
</tr>
</tbody>
</table>

Fig. 3. 10 MW MgB$_2$ superconducting direct drive wind turbine rotor, generator and nacelles component cost and weight breakdown. a) Component cost in [k€] and b) component weight in [ton] according to the components outlined in [12]. The components associated with the superconducting drive train have been displaced from the center.

### TABLE II

<table>
<thead>
<tr>
<th>Drive train</th>
<th>$E_i$ [GWh/year]</th>
<th>$\Delta$LCoE/ LCoE$_i$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgB$_2$ – No cooling loss included</td>
<td>48.8</td>
<td>1.9</td>
</tr>
<tr>
<td>MgB$_2$ – 50 kW cooling loss included</td>
<td>48.6</td>
<td>2.5</td>
</tr>
<tr>
<td>MgB$_2$ – 100 kW cooling loss included</td>
<td>48.3</td>
<td>3.1</td>
</tr>
<tr>
<td>RBCO – No cooling loss included</td>
<td>48.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Pseudo Direct drive (PDD)</td>
<td>49.1</td>
<td>1.3</td>
</tr>
<tr>
<td>10 MW reference turbine with no loss</td>
<td>49.8</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fig. 4. Efficiency of the 10 MW MgB$_2$ generator with a constant power consumption of the cryogenic cooling system of 0, 50 kW and 100 kW, a 10 MW coated conductor RBCO based generator [3] without cryogenic cooling consumption and the magnetic Pseudo Direct Drive (PDD) generator [4] investigated in the INNWIND.EU project. The Weibull wind distribution is shown on the right hand axis.
REFERENCES


[14] INNWIND.EU deliverable report D3.31, “Converter designs tailored to SC and PDD concepts”

