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Important note
To cite this publication, please use the final published version (if applicable).
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Comparison of Levelized Cost of Energy of Superconducting Direct Drive Generators for a 10-MW Offshore Wind Turbine

Asger Bech Abrahamsen, Dong Liu, Niklas, Magnusson, Arwyn Thomas, Ziad Azar, Ewoud Stehouwer, Ben Hendriks, Gerrit-Jan Van Zinderen, Fujin Deng, Zhe Chen, Dennis Karwatzki, Axel Mertens, Max Parker, Stephen Finney, and Henk Polinder

Abstract—A method for comparing the levelized cost of energy (LCoE) of different superconducting drive trains is introduced. The properties of a 10-MW MgB_2 superconducting direct-drive generator and the cost break down of the nacelle components are presented and scaled up to a turbine with a rotor diameter of up to 280 m. The partial load efficiency of the generator is evaluated for a constant cooling power of 0, 50, and 100 kW, and the annual energy production is used to determine the impact on the LCoE.

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,

A. B. Abrahamsen is with the Department of Wind Energy, Technical University of Denmark, Roskilde, 4000, Denmark (e-mail: asab@dtu.dk).

D. Liu is with the Department of Electrical Sustainable Energy, Delft University of Technology, Delft 2628 CD, The Netherlands (e-mail: D.Liu@xemc-darwind.com).

N. Magnusson is with the SINTEF Energy Research, Trondheim 7034, Norway (e-mail: Niklas.Magnusson@sintef.no).

A. Thomas and Z. Azar are with Siemens Wind Power limited, Sheffield S3 7HQ, U.K. (e-mail: arwyn.thomas@siemens.com; ziad.azar@siemens.com).

E. Stehouwer and G.-J. V. Zinderen are with the Turbine Engineering DNV GL—Energy, Groningen 9743 AN, The Netherlands (e-mail: ewoud.stehouwer@dnvgl.com; gerrit-jan.zinderen@dnvgl.com).

B. Hendriks is with the Knowledge Centre WMC, Wieringerwerf 1770 AA, The Netherlands (e-mail: h.b.hendriks@wmc.eu).

F. Deng and Z. Chen are with the Department of Energy Technology, Aalborg University, Aalborg 9220, Denmark (e-mail: fde@et.aau.dk; zch@et.aau.dk).

D. Karwatzki and A. Mertens are with the Institute for Drive Systems and Power Electronics, Leibniz Universität Hannover, Hannover 30167, Germany (e-mail: dennis.karwatzki@ial.uni-hannover.de; mertens@ial.uni-hannover.de).

M. Parker is with the Institute for Energy and Environment, University of Strathclyde, Glasgow G1 1XW, U.K. (e-mail: max.parker@strath.ac.uk).

S. Finney is with the School of engineering, The University of Edinburgh, Edinburgh EH8 9YL, U.K. (e-mail: Stephen.Finney@ed.ac.uk).

H. Polinder is with the Department of Maritime and Transport Technology, Delft University of Technology, Delft 2628 CD, The Netherlands (e-mail: H.Polinder@tudelft.nl).

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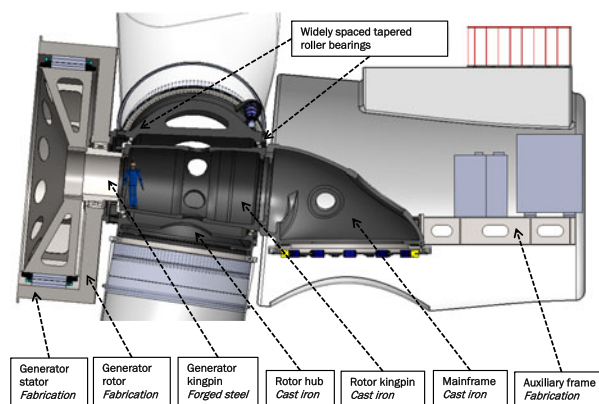
Digital Object Identifier 10.1109/TASC.2018.2810294

Fig. 1. Cross section view of the INNWIND.EU nacelle with the 10 MW MgB_2 generator mounted in front of the turbine blades [12]. The inner and stationary structure of the generator is attached to the stationary kingpin going through the rotor hub and connected to the main frame.

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 design 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 MgB_2 based superconducting direct drive generator as illustrated in Fig. 1. The determination of the LCoE of the generator is compared with a 10 MW high temperature superconducting direct drive generator [3] and magnetic Pseudo Direct Drive (PDD) generator [4] of the INNWIND.EU project.

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 dividing with the total energy produced E, whereby $CoE = C/E$ [€/MWh].

One would however often like to compare technologies before they are constructed 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 $c_{0,i}$ at the decision time ($t = 0$) in order to pay for the cost c_i after i years. The initial amount is smaller, because alternative investments with an interest rate of w has to be considered until the year of payment, whereby $c_i = c_{0,i}(1 + w)^i$. The energy E_i produced during the years will result in an income i_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 than at the beginning of the investment $i_{0,i}$, because it takes time before it can be reinvested. Thus $i_{0,i} = E_i s_i 1/(1 + w)^i$. The ratio between all the costs and the income recalculated to the beginning of the investment then becomes

$$\frac{C}{I} = \frac{\sum_{i=0}^{LT} c_i \frac{1}{(1+w)^i}}{\sum_{i=0}^{LT} E_i s_i \frac{1}{(1+w)^i}} = \frac{1}{s_{i,c}} \frac{\sum_{i=0}^{LT} c_i \frac{1}{(1+w)^i}}{\sum_{i=0}^{LT} E_i \frac{1}{(1+w)^i}} = \frac{1}{s_{i,c}} LCoE \tag{1}$$

where LT is the design 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, $s_{i,c}$ 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 $s_{i,c}$ 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 cost of the rest C_R of the turbine and foundation in case of an offshore turbine. These costs are paid at the beginning, whereas the operation cost o_i are assumed constant for every year and split into a drive train $o_{D,c}$ and rest of the turbine part $o_{R,c}$. The LCoE can then be written as

$$LCoE = \frac{C_D + C_R}{\sum_{i=0}^{LT} E_i \frac{1}{(1+w)^i}} + \frac{\sum_{i=0}^{LT} o_i \frac{1}{(1+w)^i}}{\sum_{i=0}^{LT} E_i \frac{1}{(1+w)^i}}$$

$$= \frac{C_D + C_R}{a \cdot E_{i,c}.\text{LT}} + \frac{o_{D,c} + o_{R,c}}{E_{i,c}} \tag{2}$$

where the Annual Energy Production (AEP) $E_{i,c}$ is assumed constant every year and the levelizing factor a is introduced as

$$a = \frac{1}{LT} \sum_{i=0}^{LT} \frac{1}{(1+w)^i} \tag{3}$$

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

An interest rate $w = 5.75\%$ and a design life time $LT = 25$ years can be considered as constants resulting in $a = 0.55$. The AEP 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 designs, but the operation expenditures are hard to determine before full scale demonstration of the superconducting generators have been evaluated. Thus the operational expenditures are assumed to be similar to other previous offshore wind turbines O/ $E_{i,C} = 24$ €/MWh [11].

B. Sensitivity of LCoE to Generator and Turbine Properties

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

$$\frac{\Delta LCoE}{LCoE_0} = -\frac{\Delta E_{i,c}}{E_{i,c0}}$$

$$+ \frac{LCoE_{CAPEX}}{LCoE_0} \left(\frac{\Delta C_D}{C_{D,0} + C_{R,0}} + \frac{\Delta C_R}{C_{D,0} + C_{R,0}} - \frac{\Delta a}{a_0} - \frac{\Delta LT}{LT_0} \right)$$

$$+ \frac{LCoE_{OPEX}}{LCoE_0} \left(\frac{\Delta O_{D,C}}{O_{D,C0} + O_{R,C0}} + \frac{\Delta O_{R,C}}{O_{D,C0} + O_{R,C0}} \right) \tag{4}$$

where the $\Delta E_{i,c}/E_{i,c0}$ 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 the cost of the 10 MW INNWIND.EU reference turbine and foundations being $C_R \sim$ 27 M€ [6], [7], [11].

III. 10 MW MGB2 GENERATOR

A. Generator Topology

A series of different MgB$_2$ based superconducting generator topologies have been investigated by defining the different active materials of the pole and then varying the dimensions 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 × 0.7 mm MgB$_2$ tape with a copper strip from Columbus Superconductors [8] at a cost of 4 €/m, copper armature windings (15 €/kg), magnetic steel laminates (3 €/kg), and glass fiber (15 €/kg). These unit costs represent the cost of the active material 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 MgB$_2$ generator with the current properties of the MgB$_2$ 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 MgB$_2$ 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

TABLE I
PROPERTIES OF MGB$_2$ DIRECT DRIVE GENERATORS [11].

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

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 distribution and usage of active materials of the MgB$_2$ 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 kingpin 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 MgB$_2$ generator seems to match the dimensions of the kingpin nacelle and the resulting weight of the generator is 286 tons.

Table I shows the main properties of the 10 MW MgB$_2$ 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 MgB$_2$ generator calls for a cryostat concept, where warm magnetic steel laminated poles go through the MgB$_2$ racetrack coils. This concept has been investigated in the Suprapower project [13] and has been projected onto the INNWIND.EU generator by assuming that a similar heat load will be present. This
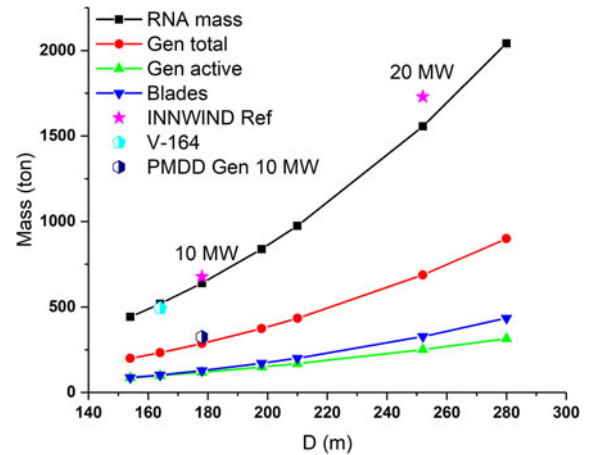

Fig. 2. Mass scaling of the main components of the front mounted MgB$_2$ superconducting direct drive generator as function of the turbine rotor diameter [11]. The MgB$_2$ generator active materials mass (green) are added to the structural generator mass whereby the total generator mass (red) is obtained. 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 [17] and the total generator mass of a 10 MW permanent direct drive generator design by Polinder [9].
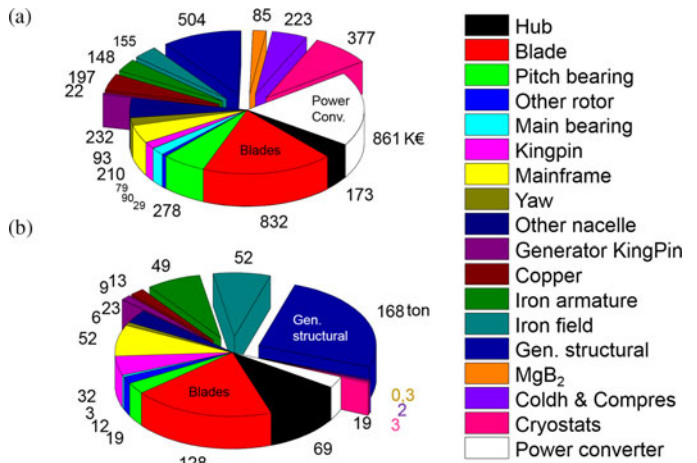

Fig. 3. 10 MW MgB$_2$ superconducting direct drive wind turbine rotor, generator and nacelles component cost and weight breakdown [11]. a) Component cost in [k€] and b) component weight in [ton] according to the components outlined in [12]. The components associated with the superconducting drive train have been displaced from the center.

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 Drive Train

The efficiency of the 10 MW MgB$_2$ superconducting generator has been determined from the joule losses in the armature windings, and the hysteresis and eddy-current losses of the
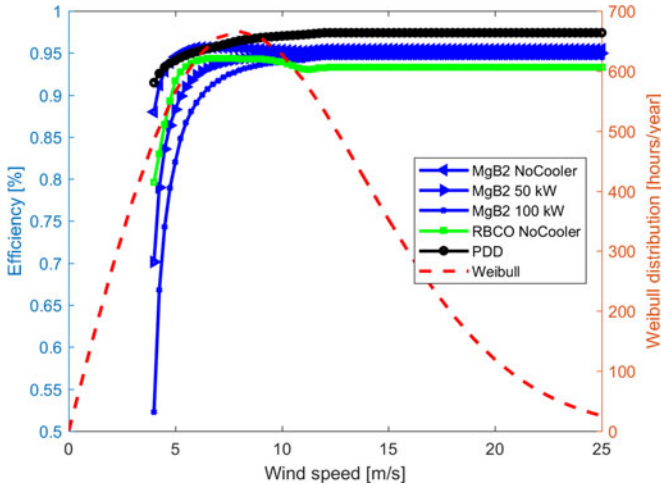
Fig. 4.   Efficiency of the 10 MW MgB$_2$ generator with a constant power consumption of the cryogenic cooling system of 0, 50 kW and 100 kW [11], a 10 MW coated conductor RBCO based generator [3] without cryogenic cooling consumption and the magnetic Pseudo Direct Drive (PDD) generator [4] investigated in the INNWIND.EU project [16]. The Weibull wind distribution is shown on the right hand axis.

magnetic steel laminates as a function of the wind speed of the 10 MW INNWIND.EU reference turbine [6], [7]. Power converters for the 10 MW generators have been investigated [14] and the efficiency of the power converter is included in the partial load efficiency shown in Fig. 4. The design Weibull wind distribution corresponding to an IEC class Ia wind resource having a mean wind speed of $v_{ave} = 10.0$ m/s and a shape parameter of $k = 2$ [15] is used. The AEP of the turbine can be calculated by integrating the mechanical power curve of the rotor blades $P_{mech}(v)$ [15] multiplied by the partial load efficiency $\varepsilon(v)$ over the wind speed distribution

$$E_{i,C} = \int_{v_{cut-in}}^{v_{cut-out}} P_{mech}(v)\,\varepsilon(v)\,P_{Weibull}(v)\,dv \quad (5)$$

where $v_{cut-in} = 4$ m/s and $v_{cutout} = 25$ m/s is giving the operational wind speed range.

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) [16]. The AEP of the different drive trains has been evaluated using (5) and the impact on LCoE from (4) is shown in Table II. The pure AEP with no losses have been used as the baseline and the increase of LCoE is therefore with respect to a loss free drive train.

V. DISCUSSION

The LCoE analysis of Table II is showing that the Pseudo Direct Drive (PDD) provides the most efficient drive train to the 10 MW INNWIND.EU turbine and jacket foundation with a LCoE about 1.3% above the loss free reference drive train. The superconducting MgB$_2$ generator provides a range of LCoE from 1.9% to 3.1% depending on the cooling compressor power.

TABLE II
ANNUAL ENERGY PRODUCTION E_i OF DRIVE TRAINS. REPRODUCED FROM [16].

Drive train	E_i [GWh/year]	ΔLCoE/ LCoE$_0$ [%]
MgB$_2$ – No cooling loss included	48.8	1.9
MgB$_2$ – 50 kW cooling loss included	48.6	2.5
MgB$_2$ – 100 kW cooling loss included	48.3	3.1
RBCO – No cooling loss included	48.5	2.6
Pseudo Direct drive (PDD)	49.1	1.3
10 MW reference turbine with no loss	49.8	0.0

The efficiency of the high temperature RBCO superconductor direct drive generator including cryogenic cooling has not been estimated, since the wire cost was concluded to be too high to compete with permanent magnet direct drive (PMDD) generators [3]. Further analysis of the INNWIND.EU reference drive trains in the form of a two stage gear box combined with a medium speed generator (MediumSpeedDrive) and PMDD generator with a shear force density of 40 kN/m^2 have revealed that the LCoE is lifted to 3.8% and 2.3% respectively [16]. This is indicating that the superconducting direct drive proposals are not orders of magnitude from being competitive, but the 10 MW generator mass of 286 tons in Table I must be compared to a PDD, PMDD and MediumSpeedDrive mass of 150 tons, 237 tons and 178 tons respectively. Reducing the cost of the MgB$_2$ wire and increasing the infield critical current density are seen as a way to increase the amount of superconducting wire and reduce the amount of magnetic steel and thereby the generator mass. However the MgB$_2$ superconductor contributes less that the cost of the cryostats and the cryogenics in Fig. 3. Thus industrialization of these components seems to be the primary target of further LCoE reductions.

By summing the drive train costs in Fig. 3 to $C_D \sim 2.6$ M€ including the power converter, one can estimate the LCoE of the 10 MW MgB$_2$ generator using (2) to be

$$LCoE = \frac{2.6\ \text{M€} + 27\ \text{M€}}{0.55 \cdot 48.3 \frac{\text{GWh}}{\text{y}} \cdot 25\text{y}} + 24 \frac{\text{€}}{\text{MWh}} = 69 \frac{\text{€}}{\text{MWh}} \quad (6)$$

This estimate is however considerably higher than most recent LCoE levels for offshore wind around 40 €/MWh [18]. The difference is believed to arise from a water depth lower than 50 m, the interest rate w used in the sector has decreased due to higher competition and the design life time of 30 year is suggested. If the cost of the 10 MW MgB$_2$ generator is decreased by 25% then the LCoE is expected to decrease by about 1.6% and can not provide large changes in LCoE towards the 40 €/MWh.

VI. CONCLUSION

The levelized cost of energy of different superconducting drive trains has shown the current MgB$_2$ and RBCO superconductors can still not compete with the traditional drive trains mainly due to the low cost of permanent magnets. Improving the cost and properties of the superconductors will be beneficial, but industrialization of the cryostat and cooling system seems to hold the largest potential for further LCoE reductions.

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