Initial performance and load analysis of the LowWind turbine in comparison with a conventional turbine

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Abstract. We present the preliminary design of a high capacity LowWind turbine rotor with a specific power of 100 W/m², a rated power of 3.4MW and a 208m diameter rotor. The turbine is designed for optimal system integration and thus with a considerably increased power production at low to medium wind speed and stopped at 13 m/s. The AEP of the turbine, due to the large swept rotor area, is 40-45% higher than the AEP of a conventional on-shore turbine, the IEA Task 37 reference wind turbine with a 130 m diameter rotor and the same rated power of 3.4 MW. Initial aeroelastic simulations show that the loads of the LowWind turbine are generally higher than on the IEA turbine although comparable for some components at steady wind. For Design Load Case 1.2 (DLC1.2) for normal operation in turbulence we see a typical increase of around 20-40% of tower and rotor fatigue loads. However, this moderate increase for such big increase of rotor diameter is only obtained due to the highly flexible light weight rotor designed with a combination of peak shaving and blade bend twist coupling and for a low stop wind speed of 13 m/s.

1. Introduction
Wind power contributes already considerably to the electricity power generation in Europe and will play an even more important role in the future transition to a fully renewable and sustainable power supply in Europe and worldwide. However, a fundamental challenge with wind power is its intermittent character and because the power is proportional to the wind speed cubed the wind turbine power production varies considerably over shorter time scales over hours, days and months. This means that in a power system supplied fully by wind power there will be lack of power at low wind speed and excess at strong wind. The solution to this is among others a flexible grid system with strong cross border links, storage systems, adaptive consumption and other flexible power supply systems.

However, the LowWind turbine concept is proposed with the objective to make a major contribution to the system integration on the wind power production side. This is achieved by the LowWind turbine which is producing much more energy at low wind speed compared with a traditional turbine, enabled by a low specific power (SP) of 100 W/m². The specific power was one of the turbine parameters investigated in a recent IEA Task 26 work looking at the impact of wind turbine design on the system value of wind in Europe in a period up to 2030 [4]. They found that a specific power of 250 W/m² is a likely scenario for main stream and that 175 W/m² would be ambitious. In that context we can characterize the 100 W/m²
as disruptive. It can also be mentioned that similar work is ongoing in the Big Adaptive Rotor (BAR) project in US, however with the target of a rotor with 150 W/m$^2$, [9]. Initial power system simulations with a LowWind type power curve have shown that this increased power production at low wind where the electricity prices often are high can be quite beneficial [12]. Another feature of the LowWind turbine is that it shuts down at a wind speed around 13 m/s where conventional turbines reach rated power and can supply power enough. However, a challenge with the low specific power rotors is the big rotor and blade size which can increase transportation and installation costs and also increased blade costs if a split of the blade is necessary. The LowWind turbine will be fully optimized to this reduced operational range from e.g. 2 to 13 m/s and it is expected that this will lead to design solutions differing considerably from the conventional variable speed, 3-bladed upwind rotor and pitch regulated turbine.

The exploration of the LowWind turbine is now ongoing in a 2.5 years project funded by the Danish research and development programme EUDP. Based on this work we will in the present paper present the preliminary design and optimization and the initial performance and load characteristics of a LowWind 3.4 MW reference turbine with a 208 m diameter rotor in comparison with a conventional reference turbine with a 130 m diameter rotor, the IEA 3.4 MW onshore reference turbine from IEA Task 37 [14].

In the present work we apply an integrated design approach, designing a detailed internal structural layout, and simultaneously optimizing the blade planform and control set points. It should however be noted that the design methodology presented in this work is intended for studying global rotor design trends relevant to the LowWind turbine concept and is for academic purposes only. As such the results, level of analysis and design assumptions are far from fulfilling the necessary requirements for a certifiable and production-intent design.

The paper is organized in the way that in Section 2 of the paper we present the methodology that is used for development of the LowWind turbine concept followed by Section 3 where the design and optimization of the LowWind turbine is presented. The aeroelastic modelling approach is outlined in Section 4 and the results on performance and loads are presented and discussed in Section 5. Finally, Section 6 contains the conclusions and outlook.

2. Methodology

The methodology that is used for developing the LowWind turbine concept in the above mentioned project is first to develop two reference turbines, a LowWind Reference Wind Turbine named LW RWT and a conventional turbine, for which we have chosen the IEA 3.4 MW from IEA Task 37 [14]. Both with the same rated electrical power of 3.4 MW (exactly 3.37 MW and 3.6 MW mechanical power) and using almost the same turbine platform. The LW RWT is designed using conventional turbine technology, up-wind 3-bladed rotor with variable speed and pitch regulation, however with the fixed design parameter of a specific power of 100 W/m$^2$. This allows a first comparison of the performance of the LowWind turbine with a similar conventional turbine for exactly the same rated power and on the same turbine platform, except for an increased tower height to 125m for the LW RWT in comparison with the 110m for the IEA RWT. However, due to the early stage in the LW RWT development the turbine platform was not redesigned for the increased load levels on the LW RWT as will be shown later. To avoid impact of non-optimal tower dynamics for the bigger and heavier LW RWT rotor on the IEA RWT tower the load time simulations were performed with stiff towers for both turbines to get a true basis for the load comparisons. In the comparison of the tower bottom moments the increased tower height was included.

This is the part of the work presented in the present paper. However, the next phase in the LW development project mentioned above is to introduce new turbine design concepts and innovations for the further LW turbine development and relaxing the constraints mentioned
above relating to the conventional turbine design of today. This work is carried out to explore
how the limited wind speed operational interval from 2-13 m/s can be utilized to lower turbine
costs. One concept that will be studied is a downwind turbine version in order to achieve even
more flexible and lightweight blades with lower loads transmitted onto the rest of the turbine
platform.

2.1. The conventional reference turbine - IEA 3.4 MW
We decided to use the IEA Task 37 3.4 MW onshore turbine as the conventional reference tur-
bine because it is open access, already known by the research community and also well described
[14]. The rotor diameter is 130 m which gives a specific power (SP) of of 256 W/m² based on the
rated electrical power of 3.37 MW. The tower height is 110m, cone angle 3 deg, tilt angle 5 deg
and the cut out wind speed is 25 m/s. It can be mentioned that the IEA 3.4 MW specifications
including the SP of 256 W/m² to some degree were based on a survey that was conducted to
identify the use cases and needs for RWTs in the research and development applications with a
total feed back from 81 respondents [14].

3. Design of the LowWind RWT
3.1. The design framework
For the design of the LowWind Reference Wind Turbine, HAWTOpt2 was used [16, 15].
HAWTOpt2 couples BECAS [3, 2], HAWCStab2 [8], and HAWC2 [6] into a monolithic
optimization framework, allowing for simultaneous design of the blade outer shape and internal
structural components using predefined airfoil series. The design tool uses a gradient based
approach and since analytic gradients are not available for the above-mentioned tools, finite
derifferencing is used to estimate gradients. In the present work, only the steady state aeroelastic
solutions coming from HAWCStab2 are used for optimization, and we thus omit full time-domain
load cases in order to allow for faster turn-around time during the preliminary design exploration
phase.

3.2. The design approach for the LowWind RWT
The Low Wind RWT targets a specific power of 100 w/m² based on a rated electrical power
of 3.37 MW, resulting in a blade length of 102 m (208m diameter rotor). Assuming the same
transmission losses as for the IEA 3.4 MW turbine the rated aerodynamic power was set to 3.6
MW. The maximum tip speed of 80 m/s was kept the same as for the IEA 3.4 MW turbine.
In the initial design phase of the LowWind reference wind turbine, cost models were not included,
and we therefore sought to maximize annual energy production, subject to various loads, mass
and geometric constraints. An initial blade model consisting of detailed internal structural
layout and blade planform was made based on a combination of the IEA 10 MW RWT and the
IEA 15 MW RWT.
To obtain a blade design with as low mass as possible and large flexibility we opted for a single
shear web design. The carbon based spar cap was set to a constant width of 0.6 m from root
to tip, and the triax skin layout used on the IEA 15 MW RWT was mimicked. The root triax
reinforcement thickness was set to 100 mm, however a detailed root design was not carried out.
The FFA-W3 airfoil family was used on the blade, using the airfoil data computed for the IEA
10MW RWT by the CFD solver EllipSys2D assuming a mix of 70% free transition and 30%
turbulent flow. Tower and drivetrain were based directly on the IEA 3.4 MW RWT¹.
The optimization problem consisted of a total of 31 aerostructural design variables, as well as
rotor RPM and collective blade pitch at each of the operating wind speeds in the range [2:13]

¹ https://github.com/IEAWindTask37
m/s, totaling 36 control variables.

The aerodynamic shape design variables consisted of chord, twist and relative thickness, as well as the chordwise offset of the cross-sections along the blade relative to the twist axis. The structural design variables controlled the carbon spar cap thickness, the trailing edge and leading edge uniaxial glass fiber thickness, while the skin and root reinforcement triaxial layers were kept constant throughout the optimization.

While the 31 aerostructural design variables all required evaluation of the full aerostructural solution for gradient estimation using finite difference, gradient estimation for the 36 control variables only required evaluations of the steady state aeroelastic solution, making addition of these design variables relatively cheap. Having pitch and RPM as design variables naturally lead to a peak shaving design, as will be shown in the results.

The steady state loads and deflections were used as constraints, both for normal operating cases, and for an off-design case evaluated in place of actual time domain cases. The off-design case was specified as operation with RPM and pitch set according to operation at rated rotational speed and 0 degrees blade pitch, but evaluated at 12.8 m/s which is 4.8 m/s above the normal wind speed of 8 m/s for this operational point. The 4.8 m/s corresponds to 3 standard deviations as detailed in the normal turbulence model in the IEC-61400 standards. Based on evaluation in time domain, reasonable limits on loads and blade deflections were obtained in this way. To evaluate ultimate strength of the materials, a simple load extrapolation method was used based on the steady state mean loads, see [7], and applied to the BECAS finite element model of each section along the blade to evaluate a strain based failure criterion. Material fatigue was not evaluated as part of the optimization, but we note that the inclusion of this constraint could change the needed amount of material in the blade.

4. Aeroelastic modeling set-up

Time domain simulations were carried out on both the IEA 3.4 MW turbine and the optimized LW RWT design at the same site conditions IEC class 3B, (V = 6.5 m/s, k = 2.4). It should be mentioned that the IEA 3.4 MW turbine was designed for IEC class 3A but in the project we decided to design the LW RWT for class 3B. In order to carry out a direct comparison of AEP and loads the simulations for both turbines were then carried out for IEC class 3B.

As the LW RWT design still is in the initial phase we have not yet a completely aeroelastically tuned tower design. Therefore we have run the aeroelastic simulations for both turbines with stiff towers which allows us to make a true comparison of blade and rotor loads without impact of possible non-optimal tower frequencies. However, the LW RWT is simulated with a 125 m tower whereas the IEA 3.4 MW turbine has a 110 m tower height.

The aeroelastic simulations were carried out using the in-house aeroelastic tool HAWC2 [6], [10] according to IEC-61400-1 [1] for power production load cases DLC 1.1 and 1.2 for which the DTU Wind Energy controller [11] is used in the simulations. The control gains of the LW RWT are tuned based on HAWCStab2, and the optimized pitch and rotor speed settings are applied.

4.1. The IEA 3.4 MW reference turbine

The IEA 3.4 MW turbine [14] developed in the IEA Wind Task 37, which reflects the current onshore wind turbine technology designed for wind class IIIA with rated wind speed of 9.8 m/s, is modelled in HAWC2 on basis of the turbine description and data from [14]. HAWCStab2 [5] is used for structural modal analysis to verify the structural properties of the HAWC2 model compared with the original design data for the IEA turbine [14] and for controller tuning.

4.2. The LowWind turbine

The LowWind RWT is likewise modelled in HAWC2 and the control parameters are tuned by HAWCStab2 using the pole placement method [13]. The proportional gain and integral gain
of the pitch and torque controller are calculated based on a simplified second-order closed-loop dynamic system by targeting the system frequency of 0.045 Hz and the damping ratio of 0.7, for both partial load and full load region.

5. Results

5.1. The LowWind RWT characteristics

Table 1 summarizes the overall characteristics of the LowWind RWT compared to the IEA 3.4 MW RWT.

| Parameter                        | IEA 3.4 MW          | LW RWT          |
|----------------------------------|---------------------|-----------------|
| Wind Regime                      | IEC Class 3A        | IEC Class 3B    |
| Rated electrical power           | 3.4 MW              | 3.4 MW          |
| Control                          | Variable Speed      | Same            |
|                                   | Collective Pitch    | Same            |
| Cut-in wind speed                | 4 m/s               | 2 m/s           |
| Cut-out wind speed               | 25 m/s              | 13 m/s          |
| Rated wind speed                 | 9.8 m/s             | 8 m/s           |
| Number of blades                 | 3                   | Same            |
| Airfoils                         | DU                  | FFA-W3          |
| Rotor Diameter                   | 130 m               | 208 m           |
| Hub Radius                        | 2.0 m               | 2.0 m           |
| Hub Height                        | 112.5 m             | 127.5 m         |
| Drivetrain                       | Medium Speed,       | Same            |
|                                   | Multiple-Stage      |                 |
|                                   | Gearbox             |                 |
| Minimum Rotor Speed              | 3.8 rpm             | 1.92 rpm        |
| Maximum Rotor Speed              | 11.75 rpm           | 7.3 rpm         |
| Maximum Tip Speed                | 80.0 m/s            | 80.0 m/s        |
| Hub Overhang                     | 5.6 m               | 5.6 m           |
| Shaft Tilt Angle                 | 5.0 deg.            | 6.0 deg.        |
| Rotor Precone Angle              | -3.0 deg.           | -4.0 deg.       |
| Blade Prebend                    | 2.5 m               | 4.3 m           |
| Blade Mass                        | 16,441 kg           | 31,652 kg       |

Table 1. Key parameters of the LowWind Reference Wind Turbine compared to the IEA 3.4 MW Reference Wind Turbine.

Figure 1 shows the LowWind RWT blade planform compared to the IEA 3.4 MW RWT. Due to the constraint on the maximum chord of 4.3 m, the LowWind RWT blade is essentially stretched in the spanwise direction, resulting in a very slender design. Due to the use of carbon in the main load carrying girder, and the narrow wind speed operating regime, the LowWind blade is aerodynamically quite efficient, with maximum relative thickness of 30% across the majority of the mid and inner part of the blade. The chordwise offset curve is tailored to achieve as forward as possible placement of the spar cap and thus shear center. This is the mechanism behind the strong flap/twist coupling of the design resulting in a maximum elastic twist of 7-8 deg. at the blade tip deloading the outboard part of the blade considerably. Figure 2 shows the lofted surface of the blade, the planform and prebend.

5.1.1. Steady state - uniform inflow

Table 2 lists overall performance characteristics of the LowWind RWT compared to the IEA 3.4 MW RWT. The AEP computed for a low wind site
Figure 1. Blade planform of the LW RWT compared to the IEA 3.4MW RWT.

Figure 2. Lofted surface of the LW RWT showing main structural components and cross-sectional meshes used in BECAS to compute structural properties.

with a mean wind speed of 6.5 m/s and a scale factor of 2.4 is 45.8% higher for the LW RWT compared to the smaller rotor. As is also shown in more detail in Figure 3 the rotor power coefficient is for the chosen airfoils quite high at low wind speeds between 2 m/s and 6 m/s
with a peak efficiency of $C_P = 0.489$. Due to the slower rotational speed, the nominal torque is considerably higher for the LW RWT which will affect the drivetrain costs. Due to the use of peak shaving, the LW RWT steady state thrust is lower than the IEA 3.4 MW RWT. Note, that peak loads predicted from dynamic turbulent simulations are increased, as will be detailed in Section 5.2.1. The blade root flapwise moment was in the design process constrained to 12,000 kNm, which is 30% higher than that of the IEA 3.4 MW RWT.

| Quantity                            | IEA 3.4 MW | LW RWT | Ratio [-] |
|-------------------------------------|------------|--------|-----------|
| Uniform inflow AEP (V=6.5, k=2.4) [GWh] | 11.754     | 17.131 | 1.458     |
| Max rotor speed [rpm]               | 11.753     | 7.277  | 0.619     |
| Max $C_P$ [-]                       | 0.505      | 0.489  | 0.969     |
| Nominal torque [kNm]                | 2.925e+03  | 4.724e+03 | 1.615 |
| Thrust normal operation [N]         | 6.377e+05  | 5.747e+05 | 0.901 |
| Flapwise moment normal operation [Nm] | -9.282e+06 | -1.198e+07 | 1.291 |

Table 2. Rotor performance metrics based on steady state aeroelastic computations. The AEP is based on electrical power where we assumed a generator loss of 6.39%.

Figure 3 shows the rotor steady state performance of the Low Wind RWT compared to the IEA 3.4 MW RWT, both computed with HAWCStab2. Due to assumption of an uniform rotor these computations do not include shaft tilt, but do include blade prebend and coning. Due to the significantly higher capacity factor of the rotor, the LW RWT produces 2.5 times more power in the wind speed range of 3 m/s to 6 m/s, compared to the conventional rotor, and reaches rated power at 8 m/s. Due to the constraint of 80 m/s tip speed, the torque of the LW RWT is significantly higher than the conventional rotor, incurring higher costs on the drivetrain, which for this work has not yet been considered. In the plots of rotor thrust and blade root flapwise moment, the effect of the integrated design of the blade and control strategy can be seen, resulting in a peak shaving control strategy between 6 m/s and 8 m/s, limiting the steady state flapwise moment to the constraint value of 12000 kNm.

Although not plotted, the RPM schedule results in tip speed ratios of approximately 10.5 with slightly higher values at low wind speeds, reducing towards the peak shaving region, constrained by the nominal torque constraint imposed in the optimization. This is somewhat different from a conventional turbine design which typically operates with a constant tip speed ratio optimized for maximizing the power coefficient. In the plots of rotor $C_P$ and $C_T$, it is seen that the LW RWT operates with quite high efficiency between 2 m/s and 6 m/s, which of course reduces when the rotor pitches towards feather to limit loads. Interestingly, the rotor $C_T$ is seen to reduce from approximately 0.8 at 4 m/s to 0.725 at 6 m/s, which is primarily due to the torsional unloading of the blade with increasing wind speed. This characteristic is clearly visible in the plots shown in Figure 4, which shows the distributed local thrust coefficient, normal force, lift coefficient, angle of attack, deflection with respect to the rotor plane coordinate system as well as torsion of the blade across the range of operating wind speeds. At peak loading the blade torsions approximately 7 degrees towards feather at the tip, and results in a change in $C_l$ of approximately 0.25 between 4 m/s and 6 m/s. This load alleviating characteristic is key for reducing ultimate and fatigue loads both on the blade itself but also on the rest of the turbine platform.

5.2. A comparison of performance and load characteristics
Due to the early stage in development and analysis of the LW RWT we present here only an initial comparison of the performance and load characteristics of the IEA and LW RWT. It
5.2.1. Steady inflow and turbulent inflow

The two turbines are compared in terms of quasi-steady load response from the time-domain cases with steady uniform flow including shear with the exponent $a=0.18$, and minimum/maximum and lifetime fatigue loads from the normal turbulence model (NTM) operation in DLC 1.2. The quasi steady time domain cases are also used for a ‘clean’ AEP metric, which shows an increase of 40.59% in AEP for the LW RWT, compared to the IEA RWT. This is notably lower than the 45.8% shown above in Table 2 and ascribed to the impact of the shear, rotor tilt and the fact that the controller does not fully
track the optimal operation of rpm and pitch.  
Due to the page limitations of the present paper we can only present a summary of the simulated load characteristics. The statistics of the load data from turbulent cases are summarized in Figure 5 (left) where the maximum and minimum values of different load components, MxBR - blade root flap, MxTB - tower bottom fore-aft moment, MxTT - tower top tilt, MxMB - main bearing tilt, MyMB - main bearing yaw, are shown for the LW RWT relative to the IEA RWT for normal turbulence DLC1.2. The flap wise moment is seen to have the highest increase for the LW RWT. This moment was constrained to 12000 kNm in the optimization and it was an active constraint. For the other load components the increase is typical between 20-40%. The moderate increase in load levels relative to big increase of rotor size indicates that the two load reduction mechanisms discussed in Section 5.1.1 are quite efficient combined with the low stop wind speed of 13m/s. The one being peak shaving, where the rotor pitches towards feather immediately before reaching rated wind speed to limit peak loads, as well as the built in structural couplings, which causes the blades to torsion to feather and thus also alleviate peak loads. These two mechanisms are seen to compliment each other well for this rotor design. The collective pitch schedule reduces the mean thrust and flapwise loads levels on the rotor very effectively, whereas the bend-twist coupling helps both reducing the overall turbine platform load levels, but also acts to progressively unload the blade tip to optimally trade-off induction under the flapwise moment constraint as rated power is approached. 

In Figure 5 (right) the lifetime fatigue loads for certain components are also compared. The platform fatigue loads are typically increased with 20-40% for the LW RWT while blade flapwise fatigue loads are increased nearly 60%.

6. Conclusions and outlook
In the present work we have performed basic preliminary design of a high capacity factor rotor with a specific power of 100 W/m² for a 3.4 MW power rating, resulting in a 102 m blade aimed for meeting the energy demand during low wind periods. The blade was designed aerostructurally using HAWTOpt2. The resulting blade was quite light weight at 31.5 tonnes, and showed an increased AEP of 40% compared to the IEA 3.4 MW turbine, which has a 130 m rotor. Subsequently the load levels of the LW RWT was evaluated in comparison with the IEA RWT by aeroelastic time simulations using HAWC2 for steady, sheared inflow and for
normal operation in turbulent inflow, DLC1.2. For both turbines a stiff tower was simulated as a redesigned tower for the LW RWT has not yet been designed. The biggest increase, 50-60% in load levels (fattique and extreme) based only on DLC1.2 simulations were seen for the flapwise blade root moment while tower and rotor loads were increased between 20-40%. We conclude that highly flexible light weight rotors designed with a combination of peak shaving and bend twist coupling can effectively reduce the load levels on both the rotor and platform.

In future work, we aim to evaluate loads across a wider range of extreme and fault conditions according to the IEC 64100-1 standards. Further we will investigate different turbine concepts for the LowWind rotor, e.g. downdraft concepts to bring the loads further down. As it is likely infeasible to introduce a 102 m blade for the onshore market due to transportation challenges and constraints, we therefore also aim to investigate the implications of using a split blade design for the LowWind concept.

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