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Evaluation of fatigue loads of horizontal up-scaled wind turbines

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Abstract

Wind turbines, especially for offshore applications, are continually being up-scaled on the basis that having fewer separate sites per installed MW will reduce balance of plant and O&M costs and hence may reduce cost of energy. Obviously the loads on a wind turbine increase with the size of the machine. However there is presently no generic, systematic study of how fatigue loads vary with wind turbine size. Both extreme and fatigue load evaluation is essential for the design of wind turbines. This paper however has its focus solely on fatigue loads.
The aim is to investigate the dependency of fatigue loads (lifetime damage equivalent loads are employed to calculate the fatigue loads) on wind turbine scale and subsequently to develop generic fatigue load trends with scale, ideally in the form of simple power law curves.
Seven wind turbine models were created from a reference model (Danish design) based on up-scaling with similarity. Such scaling does not accurately reflect commercial trends but is considered a best starting point to gain fundamental understanding. Fatigue loads in various design load cases (startups, power production, idling, and shutdowns) as specified in IEC standards are simulated and trend lines determined. This work is part of a much larger generic study of all the main influences on wind turbine loads.

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Keywords: Fatigue ; Lifetime damage equivalent loads; Scaling

1. Introduction

The wind turbine industry aims to make wind energy as cheap as possible. This can be done by reducing energy cost by increasing the size of machine. There is a strong belief that the increasing of unit size can reduce the expenses on delivery, infrastructure, operational and maintenance cost of a single unit compared with the few

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smaller machines [1]. According to these abovementioned factors the size of a wind turbine is continuously growing to decrease the energy cost produced by wind turbines.
There are two methods of investigating the increase in instantaneous loads due to the up-scaling of wind turbines.

1. Scaling with similarity: Based on several assumptions: preserve the original tip speed ratio, geometric similarity applies to modifications, type of aerofoils and materials are unchanged within the turbine [2, 3].

2. Compare data from commercial wind turbines. There is large variety of wind turbine designs due to the diverse environment of sites. In this case the gained data is scattered [3, 4].

This paper adopts the first method, as the most secure way to understand generic trends, although at a later stage, comparisons with commercial designs will be made.

2. Theory

2.1. Type of loads

A wind turbine is a dynamic system which is subjected to continuously changeable wind direction and speed. As a result the forces on a wind turbine are constantly varying. Therefore a machine needs to resist the varying loads, which are the summation and combination of different load types such as [5]:

- Aerodynamic loads: wind shear, yaw error, turbulence
- Gravitational loads: weight of blade
- Inertial loads: rotor accelerations and decelerations
- Operational loads: braking, yaw error, blade pitch control, generator disconnection
- Impulsive loads: tower shadow

Additionally these loads categories can be divided into deterministic and stochastic part of loads. Where, the deterministic loads are repeatable loads such as: wind shear, tower shadow, gravitational loading, etc. The stochastic part of loads is random and depends on turbulence of the wind flow.

2.2. Fatigue loads

As it was mentioned before this paper focuses on the fatigue loads. The source of fatigue loads per one rotor revolution is the summation of the above mentioned loads in the previous section. Typically there are 10 million revolutions during the life span of a unit, which is usually 20 years [6, 7]. Lifetime damage equivalent loads (DELs) are employed to calculate fatigue loads in this research based on IEC standards [8]. Lifetime DELs are calculated by the combination of the ten minutes load calculation of each mean wind speed with Weibull distribution of wind speed over entire year. Figure 1 depicts the method of calculation the damage equivalent loads.

Where, Markov matrix is a result of the combination Weibull distribution and ten minutes wind simulation. It demonstrates the size and number of cycles, which are calculated by rainflow counting method from the ten minutes simulations [9, 10]. Subsequently the manipulation with equivalent loads and the number of revolutions per life design gives lifetime DELs.

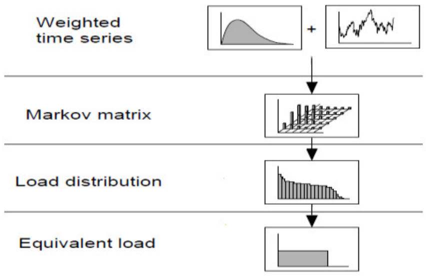

Figure 1. A method to calculate equivalent loads

3. Methodology

The research is based on the up-scaling the reference model which is a 3MW rated power, upwind, variable speed, and pitch regulated wind turbine. The general properties of the reference model are shown below:

- Aerofoil type - NACA 634XX
- Nominal rotor diameter – 100 m
- Cut-in wind speed - 4 m/s
- Rated wind speed - 11.5 m/s
- Cut-out wind speed - 25 m/s
- Tower height - 79 m
- Tip Speed Ratio – 9
- Transmission - Gearbox

The seven up-scaled models (4, 5, 6, 7, 8, 9, 10 MW) are up-scaled from the reference model by using the linear scaling technique or scaling with similarities [1]. Note the original power density (382 W/m^2) of the reference model is preserved in the up-scaled models.

Afterwards fatigue damage equivalent loads (DELs) were calculated for the reference and up-scaled models. According to the IEC 61400-1 standard [11] there are five types of design load cases (DLC) for fatigue lifetime DELs. The following figure shows the contribution of these five DLCs to fatigue damage for the different bending moments of wind turbine.

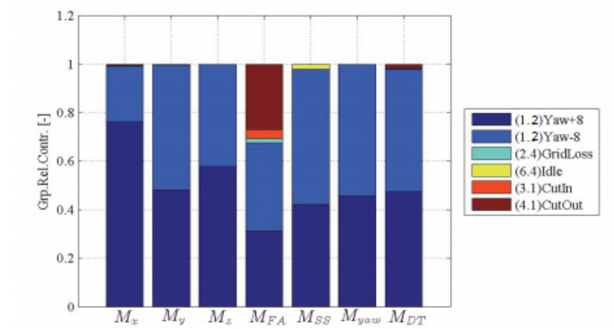

Figure 2. Relative contributions of fatigue DELs by DLC [12]. Where:

- M_x – edge-wise, M_y - flap-wise, M_z - torsional blade moment
- M_{FA} – fore-and-aft, M_{SS} - side-to-side tower moment
- M_{yaw} - tower torsional or yaw moment
- M_{DT} – low shaft moment

The biggest moment impact on the fatigue DELs is from DLC 1.2 for the all specified moments in figure 2. In this research four DLCs (1.2, 3.1, 4.1 and 6.4) of the five will be calculated for the reference and up-scaled models. DLC 2.4 is not considered in this paper because it has only a minor impact on fatigue damage and there is an assumption that the wind turbines work correctly without any faults.
The brief explanation of the four applied DLCs in this paper is below:

- DLC 1.2 is the power production range (4-25 m/s mean wind speed) with a normal turbulence model (NTM) wind field, and a mean yaw misalignment of ±8°. The wind turbine is connected to an electrical load without any faults.
- DLC 3.1 is the startup of a wind turbine from idling or standstill to power production conditions at steady wind.
- DLC 4.1 is the normal shut down from the power production or idling to standstill condition at steady wind.
- DLC 6.4 is an idling condition (3, 30, 35 m/s) with a yaw misalignment of ±8 ° using a NTM wind field.

Where, II A wind class and 0.16 turbulence reference intensity were chosen for all DLCs. The detailed explanation of each DLC and NTM can be found in the IEC 61400-1 standard [11].

4. Results

4.1. Steady state

In this section the up-scaled models are checked for accuracy of the applied linear scaling modifications to the reference model. As it was mentioned previously linear scaling technique are based on the several assumptions [2, 3]. One of these is tip speed ratio (TSR) does not change due to the up-scaling. Only two up-scaled models (6 and 10 MW) were chosen to compare with the reference (3MW) model for the accuracy of up-scaling procedure. Figure 3 depicts the TSR of the two up-scaled and reference models. All three curves overlap each other. It means the TSR has not changed due to the linear up-scaling modification. As a result the up-scaled aerofoils maintain the original power coefficient along the blade. Figure 4 shows the thrust force from aerodynamic loads at 8 m/s against the diameter of the original and up-scaled models. The equation of the trend line demonstrates that the thrust force is function of D^2. It is correct as the thrust force acts on the rotor area (Momentum theory), which is a function of diameter squared. Both figures of the steady state proved that the up-scaled modifications were applied correctly.

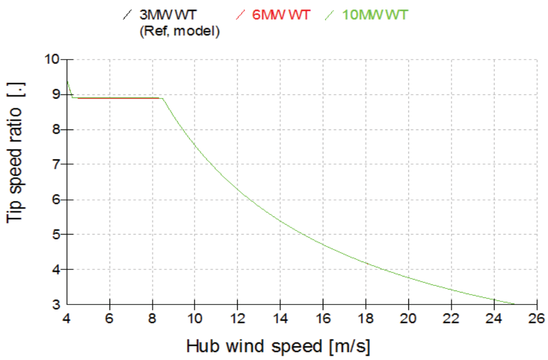

Figure 3. Comparison of TSR between the reference and up-scaled wind turbine models

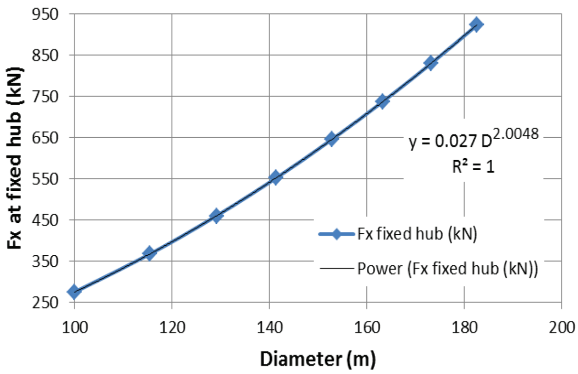

Figure 4. Thrust force at 8 m/s against the rotor diameter

4.2. Dynamic state

In this section the up-scaled wind turbines are analysed in the dynamic state. Two of the seven up-scaled models have been selected to depict and compare the behavior with the reference model in the dynamic conditions. Adding more than three models to a graph makes it unclear and difficult read. Auto spectral density (ASD) or power spectral density (PSD) is applied to investigate the three above mentioned models in the frequency domain. The two following graphs depict PSD of edge-wise (Mx) and flap-wise (My) blade root bending moments, respectively.

Figure 5 and 6 show the rotor speed (1P) of the wind turbines decrease as the size of machine scales up. The peaks (2P, 3P, 4P and etc.) are harmonic peaks of rotor frequency (1P). The frequency of the structural mode for edge-wise and flap-wise reduces due to the up-scaling of the machine. As a result the frequency of an entire machine decreases with the up-scaling. In every model there is not any peak which is higher than the rotor the frequency peak (1P). Additionally flap-wise structure modes have a lower frequency value than the structural modes of edge-wise. The aforementioned factors prove that the controller and wind turbines work correctly.

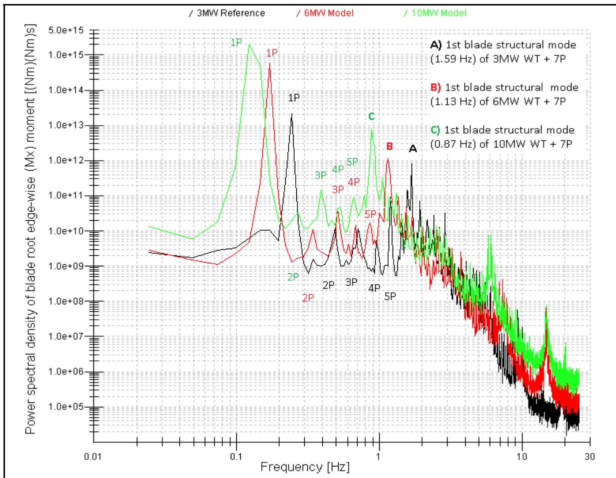

Figure 5. PSD of edge-wise blade root bending moment of 3, 6, 10 MW wind turbines at 14 m/s mean wind flow.

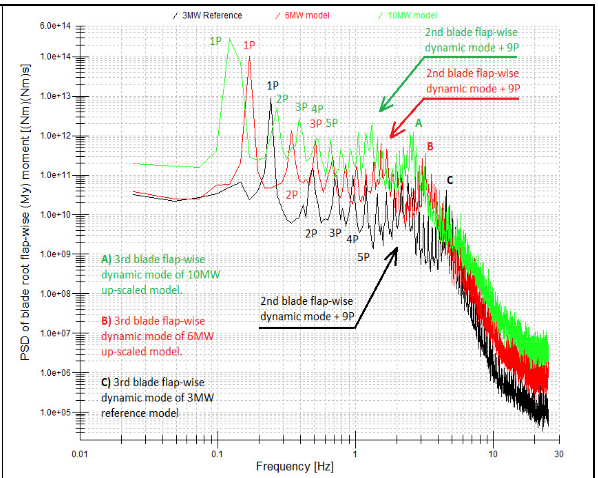

Figure 6. PSD of flap-wise blade root bending moment of 3, 6, 10 MW wind turbines at 14 m/s mean wind flow.

4.3. Lifetime Damage Equivalent Loads

Lifetime DELs of edge-wise and flap-wise blade root bending moment are investigated in this section. The two following figures show edge-wise and flap-wise of blade root bending moment lifetime DELs of DLC 1.2, respectively. In the both figures the Y axis is lifetime DELs of the bending moment and X axis is the Wohler coefficient which is the slope gradient for S-N curves. The edge-wise and flap-wise moments demonstrate that there is the same lifetime DELs pattern among Wohler coefficient at each figure.

The research is focused on Wohler coefficient 4 and 10, which represent steel and composite material, respectively. In this case additional graphs of lifetime DELs against rotor diameter graphs for Wohler coefficient 4 and 10 are required to plot. The trend and equation of trend will be developed.

The developed equation will be compared with the instantaneous moments of linear scaling rule. Where, the edge – wise instantaneous bending moment changes as R^4 because the mass (R^3) times distance (R). The mass is proportional to volume, and volume is proportional dimensions as the density of material is constant. The flap-wise instantaneous bending moment is proportional to radius cubed (R^3).

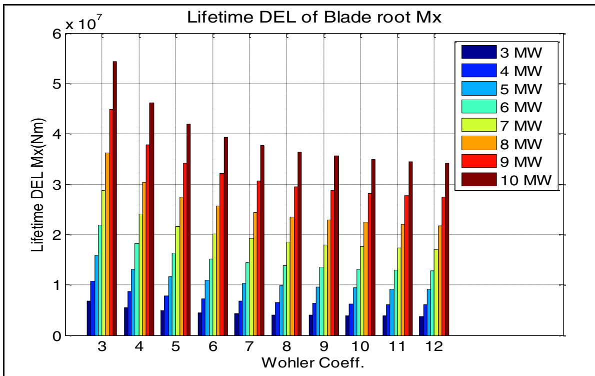

Figure 7. DLC 1.2 lifetime DELs of edge-wise blade root bending moment.

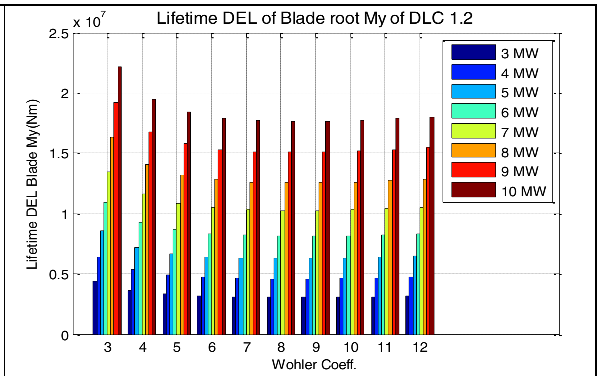

Figure 8. DLC 1.2 lifetime DELs of flap-wise blade root bending moment.

Figure 9 of DLC 1.2 lifetime DELs of edge-wise blade root bending moment depicts the trend lines with its equations. Both exponents of the trend line equations are a bit smaller than the exponent (R^4) of linear scaling rule for instantaneous bending moment. Figure 10 of DLC 1.2 lifetime DELs of flap-wise shows the exponents of trend lines almost match with the exponent of instantaneous bending moment of linear scaling rule.

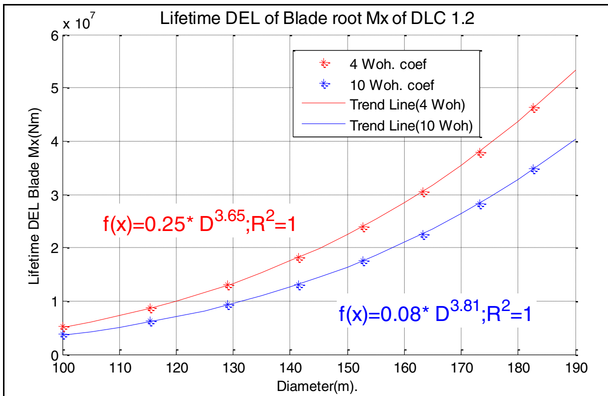

Figure 9. DLC 1.2 lifetime DELs of edge-wise blade root bending moment for Wohler coefficient 4 and 10.

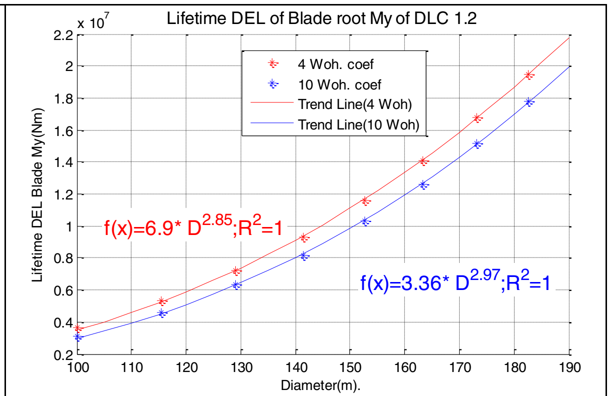

Figure 10. DLC 1.2 lifetime DELs of flap-wise blade root bending moment for Wohler coefficient 4 and 10.

There is a possibility to combine DLC 3.1 (startups) and 4.1 (shutdowns) to show the summation of startups and shutdowns of wind turbine, because the procedure of the both lifetime DLCs calculation requires the same conditions. Figures 11 and 12 depict the combination of DLC 3.1 and 4.1 of lifetime DELs of edge-wise and flap-wise blade root bending moment for Wohler coefficient 4 and 10, respectively. The exponents of trend line equation are almost 4 for the two Wohler coefficients in figure 11. This value matches the exponent of instantaneous bending moment of linear scaling rule. The exponents of flap-wise bending moment trend line equation are nearly 3 for Wohler coefficient 4 and 10 in figure 12.

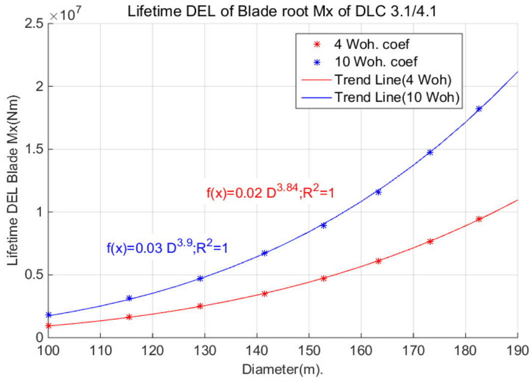

Figure 11. DLC 3.1/4.1 lifetime DELs of edge-wise blade root bending moment for Wohler coefficient 4 and 10.

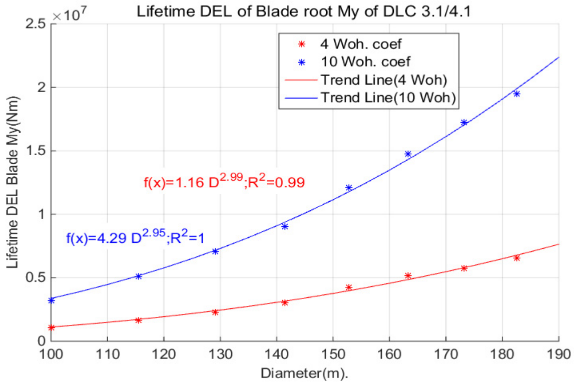

Figure 12. DLC 3.1/4.1 lifetime DELs of flap-wise blade root bending moment for Wohler coefficient 4 and 10.

The edge-wise and flap-wise of lifetime DELs blade root bending moments from idling or DLC 6.4 are demonstrated at the two following figures. The exponents of trend line equation of edge-wise are a bit smaller than 3 for the both Wohler coefficients. The exponents of trend line equation of flap-wise are slightly larger than 3. Such trends are exactly what the study has aimed to determine. It may be that the reduction in edgewise loading (relative to scaling with similarity suggesting a cubic relationship) is due to increased filtering of higher frequency variations as rotors become larger. In the more dynamically active flapping motion, mass related moments which scale as 4^{th} power may play a more significant role. This interpretation is presently quite speculative but further work will be undertaken to search for a conclusive explanation of the observed effects.

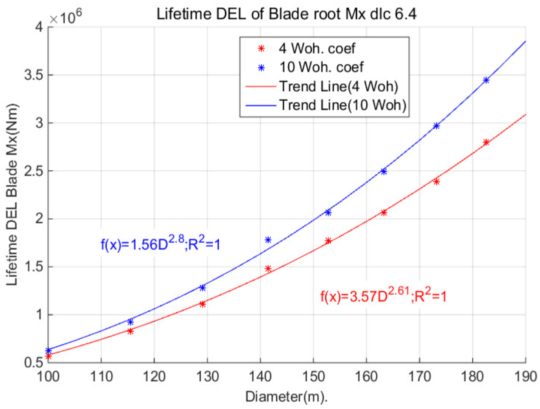

Figure 13. DLC 6.4 lifetime DELs of edge-wise blade root bending moment for Wohler coefficient 4 and 10

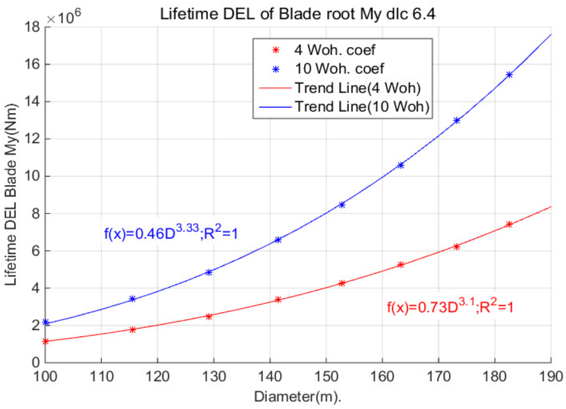

Figure 14. DLC 6.4 lifetime DELs of flap-wise blade root bending moment for Wohler coefficient 4 and 10

5. Conclusion

The aim of this paper was to generate the trend line and its equation of blade root lifetime damage equivalent loads for the different load design cases, which covered normal startups, production power, idling and shutdowns conditions with yaw misalignments at normal turbulence level. The design load case with wind turbine fault was beyond the investigation of this paper. The reference model was a three bladed, Danish design wind turbine model (3MW) which was up-scaled to 10 MW rated power based on scaling with similarities. The generated equations of trend lines showed that there is a variation among the exponent value of the four design load cases trend line equations at the edge-wise and flap-wise bending moments.

The power production of design load case demonstrated slightly lower values of lifetime DELs for flap-wise and edge-wise blade root bending moment compared to the exponents of instantaneous loads, which derived by linear scaling rule. The start-ups and shutdowns conditions demonstrated almost the perfect match between the exponents of lifetime DELs and instantaneous loads. The idling load condition generates the small exponent value of trend line equation for the edge-wise bending moment compare to linear scaling technique. The exponents value of flap-wise blade root bending moment of lifetime DELs are a bit larger than the anticipated exponent value from linear scaling rule. The major part of abovementioned exponents of edge-wise and flap-wise of blade root bending moment have quite close match to the exponent of scaling rule with similarities of instantaneous blade root bending moments.

The value of the exponents of trend equations has to be examined in the future, because the exponent is product of the gravity and aerodynamic loads. As a result the future work is required to divide the value exponent onto gravity and aerodynamic parts by switching off the aerodynamic or gravity loads in the simulations of DLCs.

Acknowledgement

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