Assessment of Gearbox Operational Loads and Reliability under High Mean Wind Speeds

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Introduction

Nowadays, **gearbox related failures** are responsible for over **20 % of downtime** of the wind turbines.

Usually they need **replacement after 6–8 years** what is much less than expected 20-years of failure free operation.

Offshore wind turbines are **exposed to extreme events** such as emergency stops, shut-downs, wind gusts and grid losses, often these events **occur at high wind speed** near 25 m/s.

These events can have **significant influence on the reliability** of drivetrains of wind turbines, especially of **gearboxes**.

In order to **reduce extreme loads** proper storm **control strategy** can be applied.

Objective and methodology

Purpose of the study is the investigation of dynamic loads occurring in the drivetrain of wind turbines with a focus on preventive maintenance in offshore applications

Electro-mechanical simulations of the wind turbine drivetrain are performed using **multibody model** and appropriate control algorithms. During simulations **normal shut-downs** are conducted at **high wind speeds**. On the basis of simulation results the **annual probability of failure of the gearbox** working in wind turbine **with storm control** is calculated, and compared with the one had the gearbox working in wind turbine **without the need for storm control.**

5 MW Reference Gearbox

To carryout simulations of wind turbine drive train, specification of the gearbox is required.

Table 1: 5 MW gearbox specification

Type	1P+2H
Ratio	81.48
Designed power [MW]	5.00
Rated generator speed [RPM]	1173.7

P: Planetary, H: Parallel helical

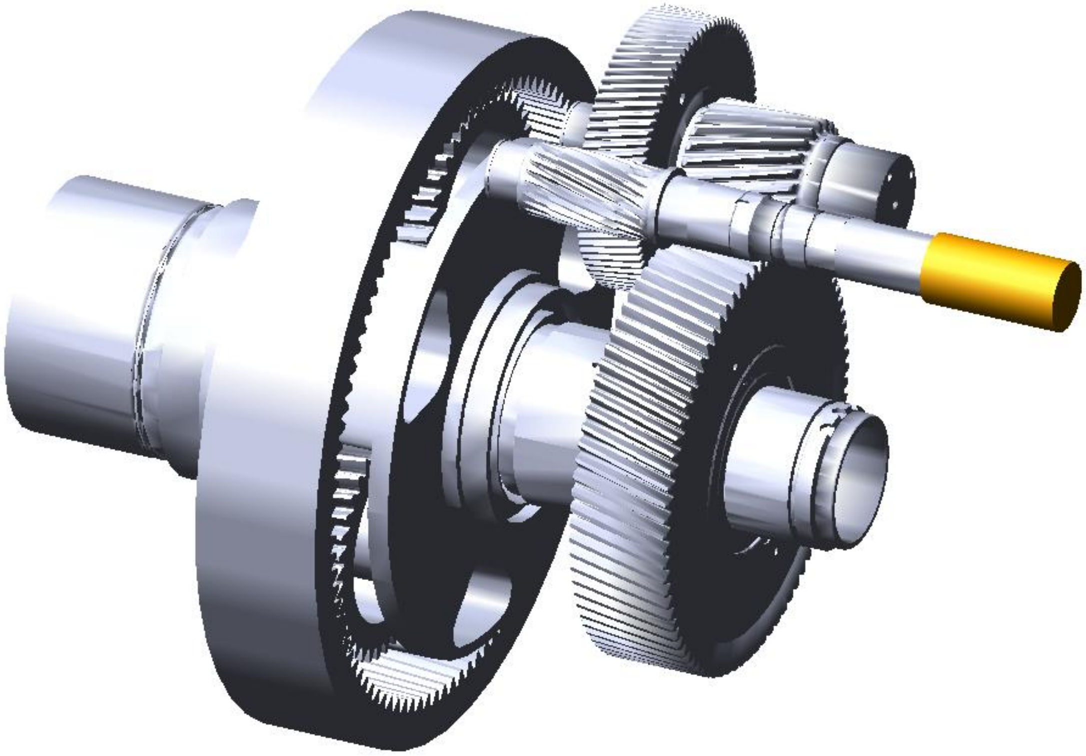


Fig. 1 Geometry of 5 MW gearbox

5 MW Reference Gearbox

The preliminary design of a **5 MW gearbox** was developed by application of **up scaling** rules to the GRC 750 kW prototype.

The upscaling rules and gearbox specification is presented in the conference paper.

Table 2. Geometrical parameters of 5 MW gearbox

Parameter	1st stage	2nd stage	3rd stage
Type	Planetary	Parallel	Parallel
Ratio	5.714	3.565	4.00
Number of planets	3	-	-
Normal module [mm]	26.5	22.1	13.3
Normal pressure angle [deg.]	20	20	20
Helix angle [deg.]	7.4947	14	14
Face width [mm]	650	-	-
Centre distance [mm]	795.2	1161.9	735.8
Number of teeth, Sun gear/Pinion	21	23	22
Number of teeth, Planet gear/Gear	39	82	88
Number of teeth, Ring gear	99	-	-
Pitch diameter, Sun gear/Pinion [mm]	556.6	509	294.3
Pitch diameter, Planet gear/Gear [mm]	1033.8	1814.8	1177.4
Pitch diameter, Ring gear [mm]	2624.3	-	-

Table 3. System parameters of 5 MW gearbox

Parameter	Component	Value
I_{axis} [kgm^2]	Sun gear	64.9
	Planet gear	334.4
	Ring gear	14685
	Carrier	7452
K_{radial} [N/m]	Bearing carrier upwind	3.18e9
	Bearing carrier downwind	2.47e9
	Bearing planet upwind	3e9
	Bearing planet downwind	3e9
$K_{contact}$ [N/m]	Sun spline	3.53e10
	Sun gear/ Planet gear Pinion/Gear	2.15e9
	Planet gear/ Ring gear	3.09e9

Multibody Model of Drivetrain

The model contains **rotor and hub inertia**, **main shaft**, **gearbox** and **generator controller** what allows to carryout **electro-mechanical simulations** of the drivetrain.

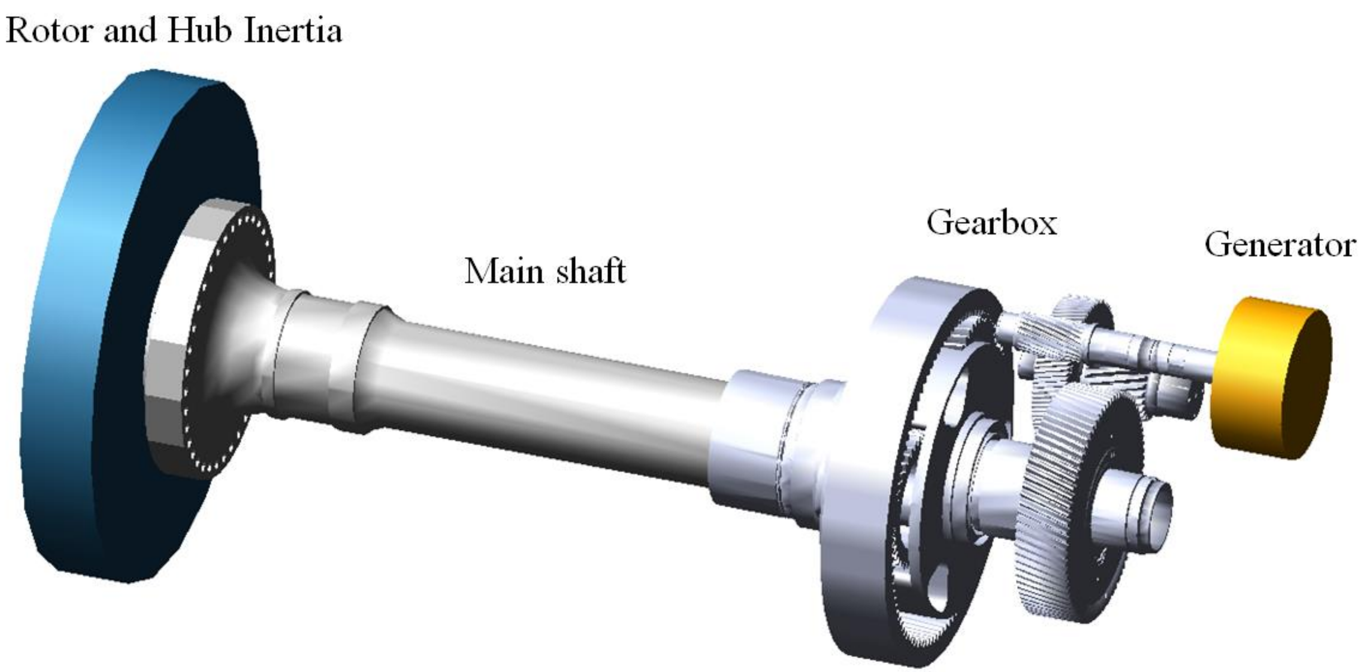


Fig.2. Drivetrain of 5 MW wind turbine.

Storm Controller

Hard Storm Transition (HST) – wind turbine **shut-down** when 1-min average wind speed reaches **25 m/s**.

Soft Storm Transition (SST) - wind turbine **decreases power** when the 1-min average wind speed exceeds **20 m/s** and stops completely when **30 m/s** is reached [1].

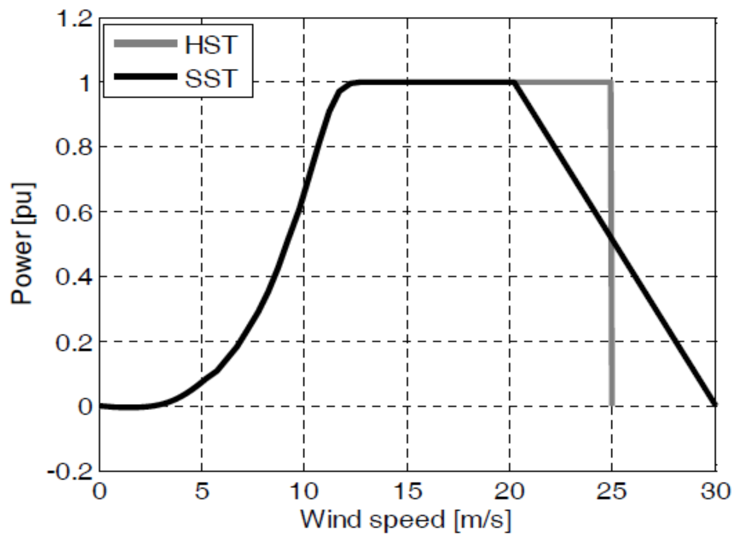


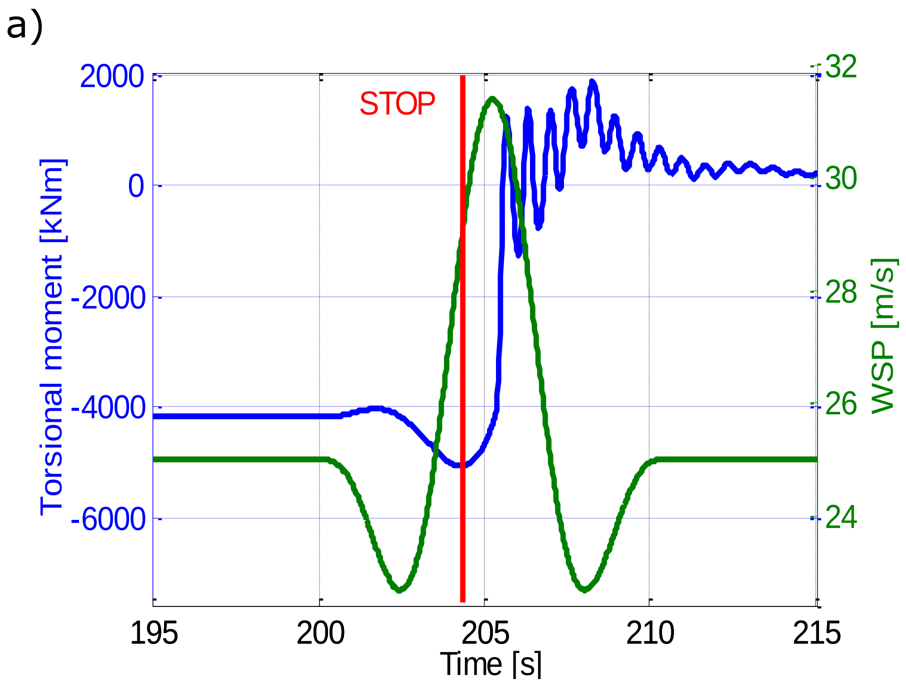
Fig.3. Power curves for two control strategy [1]

[1] Cutululis NA, Zeni L, Sørensen P. *Reliability of offshore wind power production under extreme wind conditions*. Report Project UpWind Work Package 9: Electrical grid; March 2010.

Simulated Load Cases

- **normal shut-downs** (DLC 4.2 from IEC 61400-1),
- wind conditions from an **Extreme Operating Gust** (EOG), **Normal Turbulence Model** (NTM) and **Extreme Turbulence Model** (ETM),
- Extreme Operation Gust - shut-downs were realized in three points: **minimum** wind speed **velocity**, **maximum** wind **acceleration** and **maximum** wind **velocity**,
- simulations for wind turbine with **HST control,** working at mean wind speed **25 m/s**,
- simulations for wind turbine with **SST control,** working at mean wind speed **24, 26** and **28 m/s**.

Simulations Results



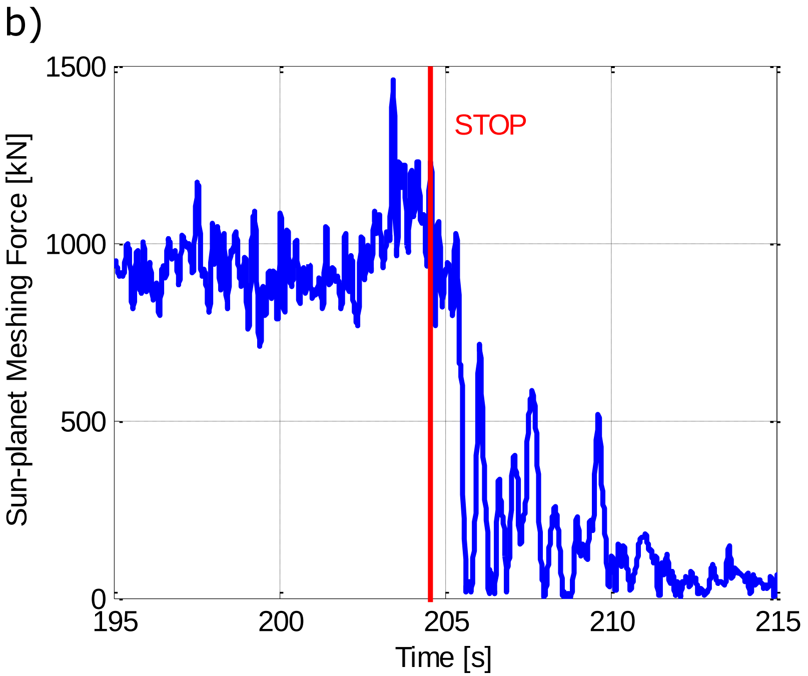
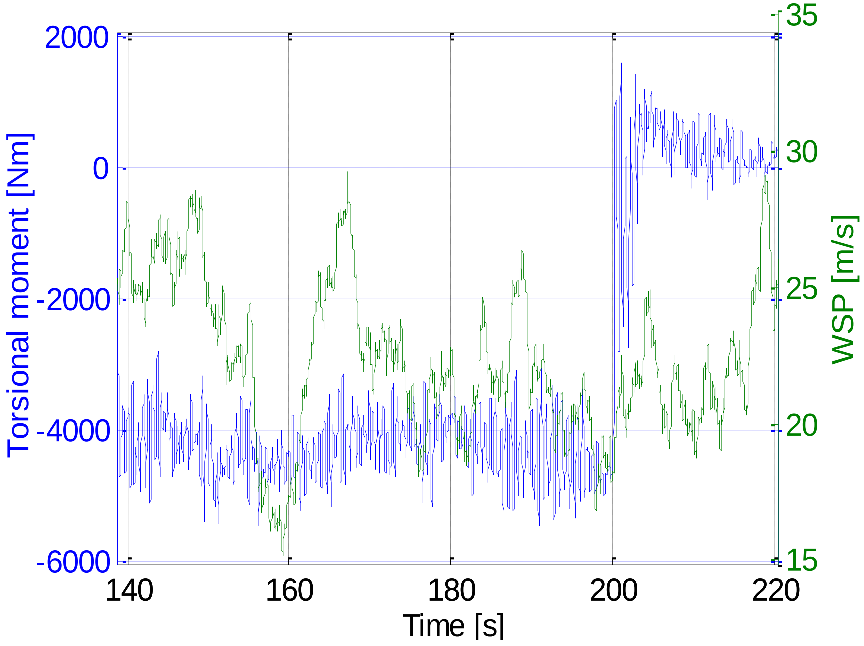


Fig.4. HST control, EOG, 25 m/s, stop at e2) (a) main shaft torsion and wind speed; (b) meshing force.

Simulations Results

a)



b)

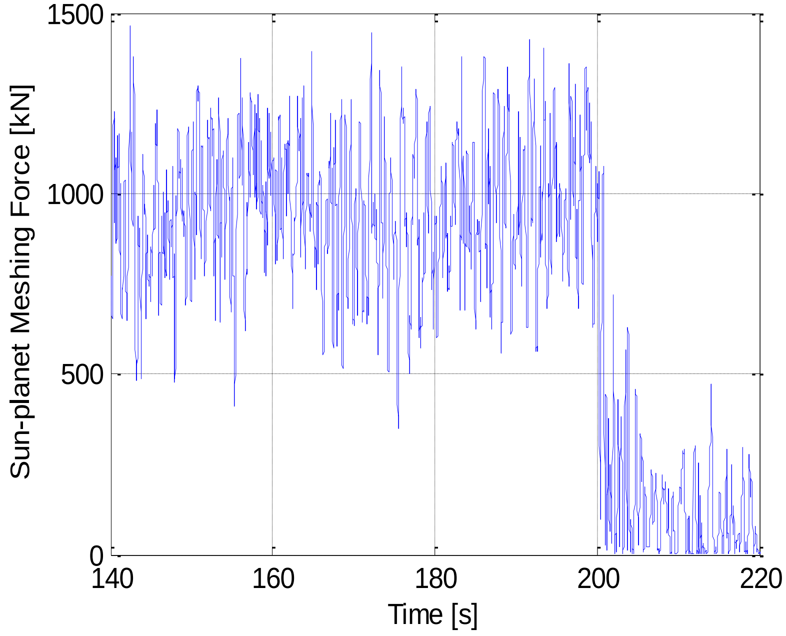


Fig.5. HST control, NTM, 25 m/s (a) main shaft torsion and wind speed; (b) meshing force.

Simulations Results

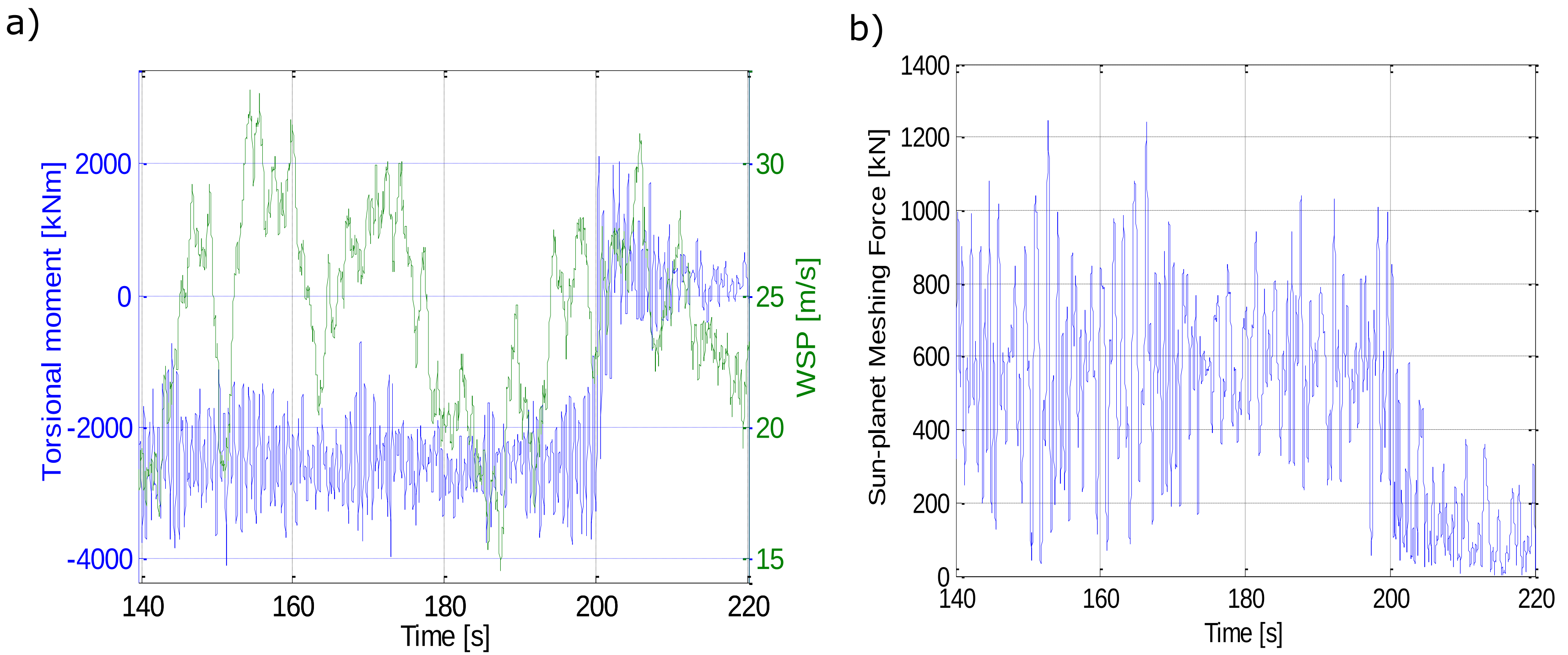


Fig. 6. SST control, ETM, 24 m/s (a) main shaft torsion and wind speed; (b) meshing force.

Gearbox Loads

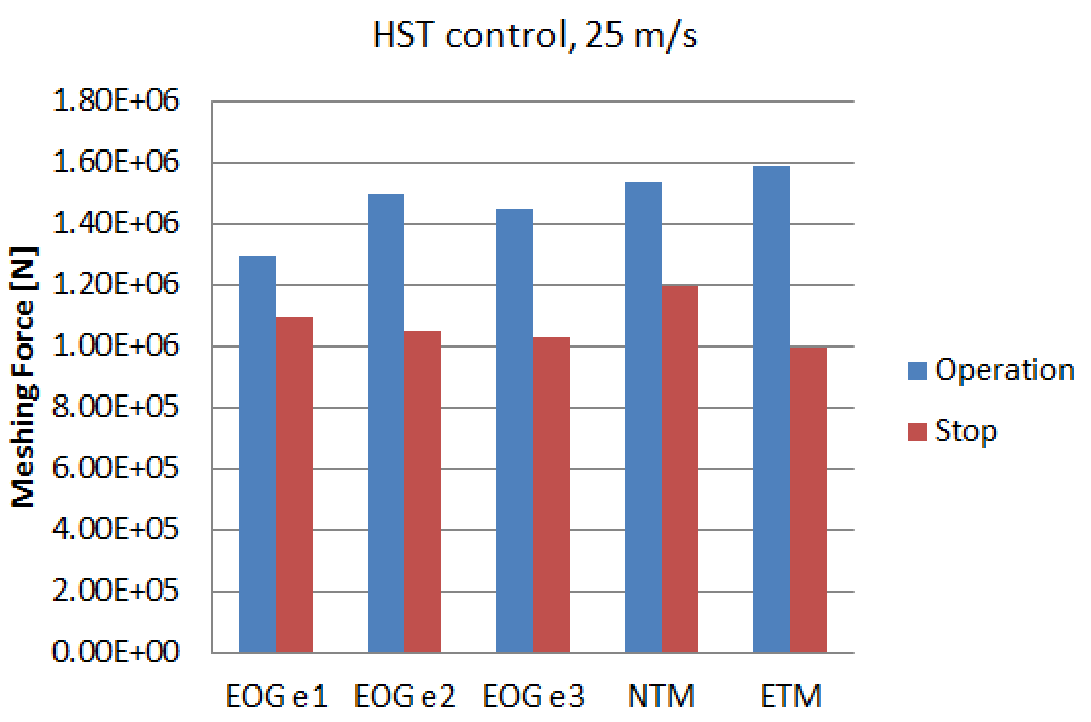


Fig.7. Maximum loads in sun-planet meshing for HST control and mean wind speed 25 m/s.

Gearbox Loads

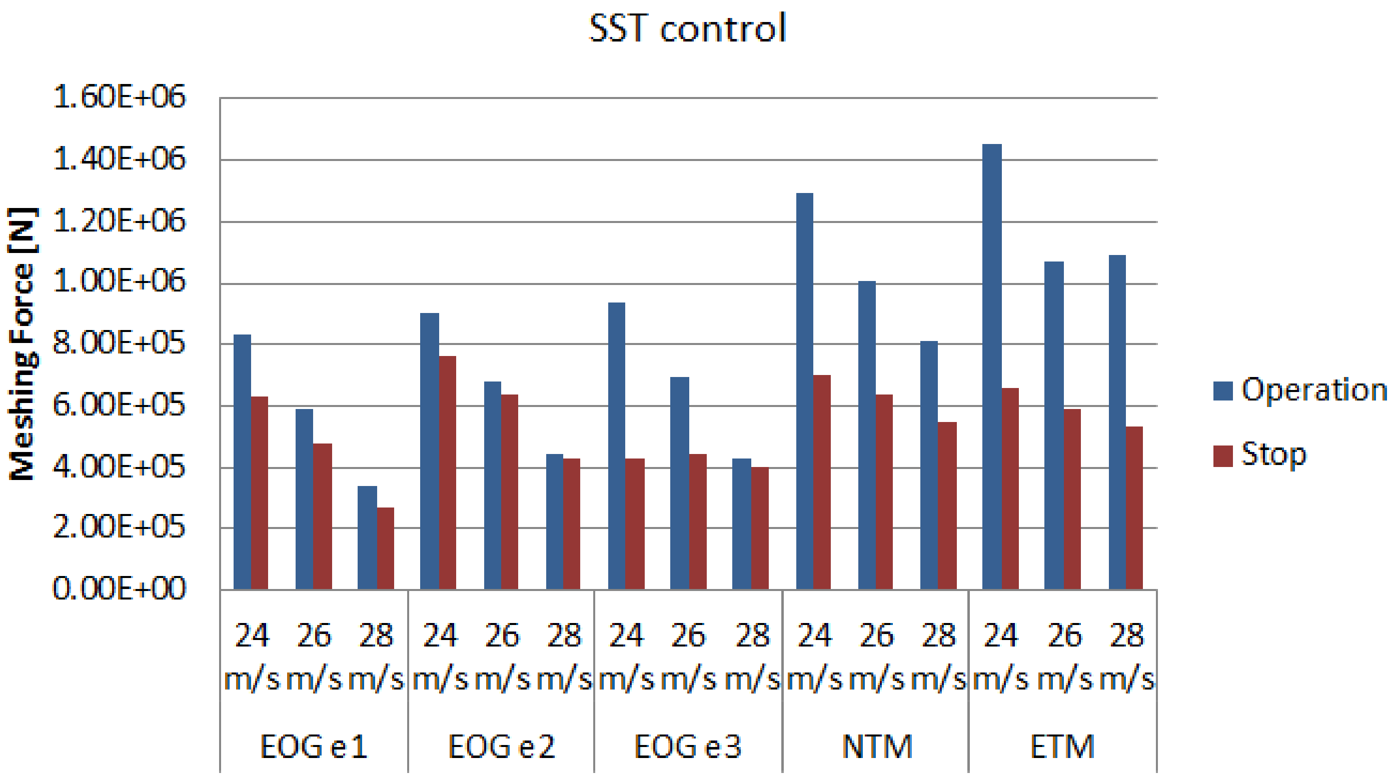


Fig.8. Maximum loads in sun-planet meshing for SST control and other mean wind speeds.

Reliability Analysis

First **O**rder **R**eliability **M**ethod for sun gear **tooth root bending** stresses.

Sun tooth root bending stresses from ISO 6336-6: $$\sigma_{tooth} = \frac{F_{\max}}{bm} Y_F Y_\beta Y_S \quad (1)$$

Failure function:

$$g(\mathbf{X}) = \frac{R_c}{S_F} X_{Resistance} - \sigma_{tooth} X_{Structuraldynamics} X_{Areodynamic} X_{Simulation} X_{Sress} \quad (2)$$

Probability of failure: $$P_f = P[g(\mathbf{X}) \leq 0] \quad (3)$$

Reliability index: $$\beta = -\Phi^{-1}(P_f) \quad (4)$$

Reliability Analysis

- The gears are made from alloyed heat treated steel **42CrMo4** with a bending strength of **550 N/mm²**.

- The safety factor for tooth root bending stresses was assumed S_F **= 1.7**, according to standard **IEC 61400-4**.

- For **HST control** maximum **load on sun gear tooth** was measured for **ETM** and has value **$1.6 \cdot 10^3$ kN** and the probability of failure for sun gear is P_f **= 0.007**, reliability index β **= 2.46**.

- For **SST control** maximum **load on sun gear tooth** was measured for **ETM** (24 m/s) and has value **$1.45 \cdot 10^3$ kN** and the probability of failure for sun gear is P_f **= 0.00084**, reliability index β **= 3.14**.

Conclusions

- **Design of a 5 MW gearbox** is characterized by simpler structure what can **reduce coasts of manufacturing and exploitation** with comparison to the other designs present in literature.

- On the basis of simulation of load cases it was found that **normal shut-downs do not have significant influence on ultimate loads** in the gearbox.

- **Maximum** values of measured **loadings** in sun planet meshing were related to the **gusts** contained in the wind.

- Application of **storm control** with **reduction** of the wind turbine **power** allowed to **increase reliability** index calculated for **sun gear** tooth root bending stresses from **2.46** to **acceptable** value of **3.14**.

Future work

- design of **5 MW gearbox** will be **changed** to gear **ratio of 97** and **standardized normal module** of gears,
- **verification of the gearbox design** according to the guidelines contained in the **standards** IEC/FDIS 61400-4, IEC 61400-1 will be conducted,
- **non-torque loads** will be included in **multibody model** of drivetrain,
- influence of other **load cases** from IEC 61400-1 on the **gearbox reliability** will be analyzed.

Acknowledgements

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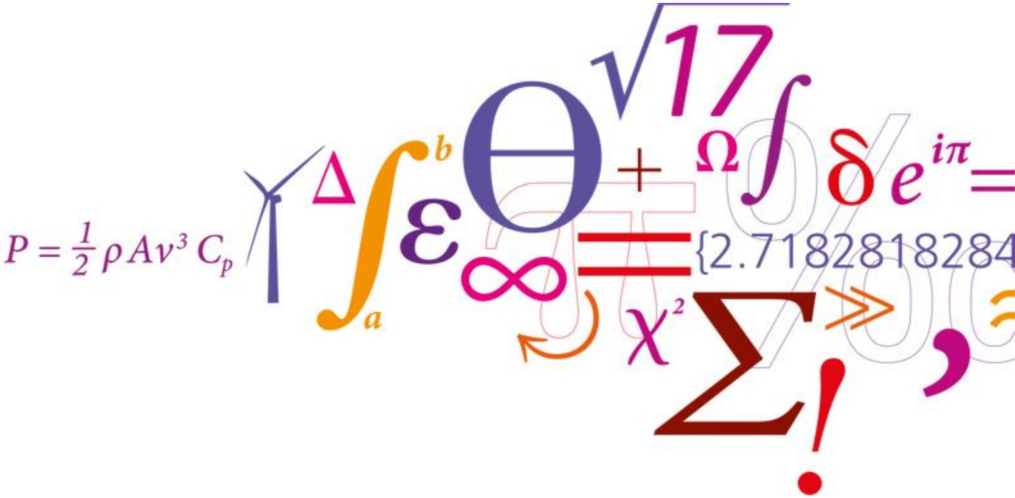

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