# Power performance optimization and loads alleviation with active flaps using individual flap control

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**Abstract**

The present article investigates the potential of Active Trailing Edge Flaps (ATEF) in terms of increase in annual energy production (AEP) as well as reduction of fatigue loads. The basis for this study is the DTU 10 MW Reference Wind Turbine (RWT) simulated using the aeroelastic code HAWC2. In an industrial-oriented manner the baseline rotor is upscaled by 5% and the ATEFs are implemented in the outer 30% of the blades. The flap system is kept simple and robust with a single flap section and azimuth-based control with wind speed, rotor azimuth and root bending moments being the only inputs. The AEP is increased due to the upscaling but also further due to the flaps while the fatigue loads in components of interest (blade, tower, tower top and main bearing) are reduced close to the level of the original rotor. The aim of this study is to demonstrate a simple and applicable method that can be a technology enabler for rotor upscaling and lowering cost of energy.

## 1. Introduction

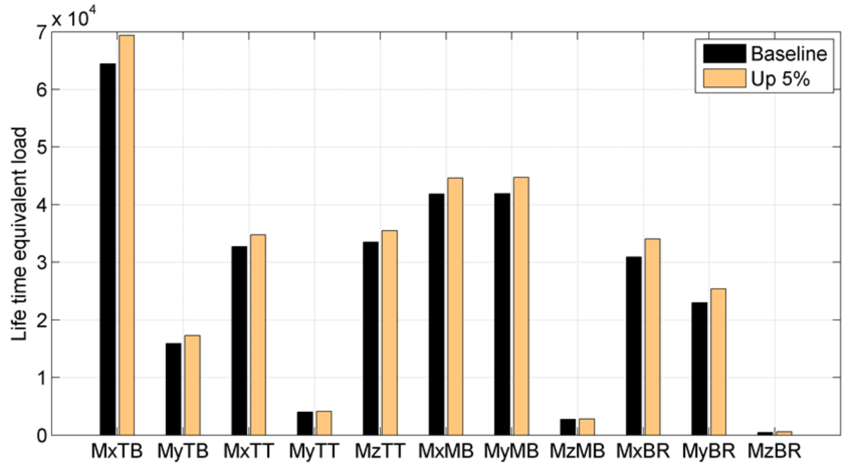
The design trend in the wind turbine industry leads towards larger multi MW rotors where the reduction of design loads and aerodynamic optimization becomes more significant. The application of ATEFs is an important part of these concepts as has been shown in previous works [**1, 2**]. In the present work all simulation activities are based on Hawc2 aeroelastic code [**3**] using the verified flap model implementation **[4]** with the unsteady aerodynamics using the ATEF dynamic stall model implementation **[5]**. In order to calculate the loads according to the industrial standard for load certification, the calculations are based on DLC 1.2 NTM (as stated on IEC standard 61400-1, third edition) an overview of which is presented at **[6]** along with the post processing tools at **[7].** The assumption that the total fatigue is derived from this DLC is valid since it has been observed that in the channels of interest more than 98% of the fatigue is attributed to DLC 1.2 NTM. In the same manner the AEP calculations are done with 10% turbulence intensity without yaw misalignment for all speeds and six turbulence seeds for each. This approach along with a robust and simplified control approach establishes a close connection to a possible industrial application of such a system.

**2. Wind turbine upscaling**

The DTU 10 MW RWT **[8]** is considered as the baseline turbine. There have been investigations on the topic of upscaling multi-MW turbines and its limitations, an overview of which can be found at **[9, 10]**. In the present case in order to formulate a business case and have a clear picture of the flap implementation potential, all the components except from the rotor are kept the same with the baseline. The already highly aerodynamically optimized rotor has the same hub in the upscaled case while the blades are elongated to a 5% total increase. In order to keep the same characteristics the solidity was kept the same as well as the airfoil profiles at the same non-dimensional positions. Hence, chord and thickness are increased to the same level while the structural properties are kept exactly the same (same mass per length, cross sectional stiffness etc.) leading to a same (performance wise) but 'softer' blade. The maximum power is limited to 10MW in order to lower the loads and utilize the same generator/electronics setup. Moreover, in order to be consistent with the upscaling procedures **[10]** and have a 'fair' case for the flaps the maximum steady state thrust of the upscaled rotor was decreased to the same level as the baseline by introducing an earlier pitch scheduling which in turn increased slightly the rated wind speed. Finally, the gains of the DTU WE controller were tuned using the DTU HwacStab2 tool **[11, 12]**. A brief overview of the two turbines as well as a comparison of their 20 year lifetime fatigue loads (derived as explained in **[7]**) can be seen in the following figure and table.

| Parameter | DTU 10 MW RWT | Upscaled Turbine |
|---|---|---|
| **Wind Regime** | IEC Class IA | Same |
| **Control** | Variable Speed/ Collective Pitch | Same |
| **Cut in speed** | 4 [m/s] | Same |
| **Cut out speed** | 25 [m/s] | Same |
| **Rated Wind Speed** | 11.4 [m/s] | 11 [m/s] |
| **Rated Power** | 10 [MW] | Same |
| **Rotor Diameter** | 178.3 [m] | 187.2 [m] |
| **Hub Diameter** | 5.6 [m] | Same |
| **Hub Height** | 119.0 [m] | Same |
| **Drivetrain** | Medium Speed, Multiple stage Gearbox | Same |
| **Minimum Rotor Speed** | 6.0 [rpm] | 5.0 [rpm] |
| **Maximum Rotor Speed** | 9.6 [rpm] | 9.2 [rpm] |
| **Maximum Generator Speed** | 480.0 [rpm] | 459.3 [rpm] |
| **Gearbox Ratio** | 50 | Same |
| **Maximum Tip Speed** | 90 [m/s] | Same |
| **Shaft Tilt Angle** | 5.0 [deg] | Same |
| **Rotor Precone Angle** | -2.5 [deg] | Same |
| **Blade Prebend** | 3.33 [m] | 3.50 [m] |
| **Rotor Mass** | 227,962 [kg] | 239,360 [kg] |
| **Nacelle Mass** | 446,036 [kg] | Same |
| **Tower Mass** | 628.442 [kg] | Same |

**Table 1 Comparison of the two turbines**




| Increase of 20 year Life Time Equivalent Load % | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MxTB | MyTB | MxTT | MyTT | MzTT | MxMB | MyMB | MzMB | MxBR | MyBR | MzBR |
| 7.7 | 8.7 | 6.3 | 3.1 | 5.6 | 6.6 | 6.7 | 2.1 | 10.1 | 10.4 | 18.4 |

**Figure 1 Comparison of lifetime equivalent loads**

The results show an increase of 6-10% for the fatigue loads in the channels investigated with the highest identified at the blade root bending moment channels. Previous results in load alleviation potential using ATEFs **[13,14,16]** agree that this reduction margin is feasible. In terms of AEP the difference for the class IA wind climate ($V_{mean} = 10\ m/s$) is 3% while for lower mean speeds this difference becomes higher.

## 3. Implementation and control of ATEF

The flap configuration applied to the upscaled rotor involves one flap section at the last 30% of the blade (29.7 m) close to the tip with individual actuators for each blade. At this section of the blade the airfoil used is the FFA-W3-241 and the flaps are occupying the 10% of the chord. The variation of aerodynamic characteristics by the flap deflection is based on 2D CFD results from the in-house code Ellipsys 2D. The deflection limit of the flap is +/- 15 degrees and the one-per-blade actuator dynamics are taken into account using a linear servo model in Hawc2 with a first order system using a time constant of 0.5s.

The main controller of the turbine (pitch and torque regulation) is the same as the baseline **[12]** with retuned gains to fit the upscaled rotor and earlier pitching scheduling to limit maximum thrust to the baseline level. The controller features both partial and full load operation as well as switching mechanisms between modes of operation, utilizing measurements of rotor speed, tower accelerations and pitch angles as inputs and the generator torque and collective pitch angle as outputs.

The flap controller is completely decoupled from the main controller and is divided into two parts. The first involves the partial load operation of the turbine. The approach for this part is the derivation of the optimal flap angle (beta) from steady state simulations. A full sweep parametrical study is carried out for each speed and all possible beta angles. Then the azimuth is divided into 10 degree bins (355-05, 05-15 etc.) and the optimal angle based on maximized tangential loads was derived for each bin. The tangential loads follow a sinusoidal pattern for a full rotation and thus for each speed a beta angle scheduling is derived:

$$b_i = K sin(\psi_i + \psi_0) + b_0$$

Where K is the gain, $\psi_i$ is the azimuth angle of each blade i, $\psi_0$ is the phase and $b_0$ is the offset.

For each speed an optimal set of $K(V)$, $\psi_0(\mathrm{V})$ and $b_0(V)$ is derived and a polynomial regression is derived for each quantity. In this manner the controller based on filtered wind speed and azimuth provides a beta value for each blade. The final offset is then fine-tuned based on full turbulence results in order to compensate the stall margin not taken into account in the steady simulations.

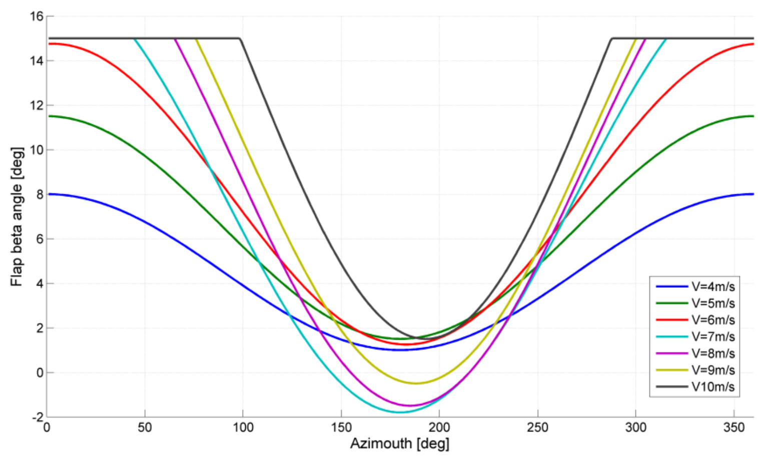



**Figure 2 Beta scheduling versus azimuth angle for different speeds below rated**

The second part of the controller is a PID cyclic flap controller operating at the full load regime which contributes more than 95% of the total fatigue damage equivalent load. The input is the blade root moment signal and the gains for each speed are found using a Ziegler-Nichols tuning method. The blade root bending moment input signals are transformed into yaw and tilt moments. 3P and 6P band-stop filters are applied on $M_{yaw}$ and $M_{tilt}$. The filtered moments are passed through a PID control element and the rotor $\beta_{yaw}$ and $\beta_{tilt}$ angles are obtained which are subsequently Coleman-transformed into flap angles for the three blades. This control approach for load alleviation in full load regime has also been demonstrated and validated in previous works **[13, 14]**. Finally, the transition region is treated with a linear part added to the controller which makes sure that the beta angle will change smoothly from one region to another when operating close to rated speed.

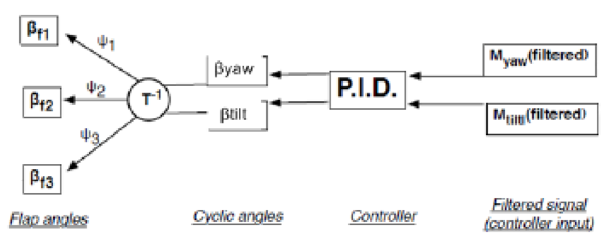



**Figure 3 Block diagram of cyclic flap controller above rated**

## 4. Results

The simulation were carried out at the baseline turbine as well as the upscaled with and without flaps. The flap controllers were implemented also separately in order to identify each contribution separately. The results indicate that the flap implementation can improve AEP by 0.4% (IEC class IA) compared to the upscaled rotor and 3.6% compared to the baseline, while the increase in fatigue loads is in the order of 1% to 2% if applied individually. The PD controller, alone shows a decrease of 5%-15% to the lifetime fatigue loads close to the level of the baseline turbine and no influence to power generation. The integrated controller is a trade-off between power increase and load alleviation resulting to a 3.6% total increase in AEP while the fatigue loads in most channels are in the level of the baseline. Blade root bending moment and main bearing channels reach the baseline level while the tower loads are increased in the order of 2% to 4%.

## 5. Conclusions

The main conclusions are summarized below:

- In terms of AEP the individual flap control can increase AEP depending on how aerodynamically optimized is the rotor and the site-specific wind shear.
- The fatigue margin of the baseline design should be taken into account in order to evaluate whether the reduction is sufficient to keep the same platform.
- This control method seems more robust and easy to apply than previous approaches since no significant increase to pitch activity is observed and the turbine–specific prescribed values are less prone to errors than other methods like MPC algorithms.

Suggested future work should also consider the extreme load alleviation. A controller approach like a threshold cut-off could also be integrated in order to alleviate extreme loads which are another significant design drive. This fully integrated controller could reveal the full potential of a practical flap implementation in large rotor wind turbines.

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