Active damage mitigation of the blade leading edge erosion for a wind turbine during rainfall events

Álvaro Úbeda Ripoll[1], Zhiyu Jiang[2], Amrit Verma[3], Jing Zhou[2]
1 Industrial Engineering, Polytechnic University of Catalonia, Barcelona, Spain
2 Department of Engineering Sciences, University of Agder, N-4898 Grimstad, Norway
3 Department of Mechanical Engineering, University of Maine, USA

E-mail: `alvaro98ubeda@gmail.com, zhiyu.jiang@uia.no`

Abstract. Leading edge erosion (LEE) of wind turbine blades is a major concern for the wind turbine industry. LEE leads to increased blade surface roughness and incurs significant repair and maintenance costs. To address this issue, the present paper proposes an active LEE mitigation method by operating wind turbines in an erosion-safe mode with reduced rotor speed during precipitation. The proposed method involves first numerically modelling the NREL 5-MW reference wind turbine in openFAST. Then, during a regular operation in the presence of rainfall, the erosion-safe mode is designed, implemented and initiated with a modified blade pitch controller in Matlab-Simulink. To evaluate the effectiveness of this mode, the long-term rainfall distribution of the De Kooy site in the Netherlands is examined. The analysis considers a comparison of power output, erosion lifetime, and levelized cost of energy (LCOE) with and without the proposed safe modes. The study shows that the erosion-safe mode can significantly extend the erosion lifetime at the cost of reduced power generation. The controller settings affect the wind turbine performance, and a reduced rotor speed of 11 revolutions per minute is recommended considering the LCOE (308.64€/MWh). While the proposed mitigation method shows promise, it requires further refinement for real-life implementation in wind turbines.

1. Introduction

The wind energy sector is currently facing a major challenge in the form of leading edge erosion (LEE) of wind turbine blades. This issue is hampering the performance and longevity of wind turbines. The damage is typically caused during rainfall when rain droplets hit the rotating blades, leading to an increase in the blade surface roughness and eventually material loss at the leading edge. As the smoothness of the blades is related to the aerodynamic performance [1], a turbine with LEE may operate with a lowered efficiency and lower energy generation [2]. Reports show that the repair and maintenance costs of LEE damages reach values over £56 million for the European offshore wind turbine sector [2, 3]. In addition, the current trends in wind turbine development indicate that the future will see turbines with larger rotor diameters. This offers multiple advantages such as lower operational and maintenance costs as well as increased energy extraction per turbine [5]. However, large wind turbines may be associated with higher tip speeds making LEE even more critical.

There have been several efforts considered to mitigate the LEE of wind turbine blades. These can be broadly classified into three categories of solutions [6] as shown in Figure 1. These categories include (a) erosion-resistant blade coatings (b) new methods to predict blade erosion

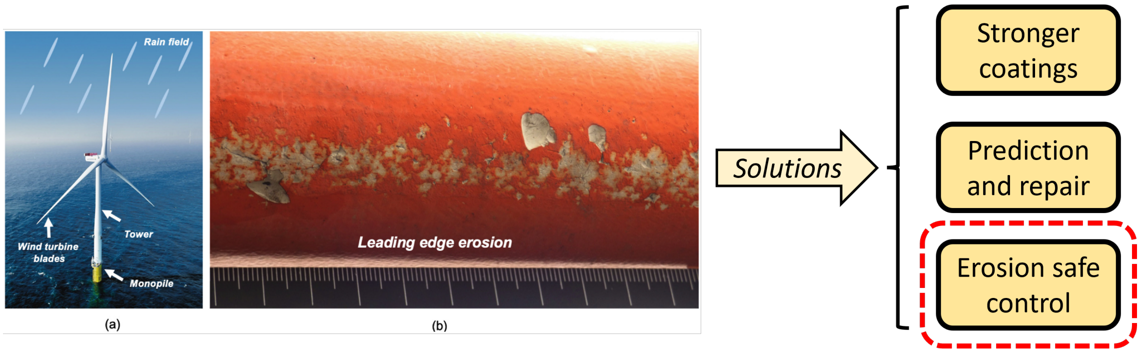

Figure 1: Image of a blade with severe LEE and mitigation solutions; the main topic of this paper marked in red [4].

and associated repair, and (c) erosion-safe controls for wind turbines. For instance, accelerated erosion tests have been performed extensively to compare the performance of several coating materials [7, 8, 9]. Computational models have also been developed to estimate fatigue life based on cyclic stresses over the service life of the blades [10, 11]. Other research has been directed at developing a control algorithm that automatically reduces the tip speed of the blade, thereby reducing the LEE damage [12]. The LEE-induced damage can also be characterised using cumulative damage models for accurate long-term blade damage predictions using site-specific wind and rain statistics [13]. More details on the review of mitigation methods can be found in [14].

The present paper focuses on the third aspect of the solution which is proposing an active LEE mitigation method by operating wind turbines in an erosion-safe mode with reduced rotor speed during precipitation. While there have been scientific work done in the past on developing similar erosion-safe control algorithm, the paper presents three novelties: (1) design and implementation of an active erosion-safe mode through numerical simulations (2) comprehensive analysis of the effect of the new control algorithm on the operational dynamics of wind turbines, and (3) systematic assessment of the performance of the control algorithms using a realistic rain and wind data from a coastal site in the Netherlands. The focus of this research article is primarily on rain-induced blade erosion, as rainfall serves as the major contributor to LEE on the blades [6]. The rest of the paper is organised into four sections. Section 2 discusses the underlying theoretical concepts that form the basis of the investigation. Following this, section 3 describes the design, implementation, and initiation of the erosion-safe control method during precipitation. A description of the numerical simulations and analysis using the long-term De Kooy site weather statistics is also presented. Following these analyses, the results and discussions are presented. Finally, the conclusions section summarises the key insights of the study.

2. Mitigation of LEE by erosion-safe control

The basis of the mitigation method considered in this work involves reducing the blade tip speed by reducing the rotor speed of the wind turbine during operation. This is done by introducing an erosion-safe mode of the controller which is activated during rainfall events. The NREL 5-MW reference wind turbine model is chosen in this project for case studies [15]. While the work can be extended to offshore conditions, this paper focused on an onshore wind turbine. In addition, selecting an open-source model is a practical approach, as it simplifies result verification, provides access to the wind turbine control, and facilitates the evaluation of system performance by comparing the findings with previous studies.

Figure 2 depicts the structure of a typical wind turbine control system consisting of two parts: the generator torque control and the blade pitch control. The generator torque control regulates the power output, and it relies on a look-up table that provides a torque for a generator speed. This system is more effective when the wind turbine is operating in below-rated conditions. The blade pitch angle control, on the other hand, controls the main shaft speed by collectively adjusting the pitch angles of the three blades. This control system is active when the rotor speed is above the rated one. By adjusting the pitch angles, the controller minimises the error between the measured and reference speeds, maintaining the rotor speed at rated values.

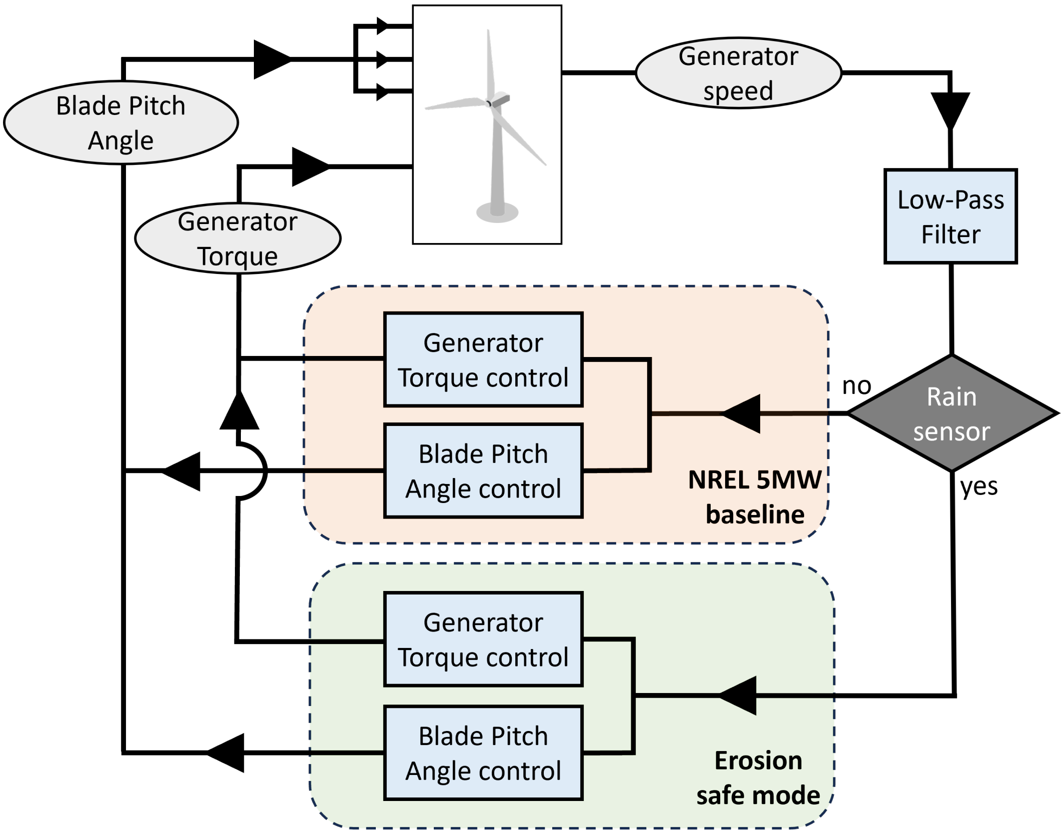

Figure 2: Schematic of the basic blocks of the proposed erosion safe mode

In this paper, a new active control algorithm is proposed to replace the original NREL controller upon the presence of erosion damages, as shown in Figure 2. The graphical representation illustrates the integration of the innovative control approach triggered by a fictitious rainfall sensor. In practice, sensors like disdrometers can be installed on a wind turbine. The new 'erosion safe mode' controller is a modified version of the 'DISCON' controller for the NREL 5-MW turbine with user-defined parameters [15]. These are the reference generator speed on the blade pitch control and the reference generator power output on the generator torque control. During rainfall events, the wind turbine's reference generator speed is adjusted to values below the rated ones. This causes the blades to pitch to a higher degree accordingly and reduce the rotational speed of the generator. Subsequently, the main shaft speed reduces and results in a reduction in the velocity at the blade tip. This is crucial in mitigating LEE as lower tip speeds mean reduced impact velocities with rain droplets. To maintain stable operation of the wind turbine, the generator torque control is also modified to have a lower target output values. Without this modification, the generator torque control would increase the generator torque to match the rated energy generation output, which is not desirable.

Reducing blade tip speeds significantly reduces the damage to the blades caused by LEE due to rainfall. Lower tip speeds result in reduced impact velocity between the surface of the blades and the rainfall droplets. The cyclic nature of the rain droplet impacts on the blade surface causes a fatigue damage phenomenon that can be characterised using the Palmgren-Miner's law for linear damage accumulation and the Springer model for damage rate [16]. This is a widely used damage accumulation model used in a few studies regarding LEE on wind turbines. [17, 18] This method considers a point of impact on the surface of the blade with which the droplets collide continuously during a rainfall. Every droplet contributes a specific amount of damage to the surface. Once the cumulative damage reaches a certain threshold, the material degradation on the wind turbine blade becomes significant and results in a noticeable decline in the aerodynamic efficiency.

$$\dot{D}_i = \frac{q \left|\vec{V}_{\mathrm{imp}}\right| \beta_d}{\left(8.9/\phi_d^2\right) \left(S/p_{wh}\right)^{5.7}} \tag{1}$$

In the Springer model (Eq. 1), $\dot{D}_i$ is the fatigue damage rate [9] of the blade coating, $\vec{V}_{\mathrm{imp}}$ is the impact velocity, q is the number of rain droplets per unit volume, ϕ_d is the rainfall droplet size, β_d is the impingement efficiency, S is the erosive strength of the coating material, and p_{wh} representing the water hammer pressure. Note that a reduction in $\vec{V}_{\mathrm{imp}}$ will have a clear contribution to the reduction of fatigue damage from the droplets and therefore LEE. D_i represents the cumulative damage on the blade and a value greater than or equal to 1 represents the onset of material removal. This also represents the end of the incubation period.

3. Analysis procedure

The performance evaluation of the proposed erosion-safe mode controller was conducted in two stages as shown in Figure 3. In the first stage, the erosion-safe mode is designed and implemented through numerical simulations using the wind turbulence field conditions and wind turbine model. The resultant blade tip speeds were extracted and the damages caused to the blades during different rainfall conditions were analysed separately using the Springer erosion model. The results of the first stage led to the creation of a look-up table that was used in the second stage. The look-up table comprises data derived from numerical simulations conducted during the first stage. It presents information regarding the rate of damage accumulation and the power output of the wind turbine under various wind and rainfall conditions and controller settings. In the second stage, the controller's performance was tested using onsite data collected over 50 years in the Netherlands. The purpose is to compare different settings of the proposed erosion-safe control for a selection of parameters, such as reduced operational blade tip speeds.

3.1. Assumptions

The following are the main assumptions used in this study:

- Detection of rainfall is achieved by fictitious sensors and these sensors are assumed to be integrated into the wind turbine.
- There is no time delay between the start of a rainfall event and the triggering of the erosion-safe mode.
- The controller's performance is tested using a numerical framework. A real scale implementation is out of the scope of this paper.
- The LEE model used in this paper is based on the surface fatigue model.
- Only one representative rain droplet size is considered for a given rainfall intensity.
- Each of the examined control modes in the second stage imposes a specific rotational speed limit on the wind turbine during rainfall events, without adjustment to accommodate varying environmental conditions it may encounter.

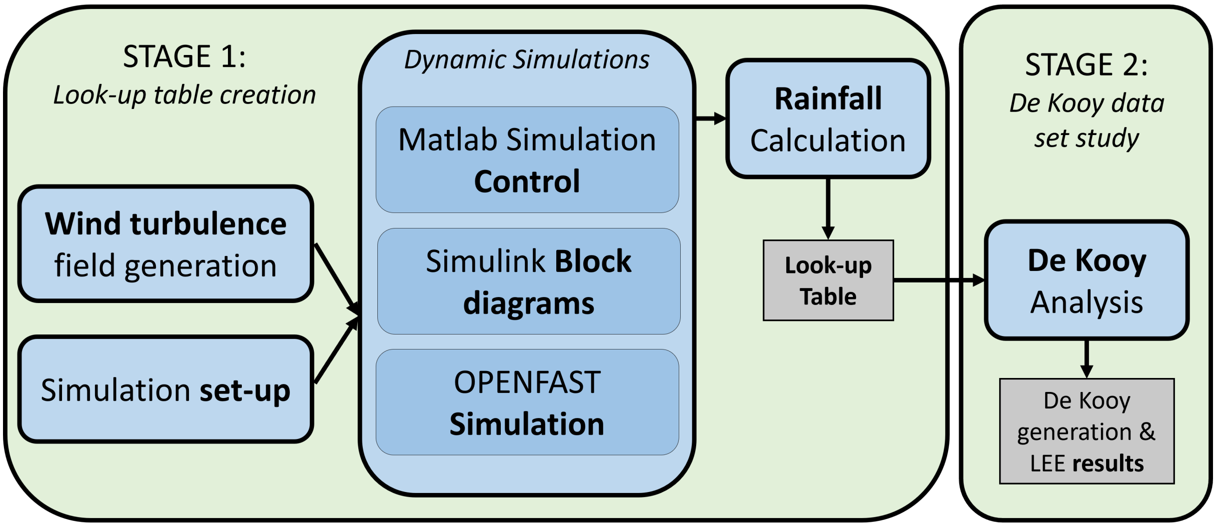

Figure 3: Overview of the workflow of the paper

3.2. Stage 1: Look-up table creation

Figure 3 shows an overview of the workflow. The first step involves generating a wind turbulence field for a class B wind, according to the Normal Turbulence Model (NTM). This determines the turbulence intensity for each wind speed considered in the study. In the second step, other aspects of the models are set up, such as the wind turbine structural models and blade properties. Finally, dynamic simulations are carried out using Matlab scripts to control the simulations, as well as Simulink block diagrams are developed to implement control algorithms together with openFAST scripts to run dynamic simulations.

Figure 4 shows the structure of the dynamic simulations. Each simulation lasts 10 minutes for a given wind condition, during which a rainfall event occurs between times t_s and t_i. The wind turbine operates using the system depicted in Figure 2. Initially, the NREL 5-MW baseline controller is used to achieve normal power production. At time t_s, the rainfall event occurs and the erosion-safe mode is activated immediately following detection by the rainfall sensor. The algorithm reduces the rotational speed of the wind turbine, which in turn minimises the LEE and reduces the energy output of the generator. This mode stays active until the rainfall event ends at time t_i. Once the rainfall sensor detects that the rain has ceased, the baseline NREL controller takes over again. Assuming the rainfall is detected by fictitious sensors, the Matlab scripts adjust the control algorithm settings according to the simulation time to activate and deactivate the baseline NREL and the erosion-safe mode controllers instantaneously at the times when the rainfall event starts, as indicated in Figure 4.

The timeline in Figure 4 demonstrates three phases that a wind turbine goes through while operating with the erosion safe mode. The first stage is the transition phase at time t_s. During this phase, the wind turbine switches from the baseline controller to the erosion-safe mode control. The second stage is the rainfall event, which is long enough for the system to stabilise with the new control mode. The third stage is the transition phase at time t_i, when the wind turbine switches back to the baseline controller. To verify the effectiveness of the second stage, it is necessary to include a reference case where only the baseline controller is active throughout the simulation. Therefore, for every environmental condition, there is also a reference case where only the baseline controller is active. The simulation process, as depicted in Figure 4, is consistent across all tests, but varies based on wind and control system conditions. We have simulated all possible combinations of the values listed in Table 1. After each simulation, we

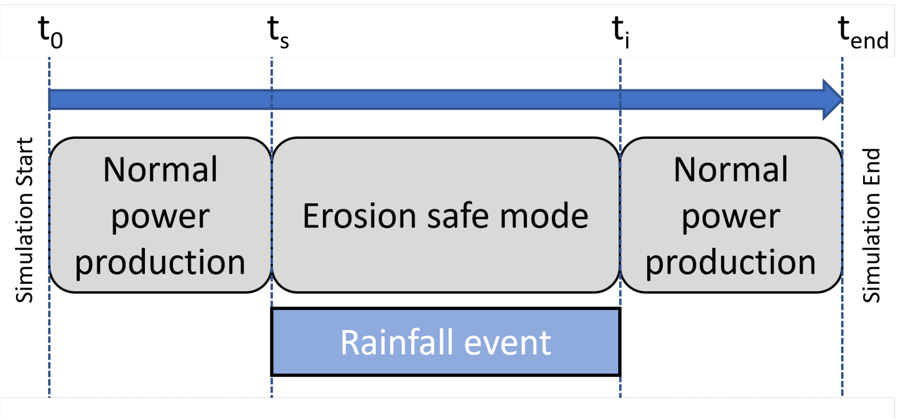

Figure 4: Overview of the basic events involved in the dynamic openFAST simulations

calculated the rainfall conditions for every possible combination of the parameters in the table by post-processing. For each combination of environmental and control parameters listed in Table 1, two variables are calculated: LEE damage rate (unit: 1/h) and generator electrical power (unit: kW). These variables are then compiled to obtain the final result of Stage 1, which is a look-up table that defines the LEE damage rate and power output value for each set of parameters.

Table 1: Wind, control and rainfall conditions parameters tested throughout all the simulations

Parameter	Interval	Values
Mean wind speed	3 m/s	6, 9,..., 24 m/s
Target reduced main-shaft speed	1 rpm	7, 8, ..., 11 rpm
Rainfall intensity	3 mm/h	2, 5,..., 50 mm/h

3.3. Stage 2: Case study of a Dutch site

In the case study, the De Kooy site in the Netherlands was chosen. The site's close proximity to the sea makes the erosion conditions more severe than those experienced by inland onshore wind turbines. Figure 5 presents the long-term wind and rainfall distribution for De Kooy. As shown, the wind speed is concentrated in the below-rated regions, with a mean wind speed of 5.79 m/s at the site. A noteworthy aspect of the site is that 78.26% of the time there is sufficient wind for the wind turbine to operate, out of which 7.21% of the time it is above the rated capacity. Figure 5 also shows relatively low rainfall intensities. However, rainfall occurred during 11.25% of the total hours over a period of almost 50 years. This information will be useful in evaluating the effectiveness of the new control mode. Few highly intensive rainfall events over 50 mm/hr are also observed, which is useful for studying the overall rainfall patterns.

The data collected at the De Kooy site comprises hourly records of rainfall intensity and mean wind speed. Using the mean wind speed, we can determine the turbulence intensity based on the turbulence class specified by the IEC standard. Additionally, we can use probabilistic rainfall models [14] to determine the mean droplet size for a given rainfall.

Each of the control parameters is tested separately, i.e., for every test of the 50 year period on De Kooy, the control parameters are fixed. Therefore, by matching the De Kooy environmental conditions to the ones found on the look-up table obtained on Stage 1, it is possible to assign a given value of power generation and LEE damage rate for every time interval of the dataset.

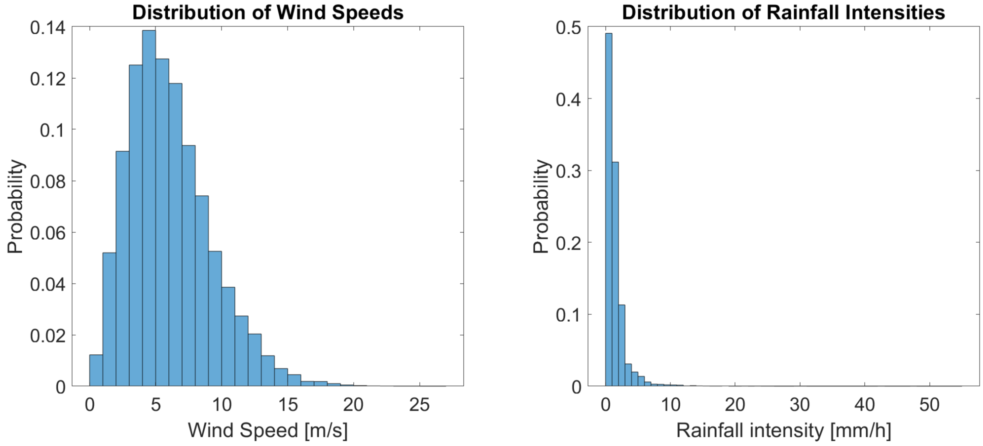

Figure 5: Distribution of wind speeds (left) and rainfall intensities (right) at the De Kooy from 1971-2020

In cases where the values of wind and rainfall conditions are not found in the look-up tables, approximate values from the look-up table close to the De Kooy conditions will be taken. By doing so, we are able to simulate the behaviour of the wind turbine during a time interval of 50 years. By studying the long-term results of these hourly behaviours, it is possible to compare the performance of the different tested control systems over an extended period of time. To facilitate a meaningful comparison we calculate the levelised cost of energy (LCOE). First, the CAPEX has been calculated to be 7180000 EUR according to [19] that estimates the CAPEX cost of a 2.6 MW wind turbine to be 1436 EUR/kW. Second, the only operational cost considered is the repair job of an LEE damaged wind turbine at 30000 EUR. [20]

4. Results and Discussion

This section is divided into two parts, each corresponding to the first and second stages shown in Figure 3. The first composed of an example of one of the simulated cases with one of the rainfall scenarios. Then, results for the De Kooy site are presented.

4.1. Time history of a numerical simulation

The parameters listed in Table 2 are considered in this numerical simulation. As the chosen wind speed is above rated, rated values of power generation are expected for simulation with the original controller. A high rainfall intensity of 50 mm/h is considered. Figures 6, 7 and 8 correspond to the timeline outlined in Figure 4. For the two periods at the start and end of the simulation, the wind turbine operates with the baseline controller. During the second stage with rainfall, the erosion safe mode is activated.

Table 2: Parameter selection for the time-series case analysis

Simulation parameter	Value
Mean wind speed	21 m/s
Turbulence intensity	0.1423
Target main-shaft speed	8 rpm
Rainfall intensity	50 mm/h
Median droplet size	1.4643 mm

Figures 6–7 show the influence on the rotational speed of the main shaft and the generator power when the proposed erosion safe mode is activated during a rainfall event. The rotational speed is reduced to 8 rpm as specified by the controller parameters in Table 2. To achieve a reduced rotor speed, the blade pitch angle must be adjusted to a higher degree. It can be seen in Figure 8 that the pitch angle increases significantly during the rainfall event, meanwhile in the reference case with the baseline controller, the fluctuation of the pitch angle remains relatively small in turbulent wind.

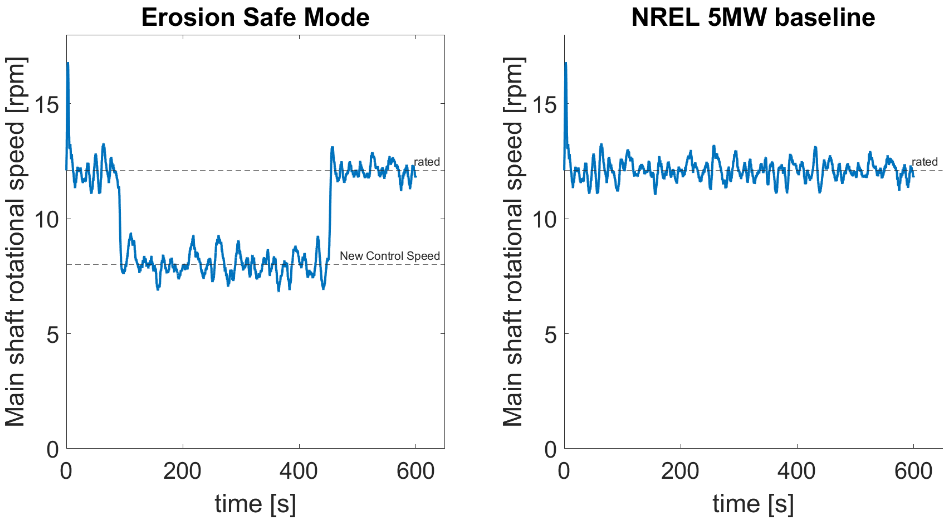

Figure 6: Rotational speed of the main shaft using the erosion safe mode (left) the baseline controller (right)

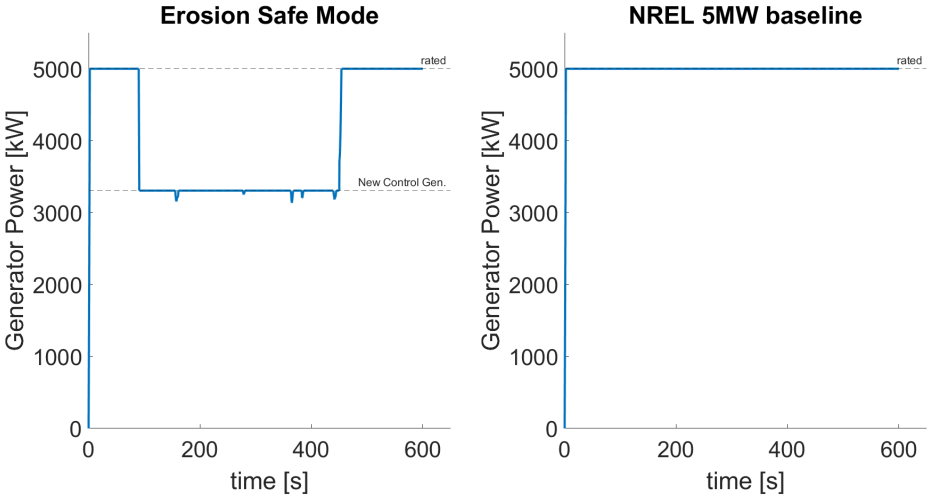

Figure 7: Generator torque during a simulation using erosion safe mode (left) and the baseline controller (right)

Figure 9 shows that the tip speed of the blades reduces substantially when the erosion control mode is activated. This reduction is due to the lowered rotor speed as seen in Figure 6. Comparing the two damage rates seen in Figure 10 it is clear that the proposed damage

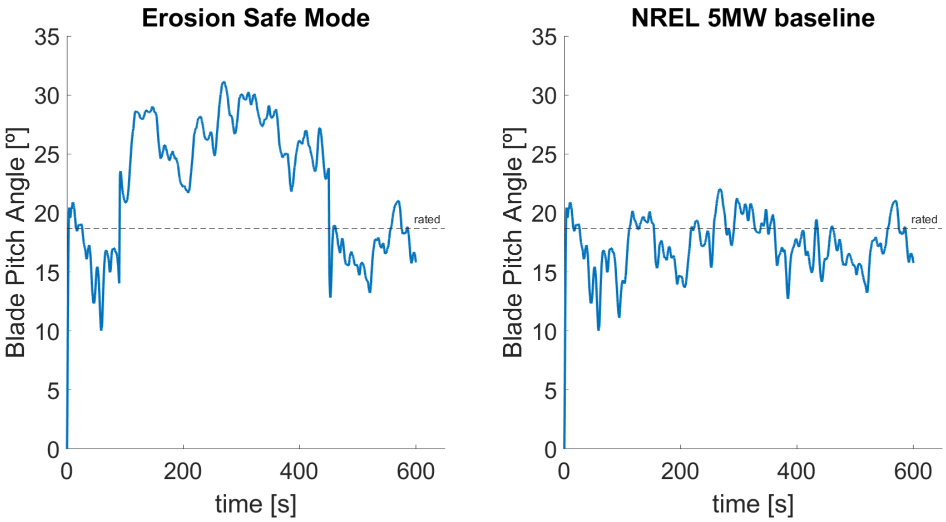

Figure 8: Collective blade pitch angle during a simulation using the erosion safe mode (left) and the baseline controller (right)

mitigation strategy by reducing the tip speeds is effective. As shown in Figure 11, the damage accumulation slopes of the baseline controller and of the erosion safe mode deviate significantly from each other, and the proposed erosion safe mode results in a significantly reduced damage rate.

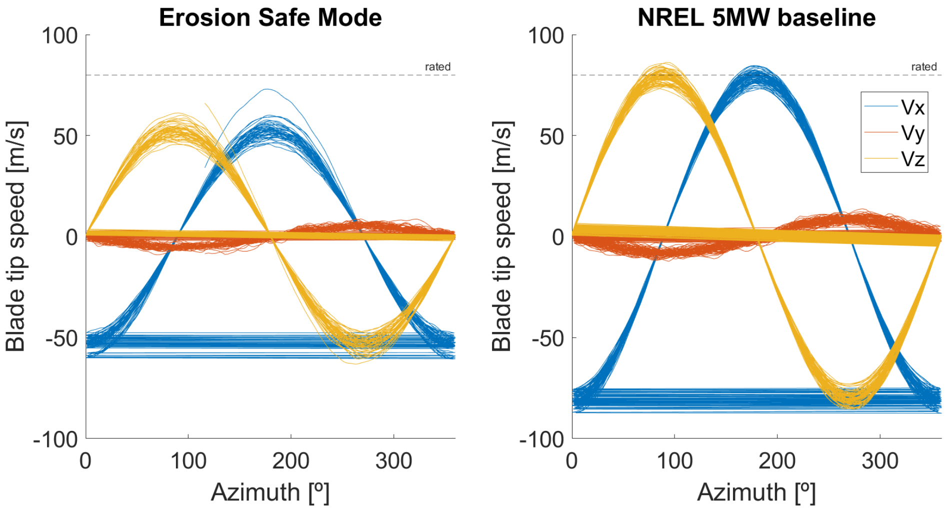

Figure 9: Blade tip speeds from a numerical simulation with the erosion safe mode (left) and baseline controller (right)

4.2. Case study results

After carrying out all the simulations with the parameters detailed in Table 1, we performed a case study simulation using the De Kooy dataset. The results show an expected difference in the energy generation using controllers with different target rotor speed, as can be seen in Figure 12. It is clear that all controllers start at the same value of energy generation (0 MWh)

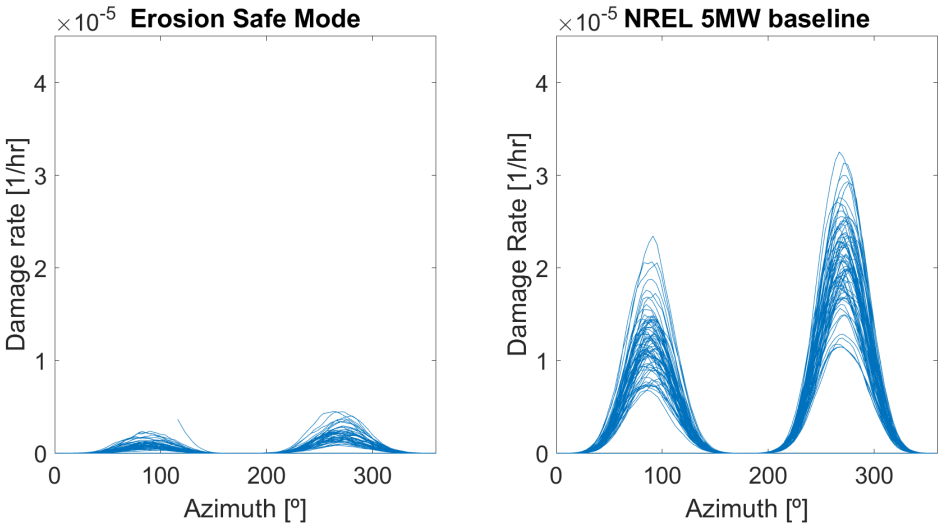

Figure 10: Resultant LEE damage rates calculated from the output data from the openFAST simulations

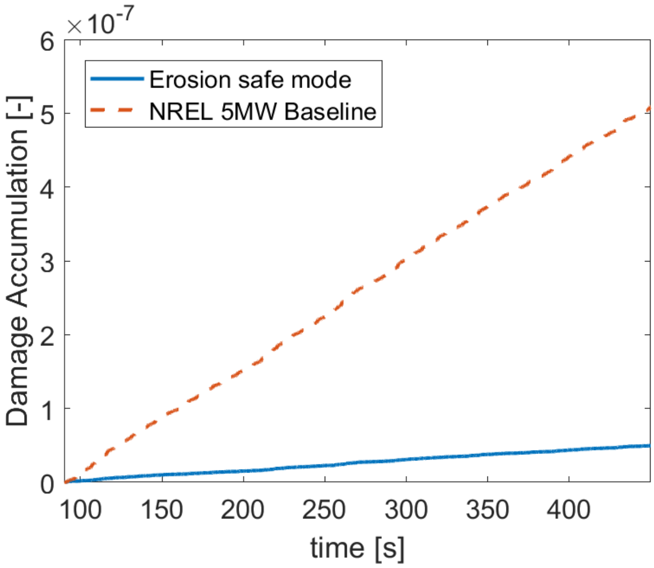

Figure 11: Damage accumulation time series through the rainfall event of the simulation for both erosion safe mode control and baseline control systems

and gradually increase the cumulative generated power over time. As expected, the baseline controller generates the most power from the beginning and keeps its power production rate during rainfall events.

Consequently, once the damage accumulation reaches a threshold, there is a need for repair and maintenance of the blades, and the energy generation reaches a plateau. This phenomena is shown in Figure 13. Here, the original baseline control results in a downtime of the wind turbine at day 773 for a duration of 3 days due to repair. In contrast, for erosion safe mode with target rotor speed of 10 and 11 rpm, the cumulative energy generation continues to increase during this period as the erosion damage has not reached a threshold yet. This example illustrates that operating the wind turbine with the erosion safe mode control can bring down costs and

increase the total power generation by avoiding premature failure and downtime.
While the 773-day (2.1 year) duration until failure may appear relatively brief, it aligns closely with findings reported in a previous study by J.I. Bech [12] which observed similar time frames for material degradation. It should also be noted that this case study is a site specific phenomenon that also appears in the paper from A.Verma [14] in which it appears as a location with highly severe rainfall intensities.

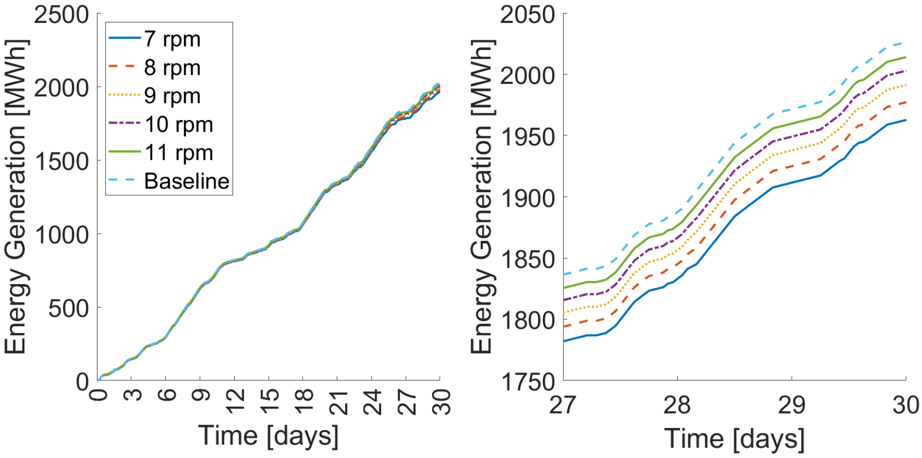

Figure 12: Cumulative energy generation for the first 30 days of the 50 year De Kooy data set (left) and for days 27 to 30 (right)

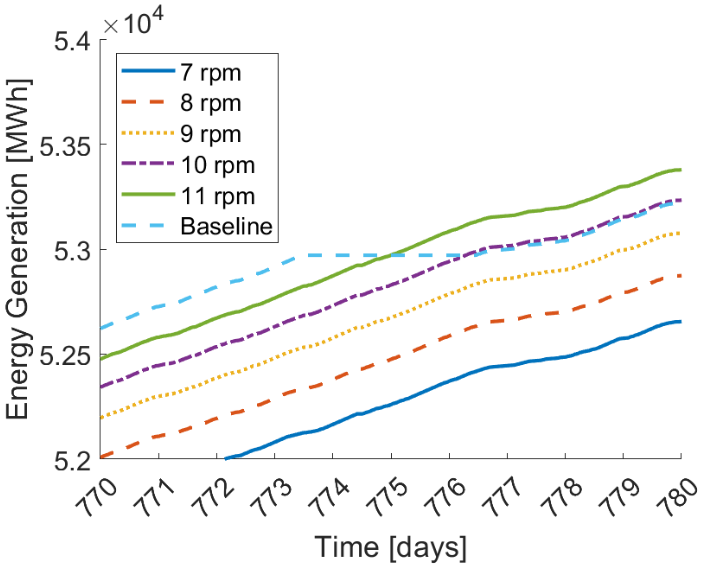

Figure 13: Cumulative energy generation for days 770-780 of the 50-year dataset of De Kooy in which the Baseline controller reaches it's first breaking point

Together with the total energy generation, the damage accumulation of the wind turbine's blades has also been analysed. The results can be seen in Figure 14. It is clear that the proposed erosion safe mode controllers are operating in a more damage-tolerant manner. Figure 15 shows that the expected lifetime of the blade's surface increases more significantly as the target rotor speed is further reduced. Note that the lifetime expectancy depicted in Figure 15, is ideal as other failure modes of the wind turbine are not considered here.

Figure 15 shows the sensitivity of the levelized cost of energy (LCOE) to the target rotor speed during control in the erosion safe mode. It is interesting to notice that the lowest LCOE is achieved when the rotor speed is reduced to 11 rpm during a rainfall, and the NREL's baseline controller ranks next to this one. This interesting observation shows that although slowing down the rotor speeds during rainfall events may penalise the LCOE due to reduced power generation. The end result always depends on balancing the downtime and repair costs with the reduced generation in the erosion safe mode.

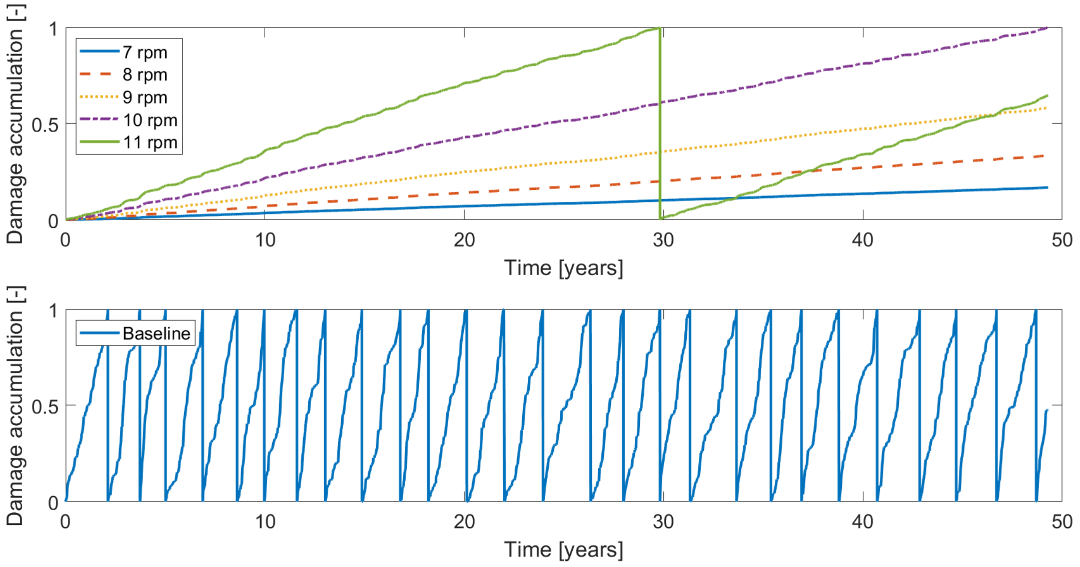

Figure 14: Damage accumulation for the erosion safe mode (top) and the baseline controller (bottom)

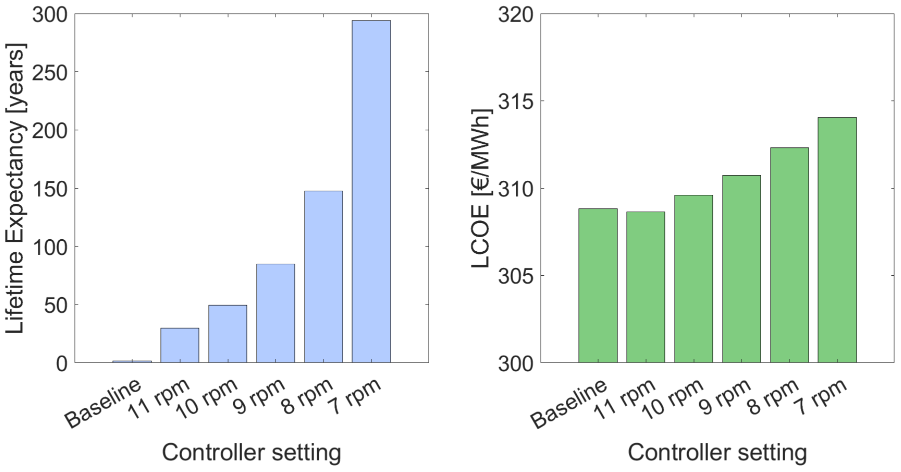

Figure 15: Lifetime expectancy(left) and LCOE (right) comparison for the different controller settings in the De Kooy 50 year data set scenario

5. Concluding remarks

The present paper conducts aero-hydro-servo-elastic simulations of a 5-MW wind turbine under various wind and rainfall conditions. To reduce the LEE damage encountered by the blades, the erosion safe mode has been proposed with several input parameters.

After a case study of the De Kooy site in the Netherlands, the main observations are as follows:

- The proposed erosion safe mode can work as an effective alternative to the original baseline controller during rainfall events. Through time-domain numerical simulations, it is demonstrated that the proposed control mode can be applied to operate the wind turbines in a stable and reliable way. The simulations also showcase that the transition from one controller to the other can be done in an efficient and safe way.
- The proposed control mode can increase significantly the lifetime expectancy of the blade's leading edge surface. This indicates that the erosion safe mode by slowing down the rotor speed is a valid method for LEE mitigation during a rainfall.
- The comparison between the several controllers on the De Kooy site is an efficient way to evaluate the performance of different controllers over an extended period of time. However, the results are highly site-specific and depend strongly on the set-up parameters.

6. Limitations and recommendations for future work

The present paper is hopefully setting the path for future efforts that may help contribute to the LEE problem on wind turbine blades. For instance, the following topics need further research:

- The design of an intelligent erosion safe mode that calculates and dynamically varies the optimal rotor speed according to the rainfall conditions.
- Consideration of the rainfall effects on the dynamic simulations. This would take into consideration any possible disturbances that the numerous rain droplet impacts could have on the behaviour of the turbine.
- Modelling the rainfall by considering the whole distribution of rain droplet sizes. In the present study, only the mean droplet size is considered for all impacts.
- Making use of the method used on this paper to compare performances other than erosion safe mode controllers. It would be possible to compare the performance of several coating materials for the leading edge of the blades or several aerodynamic designs of the blades.
- Instead of modelling the evolution of the wind turbine's leading edge state by determining the breakdown time, a gradual decrease in efficiency could be a better method of modelling the performance. It would be interesting to consider the possibility of extending the working state of a turbine even if the efficiency is lowered by some given amount due to LEE damages.

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