Estimation of Wear and Lifetime for an Improved Turbine Operation

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Abstract. Design, construction and certification of wind turbines (WT) generally target a lifetime of at least twenty years. Depending on the specified design criteria in comparison with the ‘real’ conditions on site lifetime may fall below or pass over the design lifetime targets. After installation and during operation WT continuously suffer from incremental damage due to loads, fatigue and the continuous exposure to the physical environment and operating conditions. The initially inherent wear reserve of the WT or its components permanently decreases until it finally reaches predefined safety margins or the occurrence of premature component failure. The objective of the work is to identify quantifiable wear-out metrics and to deduce information on lifetime issues in order to optimise WT operation. The method divides into a simplified approach explaining the general concept and its implementation and adaption from design to in-situ conditions. Furthermore, the methodology is transferred to a component-specific level, namely generator windings, in order to evaluate the general suitability for non-mechanical load exposures. Finally, economic issues including an economic optimisation strategy considering previously calculated wear-out figures complete the work.

1. Introduction
Wind turbines (WT) operate worldwide under a wide range of ambient conditions such as site (onshore, offshore), altitude (sea level, mountains), climate (arid, arctic) etc. During operation WT are exposed to manifold external influences such as wind forces, turbulence, wakes, atmospheric precipitation, icing, corrosion, erosion and lightning etc.

WT are generally designed and certified for a lifetime of at least 20 years. Depending on the design criteria in comparison with the ‘real’ conditions on site lifetime may fall below or pass over the design lifetime target. Although for many countries it is legally not mandatory most of the WT manufacturers decide to have their products certified by independent certification bodies. Type certificates are valuable documents for developers, customers, financing bodies and insurance companies in order to be capable of making authoritative decisions on investments or other business issues.

After installation and during operation WT suffer incremental damage due to loads, fatigue and the continuous exposure to the physical environment and operating conditions. The initially inherent wear reserve of the WT as a system continuously decreases until it reaches predefined safety margins or the occurrence of premature component failure.

Nowadays electricity generation with wind turbines is increasingly taking place under market conditions and no longer under the secure umbrella of fixed feed-in tariffs. This situation requires...
a paradigm shift in operational management: it no longer makes economic sense to use up valuable reserves of wear and tear when electricity prices fall below project-dependent margins. A cost and yield-optimised control system could override the pitfalls of fluctuating electricity prices by suspending turbine operation during these tariff phases completely or to operate only at reduced output. Within this context it is obvious that a consolidated knowledge about the actual condition of wear-out, its previous development and estimations of the expected wear-out progress is important and valuable information. Many key players like operators, service companies, suppliers and manufacturers can retrieve benefit from these findings for an appropriate and economically profitable operation.

These and other questions are being studied within the framework of the Korva project with the support of the German Federal Ministry for Economic Affairs and Energy [1]. Although there exist plenty of publications regarding the topics operation and maintenance (O&M), end-of-lifetime specific literature closely related with the subject addressed is scarce. Welte and Wang (2014) present a comprehensive survey of different kind of models and methods for lifetime estimation on wind turbines [2]. Wiggert et al. (2018) present a reliability model on main WT component level based on empirical failure statistics [3]. Shaffie and Sørensen (2017) review maintenance optimisation and inspection planning strategies in context with degradation and systems failures [4]. Lutz et al introduce the ‘monetary availability concept’ as a novel availability definition for achieving optimised revenues by shifting maintenance activities [5]. Ziegler et al. (2018) analyse issues of lifetime extension of wind turbines based on literature review and expert interviews. Within Denmark, Germany; Spain and UK several thousands of onshore WT will annually surpass the 20-years of operation level. This indicates the need and potential for gaining knowledge of the health status of WT and for methods that ensure an optimised operation.[6]

The aim of this paper is to give the reader an overview of the methodology of wear and lifetime estimation and to present first results from dynamic simulations. The outline of the paper is as follows: This section 1 Introduction concludes with brief descriptions of the technical terminologies lifetime, wear, and certification. Section 2 Wear modelling describes the mathematical deduction from the scratch. It further explains the calibration to site-specific conditions and the extrapolation for long-term developments using a simplified model. The showcase usage of the approach for a specific machine component (generator windings) concludes the section. Section 3 Economic issues covers financial aspects and presents a strategy for an optimised operation. The paper closes with conclusions and an outlook for further work in Section 4.

The authors are aware that this ‘simple’ approach is only a first step in getting insight for options to monitor the level of wear as a health indicator of the turbine or components by using information from the WT SCADA system. Other available data giving information about e.g. turbulence intensity, wakes, loads, accelerations, vibrations etc. could be usefully implemented.

1.1. Lifetime
Life cycle or expected service life of a product or component is usually described as the period between commissioning \((t = t_0)\) and decommissioning \((t = t_{\text{end}})\), see figure 1a [7]. Usually WT are designed for a service life of 20 years [8]. Depending on the actual condition and the undergone load history the actual lifetime can be shorter or can exceed the designed lifetime expectations. In case of a good condition the service lifetime from WT can exceed up to 150 percent or even more of the design lifetime.

1.2. Wear
Through use, objects wear out, which continually reduces their wear reserve compared to the initial state. The degree and thus the speed of wear and tear depends on various external factors. When the wear limit is reached, the components must be replaced or - if possible - repaired.
Figure 1: (a): Lifetime and life cycle phases in accordance with [7, p. 14], (b): Reduction and restoration of the wear reserve in accordance with [9, p. 8]

Figure 1b shows an example how the wear reserve develops over time [9]. For example, the wear or abrasion of a car tire depends on air pressure, road surface, driving speed, temperature, age, etc. The wear limit is defined by law as a minimum tread depth or age (DOT number). When either of these limits is reached, the tire must be replaced.

1.3. Certification
The testing and certification of wind turbines has been part of the standard procedure in the operating permit procedure for wind turbines for almost 40 years. After initial national variations in the certification process [10], a standardisation of requirements and norms has been established over the years. These are published by the International Electrotechnical Commission (IEC) in the IECRE Standards 61400-XY as sets of rules for a multitude of wind energy specific topics.

The high pressure on reducing cost in the wind energy sector increases the risk of compromising WT safety. Against this background the independent evaluation and certification is becoming increasingly important. According to the IEC 61400-01 WT are designed for lifetime of 20 years [8]. However, the certification scheme can also be adapted to longer lifetimes, depending on the design. [11, p. 7]

2. Wear modelling
This paper introduces a novel, simplified method of estimating the ongoing wear status progress. This information opens the opportunity to estimate how much WT lifetime respectively WT component lifetime has been used so far. As a basic approach a constant reduction of wear out is introduced in section 2.1. In the next step the approach will be modified to a more realistic wear model by means of considering wind dependent effects to the turbine (section 2.2). Finally component specific wear and tear characteristics in section 2.3 conclude the chapter.

2.1. The simplified wear model
The simplified approach assumes that the integrity of the system decays at a constant rate beginning with commissioning until the the design lifetime will be reached. This assumption is also applied to the certification of WT, i.e. it is certified, among other things, that the integrity of the plant is statistically given for the design lifetime according to the design criteria. The linear, time-dependent wear function is given as
\[ woi(t) = woi_N + \beta \cdot t \]  

where

\[ \beta = \frac{woi_{crit} - woi_N}{T_{LT}} \]

and

\[ woi_{crit} < woi_N. \]

The wear out indicator \( woi \) is a measure that quantifies the used respectively the remaining wear out reserve. Let the nominal or initial value \( woi_N = 100 \), the critical wear stock indicator limit \( woi_{crit} = 10 \) and the design lifetime \( T_{LT} = 20 \) years: this results in a wear coefficient \( \beta = -4.5 \) and the calculated wear will decrease by this value continuously. After 10 years or 50% of the design lifetime the wear out indicator reaches a value of 55, after 20 years of operation the value \( woi_{crit} = 10 \) will be reached - under nominal design conditions. However, in-situ conditions in most cases will not be identical with the underlying design parameter set. Large variations can be expected which lead to an increased respectively faster or a slower, i.e. reduced tear down of the wear out indicator. This results that the critical wear limit \( \varepsilon \) will be reached beforehand after the point of design lifetime. According to figure 2 these actual conditions are defined as the stress-factor \( \theta \). Figure 2 shows the development of wear for nominal design conditions \((\theta = 1.0; T_{end} = T_{LT} = 20 \text{ years})\), reduced load conditions \((\theta = 0.8; T_{end} = 25 \text{ years} > T_{LT} )\) and increased load conditions \((\theta = 1.2; T_{end} = 16.67 \text{ years} < T_{LT} )\). The stress factor \( \theta \) can be easily calculated as

\[ \theta = \frac{woi_N}{woi_{act}} \]

with \( woi_{act} \) as the actual wear stock indicator.

Figure 2: Decrease of the wear out indicator and resulting lifetime under design conditions (blue line), less critical (green line) or more critical load conditions (red line). \( \varepsilon \) indicates exemplary wear limit margins.
2.2. Considering power dependent wear

The constant and linear reduction of the wear out indicator over time is far from real processes which are much more complex, non-linear and influenced by many other external and internal factors. The purpose in the context of chapter 2.1 is to illustrate the wear concept from scratch. In the following step we will introduce a further elaborated approach considering on-site wind conditions as the main external driver of load dependent wear-out. Starting from the initial linear approach of calculating the wear stock reserve a minor modification of equation (1) results in a performance-dependent reduction of the wear out indicator. The basic assumption of this approach is that the loss of wear out indicator $\Delta woi$ is depending on the loads $L$.

The loads experienced by the the WT mainly depend on the characteristics of incoming wind e.g. wind conditions $v(t)$. The rationale behind this concept is based on the principle that the power $p(t)$ is proportional to the cube of the incoming wind speed $p(t) \sim v(t)^3$ and the assumption that the change of wear out indicator $\Delta woi$ is proportional to the power output $\Delta woi \sim p(t)$. The modification of equation (1) is given for discrete time intervals $\Delta t_i$ as

$$ woi(t_n) = woi_N + \sum_{i=1}^{n} \left( \beta \cdot \Delta t_i \cdot p(t_i) + \alpha \cdot \Delta t_i \cdot \omega(p(t_i)) \right) $$

(4)

with

$$ \omega(p(t_i)) = 1 + 2 \cdot p(t_i) $$

(5)

$$ p(t_i) = p(v_w(t_i)) $$

$$ \Delta t_i = t_{i+1} - t_i. $$

The factor $p(t_i)$ according to equation (4) is calculated from the power curve of a generic WT model using mean wind speed data on a 10-minute-time base. The underlying reference WT model was developed within IEA Wind Task 37 [12, p.19]. The term $\alpha \cdot \Delta t_i \cdot \omega(p(t_i))$ is a correction value. Its purpose is to initially calibrate the result of equation (4) according to the underlying design conditions, e.g. design lifetime $T_{LT}$ and design wind conditions $V_{ave}$ [8]. With respect to wear and in order to consider different load situations during normal WT operation the correction value $\alpha$ is applied by the weighting factor $w$ according to equation (5). Depending on the operational mode $w$ varies between 1 and 3. Four different modes of operation and their corresponding values of $w$ are considered according to table 1. At this stage the weighting function is user defined for testing purposes. It can be substituted by any other appropriate function.

Table 1: WT operational (OP) modes with equivalent wind speed ranges, power output and weightings of the correction value factor $\alpha$.

| OP mode | wind speed [m/s] | Power [0...1] | weighting [$\omega$] |
|---------|------------------|--------------|---------------------|
| Idling  | $\leq$ cut-in    | 0.0          | 1                   |
| Partial load | cut-in $\leq$ rated | $p(v(t_i))$ | $1 + 2 \cdot p(v(t_i))$ |
| Full load | rated $\leq$ cut-out | 1.0        | 3                   |
| Shut down | $\geq$ cut-out   | 0.0          | 1                   |

2.2.1. Calibrating $\alpha$ to design lifetime nominal values

Depending how the dynamics of the correction value $\alpha$ have been defined (see Table 1) it is necessary to calibrate $\alpha$ as an appropriate offset. The goal is to determine $\alpha$ suchlike that it sufficiently corresponds with the nominal
wear over a defined period of time. A minimum period of one year or multiples of one year is required in order to consider all seasonal fluctuations, see figure 3. In order to achieve resilient calibration results the selected wind data needs to reproduce the distribution of the average design wind conditions. Due to the variable wind conditions the resulting woi-curves will in comparison to woi\(_N\) not be a straight line but will kind of meander down the wear out indicator curve over time.

![Figure 3: Linear nominal wear out indicator (woi-lin, grey) and development of wear out indicators for different correction values \(\alpha\): 0 (blue), \(\alpha_1\) (red) and \(\alpha_2\) (green). The value \(\alpha_2\) represents an adequate approximation to the initial design values. The calculations comprise a one-year-period based on 10-minute mean values.](image)

Figure 3 shows as an example three different resulting woi-lines for arbitrarily chosen weighting factors of \(\alpha\). The first value \((\alpha = 0)\) is identical with no correction. Its slope is rather shallow implementing theoretically a strong extension of remaining wear out reserves. In a consecutive manual testing procedure \(\alpha\) is modified until an appropriate accuracy in comparison with woi\(_N\) is achieved. The simulation utilizing \(\alpha_1\) approximates the nominal wear slightly better. Finally the resulting error by using \(\alpha_2\) is within acceptable limits. It is crucial to perform the calibration of \(\alpha\) sufficiently accurate because it is a substantial requirement for the next step: the adaption of design wind conditions to the ‘true’ experienced conditions on-site.

2.2.2. Adapting design to in-situ conditions

According to chapter 1.3 the majority of wind turbines undergo a type certification process under strictly defined design conditions e.g physical environment and operating conditions, materials, load cases, minimum lifetime etc. It is obvious that the underlying design wind conditions \([8]\) are of high significance in the certification process. Since the ambient conditions on site will mostly not match with the certification assumptions but will rather vary, it is of great importance to adapt design conditions to on-site conditions in order to get a more realistic impression of in-situ wear and tear.

The basic assumption for this is that loads and thus wear and tear are depending from the actually undergone power respectively the on-site wind conditions: The power of a WT is proportional to the cube of the wind speed \(p(t) \sim v_w(t)^3\). The site adapted slope rate \(\beta^*\) is determined and modified on an annual basis by equation (6). Example: According to design conditions with a calculated nominal slope rate of \(\beta = -4.5\), a design average wind speed \(v = 10.0\, \text{ms}^{-1}\), and in-situ wind conditions of \(v = 8.0\, \text{ms}^{-1}\) results in an adopted slope rate \(\beta^* = -2.304\) by recalculating \(\alpha^*\) as

\[
\alpha^* = \alpha_N \cdot \frac{v_{w,act}^3}{v_{w,N}^3}.
\]
$v_{w,act}$ is the average wind speed for the whole time period until the actual timestamp and thus it represents cumulative on-site wind conditions starting from the date of WT commissioning. This tuning of the slope rate should be processed on a regularly basis e.g. quarterly, bi-annually or annually by applying accordingly cumulative wind conditions on-site in the calculations. This procedure enables the model, initially calibrated by design conditions, to adapt to actual conditions on-site by using updated data.

2.2.3. Adjusting lifetime to adapted site conditions

The new value $\beta^*(t)$ i.e. the slope alteration can be calculated for any time slot for which information about the current state of wear out indicator $woi(t)$ is available by

$$\beta^*(t) = \frac{woi(t) - woi_N}{T(t)}.$$  \hspace{1cm} (7)

With this information the remaining lifetime $T^*_{LT}(t_j)$ at $t = t_j$, e.g. after each year $j$, can be estimated by applying $\beta^*(t_j)$. From (2) results

$$T^*_{LT}(t_j) = \frac{woi_{crit} - woi(t_j)}{\beta^*(t_j)}. \hspace{1cm} (8)$$

Table 2 lists calculation results (wear stock index $woi$, stress value $\theta$, total lifetime $T^*_{LT}$ after one year of operation for design conditions (index N) and for different values of $\beta^*$.

| $\beta^*(t_j=1)$ [%] | $woi(t_j=1)$ [%] | $\theta$ [1] | $T^*_{LT}(t_j=1)$ [a] |
|----------------------|-----------------|---------------|-----------------------|
| -4.5$_N$             | 95.5$_N$        | 1.00$_N$      | 20.0$_N$              |
| -3.0                 | 97.0            | 1.50          | 30.0                  |
| -5.0                 | 95.0            | 0.90          | 18.0                  |

$N$, nominal (design) conditions

2.2.4. Long term dynamic behaviour

The previous paragraphs in this section outlined the general approach as well as the necessary model calibration on the basis of a mandatory initial simulation over the course of one year. After completion of the initial learning phase shorter periods of time, e.g. on a daily or weekly basis, can be chosen to calculate the $woi$ for continuous monitoring of the degradation progress. A re-calibration of the model should be repeated annually.

However, in order to implement this into actual and future wind power plants immense resources of real time and forecast data (meteorological, energy demand, energy prices, SCADA etc.) need to be available and implemented. Once the model calibration has been completed, the next step will be to continue the calculations of power depending wear and tear. By using long term wind data new virtual $woi$-states of the turbine as a whole or on component level will be calculated in an iterative process. The procedure will be terminated if the wear out indicator $woi$ falls below a defined limit, e.g. 10%.

The simulation results are compiled in figure 4. The general trend is clearly depicted: lower wind speeds deplete generally less wear due to reduced loads and vice versa. However, the nominal target of a 20-year lifetime under nominal wind conditions could not be achieved as expected. In fact it was exceeded by about 2.5 years or 12.5%. The rationale for this overshooting can be allocated to the underlying simulated wind conditions in a way that the variations of annual wind speeds do not comply with design wind conditions.
Figure 4: Development of the wear stock indicator \( w_{oi} \) for a sample of long term mean annual wind speeds \( v_w \), resulting mean wear coefficient \( \beta \), and corresponding lifetime \( T_{LT}^* \).

The next important step is to translate the described general approach to a component specific application. This can contribute to break down the complexity and to supervise and monitor the wear of relevant main turbine components e.g. tower, gearbox, generator, bearings or rotor blades. As an example the following section 2.3 applies the described method to the generator system.

2.3. Component distinctive wear models
In the previous chapter a proportional relationship between output power and degree of wear is assumed. For most components of the WT this is only partially true. Depending on the components under consideration, the load factors causing wear and tear are directly or indirectly dependent on the output power. If for example the component generator is considered then an indirect connection between output power and the dominating load quantity of the temperature can be determined [13, p. 3]. Assuming that a failure of the winding insulation leads to a total breakdown of the generator the degree of wear of the component generator windings can be modeled using the Montsinger rule and the measured temperature at the hotspots of the stator. For a constant temperature \( \vartheta \) the nominal life \( T_{G0} \) can be calculated by an empiric experimental formula [14, p. 33]:

\[
T_G = T_{G0} \cdot 2^{\frac{\vartheta - \vartheta_0}{k}}
\]  

(9)

with

- \( T_G \) := assumed lifetime,
- \( T_{G0} \) := design lifetime \([h]\),
- \( \vartheta \) := temperature,
- \( \vartheta_0 \) := design temperature \([^\circ C]\),
- \( k \) := Montsinger factor.

For simplification, a constant temperature is assumed due to the thermal inertia of the generator coils during the 10 minutes averaging time of the operating data. Based on this assumption, the thermal load, normalised to one, can be represented within this time interval according to formula (10).

\[
B_i = \frac{1}{T_{G0}} \cdot 6 \cdot 2^{\frac{\vartheta - \vartheta_0}{k}}
\]  

(10)
with

\[ B_i := \text{normalised thermal stress (heat ageing) during timestamp } i, \]
\[ \vartheta_i := \text{constant temperature during timestamp } i. \]

Corresponding to the general wear out indicator, the temperature-dependent wear out indicator \( woi_{\text{temp}} \) up to and including the time interval \( T \) results as follows:

\[ woi_{\text{temp}}(T) = 1 - \sum_{i=1}^{T} B_i \quad (11) \]

Using this formula, the change over time of the wear reserve based on the experienced temperatures can be estimated as shown in Figure 5a.

Figure 5: (a) \( woi_{\text{temp}} \) calculated with the measured temperature based on formula (11), linear regression of temperature based \( woi_{\text{temp}} \) (black), (b) adapted power depending wear model for the generator component

The wear pattern shown is based on a design temperature of 120°C, which corresponds to an insulation material of insulation class E. The Montsinger factor was set to \( k = 10 \).

Assuming that the simulated load curves represent the wear under normal conditions and are representative for the whole lifetime of the generator, the expected lifetime of the generator can be estimated at 38.1 years. Using this lifetime, it is possible to approximate the wear and tear according to formula (4) to the actual wear and tear of the generator using the method presented above, shown in figure 5b. Since the temperature temporarily continues to stress the generator coils due to thermal inertia even after switch off, the same partial load weighting was used for the calculations in all operational modes.

As can be clearly seen in figures 5a and 5b, the course of the wear reserve is approximately linear for longer periods of time. This can be calculated sufficiently by using formula (4). However, the degree of wear can vary greatly over shorter intervals as shown in figure 6. When looking at shorter time frames, it becomes clear that an approximation based on the changing power is partially erroneous. Figure 6 clearly shows the strong fluctuation of the temperature-based load, whereas the power-based load shows significantly lower levels of fluctuation. This correlation is also illustrated by the standard deviation in this time period for the reduction of \( woi \) over 10 minutes.

With the exemplary component generator it was shown that a wear model based on WT power output can approximate wear only to a limited extent. Due to the different wear mechanisms of
Table 3: average and standard deviation of the different woi methods for typical 10 minutes time intervals

| Period                        | woi method         | $\Delta woi_{avg}$ for 10 minutes [%] | $\Delta woi_{std}$ for 10 minutes [%] |
|-------------------------------|--------------------|--------------------------------------|---------------------------------------|
| one year temperature based    |                    | 4.0 $e^{-05}$                         | 4.4 $e^{-05}$                         |
| one year general              |                    | 3.8 $e^{-05}$                         | 2.2 $e^{-05}$                         |
| 31 days in April/May. temperature based |          | 4.5 $e^{-05}$                         | 5.0 $e^{-04}$                         |
| 31 days in April/May. general  |                    | 3.7 $e^{-05}$                         | 2.2 $e^{-05}$                         |

Figure 6: (a) general and temperature based wear out indicator, (b) and operational data from 15 April to 15 May

the individual components such a model can serve only as a first guess for the determination of the wear. With an observation period of one year, the deviation of the general model is still at a low level. However, if a longer period is considered, the error accumulates and larger deviations can occur.

Fitting a general model to component-specific models requires high demands on the accuracy of the individual models. For detailed evaluations of wear, it is necessary to know further input variables, but these are often not disclosed to the operators. For example, the selection of the wrong insulation class can significantly change the estimated service life of the modelled component by several years.

3. Economic issues

The economic efficiency of renewable energies is one of the biggest challenges of the energy transition. The goal in this context is to make wind energy more predictable, more economical and more efficient in terms of resources than conventional power plants (coal, nuclear power, etc.). By taking into account the wear and the associated costs, a new perspective for the operational management of WT emerges. Overall, the project Korva tries to find suitable control strategies depending on the wear costs, the electricity prices at the European Energy Exchange (EEX) and the corresponding wind conditions. Due to the limited lifetime of the WT (see chapter 1) and the fluctuating remuneration, it makes sense to develop a optimum strategy for the turbine operation. In order to achieve this a novel economic model has been developed. For this model the following assumptions are taken from the previous chapters:
- The total lifetime is limited, i.e. $0 < T_{LT} < \infty$.
- The correlation between load and wear is positive.
- The energy is sold directly via the electricity exchange market (negative revenues possible).
- The operational fixed costs are nearly constant for every year.
- There are no full maintenance contracts for the operators.

3.1. Current Cost structure

The profit $G$ can be described by the difference between the income $I$ and the costs $C$, i.e.

$$G = I - C.$$  \hfill (12)

The total costs $C$ are a composition of various financial burdens given in EUR/kW for all portions of costs. There are initial costs $C_{WT}$ for the WT and regular expected operational costs $C_{fix}$. Currently, marginal costs are neglected because they are very low compared to the other costs [15, p. 80], [16, p. 299–300]. Moreover, the depreciation of the WT takes place over longer time periods in accounting terms. In addition, the price $r(t)$ of electricity on the spot market and the wind speed $v_w$ are volatile. Whether it is worth feeding energy into the power grid is uncertain in view of the expected wear and its associated costs $C_W(t)$. For this reason, the income $I$ and costs $C$ results for closer determination of the profit $G$:

$$I(T) = \int_0^T r(t) \cdot p(t) \, dt$$  \hfill (13)

$$C(T) = C_W(T) + T \cdot C_{fix}$$  \hfill (14)

with the following variables

- $r(t) :=$ remuneration price per kilowatt-hour [kWh],
- $C_W(t) :=$ costs of wear and tear,
- $C_{fix} :=$ fix operational expenses.

For an optimised control strategy one needs above all the costs $C_W(t)$ which are to be monetised using the wear-out-indicator $woi(t)$.

3.2. Monetisation of wear and modelling

Quantifying the economics of WTs is important for technological development and promotion, as operators are focused on maximising their profits. To determine $C_W$, it is necessary to know when and under which accumulated load conditions individual components need to be replaced. After all, the individual components react differently to different load parameters. If the total repair costs $C_X$ (including component, labour costs, transport etc.) and the specific wear $woi_X(t)$ of a component $X$ are known, then the $C_W$ can be represented by

$$C_W(t) = C_X \cdot (1 - woi_X(t)).$$  \hfill (15)

If this is possible for all $n \in \mathbb{N}$ components, wear-based depreciation is calculated as

$$C_W(t) = \sum_{X=1}^n C_W(t) = \sum_{X=1}^n C_X \cdot (1 - woi_X(t))$$  \hfill (16)

for the entire WT. In equation (16), wear-based depreciation is determined as an affine linear function depending on the formula (4) to represent monetised wear. This creates a relationship
between loads and costs. For the rest of the process, it is assumed that all components react identically to the load on the output power which is the only load variable, i.e. the whole WT is treated as a single component. The wear-based depreciation costs for the model are considered similarly to marginal costs to complete the profit formula. These costs will not incur before the components fail. Therefore the calculation of wear-based depreciation would correspond closest with reserves under classical accounting. After all wear and tear increases for each additional unit of electricity generated. In total, we obtain for the profit

\[ G(T) = \int_0^T r(t) \cdot p(t) \, dt - (CW(T) + T \cdot C_{fix}) \]  

up to time \( T \leq T_{LT} \) in hours by substituting into formula (12). For this reason, it is important to know how long individual components are operating under which load so that monetisation can be estimated sufficiently. To achieve long-term profit maximisation, it is necessary to design a suitable control strategy. Another advantage would be to enable proactive strategies towards maintenance and repair work, as it is easier to predict when malfunctions or failures might occur. This could reduce labour and downtime costs and optimise workflows. However, this advantage is not taken into account in the optimisation problem.

### 3.3. Economic optimisation problem

As described in the previous section, profit maximisation is the ultimate goal. The idea is to proceed analytically in order to simplify the situation and add further constraints if necessary. For this, one looks more closely at the parameters in (17). In terms of both costs and revenues, the only opportunity to govern them at the moment is reducing the output power. For this, a suitable \( p^* \in [0, p(t)] \) is chosen in order to solve the temporally local optimisation problem by controlling the power output as the decision variable for each time instance

\[ \max_{p^i \in [0, p(t)]} G(t_i, p^*) = \max_{p^i \in [0, p(t)]} (I(t_i, p^*) - C(t_i, p^*)) \]  

from equation (12).

In order to adapt the problem to the measurement data used and to specify it further, the formula (18) in the period \((t_i, t_{i+1}) =: \Delta t_i\) for \(0 \leq p_i \leq p(t_i)\) yields the optimisation problem

\[ \arg \max_{p_i \in [0, p(t_i)]} \int_{t_i}^{t_{i+1}} r(t_i) \cdot p_i \, dt - (CW(t_i, p_i) + \Delta t_i \cdot C_{fix} - (CW(t_{i-1})) \]

\[ = \arg \max_{p_i \in [0, p(t_i)]} \Delta t \cdot p_i \cdot r(t_i) - CW(t_i, p_i) \]

where the period \((t_i, t_{i+1})\) is a 10-minute interval. In (*) we used a technique from optimisation: constant parameters that do not depend on the variable to be optimised can be omitted. If the function over the wear-out indicator is an affine linear function, then the only option is a switch-off or switch-on strategy [17, p. 841]. This assertion follows directly from the above
calculation. With the use of (4), (16) and (∗)

\[
\begin{align*}
\arg \max_{p_i \in [0, p(t_i)]} G(T, p_i) &= \arg \max_{p_i \in [0, p(t_i)]} \Delta t \cdot p_i \cdot r(t_i) - \sum_{X=1}^{n} C_X \cdot (1 - woi(t_i)) \\
&= \arg \max_{p_i \in [0, p(t_i)]} \Delta t \cdot p_i \cdot r(t_i) - \sum_{X=1}^{n} C_X \cdot (1 - (woi(t_i) + \Delta t_i \cdot \beta \cdot p_i + \omega(p_i) \cdot \Delta t_i \cdot \alpha)) \\
&\equiv \arg \max_{p_i \in [0, p(t_i)]} \Delta t_i \cdot p_i \cdot r(t_i) - \sum_{X=1}^{n} C_X \cdot (-\Delta t_i \cdot (\beta \cdot p_i + ((1 + 2 \cdot p_i) \cdot \alpha))) \\
&\Rightarrow \arg \max_{p_i \in [0, p(t_i)]} G(T, p_i) = \arg \max_{p_i \in [0, p(t_i)]} \left( r(t_i) - \sum_{X=1}^{n} C_X \cdot |\beta + 2 \cdot \alpha| \right) \cdot p_i \cdot \Delta t_i
\end{align*}
\]

the condition for switching off can be

\[
r(t_i) - |\beta + 2\alpha| \cdot \sum_{X=1}^{n} C_X < 0 \quad \Rightarrow \quad p_i := 0,
\]

for the shutdown of a WT. Remember that \(\alpha, \beta < 0\). Whether such a strategy for short time intervals is feasible from a technical point of view is negligible. Figure 7 shows the cumulative profit, which is calculated by using the wind and price data from 2018. The unit refers to the rated power of the WT. However, the control strategy in (19) depends on some simplifications. These include, in particular, the hypothesis that all components experience the same linear wear. In addition other costs such as interest have been neglected and can be considered as further limiting factors. If it is possible to add further linear constraints to the model, \(p_i\) can be determined more precisely, but would not change the strategy type. This would explain the small deviation in Figure 7, which amounts to a profit difference of 0.55 €/kW. Finally it should be noted that this is a non-linear optimisation problem that ignores complex regulatory constraints like curtailment, avifauna issues, noise reduction obligations etc.

Figure 7: 2018 profit in €/kW. Comparison between no shutdown, normal operation (shutdown condition: \(r < 0\) €/kWh) and optimised strategy by \(r \approx 0.01\) €/kWh. The operational fixed costs are assumed by \(C_{\text{fix}} = 19.4\) €/kW per year. The difference between the normal operation and the derived control strategy sums up to 0.55 €/kW after one year, (b) shows the last month in detail.
4. Conclusions and outlook
The paper proposes estimations of wear and lifetime for wind turbines. In this conceptual stage the calculations are based on just a few data e.g. wind speed, power output, etc. The results have principally proved the general feasibility of the concept. However, the integration of additional data e.g. turbulence, acceleration etc. from the SCADA-system could enhance the confidence in the results. The basic idea was applied to a specific WT (sub-)component, namely generator windings. The results have shown quite good matches in comparison with SCADA measurements, although reduced system response dynamics from the estimations were observed during high wind respectively high electrical load conditions. Furthermore the observed wear states were translated to monetary figures, e.g. €/kWh. As discussed in the paper, a linear approach with only one performance variable is not ideal for determining a control strategy. However, it is possible to determine a reasonable and economically viable strategy by demonstrating the compatibility of wear and lifetime. The demonstrated optimization strategy is not the only way to optimize the profit of a WT. The next steps will be to extend the model with a variable lifetime and the possibility of exchanging components several times for a global optimization strategy. With such a strategy the number of decision parameter will increase. For example, it might be advantageous to omit the replacement of key components towards the end of their service life and to consider repowering. The replacement of cost-intensive components might be economically unviable for the remaining lifetime. Presently and prospectively the Korva project team aims to determine wear characteristics of further components in order to develop a comprehensive tool that shall assist and enable the relevant stake holders to an improved and more cost effective turbine operation. This shall be achieved by using manifold real-time and forecast data of WT state, weather, electricity demand and prices, costs etc. for supporting an adaptive operation with resilient operational mode recommendations. In fact, in the context with operational and economic issues e.g. maintenance scheduling or wear versus earnings considerations this concept can open new opportunities and options for improving cost effective WT operation.

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References
[1] Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik 21/01/2021 KORVA URL: https://www.ife.fraunhofer.de/de/projekte/suche/laufende/KORVA.html
[2] Welte T M and Wang K 2014 Advances in Manufacturing 2 79–87 ISSN 2095-3127
[3] Wiggert M M, Meyer-Lerbs L, Wolken-Möhlmann G and Dietrich E 2018 Offshore Times: Offshore Transport, Inspection and Maintenance Software: Abschlussbericht Tech. rep. Bremerhaven URL: https://www.tib.eu/de/suchen/id/TIBKAT:1032624132/
[4] Shafiee M and Sørensen J D 2019 Reliability Engineering & System Safety 192 105993 ISSN 09518320 URL: https://www.sciencedirect.com/science/article/abs/pii/S095183201630789X?via%3Dihub
[5] Lutz M A, Görü P, Faulstich S, Cernusko R and Pfaffel S 2020 Wind Energy - Monetary based availability: A novel approach to assess the performance of wind turbines 23 77–89 ISSN 1095-4244
[6] Ziegler L, Gonzalez E, Rubert T, Smolka U and Melero J J 2018 Renewable and Sustainable Energy Reviews - Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK 82 1261–1271 ISSN 13640321
[7] Kesenheimer J 2003 Grundlagenforschung zur Restnutzungsdauer von Windenergieanlagen: Diplomarbeit, TU Hamburg URL: https://8p2.de/index.php/de/downloads/know-how/wind/39-grundlagenforschung-zur-restnutzungsdauer-von-wea/file
[8] IEC International Electrotechnical Commission Wind energy generation systems - Part 1: Design requirements (IEC 61400-1 Ed.4; 2016)
[9] DIN Deutsches Institut für Normung e V Fundamentals of maintenance (DIN 31051:2012-09)
[10] Nath C Zertifizierung von Windenergieanlagen URL http://www.rotortechnik.at/Downloads/Allgemeines/GL%20zertif%20von%20WEA.pdf
[11] DNV GL Type and component certification of wind turbines (DNVGL-SE-0441:2016)
[12] Bortolotti P, Canet Tarres H, Dykes K, Merz K, Sethuraman L, Verelst D and Zahle F Systems Engineering in Wind Energy - WP2.1 Reference Wind Turbines Tech. rep. URL https://www.osti.gov/biblio/1529216/
[13] Singh G, Sundaram K and Matuonto M 2020 Wind Engineering - A solution to reduce overheating and increase wind turbine systems availability 0309524X2091099 ISSN 0309-524X
[14] Németh-Csóka M 2018 Thermisches Management elektrischer Maschinen (Wiesbaden: Springer Fachmedien Wiesbaden) ISBN 978-3-658-20132-6
[15] Zapf M 2017 Stromspeicher und Power-to-Gas im deutschen Energiesystem (Wiesbaden: Springer Fachmedien Wiesbaden) ISBN 978-3-658-15072-3
[16] Schiffer H W 2019 Energiemarkt Deutschland (Wiesbaden: Springer Fachmedien Wiesbaden) ISBN 978-3-658-23023-4
[17] Arens T, Hettlich F, Karpfinger C, Kockelkorn U, Lichtenegger K and Stachel H 2018 Mathematik 4th ed (Berlin, Heidelberg: Springer Berlin Heidelberg) ISBN 9783662567418