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Wind Assets Lifetime Extension

How to Calculate the Remaining Useful Life (RUL) of Wind Farms

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Wind farms are part of our surroundings and therefore are in general fairly accessible power generation facilities. Safety is key to both continuation of operations and a corporate responsibility towards workers and third parties. It must be safeguarded through a comprehensive process including analytical RUL calculation, inspections and certification to confirm that there is a limited risk exposure while the installation continues operating. Once the real status of the wind turbines is characterised, smart operational strategies can be deployed to maximise the return on the investment.

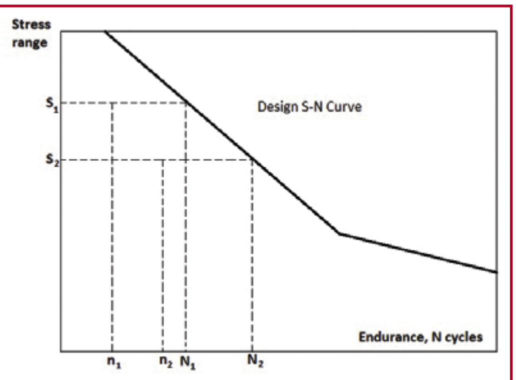

Figure 1. Wöhler for (S–N) curve

Calculating RUL

RUL is calculated by comparing the number of cycles, performed at critical locations (load stations) on the aeroelastic model, under two scenarios of power production and external conditions. The scenarios are:

- those corresponding to certification (design basis of the turbine)
- those estimated for the site-specific conditions.

The lifetime extension (LTE) factors can be determined with a certain accuracy level, which is heavily influenced by the quantity and quality of available data (from the design/certification phase and gathered from on-site conditions), wind turbine models and simulations. A refined treatment of all available data and simulations can reduce the uncertainty and increase the accuracy of the LTE estimation within the possibilities.

Technical Rationale

According to ISO 2394: General principles on reliability for structures, reliability is 'the ability of a structure or structural element to fulfil the specified requirements, including the working life for which it has been designed'. The probability of failure can be calculated as the inverse of the reliability.

Wind turbine components are usually designed considering extreme and fatigue loads. Extreme loads are defined based on the materials' ultimate strength, which from the design point of view equates to sizing the section's area, or using materials set to the proper strength.

Fatigue is more complex to manage. Loads are defined by Wöhler curves (S–N curve = fatigue curve). Damage (how the fatigue margin is consumed) is calculated by the rainflow cycles counting method, adding the damage of each cycle in line with the Palmgren–Miner theory (Figure 1).

In practical terms, instead of using a discrete calculation for each load level, the fatigue history is normally summarised in a damage equivalent load or DEL for a specific number of cycles (usually 10 million cycles as the reference).

As part of uncertainty reduction, correct wind modelling is a critical aspect. The use of a proper turbulence model such as the Kaimal model, and a proper number of turbulence seeds in order to model the wind power spectrum and spatial coherence, is a must in analytical LTE modelling. IEC 61400-1 ed. 3 standardises the number and requirements using several turbulence seeds per wind speed. The IEC proposed method is key to reducing LTE estimation uncertainty.

Figure 2 shows an example of the synthetic wind seeds with spatial coherence generated for three different turbulence intensity levels (0.5%, 5% and 18%).

Aeroelastic Model

The aeroelastic model has to reproduce the following accurately:

- Aerodynamics (using power curves and loads correlation with wind turbine field-tests if they are available to reduce the model uncertainty).
- Dynamics: mechanical models for the main components using geometry and masses. They are correlated with tested natural frequencies, Eigenmodes and their damping (or logarithmic decrement) in order to reduce uncertainty.
- Controller: the controller is mainly considered as two control sub-models. The first sub-model uses the maximum power coefficient of the rotor blades, by balancing wind speed with rotor speed to modify the generator demanded torque. The second model uses the generator nominal torque and speed and adjusts the blade pitch in order to decrease the power coefficient in the blades and allows maintaining the nominal speed by pitch variations. These two models can be adjusted by the analysis of operational data (1-second data or higher frequency must be available), power curve test and load certification test, if they are available, to reduce uncertainty in the model.

With the aeroelastic model, the load calculations can be executed and DELs for each component are obtained. Proper election of the slope on the S–N curve (Wöhler exponent, m) for each component is key. The damage of the components is related to stress time-series, not to loads, which is correct only in components supporting uniaxial load states and with no mean stress correction. Usually wind turbine components have multidirectional stress states (the fatigue damage calculation must be done using the critical plane technique) and steel, weld seams or cast iron parts must be calculated taking into account mean stress correction (Haigh diagram as state of the art or Goodman in some old analyses). Assuming this relationship between stress time-series and DEL as biunivocal implies uncertainty (taking as an input a certain number of load time-series, this number of stress time-series is obtained and the same number of different damage values are expected as output, but all considered time-series could have the same DEL value).

UL 4143 'Outline of Investigation for Wind Turbine Generator – Life Time Extension (LTE)' (UL, 2017) includes recommendations about wind turbine modelling and calculation methodologies.

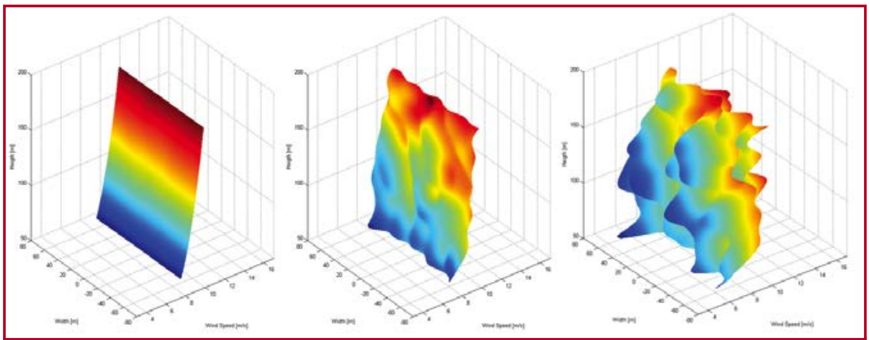

Figure 2. Synthetic wind seeds with spatial coherence generated for three different turbulence intensity levels (0.5%, 5% and 18%), with the same wind speed and wind shear

Operational Data

Operational data provides very valuable information on:

- Transient events in the wind turbine: number of start-ups and event wind speed, number of normal shut-downs and event wind speed, number of emergency shut-downs and event wind speed, number of maximum yaw misalignment errors, yaw misalignment values, lightning impacts, pitch errors, short-circuits, grid loss, voltage drops, etc. This information is required to verify that no deviations exist from the design hypothesis. If deviations do exist they must be considered in the lifetime estimation.
- The controller: data on the controller allows us to know the rotor speed and pitch position for different wind speeds. This information is key to adjusting and correlating the aeroelastic model controller.

The production data allow us to adjust the aeroelastic model by means of Cp and Ct values, which permits consequent reduction in uncertainty.

As the UL LTE guideline states, a met mast with calibrated sensors is the best source of data for external conditions to adjust operational conclusions and reduce anemometer wind speed uncertainty (which is the most relevant one).

Wind Turbine Inspections

Inspections are a key source of information to check consistency of analytical results. According to UL 4143, the inspections shall be performed by an accredited inspection entity (ISO/IEC 17020) in order to guarantee a correct methodology and inspection register. This inspection (Figure 3) allows us to understand the actual state of the turbine with regard to structural and electrical key components such as tower, blades, shaft, bearings, bolted joints, generator, cables, gearbox and lightning protection system. Additional information must be obtained by means of video-endoscopic techniques in the gearbox and main bearings, which allows detection of incipient damage in these components.

Uncertainty Calculation

With the site-specific uncertainties and the wind turbine modelling uncertainties, which are assumed to be stochastic and independent, an overall uncertainty for each LTE factor can be calculated by means of the sensitivity of the LTE factors in regard to each of the parameters. The sensitivity factors are obtained using the slope (change in LTE factor for a given change in the parameter under revision) and are specific for each load station or component. The sensitivity is critical for many of the LTE uncertainties as it is connected with the inverse of the Wöhler exponents on the S-N curves. This means that moderate variations on the load levels (DELs) may derive into significant variations on the theoretical cycles. This is particularly significant for casts (m = 8) and even more for composites (m = 10).

Figure 3. Turbine inspection UL DEWI

Conclusions

Many wind farms are reaching their design useful life (DUL) while their wind turbines are capable of continuing operation (Figure 4). It is therefore critical to determine for how long, and in which conditions, their assets can continue to operate beyond their originally intended timeline. The analytical RUL calculation provides visibility about the possibilities to extend wind turbine lifetime but it is important to reduce the uncertainties by using reliable data and well-established procedures. ■

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