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Summary:
This deliverable describes the measures by which controller performance will be judged in both simulation and test.

D5.5: Plan for performance assessment

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Abstract

This deliverable describes the measures by which controller performance will be judged in both simulation and test.

1 Simulation cost functions

In a wind power plant, a number of turbines attempt to maximize the collective energy extracted from the wind whilst also ensuring reliability of the individual components. These issues represent contrasting objectives with optimal power production often leading to damaging loads [1, p. 34]. In order to compare the performance of power plant controllers, the overall park performance $J(y_1, \dots, y_n)$ is written as a function of the vectors of n measureable outputs from the m turbines in the park, hence for example $y_1 \in R^m$ will denote the vector of power production trajectories from each of the turbines, $y_i : [0, \infty) \to R^m$ for all $i = 1, \dots, n$. We use the notation y_j^i to represent the j^{th} measurable output of the i^{th} turbine.

In an ideal world, the performance measure would include a number of production measures, for example power efficiency and power quality, as well as load penalizing terms on all of the turbine components [2, p. 16]; however, in practice, this is not sensible. The incorporation of power quality and power efficiency into the cost adds complexity to the problem with out affecting the structure of the control and hence is deemed superfluous. The term penalizing deviation in power produced will be written

$$J_1(y_1) := \sqrt{\frac{1}{T} \int_0^T \left(\frac{1}{mP_{\text{rated}}} \|y_1(t)\|_1 - P_{\text{ref}} \right)^2 \mathrm{d}t} \tag{1}$$

where $\|\cdot\|_1$ denotes the 1-norm of a vector and P_{ref} is the wind farm power reference, m is number of turbines in the wind farm and P_{rated} is the wind turbine rated power. It is worth noting that none of the elements of $y_1(t)$ can be negative for any t reflecting the fact that the turbine will either generate or be switched off.

The cost must reflect not only the power production characteristics but also the fatigue damage the turbines see. The inclusion of damage measures on a large number of components simply represents a significant modelling challenge rather than presenting a different type of control problem and so only a couple of component's loads are monitored. As two of the most expensive and, in the former's case, one of the least reliable components on a turbine, it is deemed sufficient to consider fatigue loads only resulting from the rotation of the main shaft and the fore-aft oscillation on the tower; hence $n = 3$ and $y_j : [0, \infty) \to R^m$, $j = 2, 3$ denotes the load trajectory on the main shaft and tower on the m turbines. The algorithms should be designed such that additional costs of a similar form can be easily incorporated. What is important is that the fatigue costs considered take a sensible form representative of the material's ability to withstand cyclic stress histories [2, p. 42], and are analagous to those measures used for turbine certification.

Typically, rainflow type algorithms combined with a Palmgren-Miner sum are used for such applications [2, p. 44]. For a detailed description of the algorithm see [2, Sect. 4.3.1] and for an example of its efficient computational implementation, see [3]. It should be stressed that the rainflow counting algorithm is continuous in the input data; that is the total damage is stable with respect to small variations in the measured state [4, p. 12].

Let $\mathcal{R} : \mathcal{L}_\infty \to [0, \infty)$ denote the rainflow algorithm and Palmgren-Miner sum with the output being the damage equivalent load (DEL), and let $J_j(y_j) := \sum_{i=1}^{m} \mathcal{R}(y_j^i)$, for $j = 2, 3$. Here $\mathcal{L}_\infty$ denotes the space of essentially bounded signals. The Wöhler coefficient defines the material's characteristics in the algorithm – for the two components monitored these are $k_{\text{main shaft}} = 8$, $k_{\text{tower}} = 4$ units. Note that currently there are no explicit formulations of the rainflow algorithm.

In conclusion, the cost $J(y_1, \ldots, y_m)$ is written

$$J(y_1, y_2, y_3) := J_1(y_1) + \alpha_2 J_2 \left(\frac{1}{2e6} y_2 \right) + \alpha_3 J_3 \left(\frac{1}{23e6} y_3 \right), \tag{2}$$

where α_2, α_3 define the relative importance of the three objectives. These weighting parameters are chosen by the relative costs of the components to be $\alpha_2 = 0.005$, $\alpha_3 = 0.04$.

It may be that these costs require simplification for control design purposes, but the closed-loops should be compared by this metric.

2 Evaluation of cost function using SCADA data

The SCADA server in place on the wind farm records load data with a frequency of 1 Hz. This is not high enough to accurately represent the damage with a rainflow count. Furthermore, due to the nonlinearity of the cost function mapping from load trajectory to DEL, the sum of the rainflow counts of seperate frequency sets (the union of which encapsulates the entire frequecy range) does not equal (nor is it bounded by) the rainflow count of the entire trajectory. Therefore, for the experimental tests, the variance of the trajectories will be used:

$$J_{\text{exp}}(y_1, y_2, y_3) \quad := \quad J_1(y_1) + \beta_2 \sum_{i=1}^{m} \sigma \left(\frac{1}{2e6} y_2^i \right) + \beta_3 \sum_{i=1}^{m} \sigma \left(\frac{1}{23e6} y_3^i \right), \tag{3}$$

where β_2, β_3 are the weighting paramters and $\sigma : \mathcal{L}_\infty \to [0, \infty)$ denotes the standard deviation function. The weighting parameters depend both on the relative cost of the components and their respective Wöhler coefficients thus $\beta_2 = 0.2$, $\beta_3 = 0.05$.

3 Conclusions

In conclusion, this deliverable details two cost functions J and J_{exp}. The first is the cost function by which simulation performance should be judged. This is how it would be judged in an ideal world as this directly mimicks the models of fatigue used for turbine certification. In the experiments carried out on the test farm, this will not be possible due to a sample rate of 1 Hz. The second cost is suitable for such an application.

References

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