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Up-down counter based detection of current wind direction change for a wind turbine

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Abstract: For optimizing wind turbine designs it is of importance to reduce extreme structural loads. Control schemes play an important role in this. In this work detection of Coherent gust and direction changes (ECD) is developed, which enables mitigating actions to prevent potential turbine shutdowns due to over-speed during ECD events. The proposed scheme can detect the ECD cases within to 2.5 s, which is early enough to avoid over-speed caused shutdowns of the wind turbine.

Keywords: Wind turbine, Fault Detection, Up-down Counter, Wind direction detection, Wind turbine extreme loads.

1. INTRODUCTION

As the focus in the wind turbine industry is to reduce the cost of energy it is of high importance to reduce the materials used in tower, blades etc. As these components are design to withstand the expected fatigue and extreme structural loads for the given design, it is of importance to reduce these loads. Control designs can be used to reduce both kinds of loads. Roughly, one can say that fatigue load reduction is obtained by improving the normal operation of the wind turbine, while extreme loads are handling of special events, either due to wind conditions or internal wind turbine failure or event combinations of these. In both cases fault detection, isolation and accommodation methods can be used to deal with these.

One of the difficult extreme wind conditions to deal with is the coherent wind gusts and wind direction changes, typically named ECD. If not handled in a smart way ECD cases can lead to over-speed triggered shutdowns of the wind turbine which results in high structural extreme loads, see IEC. This standard is the generally international standard for wind turbine certification, including definitions on load cases to statistical cover the wind turbine's realized fatigue loads and extreme loads on the relevant structural load components, given selected wind conditions.

The problem is to detect ECD cases fast while avoiding false positive detections as this would lead to unnecessary losses of power production. Detection of the increased wind direction change, which relative to the wind turbine direction is denoted yaw error, is an approach to detect the ECD case. Example of an ECD case can be seen in Figure 1. Even-tough the yaw error could increase with 70 - 80 degrees in 10 s, the fluctuation of the wind direction in normal operation would mean setting a simple threshold on the yaw error would lead to a slow detection of the ECD case, like 5-6 seconds detection delay, which often is to late to avoid the over-speed event, and consequently shutdown of the wind turbine. Another basic approach could be to apply a low pass filter to the yaw error to remove the fluctuations from the detection signal. Using this approach and still avoiding false positive detections would as well lead to a too slow detection of the ECD to avoid the over-speed.

Instead we propose to use an up-down counter approach to detect the numerical increasing trend of the yaw error as in the case of the ECD. An earlier example of using up-down counters in wind turbine Ozdemir et al. [2011].

In next section the up-down counter based detection scheme will be presented, followed by a section on how the parameters in the method can be tuned. The proposed scheme will when be tested in terms of its detection speed. Finally, a conclusion is drawn.

2. UP-DOWN COUNTER BASED YAW ERROR DETECTION SCHEME

In order to detect the presence of an ECD case it is important to detect the large yaw error. The first approach would be to use a time averaging filter applied to the yaw error, the problem with such a filter is that the fluctuations in the yaw error are of such a size that the yaw error in the ECD case cannot be detected before approximately 5-6 s into the ECD event at which time the over-speed event is meet anyway. One could increase the averaging time period to averaging out the yaw fluctuations in the normal operation, which would anyway lead to slow detection of the yaw error as the averaging period increases. Instead this approach detects either increasing or decreasing trend of the yaw error in the case of the ECD. The Simulink model of the scheme is shown Figure 2. This approach is normally named up-down counter, and has for example been applied for FDI in wind turbines in Ozdemir et al. [2011].

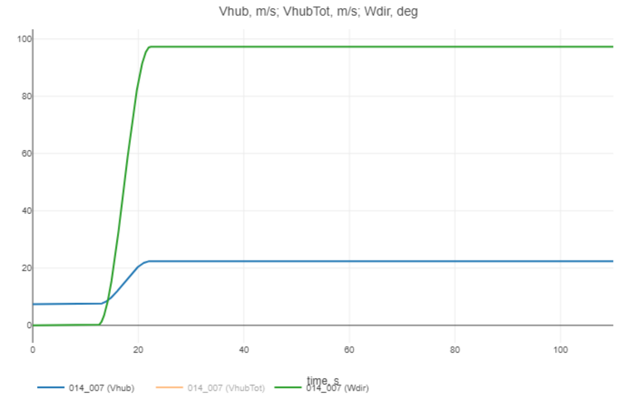

Fig. 1. Example of ECD load case, in which the wind speed increases with a gust while the direction changes as well. The blue curve is the wind speed [m/s] and the green curve is yaw error [deg]

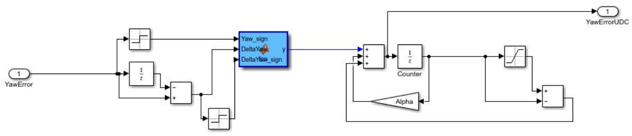

Fig. 2. Simulink model of yaw error up-down counter.

The Matlab function block in the scheme is used to either count up if yaw error is developing in the same direction as the trend, i.e. and increase for a positive yaw error or negative for a negative yaw error, by the functionality below. The counter $y[n]$ will be counted up with the value β_{su} if $\text{sign}(Y_e[n]) \cdot \text{sign}(\Delta Y_e[n]) > 0$ and $\Delta Y_e[n] \cdot \text{sign}(\Delta Y_e[n]) > T_{su}$ are true. The counter $y[n]$ will be counted down with the value $-\beta_{sd}$ if $\text{sign}(Y_e[n]) \cdot \text{sign}(\Delta Y_e[n]) \leq 0$ and $\Delta Y_e[n] \cdot \text{sign}(\Delta Y_e[n]) > T_{sd}$ are true.

In which: $Y_e[n]$ is the yaw error at sample n. The function sign() takes the sign of the function input, so $\text{sign}(Y_e[n])$ outputs the sign of the yaw error at sample [n]. $\Delta Y_e[n]$ is the difference of the yaw error i.e. $\Delta Y_e[n] = Y_e[n] - Y_e[n-1]$. The parameters are defined as: T_{su} and T_{sd} are thresholds for counting up and counting down respectively. β_{su} and β_{sd} are parameters of the respective step-up and step-down sizes.

The output of the Matlab function block is added with the last count times a forgetting factor α, which is in the interval from 0 to 1, and the anti-windup signal to keep the count at 0 or above. The summation goes as input to a unit delay block which acts as the counter, and the output from this is limited to be above 0 in the final limiting block. The current output from the yaw error up-down counter is subsequently compared with a threshold, T_{decd}, to detect the large yaw error and thereby ECD event. The value of the threshold is selected such that it does not lead to any false detections of large yaw errors in normal operation, but still detects the large yaw error early in the case of the ECD event like within 2 s. This tuning can be automatized, requiring simulation or experimental data of the yaw error.

3. PARAMETER TUNING

Tuning the yaw error UPC scheme is done using a Matlab script calling the UPC scheme with simulation data of normal wind turbine operation which is described in the IEC standard as DLC1.2, as only the yaw error is needed. Basically 5 parameters are tuned using an optimizer script using fminsearch(), where the 5 parameters are used to compute the maximum value of the counter for all the DLC1.2 cases, this value is multiplied with 1.2 to get the detection threshold, then the optimizer will reduce the maximum detection time for all the DLC1.4 cases using the same parameters. The optimal parameter set will be 5 optimized parameters plus the detection threshold computed based on the DLC1.2 cases.

In this paper the values of Y_e is simulated using a high fidelity aero-elastic simulation tool simulating a modern multi megawatt wind turbine. The thresholds parameters are set such that the up count is slightly lower than the difference in the yaw error in the ECD case. The found parameters can be seen in Table 1.

Table 1. Tuned detection parameters

Parameter	Value
T_{su}	0.0091
T_{sd}	0.1847
β_{su}	1.1149
β_{sd}	2.4665
α	1
T_{decd}	130.5276

4. TESTS OF THE DETECTION

As written before it is of high importance to detect ECD cases as fast as possible, while avoiding false positive detections, as mitigation strategies would result in loss of power production, and thereby a lost income to the owner of the wind turbine. This means with respect to testing that normal operation is test with normal and high turbulence DLC1.2 and DLC1.3, for which no false positive detections are accepted. By the tuning strategy it is already known that no false positive detections are present for DLC1.2 - normal turbulence. This means it must be checked that no false positive detects are present in the DLC1.3 cases.

Secondly, we would find the highest detection time for the DLC1.4 cases. Followed by a robustness check of the detection with respect to measurement noises and offsets on the yaw error sensor. The parameters used in the robustness test are selected based on knowledge of realistic values realized in operating wind turbines.

In this testing processes the DLC definitions described in the IEC 61400 standard ensures that the different scenarios statistically ensures that testing the schemes on the selected load cases 1.2, 1.3 and 1.4 ensures that it do false positive detections (ensured by 1.2 and 1.3) and that testing on 1.4 load cases ensures that the scheme will detect these cases in general as well. A notice here is that testing turbine with respect to extreme, they are best evaluated in a high fidelity aero-elastic model, as they are hard to test on site on a turbine. As the required conditions might not occur during the test period or even the turbines

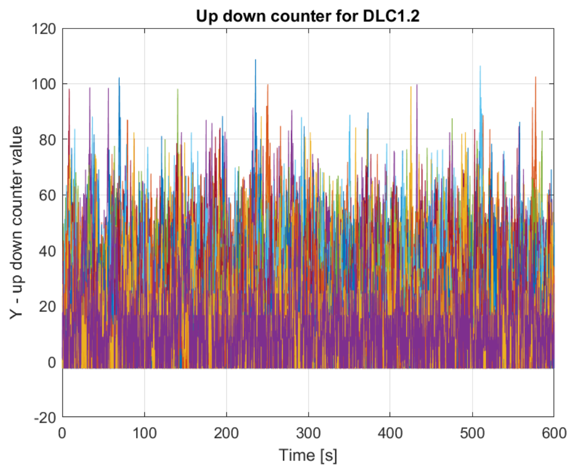

Fig. 3. Up-down counter values for all DLC1.2 cases.

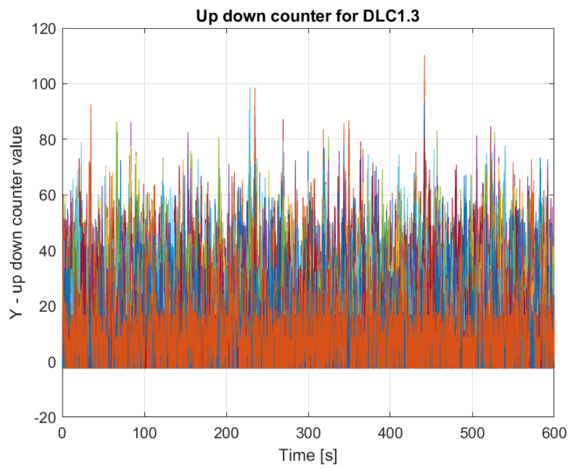

Fig. 4. Up-down counter values for all DLC1.3 cases.

life time. Secondly, the risk of testing extreme loads on site is high as they may brake the turbine if they are too high.

All these tests are made in a proprietary high fidelity aero-elastic wind turbine simulation code on an industrial multi-megawatt wind turbine.

4.0.0.1. DLC 1.2 and 1.3 This test is to compute the up-down counter value for all the cases of DLC1.2 and DLC1.3 to check these are lower than the detection threshold for detecting the ECD case. The results of these tests can be seen in Fig. 3 and 4 which shows the up-down counter values for all the DLC1.2 and DLC1.3 cases respectively, from which it is seen that the maximum count values are approx. 108 and 110 respectively which is clearly lower than the detection threshold at approximately 130.

4.0.0.2. DLC1.4 In the 14 case the detection time for all the load cases are in the interval from 2.42 2.56s, as shown in Fig. 5. If an absolute trigger was made to the yaw error based on the max errors in normal operation it would correspond to at detection time at 4s, meaning that a clear improvement is made on the detection time

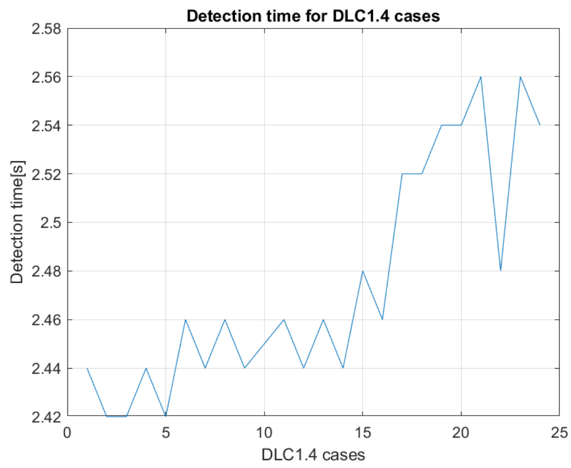

Fig. 5. Detection times for the DLC1.4 cases

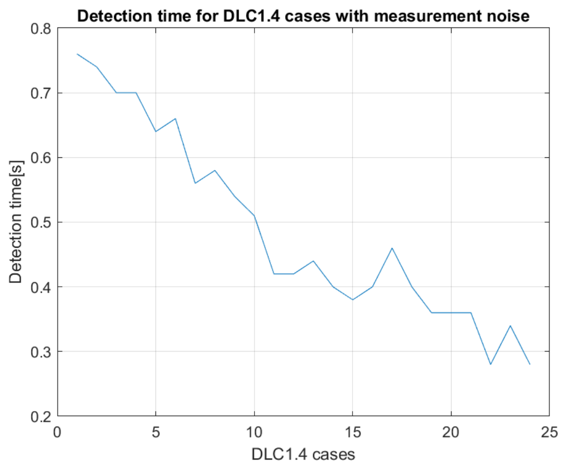

Fig. 6. Detection times for the DLC1.4 cases with measurement noise on the yaw error sensor similar in variance to yaw variations in normal operation.

of the ECD, Which is especially important to prevent an over-speed event if this is the risk.

4.0.0.3. DLC1.4 with sensor noise or offset These robustness tests are not a part of the standard but included to check the importance of the precision of the used yaw error sensor. First random noise is added to the yaw error signal with a variance corresponding to the variation in normal operation (DLC1.2). The result of this is seen in Fig. 6. The detection time lays within 0.75s after the ECD event starts, as the background counter level is already relatively high due the background yaw error variations.

With a yaw sensor offset at plus minus 8 degree the maximal detection time is not influenced, as seen from Fig. 7. The reason for this is the measured error will still converge to 0 deg as the yaw controller will position the turbine direction to zero yaw error, it will result in an offset on the actual yaw error but not the measured one.

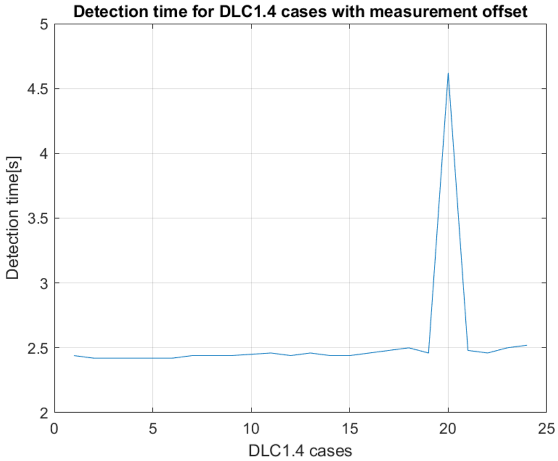

Fig. 7. Detection times for the DLC1.4 cases

5. CONCLUSION

This paper shows a potential of using an up-down counter approach for detecting ECD cases (Coherent gust and directional changes of the wind) for wind turbine controllers mitigate extreme loads potential seen during ECD cases. The proposed approach is validated on yaw error data from a high fidelity aero-elastic wind turbine simulator, simulating a multi-megawatt wind turbine. These valuations show that the scheme can detect the ECD event significantly faster than more simple current used approaches.

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