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Fault Ride-Through for a Smart Rotor DQ-axis Controlled Wind Turbine with a Jammed Trailing Edge Flap

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Abstract

A Smart Rotor wind turbine is able to reduce fatigue loads by deploying active aerodynamic devices along the span of the blades, which can lead to a reduced cost of energy. However, a major drawback is the complexity and potential for unreliability of the system. Faults can cause catastrophic damage and without compensation would require shutdown of the turbine, resulting in lost revenue. This is the first study to look at a fault ride-through solution to avoid shutdown of the turbine and lost revenue during a fault, while keeping additional damage to a minimum.

A worst case scenario of a jammed flap with no direct knowledge of its occurrence is considered, while operating a DQ-axis Smart Rotor wind turbine. A method for detecting the fault using 1P cyclic loadings is presented, as well as two fault ride-through options: setting the remaining active flap angles to zero and setting the remaining flap angles to that of the jammed flap if known. These are analysed using IEC standard load cases.

It is found that rapid detection of faults is vital for Smart Rotor controllers to avoid highly damaging cyclic loads caused by rotor imbalance, but that fault ride-through is fairly simple to implement and this allows the load benefits of the Smart Rotor to be accessible even with long fault periods.

Key words: smart rotor, fault ride-through, trailing edge flaps, DQ-axis control

1 Introduction

The Smart Rotor concept has the ability to reduce loads on traditional horizontal axis wind turbines [1]. This is done through active control of the local aerodynamic characteristics of the blade to the local inflow. These load reductions reduce the material requirements and are particularly effective on turbines with large swept areas, where the wind speed varies substantially across the rotor as a result of wind shear, tower shadow, wakes of upstream turbines and turbulence.

For the Smart Rotor, micro-tabs, jets, vortex generators, plasma fields, active twist, inflatable structures and many other control devices are being considered, along with a variety of sensors and actuators [2]. However, concerns over the implementation of these more novel control devices and the depth of knowledge already associated with trailing edge flaps, have led the two demonstration plants in operation to minimise risk and opt for these traditional control surfaces, which are similar to ailerons on an aircraft wing [3,4]. This option is therefore modelled here as well. Nevertheless, the conditions under which an aircraft and wind turbine operate are quite different. The regular maintenance and no-expense-spared safety requirements of aircraft are quite different to the repetitive continuous operation and cost-effectiveness requirements of devices on wind turbines. Reliability and maintenance are therefore key issues; especially on offshore machines where the Smart Rotor concept may be most beneficial because the high costs of foundations, cabling, maintenance etc. help weigh optimal size analysis towards larger machines.

Fears over the reliability of the devices have not yet been addressed though. Shutdown should the Smart Rotor system fail is undesirable due to lost revenue, and swift corrective maintenance is likely to be costly when considering the conditions offshore. A preferable solution is to continue to operate the wind turbine until maintenance can be conducted, while sustaining power output and not eliminating the benefits of the Smart Rotor through increased loadings. A fault ride through system has been developed that does exactly that.

2 Method

A state-of-the-art controller has been implemented for the variable speed pitch controlled NREL 5MW conceptual wind turbine modelled in Bladed, based upon the UpWind controller in reference [5, 6].

Flaps were then added to the model using aerodynamic data calculated using XFOIL [7]. Each blade was given a flap capable of ±30º deflections at a maximum rate of ±20º/s, spanning 10m, 16.3% of the blade length, on the outboard section, with a 10% chord width. A DQ-axis control system for the Smart Rotor was then developed, similar to that in reference [8] and explained below.

To aid understanding of later results: the rated wind speed of the turbine is approximately 11.5m/s, and the set point for the rotor speed above rated is 1.267rad/s (i.e. the 1P frequency). In simulations the IEC certification standard has been used [9], with 3D turbulent Kaimal spectrum wind fields for a class IIB turbine.

2.1 DQ-axis controller

The DQ-axis control strategy used for the flaps is adopted from studies involving Individual Pitch Control [e.g. 10]. The rotating blade root bending moment of each blade is converted to tilt and yaw moments in a stationary plane using the Coleman transform, Proportional Integral (PI) controllers then act to minimise these tilt and yaw offsets, before the inverse Coleman transform is used to set the demand angle for each flap. A visual representation of this is shown in Figure 1.

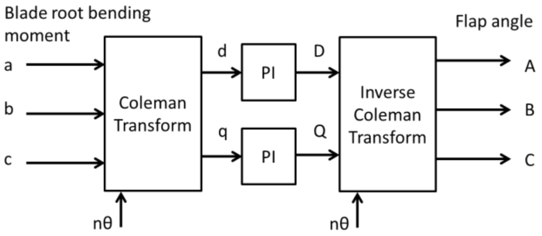

Figure 1: DQ-axis Smart Rotor control

The Coleman transform is:

$$\begin{bmatrix} d \\ q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{4\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

And the inverse transform:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta + \frac{4\pi}{3}) & \sin(\theta + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} D \\ Q \end{bmatrix}$$

The DQ-axis controller targets cyclic loads at the rotational frequency of the turbine, although harmonics may also be targeted by adjusting the rotor azimuth input, θ, to a multiple thereof. For example an input of 2θ would target 2P frequencies, and so on. To simplify analysis, reduce actuator requirements and due to the fact 1P loads cause the most significant amount of damage, only the 1P loads are targeted in this work.

This resulted in lifetime load reductions of 15% in the out-of-plane blade root bending moment, as well as load reductions on the yaw bearing and hub, comparable to those when using individual pitch control [11].

The DQ-axis control is phased out using a gain factor that decreases linearly from 1 at rated power to 0 at 80% rated power. This is so as not to disrupt optimum energy capture, but also because there is less to be gained in this operating region as the loads below rated are low regardless. The ideal trade-off between energy capture and load reduction depends on the economics of the wind turbine design.

2.2 Fault cases

It is judged that two main faults are likely: 1) a broken linkage and, 2) a jammed flap. Under the first condition, assuming the system is damped to avoid blade-flap flutter, aerodynamic pressures on the flap will keep it close to the zero angle position, meaning it may be considered as the special case where the actuator jams at a zero degree angle. Here we consider what occurs when the flap jams at a non-zero angle, as the zero angle case results in a reversion to the baseline control once all flaps are set at zero degrees.

If a flap gets jammed cyclic loadings result due an aerodynamic imbalance, caused by the one blade experiencing different aerodynamic forces than the other two. This can be exacerbated if the controller fails to recognise that a fault has occurred and continues to operate normally. This may be due to a disconnection between the flap and actuator, such that feedback sensor measurements are assumed correct, but the flap is jammed. This can be considered a worst case scenario.

As an example, a +5 degree flap angle is applied to one of the three flaps, while the other two are allowed to operate as normal. To see what affect this has, cumulative spectra are shown in Figure 2 below for the cases where a) the smart rotor system is inactive (CPC), b) the smart rotor system is active and working correctly (SRC), c) the smart rotor is active but a jam has occurred (SRC fault), and d) smart rotor fault ride-through is active with a jam having occurred (SRC corrected).

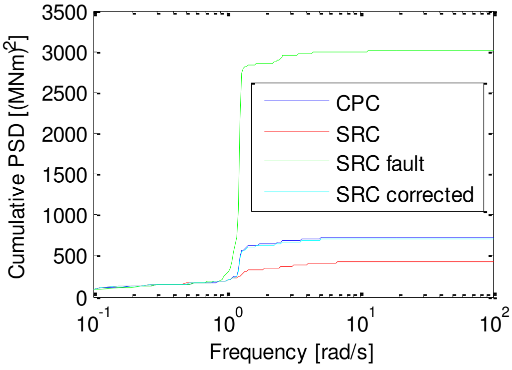

Figure 2: Cumulative Power Spectral Density plots for cases *a* to *d*. SRC corrected is now very similar to CPC

The 1P peak is particularly significant when one flap is jammed while the other two still operate to the DQ-axis regime. This 1P loading is due to the controller continuing to activate the other two flaps causing a significant aerodynamic imbalance. This can drastically reduce the lifetime of the turbine and thus highlights the importance of detection and a fault ride-through requirement.

2.3 Fault detection

Detection of a fault is possible through a number of methods: direct feedback from sensors measuring the angle of the flap, measurement of the hinge moment of the flap, or indirect measurements of the blade root bending moment, tower motion or high speed shaft, as revealed in Figure 3. A rapid automatic response is required not just to reduce loads, but also to identify the fault mode and avoid automatic shutdown due to excessive vibrations.

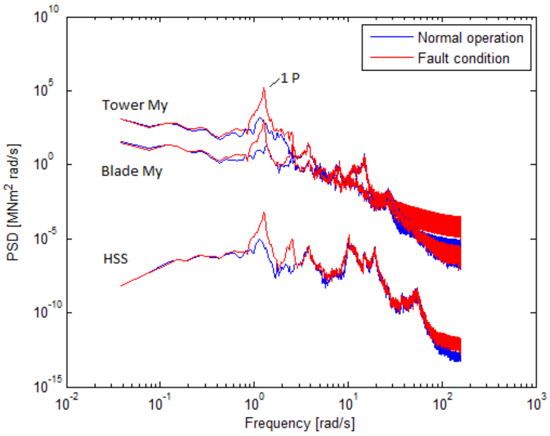

Figure 3: Power spectral density plots highlighting the 1P vibrations

Direct sensor measurement is a trivial case, and results in instantaneous detection with knowledge of which and to what degree the flap is jammed. This enables rapid and accurate adjustment of the remaining flaps to help mitigate the effect of the fault.

Indirect measurements are somewhat more complex to use. The method considered here is monitoring the average power in the signal around 1P with a trigger to activate fault ride-through should it exceed a given threshold. A band-pass filter is used to filter the 1P signal; the power in this signal over a defined window is then calculated. This condition monitoring system is shown in Figure 4, where *N* is the size of the window, *F* is the threshold limit, Z^N is an *N* sample delay, and *u* is simply the input to each block.

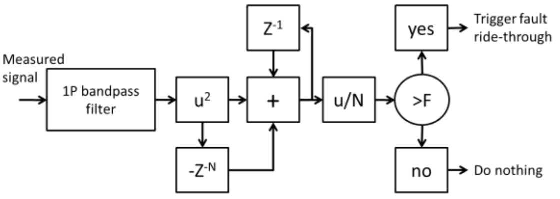

Figure 4: Block diagram of condition monitoring system

The threshold is set so that false positives do not shutdown the system and remove the benefit of the Smart Rotor control, while still being sensitive enough to detect faults. This requires that as the wind speed increases, the threshold also increases, which is handled by making the threshold a function of the collective pitch angle.

An example of this method is use of the tower vibrations. A series of simulations were run to determine that the threshold level is not reached during normal operation, and that when a fault does occur it is detected. The detection time is dependent on the wind speed. At near rated wind speeds the Smart Rotor control phases in and out, and so 1P vibrations are limited, while at high wind speeds the rotor and tower vibrations are naturally higher so that noise complicates the signal. Nevertheless, throughout all simulated wind speeds of 12-24m/s, at 2m/s intervals and six 10 minute runs at each, the fault is detected within 5 minutes.

A dynamic simulation is shown in Figure 5. The mean wind speed is 12m/s and the fault occurs at 50s. It then takes 80s for the threshold level to be reached, triggering the fault ride-through system, which in this case sets the active flap angles to zero. Actual tower vibrations due to the fault are minimal, but it is the focus at 1P that highlights the condition to the controller.

The condition monitoring system is flexible and through adjustment of the gains and threshold limits alternative sensors may be used as required for convenience. In particular measurement of the blade root bending moment, that is required for DQ-axis wind turbines due to its use in the controller, is an obvious choice.

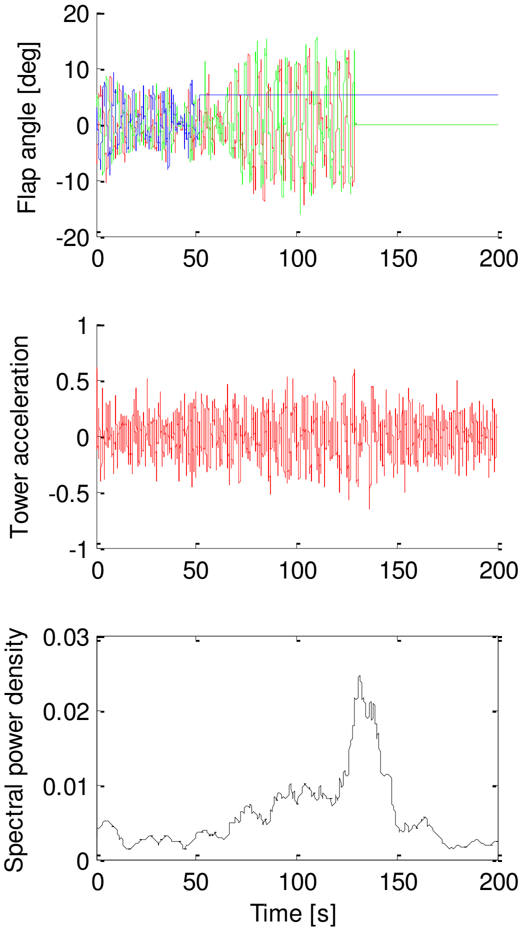

Figure 5 Dynamic simulation of fault ride-through system

2.4 Fault ride-through

The fault ride through system developed removes the cyclic loadings by adjusting the other two flaps to balance the third in a simple and effective way: the operational flaps are set to the angle of the jammed flap. If this is not possible to determine the active flap angles are initially set to zero, it may then be possible to adjust the angles further to minimise the 1P spectrum.

The fault ride-through strategy described does result in a system with increased loads compared to the case where the flaps are working; however, the improvement over the non-adjusted case is considerable. The loads are in effect reduced to those of the collective pitch control case. Energy capture is also maintained, and there is also no requirement to adjust the baseline controller.

3 Results

3.1 Loads

Calculated from IEC standard power production runs for a Class II B wind turbine, 1 Hz damage equivalent loads for the blade with jammed flap are seen to be twice those the turbine would experience under a collective pitch control strategy and 2.8 times what it would experience with correct Smart Rotor control operation under certain wind conditions, as shown in Figure 6. Indeed, if a turbine was to operate under this condition for more than 15 hours per year a collective pitch control would result in lower loads than a Smart Rotor control, Figure 7. Even onshore this time period is short when considering pitch system failures last on average 75 hours [12] and failed offshore turbines are likely to be down for much longer due to weather constraints. This highlights the requirement to recognise when a fault has occurred and act quickly. Without any fault ride-through system, catastrophic failure may result, requiring the turbine to be shutdown which will result in lost revenue.

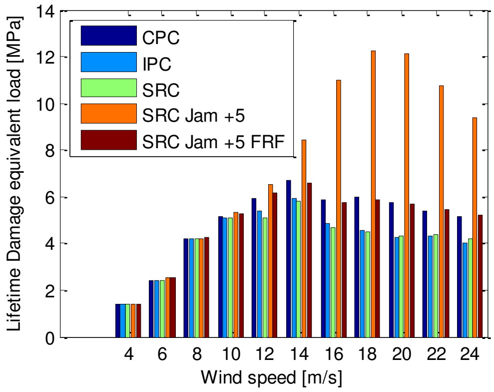

Figure 6 Lifetime damage equivalent loads

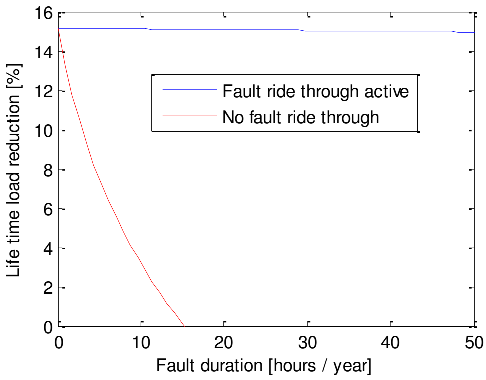

Figure 7 Lifetime load reduction due to a fault without detection and ride-through

3.2 Energy capture

After activation of the fault ride-through strategy, above rated power capture is maintained and the power quality remains unaffected by the fault ride-through system. This is due to the pitch automatically adjusting the collective pitch angle to achieve the correct torque.

Below rated there will be a loss in energy capture which is dependent on the angle of the flaps. This is due to the fact the blades are no longer of optimum design. This loss for the plus 5 degree jammed flap case is less than 0.5%. Despite this loss, this scenario is substantially better than the situation where the turbine is shut down. A larger variation from the conventional blade design characteristics though, caused by a larger jam angle, is likely to be more significant and needs consideration.

3.3 Failure rate

Naturally, the longer the fault duration, with the flaps held in position rather than operating as per the Smart Rotor control strategy, the lower the benefit the Smart Rotor control has for fatigue load reduction. However, a certain load reduction is still sustained even if corrective maintenance is delayed by weeks before the weather conditions are practicable for offshore maintenance. A fault that is present for as much as 20% of the time still allows a load reduction of 10% over the collective pitch control case using this control technique and the fault ride-through strategy described. This is portrayed in Figure 8.

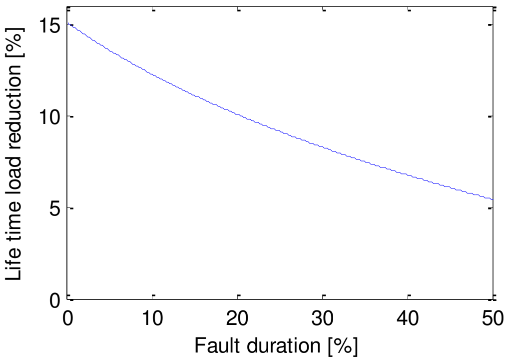

Figure 8 Lifetime load reduction for the blade root out-of-plane bending moment with varying fault durations over the turbine lifetime

4 Conclusion

The Smart Rotor has the ability to reduce loads on wind turbines, which is likely to be particularly important for the next generation of multi-MW offshore machines with large swept areas. However, one of the key concerns associated with the Smart Rotor concept is the reliability and maintenance of the system, which could lead to increased costs or lost revenue. Indeed, it is shown in this work that if a fault occurs and the wind turbine is allowed to continue to operate normally, the load reduction benefits are quickly eroded, ultimately requiring the wind turbine to be shut down. In an offshore environment, where corrective maintenance will take time due to distance, equipment and weather conditions, this is a serious problem, and could result in significant lost revenue. Fortunately, a solution has been found which is both simple and effective.

A fault ride through system has been implemented that responds rapidly to faults and allows operation of the wind turbine to continue with loads that are substantially less than that of the fault case. Operation under a fault condition has been shown to be viable even for extended periods of time, while still allowing load reductions due to the Smart Rotor system to be realisable. This conserves the benefits of the Smart Rotor, while the reliability and maintenance requirements are made not to be too arduous, as load reductions and close to optimum power output may still be achieved even in cases where a flap jams. This research then helps facilitate the deployment of the Smart Rotor on commercial wind turbines by recognising and eliminating one of the barriers.

Reliability and maintenance requirements for the Smart Rotor are much more lenient than one might expect, and the fears that faults could hinder deployment of the Smart Rotor are not wholly substantiated.

References

[1] Andersen, P. B., Henriksen, L., and Gaunaa, M., “Deformable trailing edge flaps for modern megawatt wind turbine controllers using strain gauge sensors”, *Wind Energy*, 193–206, 13 December 2009

[2] Barlas, T. K., and van Kuik, G. a. M., “Review of state of the art in smart rotor control research for wind turbines”, *Progress in Aerospace Sciences*, 46(1), 1–27, January 2010

[3] Berg, J., Resor, B., Paquette, J., and White, J. “SMART Wind Turbine Rotor: Design and Field Test”, Sandia National Laboratories, January 2014

[4] Castaignet, D., Barlas, T., Buhl, T., Poulsen, N. K., Wedel-Heinen, J. J., Olesen, N. A., and Kim, T., “Full-scale test of trailing edge flaps on a Vestas V27 wind turbine: active load reduction and system identification”, *Wind Energy*, published online January 2013

[5] Jonkman, J., Butterfield, S., Musial, W., and Scott, G., “Definition of a 5-MW Reference Wind Turbine for Offshore System Development”, NREL, February 2009

[6] Bossanyi, E., and Witcher, D., “A state-of-the-art controller for the 5MW UPWIND reference wind turbine”, *EWEA*, PO.256, March 2009

[7] Drela, M., and Youngren, H., “XFOIL Version 6.96”, MIT, January 2005

[8] Lackner, M. A., and van Kuik, G. a. M., “A comparison of smart rotor control approaches using trailing edge flaps and individual pitch control”, *Wind Energy*, 13, 117–134, July 2009

[9] International Standard, “IEC 61400-1 Ed.3: Wind turbines - Part 1: Design requirements,” *International Electrotechnical Commission*, 2005

[10] Bossanyi, E., “Individual Blade Pitch Control for Load Reduction”, *Wind Energy*, 6(2), 119–128, June 2003

[11] Bossanyi, E., “Further load reductions with individual pitch control”, *Wind Energy*, 8(4), 481–485, December 2005

[12] Spinato, F., Tavner, P. J., van Bussel, G. J. W., and Koutoulakos, E. “Reliability of wind turbine subassemblies”, *IET Renewable Power Generation*, 3(4), 387, December 2009