An Analysis of Peak Load Shaving Control Methods

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Abstract
The extreme operational loads are simulated and presented for a 13 MW, downwind, 2-bladed rotor. Active control methods for reducing those extreme structural loads are described, with reductions up to 16% in the blade flap-wise root moments. Reductions in extreme blade loads can be used to re-design blades that are lighter and less expensive or longer and capture more power.

Keywords: *Controls, Extreme Loads, Certification*

Introduction

We will present control methods for reducing the extreme structural loads on various wind turbine components. Designing lighter and less expensive blades, which are constrained by maximum load limits, reduces capital costs and ultimately the cost of energy. These load limits are simulated with standard load cases during the certification process and can be used as constraints for the turbine design and system optimization.

Control systems directly impact the structural loading on a wind turbine. Integrating control design with aerodynamic and structural design of a rotor can fully illustrate the benefits of load-reducing control for wind turbines. We will present the interaction between control systems and extreme loads in the design of a 13 MW, downwind, segmented, ultralight, and morphing rotor (SUMR) that cones downwind to alleviate the stiffness constraint on blades required to avoid tower strikes.

Methods

Over several design iterations, SUMR rotors were designed to achieve a specific annual energy production. For each iteration, a baseline control system (similar to [1]) was designed to regulate the rotor speed and maintain reasonable structural load limits. Finally, a structural layup was designed so that maximum load limits do not translate into unacceptable strains or deflections, and to ensure that fatigue resistance is adequate. The rotor was then tested in several Design Load Cases (DLCs), which are specified by the International Electrotechnical Commission [2] and include: extreme and fatigue analysis,

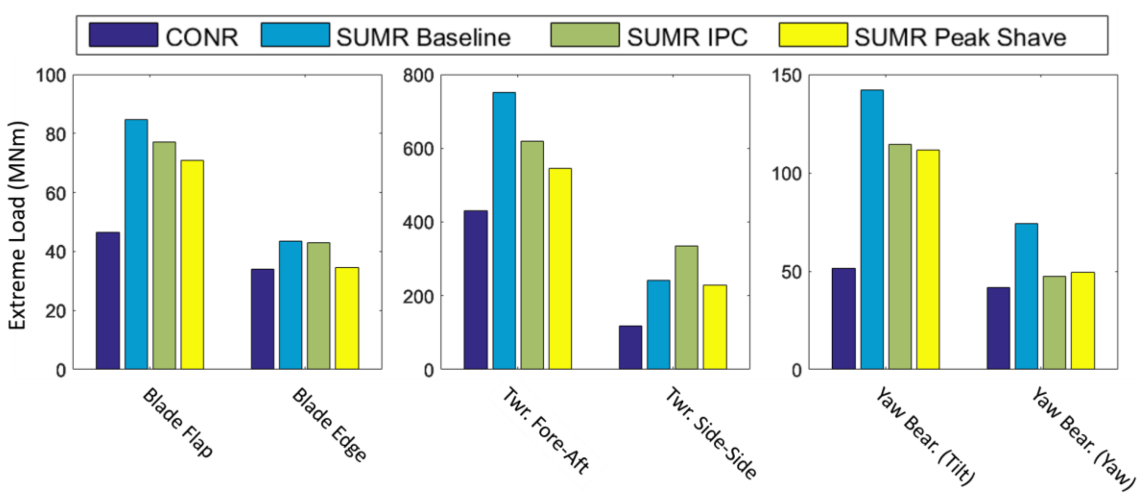

Figure 1. Extreme structural loads simulated for all power producing DLCs (1.1-1.5) for a conventional 13 MW rotor (dark blue), the SUMR with a baseline controller (light blue), the SUMR with individual pitch control (IPC) (green), and the SUMR with IPC *and* peak shaving (yellow).

normal and extreme turbulence, extreme wind direction changes and shear, shutdown, and parked operation. The maximum loads on each component are simulated for each DLC and shown in Figure 1.

The greatest blade loads occur during DLC 1.4 (Figure 2) at below rated wind speeds. Because the baseline controller is designed to regulate rotor speed to its rated value, no blade pitch action is taken before the generator reaches its rated value (13.2 MW). The blade pitch is held at its fine pitch angle θ_{fine} for optimal power capture.

A peak shaving controller is designed by increasing the fine pitch angle according to

$$\theta_{fine} = \begin{cases} \theta_{fine}, \text{ if } M_0 < M_{0,set} \\ k\left(M_0 - M_{0,set}\right), \text{ otherwise} \end{cases} \quad (1)$$

where k is manually tuned and M_0 is the collective blade load, found using the blade transformation

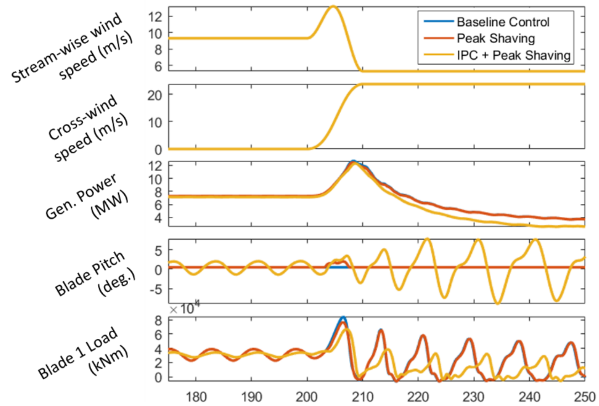

Figure 2. Extreme coherent ion change (DLC 1.4) at 2 m/s below rated; the load case with the greatest blade load. Wind speed, control signals and load simulations are shown for the SUMR rotor with baseline control (blue), peak shaving control only (red), and IPC with peak shaving control (yellow).

$$\begin{bmatrix} M_0 \\ M_1 \end{bmatrix} = \begin{bmatrix} ½ & ½ \\ ½ & -½ \end{bmatrix} \begin{bmatrix} M_{b,1} \\ M_{b,2} \end{bmatrix}. \quad (2)$$

$M_{b,1}$ and $M_{b,2}$ denote the blade root bending moment loads of blade 1 and 2, respectively. Using this method, the pitch angle will increase during high loads, before rated generator speed is reached, resulting in a reduction in maximum blade load (red, Figure 2).

From Figure 2, the maximum blade load (bottom subplot) coincides with the once-per-revolution (1P) loading due to wind shear. Individual pitch control (IPC) can be used to reduce these periodic loads by feeding back the M_1 component of (2) with an inverted notch filter at the 1P frequency and a band pass filter to attenuate unnecessary pitch action [3]. The performance is also critically dependent on the proper tracking of the 1P frequency, so a family of filters is set up in a linear parameter varying (LPV) formulation and scheduled on the generator speed signal. Finally, to avoid amplifying load signals around the 1P, a Glover-McFarlane loop shaping procedure [4] is used. Figure 2 (bottom, yellow) shows the reduction of the periodic loading due to this IPC controller.

Results and Outlook

Focusing on the blade loads across all DLCs, IPC can reduce flap-wise loads by 9% compared with the baseline control. When combined with the peak shaving controller above, the same load can be reduced by 16%. IPC with peak shaving control also reduces the extreme loads on the tower and yaw bearing; the largest loads then occurs during DLC 1.3 (extreme turbulence). Future work will look at more advanced methods for reducing maximum loads near rated wind speed where the blade loads are highest.

A reduction in extreme blade loads would allow the rotor to be redesigned with less mass, for additional cost saving, or with a longer blade, for increased power capture. However, peak shaving control results in a small amount of power loss, which needs to be quantified and compared with the benefits of using peak shaving control.

References

1. J. Jonkman et al., National Renewable Energy Laboratory Technical Report NREL/TP-500-38060, 2009.
2. International Electrotechnical Commission (IEC) 61400-1, 2005.
3. van Solingen and van Wingerden, *Wind Energy*, 2015.
4. McFarlane and Glover, *IEEE Transactions on Automatic Control*, 1992.