Active Aerodynamic Load Control for Improved Wind Turbine Design

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Abstract. Historically, cost reduction in wind energy has been accomplished by increasing hub heights and rotor diameters to capture more energy per turbine. However, larger wind turbines cannot be expected to lead to lower LCOE without the addition of new technologies. Capital costs grow rapidly with rotor diameter, faster than the rated power, because as rotor diameter increases, the blades get heavier and more costly. The growth in blade mass with blade length is accelerated by the additional structure that must be added to withstand unsteady aerodynamic loads caused by turbulence, gusts, wind shear, misaligned yaw, upwind wakes, and the tower shadow. This paper presents a holistic design solution to integrate active load control via dielectric barrier discharge (DBD) plasma actuators into wind turbine rotors along with initial findings on load reduction, actuator development, and rotor mass reduction.

1. Introduction
On-blade, segmented active load control is considered one of the most promising technical areas of focus to disrupt the growth of turbine capital costs. Wind turbines are designed to withstand unsteady aerodynamic loads, making them heavy and expensive. An active load control system could mitigate those loads before they develop, which would allow turbines to be built with less material and at a lower cost. Alternatively, blade lengths can be extended for constant load envelope, leading to increased annual energy production (AEP) and reduced LCOE. Active load control solutions have been extensively researched including trailing edge flaps, microtabs, shape changing blades, and others (Barlas & van Kuik, 2010). However, some of the challenges with these approaches lie in their mechanical complexity, costs, and maintainability in real-world conditions. In this research, we focus on the development of a new load control system based on a DBD plasma actuator (see Fig. 1) that is mechanically simple with no moving parts (Cooney et al., 2016). Further, we investigate through design studies with advanced control system development how this simple and appealing solution could lead to load reduction and lower costs that could usher in the next generation of smart, scalable turbine technology.
2. Research Methodology

We are developing a controllable Gurney flap (GF) for wind turbine blades using DBD plasma actuators with no mechanical components and no moving parts (Fig. 1). To get the most impact, we will use an integrated approach ("co-design") to design the blades, actuators, and control architecture; conceptually this co-design approach is shown in Fig. 2. Within the design approach, we integrate actuator development, control systems and design methods to determine the greatest potential impact of the technology on reducing LCOE through a combination of actuator development, design, control systems, and testing (wind tunnel testing and field demonstration).

2.1 Actuator Development

Like the conventional GF (Wang et al., 2008), we use a fixed protuberance near the trailing edge on the pressure side of the blade (see Fig. 3). However, this controllable (active) GF is rounded on the outer tip, with curvature in the upstream and downstream directions, as shown in the figure. The curvature provides a compliant surface for controlling lift with flow control. Using DBD plasma actuators to control the separation on the protrusion, the sectional lift can be made to vary between a maximum value (when the flow separates at the tip of the GF) and a minimum value (when the flow remains attached). These two states are illustrated in Figs. 4(a) and 4(b) using computational fluid dynamics (CFD) results from a study involving a flat back airfoil section (Williams, 2014). In a similar study with a NACA wing section, Williams demonstrated in both computer simulations and in wind tunnel experiments that a controllable GF could reduce the sectional lift coefficient, $\Delta C_L$, on demand by $\Delta C_L = -0.25$ for a uniform tunnel wind speed of $U_{\infty} = 20 \text{ m/s}$. This is an important result, because changes in lift coefficient of between -0.2 and -0.3 have been shown to reduce peak flapwise blade bending loads by up to 30% (Barlas & van Kuik, 2010, Aubrun et al., 2017, Liu et al., 2018).

DBD plasma actuators consist of an asymmetric arrangement of two planar electrodes separated by a dielectric material, as shown in Fig. 1. When the voltage between the exposed electrode and the surface of the dielectric reaches a threshold value, free electrons collide with air molecules, creating negative oxygen ions. Under the influence of the electric field, the cloud of ions accelerates over the dielectric, colliding with air molecules in the process. The collisions between the ions and the molecules create a plasma sheath that extends over the dielectric material. This sheath acts as a barrier to the flow, affecting the flow dynamics near the surface of the actuator. The net result is a change in the lift coefficient of the blade, which can be controlled by varying the applied voltage and the plasma parameters.
ions and the neutral air molecules result in a force that forms a wall jet—a flow created when air is blown tangentially along the surface (Corke et al., 2010).

DBD plasma actuators are solid-state devices with no moving parts; they are light-weight, with high bandwidth response, and are easily integrated on curved surfaces. The force generated by AC-driven DBD plasma actuators on the adjacent air typically induces a quasi-steady velocity of about 1-4 m/s. In ongoing research, we are implementing and optimizing new innovations aimed at increasing that induced velocity up to 15-20 m/s. These innovations will allow us to control the separation on the plasma Gurney Flap at the high Reynolds numbers associated with the flow over the outer span of utility-size wind turbine blades. The actuator research will be presented at a later date.

2.2 Design Approach and LCOE Targets

The controllable GFs will be positioned between 70% and 90% of the blade span and segmented into multiple actuators that can be controlled individually. As blades get larger, spatial disturbances become smaller than the blade. Modulating lift and drag locally is therefore likely to have the most benefit in mitigating loads for large rotors (Liu et al., 2018).

We are evaluating the benefits of the proposed active load control system through rotor blade design and system-level cost analysis for offshore Class I and land-based Class III turbines to assess the broader anticipated market benefits. Blade designs must adhere to international design standards that define design load cases and factors of safety (IEC, 2005). The types of analyses required include strength analysis, tip-tower clearance, fatigue life, buckling, and rotor aero-elastic stability.

The general design approach in this study begins with a reference turbine design. The first step is to baseline the performance of the reference design. The next step involves integration of the controllable Gurney Flap (GF) into the rotor. Note that the design of the GF and its placement on the pressure side of the airfoil leads to higher $C_l$, but also higher $C_D$. Airfoil analysis provides new polars for the designed-for GF, and with these new polars a new blade aerodynamic design (i.e., chord and twist) is produced. This is an important step to properly model the aero-elastic performance of the rotor for the times when active load control is not active. After the integration of the GF into the analysis, the next step is control system design. Final design steps involve re-design of the blade structure with load reduction and iteration between the structural design and control system design.

This iteration is a key step to maximize the benefit of the controllable GF to reduce LCOE, which is the ultimate goal. Initial work has focused on traditional, sequential design steps. However, couplings in aerodynamics, structural dynamics, and the control system are being examined in the context of the controllable GF integration to develop an improved co-design methodology. This ongoing work will be presented in the future. We note that this design process can be applied to any type of blade-mounted active load control system that modifies the local sectional lift and drag on demand.

Project success in the development of this active load control solution will lead to reduced wind energy LCOE, which in turn will lead to increased wind penetration in the U.S. grid energy market (Fig. 5). In preliminary LCOE calculations, we estimate that the proposed active load control system can reduce LCOE for 4.7 and 20 MW offshore turbines by 13% and 34%, respectively, compared to state-of-the-art turbine technology. Lowering LCOE is critical for increasing wind penetration in the domestic grid energy market (US DOE, 2015).

2.3 Sensors, Control Architecture and Algorithms

A control system (sensors, architecture and algorithms) is necessary to manipulate the DBD plasma actuators in each controllable GF. Uncertainty on exogenous disturbances (e.g., wind fluctuations) dictates the use of feedback control to mitigate loads via appropriate sensing. We shall use load sensors to measure blade moments at the root. We will also consider the use of sensors on the outer blade span (nearly co-located with the GF segments) to create local feedback loops around each GF segment. If properly designed, these local loops are expected to render the segmented GFs easier to control by
a central controller. These local loops may also serve as “tuning knobs” to explore the coupling between “passive load mitigation and GF-based flow control.” Fig. 6 illustrates the sensor type and placement.

**Figure 6** Blade with controllable GF, load sensor at blade root and sensors distributed along the blade span collocated with the segmented GF actuators.

We first consider a centralized control architecture, in which all blade root and outer span sensors communicate with a central processing unit to perform the control computations. This central controller then commands all DBD actuators. We will also evaluate the merits of a hierarchical architecture, with inner loop controllers at the local (sectional) level and a higher-level controller communicating with the local sectional controllers. The inner loop controllers are expected to reduce the propagation of unsteady loads to the blade root and therefore alleviate the requirements of the higher-level central controller. We expect to use analog electronics to close local loops. These inner loop controllers will then receive commands from a central unit based on information from the blade-root load sensors only. Both the specific hardware for inner loop control and the flow of information between inner loops and the central controllers are areas of current investigation.

For the centralized load controller, we use multi-blade coordinate transformations (Bir, 2012) to extract the relevant harmonics of the loads on the blades. As is well known, the MBC transformation can be interpreted as a mapping from a frame of reference rotating with the blades to a frame of reference fixed at the nacelle. Alternatively, the MBC may also be thought of as a spatial time-periodic filter to extract approximations of rotating blade load harmonic components (1P, 2P, 3P, …) and any neighbouring frequency components created by unsteady wind fluctuations due to turbulence for example. The control algorithm will then process the resulting “fixed frame loads” to calculate DBD-plasma actuator commands on a fictitious fixed reference frame, which are then converted to the physical rotating coordinates via an inverse MBC transformation. This formulation of the control algorithm is similar to the one used for individual blade pitch control (Bossanyi, 2002). Section 3.1 in this paper describes preliminary results using this approach. We shall also consider the case where the sensor signals are feedback to the controller with no MBC transformations.

The analysis and design of control solutions is done using a modified version of OpenFAST (NWTC, 2018), which we coined OpenFAST-SLA due to the added capability of commanding the lift coefficient of the airfoil at any section along the span. This modelling approach follows the work in Liu et. al. (2018).

### 2.4 Wind Tunnel Testing

An experimental campaign will be performed at the University of Texas at Dallas to verify the achievable change in local lift coefficient. Once an actuator is demonstrated to provide an induced velocity of 10 m/s or higher, the performance of the plasma actuator will be tested at the recently-commissioned boundary-layer and subsonic wind tunnel (BLAST) at UT Dallas (Fig. 7). A fixed straight wing will be characterized in terms of lift and drag forces with and without plasma actuators installed on the pressure side of the wing. These measurements will allow quantifying the performance of the plasma actuator over the baseline wing for a Reynolds number of about 2 x 10^6. The output of this experimental campaign will be the polar curves of the wing under investigations with and without plasma actuation, which will inform control algorithms and structural design of the blades.

Tests will be carried out in the subsonic (High-Speed) test section of the UTD BLAST wind tunnel. This facility provides a wind speed up to 50 m/s within a volume of 4-m
long, 2.1-m wide and 2.1-m tall. Tests will typically be completed at the maximum wind speed of 50 m/s, comparable to local speeds along the blade at the SWiFT site (Sandia, 2016), but reduced speeds will also be tested to accurately extrapolate the performance up to 100 m/s. A demonstration of this active load control technology is planned on the V27 turbine at the Sandia National Laboratories’ SWiFT facility in early 2021.

The wind tunnel wing model is built with a constant cross-section (NACA 63-218 airfoil), and a modular trailing edge suitable for wind tunnel testing, along with an active Gurney Flap to be mounted with the wing. The airfoils have a chord length of 23.1” and the model has a span of 75”. The section geometry matches the SWiFT V27 blade at the 88% span (the section that experiences the maximum thrust). At the maximum tunnel speed, the experiment will match both geometry and Reynolds number corresponding to that blade section. The wing model consists of four modular pieces to reduce model weight, facilitate the setup and installation of the instrumentation. The model is completely 3D printed in three sections mounted on a steel post and held together with metal endplates. A modular trailing edge and various Gurney Flap geometries will be rapid-prototyped out of nylon (specifically DuraForm PA) which is suitable for functional testing.

Using standard wind tunnel practice, we will measure lift and drag forces with a 6-DOF force sensor (Omega 331 manufactured by ATI). We will measure the forces for varying actuator frequency, sweeping between 100 Hz and 2 kHz. As per standard industry practice, we will compute the 2D lift coefficient as the lift force normalized by the product of the dynamic pressure (one-half times the fluid density times the inflow speed squared) and the chord length. This “2D lift coefficient” (also known as the “sectional lift coefficient”) is the non-dimensional lift per unit spanwise length of the wing. We will use the measured change in the 2D lift coefficient over a range of tunnel speeds to develop a curve of change in lift as a function of Reynolds number. We will use that performance curve as a semi-empirical tool to predict the change-in-lift at the higher Reynolds numbers associated with the field test and larger, utility-scale wind turbines.

We will investigate aerodynamic effects generated by the plasma actuator along the wingspan through pressure-tap measurements. An ESP pressure scanner with 128 channels will be used to characterize spanwise and chordwise pressure variability induced by the plasma actuator under different wind conditions.

The wing with the plasma actuator will then be tested under 3D complex wind scenarios to mimic conditions that blade airfoils and plasma actuators can experience during real operations of wind turbines. Force and pressure-tap measurements will be performed with the wing setup mounted at different, non-zero tilt and yaw angles to reproduce the presence of radial and tangential velocities as well. These measurements will allow estimating the performance of the plasma actuator under more realistic wind conditions. Fig. 8 shows details of the wing construction and the wind tunnel mounting structure.

Once complete, final wind tunnel testing will focus on dynamic tests of the steady wing with plasma actuator and by operating the latter in cycles with different frequencies and current intensity. The aim of this test is to investigate possible hysteresis in the performance of the plasma actuator. We will investigate how potential delays in the performance of the plasma actuator need to be handled by the control algorithm to avoid detrimental effects on the aerodynamic performance of the blade.

Figure 8 CAD models showing the wind tunnel setup with connection to the force balance (left) and the airfoil components including endplates, posts, sample profile sections, and mounting plate (right).
3. Results

3.1 Active Load Control

This section describes preliminary active load control results for a 3.4 MW wind turbine, based on the IEA 3.4MW reference turbine (Bortolotti, 2019), developed in this project. This turbine is equipped with controllable GFs and the turbine specs are given in Table 1.

| Properties for the 3.4MW Turbine (Bortolotti, 2019) |
|-----------------------------------------------------|
| Class and Category | IEC Class 3A |
| Rotor Orientation   | Upwind       |
| Number of Blades    | 3            |
| Control             | Variable speed collective pitch |
| Drivetrain          | Single Stage |
| Rated Aerodynamic Power | 3.6 [MW]  |
| Rated Rotor Angular Speed | 11.6 [RPM] |
| Rotor Diameter      | 130.00 [m]   |
| Max Tip Speed       | 80 [m/s]     |
| Wind Speed Rated    | 9.800 [m/s]  |

Fig. 9 shows the location and size of the controllable GF. Only one controllable GF is used per blade, which is placed in the outer blade section covering about 23% of the span. Each controllable GF is sent a sectional lift change command $\Delta C_L$ between $-0.2$ and $0.2$.

A block diagram depicting the major components of the feedback control system is shown in Fig. 10. Both forward and inverse MBC transformations to map signals from/to the rotating frame of reference are shown in the figure. The MBC transformations require the instantaneous value of the azimuth angle. The formulas for the MBC transformation are well known (Bir, 2012) and omitted for brevity in the exposition. The feedback controller has two components: a linear controller $K$ to provide robust stability and a nonlinear block with integral control to provide disturbance rejection at DC (1P in the rotating frame) up to a user-selected bandwidth. The MIMO I-controller incorporates saturation management to ensure that all sectional lift commands are within limits ($\pm 0.2$) and add up to zero instantaneously to avoid abrupt changes in the collective lift force at the rotor.

To develop a simple baseline load controller, the control system in Fig. 10 is designed to have a closed loop bandwidth (in the fixed frame of reference) of 0.8P approximately. With this specification, one can expect to decrease blade loads in the frequency range 0.2P to 1.8P approximately. The baseline controller is calculated using a design model obtained from our OpenFAST-SLA simulator and a standard method for system identification. The design model is obtained with a uniform steady wind input at 18 m/s (above-rated wind speed). The controller is evaluated at off-design wind speeds with vertical wind shear and turbulence.

First, we provide time series and frequency response for the case of $18 \text{ m/s}$ with wind shear exponent $\alpha = 0.2$. Then we evaluate the design using damage equivalent loads for three mean wind speeds, wind shear and turbulence.

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1. 1P is the rotor frequency at rated rotor angular speed, 1.22 rad/sec for the 3.4 MW model turbine.
Fig. 11(a) shows the time series of the sectional lift commands for the case of steady wind with vertical shear. The controller is activated at 400 sec. The controller commands three sectional lift signals within the allowable range ($\pm 0.2$). The three commands are identical, but separated in time by 1/3rd of the rotor period (~1.7 sec). Fig. 11(b) shows the time series of the flapwise bending moment at the blade root. These moments have a fundamental period of 1P and are identical except for the 1.7 sec time shift. This is due to the fact that the flow over the rotor, while not uniform, is steady. The sharper peaks on the lower portion of the cycle are due to the interaction between the blades and the tower. Once turned on (at 400 sec.) the controller reduces loads within a few seconds. Finally, Fig. 12 shows the amplitude spectrum of the flapwise blade-root moment for one of the time series in Fig. 11(b). Both the case with no control (blue line) and with control (red line) are shown. A 43% reduction of the 1P component is observed; the controller does not affect the higher harmonics (2P, 3P, …).

To demonstrate controller performance in the presence of shear and turbulence we calculate damage equivalent loads (DELs), averaged over multiple realizations of the stochastic wind input, for three different mean wind speeds but the same vertical shear exponent ($\alpha = 0.2$) and turbulence intensity (15%). The reduction in the averaged DELs is shown in Fig. 13. The bar graph also shows the reduction of the 1P load component (no turbulence) for comparison. As expected, DEL reductions are not as large as the reduction of 1P loads. The reduction in DEL is about 8% to 10% for all three cases. We expect to achieve larger DEL reductions with alternative configurations of the plasma actuator and control architectures.

**Figure 10** MBC-based control system to command the blade sectional lift coefficients $\Delta C_{L,1}$, $\Delta C_{L,2}$, $\Delta C_{L,3}$.

**Figure 11(a)** Time series of sectional lift commands generated by the controller in Fig. 10. Mean wind speed 18 m/s at rotor hub with 0.2 vertical shear exponent.

**Figure 11(b)** Time series of flapwise blade root bending moment resulting from the sectional lift commands in Fig. 11(a).
3.2 Rotor Re-design with Active Load Control

Initial rotor re-design with active load control has focused on the evaluation of improved design for the 3.4MWe baseline wind turbine. The general rotor design approach was summarized in Section 2.2 where the first step involved computing new polars for the outboard airfoils with GF. Figs. 14(a) and 14(b) compare the chord and twist of the baseline and new design with GFs in the outboard section. This re-design with higher $C_{l}$ outboard airfoils results in a smaller outboard chord and small change in twist.

The new aerodynamic design has similar but slightly higher $C_{p,\text{max}}$ (0.489 vs. 0.483). A baseline conventional turbine controller was developed and tuned prior to developing the active load controller, as described in Section 3.1. The active load controller (SLA controller) described in Figs. 11(a) and 11(b) was used to simulate fatigue loading for wind speeds from cut-in to cut-out based on the normal turbulence model (NTM) according to DLC 1.2 (IEC, 2005). Cycle counts of root-bending moments were performed to compute damage equivalent loads (DELs) for the cases of without and with SLA control. This initial re-design effort, which involved structural re-design of the composite layup along the blade span, resulted in 6% mass reduction based on fatigue load reduction with the initial Region 3 based SLA controller. The technical details behind these results, including a comprehensive LCOE analysis, will be communicated though as series of papers that are currently under preparation (Gupta et al., 2020; Chetan, et al., 2020).

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**Figure 12** Amplitude spectrum of the time series in Fig. 11(b). The controller (red line) reduces the 1P amplitude by 43% and does not affect higher harmonics.

**Figure 13** Reduction in 1P loads with no turbulence (blue) and reduction in average damage equivalent loads with 15% turbulence intensity (red) for wind speeds of 12, 18, and 22 m/s.
4. Conclusions

On-blade, segmented active load control is one of the most promising technologies to disrupt the growth of turbine capital costs as rotors grow in size. This paper presents a holistic design solution to integrate active load control via DBD plasma actuators into wind turbine rotors. Initial results for actuator development, system integration and design approach are presented along with initial implementations for control systems and rotor re-design. Actuator development has focused on a controllable Gurney Flap (GF) producing an envisioned sectional lift change command $\Delta C_L$ between 0.2 and 0.2. A system integration and design approach is presented to incorporate the GF into the aerodynamic design. A comprehensive feedback control system (sensors, architecture and algorithms) is developed and presented that, in initial results, shows 43% reduction in the 1P (1 per/rev) root bending moment and 3-11% damage equivalent load (DEL) reduction in Region 3. Based on this load reduction, rotor structural re-design was performed. Initial numerical results show that based on this DEL reduction with active load control only in Region 3, 6% blade mass reduction for the same fatigue life is achieved.

Future work includes further refinements to the control system to improve load reduction via DBD plasma actuators. Also, new design strategies focused on increasing the rotor radius for increased energy capture are envisioned. Future work also includes wind tunnel and field experimental campaigns aimed at further characterizing and developing this technology.

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