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Individual Pitch Control for Wind Turbine Load Reduction Including Wake Interaction

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Abstract—**Individual pitch control (IPC) for wind turbine load reduction in Region 3 operation is improved when wake interaction is considered. The Larsen wake model is applied for composing the rotor wind profile for downstream turbines under wake interaction. The wind profile of the turbine wake was generated by modifying the NREL's TurbSim codes. The state-space models of wind turbine were obtained via linearization of wind turbine model available in the NREL's FAST. In particular, in order to obtain more accurate state-space models, equivalent circular wind profile was generated so as to better determine the local pitch reference. Based on such models, IPC controllers were designed following the disturbance accommodating control (DAC) and periodic control framework. The simulation results showed that the turbine loads can be further reduced using the switching control scheme based on wake modeling, as compared with the generic DAC without wake consideration.**

Index Terms: *Wind Turbine, Individual Pitch Control, Wake Interaction, Disturbance Accommodating Control, Linear Quadratic Control*

I. INTRODUCTION

Wind energy is well received as the most critical renewable energy source for the decades to come. A major barrier for further development of wind energy is the relatively higher cost of energy (COE) compared to conventional energy sources. Advanced control technologies have been studied extensively for energy capture [1-2] in Region 2 and load reduction [3-16] for Region 3 operations in order to reduce COE.

This study is concerned about individual pitch control for load reduction in Region 3 operation. A major drawback of collective pitch control (CPC) is the inability of dealing with asymmetric load for wind turbines [6]. Various IPC schemes have been developed to deal with the asymmetric loads of turbine structures. Different sensing schemes have been investigated, such as strain gage at blade root [6], local blade inflow [7-8] and LIDAR [9].

Different control design methods have been applied to the IPC development. The IPC design is in principle a multi-input-multi-output control design problem. Conventionally, the IPC is designed with multi-loop decentralized PI control laws [6] but the loop coupling is a significant issue. To solve this problem, the optimal and robust control methods have been widely applied to the IPC design, such as H∞ controls [10] and the Linear Quadratic Gaussian (LQG) [11]. It is noteworthy that a particular stream of work on wind turbine control has been developed following Balas' [12] Disturbance Accommodating Control (DAC) scheme. Following this framework, several IPC schemes have been studied, e.g. by Hand [13], Stol [14] and Wright et al. [15-16].

So far, to the best knowledge of the authors, the work reported on IPC design has included only the model of vertical wind shear regarding to wind asymmetry. For wind farm operation, the wind turbine wake interaction is also significant [17]. It is potentially beneficial for further reduction of dynamic load by including wind turbine wake interaction. Numerous work on wind turbine wake modeling has been reported in the literature [18-24, 26-30]. In the current stage of study, the Larsen wake model [24] is adopted to predict the wind profile across the rotor of the downstream wind turbine. According to the composite wind profile within the rotor disc, LQ control design is performed for segments along azimuth. In order to obtain more accurate model for IPC design, an artificial wind pattern, named as equivalent circular wind profile, is generated. As benchmark, the DAC control scheme is also implemented based on the vertical wind shear only.

The remainder of this paper is organized as follows. Section 2 presents the wake model and the wind profile that accounts for wake interactions. Based on Larsen wake model, controller switching strategy is explained in the Section 3 and Section 4 presents how to obtain more accurate linearized state-space models by use of equivalent circular wind profile and different pitch reference in terms of the azimuth angle. The DAC and periodic control design is described in Section 5. The simulation study is presented in Section 6. The work is concluded and discussed in Section 7.

II. WAKE MODEL AND WIND PROFILE

Wake models are used to predict wind profile after operating wind turbines in wind energy sector. There are three different kinds of wake models including numerical models, kinematic models and field models. Numerical wake models wind turbines are described as distributed roughness elements [18-19]. Kinematic wake models are based on self-similar velocity deficit profiles obtained from experimental and theoretical work on co-flowing jets. The original work of kinematic models was developed by

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Lissaman [20]. Jensen [21] and Katic et al [22] simplied the problem further and assumed a top-hat profile everywhere. Frandsen [23] presented a nonlinear wake expansion. Larsen wake model [24] is developed based on classical wake theory [25]. Field models [26-27] calculate the flow everywhere in the wake through solving a simplied version of the Reynolds averaged Navier-Stokes flow equations.

Because the complexity of kinematic wake models mainly including Jensen and Larsen wake model are appropriate for wind turbine control and turbulence intensity factor is not considered in Jensen wake model, Larsen wake model is chosen in this paper.

A. Larsen Wake Model

$$\Delta V = V_2 - V_1 = -\frac{V_1}{9}\left(C_t A\left(x_{21}+x_0\right)^{-2}\right)^{\frac{1}{3}}\left[r^{\frac{3}{2}}\left(3c_1^2\right)C_t A\left(x_{21}+x_0\right)^{-\frac{1}{2}} - \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}\left(3c_1^2\right)^{-\frac{1}{5}}\right]^2 \quad (1)$$

$$D_2\left(x_{21}\right) = 2\left(\frac{35}{2\pi}\right)^{\frac{1}{5}}\left(3c_1^2\right)^{\frac{1}{5}}\left(C_t A\left(x_{21}+x_0\right)\right)^{\frac{1}{3}} \quad (2)$$

where D_1 is the rotor diameter, V_1 is the incoming wind speed, A Rotor Disc Area, D_2 is the wake diameter, V_2 is the mean wind speed in the wake at the distance x_{21} from rotor plane in downstream direction, and r is the radial distance from the wake centerline, as showed in Fig.1. The expression of parameters c_1 and x_0 and the second-order solution can be given in [28] and [29] and summarized in [30].

B. Cross Wind Profile across the Rotor Plane

The wake interaction induced velocity superposition is illustrated in Figure 2. The small disk refers to the downstream turbine, while the large disk refers to the wake of the upstream turbine grown at the downwind rotor disk.

The rotor disk at downstream wind turbine includes incoming wind region and wake region, showed in Figure 3. Wind profile in incoming wind region can be generated according to wind shear characteristic. Wind profile in wake region can be obtained by use of Larsen wake model but axisymmetric characteristics of Larsen wake model does not agree with the realistic case in wind farm. Wake studies [31,26,32] showed that the velocity deficit profile for axisymmetric wakes can be described by a Gaussian-type function. Based on the characteristic of Gaussian velocity deficit distribution, van Leuven [33] provided the following corrected two-dimensional Gaussian function for wind deficit across cross section of the wake

$$\Delta V(y,z) = \Delta V_{hub} e^{-[\frac{y}{R_y}]^2} e^{-[\frac{z-H}{R_z}]^2} \frac{\ln(z/z_0)}{\ln(H/z_0)} \quad (3)$$

where ΔV_{hub} is the velocity deficit at hub height, R_y and R_z are the wake radius in y direction and z direction. The wake shape was assumed as an ellipse in [33]. In this paper, we assume that the wake shape is a circle by use of Jensen and Larsen wake model.

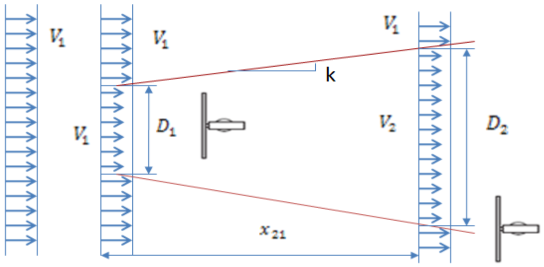

Fig. 1. Relative Position of Turbines

Finally the wind profile at downstream wind turbines is

$$V(y,z) = \left(V_1 - (V_2 - V_1)e^{-[\frac{y}{R}]^2} e^{-[\frac{z-H}{R}]^2}\right)\frac{\ln(z/z_0)}{\ln(H/z_0)} \quad (4)$$

In summary Larsen wake model can be used to calculate the wake radius and velocity deficit at the hub-height of downstream wind turbines. Then Eqn. (4) is used to calculate the wind profile in the cross section of the wake.

III. CONTROLLER SWITCHING STRATEGY

The general situation of wake interaction is plotted in Figure 2. Due to wake interaction, the wind shear characteristic is not kept anymore. In this situation, the DAC scheme suggested by Wright [15, 16] cannot be applied because this scheme is derived based on wind shear characteristics. Hence, we have resorted to the periodic control by Stol [14], where the rotor disc is divided into a number of circular sectors in terms of the azimuth angle, and LQ controller is designed for every sector, similar to the illustration in Figure 3. The overall control is realized by switching between these segmental controllers. Instead of the scheme of equal-azimuth segmentation of 24 sectors in [14], in this study, we have considered the change in the $\mathcal{H}_\infty$ norm of the wind turbine models between individual sectors and then reduce the number of sectors for controller design.

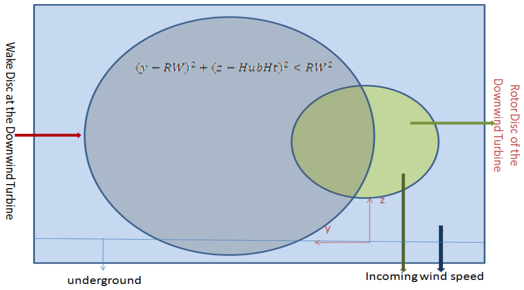

Fig. 2. Wake Interaction at the Downstream Turbine

IV. DETERMINATION OF LOCAL PITCH REFERENCE ALONG AZIMUTH

Due to the asymmetry nature of the wind across the rotor disc, the reference for the blade pitch angle varies with the azimuth angle. If the linearized state-space models along the azimuth are obtained by use of “FAST linearization” module, the blade pitch angle is kept the same for different azimuth angles. Such approximation would bring forth more inaccuracy when wake induced asymmetry is included. In order to obtain more accurate linearized state-space models of wind turbine along the azimuth, it is preferred to obtain the pitch reference for different azimuth angles for any specific wind profile.

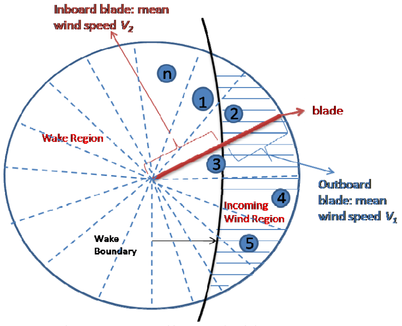

Fig. 3. Controller Switching Strategy

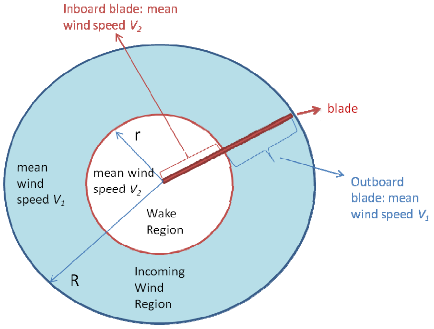

Fig. 4. Circular Wind Profile

Usually the combination of pitch angle, rotor speed and wind speed can be defined as an operating point. The detailed linearization theory and procedure for wind turbine are well described by Wright [15]. Typically, there are two approaches to obtaining linearized state-space models of wind turbine by use of "FAST linearization" module. One method is that a steady-state solution is computed to obtain the linearized state-space models and the other is that an unsteady solution is computed by use of the initial condition. For the former method, the pitch angle and the rotor speed converge to the operating point when the wind profile is provided. In order to obtain such steady-state solution, the pitch reference can be obtained for a specific azimuth angle with the help from a so-called *equivalent circular wind profile* (ECWP). For a specific radial profile of wind speed along the blade length at certain azimuth angle, an ECWP can be created by duplicating this profile for all different azimuth angles, as shown in Figure 4. Such a wind profile does not exist in reality, but is generated for obtaining steady-state solution which can help derive the local pitch reference.

When all pitch references are obtained along azimuth by use of ECWP, the corresponding linearized state-space model along azimuth can be obtained by use of unsteady state solution and original wind profile. In this situation initial pitch angle of different blades should be set as the corresponding pitch reference at the corresponding azimuth angle, the initial rotor speed should be set as rated rotor speed in Region 3 and the running time should be less than one period in order to make sure that rotor speed does not change very much.

V. DISTURBANCE ACCOMMODATING CONTROL AND PERIODIC CONTROL

The DAC control design procedure [12] is briefly presented in this section. More details are available in Wright [15]. The DAC provides an elegant solution to analytically incorporating the vertical shear into an LTI system framework. However, the disturbance generator is based on a simplification of the vertical shear, and such simplification may limit its application to actual wind turbine operation. Stol [14] adopted the periodic control strategy and divided the rotor disc into 24 segments along azimuth which means each segment includes 15°. Recently, the LQR and periodic control schemes were used for individual pith control of offshore wind turbine without disturbance terms in the state-space model [34]. In this study, the LQR and periodic control methods are used for the segmented plant models.

VI. SIMULATION STUDY

A. Simulation Platform

To evaluate the effectiveness of the proposed IPC scheme, simulation study has been conducted with the CART wind turbine model using the FAST [35], Aerodyn [36] and TurbSim [37] software packages developed by the National Renewable Energy Laboratory (NREL) and Matlab® Simulink. Control simulation with FAST has been facilitated by the Simulink interface. In this study, TurbSim is modified to generate the wind profile including wake interaction. CART [38] turbine model is used, which is a two-blade 600 kW variable-speed-variable-pitch turbine.

B. Wind Profile with Wind Shear and Wake Effect

In the simulation example Larsen wake model was used. The location of upstream and downstream turbines is the same with Fig. 1. Both turbines are assumed identical to the CART. The incoming wind speed V_1 is assumed to be 18m/s, the ambient turbulence intensity is 18%, the diameter of the upwind turbine D_1 is 46m. This study adopts 8 for x_{21}/D_1 and 0.7 for C_t. Based on the Larsen wake model, the diameter of the wake at the downwind turbine grows to 204.22 m, and the mean wind speed across the wake plane becomes 16.76 m/s.

The wind profile was generated through TurbSim by modifying the relevant program codes to incorporate the wake related wind velocity superposition. The TurbSim codes have been modified accordingly to generate the wind profile including wake effect. Figure 5 shows the profile reflecting the wind velocity overlap based on Larsen wake model.

C. Equivalent Circular Wind Profile and Different Pitch Reference along Azimuth

Recall in Section 4, the ECWP refers to the scenario that the wind speed along the azimuth direction is the same but is different along the radial direction (i.e. along the blade length). The ECWP is obtained through modifying TurbSim with the following procedure. The wind information is first extracted at some azimuth and then copied to all azimuths. For example, if we want to generate an equivalent circular wind profile at 45° azimuth as shown in Figure 5, we need to copy the wind distribution at 45° azimuth to all azimuths, as shown in Figure 6. For different azimuth angles, the corresponding ECWP needs to be generated respectively to obtain the corresponding pitch reference. All the pitch references obtained along azimuth for the special wind profile in Figure 5 are plotted in Figure 7.

D. Model Linearization for IPC

The 9-state space models were obtained by use of "FAST linearization" module, with the descriptions of the states listed in Table I. Three measurement outputs were used for state estimation: the generator speed, the tip deflection of the first asymmetric flap mode, i.e. (Δx_1-Δx_2)/2, and the fore-aft moment on the tower base. The disturbance inputs include wind shear and hub-height wind disturbances. When the periodic control and LQR methods were used, our treatment does not include disturbance input.

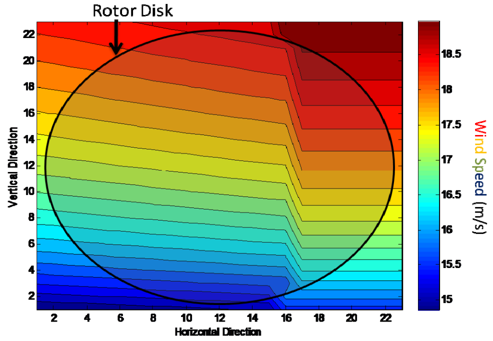

Fig. 5. Wind Profile Including Wind Shear and Wake Interaction

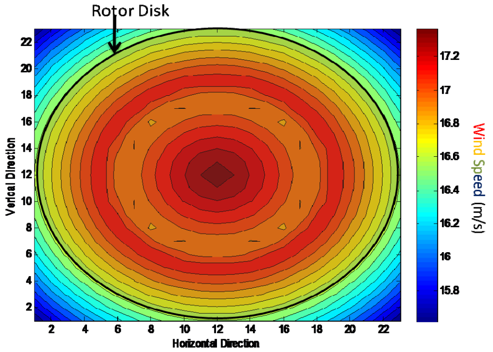

Fig. 6. Equivalent Circular Wind Profile

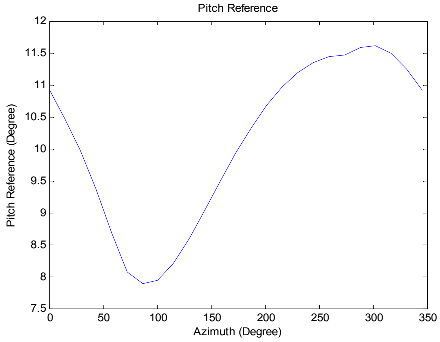

Fig. 7. Pitch Reference Along Azimuth

E. Rotor Disc Segmentation

Initially the rotor disc is divided into 24 sectors (similar to Stol [14]), each covering 15° azimuth angle. Accordingly, 24 state-space models are obtained along the azimuth angle. As the variation of wind turbine dynamics is considered non-uniform in azimuth angle, such simple segmentation may be too conservative for some sectors. Therefore, we use the variation of the $\mathcal{H}_\infty$ norm of the plants between neighbored sectors to justify the segmentation scheme. Instead of considering the infinity bandwidth, the difference of maximum singular value ranging from DC to 100 rad/second between state-space models of neighboring sectors along azimuth is plotted. The 100 rad/second is considered the Nyquist frequency for a computer controlled system implemented for this IPC.

TABLE I
STATE DESCRIPTION FOR A 9-STATE WIND TURBINE MODEL

Symbol	States
Δx_1	1st tower fore-aft bending mode
Δx_2	Drive train rotational-flexibility
Δx_3	Perturbed first flap deflection of blade 1
Δx_4	Perturbed first flap deflection of blade 2
Δx_5	Derivative of state 1
Δx_6	Perturbed Rotor rotational speed
Δx_7	Derivative of state 2
Δx_8	Perturbed first flap velocity of blade 1
Δx_9	Perturbed first flap velocity of blade 2

Segmentation along azimuth is based on the following two rules. 1) When the difference in the maximum singular value for neighboring state-space models is below 4 dB, it is merged into the neighboring segment. 2)The difference in the maximum singular value between neighboring state-space models should not be larger than 6 dB.

Notice that these two rules can be adjusted by controller designer, based on different robustness need. In other words, if lower robustness is required, the norm difference can be increased. Based on these rules, the number of the controllers is reduced from 24 to 16. The sectors centered at azimuth angle 45°, 75°, 105°, 135°, 225°, 255°, 285° and 315° were merged to their respective neighbor sectors, as shown in Figure 8.

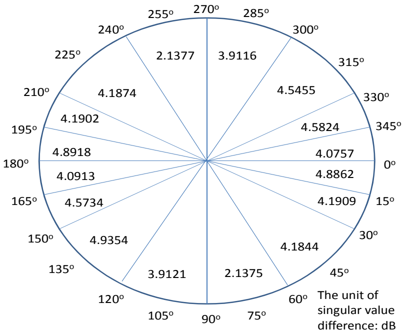

Fig. 8. Sixteen Segments of Rotor

F. *Comparison of Switching Controller and Non-switching Controller*

The wake induced wind profile in Figure 5 is then used to test the switching control schemes. DAC based controller was designed based on the averaged state-space model obtained under hub-height wind speed 16.8 m/s including wind shear. Sixteen switching controllers are designed to reduce the load based on state-space models with different pitch reference along azimuth. Figure 9(a) shows the temporal profile of the tower-base fore-aft moment using the switching controller designed based upon the wake model and the standard DAC control with only the wind shear considered. The corresponding spectra in Figure 9(b) shows that the primary mode at 1 Hz is significantly suppressed, while some higher harmonics are slightly increased.

VII. CONCLUSION

This paper presents an improvement on the IPC scheme for load reduction by including the wake interaction. The Larsen wake model is applied for composing the rotor wind profile for downstream turbines under wake interaction, and a switched control strategy is thus developed based on the composite wind profile. The wind profile was generated by modifying the TurbSim codes. The special equivalent circular wind profile was proposed to obtain different pitch references along azimuth. When different pitch references along azimuth are used, more accurate state-space models of wind turbine can thus be generated via FAST linearization. Based on such models, the IPC are designed following both the DAC and the periodic control frameworks. Simulation results showed that the tower-base fore-aft bending moment is significantly suppressed. Further work is under way to apply more realistic wake model and reduce the loads at higher frequency.

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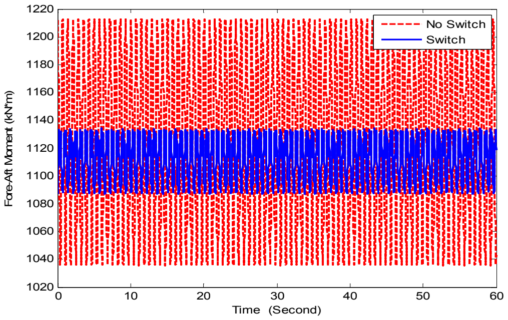
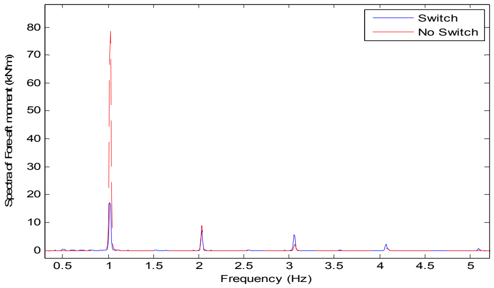


a) Steady-state Temporal Profile



b) Spectra

Fig. 9. Tower-Base Fore-Aft Bending Moment Using Proposed Method (Switch) and DAC (No Switch)

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