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A Study on the Active Induction Control of Upstream Wind Turbines for total power increases

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Abstract. In this study, the effect of active induction control of upstream wind turbines is investigated. Two scaled wind turbines having a rotor diameter of 1 m with a spacing of four times of the rotor diameter were used to experimentally validate the concept. Also, an in-house c code was used to simulate the same two wind turbines and see if the experimental observations can be obtained. From the experiment, approximately 0.81% increase of total power could be observed. Although the simulation results were not exactly the same as the experimental results but the shape was similar and the maximum power increase of 0.27% was predicted. Also from further simulation using NREL 5MW wind turbines instead of scaled wind turbines with realistic ambient turbulence intensity, it was found that the power increase could become more than 1%.

1. Introduction
The concept on active induction control of upstream wind turbines to increase the total power output from a wind farm is not new and several research articles have been published. Earlier ones were focused on physical explanation based on simulations using simple models and later, articles including experiments using scaled models and even multi-megawatt wind turbines were followed [1-4]. However, the scaled models used were much different from the actual multi-megawatt wind turbines in that no active pitch control was implemented, and also the measurements using multi-megawatt wind turbines were performed but still not complete to fully understand the effect [2]. In this study, the concept of wind farm control by active induction control of upstream wind turbines was reinvestigated. Both computational simulations and experimental study were performed using scaled models to better understand the effect.

2. Experimental Setup
Scaled wind turbines that resemble multi-megawatt wind turbines were used for experimental validation. Those wind turbines have a rotor diameter of 1 m and have pitch actuators for collective pitch control. Because the Reynolds number ranges of the flow passing through the blade of the scaled modes are much lower than those of multi-megawatt wind turbine blades, a low Reynolds number airfoil, RG 14, were used. Figure 1 shows the comparison of the lift coefficients, the lift to drag ratios and the power and the thrust coefficients with respect to the angle of attack or the tip speed ratio for two different airfoils obtained from simulation codes. One is DU40_A17 which is an airfoil used for the blade of NREL 5MW research wind turbine and the other is RG 14. As shown in the figures, the lift coefficient, lift to drag ratio, and the power coefficient of RG14 are lower than that of DU40_A17. However, the tip speed ratios of the two airfoils to achieve the maximum power coefficients are very close. The maximum power coefficient of the scaled wind turbines reached approximately 0.4. For the thrust coefficient, the values for the two wind turbine rotors were close.
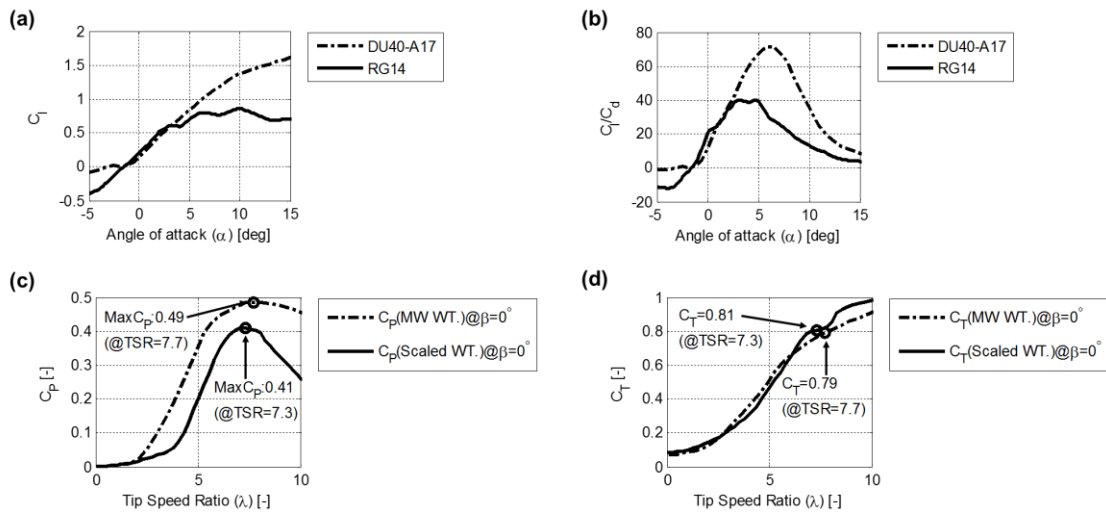
Fig.1 Aerodynamic coefficients of Scaled and NREL research wind turbines (a) Lift coefficient vs. angle of attack(Re_RG14:8.5×10^4, Re_DU40-A17:5.87×10^6), (b) Lift to drag ratio vs. Angle of attack, (c) Power coefficient vs. Tip speed ratio, (d) Thrust coefficient vs.Tip speed ratio.

The scaled models used in the wind tunnel for experimental study are variable-speed variable-pitch wind turbines and their rated power is 46W at 6.0 m/s. They are controlled by individual programmable logic controllers with algorithms in c-code including maximum power coefficient tracking below the rated wind speed and the collective pitch control above the rated wind speed. The controller also has an algorithm for a demand tracking so that if it receives a power command from a higher level wind farm controller, and if the available power is greater than the power command, it lowers the generator torque and adjusts the pitch angle to track the power command. In this study, a personal computer was used as a higher level wind farm controller, and the power commands determined by the operator were sent out to the individual controllers of the scaled wind turbines.

To experimentally simulate the active induction control of upstream wind turbines, two scaled wind turbines installed in a boundary layer wind tunnel were used as shown in Fig. 2. The spacing of the two wind turbines was four times of the rotor diameter that is approximately 4 m. For a given wind speed which is slightly less than the rated wind speed, the power of the upstream wind turbine was regulated from its normal operating condition (100%) to 80% of that with an interval of 2.5%. Each measurement of different power regulation was maintained for two minutes to remove any transient effect in the end. Also, to see the effect more clearly, no turbulence generators (wedges) were used. Without the wedges, the turbulence intensity was expected to be less than 1%.
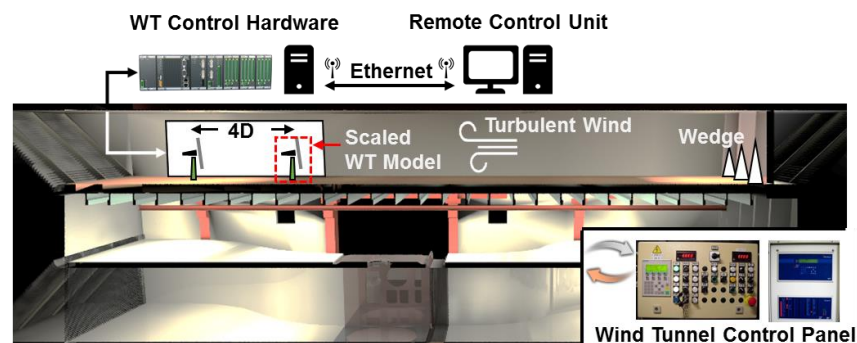

Fig.2 Experimental Setup

3. Simulation Model

For simulations, the scaled wind turbine was modelled in a commercial multi-body dynamics program (Bladed) widely used to design and test the dynamic performance of wind turbines. A look-up table that has both power coefficients and thrust coefficients of the wind turbine for various tip-speed ratios and pitch angles was obtained using a linearization module in that program and used in a simplified wind turbine model in the wind farm simulation tool. Also algorithms of basic torque and pitch control and power demand tracking control which are the same as the control algorithm used for the experimental study were implemented to the wind farm simulation model [6]. The wind farm simulation tool is an in-house c code that is based on the simulation tool developed by other researchers [7, 8] and simulates simplified wind propagation and operations of wind turbines of a wind farm. For the wind propagation, Ainslie's eddy viscosity wake model and Taylor's frozen turbulence assumption were used. More information on the models of wind turbine and wind farm simulation can be found in Refs. 7 and 8, and a schematic of the wind farm simulation tool is shown in Fig. 3. In addition to the simulations using scaled wind turbines, simulations with multi-megawatt wind turbines were also performed using the NREL 5MW research wind turbine model. Similarly to the scaled wind turbine case, the wind turbine was modeled in a commercial program and the aerodynamic performance was extracted to be used as a look-up table wind turbine for various tip-speed ratios and pitch angles [6].
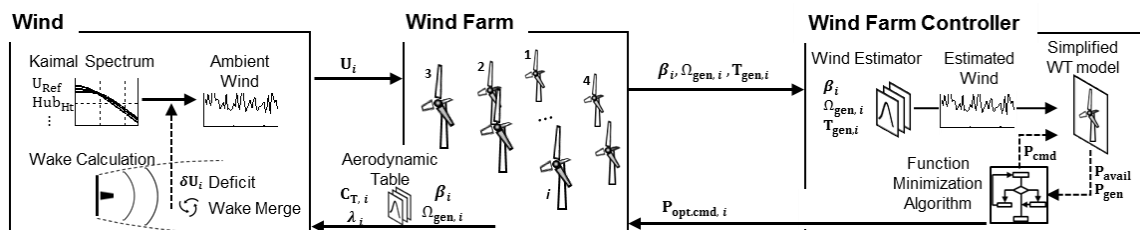

Fig.3 Schematic of the wind farm simulation tool

As shown in Fig. 3, the wind farm simulation tool has a wind farm controller which was designed to have a capability to find optimal power commands to individual wind turbines based on a simplified wind farm model, a function minimization algorithm, and the available powers calculated using the measured rotor speeds and pitch angles. The optimal power commands are then sent to individual wind turbine controllers for power maximization.

However, to simulate the power regulation experiments, the wind farm controller was used as a manual mode, in that case, a set of power commands determined by the operator are sent to individual wind turbine controllers. The same power regulations from 100% to 80% of the upstream wind turbine with an interval of 2% were applied to the simulation. Also to match the wind speed in the simulation with the wind speed in the wind tunnel experiment, the rotor averaged wind speed of the upstream wind turbine was obtained from the measured pitch angle of the blade and the rotational speed of the rotor. The rotor averaged wind speed was fed into the simulation tool as the wind. As the result of the simulation, the power outputs from two wind turbines with the power regulations were obtained.

4. Results and Discussion

Figure 4 shows both the experimental and the simulation results. Figure 4(a) shows the experimental total generated power output from two wind turbines with respect to partialization which is the ratio of power command to available power of the upstream wind turbine. The partialization of 1 (or 100%) means that the upstream wind turbine generates electricity as much as possible, and the partialization of 0.9 (or 90%) means that the upstream wind turbine is forced to generate 90% of its available power by the power regulation command. Based on the figure, the power increase was only 0.81 % when the partialization was 0.97. The results from the simulation are shown in Fig. 4(b). For the same

conditions to the wind tunnel experiment, the maximum power increase in the simulation was found to be 0.26%. In terms of the power increase, the result came out from the simulation was much smaller but the partialization values where the maximum power increase occurs were close.

More simulations were performed to see the results for NREL 5MW wind turbines instead of the small scale wind turbine and the results are shown in Fig. 4(b). The rotor averaged wind speed in this case was 10.5 m/s. Also two different turbulence intensities were used to see the variations in the power increase. When the ambient turbulence intensity was 0.03, the maximum power increase was 0.84% with a partialization of 0.97. The maximum power increase reached 1.27 % when the ambient turbulence intensity was increased to 0.16 which is more realistic with a partialization of 0.96.
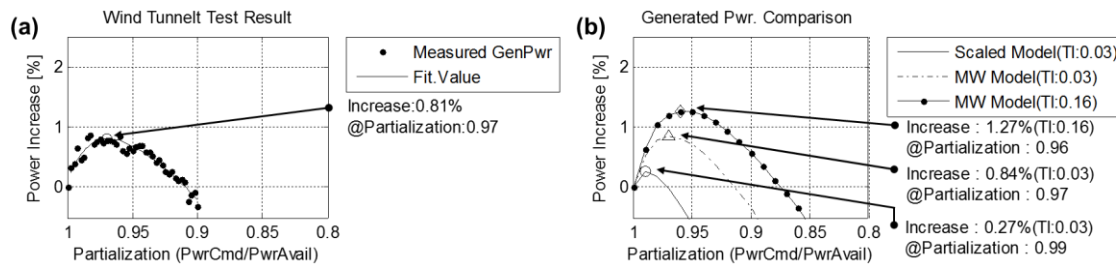

Figure 4. Results with Experiments and Simulation. (a) Experimental Results (b) Simulation Results

Although the power increases based on the simulations for both wind turbines are not large but the result of NREL 5MW research wind turbine was more than three times larger than the result of the scaled model. To find out the cause of the difference, the changes in aerodynamic performances of two different rotors of the upstream wind turbines before and after partialization were compared.
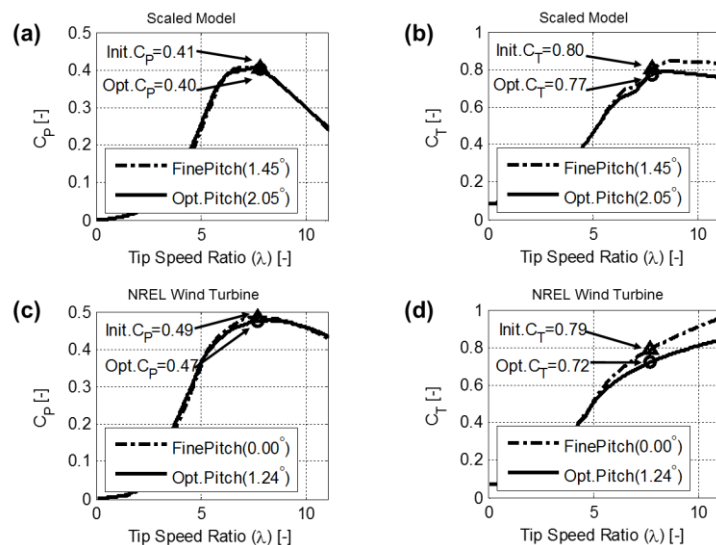

Figure 5. Power and thrust coefficients variation with respect to tip speed ratio (a) Scaled model C_P variation (b) Scaled model C_T variation (c) NREL WT C_P variation (d) NREL WT C_T variation

Figure 5 shows the power and thrust coefficients of scaled and NREL 5MW wind turbines with respect to tip speed ratio and pitch angle obtained from a commercial multi-body dynamic program. The symbols in the figure show the changes in the power and thrust coefficients of upstream wind turbines from the fine pitch (or partialization of 1) to the optimum partialization to maximize the total power. They look similar, but they are slightly different in the sensitivity of the coefficient with respect to pitch angles. For both wind turbines, the decrease in the power coefficients is similar but the decrease in the thrust coefficient for NREL 5MW wind turbines is much larger than that for scaled

models. The larger decrease in the thrust coefficient means higher downstream wind speed. Therefore, the power increase for NREL 5MW wind turbines is a few times larger than that for scaled models. This means that for multi-megawatt wind turbines, the power increase by active induction control could be large enough to be considered.

5. Conclusion

In this study, the feasibility of active induction control of upstream wind turbines of a wind farm was investigated by both experiments and simulations. Based on the experiment using scaled models in a wind tunnel, the power increase from a wind farm could be achieved but small. However, it was also found in the simulation that for multi-megawatt wind turbines, the increase could be much larger than the experimental study because the characteristics of power coefficients and thrust coefficients of scaled wind turbines are different from those of NREL 5 MW research wind turbine. Also in the experiment, to see the effect more clearly lower ambient turbulence was chosen, and this makes a negative impact on the recovery of the wake, and better results are expected with higher ambient turbulence which is more realistic. However, more research still needs to be performed to be convinced.

Acknowledgement

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