Plasma Actuation Effect on a MW class Wind Turbine

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ABSTRACT
The first trial test for applying plasma actuation technology on a 1.75 MW field rotor was carried out. Specially developed plasma electrodes of 8 m in length were installed on the surface of the leading edge of each blade. An increase in turbine rotational speed has been identified for the plasma-on cases compared with the plasma-off cases for the same wind speed. Also, histogram of inlet wind speed showed a trend that inlet wind speed was shifted to higher speed region for the plasma-on case compared with the plasma-off case. The mechanism of plasma actuation on this behaviour was examined in qualitatively using CFD analysis of model turbine. Consequently, an averaged power increase of 4.9 % was achieved in the test period. Possibility of increase in wind turbine power even in a commercial scale large turbine has been proved by leading-edge flow separation control using the plasma actuation technology.

INTRODUCTION
Owing to fluctuated natural wind, wind turbine blade constantly suffered from flow separation, as a result wind turbine performance gets worsen.

Active separation control of flow on the blade is one of the most effective techniques to reduce energy cost for wind turbines, since it has a potential both to increase energy captured and to extend blade life by reducing blade load. A nonthermal dielectric-barrier-discharged (NTDBD) plasma actuator is known as one of the active flow control device. The plasma actuator has a number of distinct advantages over other active flow control devices for flow control on the wind turbine blade [1]. Some of the advantages are as follows; 1. It can induce very thin jet flow (controls boundary layer flow efficiently), 2. It is fully electric and can provide fast response time, 3. It requires no moving parts (moving parts always brings mechanical troubles), and 4. It can laminate into the turbine blade surface (no additional drag force is generated even if the actuator is broken). Schematic view of the NTDBD plasma actuator is shown in Fig. 1. The plasma actuator consists of thin electrodes separated by a dielectric insulator. One of the electrodes is exposed to the air and the other electrode is fully covered by a dielectric material. When a high enough A.C. voltage is supplied to the electrodes the air gets ionized at the corner edge of the exposed electrode and spreads out over a region of the covered electrode. This ionized flow serves as a body force on the ambient air and results in induced thin jet flow generates from the actuator. When the actuator was operated in unsteady mode (pulsed modulation mode), separated flow of the blade was controlled most effectively (e.g., [2-4]). Effectiveness of the plasma actuation operating in unsteady mode was also reported on a periodically oscillated airfoil [5].

The mechanisms of plasma actuation on separation flow control were studied in detail using specially developed high-order CFD scheme by JAXA's group [6-9]. They reported that unsteady plasma actuation plays some role to strengthen the span-wise vortex in the blade boundary layer and this strengthened vortex brings effective separation flow control. The unsteady plasma actuation effect for rotating blade was studied both on a perpendicular axis wind turbine [10] and on a horizontal axis wind turbine [11]. Matsuda et al. carried out wind tunnel experiments using a 300 W rated small wind turbine having the plasma actuator located at the leading-edge of each of the turbine blade. By changing the inlet wind velocity, the turbine rotational speeds were measured for both the plasma-on case and the plasma-off case. Clearly the rise in turbine speed was observed for the plasma-on cases as compared to that for the plasma-off cases. The possibility of improving wind turbine performance using the plasma actuation was reported.

Based on these attractive results, the world first field test with this plasma actuation technology was carried out using Mie University 30kW (Φ10m) wind turbine [12]. Visualization test of rotor blade flow was also carried out using tuft method with wireless-LAN controlled monitoring camera fixed at the blade root. Under constant blade rotational speed of 20 rpm and fixed yaw angle, tuft behaviour was clearly visualized and it became clear that these separation flows were controlled and suppressed very effectively by this technique [13]. These test results infer that leading-edge flow separations were effectively controlled by the plasma actuation and torque augmentation in wind turbine was realized even under real wind conditions.
Following these successive results, finally, in order to realize practical advantage, plasma actuation technique has been tested in a commercial wind turbine (1.75MW, Φ 66m) at Kagoshima wind power institute owned by Hokutaku Co. Ltd [14]. A histogram of the power for both the plasma-off and the plasma-on case showed the enhancement of power generation by the plasma actuation [15].

In the present paper, plasma actuation effects on the MW class wind turbine are discussed in more detail. An increase in turbine rotational speed has been identified for the plasma-on cases compared with the plasma-off cases for the same wind speed. Also, histogram of inlet wind speed showed a trend that inlet wind speed was shifted to higher speed region for the plasma-on case compared with the plasma-off case and brings power enhancement of wind turbine for the plasma-on case. The mechanism of plasma actuation on this behaviour was examined qualitatively using modelled CFD analysis.

FIELD TEST

Test wind turbine

The experiment was carried out using a 1.75 MW rotor from Kagoshima wind power institute (Fig.2). The test turbine was a horizontal three-bladed upwind wind turbine with rotor diameter of 66 m and the hub height of 65 m. In order to avoid adverse effect on existing monitoring system, additional measuring system such as a tachometer, a yaw counter, a potential meter and an ultrasonic anemometer were introduced (Fig.3). The inlet wind speed was evaluated using this ultrasonic anemometer in the present study. Customized plasma electrode of 8 m in length was developed especially for this apparatus considering outdoor durability with flexibility of mounting it on the blade. A crane constructing of the plasma electrodes is shown in Fig.4. A total of three sets of plasma electrodes and power sources were mounted on each blade. Required voltage for plasma actuation was distributed from the power sources mounted in the nacelle through a specially mounted slip ring. All of the measuring data including the plasma operational data were transmitted to the data acquisition system using a wireless-LAN system and restored in a data server installed on the bottom of the tower. Data sampling frequency was 1Hz and averaged data for every 5 seconds were evaluated to study plasma effect on the test blades in detail.

The test has been conducted for 6 days during August 10 to 24 in 2013. The Plasma actuation was not operated during rainy periods and nights to perform the field test safely, data for a total time of 22 hours data for each case (plasma-on and plasma-off) were obtained.

In order to realize equal wind condition as possible, plasma actuation was activated and deactivated periodically in every 10 minutes of interval. The actuator was operated in pulsed modulation mode of St = fc/U = 1.0 with 1% duty at the center of each electrode.

Effect on turbine rotational speed

Typical examples of the plasma effect on the turbine rotational speed are shown in Fig.5 and Fig.6, respectively. An increase in speed has been identified for the plasma-on case compared with the plasma-off case for the same wind speed on both figures. Owing to the upper limit of the turbine rotational speed of this wind turbine, which was 21.3 rpm, data are observed to be concentrated within this limit in Fig.6.

Both figures infer that the plasma actuation can be effectively used for controlling leading-edge separation even for MW class large wind turbine.
Effect on turbine inlet speed

As mentioned above, to realize as equal wind condition as possible, plasma actuation was activated and deactivated periodically in every 10 minutes of interval. Typical time history of the inlet wind speed measured on both Aug. 10th and Aug. 19th are shown in Fig.7 and Fig.8, respectively. On Aug. 10th, a total of two hours data were obtained and on Aug. 19th, a total of 6 hours and 10 minutes data were obtained. From these time history data, we can obtain histogram of the inlet wind speed as shown in Fig.9 and Fig.10, respectively.

In both figures, a pattern of histogram of the inlet wind speed of the plasma-on case seems to move to higher speed region compared to that of the plasma-off case.

In order to confirm whether these observations are a trick of the natural wind behavior or not, the inlet wind speed of every 10 minutes interval for both plasma-off cases were examined. Fig.11 shows a time history of the inlet wind speed measured on Aug. 26th. A total of four hours data were obtained. Histogram of this inlet wind speed for plasma-off cases is shown in Fig.12. No distinctive tendency was recognized in Fig.12.

In our previous wind tunnel work, wake velocity distributions of 2D-NREL S825 blade were measured using hot-wire anemometer for both the plasma-on case and the plasma-off case. And it had become clear the plasma actuation results in a prominent decrease in wake width for the plasma-on case and contributes to drag reduction as compared to that for the plasma-off case [16]. Since, drag reduction relates to acceleration of inlet flow, tendency of these inlet wind speed shift for the plasma-on case (Fig.9 and Fig.10) seems to indicate some plasma effect on the wind turbine.
MODELLED ANALYSIS USING CFD

CFD approach

Since the inlet wind speed was evaluated using the ultrasonic anemometer mounted on the nacelle (Fig.3) in the present study, behavior of the inlet flow was not clarified in detail from the field test only. In order to evaluate above mentioned plasma effect (the inlet wind speed was shifted to higher speed region for the plasma-on case) on a wind turbine in more detail, a CFD analysis using model turbine was carried out. For three different pitch angles, flows around a wind turbine were studied and an effect of leading-edge separation flow control on flow around the wind turbine is discussed qualitatively.

Using hexahedral mesh created for 120 degree wind turbine domain by ICEM v14.5 numerical analysis was carried out using a commercial CFD solver CFX v14.5.

Fig 13 shows the computation domain considered for CFD analysis. Because of adopting the computation domain for CFD analysis from some other research project, rotor diameter D of 93 m of NREL 3MW class wind turbine [17] was used as a wind turbine model in this study.

A total of 8 million hexagonal elements were created. Maximum value of y+ was set less than 10. SST model was used as a turbulence model and steady state analysis was carried out for original design pitch angle and 5 degree rotated pitch angle and 10 degree rotated pitch angle, respectively. Inlet wind speed of 13 m/s and turbine rotational speed of 14.38 rpm were assumed. Boundary conditions of the present analysis are shown in Fig.14.

 rotor diameter(D): 93[m]

Fig.13 Modelled wind turbine domain

Fig.14 Boundary conditions

CFD result

Vector maps of flow around the blade at half span of the wind turbine model are shown in Fig.15 (a,b,c). Fig.15 (a) is the result of designed pitch angle condition. No flow separation is observed in this figure which implies flow around the blade with plasma-on case. On the other hand, Fig.15 (b) is the results of 5 degree rotated pitch angle condition and Fig.15 (c) is that of 10 degree rotated pitch angle condition, respectively. They imply the flow around the blade for plasma-off case. A clear leading-edge separation is recognised in both the figures.

Under these conditions, the inlet wind speeds of the wind turbine were evaluated.

Fig.16 (a,b,c) show change in normalized inlet wind speed distribution along the wind turbine diameter for designed pitch angle case (a), 5 degree rotated pitch angle case (b) and 10 degree rotated pitch angle case (c), respectively. As close towards the wind turbine is approached, the inlet wind speed decreases and affected by rotating wind turbine blades for all three cases tested. However, deceleration rate of the inlet wind speed is different depending on the degree of pitch angle change. With the increase in degree of pitch angle change, which implies larger flow separation situation, the inlet wind speed decreases.

Change in inlet wind speed for three pitch angle cases at 10 % span, 50 % span and 90 % span of the wind turbine blade are shown in Fig.17, 18 and 19, respectively. Deceleration of the inlet wind...
speed appears from about 2D frontward of the turbine and rapid deceleration of the inlet wind speed appears from about 1D frontward of the turbine for all three span cases studied. It is important to note that with the increase in degree of pitch angle change, which means larger flow separation situation, deceleration of the inlet wind speed becomes larger for all three span studied. Compared with design pitch angle case, more than 2% inlet wind speed deceleration is observed at 0.2D for 5 degree rotated pitch angle case and more than 4% deceleration is observed for 10 degree rotated pitch angle case for the 90% span (Fig.19).

These CFD results led to an understanding that the inlet wind speed of a wind turbine is affected by flow condition of the wind and more than 4% deceleration is observed for 10 degree rotated pitch angle case. The mechanism of plasma actuation on this behaviour was examined in qualitatively based on CFD analysis using model turbine and the results made it clear that by suppressing the leading-edge separation higher inlet wind speed can be achieved. Consequently, an averaged power increase of 4.9% was achieved in the test period.

An increase in turbine rotational speed has been identified for plasma-on cases compared with the plasma-off cases for the same wind speed. Also, inlet wind speed shift towards higher speed region is observed for the plasma-on case compared with the plasma-off case. The mechanism of plasma actuation on this behaviour was examined in qualitatively based on CFD analysis using model turbine and the results made it clear that by suppressing the leading-edge separation higher inlet wind speed can be achieved.

EFFECT ON WIND TURBINE PERFORMANCE

Finally, the plasma actuation effect on total power in the field test is discussed. Fig.20 shows histogram of the power for both the plasma-off and the plasma-on case. Every 5 seconds averaged data were evaluated. As mentioned before, each plasma electrode was operated under 1% duty, so that total electric consumption of the plasma operation was less than 1 kW. Therefore the simple output power is evaluated in Fig.20. Compared with the plasma-off case, larger power is obtained for 300 ~ 800 kW and 1600 ~ 1750 kW region for the plasma-on case. Accumulated difference in plots infers the enhancement of power generation by the plasma actuation. Cumulatively, 4.9% power increase has been recorded for 22 hours in 6 days of test.

CONCLUSION

The first trial test for applying plasma actuation technology on a MW class field rotor (Φ 66 m) was carried out. Specially designed plasma electrodes were installed on the surface of the leading edge of each blade. In order to realize equal wind condition as possible, plasma actuation was activated and deactivated periodically in every 10 minutes of interval, effect of plasma actuation on a wind turbine performance was studied.

An increase in turbine rotational speed has been identified for the plasma-on cases compared with the plasma-off cases for the same wind speed. Also, inlet wind speed shift towards higher speed region is observed for the plasma-on case compared with the plasma-off case. The mechanism of plasma actuation on this behaviour was examined in qualitatively based on CFD analysis using model turbine and the results made it clear that by suppressing the leading-edge separation higher inlet wind speed can be achieved.

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NOTE

Product names mentioned herein may be trademarks of their respective companies.
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