Plasma actuation for leading edge separation control on 300-kW rotor blades with chord length around 1 m at a Reynolds number around $1.6 \times 10^6$

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Abstract. The second field test of a plasma-assisted 300-kW wind turbine was performed to investigate the flow-control authority of plasma-actuation technology at Reynolds numbers ($Re$) exceeding $10^6$. The turbine rotational speed was regulated via pitch activation in the power-saving operation mode to limit $Re$ to approximately $10^6$. Additional generator-torque control was adopted to make the angles of attack exceed those allowable via original control. The leading-edge plasma electrode was activated at 10-min intervals and turbine characteristics with and without plasma actuation were compared using 1-min-averaged SCADA data, including wind conditions measured by a nacelle anemometer, obtained during a 6-day test. Results of this study reveal that the tip speed ratio (TSR) reduces under high-wind-speed conditions owing to additional torque control. Further, the power coefficient drops in the low TSR operating range, and improves upon plasma actuation. This has been statistically proven for at least one TSR bin. This result implies the existence of leading-edge separation under the additional torque control, and that plasma-actuation technology can effectively control the flow in the $1.6-1.8 \times 10^6 Re$ range. Results of this study demonstrate the potential of and need for further investigation of the proposed technology to facilitate its application for multi-megawatt wind-turbine.

1. Introduction
Continuous effort to adopt innovative technology is important to reduce the cost of wind energy as a major renewable energy resource. Smart-rotor technology is an emerging technology in wind energy, which utilizes distributed active flow-control devices on blades to adjust aerodynamic properties of each blade section to fluctuating, inhomogeneous inflow [1–3]. This approach has the potential to reduce the cost of energy by mitigating loads or increasing power output, especially with regard to large rotors operating under highly turbulent wind conditions. Plasma-actuation technology is one of the most practical candidates for use in smart rotors [4–7]. Using this technique, the flow around a blade can be controlled by attaching dielectric barrier discharge (DBD) electrodes to the surface. This approach is suitable for retrofitting, and its risk of downtime due to malfunctioning is less compared to other mechanical flow-control devices. Among numerous applications of this technology, leading edge separation control is the most promising, since it requires negligible power to control the flow by exciting the boundary layer using periodic plasma activation [8].

As wind turbines continue to become larger, the scale of the flow around a blade increases with Reynold’s number ($Re$) approaching $10^7$. Because flow control, in general, becomes more challenging
with increase in $Re$, it is important to investigate the effectiveness of flow-control at large $Re$. Flow-control authority and its mechanism of leading-edge separation control via plasma actuation have been previously investigated experimentally and numerically for flows with $Re$ in the $10^4$–$10^5$ range [9–11]. A series of field tests using a 30-kW turbine yielded results that directly indicated the flow-control authority of the device under actual wind-field conditions [12]. During the said tests, the measured rotor torque was improved via plasma actuation under low tip-speed ratio (TSR) operation. This improvement was due to enhanced lift of the blade sections having chord lengths in the 120–550-mm range in the post-stall condition with $Re = 3 \times 10^5$. However, only few extant studies discussed control authority at $Re > 1.0 \times 10^6$. Available works in this regard include a two-dimensional (2-D) wind-tunnel experiment [8, 13] and numerical simulations [14]. The first application of this technology to a commercial-scale turbine using a 1.66-MW machine demonstrated differences in the values of power, rotational speed, and nacelle wind-speed distributions between operating conditions with and without plasma actuation [15]. However, the phenomena behind these differences could not be investigated in detail owing to limitations encountered with regard to opening up the control sequence of the commercial turbine. One of the most important steps to facilitate implementation of this technology in the wind-energy industry is to confirm the device's flow-control authority on actual flow scales.

For this reason, we performed the proposed investigation on a 300-kW test turbine with accessible controls available at the National Institute of Advanced Industrial Science and Technology (AIST). We first performed a field test in the 10% power-saving mode to limit blade-section $Re$ to approximately $10^6$. The first trial run was performed in the beginning of 2019 to confirm the system's safety and durability [16]. The device exhibited good durability during a one-month test. The derived power curve demonstrated a slight difference between conditions with and without plasma actuation near rated power. Subsequently, a second field test was performed under identical turbine and plasma conditions during a different season to investigate further the effects of flow control.

The proposed research aims at finding the evidence of flow-control authority of the device under actual field conditions at $Re$ of approximately $10^6$. Section 2 in this paper describes the experimental method, whereas section 3 presents results obtained, which are further discussed in section 4.

2. Experimental method

2.1. Test turbine

The test turbine (Komaihaltec KWT-300) used in this study was located at the Fukushima Renewable Energy Institute of AIST. It is a collective-pitch and active-yaw controlled upwind turbine that measuring 33 m in diameter and 41.5 m in hub height. Torque control of the inductive generator could be modified by changing existing controller parameters. The turbine was operated in the power-saving operation mode, wherein the rotational speed is regulated via pitch control to keep the actual power below a set value. During experiments, the power was set at 10% (i.e., 30 kW), and the rotational speed

![Figure 1. Schematic of generator torque and pitch control sequence — a) Original control; b) additional torque control used in this study.](image-url)
was regulated to less than half the rated value. Consequently, the blade-section $Re$ was limited to approximately $10^6$.

Figure 1(a) depicts the original generator torque and pitch-control sequence in the power-saving mode. Figure 1(b) shows the additional torque increment adapted to increase angles of attack (AOA) artificially. In this sequence, when $\omega > \omega_3$, $T_g$ is increased to $T_g2$. Subsequently, the pitch reduces to zero, during this high torque is reducing $\omega$. When $\omega$ reaches a set value $\omega_2$ while pitch $= 0$, $T_g$ is reduced to the original curve. This additional control is similar to that observed in Region 2.5 corresponding to constant-speed operation in the sense that the rotational speed is regulated via torque control.

![Figure 2](image)

**Figure 2.** Latest 8-m-long DBD electrode—(a) plasma generated on electrode surface before installation; (b) schematic layout of electrodes on leading edge of each blade.

![Figure 3](image)

**Figure 3.** Schematic of voltage waveform of pulse modulated activation during plasma-ON state.

![Figure 4](image)

**Figure 4.** Average discharge power consumption by each electrode.

### 2.2. Plasma-actuation system

The latest 8-m-long flexible DBD electrodes developed by Asahi Rubber Inc. were attached to the leading edge of each blade, as shown in Figure 2. Each electrode measured 2 mm and 60 mm in thickness and width, respectively, and comprised a pair of metal-strip electrodes and silicone rubber sheet as insulation between them. The electrodes were set at radial positions of 5–13 m (30.3–78.8%). The blade chord at the center of each electrode equaled 1.2 m.

The plasma system developed by Toshiba was installed on the turbine. High-frequency AC voltage generated by inverters in the nacelle was carried to high-voltage transformers installed on the hub via a slip ring. Amplified voltage was sent from these transformers to electrodes through flat high-voltage (HV) cables attached on the pressure side of the blade surface. These electrodes were activated in the pulse-modulated mode, as described in Figure 3, at an applied activation voltage of 13 kVpp, base frequency of 15 kHz, and 5% duty cycle. It is well-known that the effect of plasma actuation for a 2-D airfoil is strongly dependent on a non-dimensional reduced frequency $F^+ = F \cdot c/U$ ($F$: pulse-modulation
frequency, $c$: chord length, $U$: freestream velocity). In this experiment, $F$ was set as $F = v/c$ ($v$: circumferential speed, $c$: chord length, both measured at the center of the electrode) to maintain a reduced frequency $F^*$ of approximately unity at the center of each electrode. Figure 4 presents the measured time-averaged discharge power consumption of each electrode on the blade as a function of the applied voltage. The figure demonstrates electrode properties to be maintained since electrode installation in early 2019. The dissipated power of approximately 5 W/m at 13 kV$_{pp}$ is negligible compared to the power produced by the turbine.

2.3. Operation, data acquisition, and filtering

A 6-day test was performed between August 1 and 6, 2019. The plasma state (ON or OFF) was changed intermittently at 10-min intervals to compare the two states under similar wind conditions. Wind conditions were measured using a nacelle anemometer. Data (nacelle wind speed, nacelle wind direction, actual power, generator torque, generator speed, and pitch angle) from SCADA as well as the plasma system were stored at each second. For analysis, data were averaged in each minute and filtered to fulfill following criteria—(1) actual power must exceed -500 W, thereby implying connection of the turbine to the grid (a value less than -500 W implies an unconnected turbine because it includes power dissipation from auxiliary equipment); (2) pitch angle must not exceed a threshold value to exclude the low-AOA condition caused by pitch activation. In this study, the threshold value was set to 0° initially, because measured values were in the range of -0.2° to 0° when pitch control was not activated; thereafter the threshold was increased to 1° and 90° to increase data count; (3) all three electrodes are simultaneously activated by their own inverters having their own protection systems. This criterion excludes unbalanced actuation.

3. Experimental results

Figure 5 depicts time-series trends of the wind speed averaged over 1 min. It is clear that data corresponding to times at which the plasma state was switched ON and OFF alternately were only extracted for analysis. High and low wind speeds were observed during day and night, respectively, thereby reflecting typical wind conditions during summer at this site.

Figure 6 presents distributions of the nacelle wind speed $U$ and nacelle wind direction $D$. As can be seen, mean values of used data—$U_{mean}$ and $D_{mean}$—are nearly identical during the ON and OFF states. These results demonstrate that data corresponding to the ON and OFF states could be compared under similar wind conditions owing to alternating plasma operation and data filtering. This experimental method is very useful compared to conducting a pair of test periods in sequence to assess the effects of some performance upgrade because the external environment during the two periods is always different [17].

Figure 5. Time series of wind speed averaged over 1 min, as extracted via filtering using pitch-angle thresholds of (a) 0°, (b) 1°, and (c) 90°.
Figure 6. Wind speed and direction distributions for plasma states ON and OFF observed for pitch-angle thresholds of (a) 0°, (b) 1°, and (c) 90°.

Figure 7. Relationship between bin-averaged wind speed and actual power filtered using pitch-angle thresholds of (a) 0°, (b) 1°, and (c) 90°.

Figure 8. Relationship between bin-averaged wind speed and TSR filtered using pitch-angle thresholds of (a) 0°, (b) 1°, and (c) 90°.
To investigate turbine characteristics, we began focusing on results obtained corresponding to a pitch-angle threshold of 0°. This criterion is ideal for elucidating flow conditions around blades, since the effect of pitch motion need not be considered.

Figure 7(a) illustrates the relationship between the binned wind speed and actual power for the plasma ON and OFF states. The wind speed was binned at 0.5-m/s intervals, and error bars represent 95% confidence intervals which the effect of data count has been accounted for. Although the normal power-saving mode limits the power to less than 30 kW, the observed power output reached to nearly 50 kW in this experiment. This is because the additional torque control increased the generator torque to regulate the rotational speed before it was regulated enough via pitch control.

Figure 8(a) depicts the relationship between the binned wind speed and TSR. TSR was calculated by dividing the tip speed by the nacelle wind speed. This approach results in a TSR value exceeding that normally used to represent wind-turbine operating conditions under which calculations are performed using the upstream wind speed. As can be observed, the TSR remains constant at moderate wind speeds but significantly decreases at higher wind speeds. Since these data were extracted with a pitch threshold of 0°, the observed decrease in TSR is caused by rotational-speed regulation via additional torque control, rather than pitch control.

Figure 9(a) shows the relationship between TSR and power coefficient $C_p$. TSR was binned at intervals of 1. $C_p$ was derived from the actual power divided by $1/2 \cdot \rho \cdot A \cdot U^3$ ($\rho$: air density, $A$: swept area) and normalized by the maximum $C_p$ value. A sudden drop in $C_p$ is evident at low TSR.

In the previous test [16], some difference was observed between actual power values corresponding to the plasma ON and OFF states around the power-saturation region, wherein TSR values are relatively low. In the present test, lower power values exist in the plasma-OFF state (as depicted in Figure 7(a)) corresponding to lower TSR values depicted in Figure 8(a). Furthermore, the $C_p$ value corresponding to this TSR is significantly decreased. However, it was difficult to derive statistical inferences because the
data count for this point was too small, as depicted in Figure 10(a). Consequently, we subsequently analyzed collected data with pitch threshold increased to 1° and 90° to increase the data count although the effect of pitch motion should be considered in understanding the flow conditions on the blade.

Figures 7(b)–10(b) and Figures 7(c)–10(c) present turbine characteristics obtained for pitch thresholds of 1° and 90°, respectively. As can be observed, data counts increase especially in the high wind-speed and low-TSR regions. The difference between the plasma ON and OFF states disappears in the power curve, but a trend can be observed wherein $C_p$ decreases in the low-TSR region, and the same improves upon plasma actuation.

4. Discussion

To analyze further the difference between results obtained under the ON and OFF states, as observed in Figures 9(b) and 9(c), we investigated the statistical significance of the difference and phenomena underlying the data.

Firstly, we performed two-sample t-tests to determine whether there existed any statistical evidence to confirm that the mean difference between the ON and OFF states was significantly different from 0. Because the data count in the TSR = 7 bin was too small, we selected the TSR = 8 bin for consideration. Figures 11(a) and 11(b) present histograms of $C_p$ corresponding to the TSR = 8 bin with pitch thresholds of 1° and 90°. The normality assumption of the distribution was checked by performing the Kolmogorov–Smirnov test. Subsequently, we performed two-sample t-tests to calculate the $p$-value under the null hypothesis that data in the ON and OFF states was obtained from independent random samples from normal distributions with equal mean and unequal variance values. An alternate hypothesis was that mean values of data collected during the ON state exceeded pertaining to data collected during the OFF state.

Table 1 presents results obtained during the t-tests. The $p$-value for the case with pitch threshold of 1° equals 0.032, thereby implying that the probability of observing a test statistic more extreme compared to the observed difference is only 3.2% under the null hypothesis. Hence, the null hypothesis can be rejected, in general, and it can be stated that there exists a significant difference at the 5% significance level.

The $p$-value for the case with pitch threshold of 90° equals 0.087, which does not support rejection of the null hypothesis at the 5% significance level. This implies that observed trends could be diluted by

| Pitch threshold | Plasma OFF | Plasma ON |
|-----------------|------------|-----------|
| Mean            | Variance   | Data count| Mean       | Variance   | Data count|
| 1°              | 0.82       | 0.050     | 17         | 0.93       | 0.0061    | 19         | 0.032      |
| 90°             | 0.82       | 0.045     | 19         | 0.90       | 0.02      | 20         | 0.087      |

Figure 11. $C_p$ distributions corresponding to TSR = 8 bin for pitch-angle thresholds of (a) 1° and (b) 90°.
the effects of pitch motion on flow conditions around the blade, which in turn, could have caused a decrease in blade AOA. To confirm this trend, further experiments must be performed with increased data count facilitating performing t-tests for TSR = 7 and below.

Understanding of underlying mechanisms is more important than the above discussion from statistics [18]. To investigate the scientific reason behind the sudden decrease in $C_p$ and observed difference between the plasma ON and OFF states at TSR = 8 bin, as depicted in Figure 9(b), a wind-tunnel test was performed using an airfoil section at 70% of the turbine-blade radius. The airfoil was scaled down to measure 200-mm in chord and 800-mm span. Figure 12 below depicts the lift performance of the said airfoil measured at $Re = 3 \times 10^5$. AOA and $C_p$ values were normalized with respect to the stall angle and maximum $C_{p_m}$, respectively. As observed, the lift coefficient $C_l$ gradually decreases from $C_{l_{max}}$ with increase in AOA owing to commencement of flow separation from the trailing edge. With further increase in AOA, a sudden stall occurs owing to leading-edge flow separation. Additionally, airfoils used at 42% and 76% of the span were observed to demonstrate similar characteristics in an extant study [19]. In accordance with these results, the sudden decrease in $C_p$ at low TSR seems to be caused by leading-edge flow separation at high AOA.

For airfoils with trailing-edge separation characteristics, Matsuda performed a wind-tunnel experiment using a 2-D S825 airfoil with plasma actuation on the leading edge at $Re = 7.5–9.1 \times 10^5$ [20]. Figure 13 depicts obtained results, thereby demonstrating that plasma-actuation with leading-edge electrode cannot affect the lift of trailing-edge separated flow; however, it results in remarkable improvement when leading-edge flow separation occurs at AOA exceeding 25°.

Based on these facts, it can be said that Figure 9(b) implies the existence of leading-edge flow separation at low TSR when using the special torque-controlled rotor and that plasma-actuation technology can reliably control lift in this separated flow. In this region, $Re = 1.6–1.8 \times 10^6$ at the center of the electrode assuming $U = 5$ m/s and TSR = 7–8.

### 5. Conclusions

In this study, field tests were performed on a plasma-assisted 300-kW wind-turbine rotor operating under the 10% power-saving mode. Generator torque was controlled to make AOA exceed the original control value. The turbine characteristics during operation under states with and without plasma actuation were compared using 1-min-averaged SCADA data obtained during a 6-day test, including wind conditions measured using a nacelle anemometer.

Results obtained in this study reveal that the additional torque control causes TSR reduction at higher wind speeds. Further, $C_p$ decreases in this low TSR region and improves upon plasma actuation. The improvement in $C_p$ at low TSR was statistically proven for at least one TSR bin. The observed trend of improvement is consistent with results obtained during a 2-D wind-tunnel experiment wherein leading-edge flow separation occurs at high AOA after occurrence of trailing-edge separation at low AOA.
Because leading-edge plasma actuation can improve $C_t$ exclusively under leading-edge flow-separation conditions, results of this study imply existence of leading-edge flow separation with implementation of special torque control. Additionally, it has been demonstrated that plasma-actuation technology can reliably control flow over wind-turbine rotor blades under conditions with $Re = 1.6–1.8 \times 10^6$.

In future investigations, in addition to performing continuous data accumulation, we intend to perform system-identification testing to confirm the effect of plasma actuation. A wind-tunnel test with flow visualization has also been planned to investigate the scale effect of the proposed flow control more fundamentally.

References

[1] Watson S et al. 2019 Future emerging technologies in the wind power sector: A European perspective Renew. Sustain. Energy Rev. 113 109270
[2] Bernhammer L O, Kuik G A M and Breuker R De 2014 How far is smart rotor research and what steps need to be taken to build a full-scale prototype? J. Phys.: Conf. Ser. 555 012008
[3] Gonzalez A G, Barlas T K, Enevoldsen P and Madsen H A 2019 Field test of an active flap system on a multi-MW wind turbine Wind Energy Science Conference 2019 (Cork) Paper No. 460
[4] Nelson R C, Corke T 2008 A smart wind turbine blade using distributed plasma actuators for improved performance 46th AIAA Aerospace Sciences Meeting and exhibit AIAA paper 2008-1312
[5] Cooney J A, Szlatenyi C and Fine N E 2016 The development and demonstration of a plasma flow control system on a 20 kW wind turbine 54th AIAA Aerospace Sciences Meeting AIAA paper 2016-1302
[6] Pereira R, Bussel G J W and Timmer W A 2014 Active stall control for large offshore horizontal axis wind turbines; a conceptual study considering different actuation methods J. Phys.: Conf. Ser. 555 012082
[7] Aubrun S, Leroy A and Devinant P 2017 A review of wind turbine-oriented active flow control strategies Exp. Fluids 58 134 21p
[8] Keisar D, Hasin D and Greenblatt D 2019 Plasma actuator application on a full-scale aircraft tail AIAA J. 57 2 616–27
[9] Post M L and Corke T C 2012 Separation control using plasma actuators: Dynamic stall vortex control on oscillating airfoil AIAA J. 44 12 3125–35
[10] Asada K and Fujii K 2010 Computational analysis of unsteady flow-field induced by plasma actuator in burst mode 5th Flow Control Conference AIAA paper 2010-5090
[11] Mitsuo K, Watanabe S, Atobe T, Kato H, Tanaka M and Uchida T 2013 Lift enhancement of a pitching airfoil in dynamic stall by DBD plasma actuators 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition AIAA paper 2013-1119
[12] Tanaka M, Amemori K, Matsuda H, Shimura N, Yasui H, Osako T, Kamada Y and Maeda T 2013 Field test of plasma aerodynamic controlled wind turbine EWEA Conference 2013 (Vienna) Presentation ID. 585
[13] Little J, Takashima K, Nishihara M, Adamovich I and Samimy M 2012 Separation Control with Nanosecond-Pulse-Driven Dielectric Barrier Discharge Plasma Actuators AIAA J. 50 2 350–65
[14] Sato M, Asada K, Nonomura T, Aono H, Yakeno A and Fujii K 2019 Mechanisms for turbulent separation control using plasma actuator at Reynolds number of $1.6 \times 10^6$ Phys. Fluids 31 095107
[15] Matsuda H, Tanaka M, Osako T, Yamazaki K, Shimura N, Asayama M and Oryu Y 2017 Plasma actuation effect on a MW class wind turbine Int. J. Gas Turbine, Propuls. Power Syst. 9 1 47–52
[16] Tanaka M, Kubo N, Kawabata H, Suzuki K, Bhandari S, Watanabe N, Sato H, Takeyama M, Minegishi K and Oryu Y 2019 The first trial operation of plasma assisted 300kw wind turbine
with durable, retrofitted DBD electrodes *Wind Energy Science Conference 2019 (Cork)* Paper No. 609

[17] Shin Y E, Ding Y and Huang J Z 2018 Covariate matching methods for testing and quantifying wind turbine upgrades *Ann. Appl. Stat.* 12 2 1271–92

[18] Amrhein V, Greenland S and McShane B 2019 Retire statistical significance *Nature* 567 21 305–7

[19] Naoki Y, Maeda T, Kamada Y, Tada T, Hanamura M, Iwai K, Fujiwara A and Hosomi M 2019 Effect on blade icing on load of horizontal axis wind turbine in cold climate *Proc. Japan Wind Energy Symposium* 41 122–5

[20] Matsuda H, Tanaka M, Shimura N, Otomo F and Osako T 2014 plasma actuation effect on flow around 2-D wind turbine blade (effect on lift increase and drag reduction) *Asian Congress of gas turbines (Seoul)* ACGT2014-0021

Acknowledgments

This research was supported in part by the Program for Promoting Technologies Invented by Industry in Disaster Areas in Tohoku. The authors acknowledge Komaihaltec Inc., Asahi Rubber Inc., and Hokutaku Co., Ltd. for their support in performing the 300-kW field test. Additionally, the authors thank Professor Maeda and Associate Professor Kamada from Mie University as well as their laboratory staff for the assistance extended in performing the 2-D wind-tunnel test.