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Effect of High Turbulence Intensity on Micro Wind Turbine Performance

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***Abstract*— Small wind turbines, particularly those generating a few kilowatts or less, are usually installed at heights below 10 m or even on rooftops. At such low heights, they experience more intense fluctuations in wind speed and direction. In this study, we conduct a field test where we install a micro wind turbine (MWT) on a rooftop and measure the effect of high turbulence intensities (TIs) around the building on its performance. Here we observed far higher TIs than are specified in the MWT design standard (IEC 61400-2 Ed. 3). For example, we found TIs ranging from 5–55% at wind speeds of around 5 m/s. Our tests also revealed that the turbine's output power lay above the manufacturer's power curve at low wind speeds (from cut-in to a particular speed), but it fell below it at higher speeds, even while the speed was still below the cut-out speed. By analyzing the changes over time and calculating the power curves for different TIs, we found that the turbine's output performance was higher at low wind speeds because its rotational speed could follow the wind speed fluctuations and capture the wind's increased inflow energy. By contrast, at higher wind speeds, higher TIs induced early cut-out due to momentary high-speed gusts. In conclusion, higher TIs yield better MWT performance at low-to-medium wind speeds and lower performance at high wind speeds around the cut-out speed.**

Keywords— Wind Energy, Small wind turbine, Micro wind turbine, Turbulence, Field test

I. INTRODUCTION

Although large wind turbines are widely used for primary electrical power generation, smaller micro wind turbines (MWTs) are still common in urban, remote or off grid areas, generating power for domestic or emergency purposes. In most cases, especially for turbines producing a few kilowatts or less, the turbine hub heights are less than 20–30 m above ground level. At such low heights, the wind is heavily affected by roughness of ground or surrounding buildings and consequently its speed and direction can fluctuate substantially. These effects can be quantified in terms of the turbulence intensity (TI), which usually increases at lower altitudes [1]. There are several previous literatures about high TI and its relation to small wind turbines. Tabrizi et al. [2] measured TI and turbulence spectra and revealed that more conservative design is appropriate than defined in IEC 61400-2 Ed.2. Tabrizi et al. [3] also tested suitability of standard turbulence spectra models and proposed adapted Kaimal approach including length scale of the complex terrain environment.

Several previous studies have investigated the effect of higher TIs on the performance of small wind turbines. For example, Al-Abadi et al. carried out wind tunnel turbulence testing at a fixed rotational speed, finding that greater turbulence led to higher power coefficients [4]. For wind turbines generating more than 20 kW, higher TIs sometimes degraded performance [5,6]. In order to normalize power curve of those relatively large pitch regulated turbines taking the effect of TI into account, IEC 61400-12-1 Ed.2[7] provides a method of turbulence normalization of turbine power curve based on the work by Albers et al.[8]. Anup et al.[9] reviewed urban wind condition and its effect on small wind turbines. They reports 25%-35% reduction in power performance has been attributed to high TI greater than 18%. However, higher TIs are also known to increase the power output at a range of wind speeds, from the cut-in speed to certain upper limit, and to reduce the cut-out wind speed for small-scale (less than a few kilowatts) wind turbines. Lubitz tested a 1 kW horizontal-axis wind turbine with furling control at a height of 18 m [10]. In their experiments, the TIs ranged from less than 14% to more than 18%, and the power output varied by ±2% as the TI increased. Tokuyama reported similar results for a wider range of TIs [11]. In their work, more than 40% of the TIs were measured at low wind speeds, and their results show that greater turbulence yielded higher output power levels, as in the other experiments.

In this paper, we investigate the effect of the TI on the performance of a small 135 W wind turbine, installed close to the roof of a 5-m-high building in order to establish appropriate method for power performance characterization of micro to small wind turbines. Section 2 describes the turbine's location, the obstacles surrounding the test site and our measurement equipment. Then, Section 3 presents how to evaluate TI and turbine performance. Section 4 presents the measured power curve and wind conditions, before going on to discuss the effect of the TI on the power curve. In addition, we measure the output performance and operating environment at different turbulence levels. Finally, Section 5 presents the conclusions of this study.

II. MATERIAL AND METHOD

A. Test site

The MWT site is located next to the wind turbine museum at Ashikaga University (Tochigi prefecture, Japan). The turbine and measurement instruments were all mounted on the building with scaffolding.

All the significant obstacles to the anemometer and wind vane are listed below, together with their directions relative to the anemometer.

- Turbine (Figure 1), located toward the north-east (45° from north).
- Utility pole (Figure 2), located toward the north-west (315° from north).
- Hand rails all around the building, about 0.8 m high (Figure 2 and Figure 3).
- Second floor of the building (Figure 3), located toward the south-west (210° from north).

Other than the above obstructions, there were no significant objects within a 20 m radius, as shown in Figure 1.

The tested wind turbine was only assumed to be a significant obstacle when determining the exclusion sector. Since the test site's dominant direction included the direction of the obstructions and they were located sufficiently far from the measurement instruments, we assumed they did not affect the inflow to the turbine. Consequently, the exclusion sector was 45 ± 45.6° from north, calculated based on Annex. A of IEC 61400-12-1 Ed. 1 [12].

Fig. 1. Satellite view of the test site. Here the blue circle has a radius of 20 m, while the blue block is the second floor of a building that was assumed to be a significant obstacle.

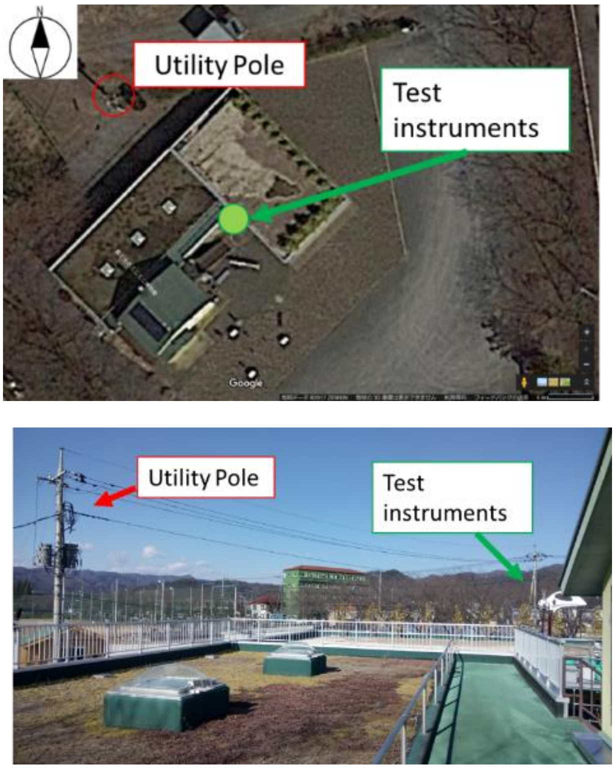


Fig. 2. Location of the utility pole, also showing the hand rails (lower)

Fig. 3. Location of the second floor of the building, also showing the hand rails (lower)

B. *Turbine and measurement equipment*

Table 1 gives the specifications of the tested turbine. We constructed a support tower using scaffolding. The tower was 4 m off the ground at its base, and the turbine's hub was 1.5 m above this (i.e. 5.5 m from the ground).

Table 2 lists the measurement instruments. A cup anemometer and a wind vane were mounted onto the support tower. The anemometer was a horizontal distance of 1.7 m from the turbine, and the other measuring instruments were also mounted onto the same Figure 4 shows mounting structure and the tested turbine. scaffolding. The data logger's sampling frequency was 1 Hz, and it recorded the wind speed and direction (at hub height), the atmospheric temperature, the atmospheric pressure, the humidity, the battery current and voltage and the generator's rotational speed. Figure 5 shows connection diagram of the electrical system. The turbine was connected to a 24 V battery charge–controller system, which managed the generator's torque–speed relationship and the turbine protection system (i.e. the braking system). In order to ensure the turbine was always available, we connected an additional 23 V power supply and a dummy load to prevent overvoltage. The turbine was therefore always on standby, and hence we assumed its operational state is not affected by battery state of charge (SoC) and only depended on the wind conditions.

Fig. 4. Mounting structure for the MWT

TABLE I. TURBINE SPECIFICATIONS

Rated output power	**135 W (10 m/s)**
Maximum output power	**500 W**
Number of blades	**5**
Cut-in wind speed	**2 m/s**
Cut-out wind speed	**16 m/s**
Rotor diameter	**1 m**
Manufacturer and model	**Nasu denki tekko ltd., AURA 1000**

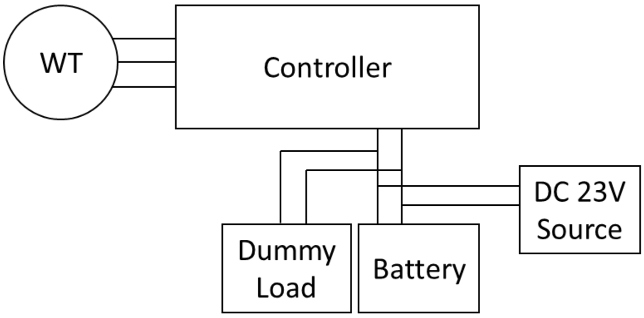


Fig. 5. Connection diagram

TABLE II. LIST OF MEASUREMENT INSTRUMENTS

Measured value	**Manufacturer and model**
Wind speed (1.5 m height)	**Climatec Inc. CYG-3002**
Wind direction (1.5 m height)	
Wind speed (5 m height)	**Climatec Inc. CYG-3002**
Wind direction (5 m height)	
Temperature	**R. M. Young company 41342**
Humidity	
Atmospheric pressure	
Current to the battery (I_1)	**URD HCS-20-10-AP**
Current to the dummy load (I_2)	**URD HCS-20-10-AP**
Load Voltage	**YOKOGAWA Datum-Y XL100**

III. Performance Measurement

The turbine's performance was measured using 0.5 m/s wind speed bins and 5% TI bins. The TI was calculated as follows:

$$TI = \frac{\sigma}{\bar{V}}, \qquad (1)$$

where $\bar{V}$ is the average wind speed over a one-minute interval and σ is the wind speed's standard deviation. We calculated the TI for each one-minute interval. The measured wind speed ranged from 5–8 m/s. The data was sorted by TI for each wind speed.

The output power *P* was also averaged over each one-minute interval, and was calculated as follows for each sample:

$$P = V_e I_e, \qquad (2)$$

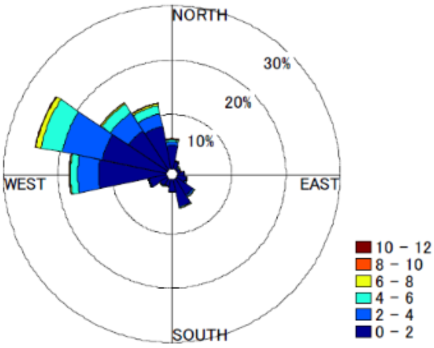
where V_e is the output voltage from the turbine controller (to parallel connected battery and dummy load) and I_e is the total current (battery charging current minus the current consumed by the dummy load). All the parameters were sampled once per second.

The exclusion sector (explained above) was calculated based on the one-minute-average wind direction.

IV. Results and Discussion

A. *Wind conditions and number of data points*

The field tests were carried out between November 2016 and February 2017. Figure 6 shows the measured wind rose, while Table 3 shows the number of data points gathered at each wind speed. Here, we considered wind speed bins with less than 30 data points (highlighted in yellow) to have insufficient data. Despite this lack of data for some bins, we include all the bins (including the insufficient bins) below, except when discussing the turbine characterisation and its power production.



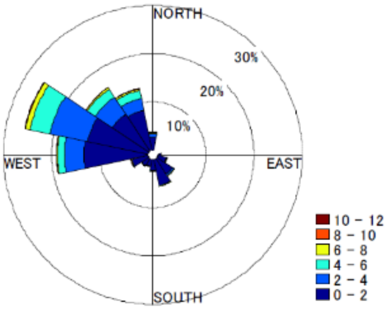


Fig. 6. Wind rose showing the one-minute-average wind speeds and directions, without sector exclusion (upper) and with sector exclusion (lower)

TABLE I. Number of one-minute turbine performance data points by wind speed (Nov. 2016 to Feb. 2017)

Wind speed	Data points (all data)	Data points (sector excluded)
0	35664	32208
0.5	19343	17963
1	19019	17948
1.5	13818	13218
2	8872	8640
2.5	7016	6874
3	6625	6512
3.5	6247	6127
4	5277	5177
4.5	4268	4183
5	3140	3076
5.5	2279	2229
6	1487	1460
6.5	965	944
7	579	567
7.5	364	358
8	196	190
8.5	104	104
9	46	46
9.5	29	29
10	15	15
10.5	2	2
11	3	3
11.5	2	2
12	0	0

B. *Site turbulence*

Figure 7 and Figure 8 show the measured TIs. Even at a wind speed of 10 m/s, the TI was more than 30%, far higher than specified in any wind turbine design standard (e.g. IEC 61400-2 Ed. 3 [13]). These results indicate that the TI at the test site was significantly different from that in a typical scenario. However, we note that installations similar to this rooftop system are very common for such low-power turbines. Another important point is that even the 90% quantile TI is high; Figure 8 shows that the raw data includes a wide range of TIs. For example, at around 5 m/s, the TI range is approximately 5–55%. This means we can classify the data according to the TI with wide range.

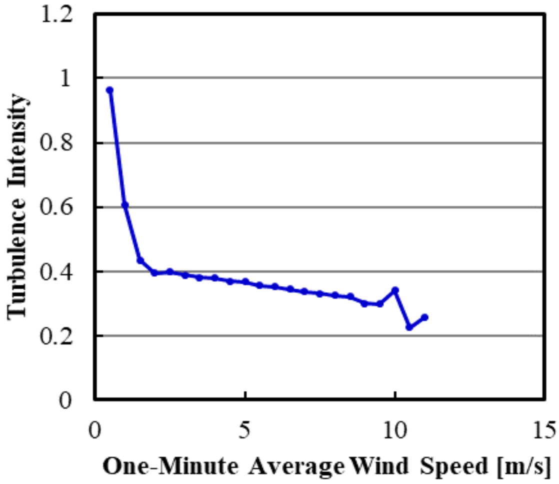


Fig. 7. TI at hub height versus one-minute-average wind speed (90% quantile)

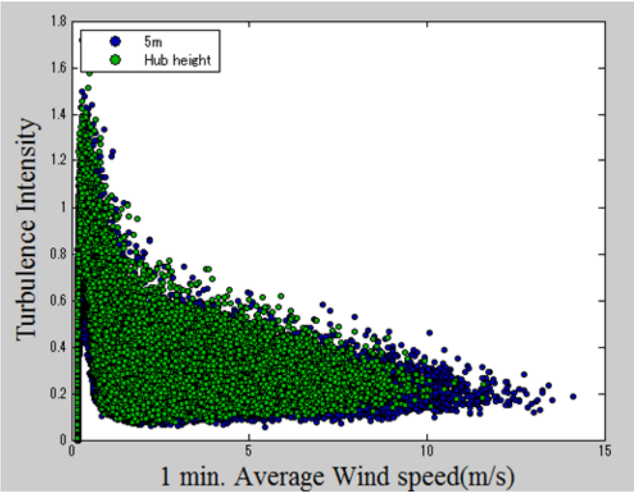


Fig. 8. Raw TI data versus one-minute average wind speed(Hub height data is used in Figure 7)

C. *Power curve*

Figure 9 compares the measured power curve with that provided by the manufacturer. According to the manufacturer, the turbine's cut-in and cut-out wind speeds were 2 m/s and 16 m/s, respectively. Our results show higher than expected output powers at low wind speeds, but lower output powers at high wind speeds (above 9 m/s), compared with the manufacturer's figures. The better low-speed performance may be due to higher inflow energies due to high TIs, while the lower high-speed performance may be due to the highly variable wind speed, with momentary gusts causing the turbine to cut out.

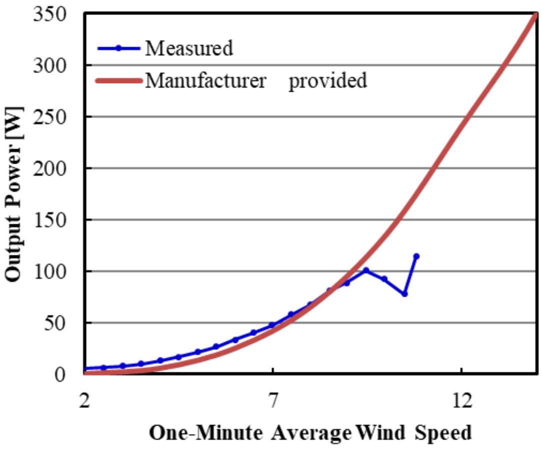


Fig. 9. Measured and manufacturer-provided power curves (one-minute average)

D. *Effect of the TI on the power curve*

Before analysing why the power curves differ for different wind speeds, we consider the effect of the TI. Figure 10 shows the power curves for different one-minute-average TIs, from which we can see that the TI is one of the main factors affecting the tested turbine's power curve. (In these figures, we include all the data, including the bins with less than 30 data points.) Here, the output power clearly increases with TI at low wind speeds (less than 8–8.5 m/s), but the trend reverses at wind speeds above 8.5 m/s. The low-speed trend may be primarily due the increased wind energy at higher TIs, while the different trend above 8.5 m/s may be due to high TIs leading to more momentary gusts and hence more frequent cut-outs. Thus, higher TIs increase the power output but reduce the virtual cut-out wind speed. These results reveal a general TI effect that does not depend on the wind direction.

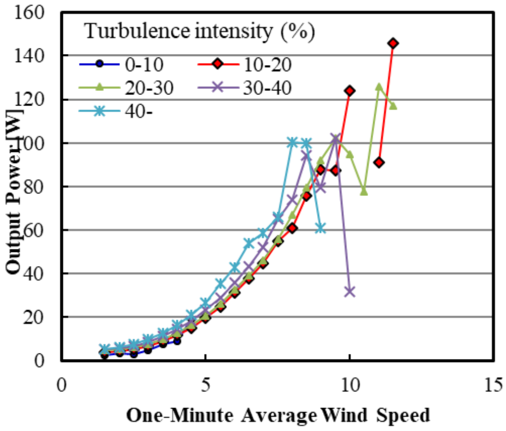


Fig. 10. Power curves for different TIs (one-minute-average)

In order to confirm these hypotheses, Figure 11–Figure 18 show time-series data for the wind speed, output power and turbine rotational speed. First, as representative examples of the results under low-wind-speed conditions, Figure 11–Figure 14 show data for wind speeds of around 6 m/s under low-TI and high-TI conditions. Figure 12 shows the rotational speed and output power under the wind conditions shown in Figure 11 (low-TI). Here, we can see gradual changes in both the wind speed and output power. By contrast, Figure 14. Changes in rotational speed and output power over time under high-TI and low-wind-speed conditions ($\bar{V}$ = 6.13 m/s, TI = 50.7%). Here, the average rotational speed and output power are 526 rpm and 63.3 W, respectivelyFigure 14 shows the rotational speed and output power under the wind conditions shown in Figure 13 (high-TI). Although there are larger wind speed fluctuations in Figure 13 than in Figure 11, Figure 14 shows that the rotational speed follows the wind speed changes and consequently the turbine captures the increased energy provided by the high-speed gust at around 13:16:29. These results for 6-m/s wind suggest that the tested MWT was able to follow the wind speed changes and capture momentary changes in the wind's input power, even at extremely high TIs with gusty wind.

Next, as representative examples of the results under high-wind-speed conditions, Figure 15–Figure 18 show data for wind speeds of around 10 m/s under low-TI and high-TI conditions. Figure 16 shows the rotational speed and output power under the wind conditions shown in Figure 15 (low-TI). Under such low-TI conditions, both the turbine's rotational speed and its output power tracked the wind speed fluctuations. Similarly to the 6 m/s results, the momentary increases in wind speed seen at 13:15:19 and 13:15:34 in Figure 15 were captured properly by the turbine, resulting in consequent output power increases at those times, as shown in Figure 16. Figure 18 shows the rotational speed and output power under the wind conditions shown in Figure 17 (high-TI). Here, we can see that the turbine cuts out at around 12:17:25 in Figure 18. As Figure 17 shows, this was due to a momentarily high wind speed of 17 m/s, which was higher than the turbine's cut-out speed. This gust caused a rapid increase in rotational speed and consequently cut-out to occur, even though the average wind speed during this time was 9.9 m/s, well below the official cut-out wind speed. These results for 10-m/s wind suggest that the turbine generally responded to wind speed changes as well as it did for 6-m/s wind, but that this response sometimes induced cut-out when the wind momentarily gusted to speeds higher than the cut-out speed. Moreover, the effect of cut-out continues tens of seconds which causes hysteresis like effect to the output power. This kind of instantaneous cut-out can be found in other non-furling regulated, micro to small wind turbines. Thus, the increased energies resulting from higher TIs were not always captured by this MWT under high-wind-speed conditions.

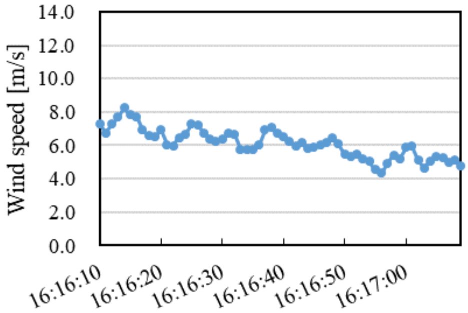


Fig. 11. Changes in wind speed over time under low-TI and low-wind-speed conditions ($\bar{V}$ = 6.17 m/s, TI = 14.4%)

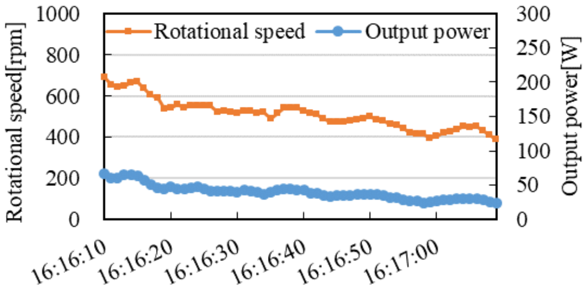


Fig. 12. Changes in rotational speed and output power over time under low-TI and low-wind-speed conditions ($\bar{V}$ = 6.17 m/s, TI = 14.4%). Here, the average rotational speed and output power are 510 rpm, and 39.8 W, respectively

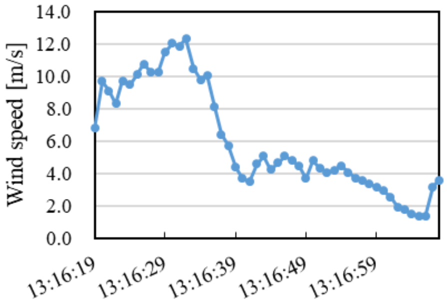


Fig. 13. Changes in wind speed over time under high-TI and low-wind-speed conditions ($\bar{V}$ = 6.13 m/s, TI = 50.7%)

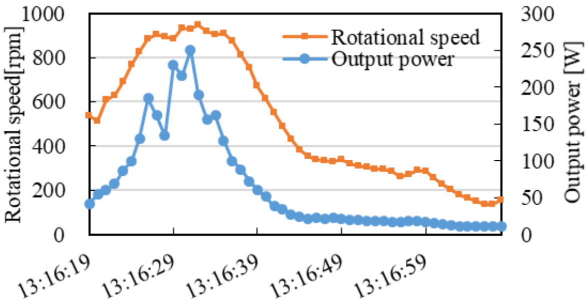


Fig. 14. Changes in rotational speed and output power over time under high-TI and low-wind-speed conditions ($\bar{V}$ = 6.13 m/s, TI = 50.7%). Here, the average rotational speed and output power are 526 rpm and 63.3 W, respectively

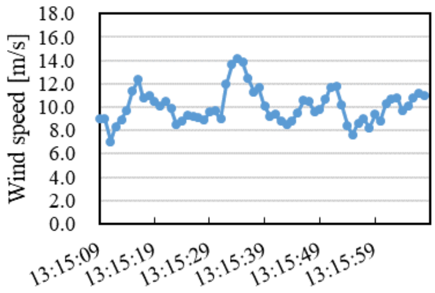


Fig. 15. Changes in wind speed over time under low-TI and high-wind-speed conditions ($\bar{V}$ = 10.1 m/s, TI = 14.2 %)

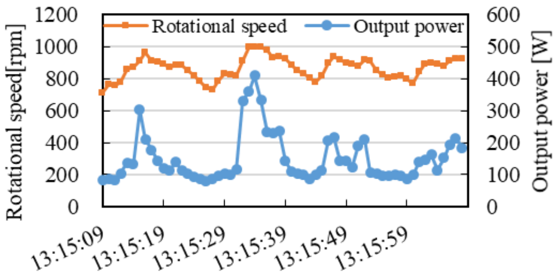


Fig. 16. Changes in rotational speed and output power over time under low-TI and high-wind-speed conditions ($\bar{V}$ = 10.1 m/s, TI = 14.2%). Here, the average rotational speed and output power were 865 rpm and 150.5 W, respectively

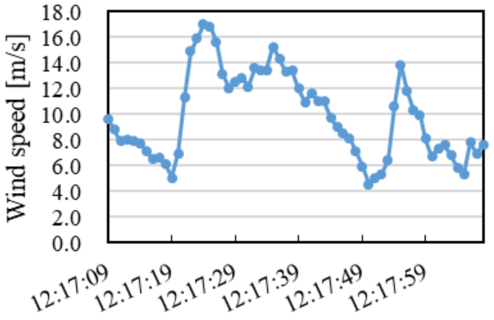


Fig. 17. Changes in wind speed over time under high-TI and high-wind-speed conditions ($\bar{V}$ = 9.9 m/s, TI = 34.1%)

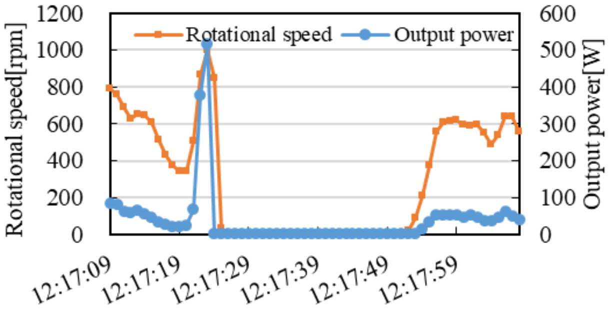


Fig. 18. Changes in rotational speed and output power over time under high-TI and high-wind-speed conditions ($\bar{V}$ = 9.9 m/s, TI = 34.1%). Here, the average rotational speed and output power were 306 rpm and 38.9 W, respectively

Figures 19 and 20 show the relationship between the TI and the one-minute-average output power at wind speeds of 6 m/s and 10 m/s. At 6 m/s, the average output power tends to increase with the TI. Based on our discussion of Figure 11–Figure 14, this is because the output power increased with the input wind power due to the turbine speed responding well to the wind speed changes. From these figures, we can see there is a simple (but non-linear) relationship between TI and output power. Therefore evaluating power performance both by TI and wind speed bin is an effective solution to this type of brake regulated low-inertia wind turbine likewise furling regulated one[10].

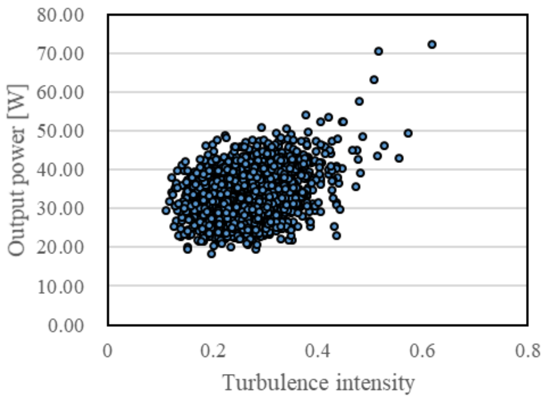


Fig. 19. Relationship between output power and TI at low wind speeds (6 m/s)

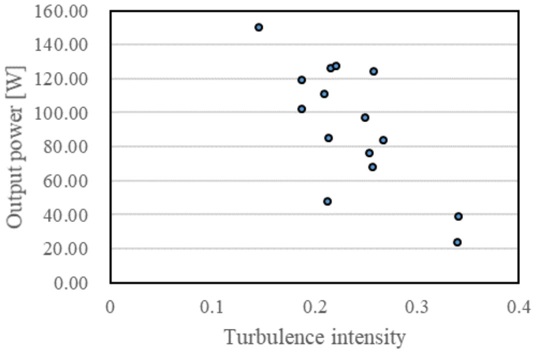


Fig. 20. Relationship between output power and TI at high wind speeds (10 m/s)

V. CONCLUSION

In this paper, we have investigated the effect of the TI on the test turbine's output power performance using both a field test, obtaining the following results.

·Higher TIs increased the output power, even when the average wind speed was unchanged.

·The TI around the building was extremely high. Even at high wind speeds, such as 10 m/s, the TI was 30% or more, well above the IEC's design requirements.

·The tested MWT's power curve tended to lie slightly above that provided by the manufacturer for medium wind speeds (up to about 8 m/s). At 9 m/s or more, however, it fell below the manufacturer's values.

・When considering the power curves for different TIs, the output increased with the TI up to wind speeds of about 8 m/s. However, at higher wind speeds, higher TIs caused the output to reduce.

・The time-series data showed that an MWT with low inertia can follow turbulent wind velocity fluctuations around the building, changing its rotational speed to capture the energy.

・Low inertia leads to increased output, but early cut-outs in high-turbulence, high-wind-speed situations decrease the output.

・Binning output power data by both TI and wind speed is a better way to characterize the performance of MWTs.

From these findings, power performance characterization of micro wind turbines includes highly non-linear phenomenon including the effect of turbulence, mechanical response and control systems. Categorization of power curve by TI showed clear trend of the output power at each wind speed which is caused by non-linear effect of whole dynamic system of the turbine.

However, it could be said that currently it is really difficult to predict power curve under different TI for the tested turbine. This is because all the evaluation are done by simple averaging and there is no parameters which correspond to time constant, hysteresis of the control or such dynamic parameters.

Looking for current situation related to TI effect on the output performance of wind turbines, IEC61400-12-1 Ed.2 [7] provides an informative method of Normalization of power curve data according to the turbulence intensity for large wind turbines which output power have relatively slower response to the change of wind. However, the method is based on the idea that the wind turbine follows, at each instant, a certain power curve. Therefore, more appropriate method should be established to characterize power performance of micro-wind turbines or those turbines which output power at each instant is difficult to be simply determined by instantaneous wind speed.

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