研究論文

Creating a new Index that Captures the Time Dependent Characteristics of Wind Speed Data

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Abstract

In this paper, the fluctuation characteristic of the time variation in wind speed data used to analyze wind power generation is examined. This examination resulted in the creation of a new index that accurately reflects relevant wind characteristics. No satisfactory index had yet been created that reflects the time dependent bias of the fluctuation of wind speed data, even though wind speed patterns are more accurately expressed by considering time dependent characteristics. Once an index has been created, the characteristics can be numerically compared, which allows for easy evaluation. The index proposed here clearly shows the time dependent characteristics of the wind speed data and, thus, allowed for improvement in the analytical accuracy of wind power generation systems.

Key Words: Wind, Wind energy, Wind power generation

1. Introduction

Recently, due to increased awareness of environmental problems, wind power generation has been heralded as a possible solution [1]-[3]. Since the electric power obtained from wind power generation is dependent on meteorological and location conditions that can change, these influences on the power system network are a concern. Thus, a system that maintains a constant level of energy production is examined [4]-[6]. Furthermore, a simulation analysis is carried out that uses the wind speed data in order to verify the effectiveness of the system [7],[8].

The primary method used to evaluate the effectiveness of the installation of the wind power generation is presented below. It is a method based on the total amount of power generation calculated from a wind histogram at the installation site for a certain period and the wind turbine's power curve [1]. However, to perform an analysis of the buffer operations and the proper capacity for the buffer medium in the electric power leveling system, it is necessary to consider not only the wind speed value but also the time dependent wind speed characteristics. Currently, the time dependent wind speed characteristics are examined using graphs [9], and not with a single numerical value.

In this paper, the measurement data were examined to produce a new index that measures the time dependent characteristics of the wind speed data.

2. Time Dependent Wind Speed Characteristics

2. 1 The Need to Consider Time Dependent Wind Speed Characteristics

For most applications, the wind speed data are evaluated using the average wind speed, and the fluctuation characteristics are expressed by the appearance rate of the wind speed value and the turbulence intensity [9]. Fig.1 shows the data obtained with an anemometer located on the roof of a building (approximately 50 m above the ground) at the Tokyo University of Science in Tokyo, Japan as a sample of the wind speed data. Fig.1(a) shows the 10-minute averaged wind speed data for April 2005. The average monthly wind speed was 3.1 m/s. The turbulence intensity that indicates the level of wind speed fluctuation by using standard deviation was 0.57. It is calculated as follows:

$$\text{Turbulence intensity} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(v_i - V)^2} \,/\, V \tag{1}$$

where V is average wind speed, v is wind speed, and n is the number of data points. Fig.1(b) shows the wind speed data shown in Fig.1(a), but here it has been permutated with the pseudo random numbers. The data were arranged according to the following procedures. The pseudo random numbers were first applied to each value of the wind speed data row, and then

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each value of the random number was permutated in ascending order. As a result, the order of each value of the wind speed data corresponding to each random numbers is replaced.

From Fig.1(b) it can be seen that the wind speed values fluctuate more frequently than in Fig.1(a). Furthermore, there does not seem to be any time dependent bias in the fluctuations. However, there is a large difference in the wind speed pattern between these data, even though the average wind speeds and turbulence intensities are the same. Thus, it can be concluded that the observed difference depends on the order of the wind speed value array. Therefore, to indicate the pattern of the wind speed data more accurately, it is necessary to consider the arrangement of the wind speed value, that is, the time dependent characteristic.

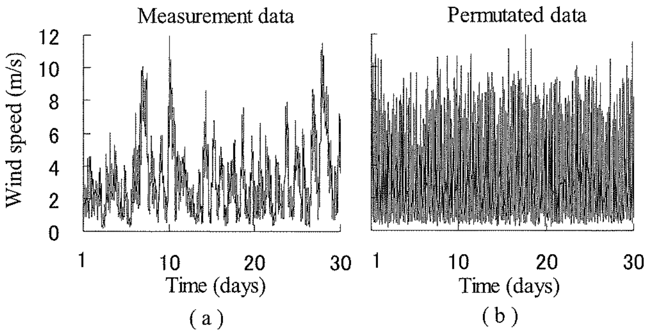


Fig.1. Wind speed data with average wind speed 3.1 m/s. (a) Measurement data. (b) Data whose arrangement has been permutated using pseudo random numbers.

2. 2 Index that Indicates the Time Dependent Characteristics

The time dependent characteristic of the wind speed data has so far been evaluated by clarifying the transitions in the diagram. However, to create a time dependent characteristic index that indicates the pattern of the wind speed data, it is necessary to express this characteristic numerically. Then, we noticed the difference of the adjacent values in the wind speed data array as a factor that indicates the time dependent characteristics of the data. Fig.2 shows the relationship between the average wind speed, V, and the average wind speed difference, Δv , at 1-hour intervals based on original data obtained at a 1-minute sampling interval (obtained from the roof of the building at the Tokyo University of Science in April 2005). The average wind speed difference, Δv , is given by equation (2). The average wind speed difference, Δv , increased with an increase in the average wind speed, V. The data lay approximately on a straight line, as shown in Fig. 2. Therefore, even if the average wind speed fluctuates with time, the ratio between the average wind speed difference and the average wind speed is almost constant.

$$\Delta v = \sum_{i=1}^{n-1} |v_{i+1} - v_i| \Big/ (n-1) \qquad (2)$$

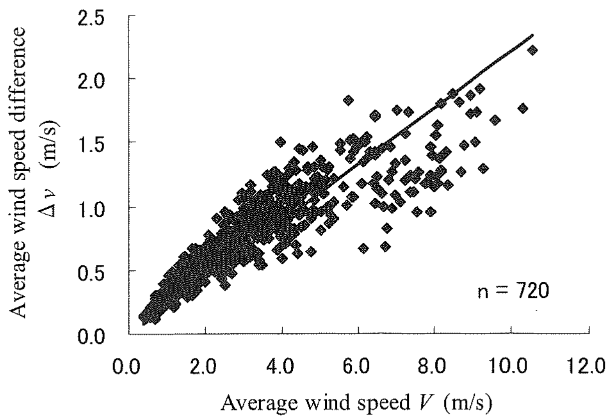


Fig.2. Relationship between average wind speed, V , and the average wind speed difference, Δv , at 1-hour intervals, based on data sampled at 1-minute intervals. (Tokyo, April 2005)

The relationship between the ratio and wind speed pattern was verified using wind speed data from the Rayleigh distribution [1], [9]. This distribution is a function that gives the probability of observing a given wind speed based on the average wind speed. The general formula is

$$R(v) = \frac{\pi}{2} \cdot \frac{v}{V^2} \exp\left\{ -\frac{\pi}{4} \left(\frac{v}{V} \right)^2 \right\} \qquad (3)$$

If no other meteorological data but the average wind speed are available, then this can be used as a rough estimate.

Fig.3 shows the sample wind speed data obtained in 10-minute intervals for a month. In all the data, the monthly average wind speeds are 6.0 m/s, and the turbulence intensities are 0.52. Fig.3(a) shows the wind speed pattern for the case where the wind speed data were given by the Rayleigh distribution permutated using pseudo random numbers, whereas Fig.3(b)-(e) shows the wind speed patterns for the case where the original wind speed data (shown in Fig.3(a)) were arbitrarily permutated. A difference exists in the wind speed pattern, though both of these had the same average wind speeds and turbulence intensities. The ratio between the average wind speed difference, Δv , and the average wind speed, V, for these cases was 0.58, 0.27, 0.14, 0.11, and 0.075 from Fig.3(a) to Fig.3(e), respectively. Thus, a correlation could be seen between the ratios and the wind speed patterns. When the ratio is comparatively large, the fluctuation pattern of the wind speed shows a tendency for the time axis to become uniform, as shown in Fig.3(a). On the other hand, when the ratio is comparatively small, it tends to cause bias in the fluctuation pattern of the wind speed, as shown in Fig.3(e). It is thought that this ratio shows the time dependent characteristics of the wind speed data. Therefore, this ratio is defined as a new index, the time dependent intensity. The time dependent intensity is calculated as follows

$$\text{Time dependent intensity} = \Delta v / V = \sum_{i=1}^{n-1} \left| v_{i+1} - v_i \right| \Big/ (n-1) \cdot V \quad (4)$$

An arbitrary wind speed pattern can be expressed numerically by using the time dependent intensity as a new index with the average wind speed and turbulence intensity used so far.

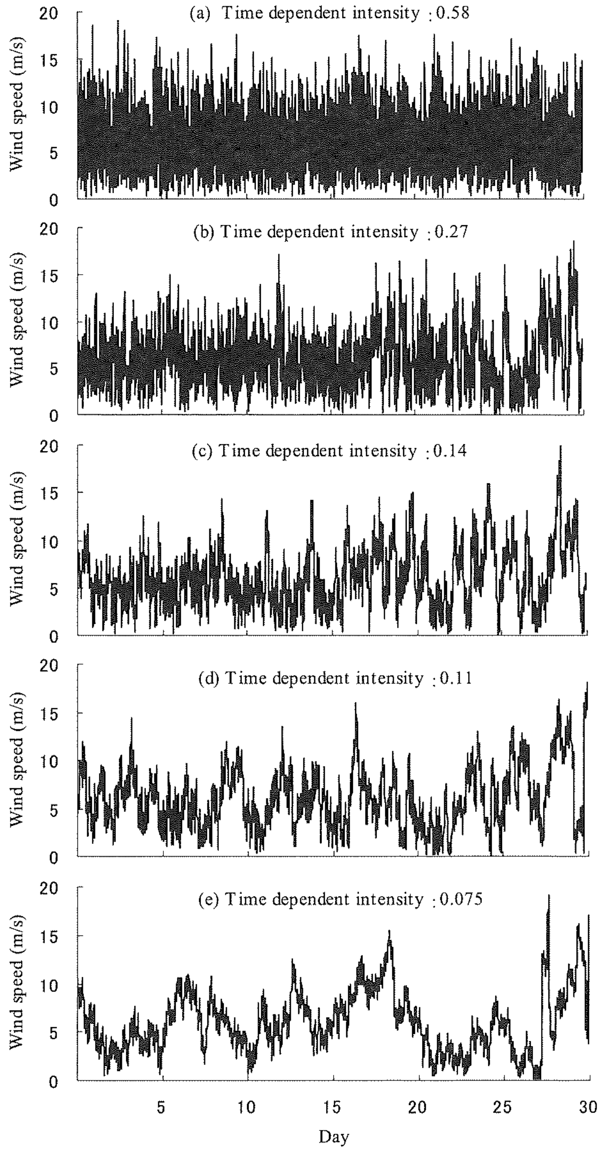


Fig.3. Transition of the wind speed pattern based on the time dependent intensity with 10-minute intervals (Average wind speed = 6.0 m/s, Turbulence intensity = 0.52).

3. Characteristics of the Time Dependent Intensity

3.1 Influence of the Time Interval of the Data

The relationship between the average wind speed data for each time interval and the average wind speed difference for every month is shown in Fig.4. The data are based on annual measurement data obtained from the roof of the building at the Tokyo University of Science during 2005. The intervals used are 1-minute, 10-minute, and 1-hour. The inclination of the approximation line or the time dependent intensity differs depending on the time interval. However, the average wind speed and the average wind speed difference are proportional for each time interval. Therefore, the time dependent intensity of the wind speed data can be used for arbitrary time intervals. Moreover, for the analyses of wind turbine and the leveling system, the wind speed data that considers the time dependent intensity at time intervals corresponding to the characteristics can be used.

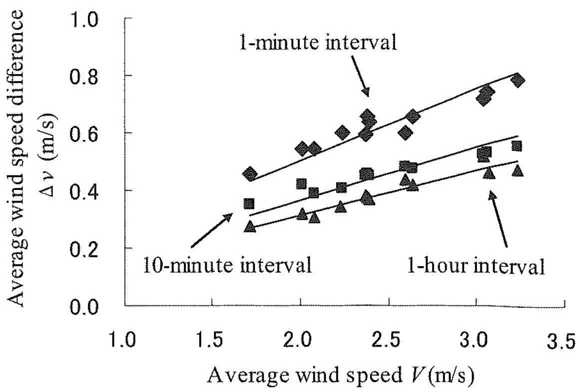


Fig.4. Relationships between average wind speed, V, and the average wind speed difference, Δv, at 1-minute, 10-minute, and 1-hour intervals for every month based on annual measurement data (2005).

3.2 Regional Characteristics

The differences in the time dependent intensity by region were verified. The following locations were used to verify the regional differences in the index: Miyako Island in Okinawa Prefecture, Choshi in Chiba Prefecture, and Urakawa in Hokkaido. The locations are shown in Fig.5.

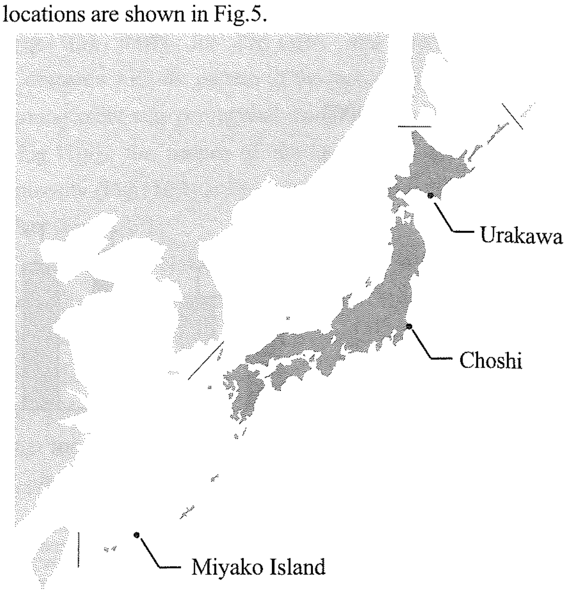


Fig.5. Location of the sites used for the analysis of regional characteristics.

The data were obtained from the Japan Meteorological Agency [10] for the year 2004. The annual average wind speed was 5.0 m/s at Miyako Island, 5.7 m/s at Choshi, and 4.4 m/s at Urakawa.

Fig.6 shows the monthly averaged time dependent intensity for each location. From this figure, it can be seen that the time dependent intensity is different for each region. Therefore, the time dependent intensity has a particular value in each region.

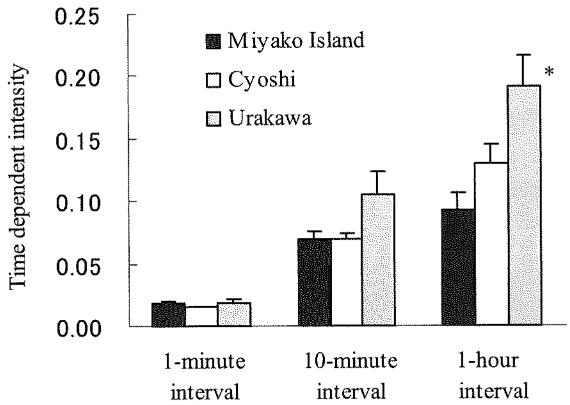


Fig.6. Comparison of the time dependent intensity of the wind speed for Miyako Island, Choshi, and Urakawa in 2004 at 1-minute, 10-minute, and 1-hour intervals. *Standard deviation

3.3 Reproducibility

The reproducibility of the time dependent intensity was verified based on the wind speed data for three years (2003-2005) on Miyako Island. The annual average wind speed was 4.6 m/s in 2003, 5.0 m/s in 2004, and 5.1 m/s in 2005. Fig.7 shows a comparison of the time dependent intensity in 2003, 2004, and 2005 at 1-minute, 10-minute, and 1-hour intervals.

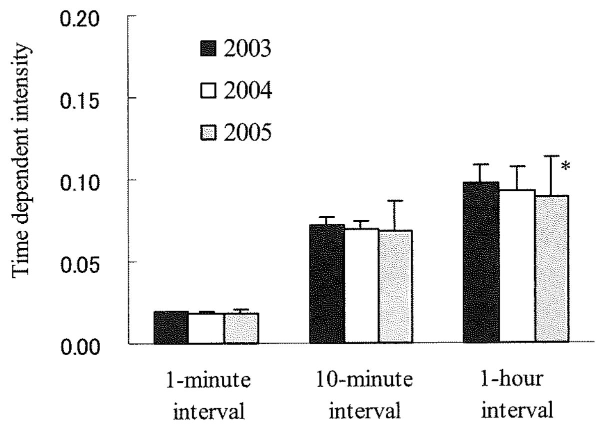


Fig.7. Comparison of the time dependent intensity of the wind speed data in 2003, 2004, and 2005 at 1-minute, 10-minute, and 1-hour intervals. *Standard deviation

The average time dependent intensity is almost equal for each year. In addition, since there was no significant difference in the data variance, which was confirmed by using a one-way analysis of variance (P=0.95), the time dependent intensity can be considered to have a high reproducibility. Therefore, the time dependent intensity has the advantage that once data have been acquired, it can be used for different time periods at the same location and time interval. Furthermore, since the time dependent intensity is practically constant, even if the average wind speed fluctuates, it does not always need to be observed at the same location.

4. Reproduction of Wind Speed Data Using the Time Dependent Intensity

When the time dependent intensity is applied to the wind speed data, the wind speed pattern can be expressed numerically. Fig.8 shows the wind speeds for 2005 based on 10-minute intervals on Miyako Island.

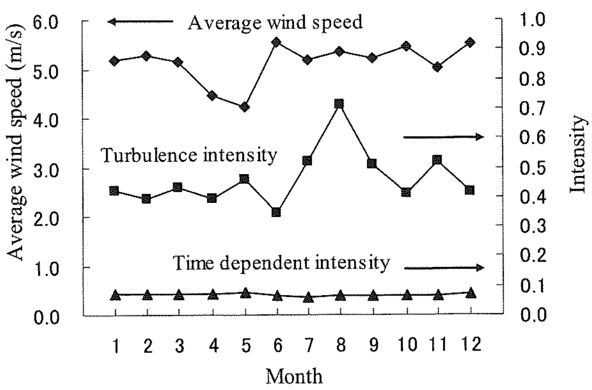


Fig.8. Annual wind speed data for 2005 on Miyako Island. The monthly average wind speed, turbulence intensity, and the time dependent intensity are shown.

In Fig.8, the data are summarized using the monthly average wind speed, turbulence intensity, and the time dependent intensity. The wind speed with a large number of data and an irregular fluctuation characteristics can be shown by only three parameters. Then, to verify the accuracy of the expression method for the wind speed data using these parameters, the annual wind speed data were reproduced using the parameters and compared with the original measured data. The following method of generating the wind speed data and arranging was used to reproduce the data.

It should be noted that the purpose of this verification is not in faithful reproduction of the original wind speed data. The purpose is in confirmation of the effectiveness of using the time dependent intensity as one index to evaluate the wind conditions.

4.1 Method of Generating Wind Speed Data

When the probability of each wind speed value is presumed from the average wind speed value, the Rayleigh distribution can be used to roughly estimate the original data [9]. However, the probability of each wind speed value given by the distribution is always constant. The probability of each wind speed value in the actual data changes with time and region. Thus, the wind speed value is given by the Weibull distribution [1],[9], which allows the probability rate to change. The general Weibull distribution is given as

$$W(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\} \tag{5}$$

where c is a scale parameter,

$$c = V / \Gamma\left(1 + \frac{1}{k}\right) \tag{6}$$

k is a shape factor, and Γ is the gamma function.

Fig.9 shows a sample Weibull distribution. The relationship is given between the wind speed and the wind speed probability for an average wind speed, V, of 6.0 m/s and for using k as the parameter.

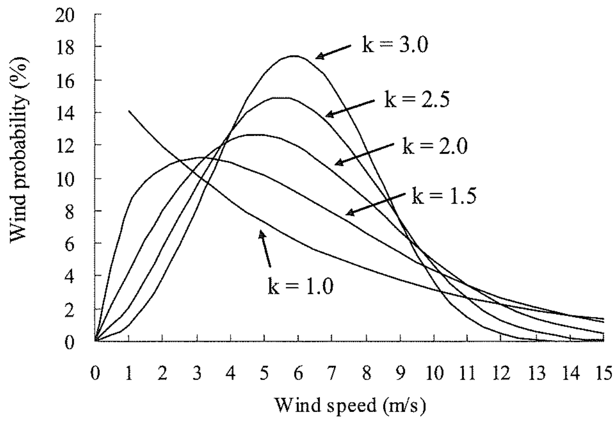


Fig.9. Wind speed distribution based on the Weibull function for an average wind speed, V, of 6.0 m/s.

4.2 Method of Arranging the Wind Speed Data

The wind speed data were arranged according to the following procedures. First, the upper limit value was determined as the wind speed difference between the adjacent data. Second, the wind speed data were arranged using pseudo random numbers. The method is described above. The lowest data point was moved to the tail of the arrangement when the difference of the two adjacent data points was greater than the upper limit value. All the other data were shifted by one. The arrangement of the wind speed data was permutated by repeating the operation. If a wind speed difference of less than the upper limit setting value was not found, the data were left unchanged, and the operation shifted to the following data. The relationship between the upper limit setting value and average wind speed difference when the above-mentioned arrangement method was used is shown in Fig.10 for an average wind speed of 6.0 m/s. The average wind speed difference depends on the upper limit setting value, as shown in the figure. Therefore, the wind speed difference can be controlled by arbitrarily choosing the upper limit setting value and permutating the data. As a result, the time dependent intensity of the wind speed data can be adjusted.

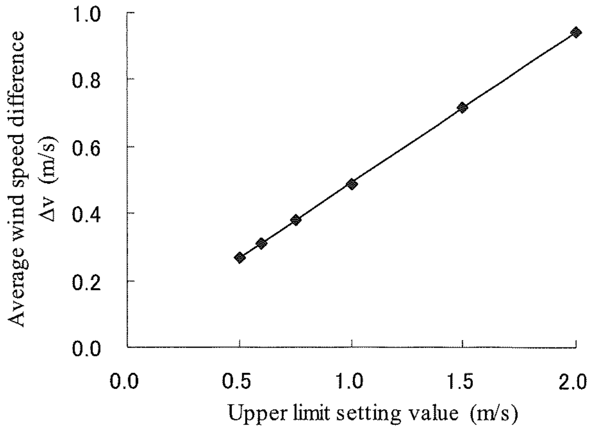


Fig.10. Relationship between upper limit setting value and the average wind speed difference for an average wind speed of 6.0 m/s.

4.3 Reproduction of the Wind Speed Data

Fig.11 shows the wind speed data for January partially reproduced using the abovementioned method. In this figure, the wind speed data are given by the Weibull distribution. The data used to permutate the arrangement were determined using the pseudo random numbers (Fig.11(a)) or the time dependent intensity (Fig.11(b)). Fig.11(c) shows the original measured data. The time dependent intensity of the wind speed for is 0.47 for Fig.11(a), 0.071 for Fig.11(b), and 0.071 for Fig.11(c). Compared with the pattern of the reproduced wind speed whose arrangement was permutated using the pseudo random numbers (Fig.11(a)), the pattern of the data using the time dependent intensity (Fig.11(b)) is much closer to the original measurement data (Fig.11(c)).

When reproducing the data, it is difficult to faithfully reproduce the original wind speed data. This is because in nature, there are factors that are dependent on local conditions. However, in order to accurately evaluate the wind power generation and leveling system of a power generator, it is necessary to use data that reflect the fluctuating distribution of the wind speed during some constant cycle, such as a year, even if the original data that accurately express the actual wind speed value are not used. Therefore, there is no need to completely reproduce the measured wind speed data, since an approximation is sufficient. The characteristics of the probability distribution and the arrangement order of the wind speed data, as well as the wind speed data that reflects these characteristics, can be reproduced by using the time dependent intensity with the average wind speed and turbulence intensity.

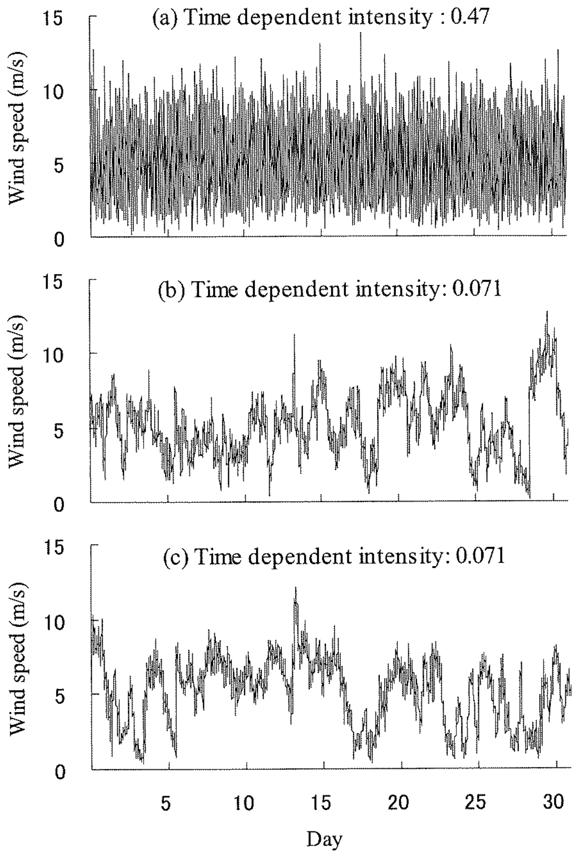


Fig.11. Comparison between the reproduced wind speed data and the measured wind speed data for January 2005 on Miyako Island. (a) Data whose arrangement were permutated using pseudo random numbers. (b) Data whose arrangement were permutated using the time dependent intensity. (c) The measured data.

5. Effect on Analysis by Applying the Time Dependent Intensity

The effect on the analysis using three different wind speed data (Miyako Island, 2005) shown in the above section was verified using the electric power leveling system of wind power generation. By buffering against the changes in power generation due to fluctuations in wind speed, the system provides a constant source of electric power to the electric load. This system is shown in Fig.12. The analytical conditions of the power control in this system are shown as follows. 1) The resultant power was equal to the total sum of generated power and the battery output power. 2) The resultant output did not exceed the rating capacity of the load. 3) The control pattern followed the flow chart of Fig.13.

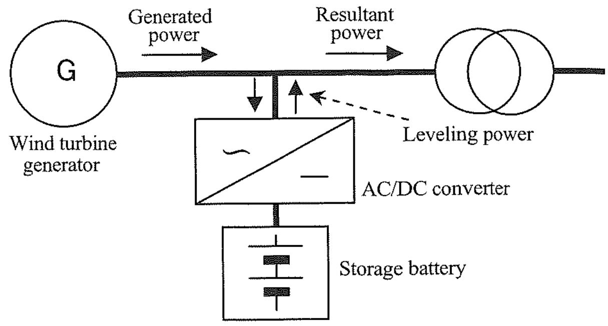
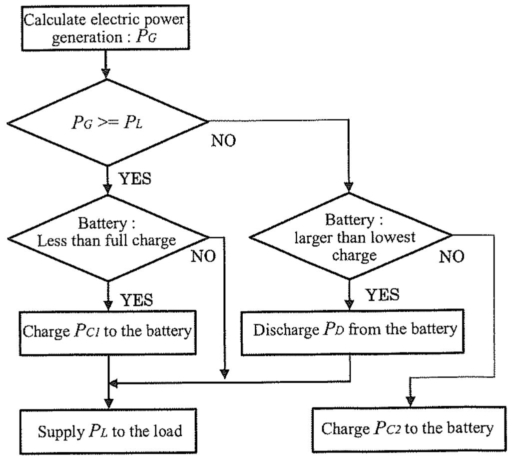


Fig.12. System configuration used for analysis.



P_G : Power generated by the wind turbine generator
P_L : Load capacity
P_{C1} : Charge power to the battery
$P_{C1} = (P_G - P_L) \times \eta_{DC} \times \eta_C$
P_{C2} : Charge power to the battery
$P_{C2} = P_G \times \eta_{DC} \times \eta_C$
P_D : Discharge power from the battery
$P_D = (P_L - P_G) \div \eta_{DC} \div \eta_D$
η_{DC} : AC/DC converter conversion efficiency
η_C : Electric charge efficiency to the battery
η_D : Electric discharge efficiency from the battery

Fig.13. Flow chart of system control.

The wind turbine generator in the system was assumed to have a rated output of 1000 kW (MWT-1000A [11], made by Mitsubishi Heavy Industry, Ltd.). The power generation was calculated from the wind speed data and the generator power curve shown in Fig.14. Moreover, it was assumed that the converter conversion efficiency was 95%, the electrical charge and discharge efficiencies of the storage battery were 90%, and the depth of discharge of the storage battery was 50%.

The hourly average power generation was 179.8 kWh using the reproduced data with either the random number arrangement, as shown in Fig.11(a), or the time dependent intensity arrangement, as shown in Fig.11(b). The result was not influenced by the arrangement of the wind speed data. However, the amount of power generation was 175.1 kWh if the original data, shown in Fig.11(c), were used. Thus, the results were practically the same.

Fig.15 shows the relationship between the capacity of the storage battery and the supply rate of the electric power to the load with each wind speed when a 150 kW load, which accounts for approximately 85% of the average hourly power generation, was assumed to be a rated load. In an analytical result using both reproduced data, the supply rate of electric power tended to increase with the increase in storage battery capacity. However, when the data using the time dependent intensity were used, the increase in the supply rate was small compared with the increase in the storage battery capacity for capacities greater than 10 kWh. This result corresponds approximately with the data curve shown by the analysis that uses original measurement wind speed data and is mainly due to the large time dependent characteristic of the wind speed data. It is suggested that the fluctuation characteristic of the reproduced data can be approximated by the original characteristics of the measured data using the time dependent intensity. In the analysis of such a buffer operation, it is important to use the wind speed data that consider the time dependent intensity because the time dependent characteristics of the wind speed data greatly influence the result.

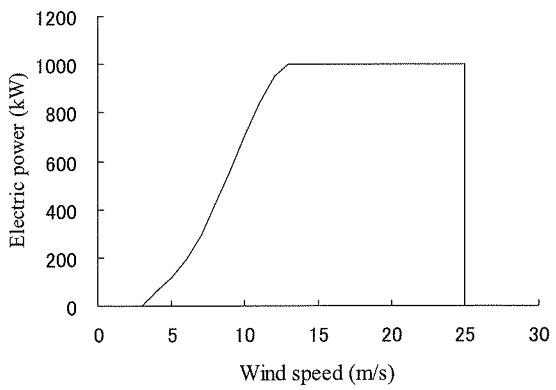


Fig.14. Power curve of a wind turbine generator, MWT-1000A.

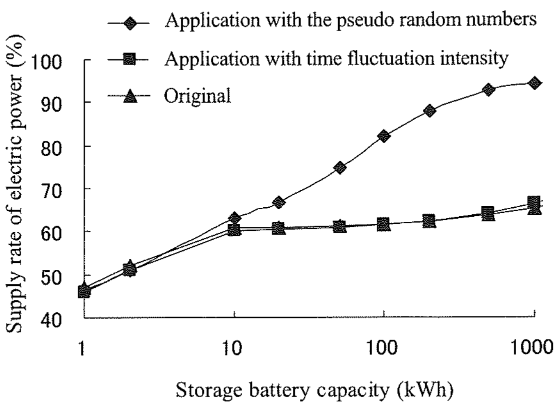


Fig.15. Relationship between storage battery capacity and supply rate of electric power for each wind speed in the electric power leveling system of wind power generation. The supply rate of the electric power was calculated by the total amount of the supplied electric power / total amount of the rated power capacity of the load × 100 in an analytical period (one year).

6. Conclusion

The time dependent characteristics of wind speed data were examined. The following results were obtained:

1. The time dependent characteristics of the data can be expressed numerically by using the time dependent intensity, defined as follows:

   Time dependent intensity $= \Delta v / V$

2. The time dependent intensity has reproducibility, although its value depends on the time interval and location of the measurement site. Thus, once acquired, the value is applicable to other periods.
3. Since the time dependent characteristics of the wind speed data have previously been evaluated based on graphs, the use of a numerical index will make this process easier. Furthermore, the wind speed data are more accurately expressed using the time dependent intensity combined with the average wind speed and turbulence intensity. Thus, this method can contribute to the improvement of the analytical accuracy of wind power generation models.

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