Detection of Lightning Damage on Wind Turbine Blades using the SCADA System

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***Abstract*-- In recent years, there have been several reports of blade damage caused by lightning strikes on wind turbines. A few of these accidents have resulted in more serious secondary damage owing to the continued rotation of the damaged blades. To prevent the initial damage from spreading in this manner, wind farms in the regions of Japan vulnerable to winter lightning were required to introduce lightning detection systems, which can accurately detect when lightning strikes the wind turbine and then immediately stop the rotation of the blades. Normally, when the system detects a lightning strike to a wind turbine and stops operation, the process of restarting is initiated only after the soundness of the blades is confirmed by visual inspection. However, in bad weather, it is often difficult to check the soundness of the blade visually, and the resulting delay in the restart process prolongs the downtime and reduces the availability of the wind turbine. In this paper, we report the results of using the supervisory control and data acquisition (SCADA) system data to check the soundness of the blades after a lightning strike to resume operations more quickly, thereby increasing up-time.**

***Index Terms*-- Lightning detection system, Lightning protection, SCADA, Wind turbine**

I. Introduction

IN recent years, increased attention to the problem of global warming has driven the growth of the use of renewable energy globally. Wind power, a renewable energy source, has attracted attention as a cost-effective power generation method, and large-scale development is being promoted including offshore. In Japan, a quarter of wind turbines are installed in the windy region along the coast of the Sea of Japan, and the wind turbines themselves are becoming larger, making them more vulnerable to damage from lightning strikes. In many cases, a lightning strike can irreparably damage the blade of a wind turbine, for example, by cracking or piercing it. There have been numerous reports of rotating blades suffering such damage and of the damage being compounded by centrifugal force, wind pressure, and other forces, leading to dangerous accidents in which component parts flew off into the surrounding area [1]-[3].

To prevent such accidents, the Ministry of Economy, Trade and Industry partially revised its guidance on the technical standards for wind power generation facilities [4]. Consequently, lightning detection systems (LDSs) were installed in wind farms in the regions vulnerable to winter lightning along the Sea of Japan. Whenever a lightning strike is detected by an LDS, the wind turbine must be brought to an emergency stop and it cannot be restarted until a safety check is conducted by visual inspection [5]. However, the wind turbines are sometimes difficult to check rapidly owing to geographical factors in the area where they are installed, which can lead to delays before the operation is resumed. In these cases, the prolonged downtime causes a decrease in availability. One wind farm reported that the inability to restart immediately after a lightning strike owing to weather or other obstacles reduced its availability by 2.23% on an annual basis [6].

To solve this problem, we attempted to use data from the Supervisory Control and Data Acquisition (SCADA) system, which is a remote monitoring and control system, for the detection of wind turbine blade anomalies. If the soundness of the blades can be confirmed using the data from the SCADA system, this will enable faster resumption of operations after an emergency stop owing to a lightning strike, as visual inspection will no longer be necessary. Furthermore, SCADA systems are installed in virtually all wind farms and offer the advantage of easy data collection.

Previous studies on wind turbine anomaly detection methods based on SCADA system data could demonstrate that wind turbine anomalies can be detected using parameters such as temperature, power curve, and blade rotational speed [7]-[9]. However, these anomaly detection methods were intended to collect long-term operation data regularly from wind turbines and detect the possibility that failure occurred several weeks to several months in the past. They were not intended for immediately determining the degree of blade damage caused by an unexpected event such as a lightning strike. This study aims to verify whether it is possible to prevent blade damage from spreading by monitoring and analyzing the SCADA system data. Accordingly, we examine four case studies of major damage caused by lightning strikes selected from among the blade damage accidents that have occurred in the regions of Japan vulnerable to winter lightning.

This paper consists of the following 4 chapters. In Chapter 2. The data of the SCADA system and lightning used for the verification of blade conditions are introduced. In Chapter 3, The verification methods and results to understand the blade conditions is explained. Finally, we conclude the paper in Chapter 4.

Manuscript received Month xx, 2xxx; revised Month xx, xxxx; accepted Month x, xxxx.

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II. Data of Lightning and SCADA System

A. SCADA System

TABLE I
Example of SCADA System Configurations

Acquisition data	Time interval [s]
wind speed, wind direction, rotational speed, power, pitch degree, nacelle degree, temperature of each part	1-600

TABLE I
Damage Accidents of Wind Turbine and Lightning Data

Name of wind farm	The time of lightning strike	Lightning data	
		Maximum current [kA]	Electric charge [C]
Wind farm Y	2013/11/20 21:38:31	45	-
Wind farm A	2013/12/1 2:11:24	-31	-
	2013/12/6 4:28:59	27	-
	2013/12/6 4:30:17	12	-
	2013/12/6 9:08:58	-14	-
	2013/12/6 9:15:15	-7	-
	2013/12/11 18:35:25	73	-
	2013/12/11 18:36:50	11	-
	2013/12/11 18:40:30	-14	-
	2013/12/11 19:59:13	238	-
Wind farm F	2014/11/6 20:31:49	87	-
Wind farm H	2018/2/14 19:46:35	19	328

Note: The lightning strike at wind farm H was measured by an LDS with a frequency band of 0.1 Hz to 1 MHz. The lightning strikes at the other wind farms are based on LLS data from Franklin Japan.

TABLE II
Targets of Examinations

Name of wind farm	Type of SCADA data	Data period of examinations	
		At the time of accident	At the time of normal operation
Wind farm Y	1-min average data	2013/11/20 19:20:00 to 2013/11/20 22:10:00	2019/5/8 9:51:00 to 2019/6/10 9:04:00
Wind farm A	1-min average data	2013/11/30 0:00:00 to 2013/12/14 12:00:00	2013/10/1 0:00:00 to 2013/10/31 23:59:00
Wind farm F	1-min average data	2014/11/6 17:30:01 to 2014/11/6 21:00:01	2019/5/8 10:04:00 to 2019/6/10 9:05:00
Wind farm H	10-min average data	2018/2/13 2:00:00 to 2018/2/17 8:40:00	2017/8/1 0:00:00 to 2018/1/31 23:50:00

SCADA systems are used to monitor the current state of the wind turbine remotely (wind speed, wind direction, rotational speed, amount of power generated, component temperatures, etc.). Most modern wind turbines can collect data every 1 s; however, as this requires large storage capacity, several systems collect average data every minute or every ten minutes. Table I lists the example of SCADA system configurations. Details in Table I are omitted due to confidentiality agreements with the business operator.

In this study, we examined and verified the relationship between the SCADA system data and the blade damage caused by lightning strikes by verifying the time characteristics and data relationships in the data acquired from the SCADA system.

B. Target of Examination

Table I lists the name of the wind farm where each accident occurred, the time at which the lightning strike is believed to have caused the accident, and the maximum current value and quantity of charge recorded by the detector. Note that an LDS was installed in wind farm H when an accident occurred there, but the other wind farms were not equipped with LDSs.

Therefore, the timing of the lightning strikes and the maximum current values for wind farms Y, F, and A were estimated based on data from the Japanese Lightning Detection Network (JLDN), a lightning location system (LLS) deployed throughout the country by Franklin Japan. The data for wind farm H was recorded by an LDS having a frequency band of 0.1 Hz to 1 MHz. In this study, we examined the SCADA system data collected at the time of the accidents listed in Table I. For the purpose of comparison with normal conditions, we also examined the SCADA system data from long periods of normal operation. Table II lists the types of SCADA system data examined in this study and the time period in which they were recorded.

III. Verification of Blade Conditions

A. Accident at Wind Farm Y

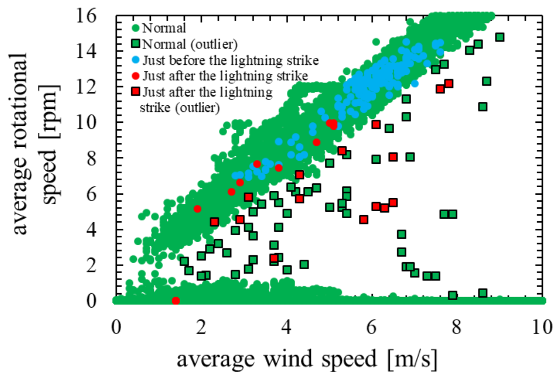
At wind farm Y, an accident was reported in which the blade broke after being struck by lightning. The following is a summary of the accident.

At 21:38:31 on November 20, 2013, a lightning strike directly hit a wind turbine blade, damaging a part of the blade. The wind turbine did not stop automatically and continued running after the lightning strike. The damage is assumed to gradually spread for approximately 20 min, subsequently resulting in breakage of the blade.

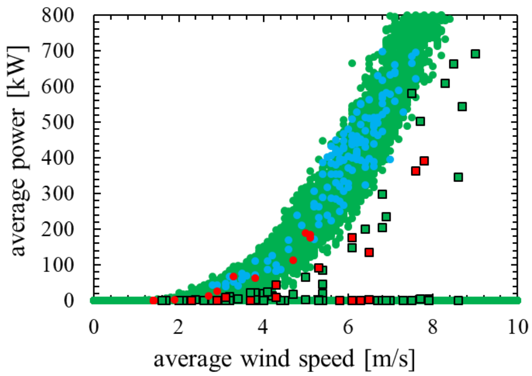
In this example, simply observing the time characteristics of each parameter in the SCADA system data (wind speed, the amount of power generated, rotational speed, etc.) did not reveal any anomalies. Therefore, we focused on the input/output relationships of the wind turbine. Here, wind speed was selected as the input data, rotational speed and the amount of power generated were selected as the output data, and these input/output characteristics were compared before-and-after the lightning strike and during normal operations to determine whether any blade anomalies could be detected.

Fig. 1 shows the wind speed–rotational speed and wind

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRD.2020.2992796, IEEE Transactions on Power Delivery



(a) Wind speed–rotational speed characteristic



(b) Wind speed–power characteristic
Fig. 1. SCADA data at wind farm Y

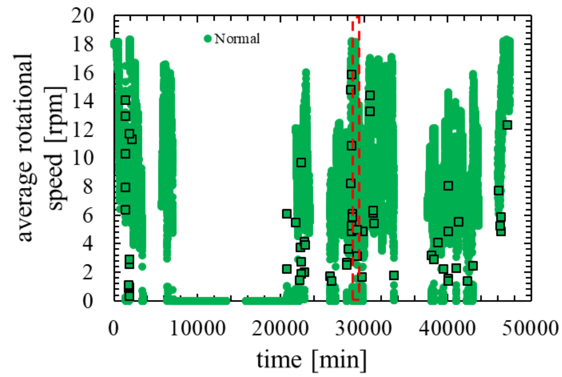
speed–amount of power generated characteristics. The SCADA system data before and after the lightning strike are plotted in separate graphs such that the values before and after the lightning can be compared. In the graphs, the green dots represent the data during normal operation, the blue dots represent the data immediately before the lightning strike, and the red dots represent the data immediately after the lightning strike. The square dots are values that fall clearly outside the overall trend (hereinafter referred to as "outliers") in wind speed–rotational speed characteristic. Fig. 2 shows the time characteristic of the rotational speed. Note that the data acquisition start time in Fig. 2 is 0 min.

From Fig. 1, it is apparent that outliers occur frequently after the lightning strike. Fig. 2 (a) and (b) show outliers occurring during normal operation; however, in all cases, one or two outliers are followed by a return to normal values. Outliers never occur three or more times in succession. In contrast, Fig. 2 (c) shows that, after a lightning strike, there is a continuous series of outliers.

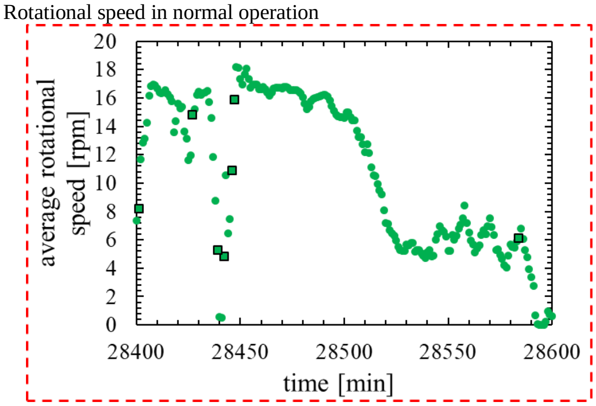
The rotational speed of the wind turbine depends on the lift L acting on the blade. The lift L can be obtained by the following equation.

$$L = \frac{1}{2} C_L \rho V^2 A \text{ [N]} \tag{1}$$

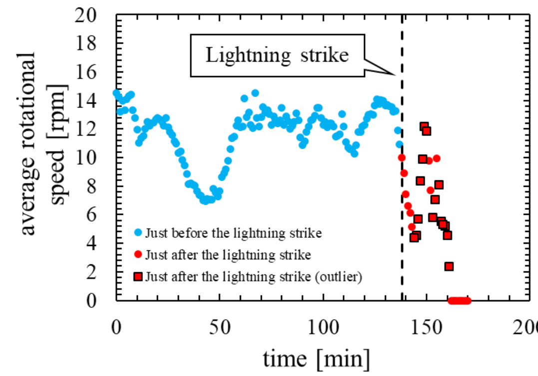
where C_L is the lift coefficient of the blade, ρ is the air density [kg/m^3], V is the wind speed [m/s], and A is the blade projection area [m^2] [10]. As the lift coefficient C_L varies depending on the shape of the blade, the value may become smaller than the design specification if lightning cracks or



(a) Rotational speed in normal operation



(b) Rotational speed in normal operation (partial expansion)



(c) Rotational speed at the time of accident
Fig. 2. Time characteristic of rotational speed at wind farm Y

pierces the blade of the wind turbine. In this case, the lift L becomes smaller for the same ρ, V, and A, thereby decreasing the rotational speed as indicated in (1). The figures confirm that, after a lightning strike, the rotational speed remains low for an extended period, as shown in Fig. 2 (c), and the lift coefficient of the blade tends to decrease, as shown in Fig. 1 (a).

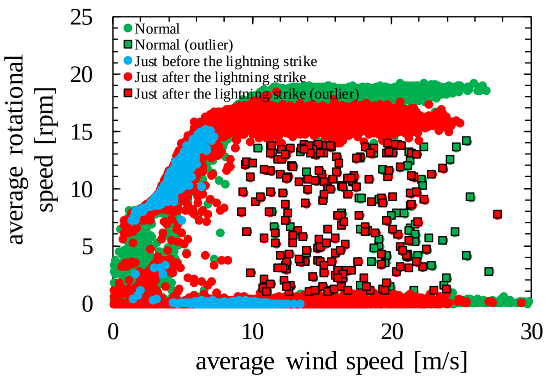
Furthermore, the amount of power generated decreases as the rotational speed decreases, as shown in Fig. 1 (b).

The analysis presented above suggests that, when outliers occur in a continuous series after a lightning strike, as shown in Fig. 1, we can assume that a blade has been damaged by a lightning strike, and that the lightning that damaged the blade greatly exceeded the lightning resistance of the wind turbine. In this case, the outliers caused by blade anomalies appear in the SCADA system data, and hence, it is likely that the accident could have been prevented by secondary use of SCADA system data.

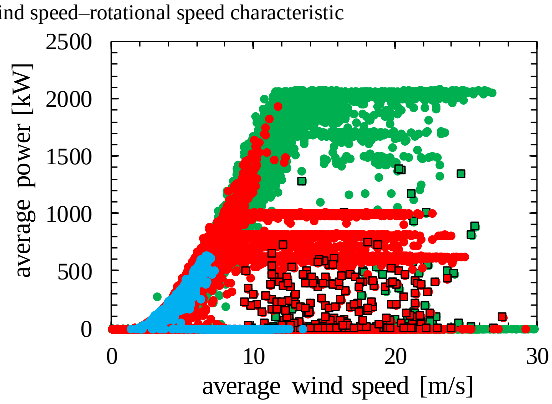
B. Accident at Wind Farm A

At wind farm A, there was an accident in which a lightning strike caused the tip receptor to fall out. The following is a summary of the accident.

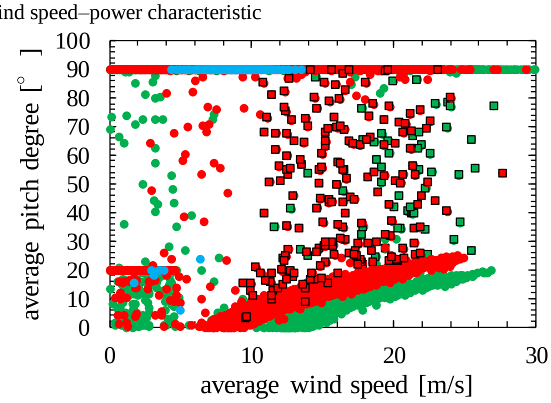
Lightning penetrated the blade skin and struck the downconductor inside the blade. Consequently, the air inside the blade tip expanded, damaging the blade. The wind farm was not equipped with an LDS, and hence, we assume that the turbine continued to run even after the lightning strike, and that the connection between the tip receptor and the blade skin with downconductor was broken, causing the tip receptor to fly apart. On November 30, 2013, a maintenance check confirmed that the blade was sound. From that time until December 14, 2013, when it was confirmed that the tip receptor had fallen out, nine lightning strikes were observed by an LLS within a radius of 3 km from the wind turbine. It is not known which lightning strike caused the receptor to fall out.



(a) Wind speed–rotational speed characteristic



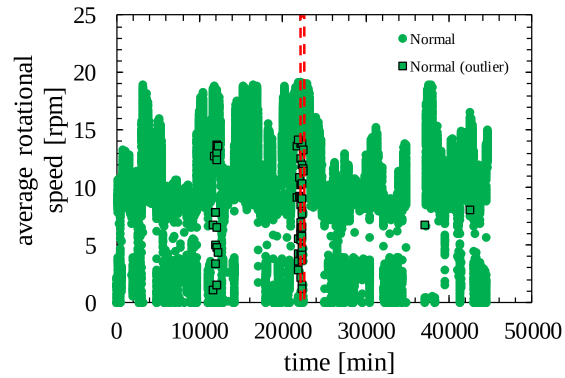
(b) Wind speed–power characteristic



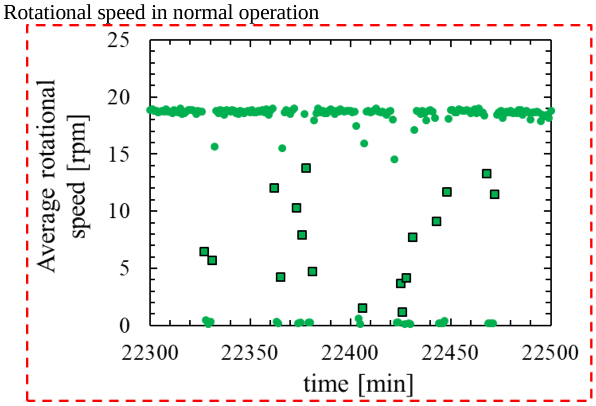
(c) Wind speed–pitch degree characteristic

Fig. 3. SCADA data at wind farm A

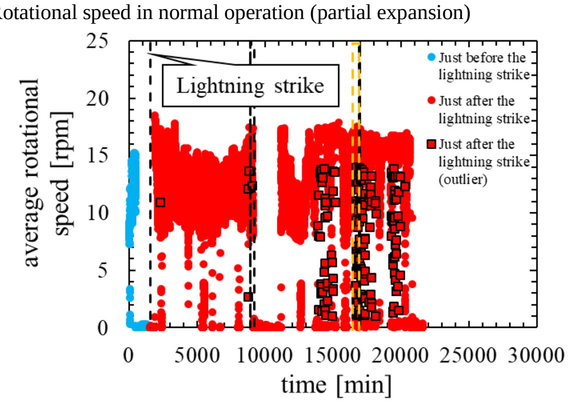
Similar to the example at wind farm Y, in this example, it would not have been possible to predict the blade anomalies from the time characteristics of the SCADA system data. Similar to the previous case, we therefore focused on the input/output characteristics of the wind turbine. Here, wind speed was selected as the input data, and rotational speed, the



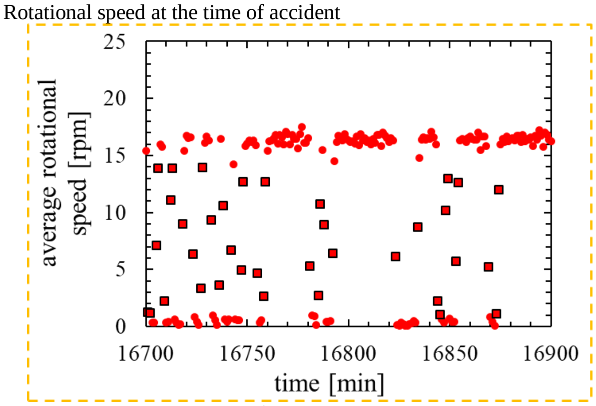
(a) Rotational speed in normal operation



(b) Rotational speed in normal operation (partial expansion)



(c) Rotational speed at the time of accident



(d) Rotational speed at the time of accident (partial expansion)

Fig. 4. Time characteristic of rotational speed at wind farm

A amount of power generated, and pitch degree were selected as the output data. These input/output characteristics were compared before-and-after the lightning strike and during normal operation to determine if any blade anomalies could be detected.

Fig. 3 shows the wind speed–rotational speed, wind speed–amount of power generated, and wind speed–pitch degree characteristics. The SCADA system data before and after the lightning strike are plotted in separate graphs so that the values before and after the lightning can be compared. Similar to the graphs for wind farm Y, the green dots represent the data during normal operation, the blue dots represent the data immediately before the lightning strike, and the red dots represent the data immediately after the lightning strike. The square dots are outliers in wind speed–rotational speed characteristic. Fig. 4 shows the time characteristic of the rotational speed with the data acquisition start time set to 0 min.

From Fig. 3, it is apparent that outliers occur frequently after the lightning strike. As shown in Fig. 4 (b) and Fig. 4 (d), outliers occur even under normal conditions, but less often than after lightning strikes. Fig. 4 (c) shows that outliers occur frequently and are concentrated approximately 14000 min after the start of data acquisition, suggesting that the blade likely suffered serious damage around this time. Outliers also occur at the same time in the wind speed–pitch degree characteristic graph in Fig. 3 (c). These outliers are believed to be due to the wind turbine control system. As shown in Fig. 5, the pitch degree is normally controlled using the power generation setting value and the current power generation value [11]. As shown in Fig. 3 (b), an outlier occurs at the same time in the wind speed–amount of power generated characteristic, which suggests that this caused the pitch degree outlier.

In this case too, as outliers caused by blade anomalies were observed in the SCADA system data, it is likely that the accident could have been prevented by secondary use of SCADA system data.

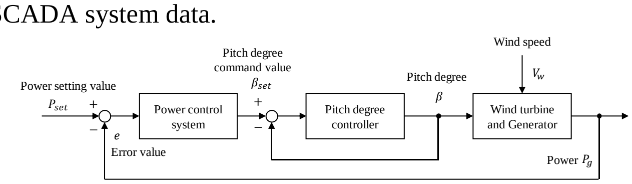


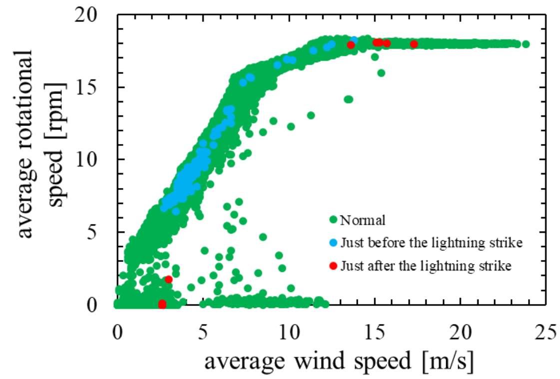
Fig. 5. Control system of wind farm

C. Accident at Wind Farm F

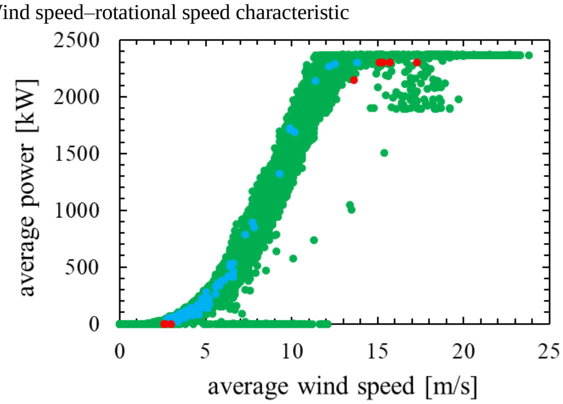
At wind farm F, an accident was reported in which the blade broke after being struck by lightning. The following is a summary of the accident.

At 20:29:49 on November 6, 2014, lightning directly struck a wind turbine blade, damaging it. At this time, a low-voltage ground fault was detected in the wind turbine, and it was stopped automatically 20 to 30 s after the lightning strike. However, it is assumed that the blade was torn as a result of wind pressure, causing the damage to spread during or shortly after the operation to stop the wind turbine.

In this example, as in the other examples, it would not have been possible to predict the blade anomalies from the time



(a) Wind speed–rotational speed characteristic



(b) Wind speed–power characteristic

Fig. 6. SCADA data of wind farm F

characteristics of the SCADA system data. Similar to the previous case, we therefore focused on the input/output characteristics of the wind turbine. Here, wind speed was selected as the input data, rotational speed and the amount of power generated were selected as the output data, and these input/output characteristics were compared before-and-after the lightning strike and during normal operations to determine whether anomalies could be detected.

Fig. 6 shows the wind speed–rotational speed and wind speed–amount of power generated characteristics. The SCADA system data before and after the lightning strike are plotted in separate graphs so that the values before and after the lightning strike can be compared. The types of plots are the same as those for wind turbines Y and A.

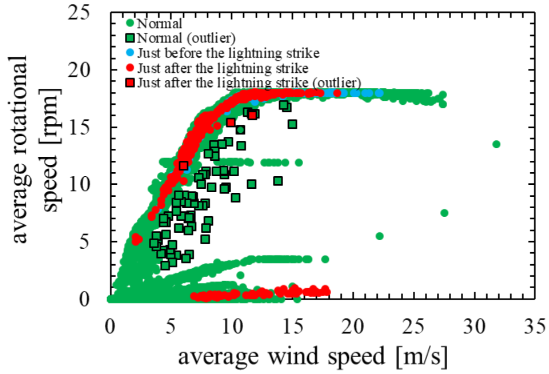
Fig. 6 shows no outliers before or after the lightning strike. In this case, no outages caused by blade anomalies were observed because the wind turbine was automatically stopped immediately after the lightning strike.

In cases like this where the blade breaks immediately after a lightning strike, no anomaly appears in the SCADA system data, making it difficult to prevent accidents by secondary use of the SCADA system data.

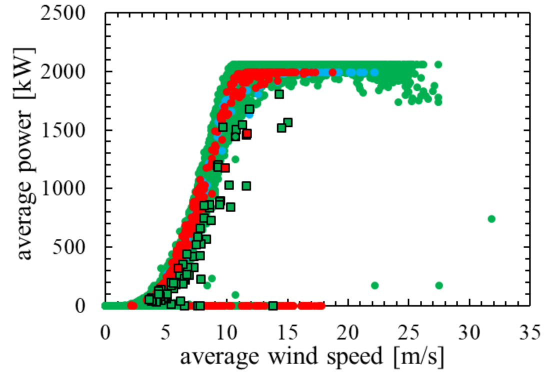
D. Accident at Wind Farm H

At wind farm H, an accident was reported in which the blade broke after being struck by lightning. The following is a summary of the accident.

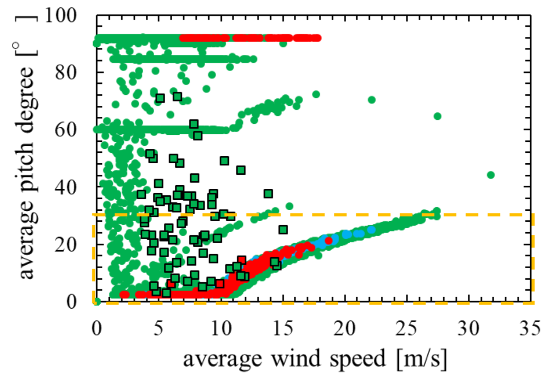
At 19:46:35 on February 14, 2018, lightning directly struck a wind turbine blade, partially damaging it. As wind farm H was equipped with an LDS, the wind turbine was automatically stopped by the lightning protection system.



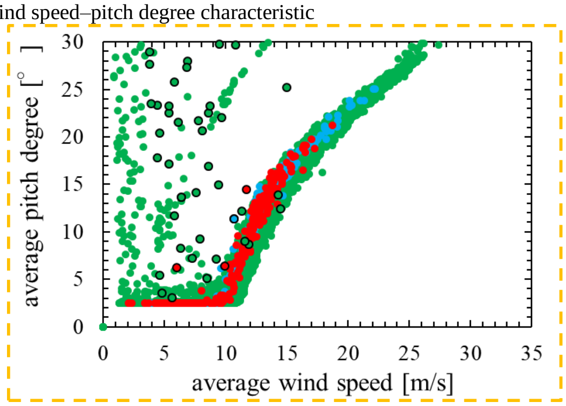
(a) Wind speed–rotational speed characteristic



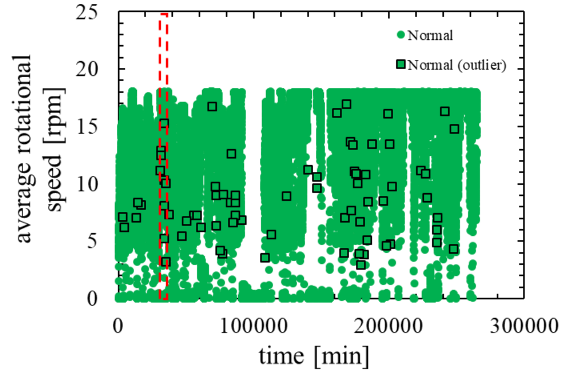
(b) Wind speed–power characteristic



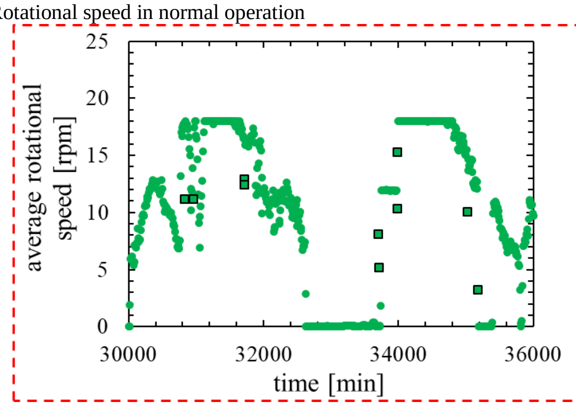
(c) Wind speed–pitch degree characteristic



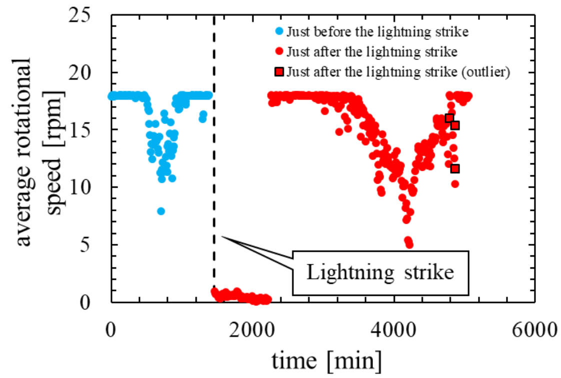
(d) Wind speed–pitch degree characteristic (partial expansion)
Fig. 7. SCADA data of wind farm H



(a) Rotational speed in normal operation



(b) Rotational speed in normal operation (partial expansion)



(c) Rotational speed at the time of accident
Fig. 8. Time characteristic of rotational speed at wind farm H

After visual inspection from the ground determined no damage, operation was resumed. However, it is assumed that damage undetected by visual inspection spread for approximately 60 h, eventually resulting in breakage.

In this example, as in the other examples, it would not have been possible to predict the blade anomalies from the time characteristics of the SCADA system data. Similar to the previous cases, we therefore focused on the input/output characteristics of the wind turbine. Here, wind speed was selected as the input data, and rotational speed, the amount of power generated, and pitch degree were selected as the output data. These input/output characteristics were compared before-and-after the lightning strike and during normal operation to determine if anomalies could be detected. Fig. 7 shows the wind speed–rotational speed, wind speed–amount of power generated, and wind speed–pitch degree characteristics. The SCADA system data before and after the lightning strike are plotted in separate graphs so that the values before and after the lightning can be compared. The types of plots are the same as those for the previous wind farms. Fig. 8 shows the time characteristic of the rotational speed with the data acquisition start time set to 0 min.

Fig. 7 shows outliers occurring after the lightning strike. At

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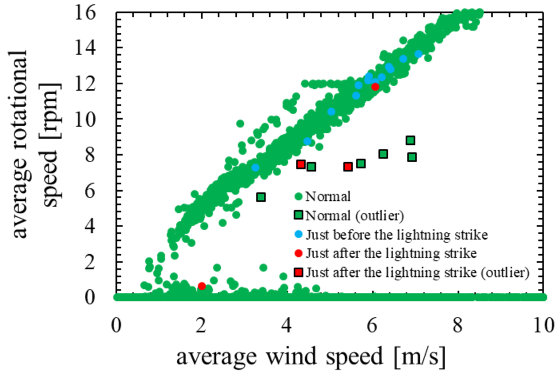
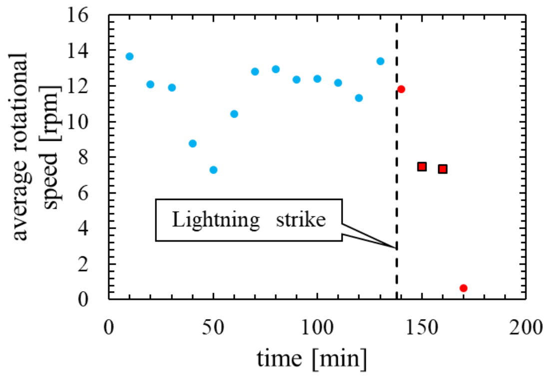


(a) Wind speed–rotational speed characteristic



(b) Rotational speed at the time of the accident
Fig. 9. SCADA data (10-min average) of wind farm Y

this wind farm, unlike in the others, the 1-min average SCADA system data were not recorded, and hence, 10-min average data were used instead. As shown in Fig. 8 (c), only two consecutive outliers were observed, unlike the situation for the 1-min average data, in which outliers were concentrated and occurred at high frequency.

Fig. 7 shows outliers occurring after the lightning strike. At this wind farm, unlike in the others, the 1-min average SCADA system data were not recorded, and hence, 10-min average data were used instead. As shown in Fig. 8 (c), only two consecutive outliers were observed, unlike the situation for the 1-min average data, in which outliers were concentrated and occurred at high frequency. The same phenomenon of isolated outliers occurs several times in Fig. 8 (b), which shows the rotational speed during normal operation. This demonstrates that the 10- min average data are inadequate for determining the condition of the wind turbine blades from SCADA system data, and 1-min average data are required.

As described previously in Section III Part A, it was possible to detect blade failure owing to lightning at wind farm Y using the 1-min average SCADA system data. Therefore, we decided to verify whether it was also possible to use the 10-min average data from wind farm Y to detect blade anomalies owing to lightning strike damage. Fig. 9 shows the wind speed–rotational speed characteristic and the time characteristic of the rotational speed based on the 10-min average data from wind farm Y. Whereas Fig. 1 (a) and Fig. 2 (c) showed outliers with high frequency and concentration, they are no longer visible in Fig. 9, demonstrating that at least 1-min average data are required when using the SCADA system data.

The above results demonstrate that, in the case of the accident at wind farm H, the outliers caused by blade anomalies appear in the SCADA system data, and hence, it is likely that the accident could have been prevented by secondary use of SCADA system data. However, as it is difficult to detect anomalies using the 10-min average data from the SCADA system, at least 1-min average data are required.

IV. Conclusions

In this paper, we reported the results of use of SCADA system data to detect blade damage caused by lightning strikes. We observed that, when a blade is damaged, outliers caused by blade anomalies appear with high frequency and concentration in the SCADA system data, specifically in the wind speed–rotational speed, wind speed–amount of power generated, and wind speed–pitch degree characteristics. We examined four case studies of blade damage owing to lightning strikes, and in three cases, we could detect blade anomalies by monitoring and analyzing the SCADA system data, suggesting that these accidents likely could have been prevented. In the remaining case, it was observed that the blade was damaged immediately after a lightning strike, making it difficult to detect anomalies in the SCADA system data. In addition, we observed that it is difficult to detect blade anomalies owing to lightning strikes using the 10-min average data from the SCADA system, suggesting that at least 1-min average data are required.

V. Acknowledgment

This paper is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

VI. References

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