Measurement Experience of Lightning Currents to Wind Turbines

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Wind power generation is growing rapidly and is acting a main role for preventing global warming. Yet the number of wind turbine failures due to severe weather conditions in Japan has been increasing. The foremost cause for this increase in the failure rate of wind turbines has been lightning. The coastal area of the Japan Sea in the Hokuriku region are prone to "Winter Lightning," a form of high-energy lightning which is rare in most other parts of the world. Winter lightning damages many wind turbines in Japan every year. Mitsubishi Heavy Industries, Ltd. (MHI) has observed and measured "Winter lightning" which strike actual wind turbines in Japan since 2002. By doing so, the company hopes to establish a technology for rapidly releasing the lightning energy to the ground whenever lightning strikes. In this paper, the authors analyze lightning current measurements recorded by wind turbines struck by lightning in various regions of Japan. Observed data reveals that IEC61400-24 protection level 1 is not sufficient for "Winter lightning." These results confirm the necessity of Japanese national research project "Guideline for Wind Turbines in Japan."

1. Introduction

As of March 2007, there were 1,314 wind turbines, with a total capacity of 1,491 MW, installed in Japan.[1] As more wind turbines are introduced, the number of wind turbine failures increase in parallel. This has led to concern that the current international design standard for wind turbines (IEC 61400), a standard established mainly by Europeans, has insufficient provisions for meteorological phenomena typical of Japan such as typhoons, mountain winds, and winter lightning. This concern has compelled the New Energy and Industrial Technology Development Organization (NEDO) to research measures to deal with winter lightning[2] and to begin drawing up "Guideline for Wind Turbines in Japan."[3]

Among the causes of wind turbine failures in Japan, the most frequent is lightning strikes[4] (**Fig. 1**). The winter lightning in the coastal area of the Japan Sea in the Hokuriku region causes especially great damage, mainly to the wind turbine blades[2, 5, 6] (**Fig. 2**). Winter **lightning** has much larger energy than ordinary lightning. The temperature differential between the warm ocean current in the Japan Sea and cold air mass in the atmosphere causes vast lightning clouds to develop and to discharge the accumulated electricity at once. To design wind turbine blades capable of withstanding the large energy discharged, the properties of the winter lightning must be grasped in quantitative terms. To attain such a grasp, MHI has observed and measured "Winter lightning" which strike actual wind turbines in Japan since 2002. The company has also participated in the NEDO research projects described above.

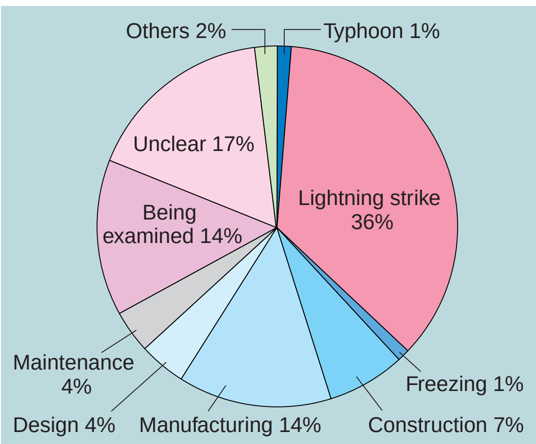

Fig. 1 Causes of failures of domestic wind turbines (4)

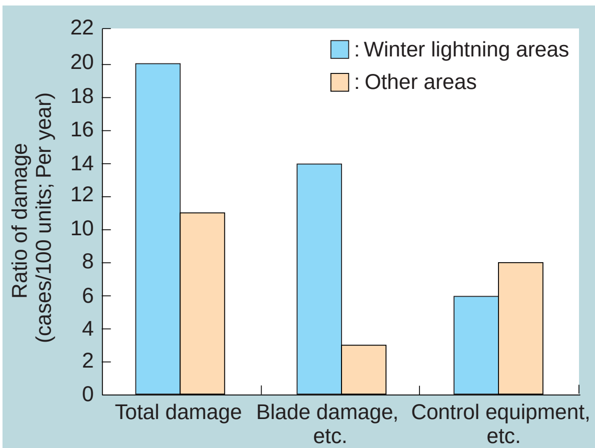

Fig. 2 Frequency of damage to wind turbines caused by lightning 5

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2. Measurement of lightning current

2.1 Measurement method

With any attempt to measure a large lightning current directly, the measurement equipment is threatened by the risk of burnout. As an alternative, the lightning current can be measured indirectly based on a non-contact method.[7] A Rogowski coil (**Fig. 3**) with a large bore diameter is looped around the tower base of a wind turbine (and the main shaft at the Goishigamine site), for use as a current sensor (**Fig. 4**). When lightning strikes the turbine and the current passes inside the loop, a magnetic field is generated and an induced current flows through the Rogowski coil. The magnitude of the original lightning current (charge amount; coulomb) can be determined by calculating the rate of change in the magnetic field from the induced current measured, and then integrating the rate of change. The composition of the measurement device is shown in **Fig. 5**. The Central Research Institute of the Electric Power Industry (CRIEPI) and Hokuriku Electric Power Co. originally developed this measurement technique while researching ways to protect transmission line towers from lightning strikes. Later, Toko Electric Co. applied this measurement technique to the tower base of a wind turbine and used actual equipment to measure lightning strikes.[8]

MHI started its lightning observations in the 600 kW wind turbine set up at the peak of Goishigamine, at the root of the Noto Peninsula in Ishikawa Prefecture, in 2002. The Rogowski coil was set in two places, i.e., the main shaft and tower base, to distinguish between the lightning strikes on the turbine blades and those on the lightning conductor on the nacelle (Fig. 4). MHI also installed a lightning strike observation camera (**Fig. 6**) in cooperation with the Lightning Center of Hokuriku Electric Power Co., in order to establish a system to visually observe areas struck by lightning.

2.2 Lightning observation implementation sites

Based on the observation experience in Goishigamine, MHI started to increase the number of measurement sites in 2005. Over the past two winters, 2005-2006 and 2006-2007, the company has collected lightning-observation data using 37 units installed at ten measurement sites in various regions of the country (**Fig. 7** and **Table 1**). The sites are geographically arranged in a configuration that will hopefully determine the boundaries of areas threatened by winter lightning dangers, with help from supplementary data collected at four surrounding sites operated under the NEDO studies on winter lightning To share information, the NEDO study also relies on measurement data from MHI's lightning observation in Goishigamine, Ishikawa Prefecture. In addition, Electric Power Development Co., Ltd. is measuring lightning strikes in Nikaho, Akita Prefecture, independently from the NEDO research[2] (Table 1).

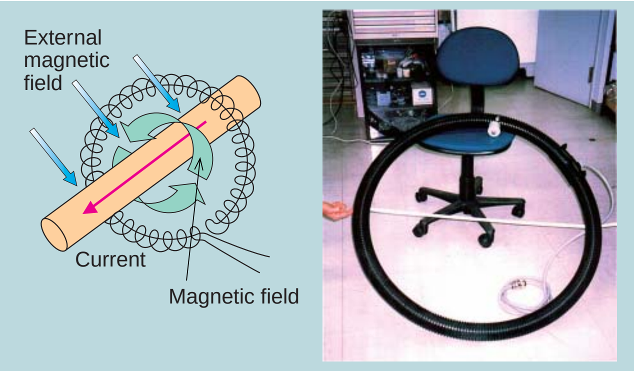

Fig. 3 Structure of Rogowski coil

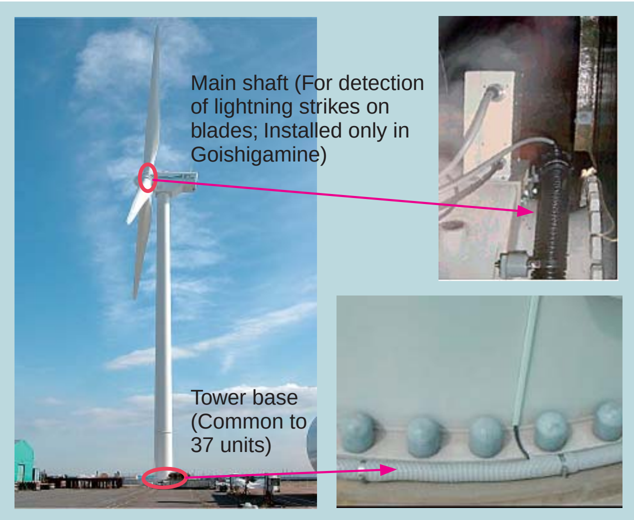

Fig. 4 Lightning current measurement device

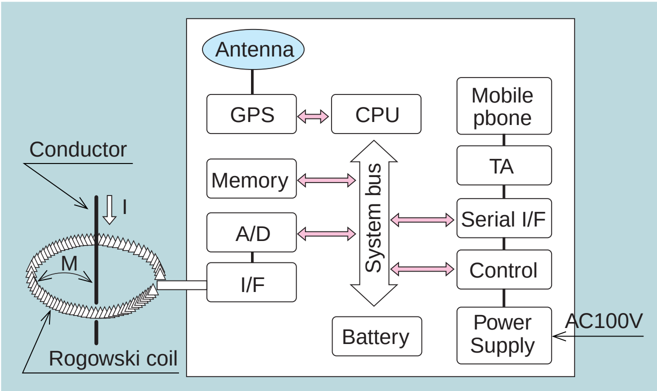

Fig. 5 Composition of lightning current measurement device

Fig. 6 Camera observation device for lightning strikes

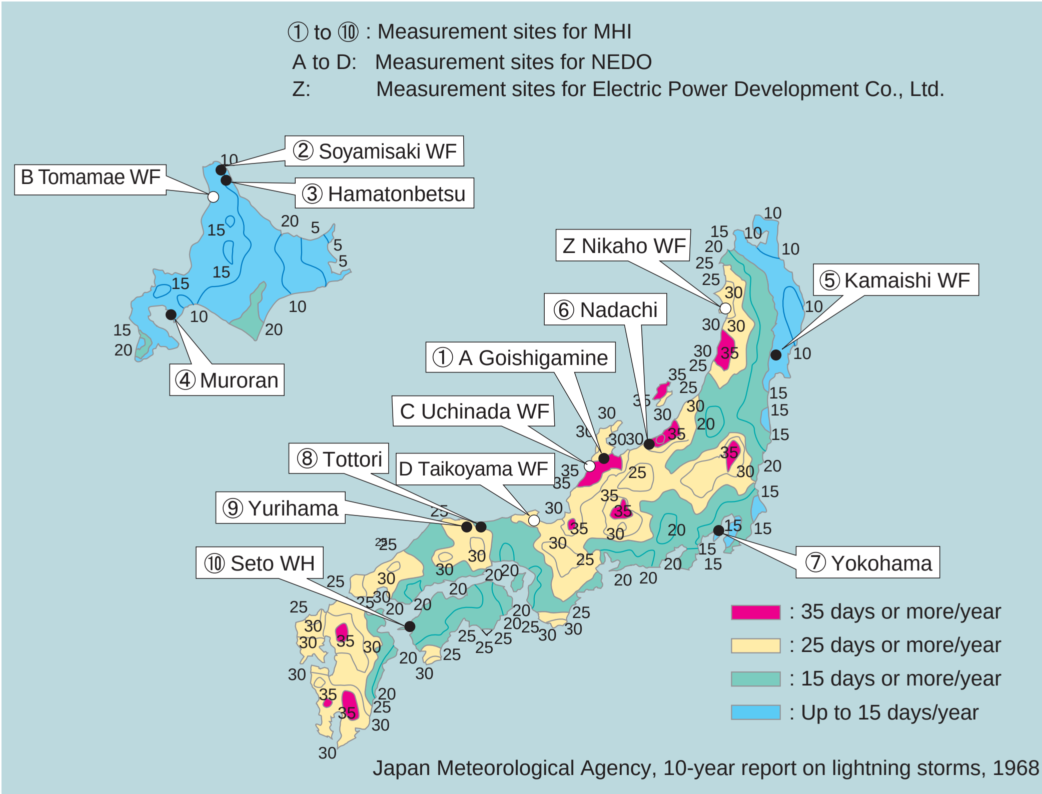

Fig. 7 Lightning observation implementation sites

Table 1 List of measurement sites and the number of lightning strikes

Colored portions are winter lightning areas.

	Measurement site	Presence or absence of winter lightning	Terrain	Rated output	Presence or absence of receptor	Number of wind turbines in the site	Number of lightning current measurement devices	Number of camera observation devices installed	Number of lightning strikes				
									2002-03	2003-04	2004-05	2005-06	2006-07
MHI	① Goishigamine, Ishikawa Prefecture	Presence	Mountain peak	600 kW	(Absence →) Presence	1	1	1	11	-	16	119	23
	② Soyamisaki WF, Hokkaido	Absence	Hill on the cape	1 000 kW	Presence	57	10		-	-	-	3	-
	③ Hamatonbetsu, Hokkaido	Absence	Sea coast	1 000 kW	Presence	1	1		-	-	-	0	-
	④ Muroran, Hokkaido	Absence	Sea coast	1 000 kW	Absence	1	1		-	-	-	6	-
	⑤ Kamaishi WF, Iwate Prefecture	Absence	Mountains	1 000 kW	Presence	43	7		-	-	-	8	2
	⑥ Nadachi, Niigata Prefecture	Presence	Sea coast	600 kW	Absence	1	1		-	-	-	1	2
	⑦ Yokohama, Kanagawa Prefecture	Absence	Sea coast	2 400 kW	Presence	1	1	1	-	-	-	5	-
	⑧ Tottori, Tottori Prefecture	Presence	Sea coast hill	1 000 kW	Presence	3	3		-	-	-	34	11
	⑨ Yurihama, Tottori Prefecture	Presence	Sea coast hill	600 kW	Presence	1	1		-	-	-	12	5
	⑩ Seto WH, Ehime Prefecture	Absence	Ridge of the cape	1 000 kW	Presence / absence	11	11		-	-	-	2	-
	Total					120	37	2	11	0	16	190	43
NEDO, etc.	A Goishigamine, Ishikawa Prefecture	The same as ①											
	B Tomamae WF, Hokkaido	Absence	Sea coast hill	1 000 kW	Presence	20	1		-	-	0	4	-
	C Uchinada WF, Ishikawa Prefecture	Presence	Sea coast	1 500 kW	Presence	1	1		-	-	14	28	-
	D Taikoyama WF, Kyoto Prefecture	Presence	Mountains	750 kW	Presence	6	1		-	-	-	-	-
	Z Nikaho WF, Akita Prefecture	Presence	Sea coast hill	1 650 kW	Presence	15	2	2	-	10	12	-	-
Grand total						162	42	4	11	10	42	222	43

3. Observation results

3.1 Results of lightning strike measurement

Table l shows the results of observations of lightning currents for the last 5 winters. Most observations are last 2 winters, during the period from September 2005 through April 2007. According to MHI's observations, 233 lightning strikes hit wind turbines at nine sites. Out of those strikes, 142 (61%) hit Goishigamine. The period from 2005 to 2006 was a lightning bonanza. On several occasions, the Goishigamine turbines were barraged by lightning strikes in quick succession over short periods. In December 2005, for example, the turbines were hit by 13 strikes on the 8th, 18 strikes on the 16th, and 10 strikes on the 21st.

When the NEDO data is included, 222 lightning strikes were measured at 12 sites with 39 wind turbines from 2005 to 2006. As this was the richest sampling of data, we selected this season for our analysis of the frequency of lightning strikes. As it turned out, the strike frequency was about 5.7 times per wind turbine per season (as opposed to about 2.7 times per wind turbine per season if excluding Goishigamine, the site subjected to the 'bonanza year' for lightning) (**Table 2**). The frequency of lightning strikes is at least tenfold higher in winter lightning areas than in other areas. We should point out, however, that this should only be considered a rough standard for areas where lightning strikes are frequent. When setting up the measurement apparatus for lightning stoke measurement, there was a bias for wind turbines with a higher risk of attracting lightning (based on past records of lightning strikes, terrain, and region). In addition, this frequency is one digit higher than the rate of damage due to lightning strikes calculated by NEDO (0.2 times per unit per year; see Fig. 2). It seems that in some cases, lightning inflicts no damage to a wind turbine when it strikes.

3.2 Results of lightning current measurement

Figure 8 shows the results of observations of the lightning current for two winters during the period from September 2005 through April 2007. According to our analysis of frequency distribution of lightning currents by magnitude shown in the figure, larger currents tended to be less frequent. Observation values exceeded protection level I (300 coulombs: Refer to **Table 3**) of the international design standard IEC 61400-24[9] ten strikes at four sites: Goishigamine, Tottori, Yurihama and Uchinada (NEDO) (all in winter lightning areas) (**Table 4**). On December 22, 2005, large lightning strikes were measured in multiple sites. The weather map[10] on this day showed a strong winter pattern (**Fig. 9**).

Table 2 Frequency of lightning strikes on wind turbines (2005 to 2006)

	Site	Number of measurement devices	Number of lightning strikes	Frequency
Winter lightning areas	5 (4)	7 (6)	194 (75)	27.7 (12.5)
Other areas	7 (7)	32 (32)	28 (28)	0.9 (0.9)
Total	12 (11)	39 (38)	222 (103)	5.7 (2.7)

Note: Values in ( ) are values when Goishigamine is excluded.

Table 3 Protection level standard in IEC 61400-24

IEC's protection level	Charge amount (C)
I	300
II	225
III & IV	150

Table 4 Observation data exceeding the IEC protection level I

	Charge amount	Measurement site	Date of measurement
1	739 C	Tottori	December 6, 2005
2	617 C	Tottori	December 22, 2005
3	525 C	Tottori	December 22, 2005
4	445 C	Uchinada (NEDO)	January 19, 2005
5	415 C	Goishigamine	December 16, 2005
6	386 C	Goishigamine	December 16, 2005
7	383 C	Goishigamine	December 8, 2005
8	356 C	Tottori	December 22, 2005
9	337 C	Yurihama	January 7, 2007
10	325 C	Uchinada (NEDO)	December 22, 2005

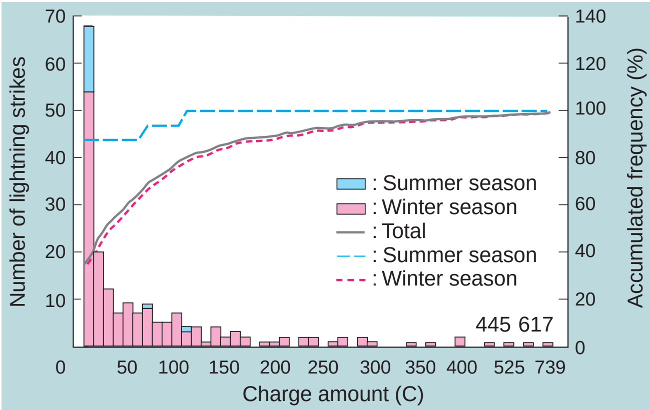

Fig. 8 Distribution of lightning currents observed

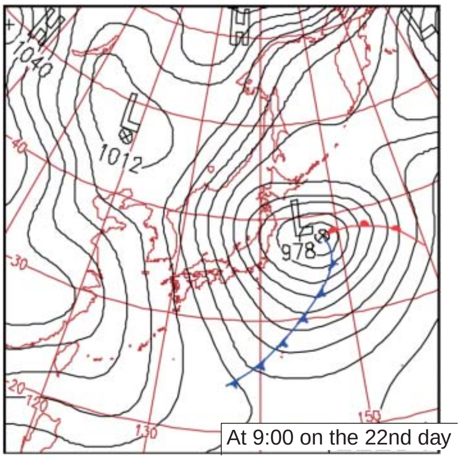

Fig. 9 Weather map (December 22, 2005)
On the 22nd day (Thursday), a strong winter pattern prevailed again. The temperature at an altitude of about 5 200 m over Yonago City, Tottori Prefecture was -40ºC or below. Akita City had 56 cm snowfall and Kagoshima City had 11 cm. Both cities broke their deepest snow records for December for the first time in 88 years. Hachijojima-machi, Tokyo, had a maximum instantaneous wind speed of 38.2m/s (northwestward).

A cold air mass moved over even the western part of Japan. The temperature difference from the warm ocean current in the Japan Sea expanded, and lightning clouds developed over wide areas, bringing about snowfall and lightning strikes. The biggest lightning charge, a 739-coulomb strike, struck Tottori on December 6, 2005. As on the 22nd later in the month, the weather map on this day (**Fig. 10**) showed a cold air mass over even the western part of Japan. Winter lightning apparently results from "a large temperature differential in the terrestrial airspace between the warm ocean current of the Japan Sea and the cold air mass up in the sky."

Figure 11 shows the probability lightning strikes based on magnitude, systematically arranged according to the IEC's protection level. The probability of a lightning strike at IEC protection level I or more is about 4%, and that of a strike with a magnitude of double level 1 or greater is 1% or more. When the high lightning-strike frequency shown in Table 2 is also considered, we can see that winter lightning in the Hokuriku region is a weather phenomenon specific to Japan and beyond the assumptions of IEC.

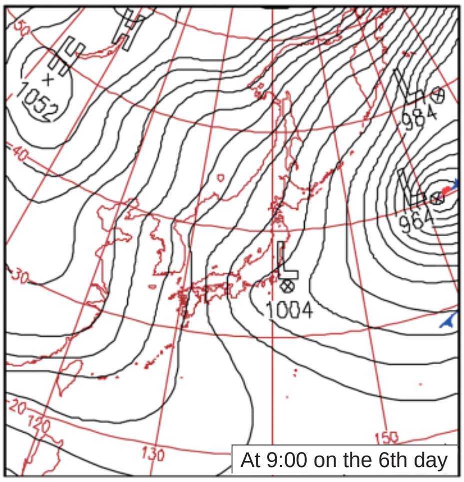

Fig. 10 Weather map (December 6, 2005)
On the 6th day (Tuesday), heavy snow fell mainly in the western part of Japan.
Cold air continued to flow mainly into the western part of Japan. Snowfall over the 24-hour period up to 9:00 was 71 cm in Gujo City, Gifu Prefecture; 40 cm in Maniwa City, Okayama Prefecture; and 38 cm in Shobara City, Hiroshima Prefecture. In Gujo City, Gifu Prefecture, the accumulation of snow reached 119 cm.

3.3 Concerning the receptor

The wind turbine in Goishigamine had non-receptor blades (nonconducting FRP solid) when it was first built. Later, in May 2005, the non-receptor blades were replaced with receptor blades (blades with a lightning conductor run through).

When the turbine operated with non-receptor blades, lightning struck the blades and the lightning conductor on the nacelle at a nearly fifty-fifty ratio. After the receptor blades were adopted, lightning struck the blade receptor with 100% probability (**Table 5** and **Fig. 12**).

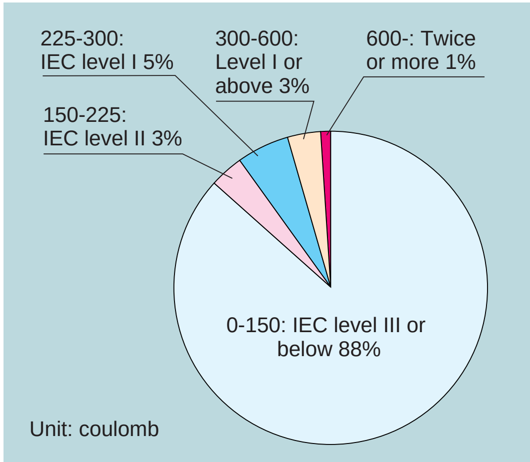

Fig. 11 Distribution of lightning current probability

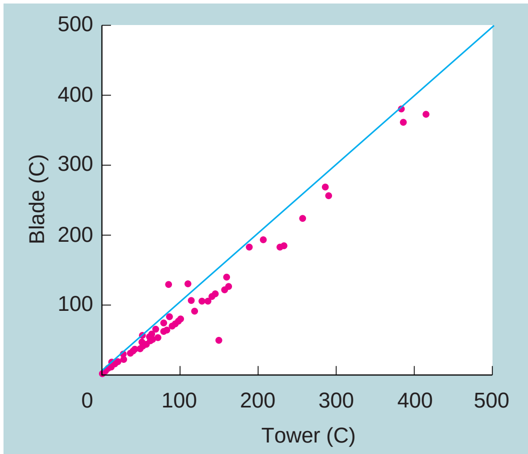

Fig. 12 Comparison between the current value in the blade and that in the tower base

Table 5 Change in the frequency of lightning strikes due to the presence or absence of receptor

Period	Presence or absence of receptor	Lightning current measurement		Camera Observation	Number of lightning strikes				Percentage of lightning strikes on blades
		Blade	Tower		Blade	Nacelle	Unclear	Total	
2002-03	Absence	-	-	Presence	6	5	0	11	55%
2004-05	Absence	Presence	Presence	Presence	6	4	6	16	60%
2005-06	Presence	Presence	Presence	Presence	113	0	6	119	100%
2006-07	Presence	Presence	Presence	Presence	22	0	1	23	100%

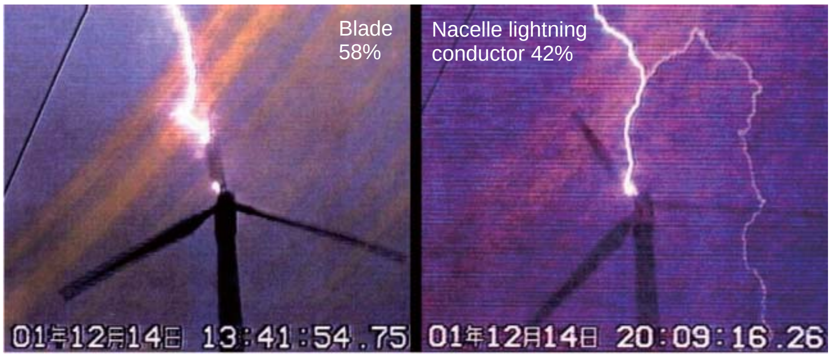

Fig. 13 No-receptor period

Fig. 14 After a receptor was adopted

This was confirmed by camera observation (**Fig. 13** and **Fig. 14**). It also appears that the overall frequency of lightning strikes on the wind turbines increased by 1.5 to 10 times after the receptor blades were replaced. But given that the seasonal variation was as large as 1.5 times to 5 times, we cannot affirm that the blade replacement had a decisive effect.

4. Conclusion

In the two winters during the period from September 2005 through April 2007, MHI observed and measured lightning strikes on 37 wind turbines set up in 10 sites in Japan. In total, 233 lightning strikes were recorded. The measurement results show that the IEC 61400-24 protection level setting is not sufficient for winter lightning.

(1) 4% of lightning strikes in winter exceeded IEC protection level I (300 coulombs).

(2) 1% of lightning strikes in winter exceeded IEC protection level I by more than twofold.

(3) The largest measured value was 739 coulombs, on December 6, 2005.

Every region on earth has its own meteorological phenomena and climate. Winter lightning is typical examples of a meteorological regionality. Similar meteorological phenomena specific to Japan will probably be found in typhoons and "mountain winds" as well. In view of this, we recommend that NEDO create a more appropriate system by establishing "Guideline for Wind Turbines in Japan."

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