Application of LLS to Detection of Winter Lightning Flashes Hitting Wind Turbines

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***Abstract*—In Japan, upward winter lightning frequently damages wind turbines in the coastal area of the Sea of Japan. Such upward lightning flashes initiate from tall structures very often, and they can be detected by LLS (Lightning location system). Therefore, "hot spots" where lightning strokes located by LLS concentrate, are formed around the location of wind turbines in winter in the coastal area of the Sea of Japan. Prediction of formation and evaluation of severity of hot spots are discussed.**

Keywords; winter lightning; upward lightning; wind turbine; hot spot; LLS

I. INTRODUCTION

From 1970's, frequent transmission line outages caused by winter lightning has been a serious problem [1]-[2] in the coastal area of the Sea of Japan. By the recent study, the outages turned out to be caused by high current upward lightning called GC strokes [1]. Damage to wind turbines has also become a serious problem in this area since 1990's [3]-[4].

The thunderstorm days in this area are even more in winter than those of summer; however, the number of lightning strokes observed by lightning location systems (LLS) in winter is much smaller. Such a feature indicates that the characteristics of winter lightning on the coast of the Sea of Japan may be quite different from those in summer. As another feature, concentration of lightning hits around tall structures is observed frequently by LLS in the coastal area of the Sea of Japan in winter. Such concentration is named a "hot spot" [5]-[7].

For investigation of characteristics of lightning hits to wind turbines, lightning current was directly observed at 27 wind turbines in Japan in the 5-year project, from 2008 to 2013, of NEDO (New Energy and Industrial Technology Development Organization), Japan [8]-[10]. In this observation, 686 lightning current records of reasonable quality were obtained at instrumented wind turbines in Japan. Among them, 676 were recorded during October to April.

The number of lightning hits is an important parameter for planning lightning protection of wind turbines. Therefore, an estimation formula for the number of lightning hits on the coast of the Sea of Japan in winter was proposed [5]. For the derivation of the estimation formula, LLS data, height of wind turbines, altitude of the site, latitude, and current observation data obtained at NEDO project were used. The number of lightning hits to wind turbines on the coast of the Sea of Japan in winter can be roughly estimated before construction by using the proposed formula [5].

This paper, summarizes characteristics of lightning strokes forming a hot spot observed by LLS.

II. MONTHLY VARIATION OF TYPES OF LIGHTNING FLASHES OBSERVED AT WIND TURBINES.

Most of the 676 current data observed at 21 wind turbines in the coastal area of the Sea of Japan in the cold months at wind turbines in the NEDO project [8]-[10] were associated with upward lightning. Monthly numbers are shown in Fig. 1. Negative upward flashes start with upward positive leaders from wind turbines, and it is natural that the majority of the upward flashes are negative because upward positive leaders initiate more easily than negative leaders. 95% of upward bipolar flashes also started with positive upward leaders [9]. The proportion of positive and bipolar flashes among observed flashes of winter lightning in Japan, 31%, is much higher than the total of only 7% at the observation of Geisberg tower in Austria [11].

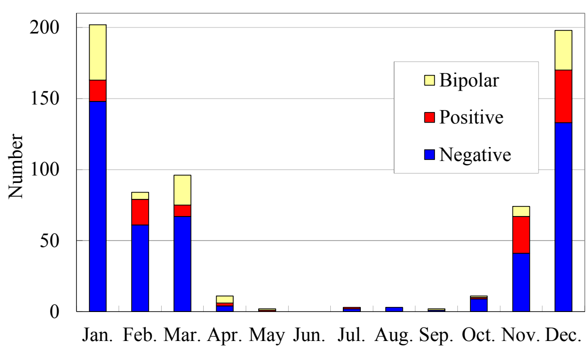

Figure 1. Seasonal variation of the monthly number of directly observed current at wind turbines in Japan (686 data) [9].

III. CHARACTERISTICS OF LIGHTNING STROKES LOCATED IN HOT SPOT AREA

Fig. 2 shows an example of a "hot spot" detected by LLS in winter, where there are two wind turbines on the top of a mountain of 640m. The dots show locations of lightning strokes irrespective of the type of strokes discriminated as CG strokes or not. The data were observed in December and January from 2001 to 2006.

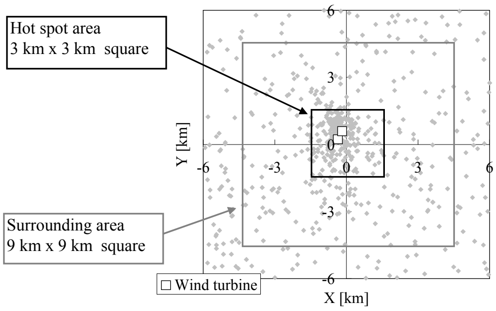

Figure 2. Hot spot detected by JLDN in winter at Mt. Kunimidake close to the coast of the Sea of Japan [5].

To characterize the property of hot spots, lightning increase rate l_i is defined as follows:

$$N_b = (N_a - N_h)/8 \tag{1}$$

$$D_b = N_b/9 \tag{2}$$

$$N_u = N_h - N_b \tag{3}$$

$$l_i = N_u/D_b \tag{4}$$

where N_a is the number of located sources of LEMP in a 9-km square (surrounding area), and N_h is the number of located sources of LEMP in the central 3-km square (hot spot area) of the selected 9-km square. So N_b is the average of the number of located sources of LEMP in a 3-km square excluding the central 3-km square, and D_b (strokes/km^2) is the lightning stroke density not being disturbed by the central 3-km square. If the central area is a hot spot, N_u is the increased number of sources of LEMP detected by LLS due to the presence of something in the hot spot. Thus, l_i (km^2) is the increase rate of the number of LEMP in the central 3-km square. It has a unit of km^2 because the central area apparently attracts lightning strokes from the surrounding area of l_i (km^2).

Sources of LEMPs associated with upward lightning from a tall structure in winter may be associated with developing upward leaders or in-cloud discharges in many cases as will be discussed in section V. The sources of such LLS data are naturally not so close to the top of the tall structures. Therefore, discrimination by LLS of the types of lightning discharges was ignored in the characterization of hot spots, and selection of the size of the search area, 3-km square, seems appropriate, as the result is reasonable [5]. The size of 9-km square is selected by considering flash density of surrounding area and variation of lightning characteristics. The characteristics of lightning flashes rapidly vary depending on the distance from the coastlines in the area. Thus surrounding area needs to be compact enough to eliminate the variation and must be large enough to accommodate sufficient number of flashes.

To investigate the factors influencing the increase rate of upward lightning in winter, 16 hot spots (7 wind turbines and 9 wind farms: 3 or less wind turbines are categorized as "wind turbine"), where there were wind turbines with known construction dates were selected. Table 1 and table 2 summarize the parameters of the 16 hot spots. H_f is the height of the turbine, and H_h is the highest altitude of the construction site above the sea level. LLS data are from December to January during 2000 to 2009 after construction of the wind turbine at each site. So the lengths of data acquisition periods are dependent on the sites.

TABLE I. LEMP INCREASE RATES OF ANALYZED WIND TURBINES [5].

No.	Hf [m]	Hh [m]	Latitude [deg]	Analyzed months	Increase rate of upward lightning	Place
1	100	0	39.9	12	43	Oga City
2	96	0	39.4	8	32	Nishime Town_1
3	47	0	37.1	16	9	Itoigawa City
4	87	320	36.7	10	31	Oyabe City
5	105	40	36.7	12	7	Uchinada_Town
6	70	500	36.3	10	42	Oki Islands
7	75	640	36.1	14	55	Mt. Kunimidake

TABLE II. LEMP INCREASE RATES OF ANALYZED WIND FARMS [5].

No.	Hf [m]	Hh [m]	Latitude [deg]	Analyzed months	Increase rate of upward lightning	Number of high structures	Place
1	120	180	39.3	10	56	15	Nishime Town_2
2	90	520	39.2	16	108	15	Nikaho Highland
3	100	0	38.8	12	47	8	Shonai Town
4	59	0	38.0	16	5	5	Kitakanbara-gun
5	74	360	37.4	14	20	5	Wajima City
6	60	240	37.2	16	32	4	Joetsu City
7	102	260	37.1	10	36	6	Mt. Mushigamine
8	75	620	35.7	16	46	7	Mt. Taiko
9	104	0	35.5	8	8	9	Hokuei Town

As the factors influencing the increase rate of upward lightning in winter, the height of wind turbines, the altitude of the construction site, and the height of -10ºC level of atmosphere, where electrical charges related to lightning discharges between cloud and ground frequently exist [10][12], are taken into account. Thus the experimental formula (5) is proposed, where l_{ei} is the estimated increase rate of upward lightning.

$$l_{ei} = A \times H_f / (H_q - B \times H_h) \tag{5}$$

The vertical distance between the charge center in cloud (altitude H_q) and the construction site (altitude H_h) is the denominator. The factor of topography is expressed by a constant B, however, as the number of samples is too small to investigate its values in detail, it is assigned a single value for the moment. A is a proportional constant.

The height of the lower charge center in clouds, represented by the -10ºC level of atmosphere, differs storm by storm. So, the average heights of the -10ºC during December and January observed at six aerological observatories along the coast of the Sea of Japan are investigated. The dependence can be approximated by a linear relationship expressed in the formula (6), which is valid for latitudes between 33 and 45 degrees north. By using the relationship of latitude and the averaged estimated charge altitudes, an optimized experimental formula (5) based on the data of Tables 1 and 2 is expressed as (7). This formula can be written as (8) by using the latitude of the site, where H_f and H_h are in [m].

$$H_q = 2.2\times10^2\times(48 - \text{Latitude}) \quad [\text{m}] \tag{6}$$

$$l_{ei} = 5.8\times10^2\times H_f / (H_q - 2.9H_h) \tag{7}$$

$$l_{ei} = 2.6H_f / ((48 - \text{Latitude}) - 0.013H_h) \tag{8}$$

The relationship between the observed increased rate in Table 1 and 2, and the estimated value using the experimental formula (8) is shown in Fig. 3. The correlation coefficient is 0.91. This correlation coefficient is much influenced by the rightmost datum of Nikaho Highland, No. 2 site of Table 2. Even by removing the data of Nikaho Highland, the correlation coefficient, 0.82, does not much deteriorate

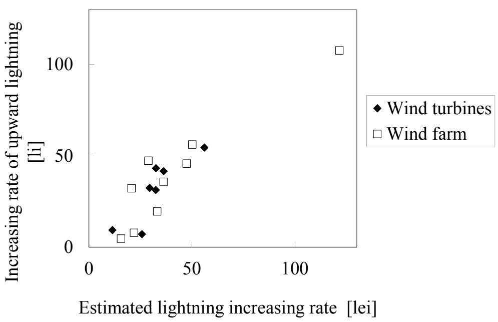

Figure 3. Relationship between estimated and observed increase rates of upward lightning at wind turbines and wind farms [5].

IV. Estimation of Frequency of Upward Lightning

LLS does not detect all the lightning discharges. Especially, upward lightning with the initial stage only, which does not radiate noticeable LEMP and is frequent in winter, is hardly detected. To estimate the actual number of upward lightning launching from a tall structure in winter based on LLS data, it is necessary to investigate the relationship between the estimated increase rate of upward lightning by (7) and the actual number of upward lightning.

The numbers of lightning current data observed in the NEDO project [5][8]-[10], in December (2010) and January (2009 and 2010) at two observation sites, where there were no tall structures except a single wind turbine, are compared with N_u, the numbers of LEMP observed by LLS in the 3-km square around the wind turbines. The ratios of the former (N_r : number of upward lightning strokes observed by Rogowski coil) to the latter (N_u) were 1.2 and 2.0, respectively. At other lightning current observation sites, more than one tall structures exist and reliable numbers of all the upward lightning in those areas were not available [5]. If other tall structures existed near the wind turbine, N_r likely was influenced. Thus, isolated wind turbines were selected.

In estimating the frequency of upward lightning in winter from a small area with tall structures, it is reasonable to multiply the ratio (N_r/N_u) mentioned above to the number of upward lightning estimated from LLS data. This ratio may be influenced by the type and the height of the structure and regional condition. It is proposed to temporarily adopt 2 for this ratio. Thus, the number of upward lightning at a site N_{er} is estimated from l_{ei} and D_b by the following formulae (9) and(10).

$$N_{er} = 2 \times l_{ei} \times D_b \tag{9}$$

$$N_{er} = l_{ugr} \times D_b \tag{10}$$

where, N_{er} is the estimated number of upward lightning strokes observed by Rogowski coil and l_{ugr} is upward generation rate, and by using formula (10), the number of upward lightning in winter in the coastal area along the Sea of Japan can be estimated from LLS data. Because this formula is derived from lightning observation at wind turbines, it is most suitable to estimate the number of lightning hits on wind turbines in this area.

In the NEDO report, similar analysis was carried out for the lightning flashes observed from November to March [10]. It aimed at estimating effective lightning stroke density experienced at tall structures influenced by upward lightning, so the parameters of the formula in the NEDO report are slightly different from those in this study. Though, as the NEDO formula is based on the same idea of this study, the result in evaluating severity of winter lightning is quite similar. Thus, these formulae can be applied to the seasons from autumn to spring, though coefficients may slightly change.

Based on the calculation by the NEDO formula, a risk map of high-energy lightning for 120-m wind turbines was proposed as shown in Fig. 4 [10]. The most dangerous area is indicated in red, and the next dangerous area is in yellow. No winter-type lightning will be expected in the blue area. However, l_{ugr} is not available in the NEDO report.

A different method to evaluate the increase of the risk by winter lightning by introducing environmental parameters is sought [13], however, to determine the practical values of environmental parameters assigned for winter lightning, it will be necessary to observe lightning hits to tall structures, even within such a small area along the coast of the Sea of Japan.

Figure 4. Risk map of high-energy lightning for 120-m wind turbines [10].

V. DETECTION EFFICIENCY OF UPWARD LIGHTNING FLASHES BY LLS

Fig. 5 shows the numbers of lightning current data depending on the amount of transferred charge, as well as the number of flashes simultaneously observed by LLS. Among the observed currents in NEDO report, 191 data observed in December (2008~2010) and January (2009~2011) at 16 wind turbines in the coastal area of the Sea of Japan were compared with location data obtained by LLS within 0.5 s of the trigger time of a current observation system [7]. Almost all of the current data are inferred to be associated with upward flashes.

A flash observed by LLS tagged as "Hot spot area" includes one or more strokes located in the hot spot area of 3 km square shown in Fig. 2. "Surrounding area" tag means the identified flash does not include a stroke located in the hot spot area. No LLS data were found for other current data. For lighting currents with transferred charge less than 100 C, only 18 % were detected by LLS in the hot spot area. For those exceeding 100 C, the probability of detection slightly rose to 23%. In the data tagged as "Hot spot area", only 10 data (10/191) were associated with subsequent return strokes included in the flashes. In the rest (24/191), LLS supposedly detected ICC pulses or IC discharges.

Detection efficiencies of only about 20% shown in Fig. 5 may look inconsistent to the ratio of N_r/N_u in the previous section. The difference comes from the difference of the way of adoption of the LLS data. For the calculation of N_r/N_u, LLS data were accumulated without considering coincidence with observation of current. Whereas in producing Fig. 5, LLS data only related to currents observed by the Rogowski coils were sought. At most of the observation sites, other than the instrumented wind turbine, there were other wind turbines or tall structures which also likely generated upward lightning.

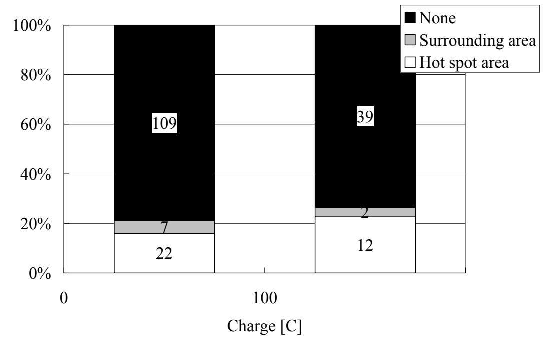

Figure 5. Number of recorded lightning currents detected or not detected by LLS, depending on the transferred charge [7].

VI. PEAK CURRENT AMPLITUDES

At winter lightning, subsequent return strokes, exceeding 2 kA in absolute values, are observed in 13% (85/676 data) of the upward flashes [9]. Table 3 shows aspect of detection of 65 return strokes exceeding 5 kA by JLDN [14] (61 negative subsequent strokes, 3 positive subsequent strokes, and 1 positive first stroke). The data were observed from October to April of 2010 to 2012 at 14 wind turbines. Fig. 6 shows the relation between estimated currents by JLDN and measured values observed by Rogwski coils of the 18 subsequent return stroke currents.

"Coefficient" in Fig. 6 indicates the ratios of peak current values to RNSS (range normalized signal strength) in "LLP unit" produced by JLDN. Although the correlation coefficient in Fig. 6 is 0.97, the estimated values are about 20% lower than those of measured values when the ratio is 0.185. The ratio of 0.185 is employed at NLDN, which was calibrated by rocket-triggered lightning in Florida [15]. 0.24 of the ratio is better to estimate the current values. The difference between Florida and Japan presumably comes mainly from the differences of average ground conductivities, terrain, current waveforms [16], and sensor locations.

Only two ground truth data of positive return strokes were observed. The estimated peak current values are proportional to the measured values. The ratios of the peak currents to RNSS values are quite similar to those for negative return strokes. The average of location errors are 0.58 km, and this value is slightly larger than the location error of rocket-triggered lightning.

TABLE III. ASPECT OF DETECTION OF RETURN STROKES BY JLDN DEPENDENT ON PEAK CURRENTS MEASURED BY ROGOWSKI COILS.

		Number of Strokes			Average [kA]
		5 kA~ 10 kA	10 kA~ 15 kA	15 kA~	
Negative	Dtected by LLS	3	11	2	-12.5
	Not detected	35	10	0	-7.9
Positive	Dtected by LLS	0	0	3	19.7
	Not detected	1	0	0	9.3

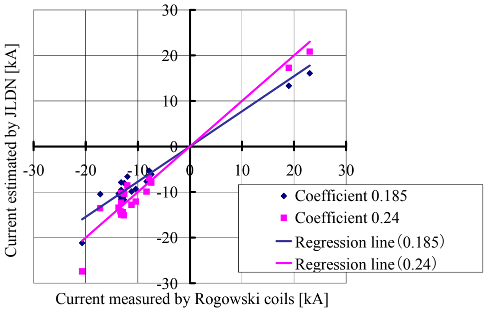

Figure 6. Estimated and measured return-stroke currents [15].

VII. Application for Lightning Protection

The estimation of the number of lightning hits to wind turbines is now possible by using the formula (10). Then, necessary lightning protection for the wind turbines, which frequently lighting hits are expected, are discussed in this section.

Table 4 shows the detailed numbers of damage incidents at instrumented wind turbines reported in [10]. Total number of incidents in [10] is 21, however, only 19 of them are shown in Table 4. Detail of one incident was missing, and one was observed in summer. “Comm. Equip.” and “Cont. Inst.” indicate “Communication equipment” and “Control instruments”, respectively. “Ex. 300 C” indicates the number of lightning flashes with transferred charge amount exceeding 300 C.

TABLE IV. Number of Damage Incidents in Winter and Their Positions at Instrumented Wind Turbines.

Site	Comm. Equip.	Cont. Inst.	Blade	SPD	Switch	Power line	Wind gauge	Total	Number of hits	Ex. 300 C
A									95	6
B					1	1		2	64	5
C				3	3			6	64	3
D									60	
E									45	2
F			1				3	4	44	1
G									42	
H									39	
I									35	
J									34	2
K									30	
L		3	2					5	28	3
M									20	2
N									19	
O	2							2	16	2
P									11	1
Q									9	
R									7	
S									6	
T									4	
U									4	
							SUM	19	676	27

As seen in Table 4, the damage incidents were reported from only 5 sites. Because of the existence of receptors, only 3 blade damages were reported. At site B, the damage at power line may have been related to an energetic flash with transferred charge amount exceeding 1000C. Other 18 incidents were caused by slightly energetic but not unusual upward winter lightning flashes. Thus, relation between the damage incidents and lightning current parameters are not obvious. Interestingly the damaged parts are different at the 5 sites.

A hypothesis can be deduced from this result. The number of incidents mainly depends on the state of lightning protection at each site. It may not much depend on lightning current parameters, because there is no clear difference in current characteristics at lightning flashes simultaneously observed with damage incidents from others.

Site A, which had the largest number of lightning hits and flashes exceeding 300C, reported no damage incidents. At Site A, there is an isolated wind turbine on the shore line. So, ordinary lightning protection with receptors, SPDs and proper grounding scheme works.

VIII. Conclusion

Lightning location systems (LLS) manufactured by Vaisala Co. used to be designed to detect return strokes. Thus, detection of upward flashes was difficult for them. Nevertheless, by properly analyzing the LLS data, they turned out to be quite useful in evaluating generation of upward flashes from wind turbines and other high structures in winter.

Experimental formulae to estimate the number of upward lightning flashes from tall structures in the coldest season as well as from autumn to spring in the coastal area of the Sea of Japan are available. The increase rate of lightning hits, normalized by the lighting stroke density observed by LLS, easily reaches to several tens at wind turbines in this area in winter. This result well explains the higher frequencies of failures in winter than those in summer experienced at transmission lines or wind turbines in this area.

Detection efficiencies of upward lightning flashes initiated from wind turbines observed in winter in the coastal area of the Sea of Japan were analyzed. About 20% of lightning flashes observed by current measuring systems employing Rogowski coils were detected by LLS. This value was slightly higher for flashes associated with transferred charge amount greater than 100C.

Good correlation was found between the current peaks of subsequent return strokes measured by Rogowski coils and estimated by LLS. The current peaks measured by Rogowski coils were about 20 % larger than those estimated by JLDN.

From the analysis of the damage data, it is inferred that the principal cause of lightning damages on wind turbines may be insufficient state of lightning protection of the overall system.

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