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Measurement of Lightning Current at Wind Turbine near Coast of Sea of Japan in Winter

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***Abstract*— The authors have carried out measurement of the current waveforms associated with lightning strokes to wind turbines at the coast of the Sea of Japan in Tohoku. In this paper measured waveforms on winter in 2014 to 2015 are reported and the initial continuous current (ICC), typical in the cases of lightning flash initiated by upward propagating leaders. The result is of practical importance for the lightning protection design of the wind turbine and the linkage distribution line on the wind farm.**

Keywords- Lightning; return stroke; lightning flash; lightning discharge

I. Introduction

Power generation by using renewable energy such as wind power and solar power becomes widely used for ecological consideration. In Japan, a lot of wind turbines are built along the coast of the Sea of Japan due to good wind condition and low construction cost. However, there is lightning activity in winter with characteristics of high energy [1] and some wind turbines suffer from the severe damage such as blowout of blades [2]. For the protection of the wind turbines, it is fundamental to accumulate the lightning current parameters such as charge transfer.

The winter lightning has another characteristic that the flash is initiated by upward propagating leaders [3] and the initial continuous current (ICC) flows sometimes with pulses. The ICC has low amplitude but large charge transfer [4]. Therefore, it is important to measure the ICC having long duration and low amplitude accurately. At the wind turbine, there is rotating blade, therefore, it is difficult to be equipped with long lightning rod even in the case of downward lightning. Lightning-inducing towers, built windward, are one of few effective protection methods to prevent lightning strokes to the turbine [5].

Even in the cases of no damages to the turbine, the fault such as flashover along the insulators or arrester damage can occur on the linkage distribution line on the wind farm due to the lightning current flowing into the line. For the protection of the distribution line, the reduction of the grounding resistance is the fundamental measures. Other method is the increase of the capacity of the arrester.

In this paper measured waveforms on winter in 2014 to 2015 are reported and the initial continuous current (ICC), typical in the cases of lightning flash initiated by upward propagation leaders, is discussed. The result is of practical importance for the lightning protection design of the wind turbine and the linkage distribution on the wind farm.

II. Measuremenet

A. *Location of measuring site*

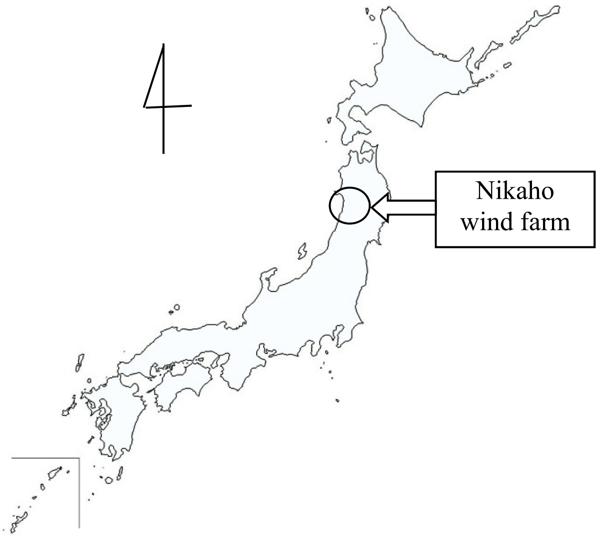


Figure 1. Location of measuring site

Fig. 1 shows the location of the measuring site, Nikaho wind farm. The wind turbines located about 500 m above the sea level and at 20 km from the coast line of the Sea of Japan. There are 16 wind turbines in the farm and the three turbines, namely No. 1, No. 4 and No. 12 turbines, are equipped with

Rogowski coils [6]. Fig. 2 shows the plan of the experimental site. The distance between No. 1 and No. 4 towers was 480 m and that between No. 4 and No. 12 towers was 1.46 km. The height of the nacelle from the ground was 60 m and the length of the blades was 30 m.

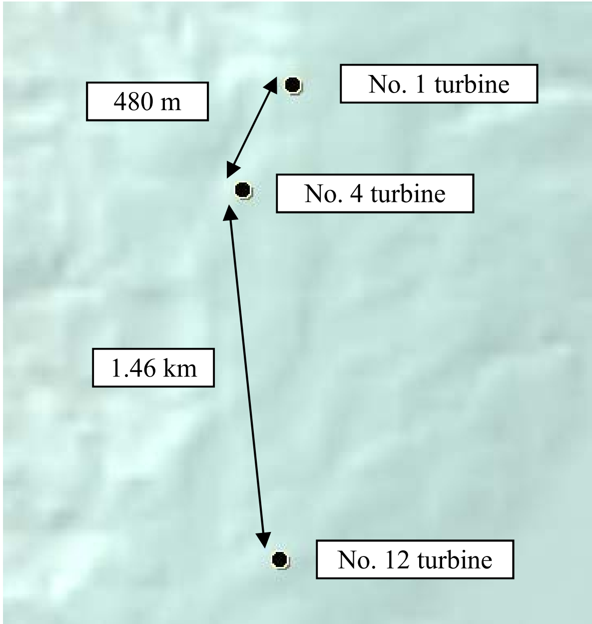


Figure 2. Plan of instrumented wind turbines

B. *Current Measurement*

A Rogowski coil for the measurement of the lightning current was installed at the bottom of a wind turbine generator at Nikaho. The signals of the lightning current waveforms observed by the Rogowski coil were transmitted via optical links and digitalized every 100 ns with the resolution of 12 bits. The total recording time was about 500 ms with pre-trigger of 20 or 25 % due to the limited memory capacity. The trigger time is also stamped on the recorded current waveforms with the precision of 2 µs. The current was measured in the frequency range from 0.1 Hz to 1 MHz. The recording system is triggered when the absolute value of the current exceeds 0.5 kA.

C. *Observation by Video Camera*

A video Camera with 60 Hz fps (frames per second) is installed around the No. 12 turbine and the total recording time was 2 s with the pre-trigger of 50 %. The recording system also had a clock with the precision of 2 µs, however, the time of the event is stamped up to the unit of the millisecond. Fig. 3 shows a sample of video pictures. Unfortunately, correlated measurement of the lightning current and the video pictures was not obtained up to September 2015 due to the malfunction of current recording systems at No. 1 and No. 4 turbines.

In Fig. 3, one can see long horizontal section, one of the characteristics of the winter lightning probably due to the low altitude of the charge center compared with the summer lightning.

Figure 3. A sample of video pictures

III. RESULTS

A. *Current Parameters*

Measurements of the lightning current at Nikaho were begun on December 2013 and 34 recordings were obtained by March 2015.

Fig. 4 shows an example of the measured waveform where the positive current flowing into turbine is defined positive, therefore, the initial negative current in Fig. 4 is associated with negative lightning and the following positive current is associated with positive lightning. Such lightning with the polarity change is called bipolar lightning [1].

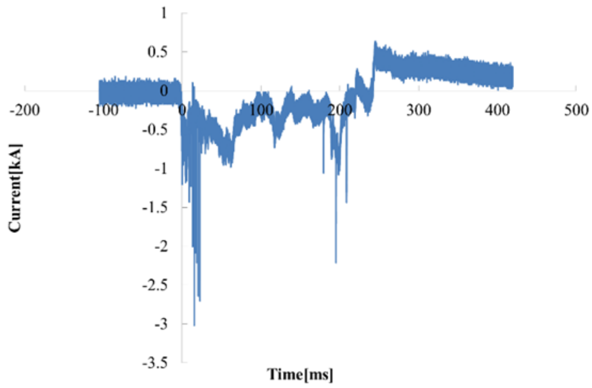


Figure 4. An example of measured current waveform

Table I shows the component ratio of the polarity of the lightning flash. For the time interval of up to about 400 ms after the trigger of the recording system, the negative lightning occupied 52 % of the observed events and the bipolar lightning occupied 32 %, considerably higher than the results at Fukui chimney in Japan [7] (9.5 %) and at Gaisberg tower in Austria (3 %) [8]. The order of the component ratio of the polarity of the flash is the same as in [4], although component ratio differs by 14 %. The polarity of the lightning flash, estimated by the current record up to 400 ms, depends on the recording length, because the polarity change after the end of the recording is not taken into account.

Table II shows the 50 % values of the current peaks, defined as the median of the mother population, and the charge transfer of lightning flash up to about 400 ms of the trigger of the recording of system. The charge transfer also depends on the recording length of the current, and the transfer in this study is underestimated since the current sometimes continues to flow after the end of the record as shown in Fig. 4. The 50 % value of the current peaks in Table II is smaller than the 50 % value associated with lightning flash initiated by downward propagating leaders. This is because almost all of the flash is initiated by the upward propagating leaders evidenced by the existence of the current variation before the occurrence of the return strokes and/or the ICC.

Fig. 5 shows the cumulative frequency distribution of the current peaks for negative and bipolar lightning flashes but that for positive lightning flashes is not shown due to the small number. The distribution over the current peaks of 5 kA for negative and bipolar lightning, corresponding to the cumulative frequency distribution of less than 50 %, seems similar.

TABLE I. COMPONENT RATIO OF POLARITY OF LIGHTNING FLASH

	This study		Ref. [4]	
	Number	Ratio (%)	Number	Ratio (%)
Negative	18	53	212	76
Positive	5	15	16	6
Bipolar	11	32	50	18

TABLE II. 50 % VALUES OF CURRENT PEAK AND CHARGE TRANSFER OF LIGHTNING FLASH

	This study		Ref. [4]	
	peak (kA)	Charge transfer (C)	peak (kA)	Charge transfer (C)
Negative	3.9	6.0	3.1	21
Positive	1.2	13	6.5	30
Bipolar	4.3	107	9.5	98

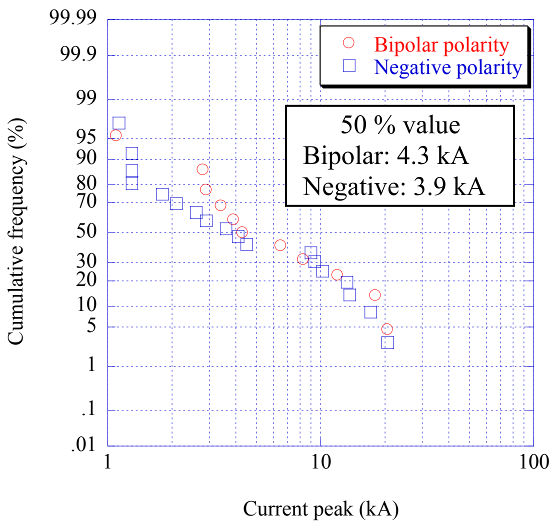


Figure 5. Cumulative distribution of current peaks dependent on polarity of lightning flash

Fig. 6 shows cumulative distribution of the charge tramsfer for negative and bipolar lightning flashes. The charge transfer for bipolar flash is larger than that for negative flash.

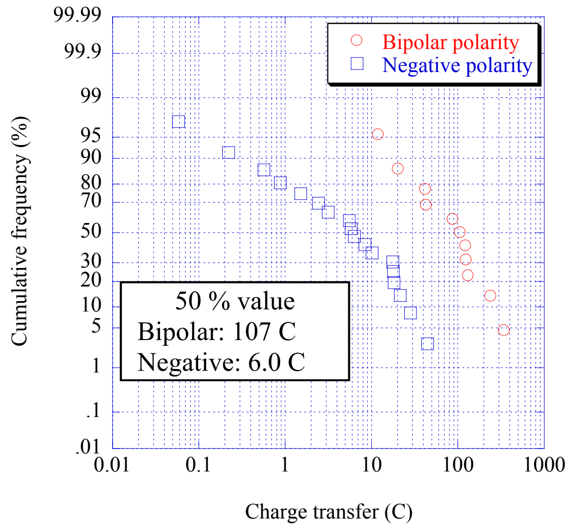


Figure 6. Cumulative distribution of charge transfers dependent on polarity of lightning flash

B. ICC

For the discussion of the dominant factor of the charge transfer of the ICC, the correlation of the current peak of the ICC and the duration of the ICC is studied. In the case of the bipolar current waveform, the relation is investigated for the current of the initial half cycle as shown Fig. 7.

Table III shows the ICC current parameters dependent on the polarity of the lightning flash. The charge transfer of ICC of the initial half cycle of the bipolar discharge is higher than those for unipolar discharges. In one samples, lightning current changes from positive to negative polarities, and in other seven cases the current changed from negative to positive polarities.

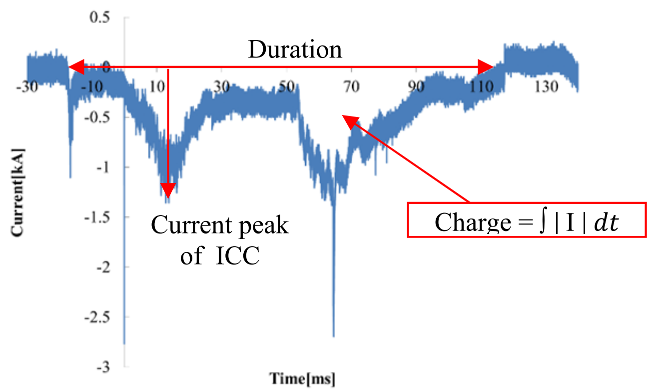
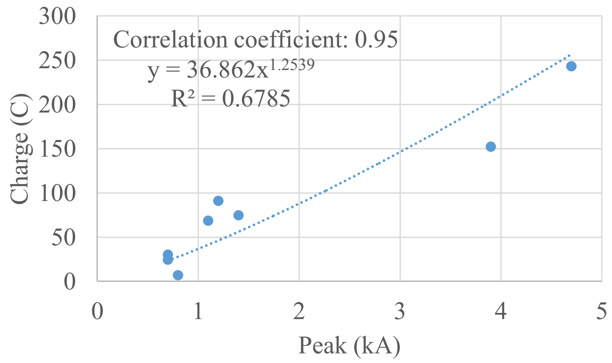


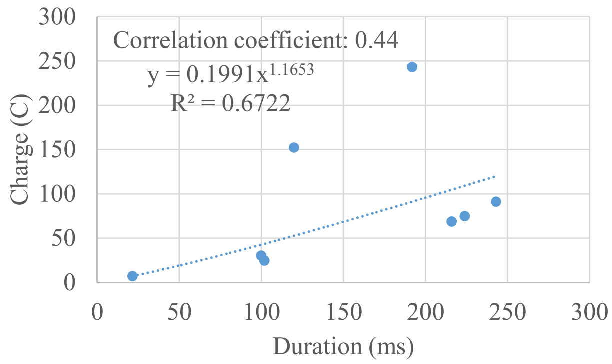
Figure 7. Definition of ICC current parameters

TABLE III. CURRENT PARAMETERS OF ICC

Polarity (Number of date)	Charge (C)	Peak (kA)	Duration (ms)
Negative (8)	2.9 - 28	0.2 - 5.3	37 -116
Positive (4)	13 - 20	0.9 - 4.3	12 - 64
Bipolar (8)	6.9 – 243	0.7 - 4.7	22 - 243



(a) Current and charge transfer



(b) Duration and Charge transfer

Figure 8. Charge transfer and current peak (a) and duration (b)

Fig. 8 shows the relation between the charge transfer and the current peak of the ICC and the duration of the initial half cycle current of the ICC current.

The correlation between the current peak and the charge transfer for bipolar discharge is higher than that between the duration of the current. When the correlation is calculated for the lightning discharge with charge transfer of less than 100 C, the correlation between the charge transfer and the current was 0.86 and that between the charge transfer and the duration of the current was 0.99.

From these results on the bipolar discharge, it is inferred that the charge transfer of larger than 150 C might be related to high ICC amplitude, and the charge transfer of less than 100 C might be intensely correlated to the duration of the ICC.

C. Charge Transfer and Cause of Thunderstorm

Table IV shows the current parameters and the height of -10ºC air layer dependent on the weather condition causing lightning, calculated from the measurements at 9 and 21 o'clock at 50 km north of the turbines [8] by the interior division. In our dataset 50 % charge transfer associated with frontal lightning was greatly higher than those associated with low-pressure lightning and lightning generated in winter pressure pattern. The weather condition is classified according to the hourly weather pattern. The charge transfer associated with frontal lightning is larger than that associated with lightning in other weather conditions.

Table V shows the ratio of polarity of lightning dependent on causative thunderstorm. In the cases of the frontal lightning, six samples (62.5 %) were associated with bipolar discharge and in the case of winter pressure pattern thunderstorm and low-pressure thunderstorm, the ratio of the bipolar discharge was 17.6 % and 33.3 %, respectively. This might indicate that the high ratio of the bipolar discharge caused the high charge transfer of the frontal lightning.

In the lightning protection design of the wind turbine and the linkage line at the area of winter lightning, the ICC with low current and with the large charge transfer should be taken into account for the stable power supply. The data in this paper is helpful for the lightning protection design.

TABLE IV. CURRENT PARAMETERS AND AVERAGE HEIGHT OF -10 DEGREE AIR LAYER

Weather condition	Number	50 % current (kA)	50 % charge transfer (C)	Height of -10℃ air layer (m)
Winter pressure pattern thunderstorm	17	4.3	10	1200
Low-pressure thunderstorm	9	4.1	20	1800
Frontal thunderstorm	8	2.9	75	2300

TABLE V. RATIO OF POLARITY OF LIGHTNING DEPENDENT ON CAUSATIVE THUNDERSTORM

Weather condition	Number	Negative (%)	Positive (%)	Bipolar (%)
Winter pressure pattern thunderstorm	17	70.6	11.8	17.6
Low-pressure thunderstorm	9	44.4	22.2	33.3
Frontal thunderstorm	8	25.0	12.5	62.5

IV. CONCLUSION

In this paper, the lightning discharge to the wind turbines at the northern area of Japan in winter is studied based on the observed results.

The large charge transfer of the ICC was observed in the cases of bipolar discharges and the ratio of the bipolar lightning was high in the frontal thunderstorm. The large charge transfer of ICC of larger than 150 C was associated with high current, whereas in the charge transfer of less than 100 C was intensely correlated with duration of the ICC.

In the lightning protection design of the wind turbine and the linkage line at the area of winter lightning, the ICC with low current and with the large charge transfer is taken into account for the stable power supply. The data in this paper is helpful for the lightning protection design although the number of the obtained data is small.

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