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Subsequent Stroke Current Parameters Associated Upward Lightning at Nikaho in Japan in Winter

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***Abstract*— The authors have carried out measurement of the current waveforms associated with lightning discharges to wind turbines near the coast of the Sea of Japan. In this paper measured waveforms in winter from 2013 to 2019 are investigated and the current waveforms associated with return strokes following the ICC (initial continuous current) are studied. The frequency of the occurrence of the ICC superposed by the pulse with the amplitude of 2 kA or more is high compared with the result in Austria. The return stroke current amplitude following the ICC is less than the amplitude of the subsequent strokes initiated by downward propagating leaders and the current amplitude of the return strokes to the tall structures in regions other than the winter lightning area in Japan.**

Keywords—subsequent stroke; upward lightning; ICC (initial continuous current); winter lightning; charge transfer

I. Introduction

Wind power generation comes to be widely used for ecology. Because of good wind conditions, 25 % of all wind turbines in Japan are built along the coast of the Sea of Japan, famous for winter lightning [1]. The winter lightning has unusual characteristics compared with summer lightning [2].

In winter the altitude of the thundercloud is so low that the lightning flash is initiated by upward propagating leaders [3] associated with the initial continuous current (ICC), sometimes with superposed pulses. Therefore, the lightning frequently strikes the high structure such as wind turbines [4]. The number of damage of wind turbines in winter is reported to be 2.5 times as many as that in summer [5].

Winter lightning has another characteristic that the energy is so high [6] that some wind turbines suffer from the severe damage such as blowout of blades [7]. The ICC has low amplitude less than a few kilo-amperes but large charge transfer [4] dominated by the time duration. It is reported that in some winter lightning waveforms pulse current with amplitude higher than a few 10 kA continues to flow for a time interval of a few milliseconds or more [8]. For the lightning protection design of the wind turbines, not only the current parameters of the wave front but also the energetic parameters intensely related to the wave tail are indispensable. Therefore, it is important to measure the ICC with long duration and low amplitude accurately [4].

The authors have carried out measurement of the current waveforms associated with lightning discharges to wind turbines near the coast of the Sea of Japan in Tohoku. It is shown that the charge transfer is dependent on the altitude of -10 °C isotherm and also the types of the thunderstorms [9]. Furthermore, it is found that the lightning flash with charge transfer exceeding 300 C occurs when the -10 °C isotherm altitude is between 1000 m and 2500 m above the sea level [9].

At the wind turbine there is a rotating blade, therefore, it is difficult for the turbine to be instrumented with a long lightning rod. Lightning-inducing towers, built windward, are one of few effective protection measures to prevent lightning strokes to the turbines [10].

In the cases of no damages to the struck turbine, the fault such as flashover along insulators or arrester damage can occur on a distribution line connected to the turbine by the lightning current flowing into the line. For the protection of a distribution line, reduction of grounding resistance is effective as well as installation of additional OHGWs (overhead ground wire) and increase of the arrester capacity [11].

In this paper measured waveforms in winter from 2013 to 2019 are investigated and the return stroke current waveforms following the ICC is studied. The result is of practical importance for the lightning protection design of the wind turbine.

II. Measurement

A. Location of measuring site

Figure 1 shows the location of Nikaho wind farm (39°N, 139.9°E). The wind turbines located on a plateau at 520 m above the sea level and at the distance of 9 km from the Sea of Japan. There are 15 wind turbines in the farm and three turbines, namely No. 1, No. 4 and No. 12 turbines, are instrumented with Rogowski coils [4]. Fig. 2 shows the plan view of the wind farm. 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 blades was 30 m.

B. *Current Measurement*

A Rogowski coil for the measurement of the lightning current was instrumented at the bottom of a wind turbine. The maximum recordable current was 100 kA at No.4 turbine and 50 kA at No. 1 and No. 12 turbines. The current was measured in the frequency range from 0.1 Hz to 1 MHz at No. 4 wind turbine and from 0.8 Hz to 1 MHz at No. 1 and No. 12 wind turbines. The signals of the lightning current waveforms were transmitted via optical links and digitalized every 100 ns or 200 ns with the resolution of 12 bits. The total recording time was about 500 ms or 1 s with pre-trigger of 5 or 20 or 25 % due to the limited memory capacity. (After October 14, 2016, the signal are digitalized every 200 ns and the total recording time is about 1s with the pre-trigger of 5 %.) The trigger time is stamped on the recorded current waveforms with the precision of 2 μs. The recording system at No. 1 and 12 turbines is triggered when the absolute value of the current exceeds 0.5 kA and the system at No. 4 tower is triggered with the current exceeding 1.0kA.

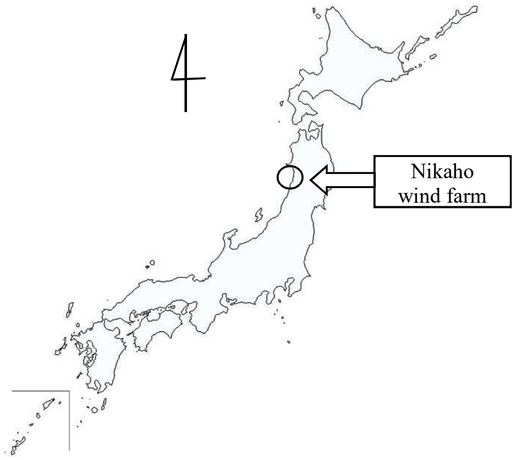


Fig. 1. Location of measuring site

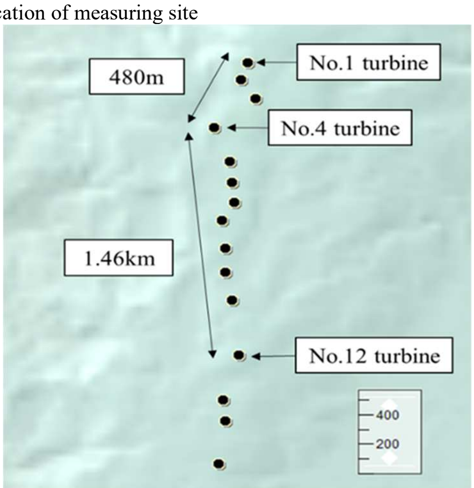


Fig. 2. Plan view of wind farm

III. RESULTS

A. *Statistics of observed data*

Up to now, 239 data were obtained in winter from 2013 to 2019 and only three lightning flashes struck the instrumented turbines in summer. The period of winter is defined from November to March, commonly used in Japan, for comparison of the data obtained in other regions [12], although the altitude of the -10 °C isotherm is sometimes below 2000 m at Nikaho in April. Fig. 3 shows annual number of lightning flashes, varying as many as 4.2 times. Average number of winter lightning of 17.2 [flashes / year / turbine] for 6 fiscal years from 2013 to 2019 was almost the same as the data obtained at four wind turbines in Nikaho for 4 fiscal years from 2005 to 2008 [12].

Fig. 4 shows the component ratio of the polarity of the lightning flash obtained for 5 years (from 2013 to 2018) for the time interval up to about 400 ms or 900 ms after the trigger of the recording system. The negative lightning occupied 75 % of the observed events and the bipolar lightning occupied 14 %, considerably higher than the results at Gaisberg tower in Austria (3 %) [13]. The order of the component ratio of the polarity of the flash is the same as in [12] and the difference of the component ratio is as low as 5 %. It is interesting that the difference of the component ratio of the lightning current at 200m-high stack at Mikuni in Hokuriku (36.2°N, 136°E), winter lightning region adjacent to Tohoku [14], is as low as 8 % although not only the height of the instrumented structure but also the location and the period (1989-2002) is different.

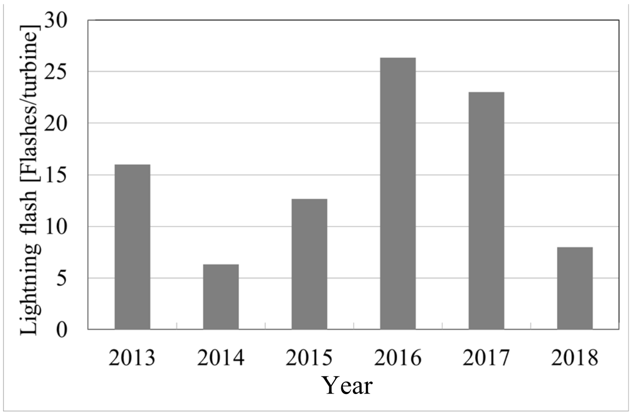


Fig. 3. Annual number of lightning flash

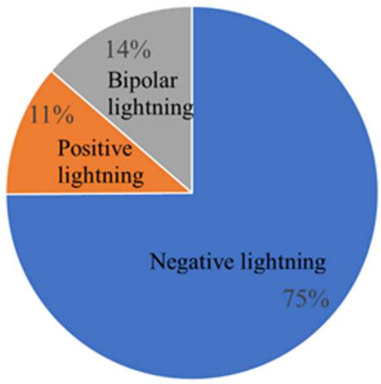


Fig. 4 Component ratio of polarity of lightning flash for 6 fiscal years.

In this paper, the negative lightning flash initiated by upward propagating leaders followed by the return strokes are subject to analysis.

Fig. 5 shows the component ratio of the ICC of the negative flash classified by the way in [15] along with the median charge transfer for 5 fiscal years (from 2013 to 2018). The way of the classification of the ICC is as follows [15].

- The ICC_{RS} is composed of the ICC followed by one or more return strokes.
- The ICC_{P} is composed of the ICC superposed with pulse current with the amplitude of 2 kA or more and not followed the return stroke pulse in the measurement period.
- The ICC_{Only} is composed of the ICC not followed by any RS and not superposed by ICC pulses > 2kA.

The median charge transfer of the ICC_{pulse} is the largest as in [15]. As is indicated in [15] the median charge transfer of the ICC_{pulse} is significantly higher than the ICC_{Only}. However, in our dataset the occurrence of the ICC_{pulse} is high in contrast to [15] where the occurrence of the ICC_{Only} is two times as frequent as the ICC_{pulse}.

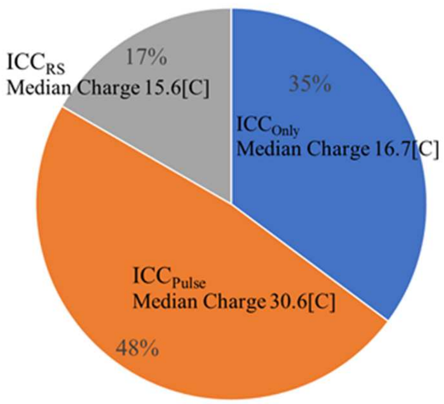


Fig. 5 Component ratio of ICC of negative lightning flash for 5 fiscal years.

B. Return stroke current parameters

1) Waveforms

In this paper, the authors analyzed 14 waveforms associated with negative lightning flashes containing return strokes and initiated by upward propagating leaders.

Fig. 6 shows an example of current waveforms subject to analysis where the positive current flowing into turbine is defined positive, therefore, the negative current in Fig. 4 is associated with negative lightning flash. The date is obtained at No. 4 wind turbine at 15:42:14 on February 9 2016. The ICC is initially seen and the duration was 182 ms. After 182 ms in Fig. 4 there seems no current period for 31.5 ms and two pulses with short duration compared with the ICC is seen.

Fig. 7 shows the first and subsequent return stroke current waveform following the ICC for the example in Fig. 6. Note that the current peak in Fig. 6 is smaller than that in Figs. 7 (a) and (b) because the resolution of the waveform in Fig. 6 is less due to the sparse plot. Two similar return stroke current waveforms following the ICC were observed and those seem to have the characteristics similar to the subsequent return strokes in the natural lightning initiated by downward propagating leaders [15], because the current follows the lightning channel created by the ICC. Therefore no first strokes flowing the channel created by the stepped leader in the case of natural downward lightning are observed in the case of upward lightning although the waveform in Fig. 7 (a) is called as the first return stroke. The peak current in Figs. 7 (a) and (b) was 9.3 kA and 8.1 kA, respectively, and the stroke charge was 0.63 C and 0.56 C, respectively. The time interval between those return strokes calculated from the onset time was 42.6 ms. The time interval between the end of the ICC and the first return stroke was 30.5 ms.

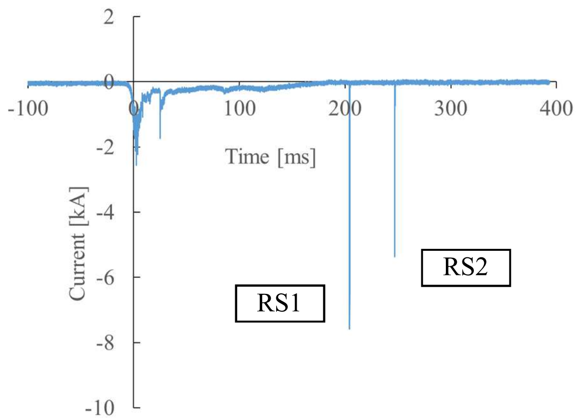
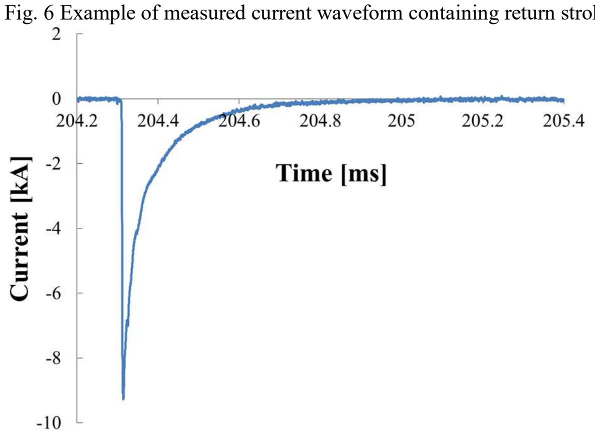
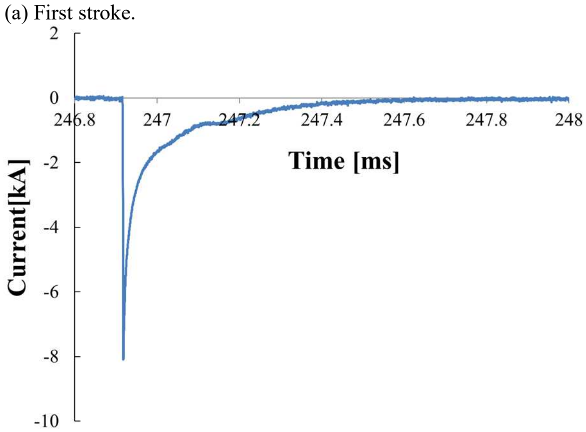


Fig. 6 Example of measured current waveform containing return strokes.



(a) First stroke.



(b) Second stroke.

Fig. 7 Example of measured current of return strokes following ICC.

2) Multiplicity

Fig. 8 shows the histogram of number of observed return strokes for 14 lightning flashes. The average number of the observed return strokes for a flash was 3.29, similar value the number of observed subsequent strokes in natural lightning [2].

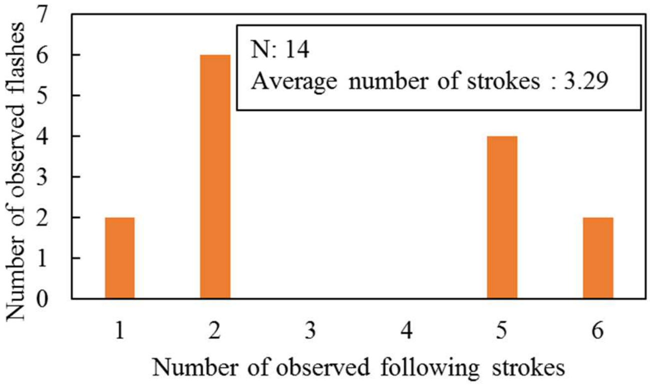


Fig. 8 Histogram of number of observed following strokes.

3) Cumulative frequency of parameters

Fig. 9 shows the cumulative frequency distribution of the current peak of the 46 return strokes. The median peak current was 6.25 kA, which is low by comparison with the results in [15].

Fig. 10 shows the cumulative frequency distribution of the stroke charge of the 46 following strokes. The median stroke charge was 0.47 C, which is almost the same as the result in [15].

Fig. 11 shows the cumulative frequency distribution of the time interval of the 32 following strokes. Note that the time interval of the ICC and the first following stroke is not included. The median time interval between the strokes was 18.3 ms and is almost the same as that in [15].

In Fig. 11, an inflection point is seen at the cumulative frequency of 95 %. This is because of the short interval of 1.6 ms, shown in Fig. 12, and such a short interval is also observed in Austria [15].

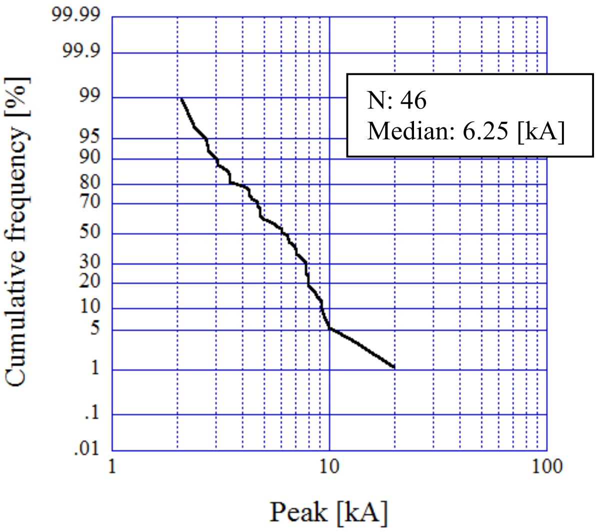


Fig. 9 Cumulative frequency distribution of current peak of following strokes.

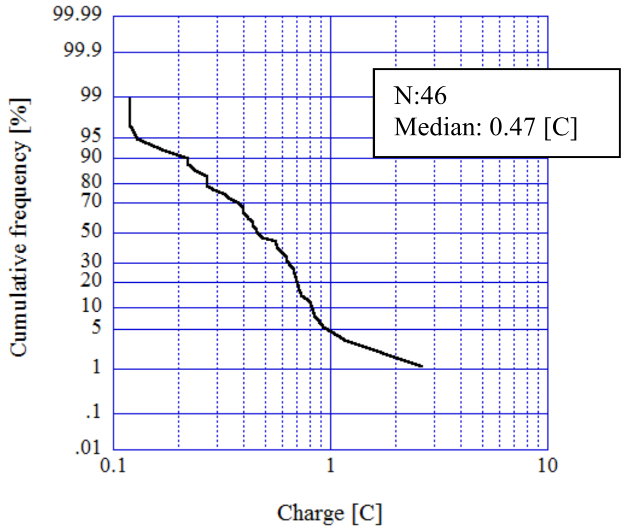


Fig. 10 Cumulative frequency distribution of stroke charge of following strokes.

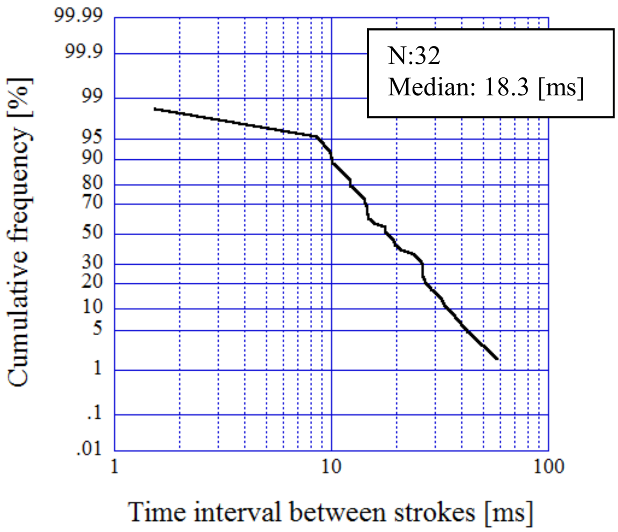


Fig. 11 Cumulative frequency distribution of time interval between following strokes.

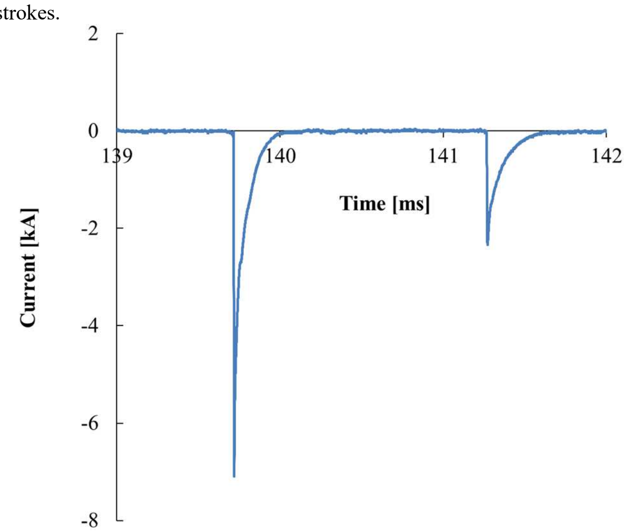


Fig. 12 Measured current waveform with time interval of 1.5 ms.

Fig. 13 shows the time interval between the apparent end of the ICC and the onset of the following stroke. As the end of the ICC is determined by the recovery to the current level prior to the onset of the return stroke, the time of the end of the ICC is ambiguous due to the noise floor of ± 25A. Although the number of the data subject to analysis is as small as 14, the median interval was 26.3 ms, almost the same as the observed stroke interval associated with return strokes initiated by downward propagating leaders, 33ms [2].

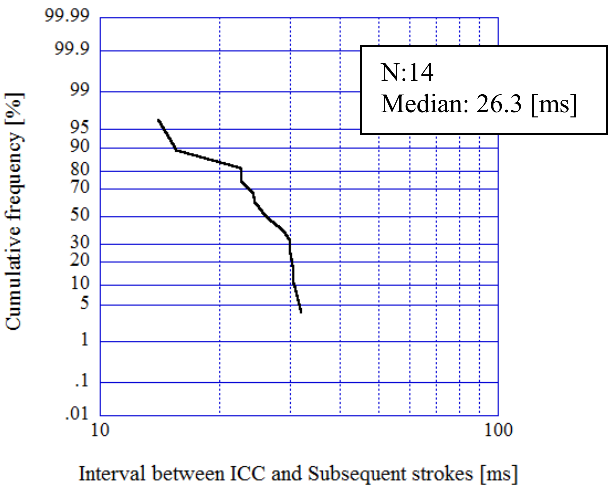


Fig. 13 Cumulative frequency distribution of time interval between end of ICC and onset of following subsequent strokes.

IV. Discussion

Fig. 14 shows the relation between the current peak and the stroke charge for 46 following strokes. There seems almost linear correlation with the correlation coefficient, 0.82. The approximate power curve is also shown in the figure and the coefficient of determination was 0.62.

Table I shows the median of current peaks, stroke charge and time interval between subsequent strokes as well as those reported in [15]. The median of the stroke charge and the time interval between subsequent strokes in this paper agrees with the median in [15], however, the median current peak in this paper is 30 % lower than that in [15]. The median subsequent stroke current at the same site in [12] is 5.65 kA, and the difference from our study is 10%. However, median of subsequent stroke current peaks is 10 kA in [2], 9kA in [16] and 10kA in [17] [3] for the lightning flash to the tall structures.

The median of the total charge of the negative lightning on the coast of the Sea of Japan [9, 12, 14] is similar to the result in [15], however, the occurrence of the bipolar lightning is frequent as indicated in Fig. 4.

One of the possible explanation of the characteristics of the winter lightning along the coast of the Sea of Japan is that in the case of the active lightning (the altitude of -10°C isotherm is between 1000 m and 2500 m) [9] the negative and positive charge distributes in a large horizontal extent [2] in the distance of the order of kilometers [18, 19] influenced by the strong updraft. The low subsequent stroke current might be due to the low density of the charge distribution.

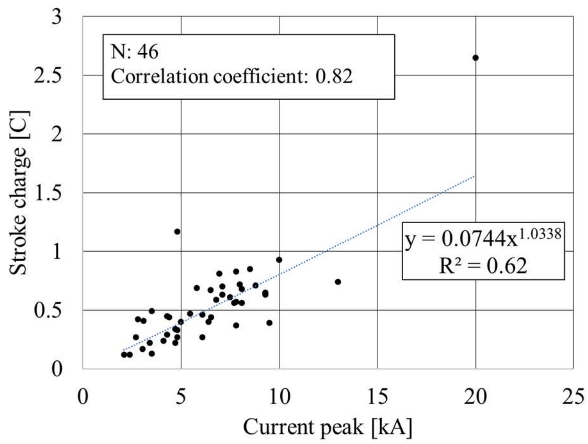


Fig. 14 Current peak and stroke charge.

TABLE I MEDIAN OF CURRENT PEAK, STROKE CHARGE AND TIME INTERVAL BETWEEN SUBSEQUENT STROKES.

	This study	Ref. [15]
Current peak [kA]	6.3 (46)	9.2 (615)
Stroke charge [C]	0.47 (46)	0.51 (615)
Time interval between strokes [ms]	18.3 (32)	18.6(476)

V. Conclusion

In this paper measured waveforms at Nikaho, close to the coast of the Sea of japan, in winter from 2013 to 2019 are investigated and the current waveforms associated with return strokes following the ICC are studied. The following insights are obtained.

- The frequency of the occurrence of the ICC superposed by the pulse with the amplitude of 2 kA or more is high compared with the result in Austria [15].
- The return stroke current amplitude following the ICC is less than the amplitude of the subsequent strokes initiated by downward propagating leaders and the current amplitude of the return strokes to the tall structures in regions other than the winter lightning area in Japan.

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