Paper

Study on Predicting Lightning Damage to Utility Power Supply Systems Using Cloud-to-Ground Lightning Information from the Internet

Member Masahito Ikeda (Nippon Soda)
Life member Susumu Aiba (Kanazawa Institute of Technology)

Lightning occurs in the Joetsu area on between 30 and 35 days per year. The Japan Meteorological Agency's lightning warnings are valid for as many as 2,170 hours per year. Moreover, electric power consumers have observed that approximately 65 incidences of grounding (zero-phase voltage of 4.5 kV or more), which are assumed to have been caused by lightning, occurred in the 66-kV systems belonging to utility power suppliers in the Joetsu area. Furthermore, there have been a number of cases of instantaneous power failure (two seconds duration or less) each year that are also assumed to be attributable to lightning. For large electric power consumers, such problems particularly instantaneous power failures which can cause serious damage to production facilities, cannot be overlooked. If predicting such types of lightning could be made relatively easily, electric power consumers would be able to establish production systems that enabled them to anticipate and deal with instantaneous power failure. Lightning prediction systems are therefore particularly important to users of utility power systems.

With the increasingly widespread use of the Internet, it has become possible to readily acquire and utilize cloud-to-ground lightning information that has been made publicly available by Tohoku Electric Power Co., Inc., and Hokuriku Electric Power Co., Inc. Therefore, the authors propose applying a prediction algorithm formulated by them to the assessment index through utilizing such Internet based lightning warnings from the Meteorological Agency and cloud-to-ground lightning information from Tohoku Electric Power Co., Inc., and Hokuriku Electric Power Co., Inc. The number of measured grounding incidences was used to determine the assessment index. During a two-year period from 1999 to 2000, lightning was predicted at the users' end of the Joetsu area's 66-kV utility power supply systems. Measurements indicated a 94.6% success rate in predicting lightning and a 100% success rate for predicting instantaneous and normal power failure, thereby proving the effectiveness of the proposed approach.

Keywords : lightning, Internet, cloud-to-ground lightning information, lightning prediction, lightning observation, Lightning Location and Protection System, direct finder

1. Introduction

In the Joetsu area, the number of days on which lightning occurs is between 30 and 35 days per year, and the number of valid lightning warnings total an average of 2,170 hours per year. The number of measured grounding incidences at the electric power consumer side (zero-phase voltage of 4.5 kV or more) that are assumed to have been caused by lightning on the 66-kV utility power supply systems averages 65 times per year. There have also been several cases of instantaneous power failure (of two seconds or less duration) observed that are assumed to be attributable to multiphase grounding caused by lightning induced grounding. For large electric power consumers, such instantaneous power failures cannot be overlooked due to the serious damage that can be caused to production facilities.

If lightning damage could be predicted with relative ease, a system that could handle anticipated instantaneous power failures could be developed. Therefore, the prediction of lightning damage to utility power systems is an extremely important issue.[1]

In recent years, the study of lightning strike point assessment has been frequently carried out utilizing lightning prediction,[2][3][4][5][6] lightning strike point prediction,[7][8][9] the Lightning Location and Protection (LLP) System, System de Surveillance et d'Alerte Foudre par Interferometrie Radioelectrique (SAFIR), and others. The accuracy in predicting the location of strike points is quite high. With the widespread use of the Internet, most lightning related information is now available to the public. Against this background, the cloud-to-ground lightning information[13][14] published by Tohoku Electric and Hokuriku Electric Power Co., Inc., has also become readily available.

Therefore, the authors have tried to determine whether it is possible to predict lightning strikes to Tohoku Electric's 66-kV Joetsu system based on the prediction algorithm that they have developed, by utilizing lightning warnings from the Meteorological Agency and cloud-to-ground lightning information from Tohoku Electric Power Co., Inc., and Hokuriku Electric Power Co., Inc., which are available on the Internet. It was then required to detect the necessary conditions for the application of the algorithm. As investigations proved the feasibility of this type of prediction, an algorithm was developed that allowed the prediction to be made. The merit of the prediction algorithm proposed herein is that it allows the prediction of lightning damage to be conducted on a specificed power line in a specific district, based on the lightning information for that district. As a prerequisite for determining this prediction, the probability of the first occurrence of lightning from a group of thunderclouds striking any point that is not on the specific power line, must be high, and if the lightning strikes the specific power line, the damage must be limited to the grounding of a single phase only. Also, the probability that the strike goes over to two or more phases and leads to an instantaneous or normal power failure, must be low. If these conditions are satisfied, lightning striking a specific power line can be predicted by observing the first lightning to occur in the specified district. The authors, under the above mentioned conditions, over a two-year period between 1999-2000, observed from the consumers' side, the first lightning produced by a group of thunderclouds. Observations indicated the probability that the first occurrence of lightning striking a point not on the specific power lines was 0.946, while the probability that the first occurrence of lightning striking the specific power lines and flows short circuiting over to two or more phases to be 0.0045. Accordingly, the authors can report that lightning striking a specified power line in a specific district can be predicted by observing, in accordance with this proposal, the first occurrence of a lightning strike in the said district. This report describes the consistent relationship between prediction and the actual occurrence of lightning, and also provides valuable data for helping prevent lightening damage to electric power systems, as verified by power consumers.

2. Lightning Assessment Data

The lightning strike location assessment system adopted by Tohoku Electric Power Co., Inc., which is now available to the public over the Internet, was developed and introduced between 1991 and 1993 in order to (a) understand in real time a fluctuation of lightning activities over the sea and mountains, which has so far proved difficult to do; (b) speed up power supply system operations and maintenance by predicting lightning strikes; and (c) clarify the characteristics of lightning, which is necessary to design a lightning protection system including preparing lightning distribution charts.

The system mainly comprises a lightning direction finder (DF). This determines the direction of the electromagnetic waves emitted by lightning, the polarity of those waves, and the intensity of their magnetic field by analyzing the waves received. DFs have been installed at nine locations in the area serviced by Tohoku Electric Power Co., Inc. The data acquired is electronically transmitted to the Advanced Position Analyzer (APA) located at the Izumi Computing Center for further calculations, indications, and recording of lightning strike locations through its data processing system. The data is also processed by the Accident/Meteorological Information System as lightning assessment data and is transmitted to each administration office in the form of a directive. Such lightning assessment data has now been made available to the public over the Internet.

Hokuriku Electric Power Co., Inc., is also operating a similar lightning location assessment system and is making its assessment data available to the public over the Internet.

For the prediction of lightning damage to utility power systems, two lightning damage assessment data were used: Tohoku Electric's Cloud-to-Ground Lightning Information and Hokuriku Electric's Cloud-to-Ground Lightning Information.

3. Prediction Algorithm

The authors decided to use the following algorithms in predicting lightning damage to power supply systems: the Lightning Warning Information, Tohoku Electric's Cloud-to-Ground Lightning Information, and Hokuriku Electric's Cloud-to-Ground Lightning Information. When the prediction judgment factor ζ of formula (1) is true, lightning will occur. When ζ is false, lightning will not occur.

$$\zeta = \kappa \wedge (\lambda \vee \mu) \qquad \cdots (1)$$

Here, $\wedge$ represents the logical operator "and," while $\vee$ represents "or." Each proposition on the right side of the formula is as follows.

- κ :Meteorological Agency's lightning warning is valid during the time the prediction is being made.
- λ :One or more bolts of lightning have been observed in the area specified in Fig. 1 of Tohoku Electric's cloud-to-ground lightning information diagram during the time the prediction is being made.
- μ :One or more bolts of lightning have been observed in the area specified in Fig. 2 of Hokuriku Electric's cloud-to-ground lightning information diagram during the time the prediction is being made.

The object of the prediction was the 66-kV Joetsu power supply system. Accordingly, two areas were designated as areas under study. One is the entire area of Niigata prefecture (Fig.1), including the Joetsu district, and the other is an area covering the Noto Peninsula and a part between the peninsula and the Joetsu district (Fig.2). The latter area is where thunder clouds are generated and move toward Niigata prefecture. The subject areas for the prediction of the lightening damage for the investigation were determined by observing the lightening that struck immediately before the arrival of the thunder clouds that were moving towards the 66-kV Joetsu power supply system.

When the prediction judgment factor θ of formula (2) is true, the algorithm cancels out the prediction that lightning will occur. When θ is false, the prediction that lightning will occur is not canceled, and the prediction stands.

$$\theta = \sigma \wedge \tau \quad \cdots (2)$$

Here, each proposition on the right side of formula (2) is as follows:

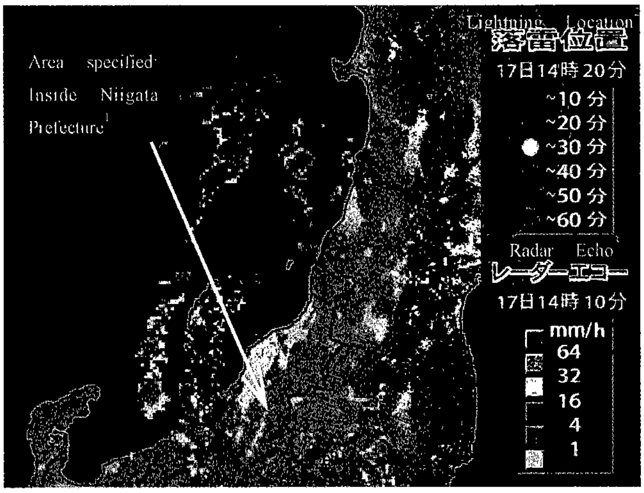
σ :At the time the prediction is made, no lightning occurs over a period of 60 minutes in the area specified in Fig. 1.

τ :At the time the prediction is made, no lightning occurs over a period of 60 minutes in the area specified in Fig. 2.

During the observation, information on whether or not formula (1) is true is available over the Internet on Tohoku Electric's Cloud-to-Ground Lightning Information Images page or Hokuriku Electric's Cloud-to-Ground Lightning Information Images page on the hour. In this case, for example, during time t_1, Lightning Warning Information is not valid. During time t_2, Lightning Warning Information is valid, and whether or not formula (1) is true is confirmed on the Internet every 15 minutes. When the prediction judgment factor ζ of formula (1) is true, the prediction is that lightning will occur. When the prediction judgment factor of formula (1) becomes true, whether the status of the prediction judgment of formula (2) is determined every 15 minutes. When the prediction canceling factor θ of formula (2) is true, the prediction that lightning damage will occur is canceled. When θ is false, the prediction that lightning damage will occur is not canceled.

During time t_1 when the Lightning Warning Information is not valid, the procedure for verifying formulas (1) and (2) is conducted every hour; when the lightning warning is valid, the above verification is conducted every 15 minutes. The reason is as follows: because the chances that lightning will strike before the Lightning Warning Information becomes valid are minimal and because the chances that lightning will strike after the lightning warning becomes valid are extremely high, it was therefore decided that verification should be conducted every hour in order to verify that there would be no lightning before the lightning warning became valid. Looking at the cell structure of thunderclouds and the duration of each development, the maturing and vanishing stages last for about 15 minutes. Therefore, it was decided that verification should be conducted every 15 minutes during the time when the lightning warning is valid.

The prediction of the lightening damage was conducted in the limited area of the Joetsu 66-kV



Notes: 1) Labeling added by authors
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Source: www.tohoku-epco.co.jp/weather/

Fig. 1 Cloud-to-Ground Lightning Information Image from Tohoku Electric

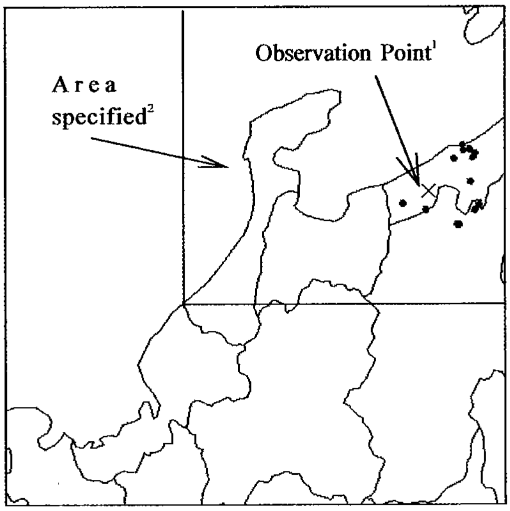

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Fig. 2 Cloud-to-Ground Lightning Information Image, Hokuriku Electric

utility power supply systems. In practice, however, it is undesirable to issue and cancel thunder strike warnings frequently (in half-hourly intervals). This would confuse electric power consumers' production systems because they are compelled to switch their production systems from the normal mode to the lightning protection mode and vice versa. An investigation conducted during the trial stage, however, revealed that the time required from the arrival of a series of thunder clouds until they leave the area after diminishing is approximately 60 minutes. Therefore, it became clear that, if thunder does not strike at all for 60 minutes, the area will not be attacked by a further series of thunderclouds for a period of a few hours. Therefore, a 60-minute period was determined as adequate waiting time for the cancellation of the lightening warning.

Fig. 1 shows a cloud-to-ground lightning information image from Tohoku Electric; Fig. 2 shows the same from Hokuriku Electric.

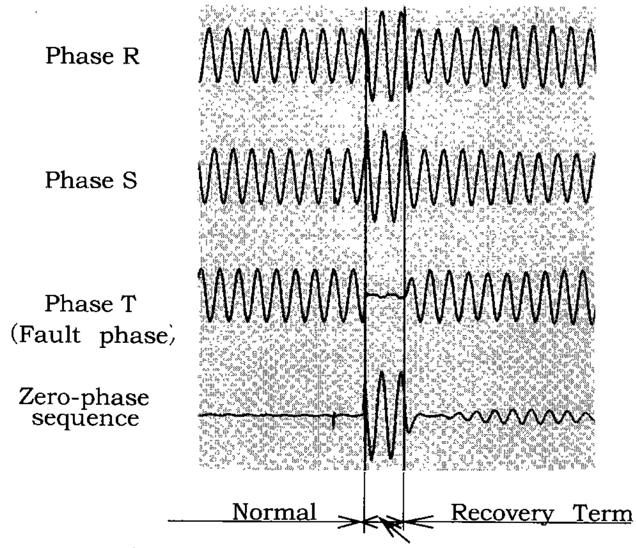
4. Assessment Method

4.1 Lightning Damage to Power Supply Systems and Grounding For this observation, the specific power supply system on which the authors intend focused their prediction was lightning damage to the 66-kV systems of Tohoku Electric, particularly voltage fluctuations at the electric power consumers' end caused by lightning strikes. In the Joetsu system, all 66-kV systems in the area are interconnected. Accordingly, if there are grounding problems anywhere in the system, the trouble can be observed by any electric power consumer at the power receiving end as grounding assumed to be caused by lightning. For example, when lightning strikes an overhead ground wire or a steel tower along Joetsu's power transmission line and causes the lightning current to flow through the tower and the grounding resistance, the resultant increase in voltage through the ground acts as arcing-horn adverse flashover between the wire and the tower, causing grounding. If grounding occurs in one line only, the voltage between the lines can be secured, and zero-phase voltage occurs. For example, Fig. 3 shows T-phase voltage waveforms , and one-line grounding. The R, S, and T phases indicate their respective between phase and ground voltages. When the increased lightning current is too large for single-line grounding to handle, two-line or three-line grounding occurs, and there is a variation in voltage between phases, i.e., an instantaneous power failure occurs. For example, Fig. 4 shows the voltage waveforms of a three-phase short-circuit fault period. In such case, a 2-phase or 3-phase short circuit may activate the overcurrent relay at the power supplier's substation, opening the power transmission circuit breaker or causing a high speed re-closing of the circuit. In this case, a power failure or instantaneous power failure occurs at the electric power consumer's end. If the electric power consumer is equipped with an inter-connected independent power plant and the point of failure is relatively close to the consumer, the electric current supplied from the consumer to the failure point activates an adverse power relay, opening a related circuit breaker, thus preventing the current from being supplied from Tohoku Electric.

Lightning damage to electric power consumers, other than insulation breakdown, usually causes damage to power transmission and distribution systems, causing multiphase grounding, including 2-phase and 3-phase instantaneous or normal power failure. The occurrence of lightning can be determined by investigating the grounding problem that is assumed to be due to lightning damage to the system from the power supplier.

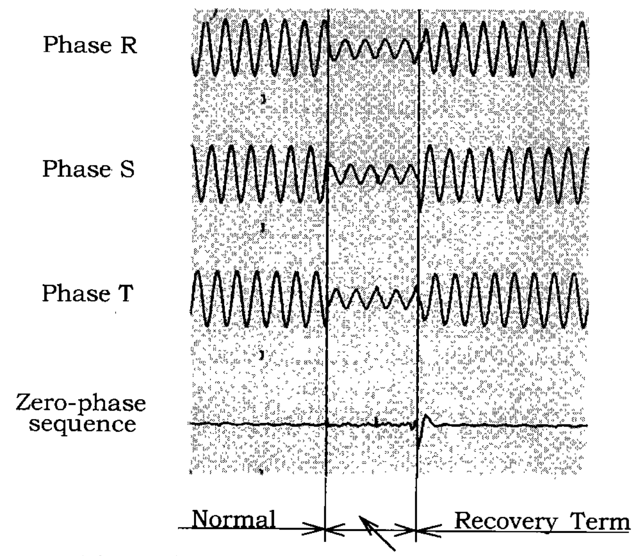
4.2 Demonstration of Predicting with the Lightning Prediction Algorithm Table 1 shows a True Value Table showing the prediction judgment (1) formula for predicting whether lightning will occur using the lightning predicting algorithm formula: Table 2 shows the True Value Table showing the cancellation judgment (2) formula for canceling the prediction that lightning will occur.

4.3 Lightning Prediction Assessment Method Regarding the concrete method of assessing lightning damage predictions, the authors decided to use a



Single-Phase Ground Fault Period
August 6, 2000, 13:19:47

Fig. 3 One-line grounding voltage waveforms



Three-Phase Short-Circuit Fault Period
August 2, 2000, 18:17:38

Fig. 4 Instantaneous power failure voltage waveforms

Table 1 True values for the prediction judgment that lightning will occur ($\zeta = \kappa \wedge (\lambda \vee \mu)$)

Judgment	Judgment factor ζ	Lightning warning information κ	Tohoku Electric's cloud-to-ground lightning information λ	Hokuriku Electric's cloud-to-ground lightning information μ
Predicting	True, Prediction	True, Lightning warning valid	True, Lightning has been observed	True, Lightning has been observed
	True, Prediction	True, Lightning warning valid	True, Lightning has been observed	False, Lightning has not been observed
	True, Prediction	True, Lightning warning valid	False, Lightning has not been observed	True, Lightning has been observed
Not predicting	False, Not predicting	True, Lightning warning valid	False, Lightning has not been observed	False, Lightning has not been observed
	False, Not predicting	False, Lightning warning has not been announced	False, Lightning has not been observed	True, Lightning has been observed
	False, Not predicting	False, Lightning warning has not been announced	True, Lightning has been observed	False, Lightning has not been observed

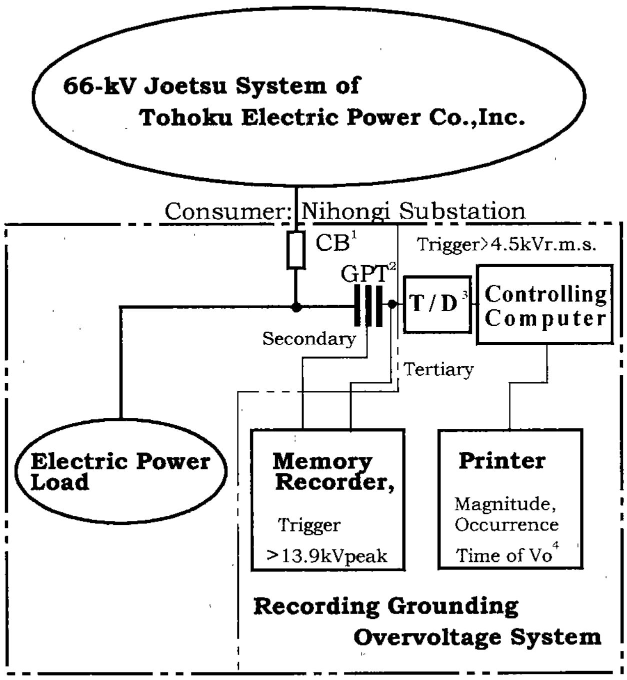
Table 2 True values for the cancellation of the prediction judgment that lightning will occur ($\theta = \sigma \wedge \tau$)

Judgment	Judgment factor θ	Tohoku Electric's cloud-to-ground lightning information σ	Hokuriku Electric's cloud-to-ground lightning information τ
Canceling	True, Canceling	True, Lightning has not been observed	True, Lightning has not been observed
Not canceling	False, Not canceling	True, Lightning has not been observed	False, Lightning has been observed
	False, Not canceling	False, Lightning has been observed	True, Lightning has not been observed
	False, Not canceling	False, Lightning has been observed	False, Lightning has been observed

number of overvoltage V_{OL} observations taken at the electric power consumer end of the Nakago A line of Tohoku Electric's 66-kV Joetsu system. The accuracy of the lightning damage prediction was assessed using the total number, N_{ALL}, of V_{OL} observations, and the number of V_{OL} observations, N_{Pred}, when it was predicted that lightning will occur. The lightning prediction success rate, F_{Pred}, that indicates the accuracy of lightning damage prediction is shown by formula (3)

$$F_{Pred} = N_{Pred} / N_{ALL} \times 100 \quad \cdots(3)$$

Here, the cloud-to-ground lightning information of Tohoku Electric and Hokuriku Electric were assessed as standards. In other words, lightning not represented in the cloud-to-ground lightning information was taken as not having occurred.



Notes: 1) Circuit breaker for receiving initial power
2) Grounding-type potential transformer
3) Peak-holding-type voltage/amperage converter
4) Grounding overvoltage (voltage of zero phase sequence)

Fig. 5 Method of recording grounding overvoltage

The cumulative time of lightning warning T_{LW} and of lightning prediction T_{Pred} were then calculated, and the ratio of these times to the total observation time calculated in percentages as H_{LW} and H_{Pred}, respectively. The rate of occurrence of meteorological lightning is indicated by formula (4) . The accuracy of lightning prediction for assessment is expressed in formula (5) .

$$H_{LW} = T_{LW} / T_{obs} \times 100 \quad \cdots(4)$$

$$H_{Pred} = T_{Pred} / T_{obs} \times 100 \quad \cdots(5)$$

Here, T_{obs} is the cumulative observation time.

4.4 Method of lightning observation It was decided that lightning observation was to be conducted by measuring the secondary phase voltage and tertiary grounding overvoltage (zero-phase voltage) of a grounding-type potential transformer of the power receiving end of the Nakago A line of Tohoku Electric's 66-kV Joetsu system, electric power consumers, and the Nihongi substation. Two methods were used for the observation, as shown in Fig. 5.

Firstly, the tertiary grounding overvoltage (zero-phase voltage) of a grounding-type potential transformer was connected to an analog inlet of a controlling computer through a peak-holding-type voltage/amperage converter. This would record the grounding overvoltage and the size and time of the grounding overvoltage (zero-phase voltage) when an overvoltage of 4.5 kV r.m.s. or more occured. An overvoltage value of 4.5 kV r.m.s. or more was determined because this value was 5% of the entire scale (90kV) of the instrument used to measure the grounding overvoltage. The response, i.e., the time required to reach 90% of the ultimate constant output, was 200msec or less. Then, the secondary and tertiary grounding overvoltage of the grounding-type potential transformer was introduced into the memory recorder through a trigger, in order to record a grounding overvoltage (zero-phase voltage) of 13.9 kVpeak and 500 μ sec or more. A voltage of 13.9 kVpeak or more was determined. This voltage was determined following a number of trials, in order to ensure the recording of the grounding overvoltage without picking up any extraneous noise. Table 3 shows the primary specifications of the grounding-type potential transformer, the peak-holding-type voltage/amperage converter, and the memory recorder.

4.5 Distinguishing Lightning Grounding from General Grounding The recorded grounding voltage data on the controlling computer and memory recorder includes both lightning and other kinds of grounding. Therefore, these records must be distinguished. The following method was used to distinguish the types of grounding. Records of the grounding that occurred during the time when no

Table 3 Specifications of the observation equipment used

Device	Item	Content
Grounding-type potential transformer	Type	FTIE-60
	Frequency	50Hz
	Primary-phase voltage	66 ⁄ √ 3kV
	Secondary-phase voltage	110 ⁄ √ 3V
	Tertiary-phase voltage	110 ⁄ 3V
	Tertiary zero-phase voltage	110V
	Probability class	Class 1P/3G
Peak-holding-type voltage/amperage converter	Type	MDVTT2-83A
	Input voltage	AC 0 ～ 120V
	Output voltage	DC 4 ～ 20mA
	Response	200msec ⁄ 90%
	Specific function	Peak hold
Memory recorder	Type	8840
	Measuring function	Memory recorder
	Number of channels	Analog 8ch + Logic 16ch
	Memory capacity	When 1 M word 8ch is used, 12bit x 100 k word/ch
	Maximum sampling speed	200kS/sec (8ch simultaneously)
	Triggering condition	Primary conversion 13.9 kVpeak can be continued for 500 μ sec or more

cloud-to-ground lightning information was given by Tohoku Electric or Hokuriku Electric over the Internet were deemed irrelevant. The recorded times of records on the controlling computer and/or memory recorder that matched either of the recorded times for the Lightning Warning Information of Tohoku Electric or Hokuriku Electric were regarded as lightning grounding.

5. Prediction Results

Fig. 6 shows figures for N_{ALL} and N_{Pred}. The diagram also indicates the number of monthly observations. According to Fig. 6, the number of N_{ALL} and N_{Pred} for two the years between 1999 and 2000, was 130 and 123, respectively. The success rate of lightning prediction F_{Pred} is indicated by formula (3) and was 94.6% for this two-year period. There were seven observations of lightning that had not been predicted. They occurred immediately before a warning that lightning will occur was given. These seven cases are considered to have been due to what is called the first lightning of a series of thunderclouds. As no thunder strike had been observed in the LLP system before any of these 7 cases of lightening strikes, it is assumed that the initial lightning of a series of thunderclouds has struck a power transmission line. Here we have evaluated the seven cases of first lightning strikes on the transmission lines. Accordingly, the probability that first lightning will strike the 66-kV Joetsu system is 7/ N_{ALL} = 0.054. The meaning of this probability is significant. Namely, according to the prediction algorithm proposed by the authors, if a lightning warning has been issued, the prediction is that lightning will occur from the time the first lightning is observed in the specified area. Therefore, to maintain the effectiveness of the prediction algorithm, it is necessary that first lightning should always occur outside of the 66-kV Joetsu system. However, in reality, the first lightning does not necessarily occur outside of the 66-kV Joetsu system. In other words, the limit of the prediction according to this system is the probability of first lightning occurring. This means that lightning cannot be predicted 5.4 times out of 100.

When lightning cannot be predicted 5.4 times out of 100, the probability that instantaneous power failure and normal power failure will occur can be assessed as follows: Out of the number of grounding incidences that were considered to be caused by lightning with a N_{ALL} of 130 times, 2-phase or more grounding occurred 11 times, including four in 1999, six instantaneous power failures in 2000 (2-phase or more, 65% voltage or below, for three cycles or more and two seconds or less duration) and one power failure (no voltage for two seconds or more). Therefore, the probability of instantaneous power failure and normal power failure was 11/130 = 0.085. Furthermore, the probability that instantaneous power failure and normal power failure will occur due to first lightning is 0.054 x

0.085 = 0.0045. This means, therefore, that for 4.5 lightning strikes out of 1,000 (one out of 222) to the 66-kV Joetsu system, instantaneous power failure and normal power failure cannot be predicted. During this two-year observation period, there were 130 incidences of lightning in the 66-kV Joetsu system. During this period the instantaneous and normal power failures of the Nakago A line occurred when the prediction was that lightning will occur, and the power failure prediction rate that was considered due to lightning was 100%. Because the observation period was short, the probability was rather coarse. However, it is considered that once in 3.4 years (222/ (130/2)), there may be situations in which predicting instantaneous or normal power failures caused by first lightning are not possible.

Materials provided by Tohoku Electric indicate that seven short circuit trips (including the successful reclosing of the circuits) caused by lightning and two short circuit trips due to unknown causes occurred in the 66-kV Joetsu system in 1999. Short circuit trips (including successful reclosing of the circuits) occurred 10 times in 2000 due to lightning. According to the authors' observations, instantaneous power failure and normal power failure occurred four times in 1999 and seven times in 2000. Tohoku Electric recorded more failures than the authors did. This is because the authors' observations were based on voltage observation at the power receiving end of electric power consumers on the Nakago A line; namely, voltages that were 65% or below the rated voltage and continued for three cycles or more were recorded as one grounding. Therefore, lightning originated multiphase grounding failures in systems farther than the Nakago A line were not recorded in the Nakago A line because a drop in voltage on the Nakago A line does fall below the rated 65% voltage.

Fig. 7 indicates the time predicted when lightning will occur. The diagram shows that the cumulative time of lightning warning announcement T_{LW} was 4,353 hours, the cumulative time of lightning prediction T_{Pred} was 1,872 hours, and the total cumulative time of observation T_{obs} was 17,544 hours. Accordingly, from formula (4) , the rate of lightning warning announcement H_{LW} was 24.8%, and from formula (5), the rate of prediction time H_{Pred} was 10.7%.

This observation employs a system, which enables predicting lightening damage by observing the time of the initial lightning from a series of thunderclouds that strikes a specific area. Accordingly, how early the prediction can be made depends on the time interval from the initial strike on the area to the strike on the specific power line. According to our two years' observations, the time preceding the prediction from the observation of the initial strike of a winter season lightening in the neighborhood of the Noto Peninsula due to the northwestern wind by the Siberian air bulk until the group moves to the Joetsu district and that causes the thunder damages on the power line, will be a matter of hours.

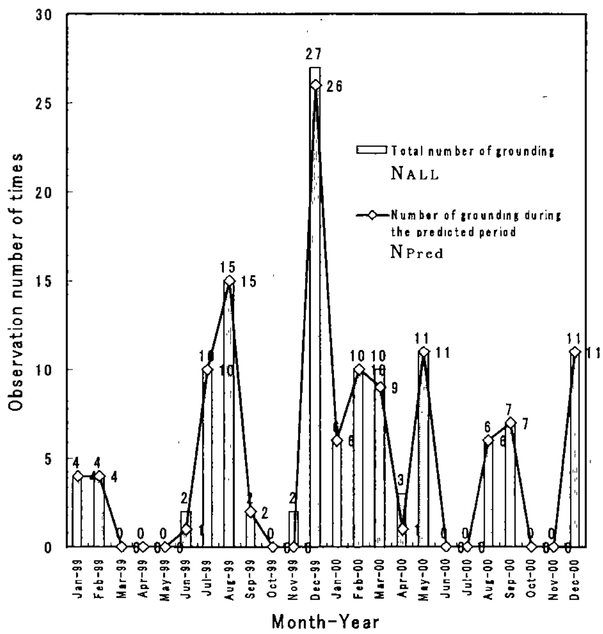


Fig. 6 Observations of grounding

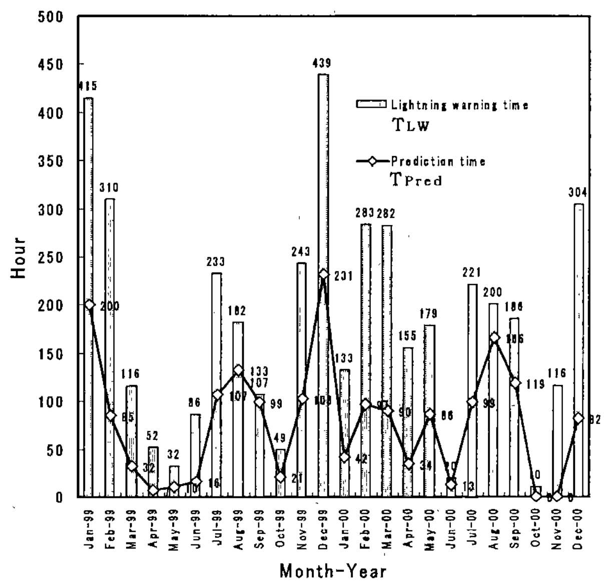


Fig. 7 Lightning prediction time

Next, we explain the relationship between this lightning damage prediction system and the detection rates of the Lightning Location and Protection Systems of Tohoku Electric Power Co., Ltd. and Hokuriku Electric Power Co., Ltd., which are very closely related to our system. It is known that the detection rates defined in equation (6) differ for the winter season (November ~ March) and the summer season (April ~ October) [16][17][18][19].

$$\text{Detection rate} = \frac{\text{Cases detected by LLP system}}{\text{Cases of transmission line trip accidents (lightning strike discharge path)}} \times 100[\%] \quad \cdots (6)$$

The documented(17) detection rate of Hokuriku Electric's LLP system is about 80% in summer and about 60% in winter. The documented detection rate (16), (19) of Tohoku Electric's LLP system is considered to be 79~83% in summer and 63~65% in winter.

On the other hand, the number of occurrences, N_{All}, of overvoltage grounding considered to be due to lightning damage was 56 in summer and 74 in winter according to the 2 years of observations by the authors. Among those, we were unable to predict 7 cases of overvoltage grounding (4 in winter and 3 in summer). The 7 cases of overvoltage grounding we could not predict were not in the LLP system records when they occurred. In other words, the LLP system could not detect those cases. Also, when we collated these 7 cases of overvoltage grounding with Takada Observation Station's original register of surface observations, the station observed thunder and lightening flashes in 4 cases of overvoltage grounding (2 in April, 1 in November, and 1 in December) . Neither the LLP system nor Takada Observation Station observed the remaining 3 cases (1 each in March, June, and November) , and the causes of overvoltage grounding as checked by Tohoku Electric were unknown. However, there was great possibility of lightning occurring under the weather conditions at those times; therefore it is not clear whether the cause was overvoltage grounding or some other cause. As a tentative assumption, the lightning damage prediction rate excluding the remaining 3 cases, is therefore: (127-4) /127 x 100 = 96.9%.

Concerning the 7 cases that could not be predicted, Takada Observation Station's original register for surface observation shows that the station did not observe any thunderstorm activity (thunder/flashes) until 24 hours before the time when overvoltage grounding occurred. Therefore, we can understand that in at least 4 of these 7 cases the overvoltage grounding was caused by a first lightning strike.

During a recent observation period, Tohoku Electric's data was renewed at 10-minute intervals, but a delay of nearly 20 minutes occurred until the timing of the newest time data was indicated; Hokuriku Electric's data was renewed at 10-minute intervals, and the delay until indication of the newest time data was about 3 minutes. Therefore, even though the renewal of each item of information was done at 10-minute intervals, when we consider that the indication of the newest information was delayed, coupled with the fact that information was confirmed at 15-minute intervals as shown in Table 4, delays ranging from 13 minutes to 45 minutes occurred. Relative to thundercloud movement speed, these delays are considered to cause no problem. Average thundercloud movement speed is 20~30 km/h according to data from a source connected with the meteorological station, and the speed of thunderclouds moving particularly rapidly is about 45 km/h. Therefore, when moving thunderclouds have

Table 4 LLP system observation data and time delay until prediction judgment

Time [min.] / Company where observation was done	Renewal cycle	Trans -mission delay	Confir -mation cycle	Delay time
Tohoku Electric Power Co., Inc.	10	20	15	30-45
Hokuriku Electric Power Co., Inc.	10	3	15	13-28

caused cloud-to-ground discharges in a location more than 45 km from the electric power system in the Joetsu region, and this is observed by the LLP system, lightning damage prediction can be made in ample time. From actual observation results, almost all predictions were made more than 90 minutes before the actual time at which overvoltage grounding was observed.

In the past, it has been rather difficult for general electric power consumers to predict lightning damage to their power supply systems due to a lack of facilities and funds. Therefore, the best they could do was to interpret lightning warning announcements or grounding observations received as lightning warnings. Lightning warnings are normally announced long before thunderclouds become active. There were problems in which the predictions that lightning will occur were announced after the lightning caused grounding, which is obviously too late. The algorithm proposed by the authors specifies an area with a wider range than the area covered by the 66-kV Joetsu system. Therefore, during the winter periods, when thunderclouds move into the 66-kV Joetsu system and lightning activity from the Noto Peninsula to the Joetsu area can be observed and dealt with, predictions can be made much nearer to the actual occurrence of lightning than the lightning warnings can forecast. Because these predictions can be readily accessed over the Internet by anyone concerned, costs and other requirements can be kept to a minimum. This is a great advantage.

Finally, we'd like to mention Takada Observation Station's thunderstorm observation method and its results, which we used to confirm the LLP system detections. Takada Observation Station's thunderstorm observations record the time of occurrence, direction, and the distance from Takada station, for 3 kinds of thunderstorm phenomena: thunder (sound), flashes (light), and thunderstorms (both sound and light) in its original register of surface observations. At the time, the direction and distance information are supplemented with information from cloud radar on the ground. Also, the maximum distance from Takada Observation Station of the thunderstorms recorded on its original register of meteorological observations in a 2-year period, was

40km. For 4 of the 7 cases of failed prediction which could not be caught by the LLP system, Takada Observation Station's thunderstorm observation records coincide within minutes with the occurrence of the overvoltage groundings that we observed.

6. Conclusions

Lightning prediction was conducted over a two-year period from 1999 to 2000, from the electric power consumers' end on the Joetsu system in the Joetsu area's 66-kV electric power system using cloud-to-ground lightning information publicly available on the Internet and by utilizing a prediction algorithm developed by the authors. For the assessment indexes of the prediction algorithm, the number of observations of grounding assumed to have been caused by lightning was used. The results are summarized as follows:

(1) The accuracy of lightning prediction over the two-year period from 1999 to 2000 using this algorithm was 94.6%.

(2) During the two-year observation period, the accuracy of instantaneous and normal power failure observations was 100%. The probability of instantaneous or normal power failure caused by first lightning was 0.0045.

(3) All of the seven incidences of grounding before the prediction announcement occurred immediately before the prediction that lightning would occur. These cases are assumed to have been caused by first lightning strikes to the 66-kV Joetsu system.

(4) The probability of first lightning strikes to the 66-kV Joetsu system during the two-year observation period was 0.054.

(5) Of the incidences of grounding that were assumed to have been caused by lightning strikes during the two-year observation period, 11 cases were of two-phase or three-phase grounding. As a result, the probability of instantaneous and normal power failures was 0.085.

(6) Using the proposed prediction algorithm, large general electric power consumers can carry out the hitherto difficult task of predicting the occurrence of lightning affecting their systems quite simply if they have access to Internet-capable terminals.

The above results confirm that the prediction algorithm proposed by the authors is effective. The authors intend to improve their approach by establishing a method that would allow them to predict first lightning and to reduce the time required to make and cancel predictions.

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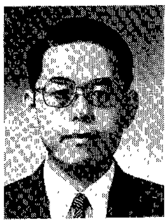

Masahito Ikeda (Member) was born in Kanagawa, Japan, on May 1, 1956. He received a B.E. degree in electrical engineering from Kanazawa Institute of Technology, Japan, in 1980. From 1980 to 1992, he worked for Hitachi, Ltd., mainly in the design section for electric power systems for electric railways. He is currently the manager of the engineering section at Nippon Soda Co.,Ltd. His research interests are in electric power systems, damages caused to them by lightning and harmonics. He is a member of the Institute of electrical Installation Engineers of Japan and IEEE.

Susumu Aiba (Life Member) was born in, Ishikawa, Japan, on May 17, 1930. He received a B.E. and M.E. degrees from Kanazawa University, Japan, in 1953 and 1973, respectively. He received a Ph.D. in engineering from Nagoya University, Japan, in 1982. He has been a professor at the Kanazawa Institute of Technology since 1979. His research area is magnetic levitation and propulsion for the linear motor train, new transit systems, new museum lighting, lightning phenomenon and lightning protection, and electric power weather environments. Dr. Aiba is a member of the Institute of Electrical Engineers of Japan, the Color Science Association of Japan, the Institute of Electrical Installation Engineers of Japan, the Institute of Image Information and Television Engineers of Japan, the Medical Electronic and Biological Engineering of Japan, and the Illumination Engineering Institute of Japan.