Paper

Lightning Protection Methods for Customer's Facilities Located in Mountainous Areas Facing The Sea of Japan

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Surge arresters which installed at customer's facilities and distribution lines are often damaged by winter lightning in mountainous areas facing the Sea of Japan. Therefore we have observed the lightning performance at a mountainous area, since 1998, in order to verify the effective lightning protection methods for customer's facilities and distribution lines. Based on the observation data and analysis results using the EMTP, we propose the effective lightning protection methods for customer's facilities.

(1) When grounding resistance of a customer's facility is less than 10 Ω, lowering the grounding resistance is one of the effective lightning protection methods for preventing a customer's arrester failure.

(2) It is effective for preventing a customer's arrester failure that grounding of a customer's facility is connected with an overhead ground wire of a distribution line through an earth wire, and it dose not increase a failure probability of a distribution arrester.

keywords: lightning, power distribution line, surge arrester, lightning protection method

1. Introduction

Lightning strokes with a large amount of energy sometimes occur on the coast of the Sea of Japan in winter [1][2]. The winter lightning strokes are concentrated on high structures located in mountainous areas, such as TV and radio broadcasting stations, and they sometimes cause damage to customer's electric apparatuses, especially surge arresters. TV and radio broadcasting stations are very important in society, and the effective countermeasures for preventing lightning-causing failures are demanded. In addition, distribution lines which supply electric power to the customer's facilities in the mountainous areas are also damaged by lightning backflow current from the customer's facilities [3][4]. Therefore countermeasures for preventing distribution outages are also demanded.

We have investigated some countermeasures for preventing arrester failures on distribution lines and have proposed the effective ones [5][6]. In order to verify the effectiveness of some countermeasures in actual fields, we have observed lightning performance of distribution lines and customer's facilities at a mountainous area facing the coast of the Sea of Japan, since 1998.

In this study, we discuss some countermeasures for customer's facilities, such as lowering grounding resistance value and connecting the grounding of a customer's facility with an overhead ground wire of a distribution line through an earth wire, based on the data observed. The effectiveness of these methods have been investigated quantitatively by using the EMTP.

2. Investigation based on observation

2.1. Observation systems There are two facilities on Mt. C., of which distance from the Sea of Japan is about 10 km and the height above the sea level is about 400 m. Taking account of the characteristics of winter lightning strokes, which are concentrated on high structures, several lightning strokes to these facilities are expected. Observation have been conducted by four still cameras equipped with liquid crystal shutter [7] and six lightning current waveshape recording systems by rogowski coil, which are referred to as "lightning surge memory". Fig. 1 shows the observation points of the still cameras on the distribution line at Mt. C., Fig. 2 shows the installation points of lightning surge memory and Table 1 shows the specifications of the lightning surge memory at Facility A. A surge memory is installed at Facility B to measure the customer's arrester discharge current.

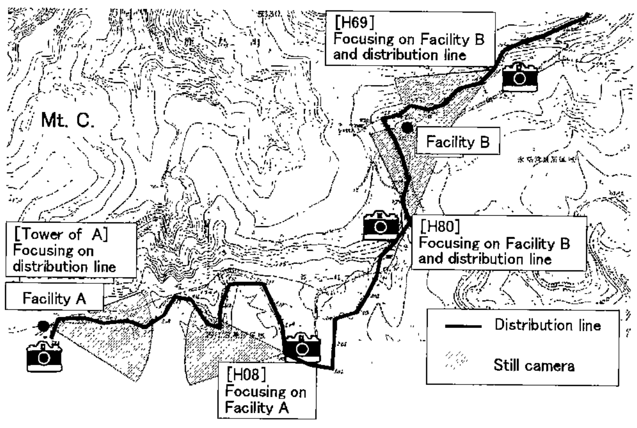


Fig. 1. Observation points of still cameras.

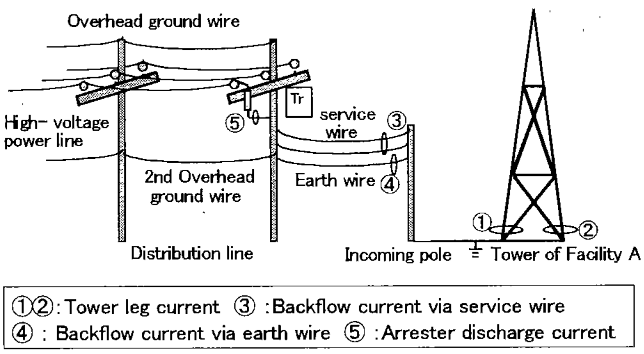


Fig. 2. Installation points of lightning surge memory.

Table 1. Specifications of lightning surge memory.

Item	Specifications
Measurement range	①②③:2.5kA～50kA,④:5kA～100kA ⑤:1kA～20kA
Measurement length	100 ms
Trigger level	5% of maxim measurement range
Frequency range	50 Hz～300 kHz
Sampling speed	250 ns / sampling
Resolution	8 bits
Record count	20 waves

2.2. Lightning protection methods of customer's facilities and distribution line

Lightning protection methods of two facilities are compared in Table 2. The grounding resistance value of Facility A is much lower than that of Facility B, and the grounding of Facility A is connected with overhead ground wires (OGWs) of the distribution line.

On the other hand, two OGWs and 10 kA rated arresters are installed on the distribution line to prevent lightning outages.

Table 2. Lightning protection methods of two facilities.

Item	Facility A (low-voltage customer)	Facility B (high-voltage customer)
Grounding resistance	1 Ω	10 Ω
Grounding system	Mesh	Depth electrode
Arrester	10kA (low-voltage)	10kA (high-voltage)
Connection with OGW	Connected	Not connected
Communication line	Optically isolated	Not optically isolated

2.3. Observation results

Table 3 shows the observation results. No outages occurred due to seven lightning strokes to the tower of Facility A. An outage, however, occurred due to one of four lightning stokes to the tower of Facility B. Fig. 3 shows the schematic of distribution line surrounding Facility B, and Fig. 4 shows photographs of a lightning stroke to the tower of Facility B. It can be seen from Fig. 4 that arresters installed at distribution line and customer's incoming pole were damaged by lightning backflow current when a lightning struck to the tower of Facility B.

There were no failure at Facility A in spite of seven lightning strokes to the tower of Facility A, which included relatively large current strokes. Compared lightning protection methods between two facilities in Table 2, no failure at Facility A is thought to be owing to considerably low grounding resistance value and the connection of the grounding of the customer's facility with the OGWs of distribution line. We investigate quantitatively the effect of grounding resistance value and the connection of both grounding on preventing apparatus failure, especially arrester failure, in Section 3.

3. Analytical study

Preventing arrester failure is very important for lightning protection against winter lightning, because it is rare that an apparatus is damaged without arrester failure. Therefore we focus some countermeasures for preventing arrester failures.

Table 3. Observation results.

Striking point	Striking Time	Observation equipment	Data observed (Sum of currents of two tower leg*)	Failed apparatus in customer's facility	Failed apparatus on distribution line
Facility A	'99.12.09 13:41:07	Camera, surge memory	Upward stroke, (+11kA)	Non	Non
	'99.12.13 05:57:27	Surge memory	(+50.5kA)	Non	Non
	'99.12.13 06:17:04	Surge memory	(-6.5kA)	Non	Non
	'99.12.16 21:51:13	Camera	Upward stroke	Non	Non
	'99.12.16 23:05:14	Camera, surge memory	Upward stroke, (-4kA)	Non	Non
	'99.12.20 01:35:00	Surge memory	(-7kA)	Non	Non
	'00.01.20 18:08:26	Camera, surge memory	Upward stroke, (+78kA)	Non	Non
Facility B	'99.12.13 05:53:31	Camera, surge memory	Stroke direction is not clear (Sum of 3-phase arrester current > +26kA)	10kA rated Arresters, communication line etc	5kA rated Arresters
	'99.12.16 17:19:24	Camera	Stroke direction is not clear	Non	Non
	'99.12.20 01:36:14	Camera	Stroke direction is not clear	Non	Non
	'00.01.20 15:41:31	Camera	Stroke direction is not clear	Non	Non

*: Currents shown in Table 3 is about half of lightning stroke current to the tower of Facility A, because the tower has four legs.

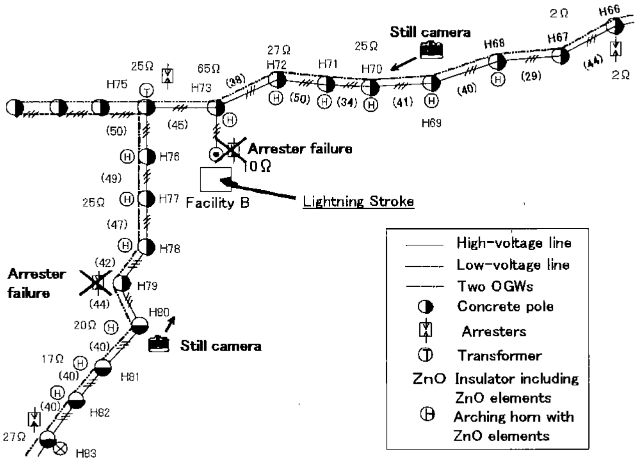
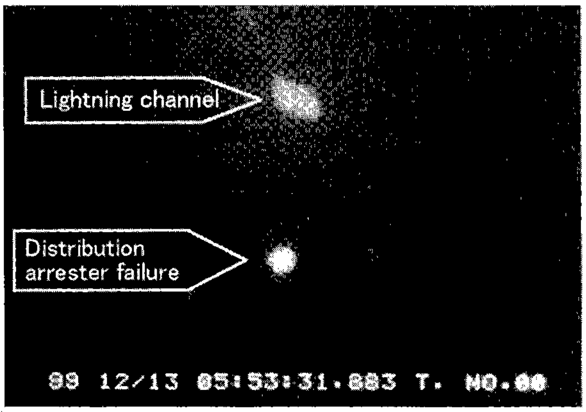


Fig. 3. Schematic of distribution line surrounding Facility B.



(a) Photograph of lightning stroke to tower of Facility B.

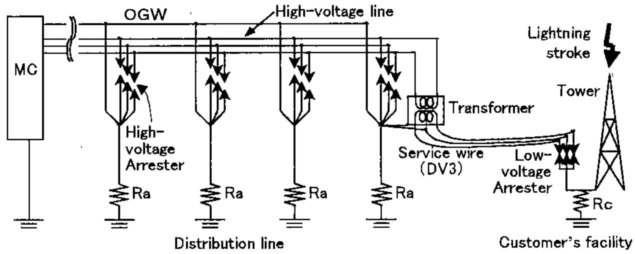
(b) Photograph of background.

Fig. 4. Photograph of lightning stroke to tower of Facility B.

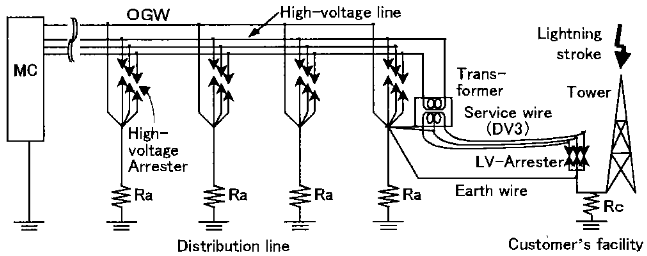
3.1. Calculation conditions

3.1.1. Distribution line configuration and line constants

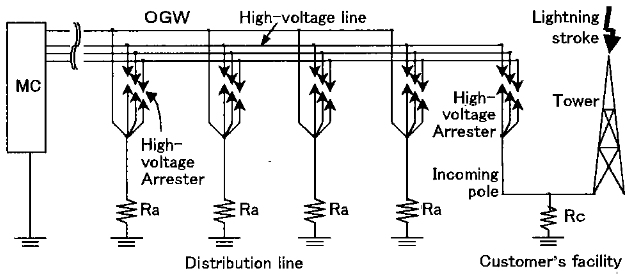
We deal with a 6.6 kV three-phase, horizontally arranged distribution line at a mountainous area. Fig. 5 shows the configurations of distribution lines with high-voltage or low-voltage customer's facilities and the model of a tower [8] and a pole transformer [9] used for the analysis. Low-voltage and high-voltage customer's facilities are connected with the end of distribution lines through high-voltage and low-voltage service wires, respectively. The length of the distribution lines is about



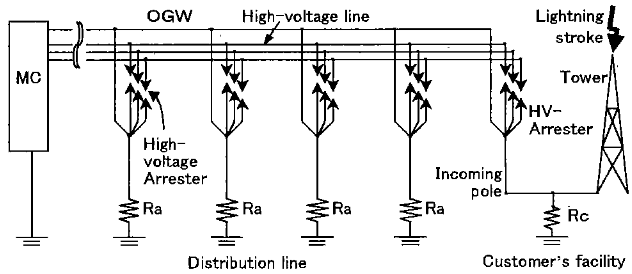
(a-1) Case of stroke to low-voltage customer's facility without connection of both grounding.



(a-2) Case of stroke to low-voltage customer's facility with connection of both grounding.

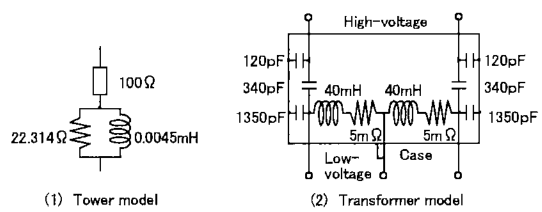


(b-1) Case of stroke to high-voltage customer's facility without connection of both grounding.



Ra: Grounding resistance of distribution arrester
Rc: Grounding resistance of customer's facility
MC: Matching circuit

(b-2) Case of stroke to high-voltage customer's facility with connection of both grounding.



(c) Tower and pole transformer model.

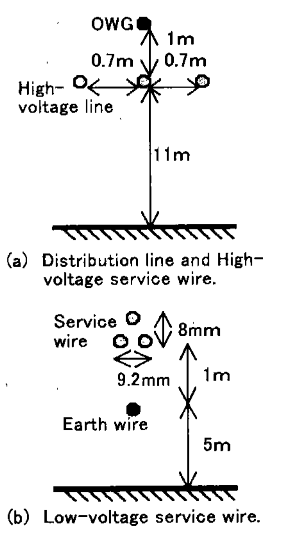
Fig. 5. Configuration of distribution lines and customer's facilities used for analysis.

2 km, and the span between the distribution poles is 40 m. Three-phase surge arresters are installed at every four poles. Three-phase high-voltage conductors and an OGW are terminated by matching circuit at the opposite end of the line to prevent current reflection.

The OGWs are grounded at the poles, where the arresters are installed, using the same grounding used for the arresters. The value of the grounding resistance (Ra) used for the distribution arresters is fixed to 30 Ω. The grounding resistance of the buried portion of the poles, on which arresters are not installed, is assumed to be infinity, because the soil condition at a mountainous area is thought to be very bad.

The frequency-dependent line model [10] of the phase conductors and an OGW is used in the analysis by the EMTP. We assume that the surge impedance of the concrete pole, with an earth wire installed along the concrete pole, is 200 Ω and the propagation velocity is 300 m/μs [11]. Main calculation conditions are summarized in Table 4.

Table 4. Calculation conditions.

Item	Conditions
High-voltage conductor	OC 5mm×3
OGW	Stranded steel wire of 22mm^2
High-voltage service wire	OC 5mm×3
Low-voltage service wire	DV3 22sq
Earth wire to connect grounding	OW 22sq
Surge impedance of concrete pole with earth wire & its propagation velocity	200 Ω 300 m / μs
High-voltage arrester	Gapped metal-oxide arrester (discharge voltage =29 kV, $V_{2.5kA}$ = 20 kV)
Low-voltage arrester	Gapless metal-oxide arrester ($V_{2.5kA}$ = 0.9 kV)
Grounding resistivity	100 Ωm
Waveform of lightning stroke current	RAMP wave with time-to-crest value of 2μs
Surge impedance of lightning channel	400 Ω
Span between distribution poles	40 m
Distance between distribution line and customer's facilities	40 m (high-voltage customer) 30 m (low-voltage customer)
Grounding of distribution line	OGW is grounded using same grounding as used for arrester
Striking point	Top of tower of customer
Distribution line arrangement	

3.1.2. Characteristics of surge arresters High-voltage surge arresters which consist of a gap and metal oxide elements and low-voltage arresters which consist of metal oxide elements without a gap are used in this study. We assume that the high-voltage arresters begin to discharge the moment the voltage in the arrester gap reaches 29 kV.

In this calculation, the damage threshold energy of the high-voltage arrester is assumed to be 15 kJ, 30 kJ and 60 kJ, corresponding to the withstand capabilities of 2.5 kA, 5kA and 10 kA rated arresters, respectively, and that of the low-voltage arrester is assumed to be 1.24 kJ corresponding to the withstand capability of a 10 kA rated arrester.

3.1.3. Failure probability of an arrester Considering the energy required to cause damage to an arrester, the threshold peak current, y(Tt), can be calculated for the time-to-half value (Tt) and the failure probability (Pf) can be estimated using equation (1) [5].

$$P_f = \int_0^{+\infty} \left\{ \int_{y(Tt)}^{+\infty} f(I_p) dI_p \right\} g(T_t) dT_t \qquad (1)$$

where

Pf: the probability that an arrester is damaged due to a direct lightning stroke to customer's facility.

f(Ip): the probability density function of the peak value of lightning current (Ip).

g(Tt): the probability density function of the time-to-half value of lightning current (Tt).

y(Tt): the minimum current required to cause damage for the time-to-half value (Tt).

In this study it is assumed that f(Ip) and g(Tt) are logarithmic normal distribution functions and are independent of each other. Constants of the cumulative frequency distribution of the lightning stroke current waveforms in winter are shown in Table 5 [1].

3.2. Analytical results

3.2.1. Case of low-voltage customer's facility Fig. 6 shows that the effects of grounding resistance value and the connection of grounding of a low-voltage customer's facility with an OGW of a distribution line on reduction of the calculated failure probability of a customer's arrester.

It can be seen from Fig. 6 that lowering the grounding resistance is one of the effective lightning protection methods for preventing customer's arrester failures when the grounding resistance of a customer's facility is less than 10 Ω. Lowering the customer's grounding resistance from 10 Ω to 2 Ω can reduce the failure probability of a customer's arrester to about 50 %. But when the grounding resistance is more than 10Ω, lowering the

Table 5. Constants of cumulative frequency distribution of lightning stroke current waveforms.

	Parameter	50%-value	16%-value	Ref.
Winter lightning	Peak value	24 kA	51 kA	[1]
	Time-to-half value	89 μs	631 μs	[1]

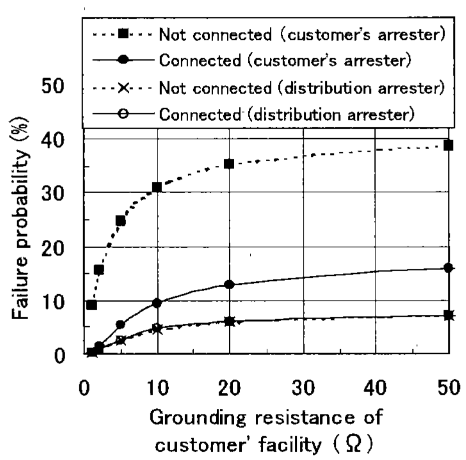


Fig. 6. Calculated failure probability of low-voltage customer's arrester and high-voltage distribution arrester (withstand capability of low and high voltage arresters are 1.24 kJ and 60 kJ, respectively).

grounding resistance is not effective in the reduction of the failure probability of a customer's arrester.

On the other hand, the connection between the customer's grounding and an OGW of distribution line through an earth wire is effective in the reduction of the customer's arrester failure probability. In a case that the grounding resistance is 5 Ω, the connection of both grounding can reduce the failure probability of a customer's arrester to about 20 %.

When this countermeasure, the connection of both grounding, is applied to an actual field, the increase of the failure probability of a distribution arrester may be anticipated. However, it can be seen from Fig. 6, the failure probability dose not increase due to the connection of both grounding. Therefore this countermeasure is thought to be applicable.

3.2.2. Case of high-voltage customer's facility Fig. 7 shows that the effects of grounding resistance value and the connection of grounding of a high-voltage customer's facility with an OGW of a distribution line on reduction of the calculated failure probability of a customer's arrester.

Lowering the grounding resistance is one of the effective lightning protection methods for preventing customer's arrester failures when the grounding resistance of a customer's facility is less than 10 Ω. Lowering the customer's grounding resistance from 10 Ω to 2 Ω can reduce the failure probability of a customer's arrester to about 30 %. But when the grounding resistance is more than 10Ω, lowering the grounding resistance is not effective.

On the other hand, the connection between the customer's grounding and an OGW of distribution line through an earth wire is effective for reducing the customer's failure probability. When the grounding resistance is 5 Ω, the connection of the grounding can reduce the failure probability of a customer's arrester to about 20 %.

Failure probability of a distribution arrester in a case that both

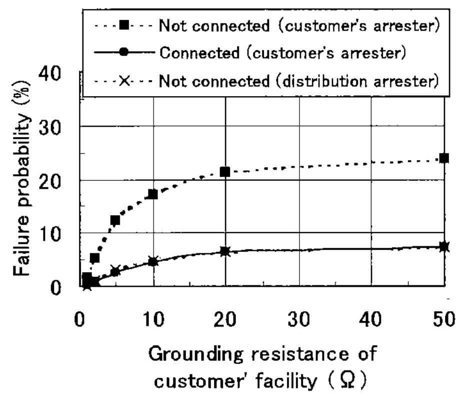


Fig. 7. Calculated failure probability of high-voltage customer's and distribution arrester (withstand capability of high voltage arrester is 60 kJ).

grounding are connected is not plotted in Fig. 7, because the distribution arrester failure probability can not be estimated quantitatively. In a case of Fig. 5 (b-2), an arrester which absorbs the largest energy is always the customer's one, but that which absorbs the second largest energy is not the same one, according to the stroke current and grounding resistance of customer's facility. Therefore the failure probability of a distribution arrester which receives the highest energy stress can not be estimated.

However, it can be seen from Fig. 7 that the distribution arrester failure probability in a case of "not connected" is nearly equal to the customer's arrester failure probability in a case of "connected". Therefore the distribution arrester failure probability in a case of "connected" is estimated to be less than that in the case of "not connected", because the failure probability of distribution arrester is always less than that of customer's one.

The reason that the connection of both grounding reduces distribution arrester failure probability is that the connection can reduce not only lightning stroke current flowing into high-voltage conductors through customer's arresters at a incoming pole but also distribution arrester discharge current.

4. Conclusions

We have investigated the effectiveness of some countermeasures for preventing arrester failures of customer's facilities and distribution lines at mountainous areas, based on the observation results and the analysis using the EMTP. The main conclusions are summarized as follows:

(1) Lowering the grounding resistance is one of the effective lightning protection methods for preventing customer's arrester failures, as far as the grounding resistance of a customer's facility is less than 10 Ω.

(2) Connection of the grounding of a customer's facility with an overhead ground wire of a distribution line through an earth wire is effective for preventing customer's arrester failures.

(3) The connection of the grounding of a customer's facility with an overhead ground wire of a distribution line dose not increase a distribution arrester failure probability.

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