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A Study of Rational Lightning Protection Measures for Power Distribution Lines in the Chugoku Region

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***Abstract*—Recently, current-limiting arcing horn with zin c oxide elements have been installed on distribution lines as lightning protection equipment. In this paper, we show an analytical study of rational lightning protection measures with the above equipment on power distribution lines using the assessment method of lightning risk.**

Keywords- Distribution lines; Lightning Protection Measures; Surge Arrester; Assessment Method of Lightning Risk

I. INTRODUCTION

In Chugoku, located in the west of Japan and whose electricity is managed by the Chugoku Electric Power Company, the lightning outage of power distribution lines due to summer lightning is about 80% of the total annual lightning outage. It is important to reduce summer lightning outage in the Chugoku region.

In Japan, including in Chugoku, overhead groundwires (OHGWs) and surge arresters are used as lightning protection equipment on power distribution lines. Nowadays, surge arresters (Arr A) are installed at regular intervals (200-300m; every 4-6 spans) on distribution lines. The Chugoku Electric Power Company, similarly to other electric power companies in Japan, has been spending a large amount of money on the construction and maintenance of grounding to maintain low ground resistance. Recently, current-limiting arcing horn with zin c oxide elements have additionally been installed on power distribution lines as lightning protection equipment [1]. Such equipment reduces the lightning voltage occurring on distribution apparatus by discharging voltage of the equipment to protect it from lightning outage. Hence, the equipment does not require the construction of grounding. The Chugoku Electric Power Company has examined the feasibility of expanding the installation of such equipment (Arr B) in expectation of low construction cost than that of installing Arr A. However, there has been little quantitative evaluation of the effect of installing Arr A and Arr B on distribution lines on reducing lightning outage and the construction cost. It is very important to evaluate their cost and their effect on reducing lightning outage. In this paper, we show an analytical study of the rational lightning protection measures of installing Arr A and Arr B on power distribution lines using the assessment method of lightning risk.

II. CALCULATION RESULTS AND ANALYSIS

A. Assessment method of lightning risk

We use the assessment method of lightning risk [2], which can evaluate the reduction of lightning outage while taking into account the installation rate of lightning protection equipment, the density of lightning strokes, and other factors. In this paper, we define the number of lightning outages per $1km^2$ per year as the value of the lightning risk (R_L) [times/km^2/year)], and calculate R_L using the following equation.

$$R_L=(K/N)\times k(L,b)\times GFD\times\alpha \quad (1)$$

N: number of trials to investigate the lightning outage rate [times].

K: number of sparkovers and/or surge arrester failures [times/km].

k(L,b): correction coefficient between density of power distribution lines (L) and numbers of wire branches (b).

GFD: density of flashes per $1km^2$ per year obtained using the Lightning Location System (LLS) [times/km^2/year]

α : correction coefficient of density of flashes considering the effect of lightning shielding by trees and high buildings around the distribution apparatus.

We formed a map by dividing the Chugoku region into a mesh consisting of $6\times 8km^2$ rectangles and calculated R_L in each rectangle (calculated map). The value of R_L is equal to the number of lightning outage.

B. Calculation conditions

The assessment method of lightning risk involves three steps as follows. I) Calculation of the ratio of lightning outage due to direct lightning hits. II) Correction of the direct lightning hit occurrence rate obtained in I) using the density of the distribution lines. III) Calculation of the density of flashes considering the effect of lightning shielding by trees and high buildings around the distribution apparatus. R_L calculate multiplying these values obtained in above three steps.

I) In this paper, the target area is assumed to be $0.8 \times 1 km^2$ as shown in Fig.1, and whether a lightning strike is a direct stroke or an indirect stroke is judged by comparison of the lightning point sampled by the Monte Carlo method and the critical distance evaluated by (2) [3], which is based on an electro-geometrical model.

$$r_c = 8 \times I^{0.65} \quad (2)$$

r_c: striking distance [m].

I: lightning peak value [kA].

Table 1 shows the cumulative frequency distribution of the lightning current obtained in [1,4]. The cumulative frequency is sampled by the random number. Then, the peak value of the lightning, the wavefront and wavetail of the lightning are also sampled by above number in consideration of their relationship with the cumulative frequency.

Fig.2 shows an example of a power distribution line subject to analysis, Fig.3 shows the arrangement of the distribution line and Table 2 shows the parameters used in the analysis. The 800m-long model line consists of three phase wires, an OHGW and an under power line ground wire (UGW). The eXpandable Transient Analysis Program (XTAP) [5] developed by Central Research Institute of Electric Power Industry is used in the calculation.

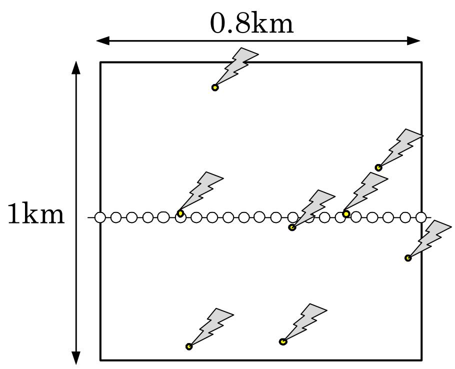


Fig.1 Arrangement of the power distribution line and the points of lightning strike

TABLE 1. Cumulative frequency distribution of lightning current parameters used in this study

	50% Value	16% Value
Lightning current I[kA]	26	55
Wavefront time T_f [μs]	3.5	5.3
Wavetail time T_t [μs]	40	59

The sparkover voltage of the line- post insulator of the distribution line is postulated to be 150kV. The insulator is modeled as a voltage switch. Arr A and Arr B are modeled as a gap, with sparkover voltages of 29kV and 130kV, respectively, and nonlinear resistance as shown in Fig.4. The outage caused by sparkover is assumed to occur when the multiple phase wires are grounded, and arrester failure is assumed to occur when the absorption energy of the surge arrester exceeds its rated capacity of 15kJ.

The facilities of distribution lines vary with the area. Therefore, we analyzed outage rates for various conditions. Fig.5 (a) shows examples of distribution lines in which Arr A and Arr B are installed. Fig.5 (b) shows the calculation results when Arr A, and Arr B are installed at intervals of 160m and 80m. As shown in Fig.5 (b), the outage rate decreases with increasing number of Arr A or Arr B (see cases (ii) and (iii)). The installation of Arr A decreases the outage rate more than that of Arr B.

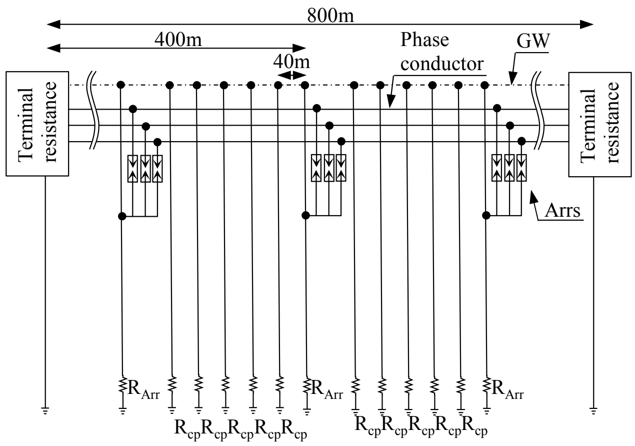


Fig.2 Example of XTAP model

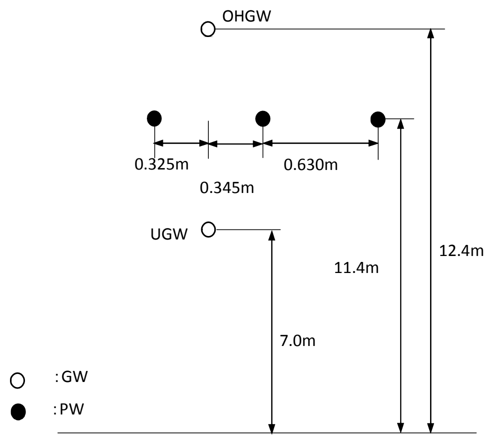


Fig.3 Arrangement of distribution line

TABLE 2. Conditions for calculating lightning outage rate.

Current waveform	Ramp
Lightning path impedance	1000Ω [6]
Span length	40m
Overhead ground wire (OHGW)	Steel wire-22mm² (height: 12.4m)
Under power line ground wire (UGW)	Steel wire-22mm² (height: 7.0m)
Power line	Al-25mm² conductor cross-linked and insulated with polyethylene (height: 11.4m)
Ground resistivity	1000Ωm
Surge impedance of concrete pole: Z_{cp}	250Ω
Grounding resistance of concrete pole: R_{cp}	100Ω
Grounding resistance of GW	Shared with grounding resistance of surge arresters
Grounding resistance of Arr A : R_{arrA}	30Ω
Grounding resistance of Arr B : R_{arrB}	R_{cp} = 100Ω
Discharge voltage of Arr A	29kV
Discharge voltage of Arr B	130kV [7]
Sparkover voltage of high-voltage insulator	150kV [7]
Energy capability of arrester	15kJ

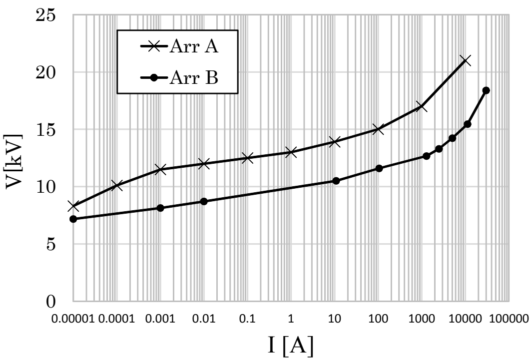
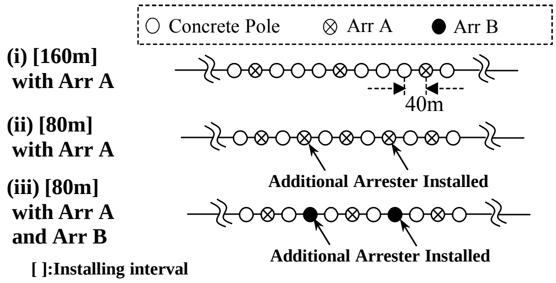


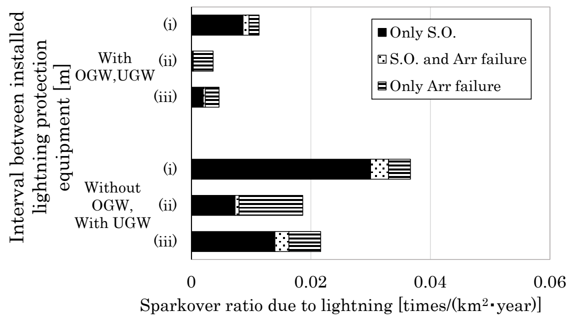
Fig.4 Characteristics of surge arresters

II) In fact, the rate of direct lightning hits to a distribution line is depends on the area because of differences in the density of distribution lines and the number of wire branches in each area. Therefore, the results obtained in I) are multiplied by a corrective factor determined by the density of distribution lines and the number of wire branches. An example of a lightning strike area based on an electro-geometrical model taking these factors into consideration is shown in Fig.6.

III) We estimate GFD with Lightning Location System (LLS) data in each area. These data are taken, excluding peak values of 10kA or less, for every summer (Apr. to Sep.) from 2004 to 2013 in the Chugoku region.



(a) Arrangements of distribution lines used in calculation



(b) Calculation results of outage rate due to direct lightning

Fig.5 Calculation of outage rate due to direct lightning

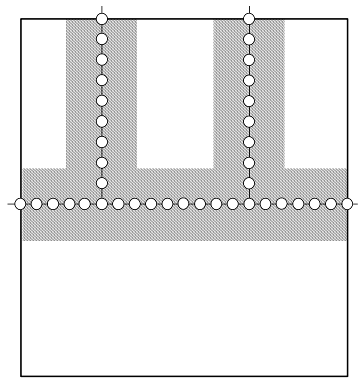
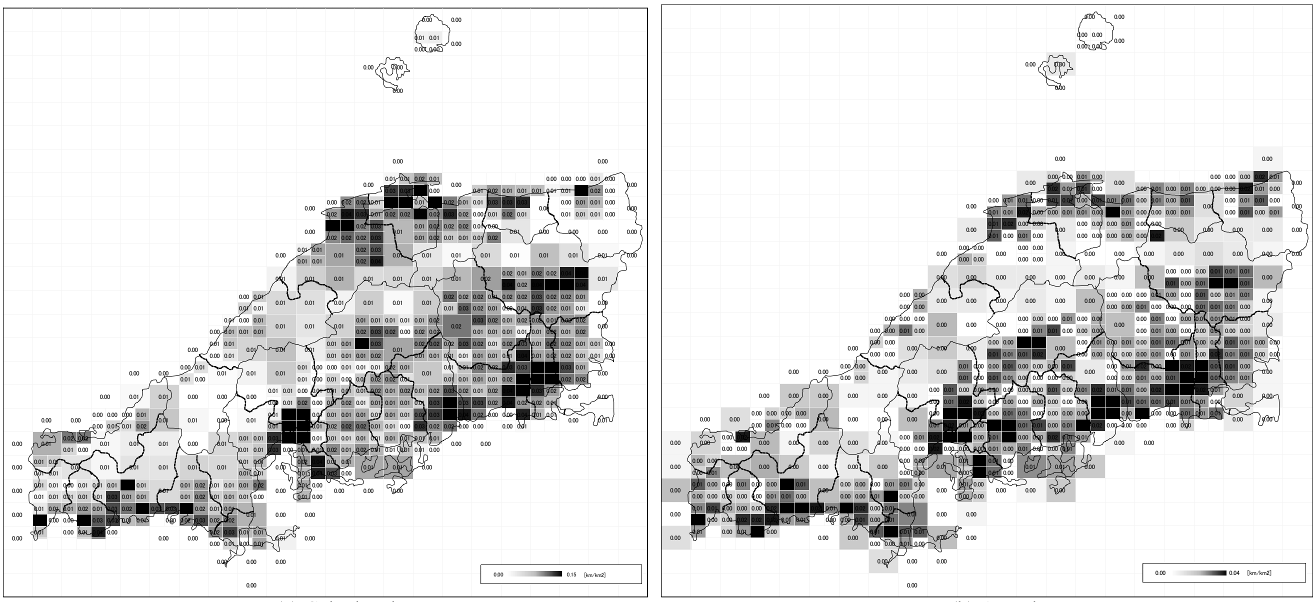


Fig.6 An example of a lightning strike area based on an electro-geometrical model taking the density of distribution lines and the number of wire branches into consideration

Our calculation takes into consideration the lightning shielding effect owing to the existence of trees and buildings around the distribution apparatus. Numerical data for forested area and buildings were obtained from the homepage of the Ministry of Land, Infrastructure, Transport and Tourism of Japan.

Using the results of these calculations, we formed a map consisting of a mesh of 6 × 8km² rectangle showing the calculated R_L in the Chugoku Region. The OHGW installation rate in each rectangle was evaluated as follows.



(a) Calculated (b) Actual

Fig.7. Lightning risk map consisting of rectangles showing evaluated lightning risk

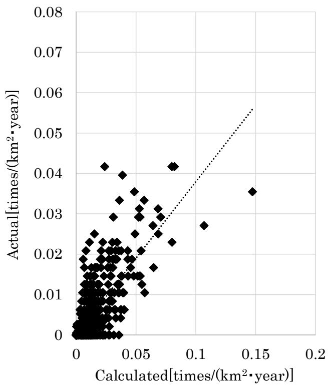


Fig.8 Scatter diagram of calculated results and the actual values

$$K = K_{GW} \times D/100 + K_{NGW} \times (100-D)/100 \quad (3)$$

D: OHGW installation rate.

K_{GW}: calculated lightning outage rate with OHGWs.

K_{NGW}: calculated lightning outage rate without OHGWs.

C. Validity of the calculated map for the Chugoku region

We evaluate the validity of the calculated map for the Chugoku region. Fig.7 shows the calculated map and a map consisting of the number of lightning outage every summer (Apr. to Sep.) from 2004 to 2013 (Actual map). Fig.8 shows a scatter diagram of the calculated results and the actual values in each map. Table 3 shows the averages of the calculated results and the actual values for the rectangles, and the correlation coefficient. The average calculated result is 2.5 times larger than the average of the actual values. However, we concluded that this calculated map can be used for qualitative evaluation because of the correlation coefficient 0.61.

TABLE 3. Average of calculated results, actual average value, correlation coefficient

Average: Actual value [times/(km2・year)]	0.0058
Average: calculated result [times/(km2・year)]	0.0146
Correlation coefficient	0.61

In the next section, some case studies involving relative evaluation using the calculated map are reported.

III. RESULTS OF CASE STUDIES

We evaluate the effect of installing lightning protection equipment on lightning outage reduction using the calculated map. We estimate the number of additional electric concrete poles that must be installed as additional equipment to reduce of lightning outage by 10%. The calculation conditions are as follows.

- The equipment is installed in areas in descending order of R_L in the calculated map.
- The equipment is installed uniformly in each rectangle.

The following three case are compared as case studies.

Case A : The value of R_L is reduced by the additional installation of Arr A or Arr B in each rectangle to the value obtained by calculation when the lightning outage in the Chugoku region is reduced by 10%.

Case B : Arr A or Arr B is additionally installed with a 30% increase in the number of concrete poles in each rectangle.

Case C : Arr A or Arr B are additionally installed at intervals of 80m.

A. Effect of installation of Arr A or Arr B on power distribution lines on lightning outage reduction

Fig.9 shows the number of electric concrete poles on which Arr A or Arr B are additionally installed in each case to reduce lightning outage by 10%. As shown in Fig.9, The number of poles on which Arr A is installed is about 10% lower than that for Arr B in every case. In case C, the least number of concrete poles is required among the three cases. As shown in Table 4, a similar tendency is observed for Arr A and Arr B when considering the reduction of lightning outage by 20 and 30%.

Fig.10 shows the relative construction cost of the power distribution lines for the installation of Arr A and Arr B. Here, the construction cost of case A with the installation Arr B is normalized to 1.0. In every case, construction cost of Arr B is about one third of that of Arr A. This is because, with the installation of Arr A, it is necessary to construct of grounding.

Hence, the installation of Arr B is more cost-effective than that of Arr A.

B. Effect of installation of Arr B without Arr B on one phase of distribution lines to lightning outage reduction

General distribution systems in Japan are isolated neutral systems, and if a sparkover of an insulator occurs only at one phase owing to a lightning-related overvoltage, the following current will naturally disappear because of a small ground-fault current. Therefore, if surge arresters are installed on only two phases, it is possible to prevent short-circuits causing phase-wire breakage [8]. We evaluate the effect of the installation of Arr B without Arr B on one-phase (two-phase Arr B) on distribution lines on lightning outage reduction.

Fig.11 shows the number of concrete poles required to reduce lightning outage by 10% when two-phase Arr B and three-phase Arr B are additionally installed in each case. As shown in Fig.11, the number of concrete poles is almost the same in each case, with case C requiring the least number of concrete poles. As shown in Table. 5, a similar tendency is observed for Arr A and Arr B when considering the reduction of lightning outage by 20 and 30%.

Fig.12 shows the relative construction cost of power distribution lines for the installation of two-phase Arr B and three-phase Arr B. In this case, the construction cost of three-phase Arr B is normalized to 1.0. In every case, the construction cost of two-phase Arr B is lower than that of three-phase Arr B. This is because the installation of two-phase Arr B does not include the construction cost of one phase of Hence the installation of two-phase Arr B is more cost-

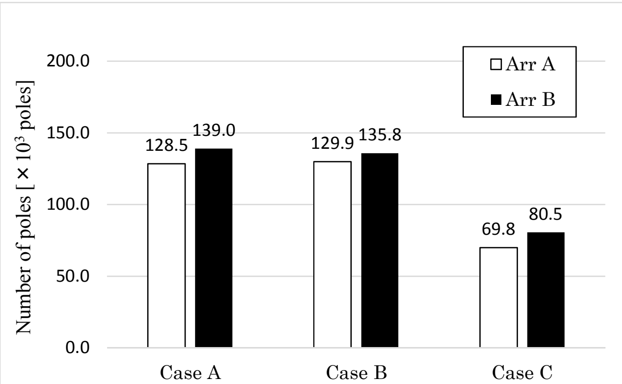


Fig.9 Number of additional arresters installed to reduce lightning outage by 10%

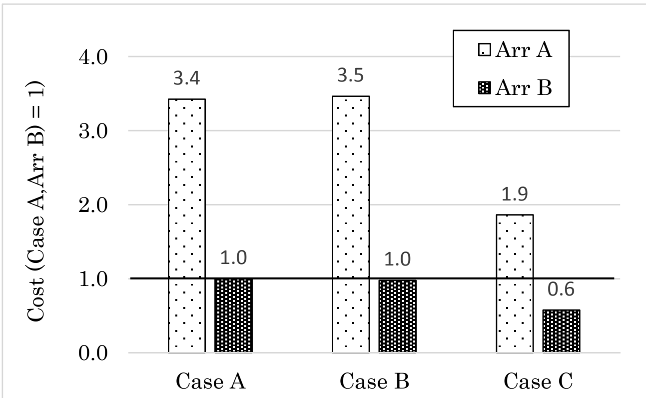


Fig.10 Cost of lightning protection to reduce lightning outage by 10%

TABLE 4. Numbers of additional arresters installed to reduce lightning outage [$\times 10^3$ poles]

	Case A		Case B		Case C	
	Arr A	Arr B	Arr A	Arr B	Arr A	Arr B
by 10%	128.5	139.0	129.9	135.8	69.8	80.5
by 20%	202.8	234.2	210.4	225.8	126.8	157.9
by 30%	280.2	330.9	288.7	317.2	184.4	243.0

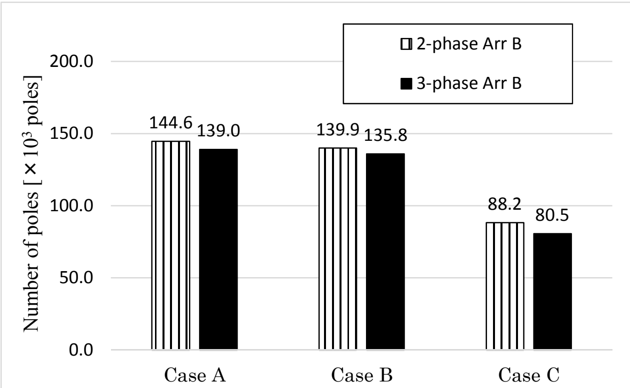


Fig.11 Number of additional Arr B installed to reduce lightning outage by 10%

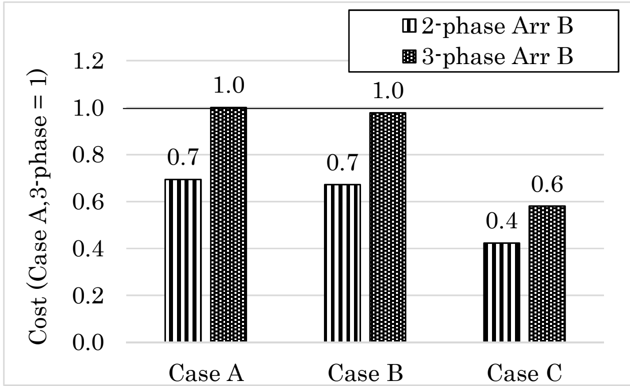


Fig.12 Cost of lightning protection to reduce of lightning outage by 10%

TABLE 5. Numbers of additional Arr B installed to reduce lightning outage [$\times 10^3$ poles]

	Case A		Case B		Case C	
	3-phase	2-phase	3-phase	2-phase	3-phase	2-phase
by 10%	139.0	144.6	135.8	139.9	80.5	88.2
by 20%	234.2	243.4	225.8	232.6	157.9	166.7
by 30%	330.9	342.5	317.2	327.5	243.0	289.0

effective than that of three-phase Arr B.

IV. CONCLUSION

We have reported an analytical study of rational lightning protection measures with lightning protection equipment for power distribution lines in the Chugoku region using the assessment method of lightning risk. The main results are as follows.

- The assessment method of lightning risk is valid for the Chugoku region.
- The installation of Arr B is more cost-effective than that of Arr A.
- The installation Arr B without Arr B on one-phase is more cost-effective than that of Arr B on three-phase.

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