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Estimation of Fault Rate of 6.6kV Distribution Line Considering Surge Arrester Damages

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Abstract— **In Japan, surge arresters are widely used as the lightning protection devices of a power distribution line and in Kyushu all poles are equipped with protection devices. In such cases, the cause of the outages is the damage of the surge arresters. In this paper, the method of analysis of the arrester damage is presented and the fault rate calculated as the sum of the sparkover rate and the rate of the arrester damage is estimated by using Berger's return-stroke current parameters.**

Keywords-surge arretsers; power distribution line; fault rate; sparkover

I. INTRODUCTION

In Japan, the total number of the faults on a medium-voltage line has decreased due to improvement in facilities and maintenance. The proportion of faults caused by lightning, however, tends to increase with often reaching beyond 30 %. The lightning overvoltage on a power distribution line, associated with direct hits, is looked upon as the main factor in its insulation design [1-6].

In the protection design of the power distribution line the surge arresters play an important role in reducing the number of faults caused by the sparkover along the insulators. However, the surge arresters are damaged by exceeding the absorption energy and the number of damaged arresters occupy 25 % in the lightning damaged equipment. Therefore, the lightning flash with the high energy draws much attention in Japan recently.

Estimation of the fault rate associated with lightning flashes is fundamental for the insulation design of a medium-voltage line. In [5], the flashover rate of a distribution line over perfectly conducting ground due to direct lightning flashes is estimated based on the insulator voltage in addition to that due to indirect lightning flashes. In [5], the current parameters for only first strokes obtained in Japan [7,8] is used in the simulation and the Monte Carlo method is adopted in sampling the parameters of return-stroke current as well as the lightning striking points.

The authors have proposed a method of analysis to evaluate the flashover rate due to indirect lightning strokes based on numerical calculation of the insulator voltage and statistical analysis [9]. It is demonstrated that regardless of the closeness of the correlation between the peak and the front duration of the return-stroke current waveform, the flashover rate associated with subsequent strokes is higher than that for first strokes when the line is equipped with surge arresters every 200 m. However, the flashover rate associated with indirect strokes is much lower than that associated with direct strokes [10].

In this paper, the fault rate of a power distribution line associated with direct negative lightning flashes, calculated as the sum of the sparkover rate and the damage rate of the surge arresters due to the excess of the energy, is investigated based on numerical calculation through the EMTP [11] and the Monte Carlo simulation of the return-stroke current parameters.

II. METHOD OF ANALYSIS

A. *Return-stroke Current parameters*

The waveform of the return-stroke current is assumed triangular. In this paper, the authors employ the return-stroke current waveform parameters obtained by Berger et al. [12].

Table I shows the statistics of the peak values, the front duration of the return-stroke current waveform and the charge transfer obtained by Berger et al. [12]. In the simulation, the peak is assumed in logarithmic normal distribution estimated based on the 50 % and 5 % values together with the impulse charge. The front duration is also assumed in logarithmic normal distribution estimated based on 50 % and 95 % values. In sampling current parameters through the Monte Carlo simulation, the correlation between current peaks and front duration is taken into account as well as that between the impulse charge and the current peak. The stroke duration of the current waveform is determined so that the sampled impulse charge is given for a sampled current peak. In the simulation, the lightning flash is assumed to be composed of two strokes.

TABLE 1. RETURN-STROKE CURRENT PARAMETERS OBTAINED BY BERGER.

		95% value	50% value	5% value
First stroke	Peak [kA]	14	30	80
	Front duration [μs]	1.8	5.5	18
	Impulse charge [C]	1.1	4.5	20
Subsequent stroke	Peak[kA]	4.6	12	30
	Front duration[μs]	0.22	1.1	4.5
	Impulse charge [C]	0.22	0.95	4.0

B. *Model Line*

Figures 1 and 2 show front and side views of an example of a line subject to analysis, respectively, and Table II shows the parameters used in the analysis. A 1000m-long model line is composed of three phase wires at 12 m above the ground and the distance between adjacent phase wires is 0.84 or 0.85 m. When an overhead ground wire is installed, it locates 0.8 m above the middle phase wire and its grounding interval is 40 m. Both ends of a line are terminated with resistor networks so that no reflection of travelling waves can occur. The grounding resistance of the OHGW (overhead grounding wire) and the surge arresters is assumed 30 Ω. The J. Marti set up program in EMTP [11] is used to model the horizontal line.

In case of direct strokes to the line, the voltage between the grounding wire and reinforcing rods in the concrete pole usually exceeds some tens of kilo-volts due to the lightning current flowing through the wire. In that case flashover occurs, therefore, the concrete pole is modeled as the distributed constant circuit of 300 Ω with footing resistance of 60 Ω in the simulation. The cross arm influencing the occurrence of the multi-phase flashover is modeled as inductance.

When the line is equipped with the OHGW and/or surge arresters with grounding interval of less than a few hundred meters, the voltage waveform along the insulator becomes short-tailed, usually less than a few microseconds [1, 13]. In this paper, the flashover voltage of a line-post insulator of LIWL (Lightning Impulse Withstand Level) 90 kV is assumed to be 200 kV [5] according to the experimental results obtained by applying the short tailed impulse voltage waveform (about 0.5/1.0 μs) [1]. Such a simple discharge model of a constant flashover voltage is used because the principal objective of this paper is to investigate the fault rate of the medium voltage line including the rate of arrester damage. When the v-t characteristics of the insulator are considered, the estimated flashover rate is not influenced so much.

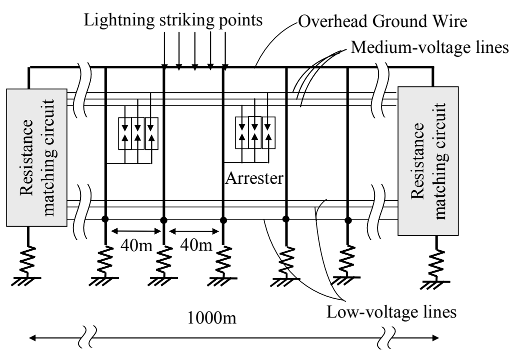
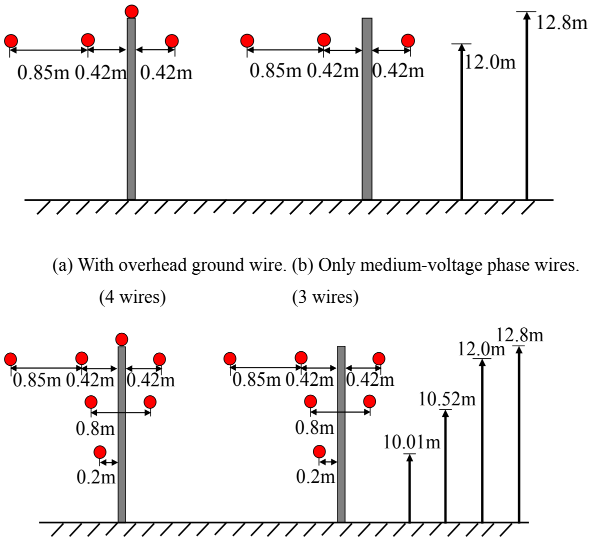


Figure 1. Example of Front view of line subject to analysis



(a) With overhead ground wire. (4 wires)
(b) Only medium-voltage phase wires. (3 wires)
(c) With overhead ground wire and three low-voltage wires. (7 wires)
(d) With three low-voltage wires. (6 wires)

Figure 2. Side view of line.

TABLE II. PARAMETERS USED IN ANALYSIS.

Medium-voltage phase wire	Line typs	ACSR-OC of 32mm^2
	Sparkover voltage	200 kV
Low-voltage phase wire	Line type	ACSR-OC of 32mm^2
	Sparkover voltage	60 kV
Overhead ground wire	Line type	Hard-drawn copper stranded conductor of 22mm^2
	Grounding resistance	30 Ω
	Grounding interval	40 m
Surge arresters with gap	Installing interval	80 m or 160 m
	Grounding resistance	30 Ω
	Absorption energy	15 kJ
Concrete pole	Surge impedacne	300 Ω
	Span length	40 m
	Propagation speed	300 m/μs
	Grounding resistance	60 Ω
Cross arm	Material	Steel
	Inductance	5 μH /m
Ground resistivity		100 Ω·m
Impedance of lightning channel		1 k Ω

The height of a concrete pole influential on the striking distance is 12.8 m. The ground resistivity, little influencing the fault rate, is assumed 100 Ω · m.

Figure 3 shows the assumed V-I characteristic of a surge arrester, which is simply modelled as a piecewise-linear resistance in the analysis for simplicity instead of frequency-dependent model of a metal-oxide arrester [14], suitable for accurate modeling. Numerical simulation by taking account of the capacitance of about 200 pF of the ZnO element is carried out and it turns out that the capacitance little influences the calculated results.

The impedance of the return-stroke channel is assumed 1 kΩ [15]. The variation of the channel impedance from 1 kΩ to 400 Ω, often used in the simulation of the direct strokes to the medium-voltage line [4, 6], results in little difference of the estimated fault rate.

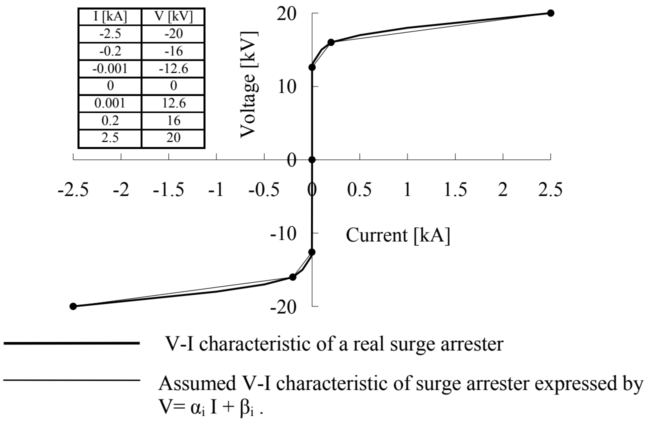


Figure 3. Assumed V-I characteristic of surge arrester passing points in the table.

III. Process of Analysis

Figure 5 shows the range of the lightning current dependent on the distance from the line, ending up with direct or indirect strokes to the line with the OHGW. The range is evaluated by the EGM (Electrogeometric model) based on the striking distance rs (m) dependent on the lightning peak current I (kA) expressed by (1) [16].

$$r_s = 10 \cdot I^{0.65} \text{ (m)} \quad (1)$$

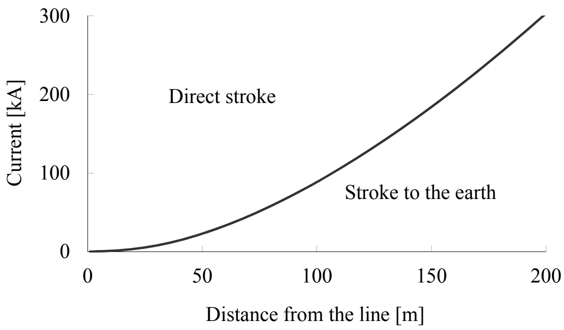


Figure 4. Range of lightning current dependent on the horizontal distance, resulting in direct or indirect stroke to the line.

In the case of direct strokes to the line with the OHGW, the stroke is assumed to hit the OHGW while in the absence of the OHGW the stroke hits either the phase wire or the concrete pole.

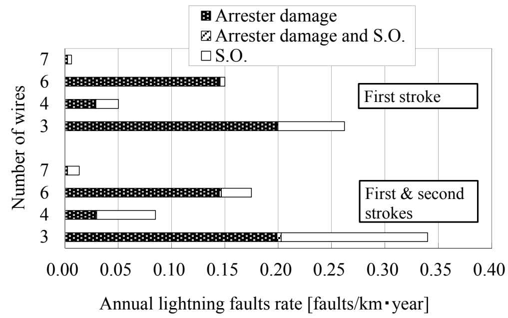
The authors assume 1000 strokes for each lightning striking point, placed every 10 m as in Figure 1. The current peaks are first sampled by the Monte Carlo simulation, then the front duration and the impulse charge is also sampled by the Monte Carlo simulation by taking account of the correlation between parameters. The lightning striking point is also sampled by the Monte Carlo simulation. By comparing the distance between the line and the lightning striking point and the range of the current in Figure 4, one can judge whether the stroke hits the ground or the line. When the stroke hits the ground, no fault is assumed and in the case of direct strokes to the line, the numerical simulation by using the EMTP is carried out. The terminating pole, actually existing, is not taken into account, since the simulation is carried out for a line of infinite length.

One can calculate the probability of occurrence of flashover at multiple phase wires for each lightning striking point and/or the probability of the arrester damage. Then the flashover rate is given as the sum, for a unit length of the line, of the product obtained by multiplying the probability of occurrence of lightning fault for a lightning striking point and the flash density for the point. A ground flash density of 3 per km^2 per year was used.

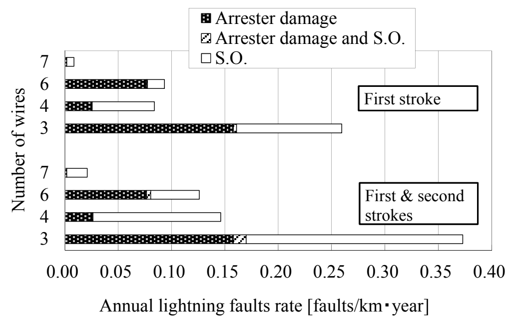
IV. Results

A. Influence of Installing Interval of Surge Arresters

Figure 5 shows the annual lightning fault rate dependent on the installation interval of surge arresters. Comparing the fault rate of the medium-voltage line with the OHGW in the cases of the number of wires of 4 and 7, the fault rate can be reduced by the shortening of the installation interval of the surge arresters regardless of the existence of the low-voltage line. This is because the insulator voltage is greatly suppressed by the shortening of the installing interval of the surge arresters, although the rate of arrester damage is little influenced.



(a) Installation interval: 80 m



(b) Installation interval: 160 m

Figure 5. Annual lightning faults ratio dependent on installing interval of surge arresters.

Comparing the fault rate of the medium-voltage line without the OHGW in the cases of the number of wires of 3, the fault rate is little influenced by the shortening of the installation interval of the surge arresters. This is because the arrester-damage rate increasers by the shortening while the sparkover rate decreases. In case of the number of wires being 3, fault occurs at the ratio of more than half of the direct strokes to the line (0.44 strokes/ km /year). Comparing the fault rate of the medium-voltage line without the OHGW in the cases of the number of wires of 6, the fault rate is unexpectedly increases by the shortening of the installation interval of the surge arresters. This is because the arrester-damage rate increases by the shortening of the installing interval of the surge arresters, although the sparkover rate is reduced.

The low-voltage line plays a role similar to the OHGW in the sense that the line provides the path to the lightning current due to the preceding sparkover of the low-voltage insulators to the medium-voltage insulators although the line can't prevent the stroke to the power line. Therefore, the fault rate of the medium-voltage line decreases by the existence of the low-voltage line.

B. Comparison with Actual Fault Rate

Figure 6 shows the estimated fault rate with the actual rate, defined as the rate of the relay operation at the sub-station due to lightning, 0.02 faults/ 100km/ year. Note that the outage rate of a medium-voltage line in Japan, defined as the outage with the blackout for more than 10 minutes, is less than 0.004 outages /year/km. The estimated fault rate is shown as the range by assuming the minimum rate is given as the rate for the first strokes and the maximum rate is given as the rate for first and subsequent strokes. The estimated fault rate is higher than the actual rate except the rate for the line composed of 7 wires, 45-100% of the actual rate.

Figure 7 shows the aspect of the lightning fault. The arrester-damage rate is overestimated compared with the actual aspect except the cases of the line composed of 7 wires where the actual aspect is reproduced by the simulation.

From above discussion, the Japanese actual lightning fault is successfully estimated by using Berger's data by the condition that the line is composed of 7 wires, namely the OHGW, the medium-voltage line and the low-voltage line consisted of 3 wires.

In cases other than 7 wires, the estimated fault rate is higher than the actual rate. In Japan, the installing rate of the OHGW is about 60 % in average, and the surge arresters are installed usually at the interval of less than 200m in the area of high flash density with the IKL of higher than 20. Furthermore, the medium-voltage line is not always jointly used with the low-voltage line. Therefore, as shown as the average in Figs. 6 and 7, it is possible that the calculated fault rate of the medium-voltage line might overestimate the actual rate. To achieve the good agreement between the calculation and the actual rate, some modification of the applied models such as the flashover model and the grounding resistance model is required. At the same time, lightning parameters vary dependent on the location and the season. To estimate the lightning current parameters in this area, the authors measure the current at the equipped wind turbine [17] and also investigate the accuracy of the current estimated by the JLDN (Japan Lightning Detection network), the largest lightning detection network in Japan [18].

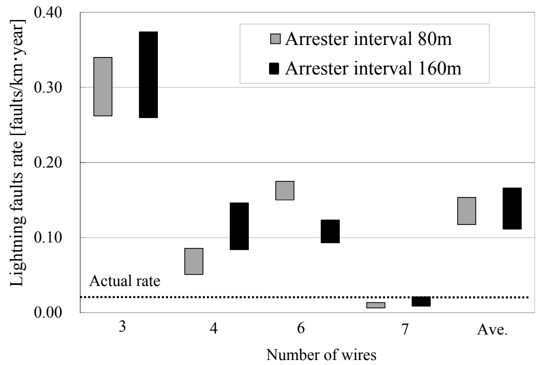
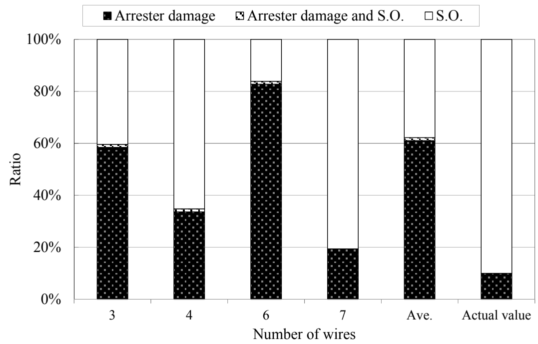
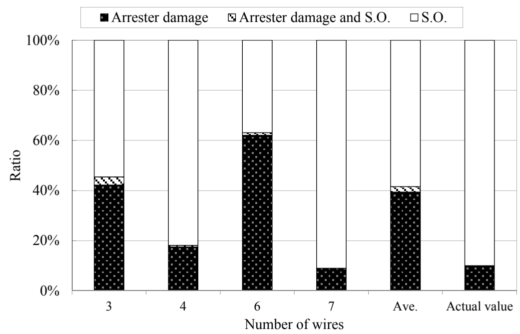


Figure 6. Lightning faults rate for a lightning flash.



(a) Installation interval 80 m



(b) Installation interval 160 m

Figure 7. Aspects of lightning faults

V. CONCLUSION

The following insights are newly obtained in this paper;

(1) The sparkover rate decreases by the installation of the low-voltage line below. This is because the low-voltage line after flashover plays a role similar to the OHGW by providing path to lightning current.

(2) The Japanese actual lightning fault rate is successfully estimated by the condition that the line is composed of 7 wires, namely the OHGW, the medium-voltage line and the low-voltage line consisted of 3 wires.

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