Flashover Rate of Distribution Line Due to Indirect Negative Lightning Return Strokes

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Abstract—The flashover rate of a distribution line associated with indirect lightning flashes is investigated based on numerical calculations and statistical analysis by taking account of the correlation between the peak value and the front duration of negative return-stroke current waveforms. When the grounding interval of an overhead ground wire and/or surge arresters is 200 m, surge arresters are more effective than an overhead ground wire in suppressing flashover of the power lines, and installation of both is very effective. The flashover rate decreases if there is correlation between the peak and the front duration of lightning current; and it significantly decreases with the increase of the ground conductivity. When the line is equipped with surge arresters only, the flashover rate associated with subsequent strokes is higher than that associated with first strokes; and calculation with the fixed front duration of 2 μs for first stroke current does not always result in good estimates of flashover rate.

I. Introduction

- Decrease of lightning fault rate in Japan
- Proportion of lightning fault tends to increase
- Lightning-induced voltage on a medium-voltage line is one of factors for insulation design, although the flashover rate due to indirect strokes is very small compared with that due to direct strokes.
- the flashover rate of a distribution line associated with indirect negative lightning flashes is investigated based on numerical calculation of the insulator voltage and statistical analysis.

II Model Of Analysis A. *Model line*

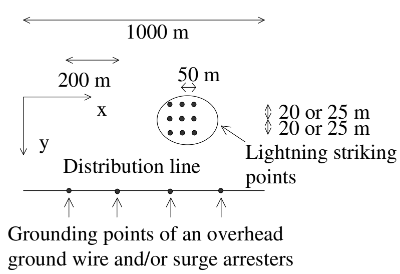
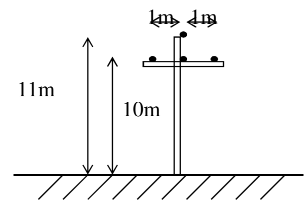


Fig.1. Arrangement of distribution line and lightning striking points.



Configuration of line.

Radius of all wires	2.5mm
Termination of line	Resistor network equal to surge impedance
Grounding interval	200m
Grounding resistance	30Ω
Grid points	Representing strokes at the area of 50 m in x-axis and 20 m or 25 m in y-axis.
Sparkover voltage of a line-post insulator (LIWL 90kV)	200kV

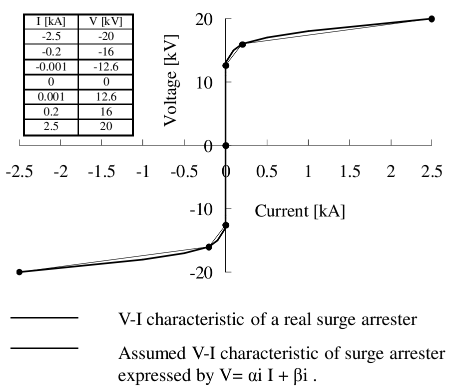


Fig.2. Assumed V-I characteristic of surge arrester passing points in the table.

Return-stroke model: Transmission Line Model

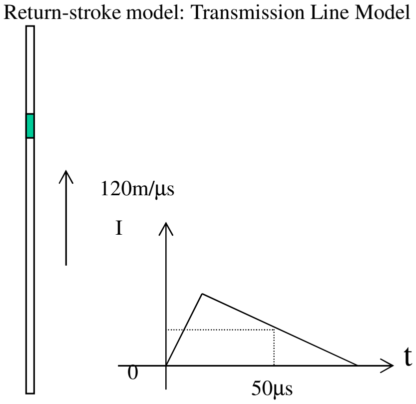


Table 1. Return-stroke current parameters obtained by Berger[15]

		95 % value	50 % value	5 % value
First Stroke	Peak value [kA]	14	30	80
	Front duration [μs]	1.8	5.5	18
Subsequent Stroke	Peak value [kA]	4.6	12	30
	Front duration [μs]	0.22	1.1	4.5

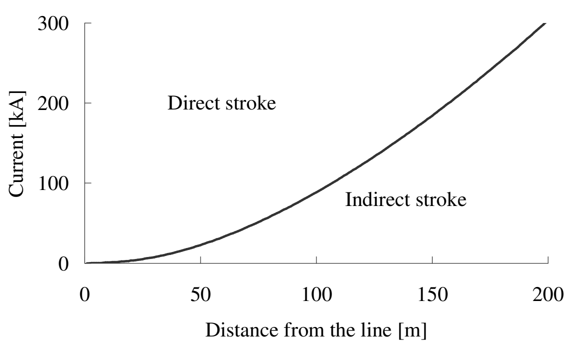
Table 2. Return-stroke current parameters obtained by Garbagnati[16]

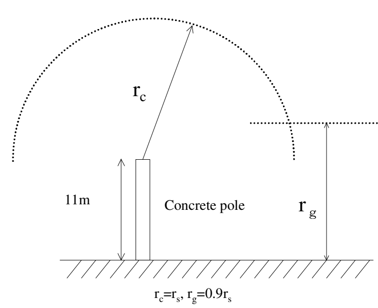
		95 % value	50 % value	5 % value
First Stroke	Peak value [kA]	13	33	85
	Front duration [μs]	2	9	41
Subsequent Stroke	Peak value [kA]	8	18	42
	Front duration [μs]	0.32	1.1	3.8

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

r_s (m) : striking distance

I (kA) : lightning peak current





EGM(Electrogeometric model)

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

III. Method of Analysis

$$RI + L\frac{\partial I}{\partial t} + \frac{\partial V_s}{\partial x} = E_x^i \quad (1)$$

$$\frac{\partial I}{\partial x} = C\frac{\partial V_s}{\partial t} \quad (2)$$

$$V(x) = V_s + \int_0^h E_z^i(x,z)dz \quad (3)$$

$$V(0) = -Z_0 I(0) \quad (4)$$

$$V(\ell) = Z_\ell I(\ell) \quad (5)$$

E_x^i :Incident horizontal electric field along the line
E_z^i :Incident vertical electric field
R, L :Resistance and inductance of a unit length of the line including those of the ground-return circuit
V_s :Scattered Voltage of a line
I :Current on the line
C :Capacitance of a unit length of a line

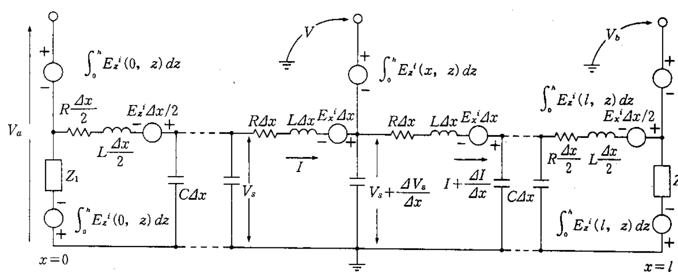
$V(x)$:Induced voltage at x
ℓ :Length of the line
h :Height of the line
x :Horizontal coordinate parallel to the line
z :Vertical coordinate perpendicular to the line
Z_0 :Impedance terminating at the left end of the line
Z_ℓ :Impedance terminating at the right end of the line

Impedance of the ground-return circuit

$$Z_g = -\frac{j\gamma_s}{2\pi h\sigma}\frac{H_0^{(1)}(j\gamma_s h)}{H_1^{(1)}(j\gamma_s h)} = R + j\omega L_g \quad (6)$$

$$\gamma_s = \sqrt{j\omega\mu_0(\sigma + j\omega\varepsilon)} \quad (7)$$

$H_0^{(1)}, H_1^{(1)}$:Hankel functions of the first kind of the zeroth and the first order respectively.
σ, ε :Conductivity and permittivity of the ground
μ_0 :Permeability of the air.

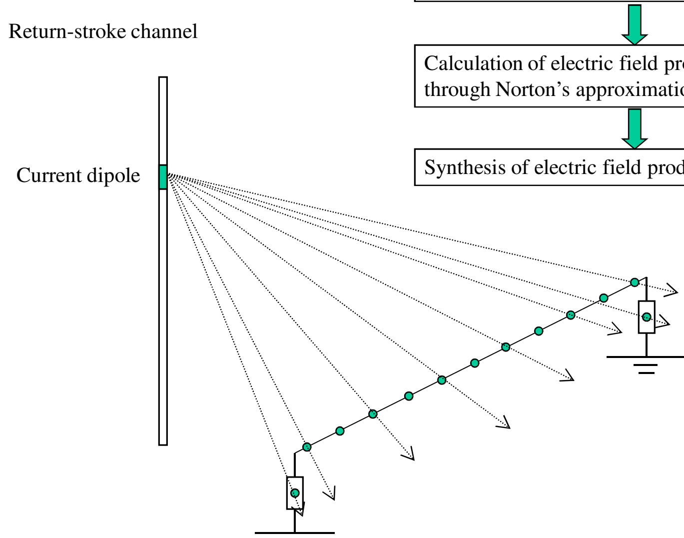


Calculation of induced voltage in the frequency domain

Synthesis to yield solution in time domain

Equivalent circuit of an overhead wire for calculation of induced voltage :

Calculation of electric fields



Calculation of complex amplitude of dipoles

Calculation of electric field produced by dipoles through Norton's approximation

Synthesis of electric field produced by dipoles

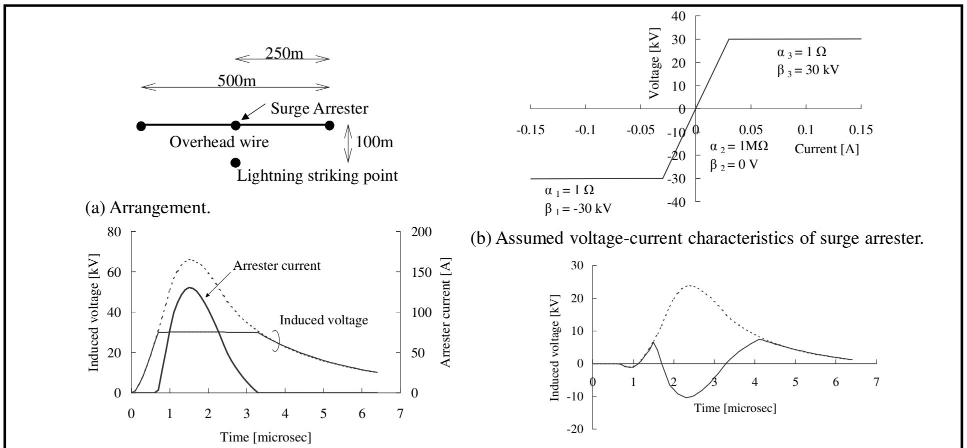


Fig. 3. Lightning-induced voltage waveform on overhead wire (c) (d) with (solid line) and without (dashed line) surge arrester. Ground conductivity is 1 mS/m and both ends are terminated with resistors of 539 Ohms.

The arrester current and the voltage mitigated by an arrester

$$\Delta I_{\mu} = \frac{V_{\mu} - \beta_i}{\alpha_i + R_e + \frac{1}{2} Z_{\mu\mu}} \qquad (2)$$

$$V_{\eta}' = V_{\eta} - Z_{\mu\mu} \frac{\Delta I_{\mu}}{2} \qquad (3)$$

where $\Delta I\mu$ is the current flowing through a surge arrester into the ground, βi and αi are constants in V-I characteristics of a surge arrester, and *Re* is the earthing resistance of a surge arrester, $Z\mu\mu$ is the self surge impedance of the conductor μ, $V\eta$' is the voltage on the conductor η in the presence of a surge arrester, and $V\eta$ is the voltage on the conductor η in the absence of a surge arrester

IV. Flashover Rate Of Line With Surge Arrester And/Or Ground Wire

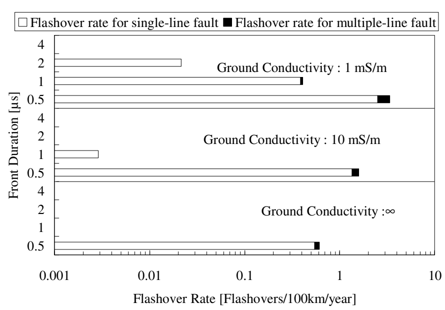


Fig. 5. Flashover rate of the line equipped with surge arresters calculated without taking account of the correlation between the peak values and the front duration of the return-stroke current waveform

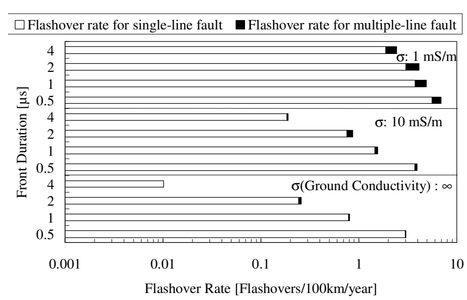
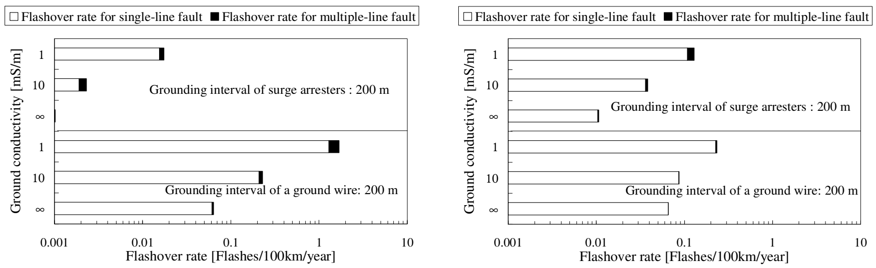


Fig. 6. Flashover rate of the line equipped with a ground wire calculated without taking account of the correlation between the peak values and the front duration of the return-stroke current waveform.

The flashover rate increases with the decrease of the ground conductivity
The flashover rate increases with the decrease of the front duration
The flashover rate of the line equipped with a ground wire only is higher than that equipped with a surge arrester only.
When both are grounded at the same points, flashover never occurs .

V. Flashover Rate Associated With First And Subsequent Strokes

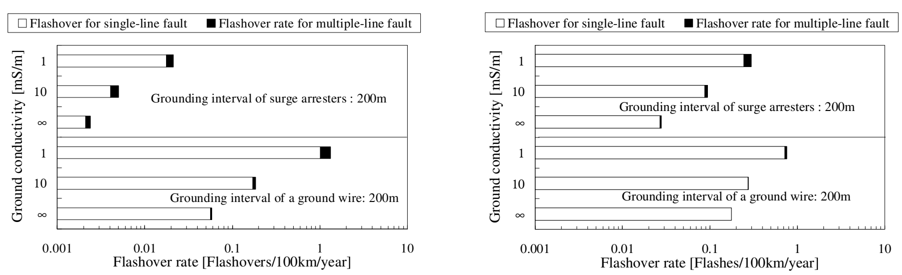


(a) First stroke. (b) Subsequent stroke.

Fig.7. Flashover rate associated with first and subsequent strokes estimated by using the return-stroke current parameters obtained by Berger et al. [15]. The rate is evaluated without taking account of the correlation between the peak values and the front duration of the return-stroke current waveform.

When the line is equipped with a ground wire only, the flashover rate associated with a first stroke is higher than that associated with a subsequent stroke. This is because the flashover rate is sensitive to the amplitude of the return-stroke current.

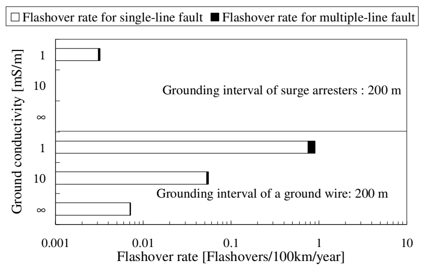
When the line is equipped with surge arresters, the flashover rate associated with a first stroke is lower than that associated with a subsequent stroke. This is because the flashover rate is sensitive to the steepness of the return-stroke current waveform.



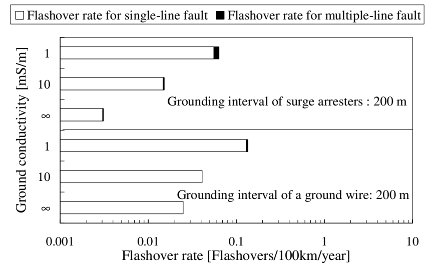
(a) First stroke. (b) Subsequent stroke.

Fig. 8. Flashover rate associated with first and subsequent strokes estimated by using the return-stroke current parameters obtained by Garbagnati [16]. The rate is evaluated without taking account of the correlation between the peak values and the front duration of the return-stroke current waveform.

The first stroke flashover rate slightly decreases when shifting from parameters of Berger et al. to those of Garbagnati et al. This is because the front duration obtained by Garbagnati et al. (50% value is 9 µs) in the case of first strokes is longer than that obtained by Berger et al. (50% value is 5.5 µs).
For subsequent strokes, the flashover rate of the line with ground wire only evaluated with Garbagnati et al. parameters is:
•about twice that evaluated with Berger et al. [15] parameters for the line with arresters only, and
•about three times that evaluated also for a line with a ground wire only but with Berger et al. parameters.
This is because peak currents of subsequent strokes obtained by Garbagnati et al. (50% value is 18 kA) are greater than those obtained by Berger et al. (50% value is 12 kA).



(a) First stroke.



(b) Subsequent stroke.

Fig.9. Flashover rate associated with first and subsequent strokes estimated by using the return-stroke current parameters and the correlation coefficient obtained by Berger et al. [15].

When the line is equipped with a ground wire the flashover rate associated with first strokes is higher than that associated with subsequent strokes. However, when the line is equipped with surge arresters the flashover rate associated with first strokes is lower than that associated with subsequent strokes.

The flashover rate associated with flashes is of more concern than that associated with individual strokes. Nevertheless, the flashover rate is shown for first and subsequent strokes in this paper, since it is difficult to calculate the flashover rate associated with lightning flash due to lack of accurate statistics of some parameters such as number of subsequent strokes per flash and the correlation of current parameters between first and subsequent strokes.

Table 3. Line Flashover rate summary accroding to protection means evaluated based on first return-stroke parameters obtained by berger et al. [15].

	Flashover rate [Number/100km/year]	
Conductivity	10mS/m	1mS/m
Surge arrester (SA) with 2μs front	0.0	0.021
Ground wire (GW) with 2μs front	0.87	4.1
Surge arrester with no correlation	0.002	0.017
Ground wire with no correlation	0.23	1.7
Surge arrester with correlation	0.00023	0.003
Ground wire with correlation	0.055	0.90

When the ground conductivity is higher than 10 mS/m, the flashover rates for single-line and multiple-line faults obtained by assuming the constant front duration are less than the rates calculated by taking account of the variation, although the estimated values are very small. This shows that the assumption of a constant front duration of 2 μs does not always result in the conservative flashover rates when the line is equipped with surge arresters only.

When the line is equipped with an overhead ground wire, the flashover rates for single-line and multiple-line faults obtained by assuming a constant front duration of 2 μs are more than twice as high as the rates calculated by taking account of the variation.

VI. CONCLUSION

In this paper, the flashover rate of a distribution line associated with indirect negative lightning flashes is investigated based on numerical calculations by taking account of statistics on return-stroke current and the correlation between the peak and the front duration of the return-stroke current waveform, where an overhead ground wire and/or the surge arresters are grounded every 200 m. The following insights are obtained.

(1) For first return strokes, the flashover rate of the line equipped with an overhead ground wire is more than 100 times higher than that of the line equipped with surge arresters when the interval of grounding of the ground wire or the surge arresters is 200 m. When both an overhead ground wire and surge arresters are installed and grounded at the same points with the interval of 200 m, the flashover rate becomes zero, irrespective of the ground conductivity.

(2) When the line is equipped with an overhead ground wire only, the flashover rate associated with first strokes is higher than that associated with subsequent strokes. When the line is equipped with surge arresters only, the flashover rate is sensitive to the steepness of the return-stroke current. In the result, the flashover rate associated with subsequent strokes is higher than that associated with first strokes.

(3) 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 a subsequent stroke is higher than that associated with a first stroke when the line is equipped with surge arresters. Furthermore, it is shown that the flashover rate significantly decreases with the increase of the correlation coefficient. This demonstrates the importance of the investigation on the correlation among the return-stroke current parameters.

(4) It is shown that the assumption of a constant front duration of 2 µs in the case of a first stroke, less than half of the 50 % value of 5.5 µs, does not always result in conservative flashover rates when the line is equipped with surge arresters.