Measurements of A Concrete Pole Impedance with An Impulse Current Source

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ABSTRACT - This paper presents experimental results of surge characteristics of a concrete pole and the grounding resistance of the pole. The surge impedance and the travelling velocity are similar to those of a vertical conducor. Its grounding resistance for a high impulse current is heavily dependent on the crest value of the current.

1. INTRODUCTION

The lightning protection for power-distribution system has been mainly designed for the indirect-lightning strokes based on the insulation level to the lightning-induced voltages [1]. The numbers of faults in the system caused by the indirect-lightning strokes are remarkably reduced with the clarification of the mechanism for the lightning-induced voltage [2] and the development of protection techniques [3]. From a surge analysis using the EMTP [4] and an experimental study [5], it is cleared that the direct-lightning hits to the ground wires with the capacity of several ten kA can be prevented by a proper arrangement of metal-oxide arresters. The protection for the power-distribution system from the lightning is emphasized to take into account for the direct-lightning strokes.

A concrete pole is used to sustain the ground wire in power-distribution system in Japan. The direct-lightning hit causes flashovers at the low-tension insulators, which insulate the concrete pole from the ground wire, and the ground wire is electrically short-circuited to the concrete pole. Then the lightning current flows into the concrete pole. The concrete pole can be treated as a kind of a grounding lead conductor with a low grounding resistance [6,7], and is expected to be an important factor on the protection design for the direct-lightning strokes. However, the electrical characteristics such as the surge impedance and the grounding resistance of the concrete pole are still not enough for lightning surge analysis [7,8].

In this paper, experimental results are described to clarify the surge characteristics of the concrete pole using a low-steep current source (a steep front current test) and the reduction effect of the grounding resistance using a high impulse current source (a high impulse current test) to obtain the data for the sake of the development of a nonlinear grounding resistance model.

2. EXPERIMENTAL SETUP

A concrete pole as shown in Fig.1 is employed for the experiments, and Fig.2 shows the layout of the experimental arrangement.

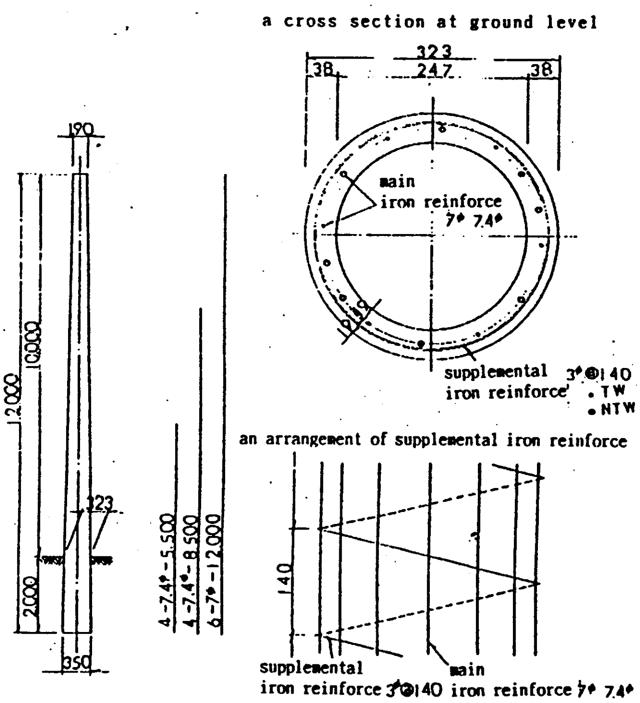


Fig.1 Dimensions of a concrete pole.

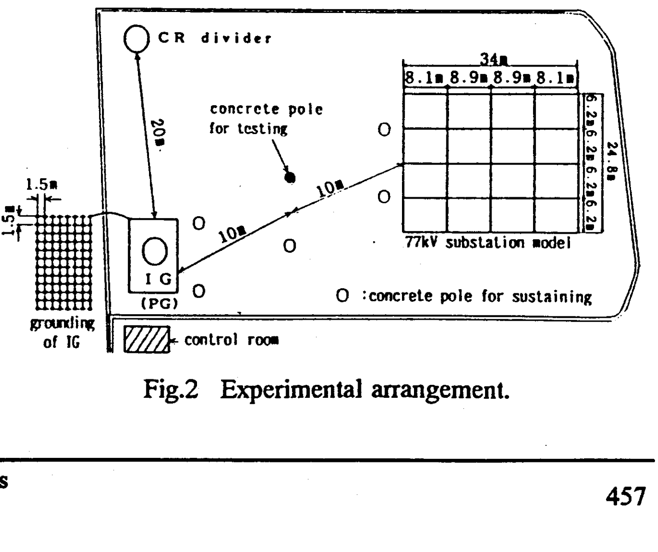


Fig.2 Experimental arrangement.

Table 1 Experimental equipments.

equipment	steep front current test	high impulse current test
current generator	pulse generator (TOKIN MODEL-5556A, rise time=1ns)	all-weather-type mobile impulse voltage generator [9]
CT	PEASON MODEL-2877, rise time =2ns	PEASON MODEL-1330, rise time= 0.3 μs
voltage divider	high-voltage probe (SONY TEKTRONIX P6009, frequency band= 120MHz); directly connecting to pole top	CR-type voltage devider (C=2.97 nF, R=2.58kΩ, rise time=0.3 μs) ;connecting to pole top with auxiliary potentail wire
oscilloscope	SONY TEKTRONIX TDS540, frequency band=500MHz	
optical fiber	SONY TEKTRONIX P6904A, frequency band=100MHz	

The other grounding electrodes exist as shown in Fig.2; a 77kV substaion model, concrete poles for sustaining a bundled current lead conductor, which consists of eight alminium pipes with the radius of 15 mm spacing out on a circle with the radius of 250mm for preventing from a corona discharge and for reducing an inductance, and a grounding of the IG consisting of 8x12 driven rods [9].

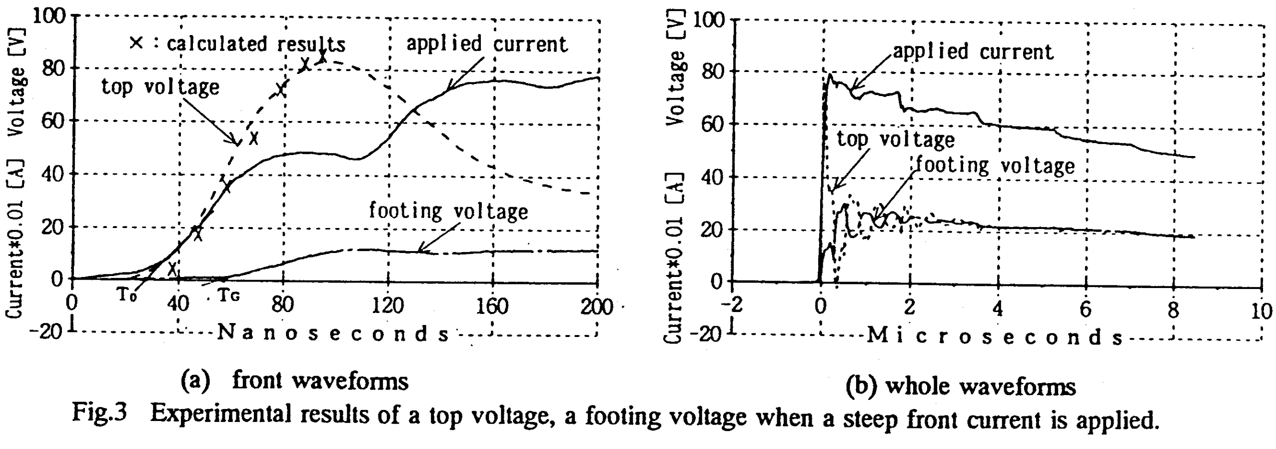
The current lead conductor is connected to the iron reinforces at the top of the concrete pole for applying the current. An auxiliary potentail wire is arranged in perpendicular to the current lead conductor. It is used for guiding the ground potential at the point of 100m departed from current generators to a voltage probe connected at the top of the concrete pole for the steep front current test and the pole top voltage to a CR-divider for the high impulse current test. Table 1 lists the experimental equipments used for the experiments. A 5.5mm^2 IV wire is used for a grounding lead wire along the concrete pole, and the grounding resistivity around the concrete pole is approximately 170 Ω m.

3. STEEP FRONT CURRENT TEST

3.1 SURGE CHARACTERISTICS OF CONCRETE POLE

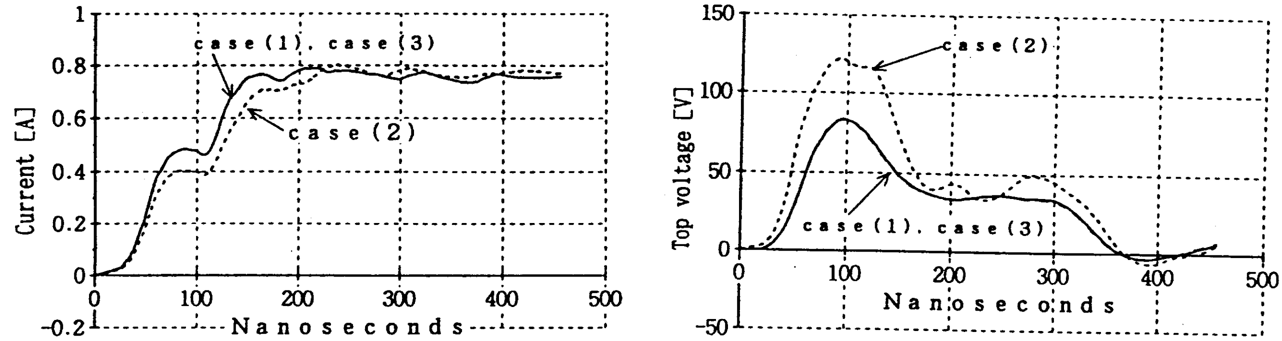
The changes of wavefront voltages and wavetail voltages in the top voltage and the footing voltage for the steep front current applied to the top of the concrete pole are plotted in Fig.3. The current is generated by a pulse generator. It is clear from Fig.3(a) that the surge impedance of the concrete pole varies with the time elapse until the reflected surge arrives at the top from the ground through the pole, and this characteristic is similar to the case for a vertical conductor [10]. Fig. 3(b) indicates that the top voltage coincides with the footing voltage after 4 μ s from the start of the applied current because the voltage drop in the pole depending on the pole inductance becomes to be negligible small after 4 μ s for di/dt=0. Hence, a ratio of the pole top voltage to the applied current gives the grounding resistance 38.5 Ω .

The experimental results shown in Fig.3 are adjusted the time scale in more precisely with using the optical fibers. The origin of the surges is defined by the intersection of a tangent line at the rapid change of the surge and the time scale. The time difference between starting points of the pole top voltage [T_o] and of the footing voltage [T_G] shows that the propagation velocity of the surge coincides closely to the light velocity.



(a) front waveforms (b) whole waveforms

Fig.3 Experimental results of a top voltage, a footing voltage when a steep front current is applied.



(a) applied current (b) top voltage

Fig.4 Effect of a grounding lead wire when a steep front current is applied.

The surge impedance of the concrete pole may be simply calculated by dividing the peak pole top voltage with the maximum applied current, and its value becomes 175 Ω . However, the surge impedance should be modified by taking into account the time duration T until the reflected wave from the ground for the applied current returns again to the top of the concrete pole because eq.4 is obtained for a step current. The time duration is expressed as;

$$T=2h/c \qquad (1)$$

where h is the height of the concrete pole, c is the light velocity. Then, the calculated result from eq.7 is 202 Ω by instituting β =0.6 obtained in Fig.3(a). And also eq.4 is tried to calculate the surge impedance on the condition that the equivalent radius of the concrete pole is the same as the average of those at the top and at the ground level [8]. In this case, the surge impedance is calculated as 204 Ω at t=T. It agrees quite closely to the modified value. Calculated results of the pole top voltage using eq.6 are included in Fig.3(a). The calculated results agree well with the experimental results.

3.2 SURGE CHARACTERISTICS OF GROUNDING LEAD WIRE

To investigate the influence of the grounding lead wire to the surge impedance of the concrete pole, the change of the top voltages are measured in three cases: (1) the concrete pole alone, (2) the grounding lead wire alone, and (3) the grounding lead wire connected to the concrete pole at the top. The grounding lead wire and the concrete pole are connected at the bottom during the steep front current test. Experimental results of the three cases are shown in Fig.4. The surge impedance for the grounding lead wire only is 330 Ω using eq.7. Hence, it is clear from Fig.4 that the surge impedance in the case (3) is almostly same as that in the case (1).

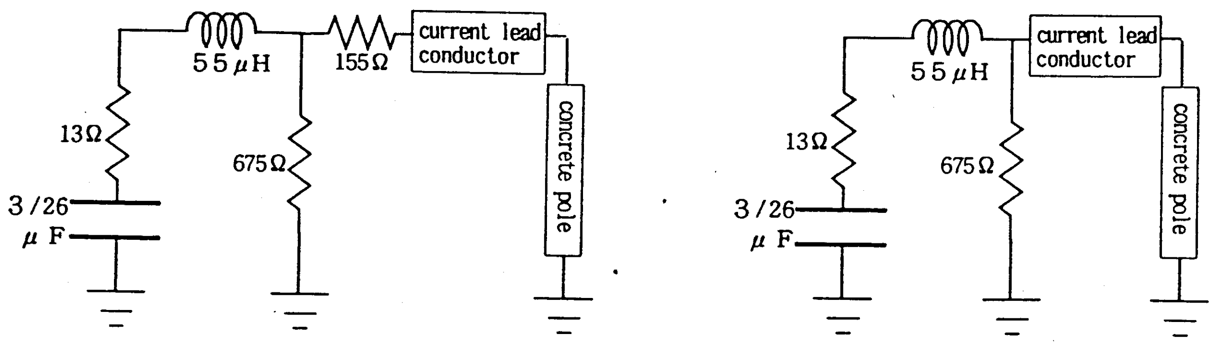
4. HIGH IMPULSE CURRENT TEST

The pole grounding resistance obtained from the steep front current test is approximately 40 Ω , and the impedance of the pole in the air is $20/(3T_f)$ Ω , where T_f is the wavefront duration of the impulse current. Hence the pole top voltage is dominated by the voltage of the grounding resistance.

An applied current is generated by an all-weather-type mobile impulse voltage generator (IG), which can generate several ten kA [9]. Fig.5 shows an equivalent circuit of the IG.

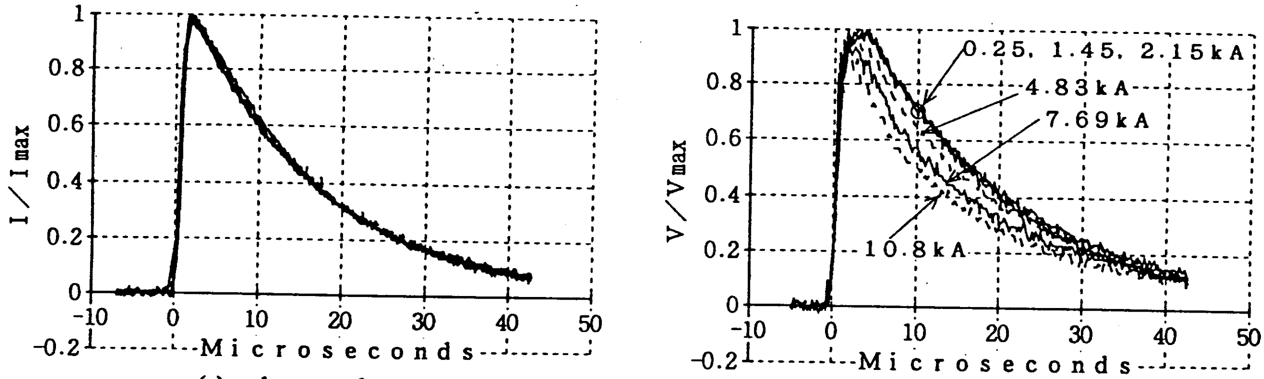
4.1 CHARACTERISTICS OF CONCRETE POLE GROUNDING RESISTANCE FOR HIGH IMPULSE CURRENT

Figs.6 and 7 show experimental results of normalized waveforms of pole top voltages and applied currents for the lightning impulse circuit and the high



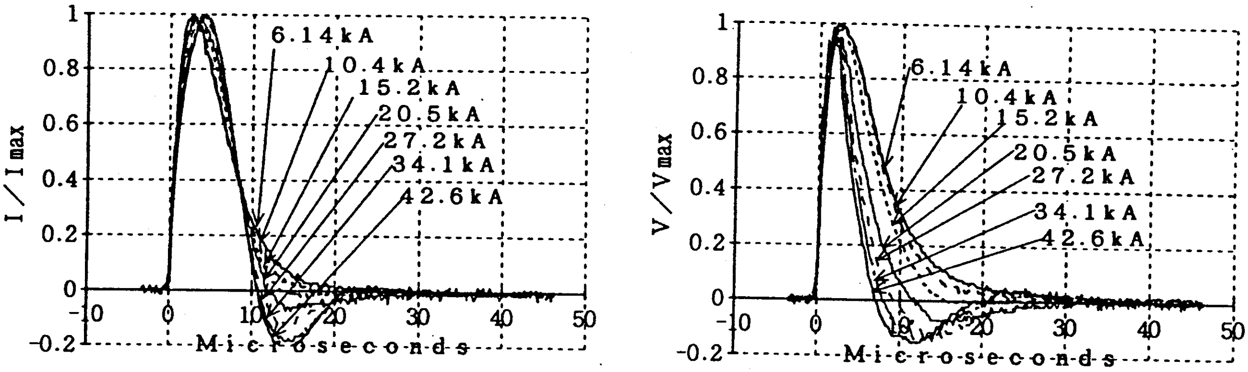
(a) lightning impulse circuit (b) high impulse current circuit

Fig.5 Equivalent circuit of an impulse voltage generator.



(a) pole top voltages (b) applied currents

Fig.6 Experimental results of normalized pole top voltages and applied currents for a lightning impulse circuit.



(a) pole top voltages (b) applied currents

Fig.7 Experimental results of normalized pole top voltages and applied currents for a high impulse current circuit.

impulse current circuit, respectively. The waveforms for the high impulse current vary from non-oscillation to oscillation because the internal damping resistance of the IG (13 Ω) and the reduced grounding resistance for the high impulse current satisfy the oscillation condition of RLC series circuit consisting of an internal impedance and a grounding impedance of the IG, an inductance of the current lead conductor and the concrete pole impedance. The grounding impedance is ordinary either capacitive or inductive. For the simplicity, the pole impedance including the grounding resistance is evaluated by the following equation.

$$Z(I_m) = \frac{\text{maximum pole top voltage } (V_m)}{\text{maximum applied current } (I_m)} \quad \cdots\cdots(2)$$

Fig.8 shows the calculated results from eq.2. It is clear that Z is heavily dependent on the crest value of the applied current over 1kA, and is not affected by the polarity of the applied current. Z at 40kA is half in the value at a low current. It is expected that this characteristic is caused by a discharge in the soil [11].

Fig.9 shows the step responses in the pole top voltages calculated by a numerical Laplace transform

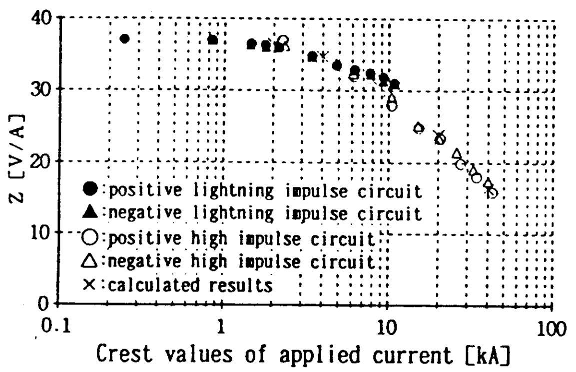


Fig.8 Pole impedance characteristic as a function of the crest current.

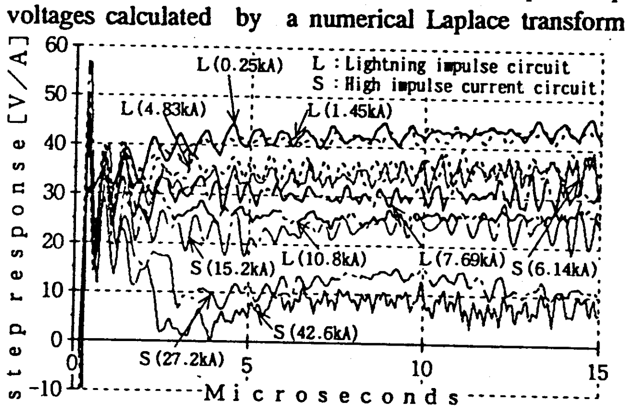


Fig.9 Step response of experimental results of pole top voltage.

method [12]. It is observed from Fig.9 that the grounding resistance changes from a capacitive type for a low current to an inductive type for a high current. A steady-state grounding resistance is 44 Ω for a low current, and the value agrees satisfactorily with that for the steep front current test.

From Fig.8, the grounding resistance is current-dependent for the high impulse current. Hoki and Mita [13] proposed the following current-dependent formula.

$$Z(I_m)=\frac{R_0}{1+A(I_m \cdot R_0)^B} \quad \cdots\cdots\cdots\cdots\cdots(3)$$

where R_0 :stedy state resistance, I_m :crest value of applied current [kA], A,B:constants

Calculated results from eq.2 using eq.3 agree well with the experimental results, where $A=2.6\times10^{-4}$, B= 1.14 and R_0 =44 Ω as shown in Fig.8.

4.2 EFFECT OF AUXILIARY GROUNDING

Fig.10 shows the equivalent impedance (eq.2) evaluated from experimental results in the case that the grounding lead wire along the concrete pole connected to the top of the concrete pole, and their grounding are geometrically independent. The grounding of the grounding lead wire consists of 6 driven rods (steady-state resistance is 38 Ω) at the point of 1m departed from the concrete pole. From Fig.10, it is clear that the independent auxiliary grounding reduces the pole top voltage. A flashover occures between the grounding lead wire and the concrete pole at 27kA, then the concrete at the flashover is partialy broken. Experimental results for the high impulse current existing the auxiliary grounding as the same way in § 4.1 did not differ remarkably from those without the auxiliary grounding .

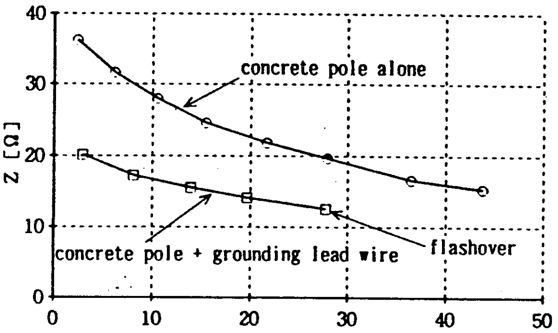


Fig.10 Effect of an auxiliary gronding for a high impulse current.

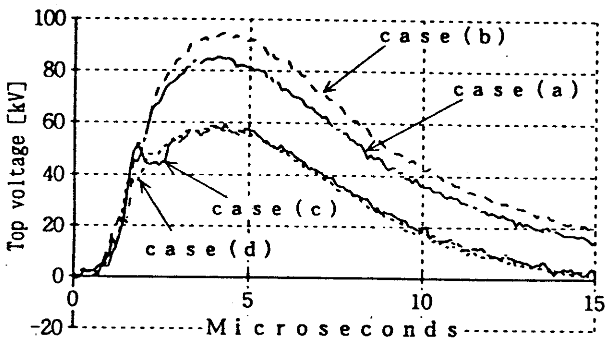


Fig.11 Experimental results of top voltages for the cases (a) to (d).

Fig.11 shows top voltages of the concrete pole and of the grounding lead wire when a charging voltage of the IG is 260kV measured in the cases: (a) the current applies to the iron reinforce, (b) the current applies to the concrete, (c) the current applies to the grounding lead wire, and (d) the grounding lead wire connects to the concrete pole at the top, where the grounding lead wire is aparted from the concrete pole in the cases (a) to (c).

In the case (c), a flashover between the grounding lead wire and the concrete pole makes them short-circuited, then the top voltage coincides the voltage in the case (d). This fact indicates that when a direct-lightning stroke hits to the ground wire, an auxiliary grounding (a grounding of the ground wire) is short-circuited to the concrete pole.

5. CONCLUSIONS

(1) The surge impedance of a concrete pole is measured to be 200 Ω , and the travelling velocity of the surge is about the same as the light velocity in free space. The surge impedance of the concrete pole is similar to that of a vertical conductor.

(2) The grounding resistance of the concrete pole is heavily dependent on the crest value of an applied current.

(3) The resistance is not affected by the polarity of the applied current.

(4) An auxiliary grounding reduces the pole top voltage.

REFERENCES

(1)Lightning Protection Design Study Committee: "Lightning Protection Design Guide-Book for Distributio Lines", CRIEPI Report, No.175030 (in Japanese), 1976

(2)Lightning Overvoltage on Distribution Lines Study Committee:"Lightning-Induced Voltages on Overhead Wires", IEEJ Report No.522 (in Japanese), 1994

(3)S.Yokoyama: "Lightning Protection on Power Distribution Lines against Direct Lightning Hits", IEEJ Trans., vol.114-B(6), pp.564-568 (in Japanese), 1994

(4)Y.Imai, T.Matsuura, K.Ito, S.Ishibe, M. Azuma & T.Shimomura:"Protective Effects of Surge Arresters on Power Distribution Lines against Direct Lightning Hits to Overhead Ground Wire", ibid., vol.111-B(6), pp.619-627 (in Japanese), 1991

(5)S.Yokoyama & A.Asakawa: "Experimental Study of Response of Power Distribution Lines to Direct Lightning Hits", IEEE Trans., vol.PWRD-4(4), pp. 2242-2248, 1989

(6)H.Taniguchi, A.Asakawa, S.Yokoyama, K.Nakata, K.Ohnishi & T.Motobayashi: "A Study on Lightning Performance of Power Distribution Line without Surge Arresters on One Phase", ibid., vol. 114-B(11), pp.1150-1159 (in Japanese), 1994

(7)T.Masaki, K.Higuchi & Y.Yokoi:"Study on the Effective Lightning Protection Schemes for Distribution Line", ibid., vol.114-B(6), pp.649-656 (in Japanese), 1994

(8)K.Yamamoto, K.Matsuura, S.Sekioka & S. Yokoyama:"A tudy of Surge Impedance of Distribution Concrete Pole and Grounding Lead Wire using Scale Model", High Voltage Conference of IEEJ, HV-94-177 (in Japanese), 1994

(9)A.Morimoto, H.Hayashida, S.Sekioka, M. Isokawa, T.Hiyama & H.Mori:"Development of All-Weather-Type Mobile Impulse Voltage Generator", Discharge & High Voltage Joint Conference of IEEJ, ED-94-124, HV-94-83 (in Japanese), 1994

(10)T.Hara, O.Yamamoto, M.Hayashi, T.Higuchi & K. Saikawa: "Lightning Surge Response of a Cylindrical Tower", 5th ISH, 81.05, 1987

(11)A.M.Mousa: "The Soil Ionization Gradient associated with Discharge of High Currents into Concentrated Electrodes", IEEE Trans., vol.PWRD-9(3), pp.1669-1677, 1994

(12)N.Nagaoka & A.Ametani:"A Development of A Generalized Frequency-Domain Transient Program - FTP", IEEE Trans., vol.PWRD-3(4), pp.1996-2004, 1988

(13)S.Hoki & N.Mita:Insulation and Flashover Protection, OHM Pub. (in Japanese), 1951

Appendix

A surge impedance of a vertical conductor is proposed by Hara, et al. [10] as follows.

$$Z_0(t)=60\{\ln(\sqrt{2}ct/r)-2\} \quad \cdots\cdots(4)$$

where $Z_0(t)$:conductor surge impedance,
r: conductor radius

Eq.4 is the surge impedance for a step current. If an applied current is represented as;

$$i(t)=\alpha t\cdot u(t)-\alpha t\cdot u(t-T_f) \quad \cdots\cdots(5)$$

where T_f:front dulation of the current, Imax:crest value of the current, α=Imax/T_f, u(t):a step function and tail duration is infinite. The pole top voltage for the current expressed eq.5 is obtained by the convolution of eq.4 and eq.5 as follows.

$$V_{0t}=\alpha t\{Z_0(t)-60\}\cdot u(t)-\alpha(t-T_f)* \{Z_0(t-T_f)-60\}\cdot u(t-T_f) \quad \cdots\cdots(6)$$

Since eq.6 is a monotonous increase function, the pole top voltage reaches the maximum value at t=T. By substituting t=T for eq.6 and by expanding logarithm into a series function, eq.7 is obtained.

$$Z_T=Z_0(T)-30\beta-20\beta^2-7.5\beta^3 \quad \cdots\cdots(7)$$

where $\beta=T_f/T$