A Current-Dependent Grounding Resistance Model Based on an Energy Balance in Ionization Zone

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Abstract – **Soil ionization occurs around a grounding electrode when current density in the soil exceeds a critical value. The grounding resistance for lightning currents is decreased due to the soil ionization. This paper proposes a new current-dependent grounding resistance model of a rod electrode considering the soil ionization. The proposed model is derived from energy balance in the soil ionization zone. The resistivity of the ionization zone is dependent on energy stored in the zone. The proposed model can treat the soil ionization as well as deionization.**

Keywords: Soil Ionization, Soil Deionization, Grounding Resistance, Current Dependency, Energy Balance, Arc Model.

I. INTRODUCTION

The grounding resistance is one of the most basic and important factors in determining lightning overvoltages in electric power systems, and affects a lightning outage rate on distribution and transmission lines and substation insulation coordination. The magnitude of a lightning current is estimated to range from several kA to a few hundred kA. The grounding resistance is decreased due to soil ionization, which is a kind of discharge in soil, caused by a high impulse current [1-10]. Thus, the nonlinear characteristic of the grounding resistance should be taken into account for accurate lightning surge analysis.

Bellaschi introduced effective radius and length, which are dependent on injected current, of a driven rod to estimate the current dependency of the grounding resistance. Ionization zone with low resistivity due to soil ionization grows with the increase of the injected current [2]. Bellaschi's model is very convenient to calculate the grounding resistance for high currents, considering that the ionization zone is assumed to become perfect conductor, while actual soil ionization zone does not always grow homogenously [11]. Liew and Darveniza proposed a dynamic grounding resistance model, which can take account of the resistivity of the ionization zone and the hysteresis effect [3]. In the model, the ionization zone is divided into many segments, and the resistivity of the each segment is a function of time and current density. Calculated waveforms using the Liew and Darveniza's model agree well with experimental results. However, the physical meaning of the model is not clear.

One of the authors measured a number of data on the grounding resistance for high impulse currents [7-9]. The measured data are useful to verify a current-dependent grounding resistance model. This paper proposes a new grounding resistance model of a rod electrode such as a driven rod or a reinforced concrete pole for high impulse currents based on an energy balance in the soil ionization zone. The proposed model is determined from the rod dimension, the injected current and the energy stored in the zone. The proposed model shows a good accuracy in comparison to the measured results.

II. SOIL IONIZATION

Fig. 1 illustrates an arrangement of a single rod electrode associated with soil ionization.

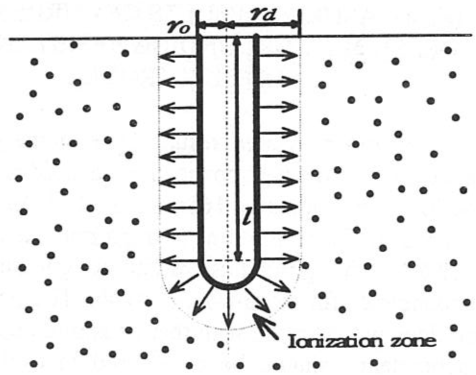


Fig. 1 An illustration of a rod electrode for high impulse currents.

A distribution of actual soil resistivity is not homogeneous [6]. This paper assumes the distribution of the resistivity to be homogeneous for simplicity. The nonlinearity of grounding resistance for high currents is represented by the following components.

A. *The Increase of Ionization Zone*

Wherever current density branching off through an electrode exceeds a critical value, the soil ionization occurs. The ionization zone of which the resistivity is much lower than the soil resistivity develops as the injected current increases. A relation between the critical injected current I_c at a point on the contour of the ionization zone and soil ionization gradient E_d is given by [6]:

$$E_d = \frac{\rho_0 I_c}{S(r_d)} \quad (1)$$

where $S(r_d)$: surface area of ionization zone within distance r_d from the rod, ρ_0 : soil resistivity.

E_d gives effective radius r_d by eq. (1). Therefore, E_d is one of the most important factors to estimate the current dependency of grounding resistance because the grounding resistance for high currents is determined from r_d for low resistivity of soil ionization zone. The recommended value of E_d is 300kV/m [6], 400kV/m [12] and 1000kV/m [5, 13]. Thus, E_d has not been established.

B. The Variation of Resistivity of Ionization Zone

The soil ionization zone shows low resistivity due to discharge in soil. The current dependency can be easily estimated using a simplified model [2], which is obtained assuming the resistivity of the zone to be zero, by choosing E_d appropriately. However, the resistivity does not rapidly converge to zero, and may depend on such factors as current density, time constant [3], water content [14] and temperature. The decreased grounding resistance gradually recovers its initial value in the wavetail. This fact indicates that the resistivity of the ionization zone is increased in soil deionization process. Therefore, the resistivity of the soil ionization zone should be considered.

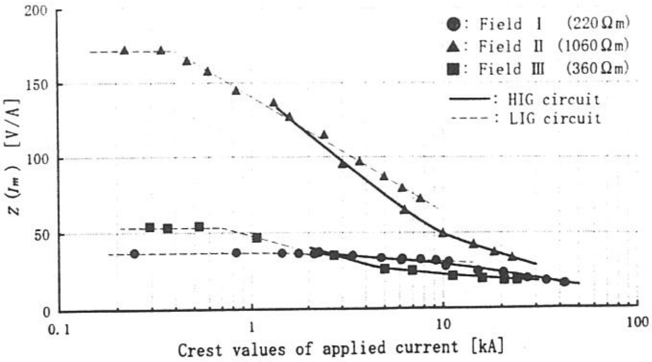
III. MEASURED RESULTS OF CURRENT-DEPENDENT GROUNDING RESISTANCE OF ROD ELECTRODE

Fig. 2 shows measured results [15] of the grounding resistance of a reinforced concrete pole used in Japanese distribution lines (radius r_0=168mm, length l=2m) [16] and a driven rod (r_0=7mm, l=1.5m) for high impulse currents of about 20kA. The grounding resistance generally shows time dependency for steep-front currents. The time to crest voltage does not coincide with that of applied current. The time dependency should be considered in evaluating the current dependency. This paper adopts the following definition of the grounding resistance for high impulse currents for simplicity [8].

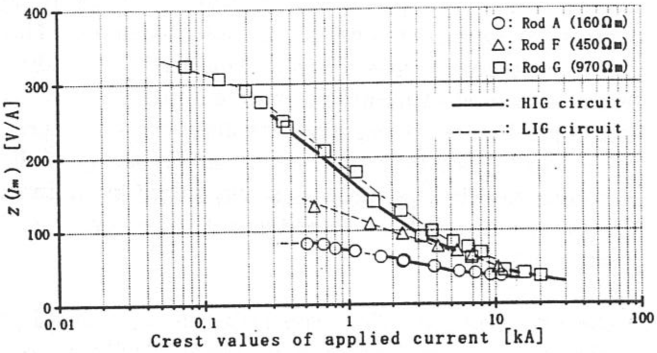
$$R(I_m) = \frac{\text{Crest rod voltage} \quad (V_m)}{\text{Crest applied current}\ (I_m)} \quad (2)$$

LIG circuit in Fig. 2 includes a damping resistor, which is connected between a grounding electrode for testing and a current lead conductor of HIG circuit, to reduce applied current. The current waveform of the LIG circuit is different from that of the HIG circuit by the existence of the damping resistor as shown in Appendix. Soil resistivity in Fig. 2 is calculated from measured steady-state grounding resistance shown in Table 1 using eq. (3) [3].

$$R = \frac{\rho_0}{2\pi l}\ln\left(1+\frac{l}{r_0}\right) \quad (3)$$



(a) Reinforced concrete pole



(b) Driven rod

Fig. 2 Measured results of current-dependent grounding resistance as a parameter of soil resistivity.

Table 1 Measured steady-state grounding resistance.
(a) Reinforced concrete pole

Test field	I	II	III
Symbols	●	▲	■
Resistance	44 Ω	217 Ω	73 Ω

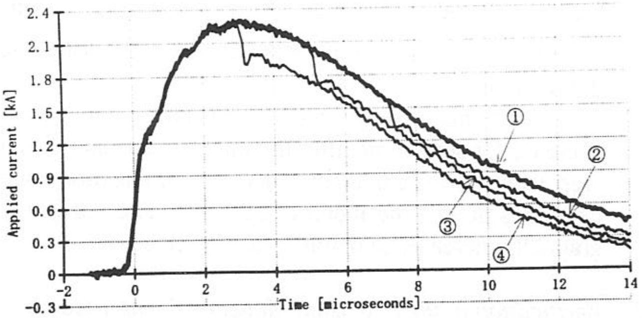
(b) Driven rod

Electrode	Rod A	Rod F	Rod G
Symbols	○	△	□
Resistance	92 Ω	256 Ω	555 Ω

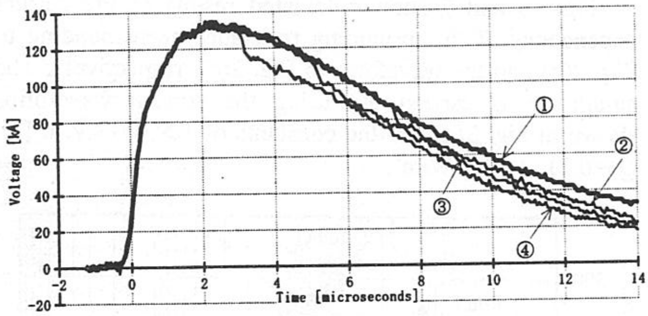
It is clear from Fig. 2 that the grounding resistance is greatly dependent on the crest value of the applied current, and becomes almost the same value for high impulse currents of above 10kA although the soil resistivity is different. This fact indicates that the resistivity of the ionization zone plays an important role to determine the grounding resistance for high currents.

A diffrence of the current dependency between the LIG and HIG circuits is observed in Fig. 2. The wavefront duration of the applied current of the HIG circuit is longer than that of the LIG circuit as shown in Figs. A1 and A2. This difference can be explained by an energy dependency of the grounding resistance [8, 17].

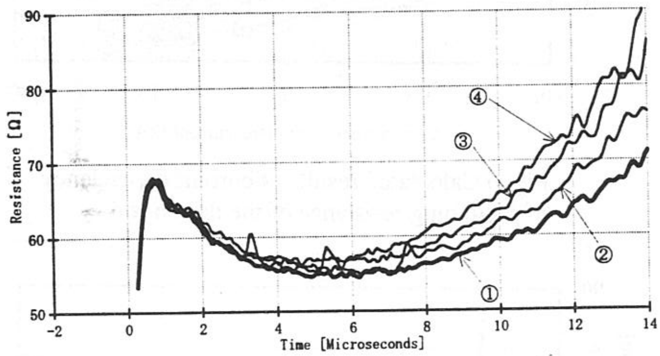
Fig. 3 shows measured results of applied current, rod voltage and grounding resistance, which is defined as the ratio of the voltage to the applied current at the same instance of time, of the driven rod A for various wavetail shape of the applied current.



(a) Applied current



(b) Voltage



(c) Resistance

Fig. 3 Measured results for various wavetail shape of the applied current.

The time constant of the grounding resistance of the driven rod measured by using a pulse generator with a step current is about 1 μs . This time constant is sufficiently shorter than the duration after the applied current is changed in the wavetail, and the transient characterisitc of the grounding resistance is negligible for rough evaluation. Therefore, the difference of the grounding resistance in the wavetail is caused by the difference of the applied current waveform, and the resistivity of the ionization zone is increased and is dependent on the waveshape.

As mentioned above, the resistivity of the ionization zone affects the grounding resistance for high currents, and should be considered for accurate surge analysis.

IV. CURRENT-DEPENDENT GROUNDING RESISTANCE MODEL BASED ON ENERGY BALANCE IN SOIL IONIZATION ZONE

A. *The Increase of Ionization Zone*

This paper adopts the Liew and Darveniza's contour model of the ionization zone. The surface area of the contour with radius r_d in the model is [3]:

$$S(r_d) = 2\pi r_d (r_d + l) \tag{4}$$

From eqs. (1) and (4), the effective radius is given by:

$$r_d = \frac{l}{2}\left(-1 + \sqrt{1 + \frac{2\rho_0 i}{\pi l^2 E_d}}\right) \tag{5}$$

where i : injected current.

The contour of the soil ionization zone is detrmined from eq. (5) for the instantaneous injected current i in the wave-front.

The grounding resistance for high currents shows low value in the wavetail [8]. The proposed model assumes that the ionization zone keeps its contour even if the applied current becomes lower than the crest value. This representation simulates a hysteresis characteristic.

B. *The Variation of Resistivity of Ionization Zone*

The soil ionization may be regarded as a kind of discharge. Accordingly, the resistivity of an ionization zone should be determined based on an energy balance of the discharge. Fig. 4 illustrates the energy balance in a segment w, which is one of the segments of the ionization zone divided.

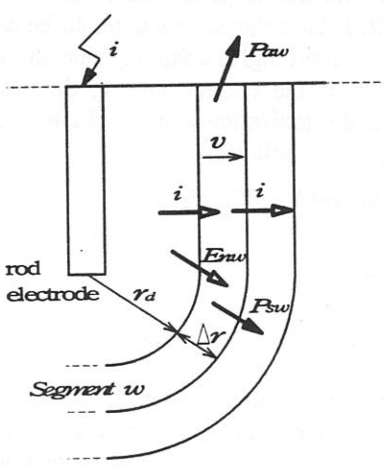


Fig. 4 Energy balance in ionization zone.

The energy balance of the discharge yields [18]:

$$\frac{dQ}{dt} = vi - P \tag{6}$$

where Q: accumulated energy, v: discharge voltage, i: discharge current, P: removed power.

The same energy balance is valid in the arc discharge, for which Mayr proposed the following relation between the arc conductance g and the accumulated energy Q [19].

$$g = K\exp(Q/Q_0) \tag{7}$$

where K and Q_0: constants

Assuming that the Mayr's formula is applicable to the soil ionization, the following differential equation is obtained from eqs. (6) and (7) by an analogy.

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{Q_0}(vi - P) \tag{8}$$

The current-dependent grounding resistance with the soil ionization is calculated by the sum of the resistance of each segment obtained from the conductance g. The injected current i or voltage v should be solved with an external electrical circuit based on the differential equation (8) as a black box model [19].

The energy loss P is generated mainly from a heat-dissipation/conduction, and should be denoted as a function of temperature [20]. In this paper, the energy loss is assumed to be proportional to the surface area of the segment according to Cassie's arc model [21] for simplicity. The loss is given by:

$$P = \lambda S \tag{9}$$

where λ: constant.

Eq. (8) is valid for $g > g_0$, where g_0 is a conductance of the segment with no soil ionization.

C. Approximate Analytical Expression of Resistivity of Ionization Zone

Electric power input vi of arc is approximately constant during the resistivity of the arc is rapidly and extremely decreased with the increase of arc current after the arc is initiated [22]. This characteristic might be same as the soil ionization. Accordingly, assuming that the power input is independent of the conductance g, the resistivity of the segment of the ionization zone is obtained analytically by solving eq. (8) as follows:

$$\rho = \rho_0 \exp\{-(E_n - N)/Q_0\} \tag{10}$$

$$E_n = \int vi\,dt \tag{11}$$

$$N = \int P\,dt \tag{12}$$

E_n and N have a unit of energy. Therefore, the proposed model shows an energy dependency, and takes into account the influence of the voltage and current waveform. The resistivity ρ does not increase rapidly after the injected current begins to decrease, because the energy E_n–N stored in the segment continues to increase for some time in the wavetail. As a result, the soil resistivity has a hysteresis characteristic. These characterisitics are observed in expermental results [8].

The proposed grounding resistance model has the following physical meanings.

(1) *Current dependency*: the higher the injected current, the soil ionization zone becomes larger.

(2) *Energy dependency*: the resistivity of the ionization zone decreases as the energy E_n–N stored in the ionization zone increases.

(3) *Soil deionization*: when the power input vi is less than the power loss P, the resistivity of the ionization zone increases, and finally the reduced resistivity recovers the initial value ρ_o. From eq. (8) with vi=0, Q_0/P means the time constant of the resistivity in recovering the initial value.

(4) *Hysteresis effect*: the grounding resistance continues to decrease for some time after the injected current takes a crest value because the resistivity of the ionization zone decreases due to the increase of E_n–N. The resisitvity gradually increases in deionization process.

D. Verification of the Proposed Model by Comparison of Calculated and Experimental Results

Figs. 6 and 7 show calculated results of the current dependency of the grounding resistance corresponding to Fig. 2(b) and the waveform to Fig. 3(c), respectively. The simulation is carried out using the current waveforms shown in Fig. 3(a) and the constants of E_d=300 kV/m [6], Q_0=0.2J, $\lambda=10^6$ W/m^2.

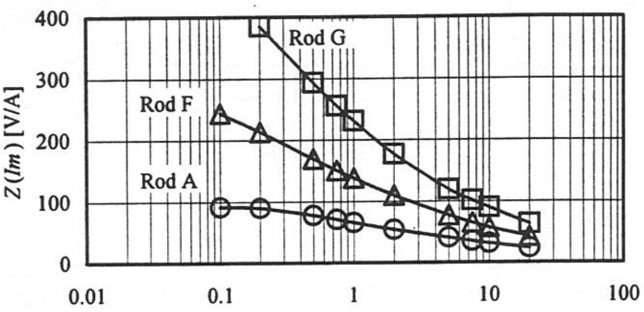


Fig. 6 Calculated results of current dependency of grounding resistance of the driven rod.

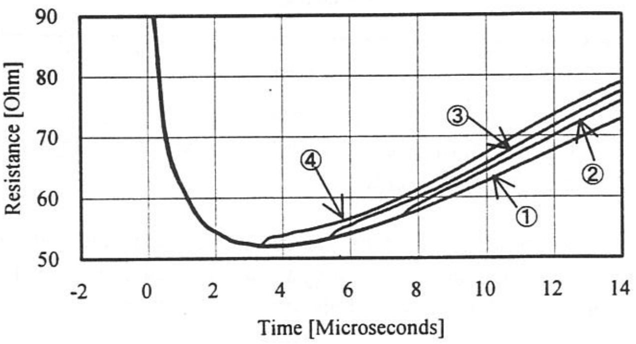


Fig. 7 Calculated results of grounding resistance for various wavetail shape of applied current.

From Figs. 6 and 7, the proposed grounding resistance model shows relatively good accuracy. The differrence between the measured and calculated results is mainly caused by the time dependency of the grounding resistance and possibly by the simplifying assumption of the energy loss, expressed in eq. (9).

V. DISCUSSIONS

A. Comparison of the Proposed Model with Liew and Darveniza's Model

Assuming *vi* and *P* or *vi-P* are constant in each segment, eq. (10) is rewritten as follows:

$$\rho = \rho_0 \exp(-\alpha t) \tag{13}$$

where α : constant.

Eq. (13) is the same as the Liew and Darveniza's model in soil ionization process.

The equation of the Liew and Darveniza's model in deionization process is different from that in ionization one. However, the poroposed model uses a same equation. The Liew and Darveniza's model in soil deionization process is given by:

$$\rho = \rho_i + (\rho_0 - \rho_i)\left(1 - \exp\frac{-t}{\tau_2}\right)\left(1 - \frac{J}{J_C}\right)^2 \tag{14}$$

where τ_2 : deionization time constant, J: current density, J_c: critical current density, ρ_i : resistivity where $J=J_c$ on current decay.

When $J=0$ and $\rho_0 >> \rho_i$, eq. (14) yields:

$$\rho = \rho_0\left(1 - \exp\frac{-t}{\tau_2}\right) \tag{15}$$

The deionization time constant τ_2 in eq. (15) corresponds to the time constant Q_0/P in the proposed model. Thus, the proposed model gives a physical meaning of the Liew and Darveniza's model.

B. Cnstants of Eq. (10)

Figs. 8 and 9 show calculated results of grounding resistance with parameters of the constants Q_0 and ρ_o in eq. (10) respectively, where E_d=300kV/m, P=0 and Δr =1mm illustrated in Fig. 4. Applied current waveform is ramp wave of 2/40 μs. The grounding resistance in these figures is defined as the ratio of the voltage to the applied current at 2 μs.

From Figs. 8 and 9, Q_0 affects the current dependency of the grounding resistance for comparatively low currents, and is important only for large ρ_o

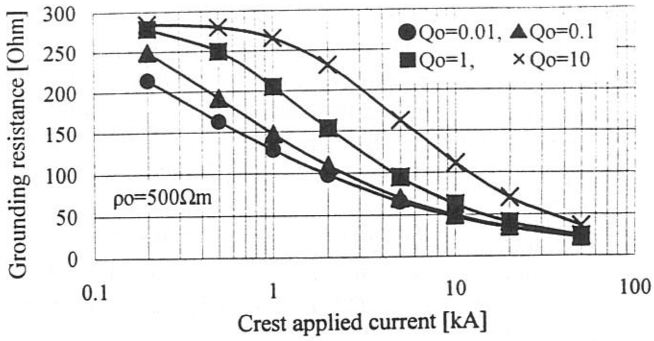


Fig. 8 Calculated results of current dependency of grounding resistance using the proposed method.

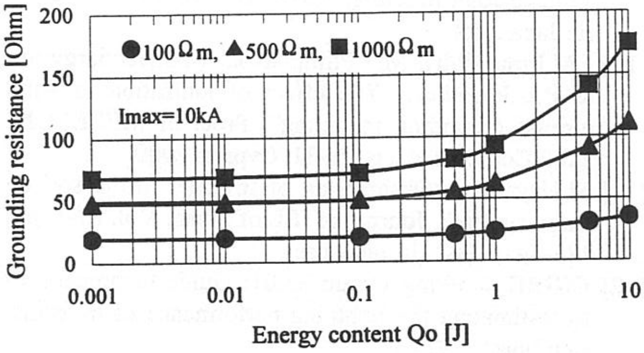


Fig. 9 Effect of parameters of the proposed method on grounding resistance.

VI. CONCLUSIONS

This paper has described an importance of resisitivity of soil ionization zone to simulate current dependency of a grounding resistance based on measured results of the grounding resistance for high impulse currents of about 20kA. Then, the paper has proposed a current-dependent grounding resistance model of a rod electrode considering an energy balance in the ionization zone. The model can treat the influence of an injected current waveform and soil deionization on the resistivity of the ionization zone. The proposed model gives physical meanings of the nonlinear characteristics such as the current dependency or hysteresis effect of the grounding resistance due to the soil ionization. The model has been verified by the comparison with the measured results.

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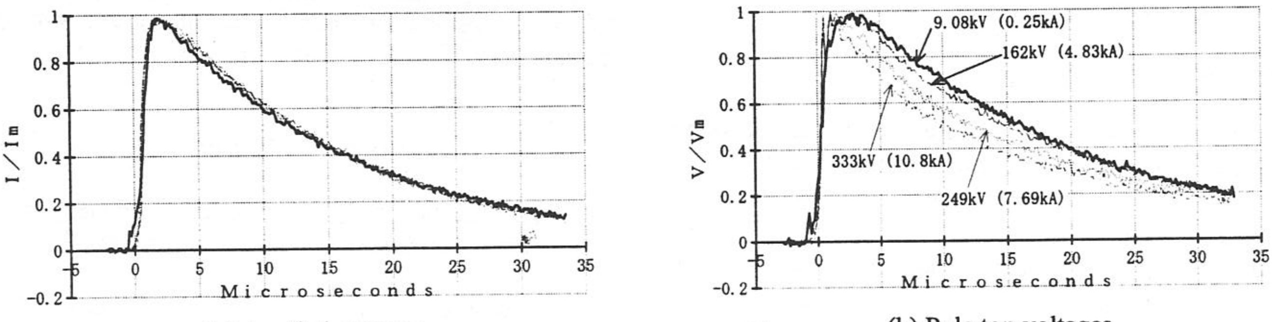
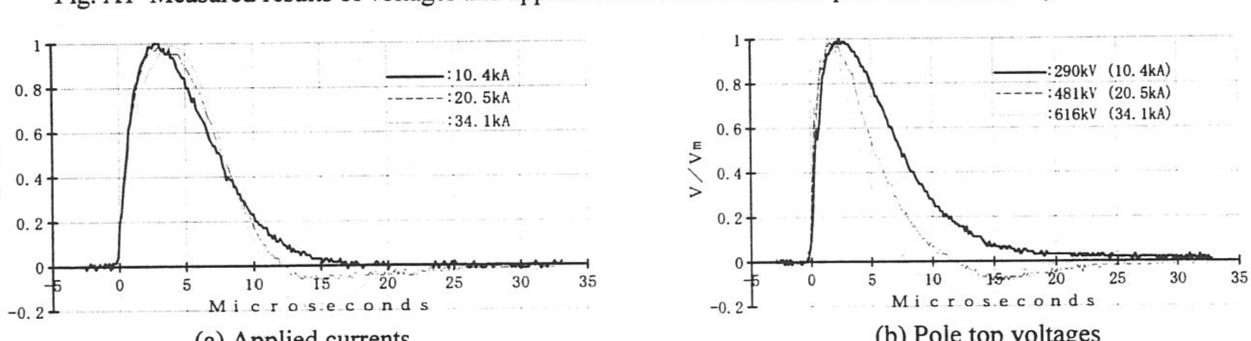
VIII. APPENDIX

Measured Waveforms of Applied Current and Voltage



(a) Applied currents (b) Pole top voltages

Fig. A1 Measured results of voltages and applied currents of a concrete pole in test field I by the LIG circuit.



(a) Applied currents (b) Pole top voltages

Fig. A2 Measured results of voltages and applied currents of a concrete pole in test field I by the HIG circuit.