Development of A Nonlinear Model of A Concrete Pole Grounding Resistance

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ABSTRACT - An energy-dependent concrete pole grounding resistance model to describe the nonlinear surge characteristics has been developed based on experimental results for a high impulse current. The model takes account of current dependency and hysteresis characteristics. Calculated results by the model using the EMTP agree well with the experimental results.

1. INTRODUCTION

A grounding resistance is one of the most important factors for a lightning surge analysis in the power system. It is well-known that the grounding resistance is nonlinear against a high impulse current flowing through the resistance [1-12]. Experimental results for the high impulse current show a hysteresis characteristic of the grounding resistance [6], and the higher the steady-state grounding resistance, more the rate of the surge grounding resistance reduction [4].

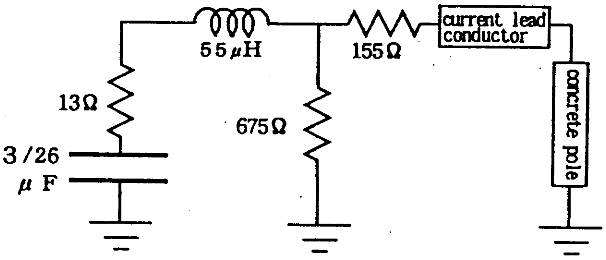
The concrete pole widely used for sustaining a ground wire in power distribution systems in Japan is insulated from the ground wire by a low-tension insulator. However, a direct lightning hits to the ground wire causes flashovers at the low-tension insulators and the ground wire is electrically short-circuited to the concrete pole because the insulation level is very low. Then the lightning current flows into the concrete pole and the grounding resistance [13].

Liew and Darveniza proposed a dynamic model of a concentrated grounding. The model can take account of dimensions of the driven rods, soil resistivity and hysteresis effect. In the model, however, the soil is divided into several segments and is time-dependent. Thus, Liew-Darveniza model becomes too complicated and time consuming for computation [14].

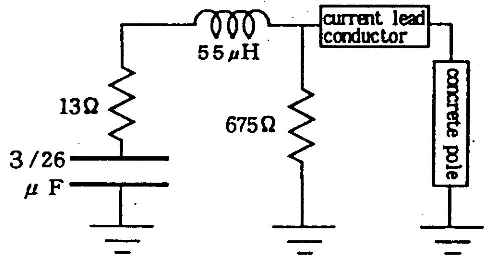
This paper proposes a new model of the grounding resistance based on experimental results of a concrete pole for a high impulse current [10]. The model is determined by a steady-state resistance, an injected current and an energy through the resistance. The proposed model is very useful to simulate a lightning surge calculation. Calculated results by the proposed model using the EMTP are compared with the experimental result.

2. EXPERIMENTAL RESULTS FOR A HIGH IMPULSE CURRENT [10]

Dimensions of a concrete pole for testing are as follows; height above the ground=10m, depth under the ground=2m, diameter at the top=190mm and diameter at the bottom=350mm. An all-weather-type mobile impulse voltage generator (IG), which can generate a several ten kA impulse current [15], was used in order to generate a high impulse current. Fig.1 shows an equivalent circuit of the IG. The soil resistivity around the concrete pole was about 170 Ω m.



(a) Lightning impulse circuit



(b) High impulse current circuit
Fig.1 Equivalent circuit of the IG.

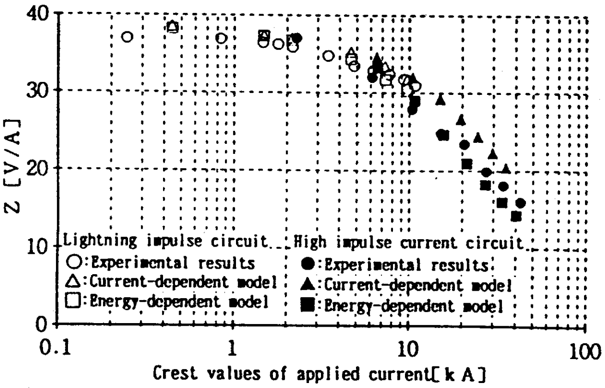
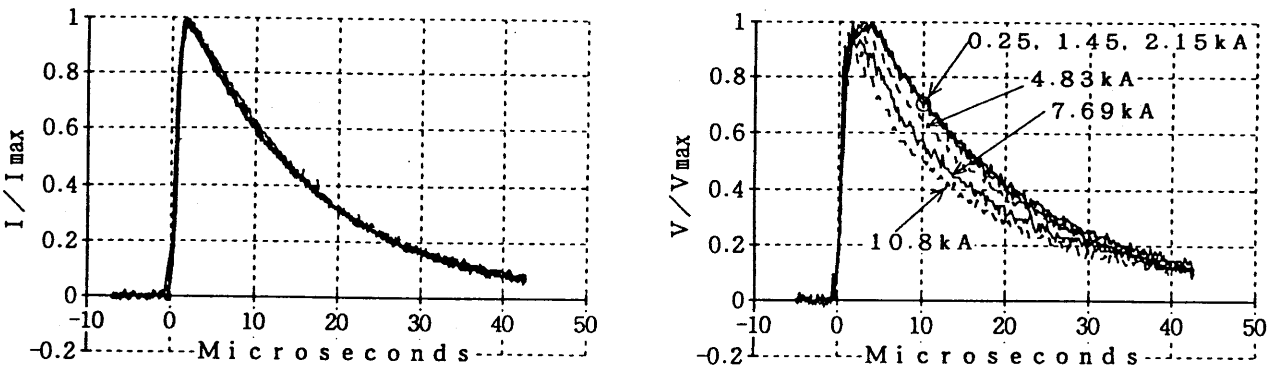
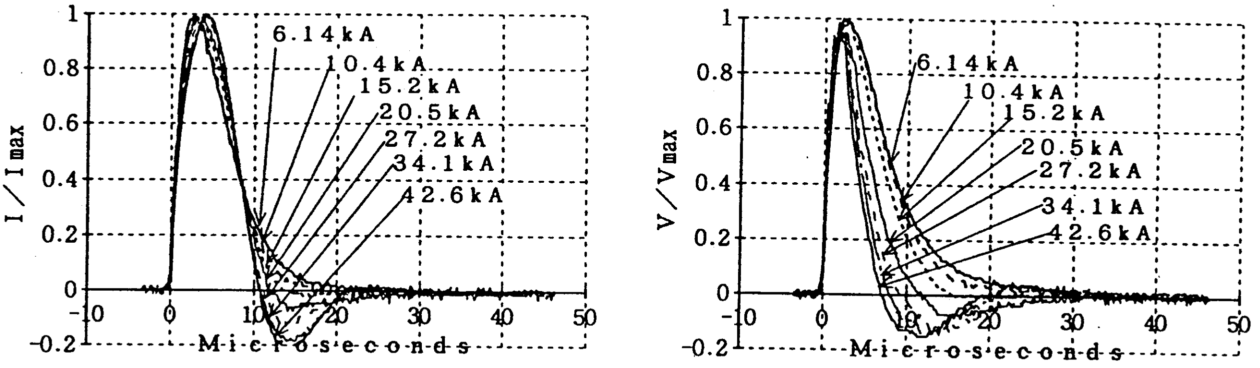


Fig.2 Pole impedance characteristic as a function of the crest current.



(a) Applied currents
(b) Pole top voltages

Fig.3 Experimental results of applied currents and pole top voltages of a concrete pole by a lightning impulse circuit.



(a) Applied currents
(b) Pole top voltages

Fig.4 Experimental results of applied currents and pole top voltages of a concrete pole by a high impulse current circuit.

Fig.2 shows the impedance evaluated by the following equation.

$$Z(I_m)=\frac{\text{maximum pole top voltage }(V_m)}{\text{maximum applied current }(I_m)}\cdots\cdots(1)$$

Figs.3 and 4 show normalized experimental waveforms of applied currents and pole top voltages by the lightning impulse circuit and the high impulse current circuit, respectively.

Fig.2 indicates that the pole impedance is heavily dependent on the crest current over 1kA. The pole top voltages for the wavetail shown in Figs.3 and 4 drop as the crest value of the applied current increases.Because the surge impedance of the concrete pole is relatively lower than that of the grounding resistance,the concrete pole impedance is significantly affected by the grounding resistance [10].

For the output waveform of the high impulse current generator varies with the maximum value of the current,it is difficult to evaluate an impedance of the concrete pole for a high impulse current. Hence, the paper adopts the step response of a pole top voltage to obtain an equivalent impedance depending on time and an applied current to develop a nonlinear grounding resistance model. Fig.5 shows the step response evaluated from the experimental results of the pole top voltage using a numerical Laplace transform method, which is highly efficient because of using the Fast Fourier Transform [16].

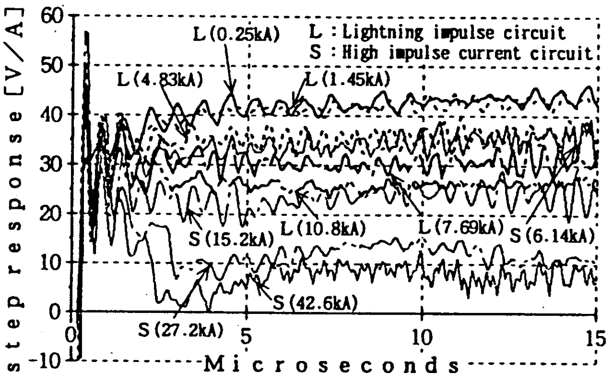


Fig.5 Step response of experimental results of pole top voltage.

Fig.5 shows that the step response for a low current does not depend on the crest value of the applied current, but depends on time (capacitive type). However, the step response for a high current shows a low impedance for the wavetail.

Fig.6 shows the step response against the instantanous current value. The impedance shows a hysteresis characteristic as is clear from Fig.6.

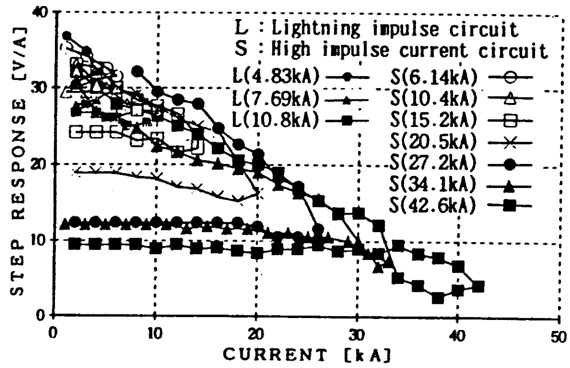


Fig.6 Step response of pole top voltage as a function of instantaneuos current.

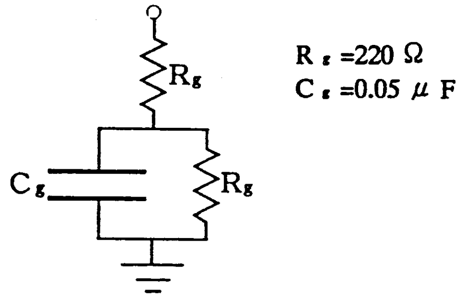


Fig.7 A grounding resistance model of a concrete pole for a low current.

The concrete pole is modelled by a distributed line (surge impedance=200 Ω , velocity= light velocity in free space [10]) and by a capacitive-type grounding impedance illustrated in Fig.7, which is derived from the step response for a low current.

3. CURRENT DEPENDENCY OF GROUNDING RESISTANCE

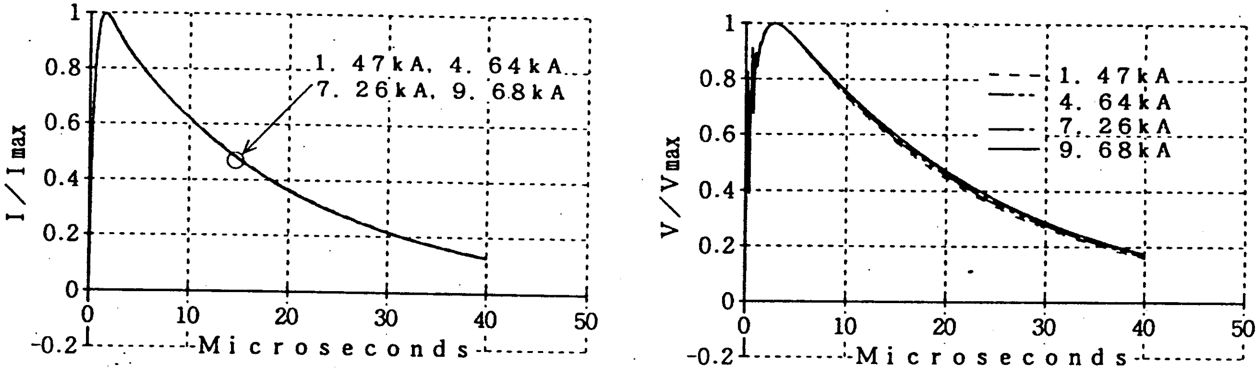
A grounding resistance is current-dependent for a high impulse current. Hoki and Mita [4] proposed the following current-dependent formula.

$$R(i)=\frac{R_0}{1+A(R_0\cdot i)^B} \quad \cdots\cdots\cdots\cdots\cdots\cdots(2)$$

where i:instantaneous injected current [kA], R(i):grounding resistance at i, R_0 :steady-state resistance, A, B:constants

Eq.2 is very convenient to evaluate the reduction effect of a grounding resistance because the reduced resistance is represented by a steady-state grounding resistance and an injected current.

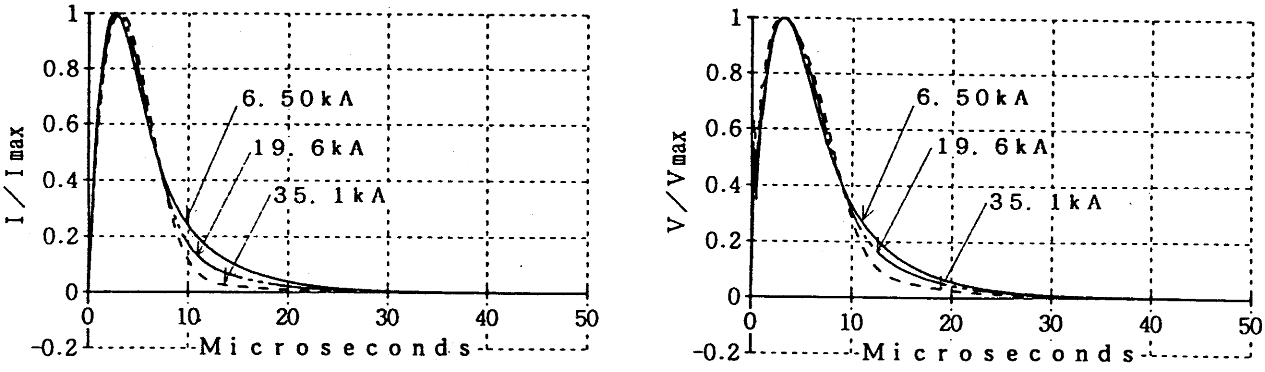
Calculated results of normalized waveforms by the EMTP are shown in Figs.8 and 9 using a current-dependent grounding resistance model, in which R_g of Fig.7 is replaced by a half value of eq.2 (R_0 =44 Ω , A=2.6x10^{-4} and B=1.14 [10]). Evaluation of eq.1 is



(a) Applied currents

(b) Pole top voltages

Fig.8 Calculated results of applied currents and pole top voltages using the current-dependent model for a lightning impulse circuit .



(a) Applied currents

(b) Pole top voltages

Fig.9 Calculated results of applied currents and pole top voltages using the current-dependent model for a high impulse current circuit.

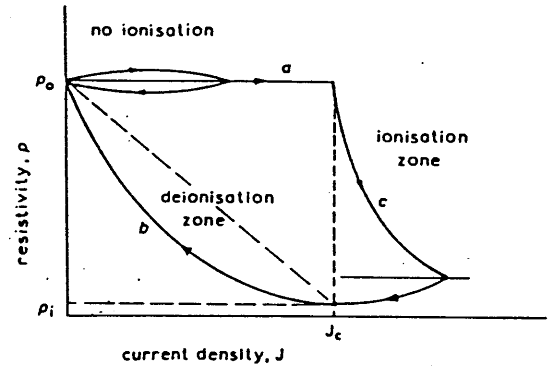
included in Fig.2 with a symbol (△ or ▲).

The calculated results using the current-dependent model agree satisfactorily with the experimental results except for an wavetail. The difference between the calculated results and the experimental results is caused by the fact that the grounding resistance for the wavetail in the calculation is higher than that in the experiment; i.e. a hysteresis characteristic of the grounding resistance is not considered.

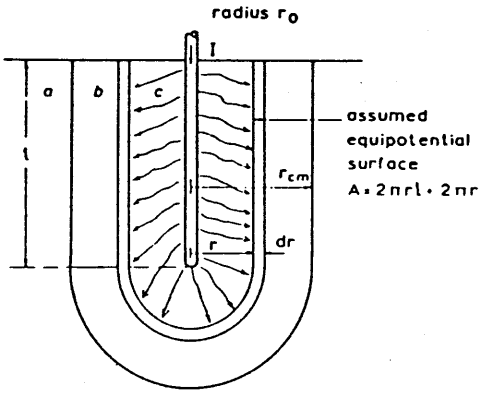
4. ENERGY-DEPENDENT GROUNDING RESISTANCE

It might be sufficient to calculate a lightning surge only using a current-dependent grounding resistance model in many cases. The approach, however, is not sufficient to analyse the surge in the case of a multiple flashover analysis and an enrgy absorption of a metal-oxide arrester because a hysteresis characteristic is not considerd.

Liew and Darveniza proposed a nonlinear grounding resitance model considering the hysteresis characteristic [6]. The model is devided into several segments as illustrated in Fig.10, and calculates decaying or recovering resistivity of the each segment. Hence, the calculation is complicated and requires a large computation time. Thus, it is difficult to calculate a lightning surge efficiently using the model [14].



(a) Resistivity profiles in Liew-Darveniza model



(b) Liew-Darveniza model for a single driven rod

Fig.10 Liew-Darveniza model [6].

Kojima et al. proposed an energy-dependent hysteresis model of a metal-oxide arrester [17]. Both the metal-oxide arrester and the grounding resistance can be modelled by a nonlinear resistance. This paper applies the concept of Kojima's energy-dependent model to a grounding resistance, which is dependent on an injected current and an energy through the grounding resistance in the following equation.

$$R'(i,en)=R(i)f(En) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where En: energy of grounding resistance [J],
R'(i,en): step response of grounding resistance,
R(i): resistance calculated by eq.2, f(En): a function of En, f(0)=1

The energy-dependent model means:

(i) R(i) is determined by ionization of the air in voids within the soil grains [3].

(ii) f(En) is determined by resistivity decrease of the water coating of soil particles due to I^2R heating [18].

This model is mainly determined by R(i) and effect of f(En) appears when a high current is applied or grounding resistance is high. Fig.11 illustrates the change of R'(i,En), R(i) and f(En).

f(En) is determined by a step response of the gronding resistance and eq.2. Fig.12 shows calculated results of 1/f(En).

Finally f(En) of the concrete pole grounding resistance is approximated by the following equation.

$$f(En)=\frac{1}{1+2.5\text{x}10^{-5}\,En} \quad \cdots\cdots\cdots\cdots\cdots (4)$$

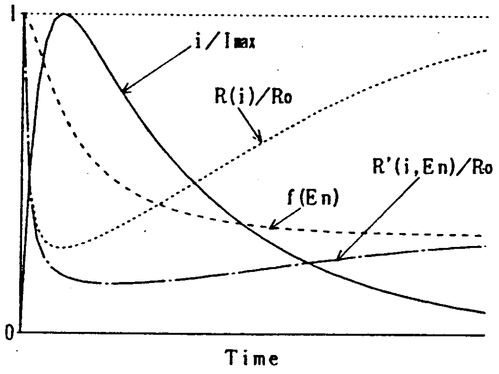


Fig.11 Illustration of energy-dependent model.

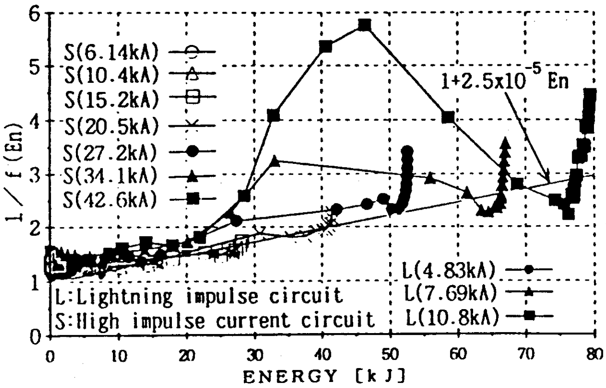
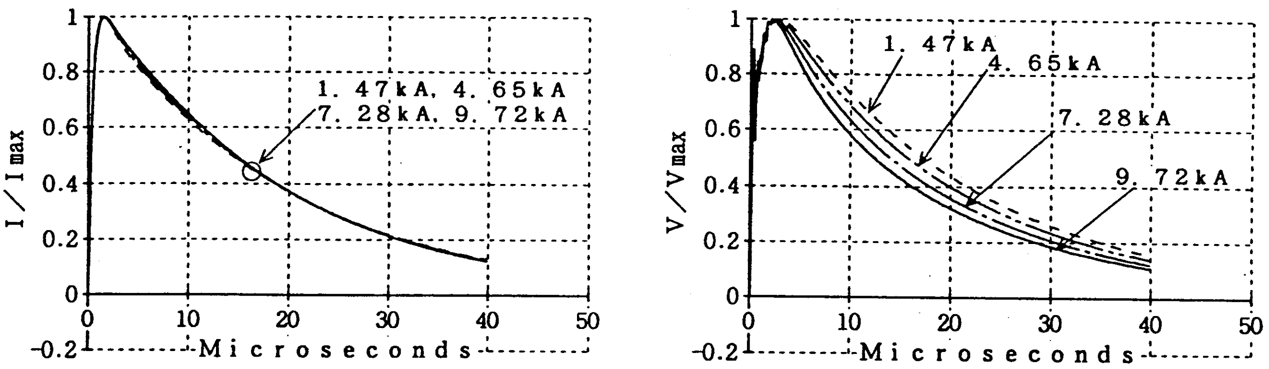


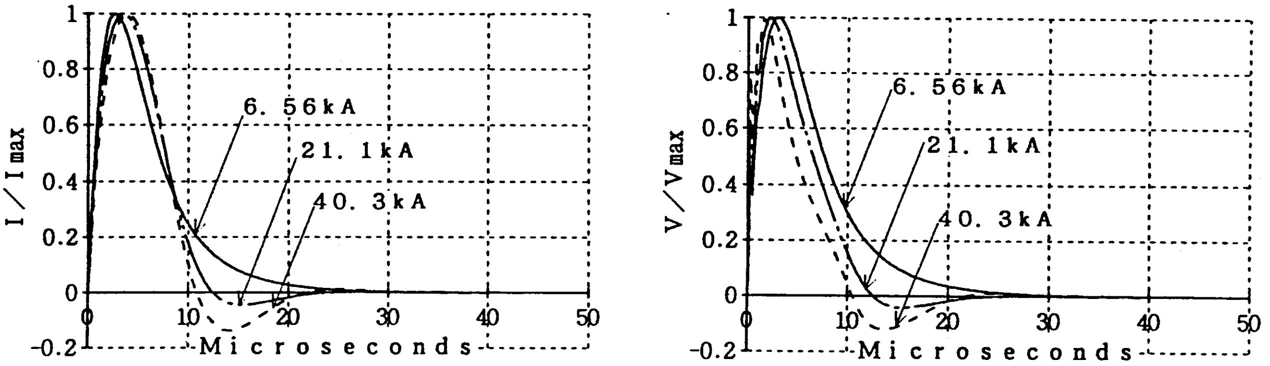
Fig.12 Energy coefficient.



(a) Applied currents

(b) Pole top voltages

Fig.13 Calculated results of applied currents and pole top voltages by the energy-dependent model for a lightning impulse circuit.



(a) Applied currents

(b) Pole top voltages

Fig.14 Calculated results of applied currents and pole top voltages by the energy-dependent model for a high impulse current circuit.

The energy-dependent grounding resistance model can be easily evaluated in the EMTP by means of TACS-controlled nonlinear resistance model.

Calculted results of normalized waveforms by the energy-dependent model using the EMTP are given in Figs.13 and 14, and evaluation of eq.1 is included in Fig.2 with a symbol (☐ or ■). The calculated results agree well with the experimental results. It is clear that the energy-dependent grounding resistance model is highly efficient.

5. CONCLUSIONS

The grounding resistance is dependent on an injected current, and has a hysteresis characteristic.The paper has clarified that a current-dependent grounding resistance model does not have a sufficient accuracy, and has proposed an energy-dependent model of the grounding resistance in order to account for the hysteresis characteristic. The model can be easily realized in the EMTP usingf a TACS-controlled nonlinear resistance model. Calculated results by the proposed model agree well with experimental results.

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