Paper

Sensitivity Analysis on Grounding Models for 500 kV Transmission Lines

Member YASUDA Yoh (Kansai University)
Member HIRAKAWA Yuji (Kansai University)
Non-member SHIRAISHI Koichiro (Kansai University)
Member HARA Takehisa (Kansai University)

In order to calculate lightning surge analysis in power systems, appropriate models and parameters describing the components of systems should be required. Moreover, it is necessary to clarify how much those models would influence result of simulation. In other words, it is important to confirm how much probability of back flashover accidents would occur in changing grounding model or its input parameter. This paper will examine to compare some models for components in transmission tower and will show influence to the back flashover result, especially focusing on grounding impedance model.

Keywords: lightning surge, back flashover, transmission line, grounding impedance (resistance), EMTP/ATP

1. Introduction

How should we evaluate a result of a computer simulation if we could not know an accurate model or parameter for some reasons or other? This is an unwelcome problem but unfortunately it is not a special case in the world of the computer simulation.

In lightning surge analysis, especially as far as the grounding impedance model, we often face such a problem that the model or the parameter might be inaccurate on the present conditions. To give some examples; soil resistively ρ, soil permeability μ, capacitive or inductive element in soil C (or L), critical soil potential gradient E_0, these parameters are unpredictable unless they are measured in practice and, unfortunately in almost cases, it is impossible or very difficult to measure them in advance.

The goal of this study is, thus, the sensitivity analysis to show how the result of a simulation will change when a model or a parameter will be changed. That is, we will examine how the number of failures due to back flashover will be changed when ρ, C, E_0 will be changed in several grounding models.

Modern computed simulations including EMTP/ATP have been developed with the progress of various models of components. As far as a grounding impedance (resistance) model, there are a lot of models describing the behavior of complex and unpredictable time-dependent impedance curve. Some of the models are authorized, accepted, or used widely nowadays. But even such widely-used models do not always agree with practice phenomena under all conditions. And there seems to be some limitations to adopt them to the desired situation in some conditions.

It has been suggested that the decrease in the impedance, which results from soil ionization processes under high-voltage conditions, should be taken into account in order to optimize the accurate results when the lightning performance of lines is analyzed. For example, Liew & Darveniza[1] reported nonlinear behavior of dynamic profile for soil resistively and Mousa[2] and Oettle[3] suggested the recommended value for critical electric field. Moreover, the report by CIGRE's working group [4] recommend a nonlinear curve to describe resistance reduction phenomena because of soil ionization.

The authors focused on the characteristic of grounding impedance and have experimented on that of a practical 500 kV transmission tower footing[5]-[9]. We, furthermore, have investigated on lightning surge analysis on 500 kV transmission line using EMTP/ATP to find that the choice of grounding impedance model may considerably influence to the result of back flashover accidents.

A problem with these models or parameters caused by that it is very difficult to compare with experimental result and confirm the accuracy of models. The reason seems to be that; (i) the mechanism of ionization and discharge phenomena in soil still remains to be unsolved and must await more detailed study; (ii) the soil in practice is not a homogenous medium due to the variation of water content and the variation in grain size, therefore, an ideal model does not always agree with the practical result; (iii) the cost for the experiment using a full-size tower footing on an extensive site would be very expensive; and so on.

There are always some problems to determine such a parameter in calculating lightning surge analysis. For example, electric resistively of soil r in a test site is not homogenous neither on every point nor in every depth and each tower footing in a transmission line does not always have the same resistively. It is therefore almost impossible to use accurate resistively for all of tower to simulate in analysis. In the matter of critical soil ionization gradient E_0, thing goes to worse. Though several investigators have reported on the soil ionization phenomena, there seems to be no collective view and there are several "recommended value" for E_c ranging from 300 to 1,000 kV/m[2]-[4].

Thus, we will make an attempt at analyzing EMTP/ATP simulations using various values of doubtful parameters and exam the influence of back flashover accidents as a result of analysis. In this paper, focusing on an ideal 500 kV transmission line, lightning surge analysis is discussed under various grounding conditions.

2. Grounding Impedance Models

One of the critical parameters in the lightning performance of transmission lines is the impulse impedance of the tower footings. In this chapter we will prepare various grounding impedance (resistance) models to calculate lightning surge analysis in the Chapter 4.

<2.1> Constant resistance model A constant resistance model for a tower is simply given as a lump constant resistance R_0. The value of the resistance is determined by the theoretical formula for a hemisphere electrode;

$$R_0 = \frac{\rho}{2\pi r} \times \frac{1}{n}, \tag{1}$$

where ρ is a resistively of the surrounding soil, r is the radius of the electrode (or equivalent radius of the tower footing), and n is the number of footings per a tower (normally n = 4). The value of r is assumed to be 2.26 m through the present analysis because this size is for typical tower footing for 500 kV transmission lines in Kansai district, Japan[6],[7]. The constant resistance model has been widely used for EMTP/ATP lightning surge analysis and various calculations for lightning protection because of its simplicity and convenience. It is still useful under the condition that neither the lightning amplitude nor the soil resistivity is very high.

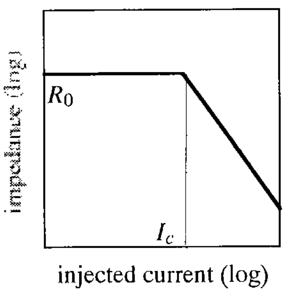

Fig.1 Nonlinear model for grounding impedance

<2.2> Nonlinear impedance model It is generally agreed that the resistance of an earth electrode or a tower footing decreases with the applied current due to ionization of the soil. Several explanations for the phenomena responsible for this resistance decrease with current have already been given in Ref.[2]-[4]. The authors also proposed the appropriate model after the experimental result using a 500 kV tower footing, that is,

$$R = \begin{cases} R_0 & (I < I_c) \\ \dfrac{R_0}{\sqrt{\dfrac{I}{I_c}}} & (I \geq I_c) \end{cases}, \tag{2}$$

where I_c is a critical current for soil ionization[5]. Figure 1 illustrates the characteristic curve of Eq.(2). Although Eq.(2) is very similar to the CIGRE's model, we employ above model for the better agreement with the experimental result.

The critical current I_c depends upon an ionization gradient of the soil E_c, which is a particular constant for the surrounding soil and very important value whether soil breakdown would occur or not. The relationship between both values is given as

$$E_c = \frac{\rho I_c}{2\pi r^2 n}. \tag{3}$$

Several researchers conducted various tests and some of them used their results to estimate the related soil ionization gradient[2]-[4]. As the result, there are several "recommended" values for E_c ranging from 300 to 1,000 kV/m.

It is easily understood that the result of lightning surge analysis would be significantly influenced by this value. Moreover, it is difficult to confirm the "recommended" assumption comparing simulation results and experimental results for each desired case one by one. Thus, in this paper, we will make the sensitivity analysis of the ionization gradient E_c in the grounding impedance model. In other words, we will exam how the back flashover accident would be influenced by the value of E_c.

<2.3> Capacitive impedance model Several reports including our previous experimental result[5],[8] indicate that capacitive characteristics are often measured in the grounding impedance on high-resistivity soil. Figure 2(a) shows commonly-used grounding model with capacitive component. The existence and the value of the capacitive element would have a significant influence on the back flashover accidents due to lag of

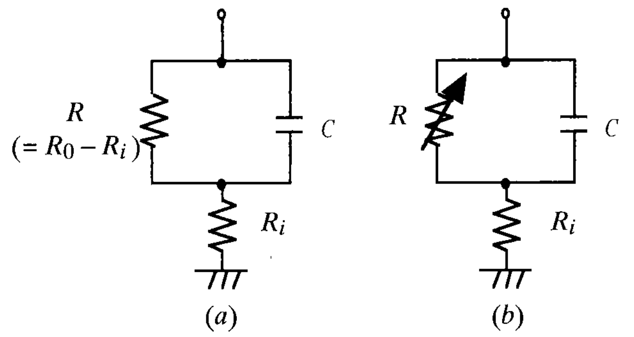

Fig.2 Capacitive impedance model(a) and Combined model(b)

the current crest. There is no doubt that it is not easy to know the correct capacitance before simulations unless that of each tower footing was measured respectively. In the Chapter 4, we will calculate the lightning surge analysis changing the capacitance ranging from 10^{-12} to 10^{-3} F.

Moreover, there is another uncertain parameter in this model. That is the ratio R_i and R, where R_i is an initial resistance and R is given as R_0 minus R_i. The initial resistance measured in capacitive transient since a time-dependent impedance curve sometimes starts at a certain value in spite of zero impedance. We also measured such a phenomena in our previous experiment[8], where the ratio of R_i to R_0 was 0.75. This is also unpredictable parameter without practical measurements in advance.

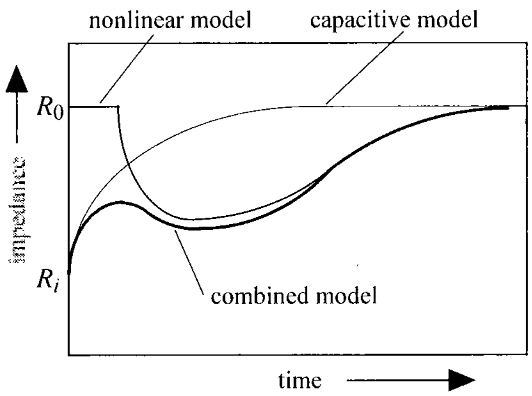

Fig.3 Conceptual illustration of various grounding models

Table 1 Examining models and parameters

	changing parameter	examining range	measured value [6]	result of analysis
Constant Model				§4.1
Nonlinear Model	E_0 [kV/m]	300 - 1000	600	
	ρ [Ωm]	2000, 4000		§4.2
	I_{max} [kA]	150, 200		
Capacitive Model	C [F]	10^{-12} - 10^{-3}	320×10^{-9}	§4.3
	R_i / R_0	0.75, 0.5	0.75	
Combined Model	combination of above			§4.4

<2.4> Combined model This model is the combined model with the nonlinear impedance model and the capacitive impedance model as shown in Fig.2(b). In this model, the grounding impedance has the characteristic curve with slow starter transient and temporary reduction. In fact, we obtained this type in experimental result[7]. It is important to exam which element and how does it affect the back flashover phenomena.

A conceptual illustration drawing transient curves of above models is shown in Fig.3. A brief summary of this chapter is also shown in Table 1.

3. Other Components for EMTP/ATP Analysis

In this chapter we will introduce the common components for the sensitivity analysis in Chapter 4.

<3.1> Tower model One of the authors has investigated on modeling to describe a typical 500 kV transmission tower with 82 m height in Japan and proposed the equivalent impedance model[10]. This model includes three elements, main legs Z_T, branching Z_L, and cross arms Z_A, each of whose surge impedance is given in Ref[10]. It was already found that the shapes of calculated voltage waveforms with the model closely fit

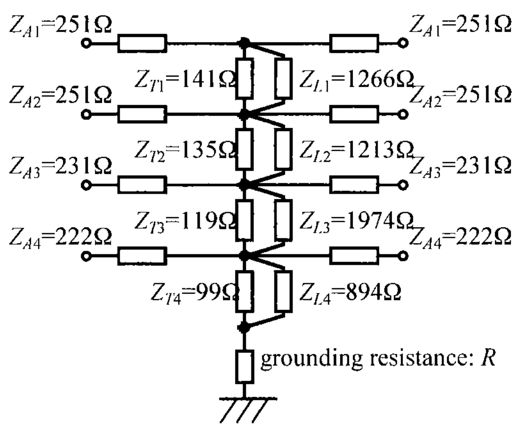

Fig.4 Equivalent impedance model of the standard 500kV-transmission tower. [10]

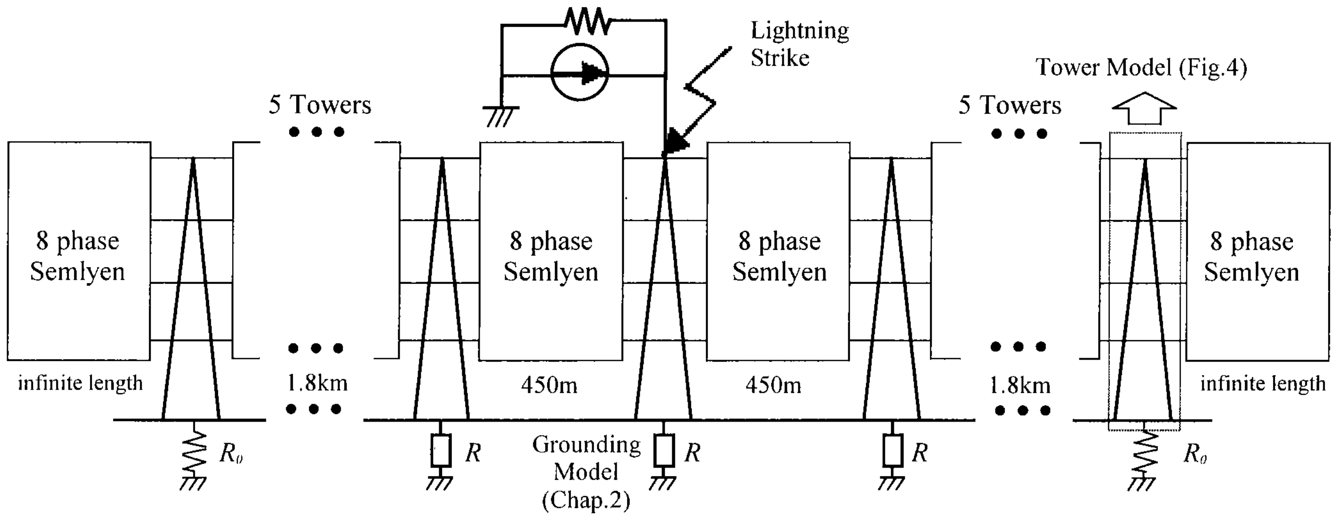

Fig.5 Schematic diagram of a standard transmission line system with 11 towers.

those from an actual experiment[10]. Thus, in this paper, we employ this model in common for the comparison of various grounding models.

<3.2> Flashover model Back flashover phenomena at an arcing horn are regarded as one of the most important parameter on the lightning surge analysis. Many investigators, for example Shindo *et al.*[11], Ueda *et al.*[12], and Motoyama[13], have researched on the flashover phenomena to develop an accurate model for lightning surge analysis. Among the several pioneer's models, we will adopt the Ueda's model from the viewpoint of its simplicity in adopting to EMTP/ATP simulation. The length of the arcing horn for the present analysis is assumed as 3.8 m.

<3.3> Line model and other elements We prepare here an ideal 500 kV transmission line system for the present analysis. The line-system model has eleven towers placed on the level, in a straight line and at even interval of 450 m. Each of towers is assumed as the standard impedance model given in §3.1 and grounding model. The grounding impedance models described in §2.1 - §2.4 are adopted to the middle three towers, that is, the tower struck by the lightning and the neighboring towers. For the detail condition of the line system, see Ref.[8] and [9].

In the following chapters, the lightning assumed to hit the cross arms' edge holding overhead grounding wire on the middle tower. The lightning is simulated by a current source with a 1/70 μs ramp wave and a lightning path impedance of 400 Ω. The maximum value of the injected current I_{max} is assumed as 150 and 200 kA as shown in Table 1.

A Semlyen's model for eight phases was adopted here to simulate traveling waves on the transmission lines. In this model, we assumed the length of the lines beyond the fifth tower be enough long to neglect reflex wave from open terminals at infinity. The calculation was performed using ATP for Windows98 on an IBM compatible machine.

4. Sensitivity Analysis on Grounding Models

This chapter provides sensitivity analyses on the various grounding models and parameters previously discussed in Chapter 2.

Table 2 An example of a situation of back flashover accident
(with constant model, I_{max} = 200 kA, ρ = 2000 Ωm)

base angle on 1A	Line #1			Line #2		
	Upper (A)	Middle (C)	Lower (B)	Upper (B)	Middle (C)	Lower (A)
0			✓	✓		
30			✓	✓		
60		✓	✓	✓	✓	
90		✓	✓	✓	✓	
120		✓	✓	✓	✓	
150		✓			✓	
180		✓			✓	
210	✓	✓			✓	✓
240	✓	✓			✓	✓
270	✓					✓
300	✓		✓	✓		✓
330	✓		✓	✓		✓

" ✓ " denotes a failed phase due to back flashover

To begin with, we present our methodology for back flashover analysis. We here propose a terminology *expectation of failed phases due to back flashover* to evaluate the situation of back flashover accident. The expectation is defined as the average number of failed phases in case of lightning strike on all electric angles. Table 2 shows an example of the result of EMTP/ATP surge analyses. This table has twelve raw, each of which corresponds each analysis under the condition of electric angle of upper phase (phase A) on line #1 on the moment of lightning strike. The symbol " ✔ " in the table denotes an arcing horn failure caused by back flashover at the corresponding phase on the corresponding angle. Because the geometric distance between the point of lightning current injection and an arcing horn on each phase, there is some difference in combination of failed phase each other. Thus, this table clarifies the situation of back flashover accident. Summing the number of ✔ and dividing by twelve, the *expectation of failed phases due to back flashover* is obtained. In the case of the example shown in Table 2, the expectation of failed phases is calculated as 58 % at a lightning strike.

In the following sections, the expectation of failed phases is mainly discussed to evaluate each model and parameter. Tables 3 and 4 indicate parameter settings concerning initial conditions for the analyses through this chapter.

<4.1> Comparison between constant model and nonlinear model Adopting the nonlinear grounding model (where E_0 = 600 kV/m) in spite of the constant resistance model, the result of EMTP/ATP analysis shows that the total number of failed phase by back flashover was reduced. This is because the impedance-decreasing characteristic caused the reduction of voltage on the arcing horn in each phase. Figure 4, the comparison between two models, expresses that there is evident difference of expectation of failed phases. It indicates that the conventional constant model might estimate failed phase too much.

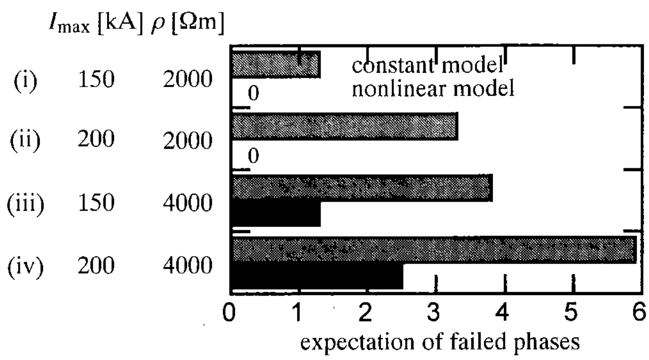

Fig.6 Comparison between constant model and nonlinear model (E_0 = 600 kV/m)

Table 3 Parameter settings for Figs.6-11

	I_{max} [kA]	ρ [Ωm]	R_0 [Ω]	R_i [Ω]	R_0/R_i
(i)	150	2000	35.2	26.4	0.75
(ii)	200				
(ii')				17.6	0.5
(iii)	150	4000	70.4	52.8	0.75
(iv)	200				
(iv')				35.2	0.5

Table 4 Parameter settings for Fig.7

E_c [kV/m]	300	600	1000
I_c [kA] (ρ = 2000 Ωm)	19.26	38.51	64.18
I_c [kA] (ρ = 4000 Ωm)	9.63	19.26	32.09

<4.2> Examination of parameter E_0 at nonlinear model As mentioned in §2.2, the critical soil ionization gradient E_0 is assumed (or measured in practice) as various value. Then, it is important to examine a sensitivity analysis. In this section, we show EMTP/ATP analyses under the condition of various E_0 ranging from 300 to 1000 kV/m. The result is shown in Fig.7. The smaller E_0 causes the higher effect of the decrease of impedance and therefore results in the lower expectation of failed phases. Noteworthy is that there is no flashover failure in any case of E_0 = 300 kV/m. As

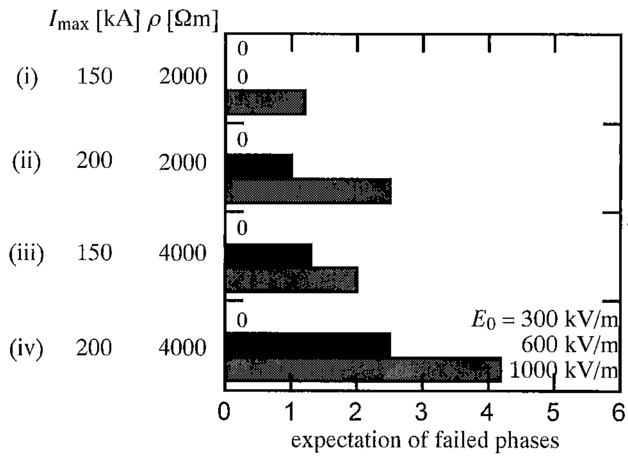

Fig.7 Comparison among various value of E_0 in the nonlinear model

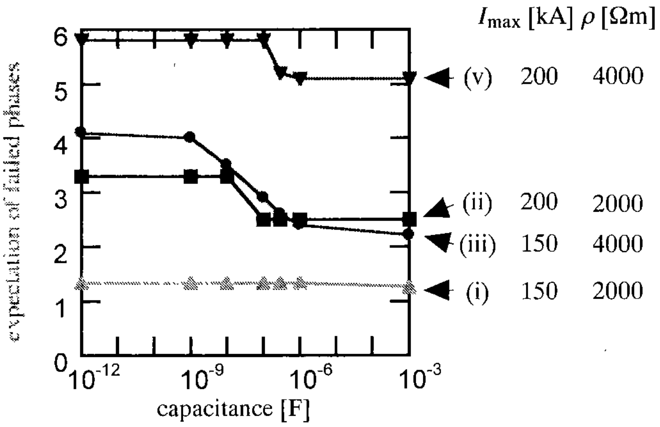

Fig.8 Comparison upon parameter C ($R_i/R_0 = 0.75$)

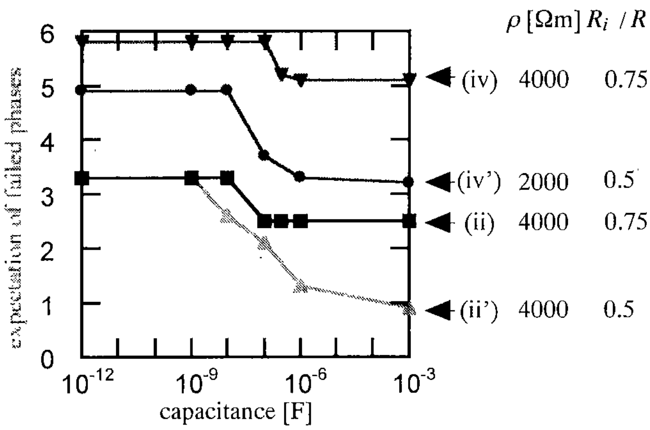

Fig.10 Comparison upon parameter R_i/R_0 (I_{max} = 200 kA)

the result, the assumption reported in Ref.[2] seems to be too low and unrealistic from the viewpoint of back flashover analysis.

<4.3> Comparison of several parameters in capacitive model This section focuses or capacitive impedance model for grounding of tower footing. It has not been clarified why and how the soil has capacitive element satisfactorily. Then, we examine various cases of C and R_i to know how influence would occur in advance.

First, the sensitivity analysis under the condition of C ranging form 10^{-12} to 10^{-3} F is examined. Figure 6 expresses the result of EMTP/ATP analysis that indicates the relationship between the value of capacitive element and expectation of failed phases. This graph says the influence due to capacitance clearly occurs on the condition of C of over 100 nF in each case.

The decrease of the expectation of failed phases is thought to concern with the relationship between the wavefront of injected lightning current and the time constant RC in the circuit in Fig.2. A conceptual illustration in Fig.9 shows more detail explanation. Among three impedance curves, a rise of the upper curve ($C = 1 \times 10^{-8}$ F) is too steep to affect the value of grounding impedance at the moment of the maximum lightning current. On the other hand, a gentle rise of the lowest curve ($C = 1 \times 10^{-6}$ F) may cause significant decrease of grounding impedance and, furthermore, may have a serious influence upon the number of back flashover failure.

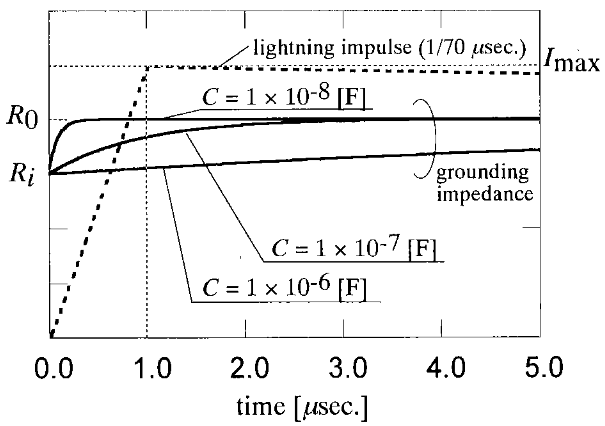

Fig.9 Comparison of grounding impedance curves with various values of capacitance (ρ = 2000 Ωm, $R_i/R_0 = 0.75$)

Such a comparison of parameters thus made it clear the influence of capacitance. For examples, you had better adopt the capacitive impedance model if the soil is expected to have enough capacitance, while you may not use it if the soil has less capacitance than several nF.

The second problem concerning the capacitive grounding model is the existence of initial resistance R_i as shown in Fig 3. Thought it is confirmed that the ratio R_i / R_0 is approximately 0.75 in our previous measurement[6],[8], there is no guarantee that the ratio will be accurate in any soil. Accordingly, we examine the analyses changing the value of the ratio as shown in Fig.10. The figure gives us the information that the initial resistance R_i makes huge influences to the back flashover accident. It suggests that more research and practical measurement on grounding is necessary to establish the universal model.

<4.4> Effect of adopting of combined model Summarizing this chapter, we here adopt the combined model with nonlinear and capacitive impedance models. As shown in the followed sections, it is clear that both nonlinear and capacitive model have an effect upon the expectation of failed phases, that is, the situation of back flashover accident. In this section, we exam which

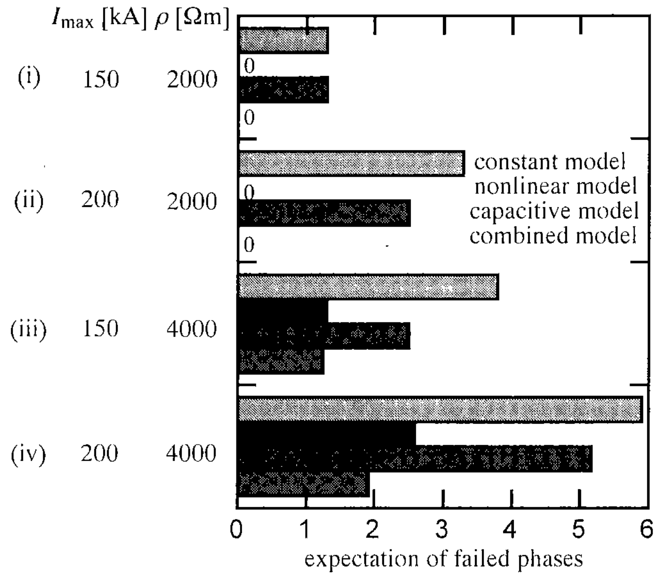

Fig.11 Comparison among various models for grounding impedance (E_0 = 600 kV/m, C = 320 nF, R_i/R_0 = 0.75)

model, nonlinear or capacitive, makes more influence on the expectation of failure.

The result of EMTP/ATP analysis using each models are arranged in Fig.11. In the present analysis, we tentatively choose the value of 320 nF for C and 600 kV/m for E_0 according to the experimental result. It is easy to understand that capacitive model in this case has less influence from the previous discussions. In this way, in analyzing lightning surge, we must carefully choose grounding model and parameters according to simulating situation and circumstance.

5. Conclusion

Lightning surge analysis of power electric systems requires special attention to the grounding conditions with the knowledge of the properties of grounding models and surrounding soil. Unfortunately, it seems that the universal agreement on the soil ionization mechanism has not established yet. For this reason, the authors examined the sensitivity analysis on the various grounding model.

The authors, in this paper, made it clarify that how much influence would be expected according to the choice of a model and a parameter. Various analyses were tested changing the grounding models including the constant model, the nonlinear model, the capacitive model and the combined model. The result of the sensitivity analysis shows that there is accurate methodology to employ the grounding model according to the desired conditions. For example;

- The nonlinear model is more accurate than the constant one especially under the condition of higher resistively and injected current.
- The capacitive model gives less influence to back flashover analysis unless the value of capacitance is higher than several microfarads.

Also, the analysis result says that some parameters in those models are very sensitive and give much effect to the back flashover analysis;

- The critical soil ionization gradient E_0 is very important parameter. It gives significant influence to the result of the back flashover analysis.
- The initial resistant in the capacitive model is sensitive and gives much influence to the back flashover analysis.
- The major influence, whether nonlinear element or capacitive one, in the combined model depends upon the condition of parameters, especially upon the value of the capacitive element.

These results suggest us that we had better employ accurate model and parameters according to the actual circumstance of the tower that we are going to examine. This paper will, it is hoped, contribute to the methodology of reasonable design of lightning protection.

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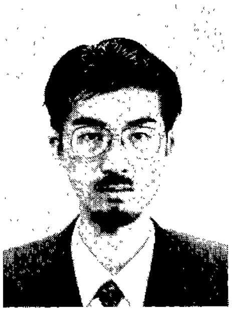
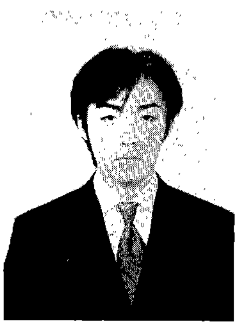


YASUDA Yoh (*member*) was born in Tokyo, Japan, on February 15, 1967. He graduated from the Department of Electronics and Information Engineering, Yokohama National University in 1989. He received the Dr. of Eng. degree from Yokohama National University in 1994. Since 1994 he has been with the Department of Electrical Engineering, Kansai University, where he is presently a lecturer in the department. His current research interests are development of micro wind turbine as well as analysis on cable and overhead line. He is a member of The Institute of Electronics, Information and Communication Engineers, Japan, Japan Society for Simulation Technology, Japan Solar Energy Society, and Japan Wind Energy Association.



HIRAKAWA Yuji (*member*) was born on May 10, 1974. He graduated from the Department of Electrical Engineering, Kansai University in 1998 and received his Ms.E degree from Kansai University in 2000. His main subject of research is lightning surge analysis using EMTP. He is presently join the Chugoku Electric Power Co., Inc., Japan.

SHIRAISHI Koichiro (*non-member*) was born on October 14, 1977. He graduated from the Department of Electrical Engineering, Kansai University in 2000 and currently studying in the Graduate School of Kansai University. His main subject of research is lightning surge analysis using EMTP.

HARA Takehisa (*member*) was born on February 18, 1943. He received his Ph.D. degree from Kyoto University in 1970. He joined as a research associate and an associate professor at the Department of Electrical Engineering, Kyoto University in 1970 and 1975, respectively. Since 1997, he has been with the Department of Electrical Engineering, Kansai University as a professor. His research fields include various simulations and analyses of lightning protection, isolation, discharge, electromagnetic analysis with FEM, application of neural networks and so on. He was awarded Excellent Paper Awards from IEEJ in 1974 and from Japan society for Simulation Technology in 1993, respectively. He is a member of Japan Society for Simulation Technology, Institution of Energy and Resource, Japan Society for Air Electrical Engineering and Discharge Research Group, Japan.