Effective Length of Long Grounding Conductor in Windfarm

S. Sekioka, T. Funabashi

Abstract—Windfarms need low steady-state grounding resistance. A horizontal long grounding electrode is often used to obtain the low grounding resistance. The long grounding conductor has an effective length for lightning currents. The authors propose analytical formulas of sending-end voltage of the conductor in time domain using the lattice diagram method. This paper discusses the effective length of the grounding systems of the windfarms using the proposed formulas.

Keywords: Grounding electrode, Windfarm, Lightning, Effective length, Surge characteristic.

I. INTRODUCTION

Lightning performance of a large grounding system such as a windfarm and a transmission line must be considered for lightning protection design. Horizontal long grounding conductors are often used to obtain low grounding resistance [1]. The conductor length is determined so that its steady-state grounding resistance is lower than a standard value. Surge propagation characteristics of the long grounding conductor are quite different from those of the overhead conductor due to the existence of shunt conductance, and it is difficult to represent the surge characteristics in time domain. The author derived an analytical formula of both-ends voltages on the long grounding conductor in time domain based on a lattice diagram method [2, 3]. The formula makes clear physical meanings of the surge characteristics of the grounding conductor, and gives an effective length in time domain.

Windfarms are recently spread all over the world as a clean and new energy from an environmental problem of view. The long grounding conductor is frequently used to meet the IEC standard [4]. The grounding system consists of a tower base and such auxiliary electrodes as a ring type and a counterpoise. The grounding electrodes of the tower in the windfarm are sometimes connected each other to obtain the much low steady-state grounding resistance using the long horizontal grounding conductors [5]. The voltages on the grounding conductor are attenuated along the conductor. Lightning current has short wavefront duration [6], and peak voltage often appears before reflection voltage from the receiving end reaches. Therefore, effective length, which is defined as the length above which no further reduction of impedance of a grounding conductor is observed, should be investigated to prevent from lightning-caused damages in wind turbines.

This paper derives analytical formulas of voltage at lightning striking point with special reference to grounding systems of a windfarm. Then, influence of some parameters such as soil resistivity and terminal impedance on the effective length of the grounding system is discussed using the analytical formulas. The estimation results are useful for the lightning protection design of the windfarm.

II. APPROXIMATE FORMULA OF TERMINAL VOLTAGES ON GROUNDING CONDUCTOR

A. Lattice Diagram Method to Derive Approximate Formulas of Long Grounding Conductor

The lattice diagram method [7] is applicable to a non-uniform line such as a tapered line [8] and a nonparallel line [9]. Sending-end voltage on the nonuniform line is given by the sum of applied voltage and the voltages reflected on the line due to the discontinuity of impedance. A horizontal grounding conductor is a uniform line. Surge impedance of the horizontal grounding conductor is independent of location, but the shunt conductance is distributed along the conductor. Consequently, the voltages reflected at each node of the segment of the grounding conductor appear. The same manner of the nonuniform line is applicable to the horizontal long grounding conductor.

Fig. 1 illustrates a part of an equivalent circuit of the long grounding conductor [2]. *A* and *B* are refraction and reflection coefficients from segment *k* to *k*+1, and *A'* is refraction coefficient from *k*+1 to *k*.

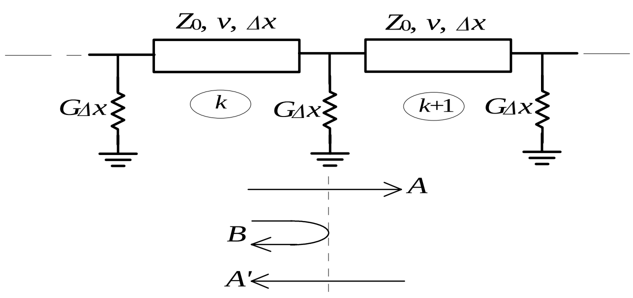

Fig. 1. An equivalent circuit of a long grounding conductor.

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Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

Fig. 2 illustrates a lattice diagram along a long grounding conductor, where Q is reflection coefficient at the sending end. Symbol Q is used to denote the variable easily in the lattice. Considering the reflection voltages within length x, where x is the distance from the sending end, the number of segments n is given by

$$n = \frac{x}{\Delta x}. \tag{1}$$

The coefficients A, B, and A' can be written as follows:

$$A = \frac{1}{1+\theta\Delta x},\quad B = \frac{-\theta\Delta x}{1+\theta\Delta x},\quad A=A' \text{ and } \theta = \frac{1}{2}Z_0 G. \tag{2}$$

where $R=(G\Delta x)^{-1}$, G: shunt conductance per length of the grounding conductor, Z_0: surge impedance of the loss-less line in the equivalent circuit, v: surge velocity on the conductor, Δx: elementary length of the segment.

Steady-state grounding resistance Rs of the grounding conductor is given by

$$R_s = \frac{R}{l}. \tag{3}$$

where l: conductor length.

Voltages on the grounding conductor can be approximated using the coefficients A and B by the sum of reflection voltages on the conductor and at the terminals as illustrated in Fig. 2.

First-order B component gives sufficient accuracy for rough estimation of the voltages on the grounding conductor [3]. Higher order B component gives higher accuracy, but shows complicated expression. Thus, this paper concerns only 0^{th}- and 1^{st}- order B components.

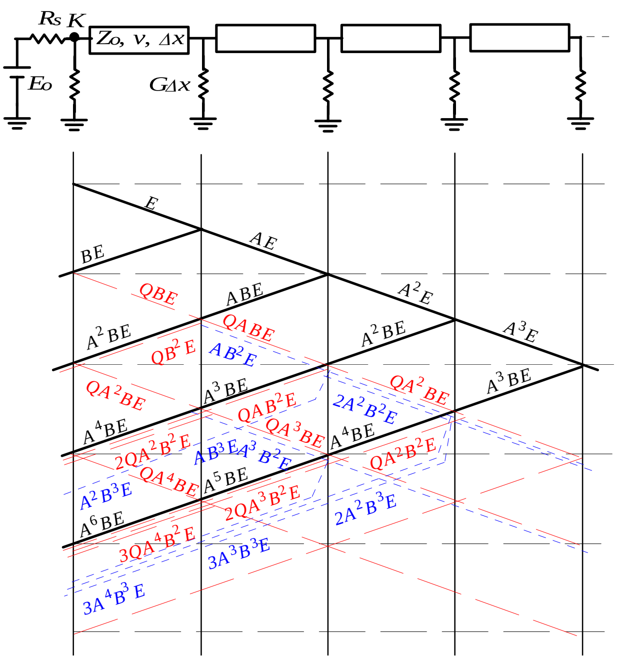


Fig. 2. A lattice diagram along a long grounding conductor.

B. Sending-End Voltage

Voltage V_{s1}^{1} reflected once on the grounding conductor is observed at the sending end of the conductor, and is given by (see Appendix)

$$V_{s1}^{1} = \lim_{\Delta x\to 0} EB\sum_{i=1}^{n} A^{2(i-1)} = -E\frac{1}{2}\left(1-e^{-2\theta x}\right) \tag{4}$$

where E: original sending-end voltage with step waveform, $x = \frac{1}{2}vt$.

The original sending-end voltage E of the circuit in Fig. 2 is given by

$$E = \frac{Z_0}{Z_0 + R_s}E_0. \tag{5}$$

The sending-end voltage, till an influence of the receiving-end circuit appears, is calculated by the following relation.

$$V = E + P_s V_{s1}^{1} \tag{6}$$

where P_s: refraction coefficient seen from the conductor to the source voltage

The voltage, which is reflected at the receiving end, produces some traveling voltages. The sending-end voltage for $2T<t<4T$, where T is traveling time of the grounding conductor, is given by the voltages reflected at the receiving end plus the reflected voltages at $t=2T$ [8].

1) 0^{th}-order B component

The reflection voltage V'^{1}_{s0}, which is not reflected on the conductor, is given by

$$V'^{1}_{s0} = \lim_{\Delta x\to 0} EQ_r A^{2N} = EQ_r e^{-2\theta l} \tag{7}$$

where Q_r: reflection coefficient at the receiving end, $N=l/\Delta x$.

2) 1^{st}-order B component

The voltage V'^{1}_{s1}, which is reflected twice at the receiving end, is given by

$$V'^{1}_{s1} = \lim_{\Delta x\to 0} EQ_r^{2} A^{2N} B\sum_{i=1}^{n} A^{2(i-1)} = -EQ_r^{2} e^{-2\theta l}\frac{1}{2}\left(1-e^{-2\theta x'}\right) \tag{8}$$

where $x' = \frac{1}{2}vt - l$.

The voltage V'^{1}_{s2}, which is reflected once at the receiving and sending ends one each, is given by

$$V'^{1}_{s2} = \lim_{\Delta x\to 0} EQ_sQ_r A^{2N} B\sum_{i=1}^{n} A^{2(i-1)} = -EQ_sQ_r e^{-2\theta l}\frac{1}{2}\left(1-e^{-2\theta x}\right). \tag{9}$$

The sending-end voltage for $2T<t<4T$ is given by

$$V = E + P_s\left([V_{s1}^{1}]_{x=l} + V'^{1}_{s0} + V'^{1}_{s1} + 2V'^{1}_{s2}\right). \tag{10}$$

C. *Receiving-End Voltage*

Formulas of the receiving-end voltage are derived by the same manner as the sending-end voltage. Table I shows the formulas. The receiving-end voltage is expressed by

1) $T<t<3T$

$$V = P_r\left(V_{r1}^{\ 0} + \sum_{i=1}^{2} k_i V_{ri}^{\ 1}\right) \qquad (17)$$

2) $3T<t<5T$

$$V = P_r\left[\left(V_{r1}^{\ 0} + \sum_{i=1}^{2} k_i V_{ri}^{\ 1}\right)_{x''=l} + V'^{\ 0}_{r1} + \sum_{i=1}^{2} k_{i1} V'^{\ 1}_{ri}\right] \qquad (18)$$

where $x'' = \frac{1}{2}vt - \frac{1}{2}l$, $x''' = \frac{1}{2}vt - \frac{3}{2}l$, P_r: refraction coefficient at receiving end, Q_s: reflection coefficient at sending end.

D. *Formula for Source Voltage with Double Exponential Waveform*

The voltage source to derive the approximate formulas of the terminal voltages on the grounding conductor is assumed to have step waveform. Actual lightning current, however, shows a variety of waveforms [9]. Lightning impulse voltage for testing power apparatuses shows double exponential wave-form, which is expressed by $e^{-\alpha t}$- $e^{-\beta t}$. The double-exponential waveform is convenient to estimate lightning overvoltages. The approximate formulas for a voltage source with the double exponential waveform can be derived using Laplace transform technique. The step response 1-e^{-kt}, where $k=\theta v$, in (4) and (8) can be converted to the response for the double exponential waveform, and is expressed by

$$e^{-\alpha t} - e^{-\beta t} - \frac{\alpha}{k-\alpha}\left(e^{-kt} - e^{-\alpha t}\right) + \frac{\beta}{k-\beta}\left(e^{-kt} - e^{-\beta t}\right) \qquad (19)$$

TABLE I
FORMULAS OF RECEIVING-END VOLTAGE

(a) $T<t<3T$

B^n	Equation	k_i	No.
0	$V_{r1}^{\ 0} = Ee^{-\theta t}$	1	(11)
1	$V_{r1}^{\ 1} = -\frac{1}{2}EQ_r e^{-\theta t}\left(1-e^{-2\theta x''}\right)$	1	(12)
	$V_{r2}^{\ 1} = -\frac{1}{2}EQ_s e^{-\theta t}\left(1-e^{-2\theta x''}\right)$	1	(13)

(b) $3T<t<5T$

B^n	Equation	k_i	No.
0	$V'^{\ 0}_{r1} = EQ_sQ_r e^{-3\theta t}$	1	(14)
1	$V'^{\ 1}_{r1} = -\frac{1}{2}EQ_sQ_r^{\ 2} e^{-3\theta t}\left(1-e^{-2\theta x'''}\right)$	2	(15)
	$V'^{\ 1}_{r2} = -\frac{1}{2}EQ_s^{\ 2}Q_r e^{-3\theta t}\left(1-e^{-2\theta x'''}\right)$	2	(16)

III. ANALYTICAL EXPRESSION OF LIGHTNING PERFORMANCE OF GROUNDING SYSTEM OF WINDFARM

A. *Grounding System of Windfarm*

The steady-state grounding resistance of a wind power generator is designed to be as low as possible [5]. The tower base can be regarded to be a large grounding electrode. However, it is difficult to obtain the low grounding resistance, when the windfarm is constructed in high-soil-resistivity yard. A ring electrode or a long horizontal grounding conductor is often used to obtain the low steady-state grounding resistance. The grounding electrodes of the towers in the windfarm are sometime connected using the long grounding conductors.

This paper concerns the following grounding systems of towers in a windfarm as illustrated in Fig. 3.

(a) Tower base alone

Only a tower base is considered as a grounding electrode of the tower. The grounding resistance of the tower base is R_T.

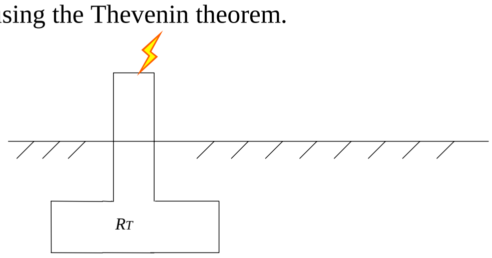
(b) Tower base + a horizontal grounding electrode

A horizontal grounding electrode is connected to the tower base as an auxiliary grounding electrode. Surge impedance of the grounding conductor is Z_0 [Ω], surge velocity v [m/s], conductance G [S/m], and conductor length l [m].

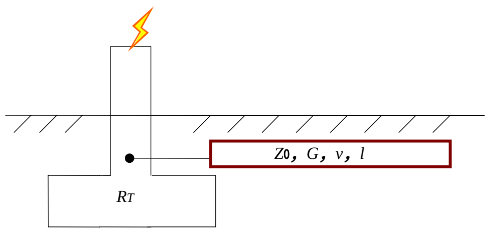
(c) Tower bases connected using grounding conductors

The tower bases are connected using the horizontal grounding conductors. For simplicity, the tower bases and the grounding conductors have same constants.

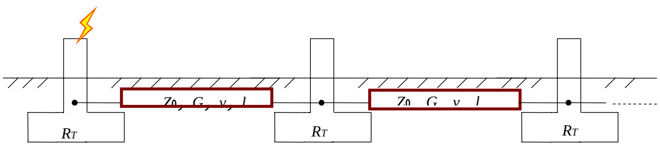
Fig. 4 illustrates a simulation circuit in case (c). The circuit surrounded by a broken line is equivalent to a circuit shown in Fig. 5 using the Thevenin theorem.



(a) Tower base alone



(b) Tower base + a grounding conductor



(c) Tower bases being connected via grounding conductor

Fig. 3. A grounding system of windfarm

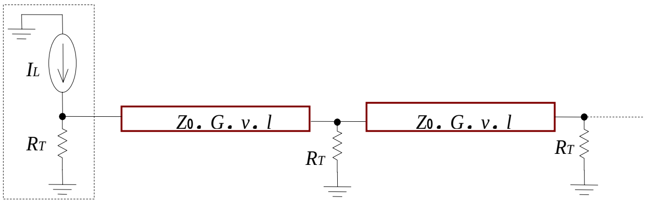


Fig. 4. Simulation circuit

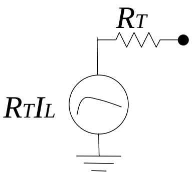


Fig. 5. Equivalent source circuit

B. Approximate Formulas of Grounding System of Windfarm

An approximate formula of lightning overvoltage at lightning striking point, which is located at the end of a windfarm, can be derived using the lattice diagram method as mentioned before. This paper considers lightning performance for $t<4T$, where $T=l/v$.

Table II shows the approximate formulas of sending-end voltage in the grounding system (c). The sending-end voltage is expressed by

1) $0<t<2T$

$$V = E + P_s V_{s1}{}^1 \tag{25}$$

2) $2T<t<4T$

$$V = E + P_s\left([V_{s1}{}^1]_{x=l} + V'_{s0}{}^1 + \sum_{i=1}^{3} k_i V'_{si}{}^1 \right). \tag{26}$$

TABLE II
APPROXIMATE FORMULAS OF SENDING-END VOLTAGE OF SYSTEM (C)

(a) $0<t<2T$

B^n	Equation	k_i	No.
1	$V_{s1}{}^1 = -\frac{1}{2}E\left(1 - e^{-2\theta x}\right)$	1	(20)

(b) $2T<t<4T$

B^n	Equation	k_i	No.
0	$V'_{s0}{}^1 = EQ_t e^{-2\theta l}$	1	(21)
1	$V'_{s1}{}^1 = -EQ_s Q_t e^{-2\theta l}\frac{1}{2}\left(1 - e^{-2\theta x}\right)$	2	(22)
	$V'_{s2}{}^1 = -EQ_t{}^2 e^{-2\theta l}\frac{1}{2}\left(1 - e^{-2\theta x}\right)$	1	(23)
	$V'_{s3}{}^1 = -EP_t{}^2 e^{-2\theta l}\frac{1}{2}\left(1 - e^{-2\theta x}\right)$	1	(24)

where
$$P_s = \frac{2R_T}{R_T + Z_0},\ Q_s = \frac{R_T - Z_0}{R_T + Z_0},\ P_t = \frac{2R_T}{2R_T + Z_0},$$
$$Q_t = \frac{-Z_0}{2R_T + Z_0},\ E = \frac{Z_0}{Z_0 + R_T}E_0,\ E_0 = R_T I_L$$

$V'_{s3}{}^1$ is an additional voltage due to connecting the neighbor tower. P_t and Q_t are refraction and reflection coefficients at receiving end of the grounding conductor.

The voltage in the grounding system (a) is given by

$$V=R_T I_L, \tag{27}$$

and that in the system (b) is given by the formulas mentioned in chapter II.

IV. Effective Length of Grounding System of Windfarm

A. Effective Length in Time Domain

An "effective length" is defined as the length, above which no further reduction of impedance of a grounding conductor is observed [10]. The effective length depends on source voltage waveform. This paper estimates the effective length in time domain. The "effective length" can be also defined as the length, above which the reflection voltage from the receiving end does not affect the peak value of the sending end voltage. This paper discusses this "effective length".

For simplicity, this paper discusses an influence of wave-front duration of lightning current on the effective length by the double exponential function with α=0. This current is given by

$$I_{Lf} = I_f[1 - \exp(-t/T_f)] \tag{28}$$

where T_f: time constant of lightning current

B. Constants of Grounding Conductor by Sunde's Formulas

Sunde derived the following formulas of constants of a horizontal grounding conductor [1].

$$\text{Inductance:}\quad L = \frac{\mu_0}{2\pi}W \quad \text{[H/m]}$$
$$\text{Capacitance:}\quad C = 2\pi\varepsilon_r\varepsilon_0 W^{-1} \quad \text{[F/m]} \tag{29}$$
$$\text{Conductance:}\quad G = \frac{\pi}{\rho}W^{-1} \quad \text{[S/m]}$$

where $W = \ln\frac{2l}{\sqrt{2rd}} - 1$, r: conductor radius, d: burial depth, ρ: soil resistivity, ε_r: soil relative permittivity.

The surge impedance Z_0 and the velocity v of the loss-less line of the equivalent circuit shown in Fig. 1 are given by

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{60W}{\sqrt{\varepsilon_r}} \tag{30}$$

$$v = \frac{1}{\sqrt{LC}} = \frac{v_0}{\sqrt{\varepsilon_r}}. \tag{31}$$

Substituting the Sunde's formulas into θ,

$$\theta v = \frac{30\pi}{\rho\varepsilon_r}v_0 = \frac{1}{4\rho\varepsilon_r\varepsilon_0} \tag{32}$$

is obtained. Equations (31) and (32) indicate that the wave deformation and the surge velocity of the voltages on the grounding conductor are independent of the configuration and dimension of the conductor. On the other hand, the surge impedance depends on them. Reference [12] on the basis of experimental results suggests that the surge impedance of a horizontal long grounding conductor is not dependent on its length and the soil resistivity. Here the surge impedance of 100Ω is used from the experimental results, and is independent of the soil resistivity.

C. Effective length of Grounding System in Windfarm

An influence of such soil parameters as soil resistivity and soil permittivity on the effective length is investigated using the approximate formulas of the sending end voltage in the grounding system. Mutual grounding resistance between the tower base and the horizontal grounding conductor is not considered here. Current dependency due to soil ionization reduces the grounding resistance. Long grounding conductor shows little current dependence based on experimental study [13]. Frequency dependence can be modeled by adding a series circuit of resistance and capacitance in parallel with the conductor conductance [14]. However, the value cannot be determined without any experiments. Thus, the frequency and current dependencies are taken into no account in this paper.

The voltage in the grounding system (a) is expressed by $R_T I_L$, and takes its peak value at the same time of the lightning current peak. This voltage corresponds to the source voltage in the grounding systems (b) and (c).

R_T is assumed to be 10Ω in the yard of ρ=100Ωm. The grounding resistance is proportional to the soil resistivity. The simulation is carried out for parameters of ρ=100, 1000, and 10000Ωm, and the relative soil permittivity ε_r=1, 10, and 100.

Fig. 6 shows examples of calculated results of the sending-end voltage in the grounding systems (b) and (c). As is shown in Fig. 6, voltage rise is observed after the voltage reflected at the receiving end reaches for short conductor length. The crest value of the sending-end voltage after the reflection reaches coincides with that before the reflection voltage does not arrive when the grounding conductor has the effective length. This variation is not always observed, and depends on the soil parameters and the terminal impedances.

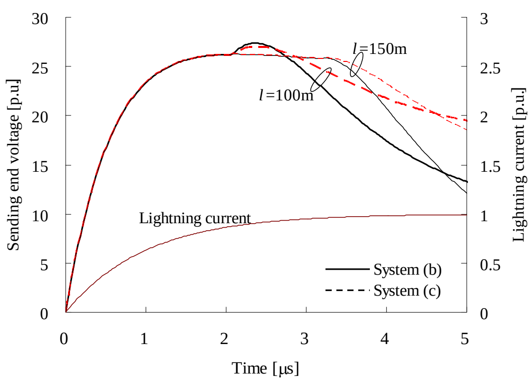


Fig. 6. Sending-end voltage in grounding systems (b) and (c). T_f=1μs, ρ=1000Ωm, and ε_r =10.

Fig. 7 shows the effective length of a grounding conductor buried in the soil with parameters of ρ and ε_r as a function of the time constant T_f of the lightning current given by equation (28). T_f corresponds to the wavefront duration of the current. The receiving end of the grounding conductor in the grounding system (b) is open circuit, and Q_r=1. Q_t always shows a negative value in the system (c). The effective length in the system (b) is not available in some conditions because of Q_r=1.

As is shown in Fig. 7(a), the effective length is linearly increased against the wavefront duration for $\rho\varepsilon_r$ =10^5, and shows divergence for low $\rho\varepsilon_r$. The traveling voltage along the grounding conductor is heavily attenuated for low $\rho\varepsilon_r$ considering the wave deformation of the voltage is expressed by attenuation factor θv, which is inversely proportional to $\rho\varepsilon_r$ from (32). Therefore, the reflection voltage becomes very small for low $\rho\varepsilon_r$. and the reflection voltage does not contribute the peak value of the sending-end voltage. As a result, the effective length is not available. On the other hand, the effective length can not also be obtained in case of large $\rho\varepsilon_r$. The grounding conductor in this case can be regarded to be isolated wire. The conductance of the grounding conductor does not contribute the reduction of the sending-end voltage, and the reflection voltage with positive value because of Q_r=1. Accordingly, large $\rho\varepsilon_r$ does not give the effective length.

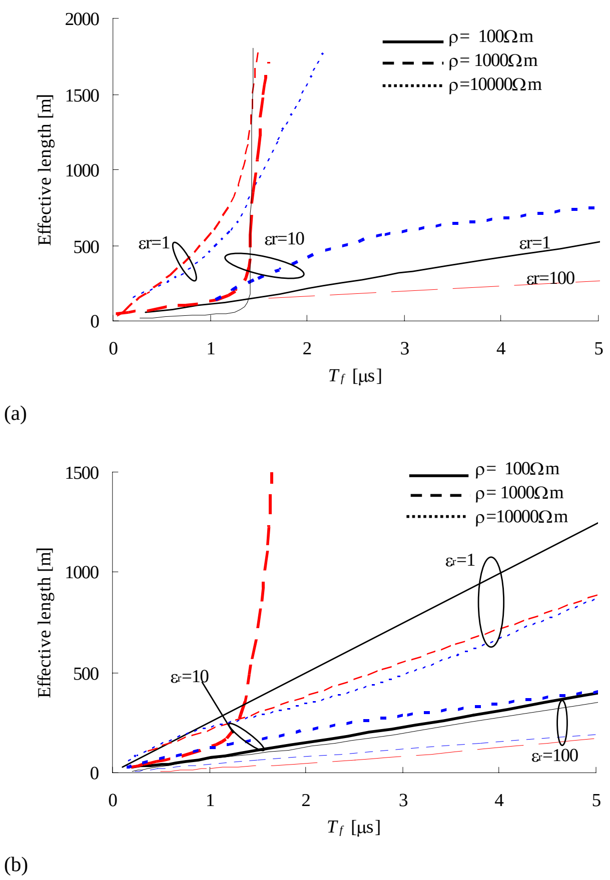


Fig. 7. Effective length for various soil parameters as a function of wavefront duration of lightning current. (a) System b. (b) System c.

It is clear from Fig. 7(b) that the wavefront duration affects the effective length. The effective length becomes longer as the wavefront duration of the lightning current is longer. The effective length is linearly increased against the wavefront duration. The effective length is also becomes longer as the relative soil permittivity is larger. Thus, the lightning current with slow wavefront needs long grounding conductor.

The approximate formulas of the voltages on the grounding conductor include boundary conditions. As a result, the effective length is affected by the boundary conditions. Fig. 8 shows example of sending-end voltage in the grounding system (c) as a function of the tower base grounding resistance, where the conductor length is 100m, ρ=1000Ωm, and ε_r=10. The curves are normalized by the value at 1μs.

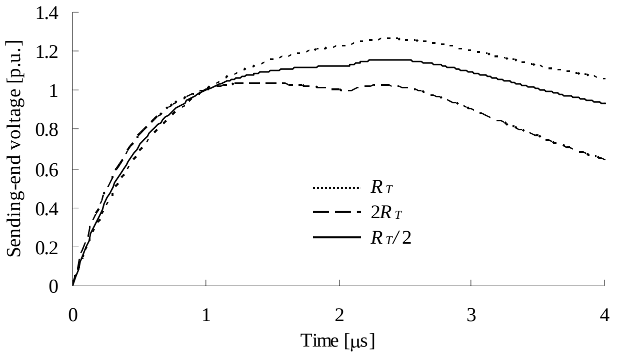


Fig. 8. Influence of boundary condition

As shown in Fig. 8, the waveform is greatly dependent on the boundary conditions. The difference of peak value between the first peak for t<2T and the second one for t>2T becomes larger as R_T is higher. This phenomenon indicates that the effective length depends on the boundary condition. Thus, it is not sufficient for the effective length to investigate only the conductor and soil parameters, and the boundary conditions must be considered.

V. CONCLUSIONS

This paper has proposed approximate formulas of voltages in a grounding system of a windfarm. The proposed formulas are expressed in time domain, and are very simple. Effective length of the grounding system has been discussed using the approximate formulas. This paper has shown that the effective length, which is estimated in time domain, is greatly dependent on soil resistivity and permittivity. The paper has shown that the boundary conditions must be considered to determine the effective length. The proposed formulas are useful for lightning protection design of the grounding system in wind farms.

VI. REFERENCES

[1] E. D. Sunde, *Earth Conduction Effects in Transmission Systems*, New York: *D. Van Nostrand Co.*, 1949.

[2] S. Sekioka, M. I. Lorentzou, and N.D. Hatziargyriou, “A simplified formula of surge characteristics of a long grounding conductor,” in *Proc. International Conference on Power Systems Transients*, 7-2, New Orleans, USA, 2003.

[3] S. Sekioka, M. I. Lorentzou, and N. D. Hatziargyriou, “A simplified formula of surge characteristics of a long grounding conductor (II),” in *Proc. International Symposium of Lightning Protection*, pp. 94-99, Curitiba, Brazil, 2004.

[4] IEC TR 61400-24:2002-07 Wind turbine generator systems – Part 24: Lightning protection

[5] I. Cotton, “Windfarm earthing,” *in Proc. International Symposium on High Voltage Engineering*, vol. 2, pp. 288-291, London, UK, 1999.

[6] R. B. Anderson, and A. J. Eriksson: "Lightning parameters for engineering application," *Electra*, no.69, pp.65-102, 1980.

[7] L. V. Bewley, *Traveling Waves on Transmission Systems*, New York: John Wiley, 1951.

[8] L. O. Barthold, "An approximate transient solution of the tapered transmission line," *AIEE Trans., Power Apparatus and System*, vol. 77, pp. 1556-1561, Feb. 1958.

[9] K. Kotaki, A. Hashimoto, H. Isa, and S. Sekioka, “Wave propagation characteristics of a lightning surge on an incoming line,” *Trans. of IEE of Japan*, vol. 113-B, no. 9, pp. 1019-1028, Sep. 1993 (in Japanese).

[10] R. B. Anderson, and A. J. Erikson, "Lightning parameters for engineering application," *ELECTRA*, no. 69, pp. 65-102, 1980.

[11] M. I. Lorentzou, “Contribution to modeling and analysis of the transient behavior of grounding systems,” Ph.D. Thesis, National Technical University of Athens, November, 2001.

[12] H. Motoyama, and T. Noda, “Experimental study on lightning surge characteristics of a buried bare wire,” *CRIEPI Report*, no. T00062, 2001 (in Japanese).

[13] S. Sekioka, H. Hayashida, T. Hara, and A. Ametani, "Measurements of grounding resistances for high impulse currents," *IEE Proc. of Gener., Transm. & Distrib.*, vol. 145, no. 6, pp. 693-699, 1998.

[14] S. Yamaguchi, M. Inoue, S. Sekioka, T. Sonoda, Y. Kato, N. Nagaoka, and A. Ametani, "A frequency-dependent counter-poise model for a transient analysis," in *Proc. of ICEE’98*, vol. 1, pp. 753-756, Kyongju, Korea, 1998

VII. APPENDIX

$$\lim_{\Delta x \to 0} \ln A^{2n} = \lim_{\Delta x \to 0} \frac{-2x}{\Delta x} \ln(1+\theta\Delta x) = \lim_{\Delta x \to 0} (-2x)\frac{\theta}{1+\theta\Delta x}$$
$$= -2\theta x$$
$$\therefore \lim_{\Delta x \to 0} A^{2n} = e^{-2\theta x}$$

$$\lim_{\Delta x \to 0} A = 1$$
$$\therefore \lim_{\Delta x \to 0} \frac{B}{1-A^2} = \lim_{\Delta x \to 0} \frac{B}{(1-A)(1+A)} = \lim_{\Delta x \to 0} \frac{-1}{1+A} = -\frac{1}{2}$$

VIII. BIOGRAPHIES

Shozo Sekioka was born in Osaka, Japan on December 30, 1963. He received the B. Sc. and D. Eng. degrees from Doshisha University, Japan in 1986 and 1997 respectively. He joined Kansai Tech Corp., Japan in 1987, and is an Associate Professor at Department of Electrical and Electronic Engineering of Shonan Institute of Technology, Japan since 2005. He has been engaged in the lightning surge analysis in electric power systems. He is a member of IEE (U.K.), IEEE and IEE of Japan.

Toshihisa Funabashi was born in Aichi, Japan, in 1951. He graduated in March 1975 from the Department of Electrical Engineering, Nagoya University, Aichi, Japan. He received, in March 2000, a Doctor degree from Doshisha University, Kyoto, Japan. He joined Meidensha Corporation in April 1975 and has engaged in research on power system analysis. Currently, he is the Senior Engineer of the Power Systems Engineering Division. Dr. Funabashi is a chartered engineer in UK, and a senior member of IEEE and a member of the IET (the former IEE) and the IEE of Japan.