Incoming Lightning Surge Analysis Considering Return Stroke Parameters

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Abstract – **This paper clarifies the influence of an electromagnetic field radiated from a return stroke on an incoming lightning surge at an EHV substation. Return stroke parameters such as a lightning striking angle, a return stroke velocity, a current waveform and a crest current are examined by numerical analysis. The electromagnetic field greatly affects the lightning surge, and should be taken into account for accurate lightning surge analyses.**

Keywords: Return Stroke, Lightning-Induced Voltage, Lightning Surge, Back Flashover

I. INTRODUCTION

An electromagnetic field generated by a return stroke current in a lightning channel induces an overvoltage on overhead lines [1]. The main object for the lightning protection design of distribution lines is the induced overvoltage, which is called lightning-induced voltage, due to a nearby lightning stroke. A conventional return stroke model of a direct lightning hit to a transmission-line tower, however, consists only of a lightning-path impedance and a return stroke current source, and ignores the electromagnetic field radiated from the return stroke [2].

The authors have pointed out that the influence of the electromagnetic field should be considered to predict accurately the lightning performance even in case of a direct lightning hit to the tower [3-7]. Reference [3] shows that the lightning striking angle affects the arcing-horn voltage based on experimental study. Reference [7] states that the arcing-horn voltage becomes higher, and the number of flashover phases increases as the return stroke velocity becomes slower. An observation of incoming lightning surges at a HV substation shows that the polarity of incoming overvoltage on the phase wire varies before and after a back flashover [4]. Reference [4] explains this phenomenon by introducing an induced voltage caused by a return stroke current.

This paper describes the influence of return stroke parameters such as the return stroke velocity, the lightning striking angle and the lightning current amplitude in case of a direct lightning hit to a tower top on an incoming lightning surge at an EHV substation.

II. CALCULATION METHOD OF LIGHTNING-INDUCED VOLTAGES

The effect of the electromagnetic field generated by the return stroke current on a lightning overvoltage on a transmission line is treated as a lightning-induced voltage in this paper. The calculation method [5] of the lightning-induced voltage is composed of a finite difference method [8] to solve line equations with distributed voltage sources and Dommel's method [9] to calculate transition-point circuits transients using an equivalent circuit illustrated in Fig. 1, and is installed in the EMTP [10]. The calculation method is described in the appendix.

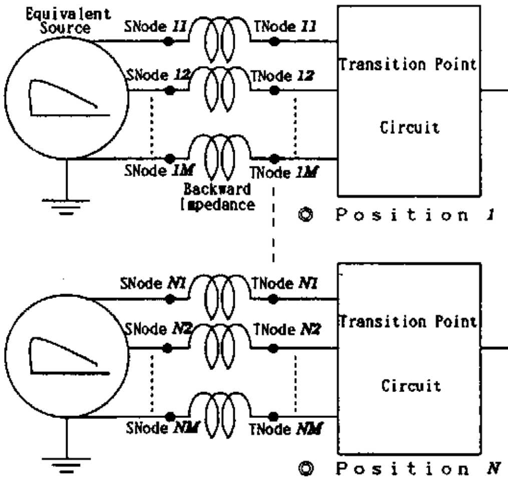


Fig. 1 An equivalent circuit for solving transition point circuits by Dommel's method.

The calculation method can not accurately handle a very steep-front current because the electric field generated by the current in the conductor is assumed to be a TEM wave. Okumura pointed out that when a lightning current $i(t)$: $1-exp(-t/T_a)$ is injected into the top of a tower with height H, calculated results by a distributed-parameter line theory satisfactorily agree with those by an electromagnetic field theory for $T_a \geq H/c$, where c is the velocity of light [11].

A direct lightning hit to a tower top is represented by a parallel circuit consisting of a current source with ramp wave and a 400 Ω resistor for lightning channel impedance. Assume that the lightning current in the return stroke is not affected by the tower and the transmission line. The equivalent circuit for the direct lightning hit is added in the circuit in Fig. 1 to the lightning-hit circuit consisting of the current source and the resistor.

Following assumptions of the return stroke are used in this paper.

- The return stroke current develops upward from the center of the tower top to a cloud.
- The velocity of the return stroke current is constant.
- The waveform of the return stroke current does not vary in the lightning channel.
- *t*=0 is defined as the time when the return stroke starts developing. All line voltages, currents and return stroke current are zero at *t*=0.

III. ANALYSIS CIRCUIT

Fig. 2 illustrates an analysis circuit of a 500kV transmission line and a gas insulated switchgear (GIS) substation [13]. The surge impedance of the bus in the substation is 70 Ω and the surge velocity is 270m/ μ s. Fig. 3 illustrates the configuration of the tower and the transmission line. The tower model [12] used in this analysis is shown in Fig. 4. The conductivity of the conductors in the circuits and the soil is assumed to be infinite.

The transmission line for simulating consists of three conductors. One is the 1L upper phase wire (PW). The bundled conductor of the phase wire is reduced to a single conductor by means of a geometric mean distance. The others are shielding wires (SW).

The current dependence of the grounding resistance is very important for lightning analyses. The tower-footing resistance of the EHV tower base, however, shows little current dependence because the base is extremely large [14]. Accordingly, the current dependence of the tower-footing resistance is not considered in this paper. A corona wave deformation may also affect the incoming voltage [15]. For simplicity, the line model does not include a corona effect.

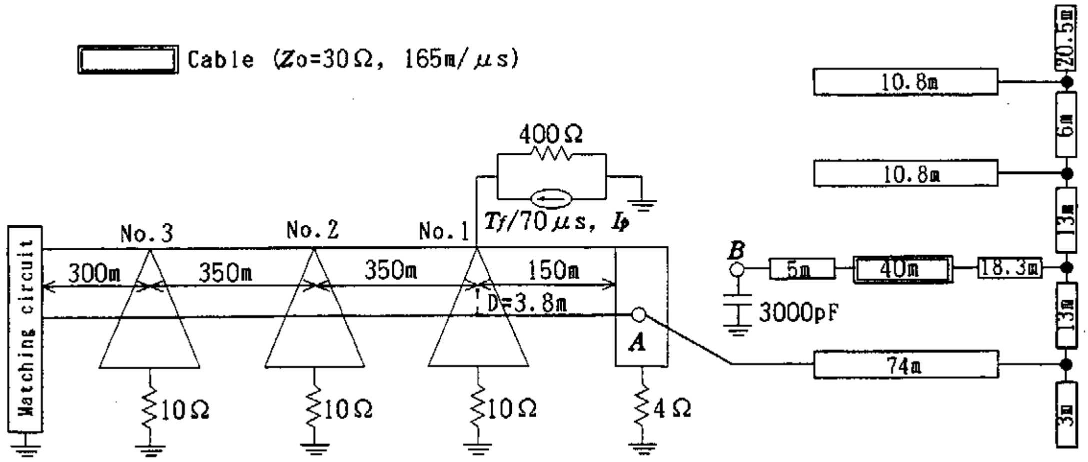


Fig. 2 An illustration of analysis circuit.

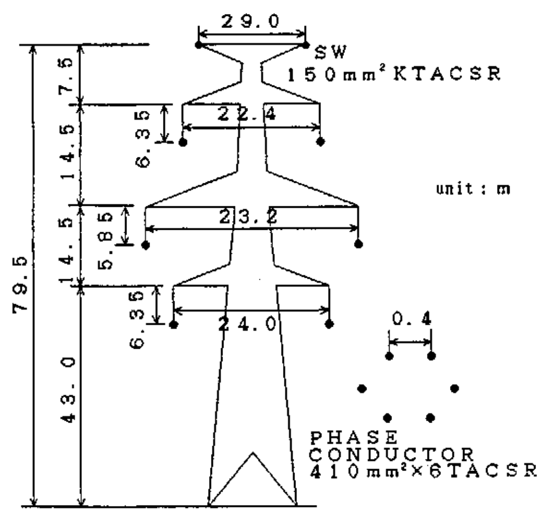


Fig. 3 Configuration and main dimensions of transmission line and tower.

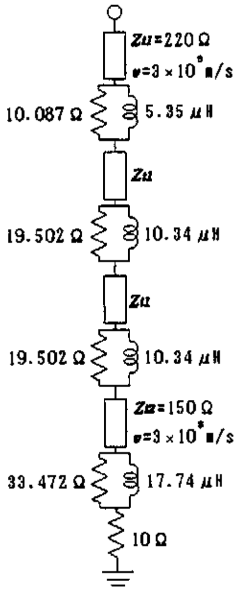


Fig. 4 A tower model.

A flashover on an arcing horn at a lightning striking tower is modeled by a leader development model [16], which can realize an accurate impedance variation of the arcing horn. The leader development model is also installed in the EMTP. The flashover model is only a nonlinear characteristic in the analysis circuit, and the suppression of an overvoltage by a surge arrester is not taken into account.

Fig. 5 illustrates a coordinate system of a return stroke.

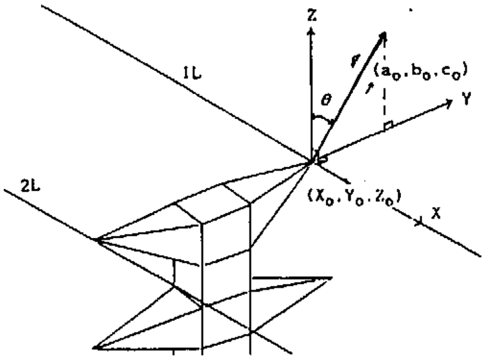


Fig. 5 Coordinate system of a return stroke.

IV. INFLUENCE OF RETURN STROKE PARAMETERS ON LIGHTNING OVERVOLTAGE

This paper carries out lightning surge analyses of an incoming surge at the GIS substation for parameters with a lightning striking angle θ, a return stroke velocity v_r, a wavefront duration T_f and a return stroke crest current I_p.

A. Lightning Overvoltages on Infinite Line

A simulation of a transmission line as an infinite line should be carried out to clear the influence of the electromagnetic field radiated from the return stroke. The arcing horn is open-circuited, and line voltages at the lightning striking tower are calculated.

Fig. 6 shows calculated results using Dommel's line model (conventional model) and a line model that takes into account the electromagnetic field generated by the return stroke current.

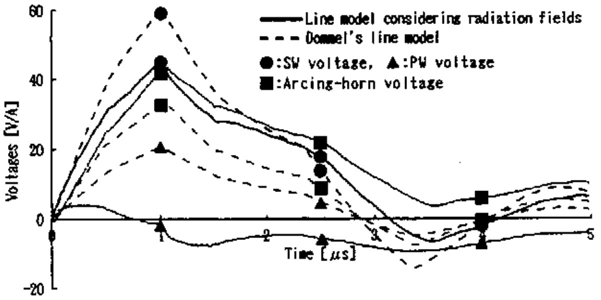


Fig. 6 Comparison between Dommel's line model and a line model considering electromagnetic field radiated from the return stroke (θ =0° , v_r=100m / μ s, T_f=1 μ s).

An apparent difference of the waveforms and the crest values between the line models is observed in Fig. 6. The PW voltage consists of two components; one (V_{Si}) is determined from the coupling factor between the SW and the PW, and proportional to the SW voltage, and the other (V_{Ri}) is caused by the electromagnetic field generated by the return stroke current. The PW voltage by the conventional model corresponds only to V_{Si}. The PW voltage by using the proposed method, however, is given by the sum of V_{Si} and V_{Ri}. The influence of V_{Ri} makes the PW voltage difference. The PW voltage considering the electromagnetic field shows the opposite polarity of the SW voltage. The polarity of the return stroke current in the lightning channel is opposite to that of the tower injected current. Accordingly, the polarity of the induced voltage on the PW caused by the electromagnetic field is opposite to that of the tower potential rise due to the tower injected current. As a result, the polarity of the PW voltage becomes opposite to that of the SW voltage. Thus, the electromagnetic field radiated from the return stroke greatly affects the lightning overvoltages.

Calculated results of crest voltage for parameters with θ and v_r are shown in Figs. 7 and 8.

From Fig. 7, it is shown that the greater the striking angle, the higher the arcing-horn and PW voltages are. It is observed in Fig. 8 that the SW voltage decreases as the return stroke velocity becomes slower. The arcing-horn and PW voltages, however, increase. Thus, the

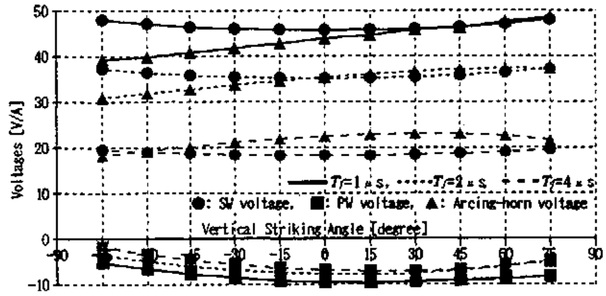


Fig. 7 Calculated results of SW, PW and arcing-horn voltages at lightning striking tower as a function of striking angle θ (v_r=100m/ μ s).

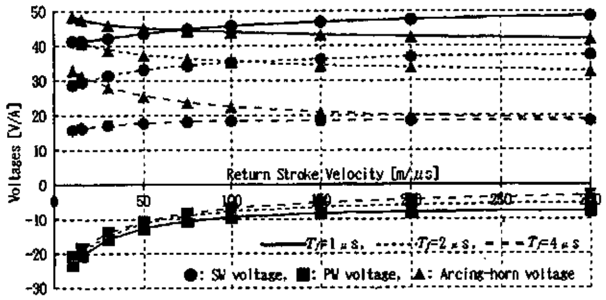


Fig. 8 Calculated results of SW, PW and arcing-horn voltages at lightning striking tower as a function of return stroke velocity v_r (θ =0°).

return stroke parameters of the lightning striking angle and the return stroke velocity are very important factors for accurate lightning surge analyses.

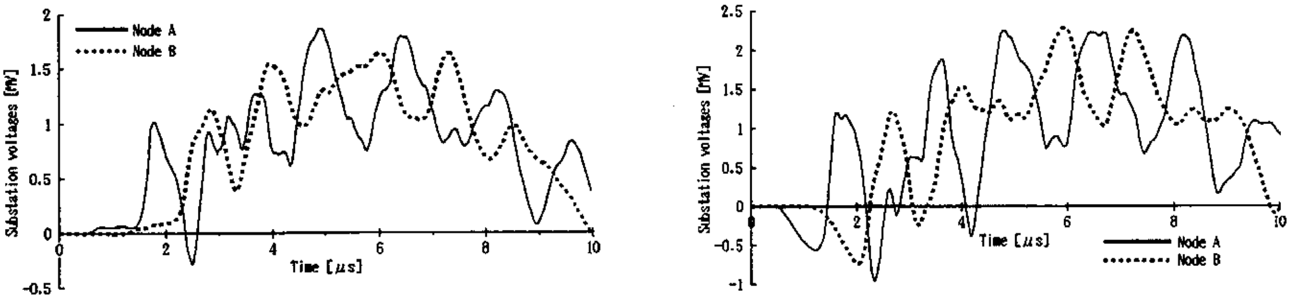
B. Incoming Lightning Surges at Substation

The return stroke parameters affect the arcing-horn voltage. Therefore, simulations in this chapter consider the characteristic of the leader development in the arcing horn. The circuit for analyses is Fig. 2, and voltages at ***nodes*** A and B are calculated.

Fig. 9 shows voltage waveforms calculated by using the conventional line model and by considering the radiation field of $\theta = 0^\circ$, v_r=100m/ μ s, T_f=1 μ s and I_p=150kA.

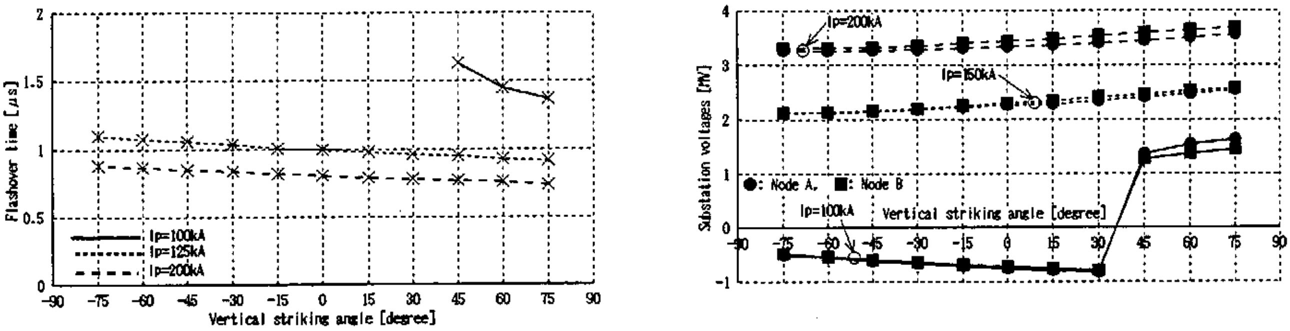
The polarity of the substation voltages using the conventional line model almost keeps positive as shown in Fig. 9(a). The substation voltages considering the radiation field, however, show negative values at first. The voltages suddenly vary to positive values after the back flashover. Observation results of lightning over-voltages at a HV substation by one of the authors also show such a variation [17]. The influence of the radiation field generated by the return stroke current, therefore, should be taken into account.

Figs. 10 and 11 show calculated results of flashover time and substation voltages for parameters with the lightning striking angle and the return stroke velocity. Back flashover does not occur at $\theta < 45^\circ$ and v_r >100m / μ s in case of I_p=100kA.



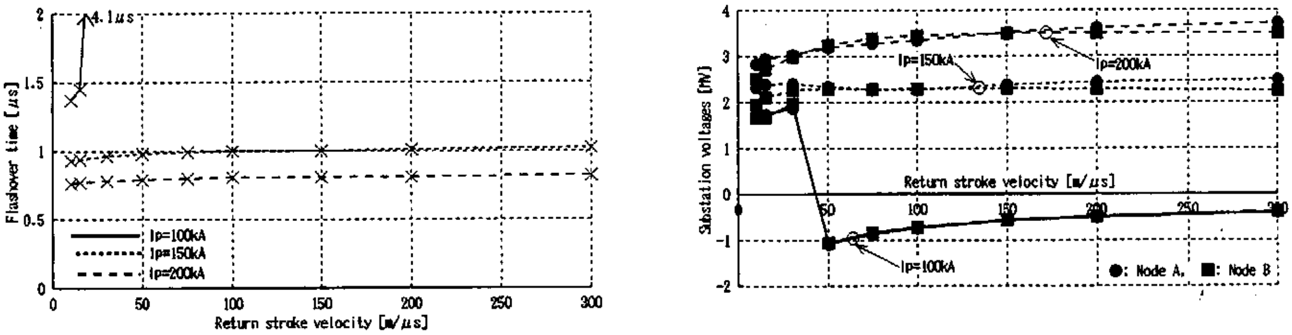
(a) Conventional line model (b) Line model considering the radiation fields

Fig. 9 Waveforms of substation voltages at ***nodes*** A and B for $\theta = 0^\circ$, v_r=100m/ μ s, T_f=1 μ s and I_p=150 kA.



(a) Flashover time (b) Substation voltages

Fig. 10 Calculated results of flashover time and crest substation voltages considering the radiation field as a function of striking angle θ (v_r=100m/ μ s).



(a) Flashover time (b) Substation voltages

Fig. 11 Calculated results of crest substation voltages considering the radiation field as a function of return stroke velocity v_r ($\theta = 0^\circ$).

The calculated results in Figs. 10 and 11 lead to the following conclusions:

(1) Back flashover occurs earlier as the lightning striking angle becomes larger or the return stroke velocity becomes slower.
(2) The substation voltages increase as the lightning striking angle becomes larger.
(3) The substation voltages increase as the return stroke velocity becomes slower in the case of no flashover. Conversely, the voltages decrease as the velocity becomes slower after a back flashover occurs.

V. DISCUSSIONS

The above conclusions (1) to (3) can not be obtained from conventional lightning surge analyses. This chapter investigates the conclusions.

A. No Flashover

The analysis circuit without a flashover is similar to that used in the calculation of Figs. 6 to 8. Accordingly, the variation of the substation voltages against the lightning striking angle and the return stroke velocity coincides with that in Figs. 7 and 8.

B. Influence of Lightning Striking Angle

Fig. 12 shows calculated results of the voltage at ***node A*** as a function of a flashover time, where the arcing horn is modeled by a time-controlled switch.

It is clear from Fig. 12 that the substation voltage increases as the flashover time becomes faster. Accordingly, the flashover time becomes faster in relation to increase of the lightning striking angle as shown in Fig. 10(a), and the substation voltages increase as the lightning striking angle becomes larger.

C. Influence of Return Stroke Velocity

The flashover time does not vary in relation to the return stroke velocity. The variation of the substation voltages, therefore, is mainly determined by the radiation field.

The induced voltage on an overhead conductor caused by the electromagnetic field radiated from the return stroke is inversely proportional to the return stroke velocity [1]. The conductor voltage, therefore, increases due to a slower return stroke velocity. As a result, the radiation field acts to decrease the tower voltage against the slower velocity. The PW voltage becomes approximately equal to the tower voltage after the back flashover occurs. Consequently, the substation voltages become lower as the return stroke velocity becomes slower.

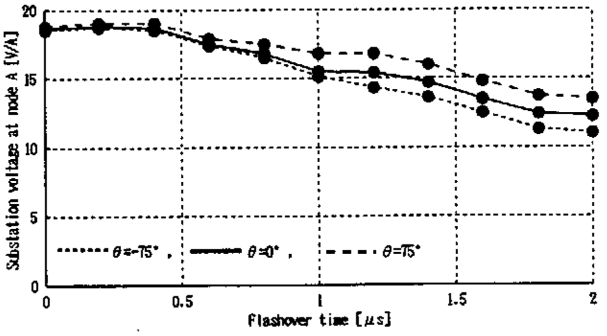


Fig. 12 Calculated results of crest substation voltage at ***node A*** considering the radiation field as a function of flashover time (v_r=100m/ μ s).

VI. CONCLUSIONS

This paper has described that an electromagnetic field radiated from a return stroke greatly affects incoming lightning overvoltages at a substation in case of a direct lightning hit to a tower top, and return stroke parameters such as a return stroke velocity and a lightning striking angle are very important factors in determining overvoltages. The calculation method considering the electromagnetic field is realized in the EMTP using a difference method to solve line equations with distributed voltage sources and Dommel's method to calculate transition point transients.

Calculated results of incoming lightning overvoltage at a substation by a conventional model are different from those considering the electromagnetic field. Especially, the polarity of the voltage considering the field varies before and after a back flashover. This paper clarifies the necessity of the parameters for accurate lightning surge analyses.

VII. REFERENCES

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VIII. APPENDIX

Calculation Method of Solving Line Equations with Distributed Sources Including Transition Point Circuits

Appendix describes a calculation method [5] to solve line equations with transition points based on a finite difference method [8] and Dommel's method [9]. Let a point with a grounded shielding wire, and the end of the line be called a transition point, and the other be called a general section.

Line equations for lightning-induced voltages caused by an inclined lightning stroke are given in the following equations.

$$\frac{\partial V_s}{\partial x} = -L\frac{\partial I}{\partial t} - E_{mx} \tag{1}$$

$$\frac{\partial I}{\partial x} = -C\frac{\partial (V_s - e_s)}{\partial t} \tag{2}$$

$$V = V_s + e_m \tag{3}$$

where L: inductance matrix per meter, C: capacitance matrix per meter, V: induced voltage vector, V_s: induced scalar potential vector, I: current vector in conductors, E_{mx}: horizontal component of electric field strength due to inclined return stroke, e_s: inducing scalar potential, e_m: inducing vector potential

Transforming eqs. (1) and (2) into difference equations, and arranging them, result in the following equations.

$$V_s(x_i, t+\Delta t) = V_s(x_i, t) - C^{-1}\kappa^{-1}\{I(x_i, t) - I(x_{i-1}, t)\} + \Delta t\{\partial e_s(x_i, t)/\partial t\} \tag{4}$$

$$I(x_i, t+\Delta t) = I(x_i, t) - L^{-1}\kappa^{-1}\{V_s(x_{i+1}, t+\Delta t) - V_s(x_i, t+\Delta t) - E_{mx}(x_i, t)\Delta x\} \tag{5}$$

where $\kappa = \Delta x/\Delta t$

The line voltages and currents are calculated by an iterative procedure using eqs. (3) to (5).

Applying Kirchhoff's first law to ***node n***, and substituting eq. (4) at ***node n*** yields:

$$V_n = \underline{\frac{V_{s,n-1} + E_{mx,n-1}\Delta x' + V_{s,n+1} - E_{mx,n}\Delta x'}{2} + e_m} - L\,\Delta x'\frac{1}{2}\cdot\frac{dI_T}{dt} \tag{6}$$

where $\Delta x' = \Delta x/2$ [11].

Let the terms with an underline in eq. (6) be $V_{a,n}$, which is a voltage source consisting of V_s on the general sections, horizontal fields and e_m at the transition point. The last term in the equation represents the voltage drop in the impedance (backward impedance), which is the parallel line impedance of both sides of the transition point. Therefore, it represents Thevenin's theorem, and the equivalent circuit is given by Fig. 1. When the circuit consists of electric elements, the circuit is easily solved by Dommel's method, while the program using the proposed method is able to handle the complicated transition point circuits.

The circuit at the right end of the line can be solved using $V_{s,N-1} - E_{mx,N-1}\Delta x' + e_{m,N}$ as an equivalent source and $L\Delta x'$ as an equivalent backward inductance.