論 文
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時変 塔脚 接地 抵抗値를 가지는 鉄塔의 過渡 過電圧 特性

Characteristics of Transient Overvoltages for the Towers with Time Varying Tower Footing Resistance

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요 약

本 論文에서는 送電線路에서 雷擊電流가 大地로 흐를 경우 時変塔脚接地抵抗에 의한 鐵塔의 過渡過電壓特性에 대하여 硏究検討하였다. 時変塔脚接地抵抗을 갖는 鐵塔을 simulation 하고 雷擊電流에 의한 鐵塔의 過渡過電壓을 Nodal Solution Method에 의해 計算하였다. 그 결과로 부터 誘導性塔脚接地抵抗의 上限値를 定常値로 決定할 경우 애자련의 CFO 電壓보다 높은 過渡過電壓을 유발할 수 있고 逆閃絡率을 計算할 때 애자련의 V －T 特性도 고려되어야 함을 알 수 있었다.

Abstract

This paper investigated the characteristics of transient overvoltages on the tower caused by time varying tower footing resistance in the path of lightning stroke current entering earth on transmission lines. The tower with time varying tower footing resistance was simulated and the transient overvoltages on the tower due to lightning stroke current were computed by Nodal Solution Method. From the results, it was found that the determination of the steady state values as a limit of inductive tower footing resistance causes higher transient overvoltages than CFO voltages of insulator strings and V-T characteristics of the insulator strings should be considered for computation of backflashover rate.

1. Introduction

Lightning surges on transmission lines can arise by several mechanisms. The least harmful are the voltages induced by strokes to ground in the vicinity of a line. Lightning strokes to the phase conductors produce the highest overvoltages for a given stroke current.

On important lines of high lightning incidence, it is accepted practice to seek to prevent direct strokes to phase conductors by arranging one or more shielding wires above the phase conductors to intercept lightning strokes and conduct them to ground.

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The potential created by current flowing through grounded parts of the line is much lower than that due to direct strokes; however, given a large enough current it can be sufficient to cause backflashovers[1),2)].

The stroke current to cause the backflashover is very much dependent on the magnitude of tower footing resistances, and these tower footing resistances are generally time varying, however, in most of the papers or books, only the constant values would be used[1),2),8)].

This paper is mainly concerned with the impacts of the time varying tower footing reistances to the temporary overvoltage due to the stroke current on the tower to cause backflashover on the high voltage transmission line.

The general phenomena of strokes to tower are

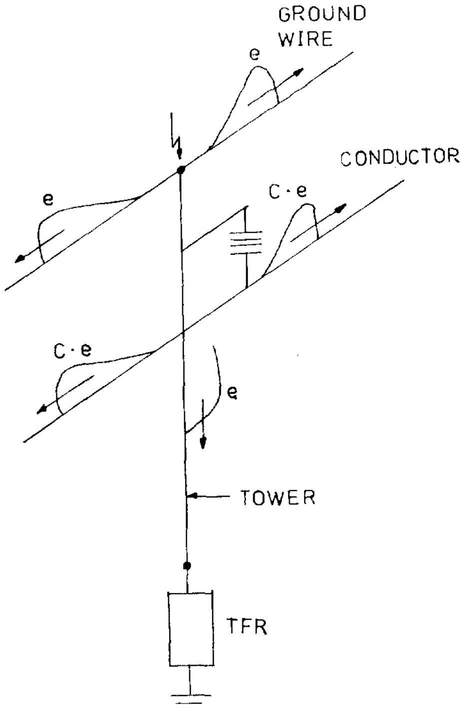


Fig. 1. Stroke to the Tower

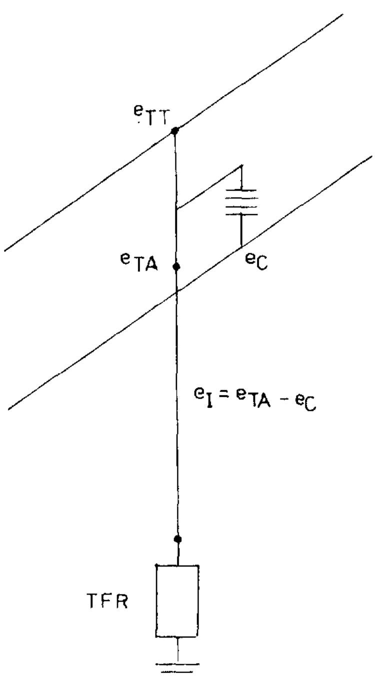


Fig. 2. The Voltage across the Tower Insulation

shown in the simple circuits of Figure 1 and 2. The stroke having a magnitude, I, and a steepness, S, terminates on the tower top.

This current produces traveling waves of voltage which travel outward on the ground wire and down the tower. Traveling with the surge voltages on the ground wire are surge voltages coupled onto the phase conductor. These surge voltages are reflected at the tower footing and at adjacent towers. Let the voltage, after all reflections, at the tower top be e_{TT}, the voltage on the phase conductor be e_c, the voltage on the tower opposite the phase conductor be e_{TA}.

Also let the respective crest magnitudes of these voltages be denoted by V_{TT}, V_c, and V_{TA}. Therefore, the voltage across the tower insulation, e_I is

$$e_I = e_{TA} - e_c$$
$$= e_{TA} - C_A \cdot e_{TT} \qquad (1)$$

where C_A is the coupling factor and therefore $e_c = C_A \cdot e_{TT}$.

The shapes of the surge voltages e_{TA} and e_{TT} are approximately identical and therefore the crest voltage across the tower insulator, V_{IA} is

$$V_{IA} = V_{TA} - C_A V_{TT} \qquad (2)$$

The voltages V_{TA}, V_{TT}, and therefore V_{IA} are linear with respect to I, that is

$$V_{TT} = K_{TT} I \qquad (3)$$
$$V_{TA} = K_{TA} I \qquad (4)$$

and therefore

$$V_{IA} = (K_{TA} - C_A K_{TT}) I \qquad (5)$$

For flashover to occur, V_{IA} must be equal or greater than the critical flashover (CFO) voltage of the tower insulation.

2. Nodal Solution Method for Constant Tower Footing Resistances

The method to be described here can solve any network consisting of resistances, inductances, capacitances, and transmission lines with distributed parameters[3),4)].

Figure 3 will be used to explain the technique for these linear elements first. It represents the details of system model around node 2.

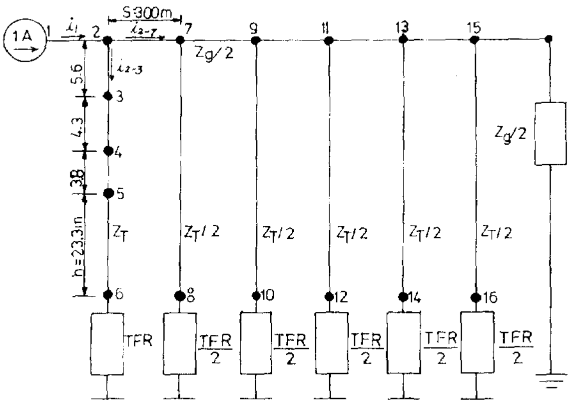


Fig. 3. Modelling of Stroke to the 154KV Tower Top

Suppose that voltages and currents are just being computed at time t. This implies that the values at preceding time steps t-Δt, t-2Δt, … are already known. Since the sum of the currents flowing away from node 2 through the connected branches must be equal to the injected current i_1, it follows that

$$i_{2-7}(t)+i_{2-3}(t)=i_1(t) \tag{6}$$

As the branches 2-7, and 2-3 are lines with distributed parameters, it can easily be derived if losses are first neglected, to be approximated later on. In these cases, the wave equations

$$-\frac{\partial v}{\partial x}=L'\frac{\partial i}{\partial t}, \qquad -\frac{\partial i}{\partial x}=C'\frac{\partial v}{\partial t}$$

with L' and C' being the distributed inductance and capacitance per unit length, have the following solution,

$$i=F(x-\alpha t)+f(x+\alpha t)$$
$$v=\frac{Z_g}{2}\cdot F(x-\alpha t)-\frac{Z_g}{2}\cdot f(x+\alpha t) \tag{7}$$

Here F and f are arbitrary functions, to be determined from problem boundary and initial conditions; the parameters Z_g and α are defined by

surge impedance $\quad Z_g=2\sqrt{\frac{L'}{C'}}$

velocity of propagation $\alpha=\sqrt{\frac{1}{L'C'}}$

The desired branch equation is derived by multiplying i in Eq. (7) by $\frac{Z_g}{2}$ and adding it to v;

$$v+\frac{Z_g}{2}\cdot i=Z_g\,F(x-\alpha t) \tag{8}$$

Note that the value $v+\frac{Z_g}{2}\cdot i$ in Eq.(8) does not change when x-αt does not change. With the travel time being

$$\tau=\frac{\text{line length}}{\alpha}$$

a fictitious observer leaving node 7 at time t-τ will see the expression $v_7(t-\tau)+\frac{Z_g}{2}\cdot i_{7-2}(t-\tau)$; when he arrives time τ later at node2, he will see the expression $v_2(t)+\frac{Z_g}{2}(-i_{2-7}(t))$. Since both must be equal

$$v_2(t)+\frac{Z_g}{2}(-i_{2-7}(t))=v_7(t-\tau)+\frac{Z_g}{2}\cdot i_{7-2}(t-\tau) \tag{9}$$

Finally, Eq. (9) can be rewritten in the form of the desired branch equation

$$i_{2-7}(t)=\frac{2}{Z_g}\cdot v_2(t)+I_{2-7}(t-\tau) \tag{10}$$

where the term I_{2-7} is again known from previously computed values;

$$I_{2-7}(t-\tau)=-\frac{2}{Z_g}v_7(t-\tau)-i_{7-2}(t-\tau) \tag{11}$$

With the similar manner, the desired 2-3 branch equation

$$i_{2-3}(t)=\frac{1}{Z_T}\cdot v_2(t)+I_{2-3}(t-\tau') \tag{12}$$

where the term I_{2-3} is;

$$I_{2-3}(t-\tau')=-\frac{1}{Z_T}\cdot v_3(t-\tau')-i_{3-2}(t-\tau') \tag{13}$$

Eq. (10) and (12) provide an exact solution for the lossless line at its terminals, and are the basis of *Bergeron's graphical method* [3]. This relation is also valid for distortionless lines if I_{2-7} (t-τ) and I_{2-3} (t-τ) in Eq. (10) and (12) are multiplied by an attenuation factor exp(-R'τ/2L') and exp(-R''$\cdot\tau'$/2L'') respectively.

As overhead lines are not distortionless, a better approximation is obtained by adding lumped resistance R/2 at the ends, or by adding R/4 at the ends and R/2 in the middle[4]. Upon building branch equations for all nodes, the node equation is obtained in the general form,

$$[G]\ [v(t)] = [i(t)] - [I] \qquad (14)$$

where

[G] nodal conductance matrix,

$[v(t)]$ column vector of the n node voltages,

$[i(t)]$ column vector of current sources,

[I] column vector of "past history" terms.

If the network contains voltage sources connected to ground, then Eq. (14) can be partitioned into part "A" with unknown voltages, and part "B" with known voltages. The unknown voltages are found from

$$[G_{AA}]\ [v_A(t)] = [i_A(t)] - [I_A] - [G_{AB}]\ [v_B(t)] \qquad (15)$$

The actual computation procedures are well-known[3),4),5)].

The past history terms are simply preset to zero if the simulation starts from zero initial conditions. For cases which start from linear ac steady-state conditions, a subroutine must be used to compute the ac steady-state solution. The past history tables can then be preset with the correct values.

3. Extension To Nonlinear and Time Varying Elements

With only one nonlinear parameter in the network, the solution can be kept essentially linear by confining the nonlinear algorithm to the branch with the nonlinear parameter. Let's suppose that a nonlinear element is connected between node k and node m.

To accomplish this the nonlinear parameter is not included in the matrix; its current $i_{k,m}$ is simulated with two additional node currents;

$$i_m = i_{K,m}, \text{ and } i_K = -i_{K,m}.$$

Let [Z] be the precalculated difference of the m th and k th columns of $[G_{AA}]^{-1}$, which is readily obtained with a repeat solution of Eq. (15). Ignoring the nonlinear parameter at first, we get $[v_A^{(linear)}(t)]$ from Eq. (15); the final solution follows from superimposing the two additional current $i_k = -i_m = -i_{k,m}$;

$$[v_A(t)] = [v_A^{(linear)}(t)] + [Z]\cdot i_{K,m}(t). \qquad (16)$$

The value $i_{k,m}$ (t) in Eq. (16) is found by solving two simultaneous equations, the linear network equation

$$v_K(t) - v_m(t) = v_K^{(linear)}(t) - v_m^{(linear)}(t) + (Z_K - Z_m)\cdot i_{K,m}(t) \qquad (17)$$

and the nonlinear equation in the form of the given characteristics

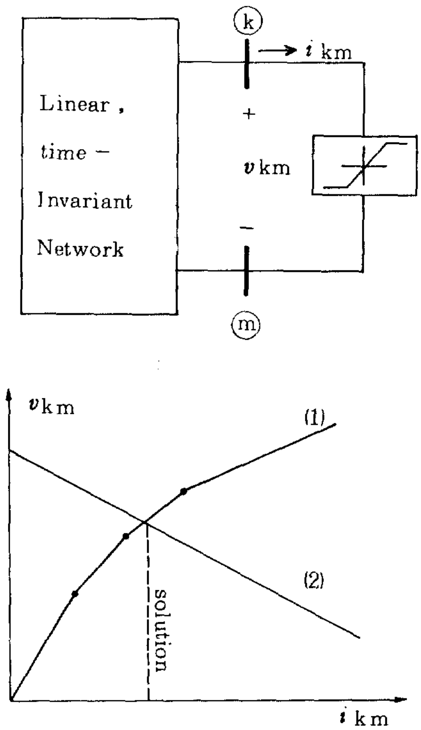
$$v_K(t) - v_m(t) = f(i_{K,m}(t)) \qquad (18)$$

where $v_k(t)$ and $v_m(t)$ are line to ground voltages of node k and node m.

The nonlinear characteristic in Eq. (18) is usually represented by point-by-point as piecewise linear (Figure 4), but any mathematical function could be used instead.

For a time varying resistance, Eq. (18) must be replaced by the simpler equation

$$v_K(t) - v_m(t) = R(t_R)\cdot i_{K,m}(t) \qquad (19)$$



(1) Time varying characteristic at time t (eq. 8)

(2) Thevenin Characteristic (eq. 17)

Fig. 4. Compensation method for a single nonlinear or time varying resistance

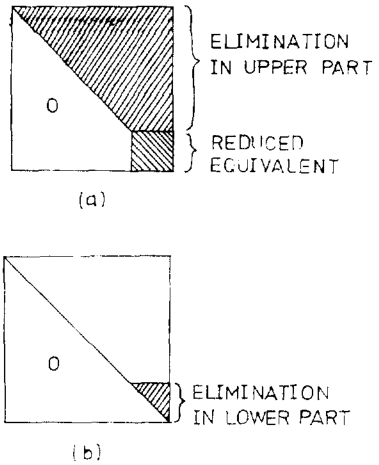


Fig. 5. Reduction for network equivalent.

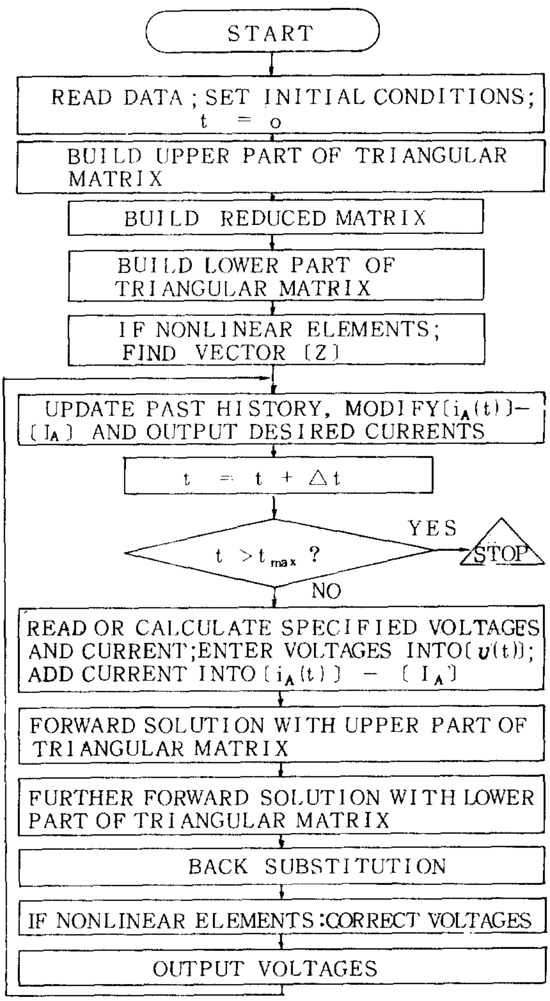


Fig. 6. Flow chart for program.

where $R(t_R)$ is given as a function of the time t_R.

The time count t_R may be identical with the time t of the transient study, or it may start later according to defined criterion. If more than one nonlinear branch exists per disconnected subnetwork, the compensation procedure could still be used, though complications enter. For N nonlinear elements in a given subnetwork, the preceding scalar $(Z_k\text{-}Z_m)$ in Eq. (17) is replaced by an N x N square matrix, and an iterative, simultaneous solution of N nonlinear equations would thus be required. A related but distinct technique is that of network equivalents [6], wherein elimination of all voltages for nodes not incident to nonlinear or time varying elements is performed as shown in Figure 5. In this way, an equivalent system of nonlinear or time varying equations among the remaining nodes is produced. Any iteration due to the nonlinearities, or changes with time, need only be applied to this reduced system of equations. The flow chart for transients program according to the previous algorithm is shown in Figure 6[4].

4. Simulation and Results

Simulation has been performed for the model shown in Figure 3. The surge impedance of overhead ground wire Zg is 580Ω according to the "line constants" subroutine of ref. 7).

The tower surge impedance has been computed according to the following formula for cylindrical towers[1]

$$Z_T = 60\ln h/r + 90\, r/h - 60\,(\text{ohm}) \qquad (20)$$

where h and r are the height and equivalent radius (mean periphery divided by 2π) of the tower.

The characteristics of tower footing resistances during transients are quite different as shown in Figure 7 according to the circumstances

The curve a in Figure 7 is called capacitive, b is flat and c is inductive, however, inductive characteristic is more important than any other characteristics because the tower footing resistances (TFR) during the transients are higher than steady state values only for the inductive characteristic[8]

Intensive simulations, therefore, have been

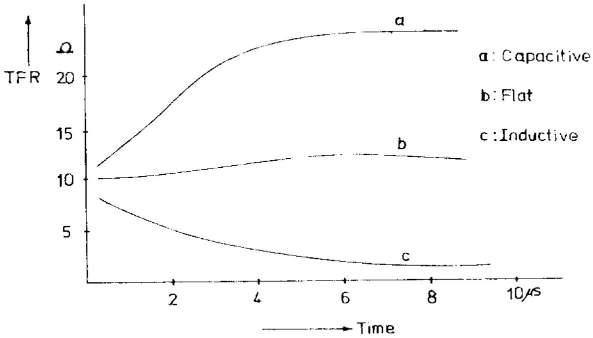


Fig. 7. The classification of TFR according to the characteristics during transients.

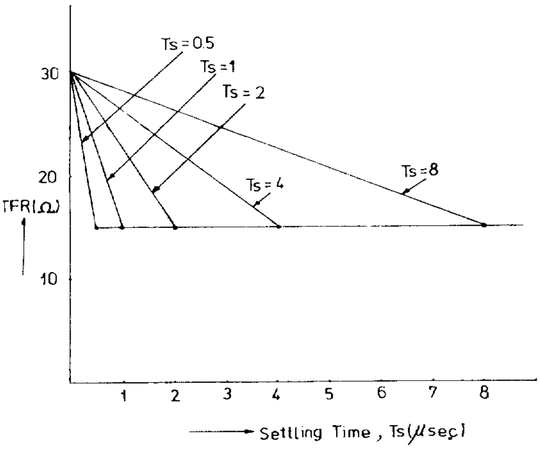


Fig. 8. Settling Time of Time Varying TFR.

performed for the inductive tower footing resistances. And the time varying characteristics of TFR are modeled as piecewise linear with two slopes. The initial value of TFR was assumed to be 30Ω and the steady state value of TFR was assumed to be 15Ω as a sampling case. The settling time which is the time interval from the initial value to the final steady state value of TFR was varied from 0.5 μs to 8 μs as shown in Figure 8, based on the measured data from the field[8).

Beside the settling time of time varying TFR, the front time (T_f) of lightning surge current affects in great to the tower top voltage (V_{TT}), so it does to the possibility of backflashover.

Figure 9 shows the results of computation for the tower top voltage under the various front times of lightning surge current with different settling time of TFR. In Figure 9, the values of V_{TT} at TFR=15Ω and TFR=30Ω represent the values of V_{TT} in case of zero and infinitive settling time of TFR.

From these results we can deduce that as the settling time becomes shorter, V_{TT} is closer to that for the steady state value of TFR.

However, as the setlling time is longer, V_{TT} becomes closer to that for the initial value of TFR. Therefore, if the designers of transmission lines apply the initial value of TFR for the inductive characteristic as a limit of TFR it is too pessimistic and expensive although it may be more safe to prevent backflashover.

On the other hand, if the designers apply the steady state value as a limit of TFR, it may be too optimistic even though it is less expensive.

Also, as shown in figure 9, the steeper the rise time of lightning surge, the higher the overvoltage on the tower. Therefore lightning flashover rate would be affected by V-T characteristics of insulator strings.

Once the V_{TT} is computed together with V_{TA} and C_A, the back-flashover rate per unit length (usually 100 Km) period (usually one year) can

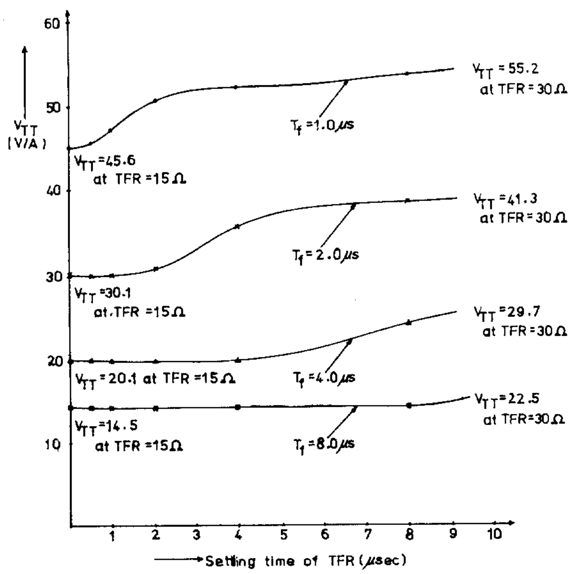


Fig. 9. Tower Top voltage (V_{TT}) under the Various Settling time of TFR (T_S)

be determined either by deterministic or by probabilistic methods.

This paper does not represent the calculation of backflashover rate in detail because it only concentrates the overvoltage variation at the tower due to the time varying tower footing resistance for the various strokes to the tower.

5. Conclusions

There are many considerations involved in the computation about transient overvoltage on the tower due to lightning strokes. In this paper, consideration has been concentrated on the time varying tower footing resistance.

For inductive time varying tower footing resistance , if the steady state values as a limit of TFR is applied, transient overvoltage can be higher than CFO voltage of insulator strings.

Therefore the designers of transmission lines should decide the limit of TFR in consideration of backflashover rate per 100 Km · year of transmission lines by probabilistic methods.

Also, the steeper the rise time of lightning surge, the higher the overvoltage on the tower, and thus V-T characteristics of insulator strings should be considered.

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