A Study on Lightning Surges due to Back Flashovers at Multiple Towers

Yuma YAMAMOTO, Akihiro AMETANI, Osamu SAKAI and Hidetaka YUASA

***Abstract*-- When a tower is struck by lightning it is quite possible that flashovers occur on more than one phase. There are a number of papers that deal with lightning surges due to multiple phase flashovers. It is also possible that flashovers occur at towers near the tower of the first back flashover. In this paper, a possibility of back flashovers at multiple towers of an EHV transmission line is investigated based on EMTP simulation. It is clear that when tower footing resistance is greater than and equal to 20Ω, it is quite possible that a back flashover occurs at towers near the lightning struck towers. Voltage and current distributions along ground wires, towers and tower footing resistances are investigated under various system conditions, and a possibility of back flashovers at multiple towers is discussed.**

Keywords*: *Lightning surge, back flashover, EMTP, EHV transmission line

I. INTRODUCTION

THE principal cause of the hindrance of supply in a transmission system is a lightning stroke to the transmission line tower. One of the issues associated with a lightning is a back flashover. Overvoltage is a dominant factor in insulation design and co-ordination of a substation and a transmission line[1]-[3]. There are a number of publications discussing lightning surge overvoltage due to a back flashover. It is quite possible that flashovers occur on more than one phase at a tower struck by lightning, and some papers deal with lightning surges due to multiple phase flashovers[4][5]. It is also possible that flashovers occur at towers near the tower of the first back flashover. Occasionally such information is given by a transmission engineer and a cable manufacturer. However, back flashovers at multiple towers have not been investigated.

In this paper, a possibility of back flashovers at multiple towers of an EHV transmission line is investigated based on EMTP simulations. Voltage and current distribution along ground wires, towers and tower footing resistances are investigated under various system conditions, and a possibility of back flashovers at multiple towers is discussed.

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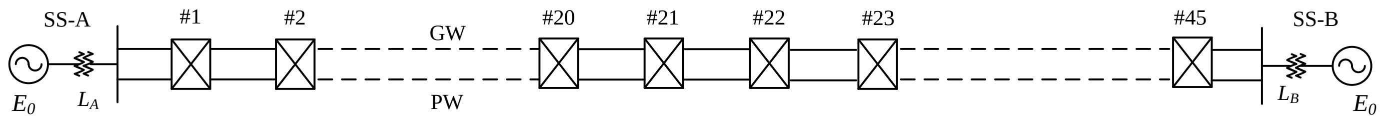
II. SIMULATION CIRCUIT

Fig.1 illustrates a single line diagram of an EHV transmission system investigated in this paper. Altogether 45 towers are considered between substations SS-A and SS-B[5][6]. The substations are represented by a transformer of which the stray capacitances between phases and to ground are considered. The secondary winding of the transformer is connected to either a generator or a star-connected load with the neutral grounded. Fig.2 illustrates a tower model. The tower surge impedance Z_t is fixed to be 121.3Ω which is a measured result[5]. Distance between towers is 300m, and the transmission system has a total length of about 15km. It is assumed that the footing resistance R_f is the same in every tower. Since a back flashover across an arc-horn at the upper phase is assumed, the upper arm is only considered in the tower model, ignoring the middle arm and lower arm. Fig.3 illustrates a lightning current waveform. A standard lightning impulse current 2×70μs with the amplitude of 100kA is applied at a tower. The simulation of the back flashover across an arc-horn is simplified by using the V-t intersection method. The withstand voltage of the arc-horn and insulator strings 1170kV and 1300kV respectively.

III. SIMULATION RESULTS

A. Basic case

As a basic case, a back flashover is investigated by EMTP simulation when a lightning current is applied at tower No.23(#23), which is located in the middle point of the system. The tower footing resistance is assumed to be 10, 20, and 50Ω, and the earth resistance is taken to be 100Ωm and 2000Ωm considering the transmission line in an urban area and a mountain site. Fig.4 illustrates simulation results of the upper phase arc-horn voltage at the tower next to the tower struck by lightning (towers No.22 and 24). It is observed from Fig.4 that there is no possibility of a back flashover in the case of the tower footing resistance R_f=10Ω. However, when the tower footing resistance is greater than and equal to 20Ω, it is quite possible that a back flashover occurs at towers near the lightning struck tower.



B. A location of the lightning struck tower

In the EMTP simulation results in the previous section, it is clear that a back flashover occurs at towers near the lightning struck tower in the case of the tower footing resistance R_f=50Ω and the earth resistance ρ_e=2000Ωm.

In this section, when a location of the lightning struck tower shifts ; CaseA(lightning to #10 tower in Fig.1), CaseB(lightning to #20 tower), CaseC(lightning to #30 tower), and CaseD(lightning to #40 tower), lightning surges due to back flashovers are investigated in the same case.. Fig.5 illustrates the time of occurrence of maximum arc-horn voltage plotted vs distance, when the position of substation SS-A is defined as X=0. Fig.6 illustrates simulation results of the upper phase arc-horn voltage, voltage on the top of the lightning struck tower and ground wire currents. It is clear from Fig.5 that lightning surges due to back flashovers are distributed symmetrically with respect to the lightning struck tower regardless of the lightning struck tower location. There are no differences in arc-horn voltage, voltage on the top of the lightning struck tower and ground wire currents.

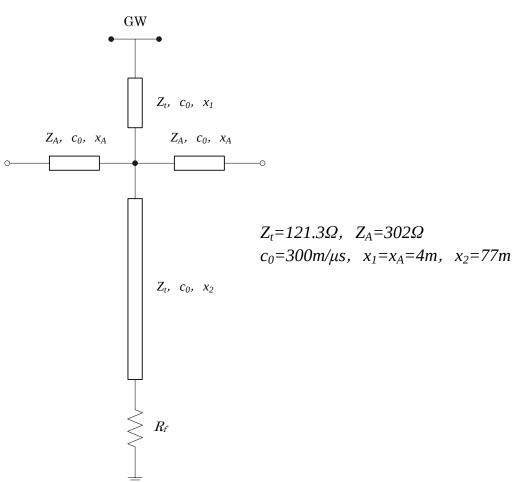


Fig.2 A tower model

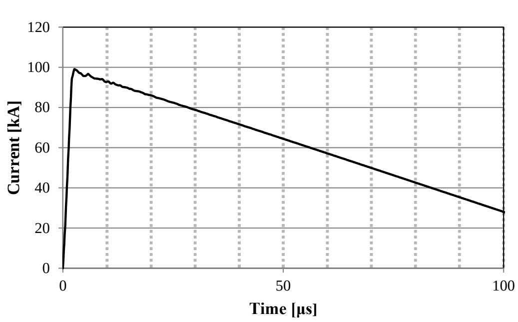


Fig.3 A lightning current

C. A back flashover at multiple towers

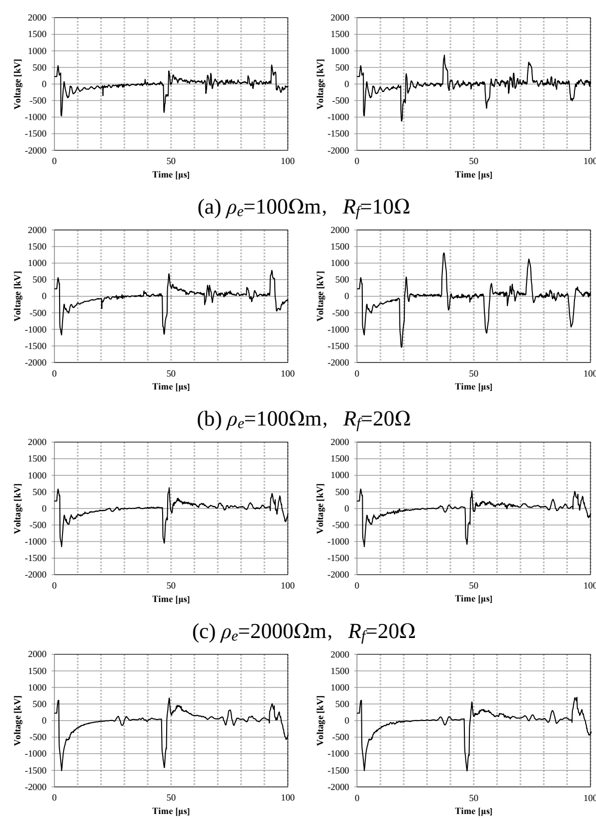
After a back flashover occurs at the lightning struck tower, back flashovers occur sequentially at other towers.

In this section, lightning surges due to back flashovers at multiple towers are calculated by EMTP under the following conditions.

$$\begin{cases} CaseA1: \#10 \\ CaseA2: \#10 \rightarrow \#9 \\ CaseA3: \#10 \rightarrow \#9 \rightarrow \#11 \\ CaseA4: \#10 \rightarrow \#9 \rightarrow \#11 \rightarrow \#8 \end{cases}$$

Fig.7 illustrates simulation results of phase wire voltages, tower top voltages and ground wire currents. The phase wire voltages are about 3000kV. However, these voltages are mitigated less than 750kV by arresters set in the end of a substation. The discharge voltage of the arresters in a 275kV system is 1050kV.

As back flashovers occur sequentially at multiple towers, phase wire voltages, arc-horn voltages and ground wire currents become smaller. There are no differences between tower top voltages.



(a) ρ_e=100Ωm, R_f=10Ω

(b) ρ_e=100Ωm, R_f=20Ω

(c) ρ_e=2000Ωm, R_f=20Ω

(d) ρ_e=2000Ωm, R_f=50Ω

Tower No.22 Tower No.24

Fig.4 Voltages across arc-horn

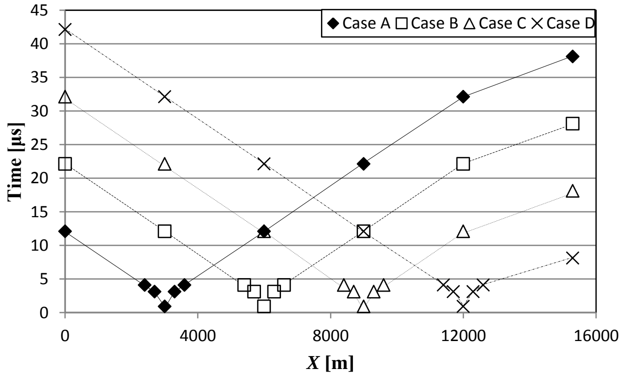
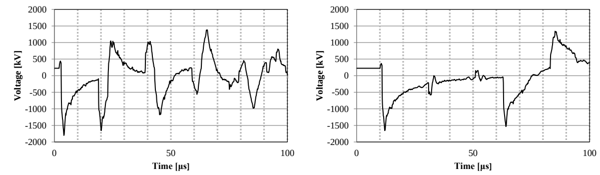
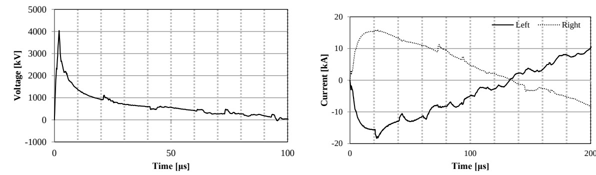


Fig.5 Time of occurrence

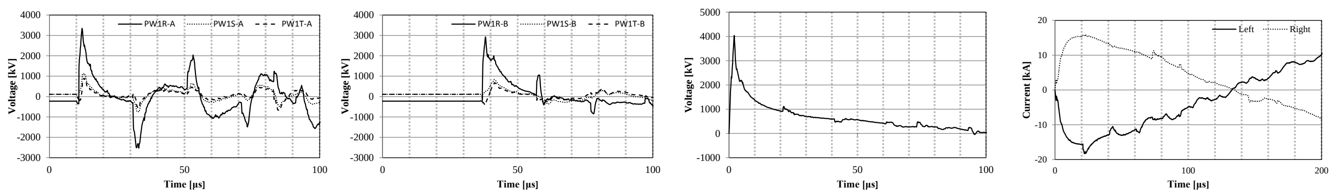


Voltage arcing horn (#8) Voltage arcing horn (#20)

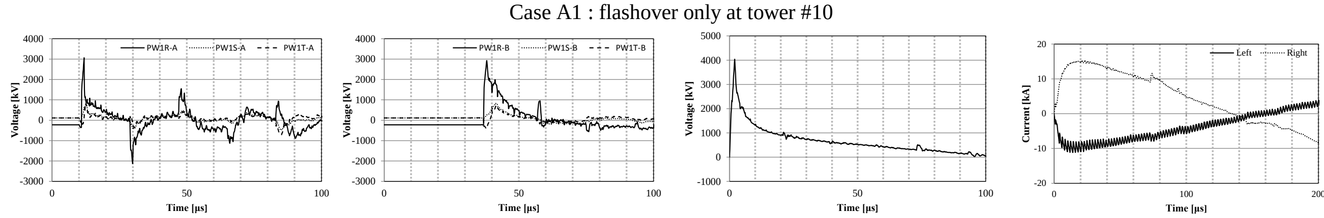


Top of tower voltage (#10) GW current (#10)

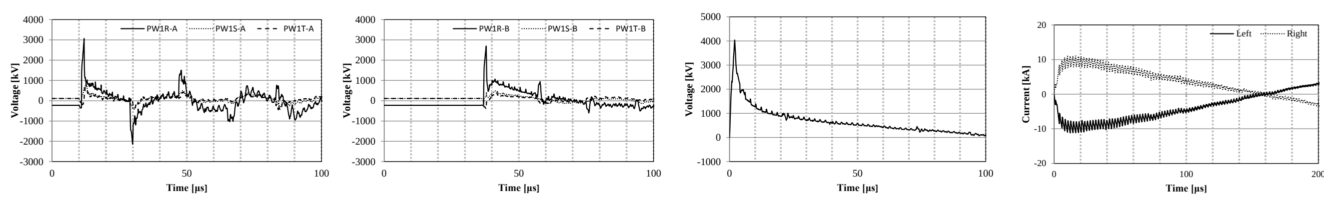
Fig.6 Simulation results for Case A : lightning to #10 tower



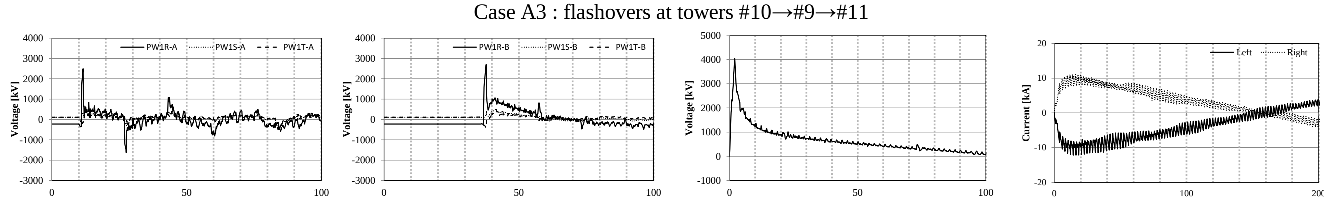
Case A1 : flashover only at tower #10



Case A2 : flashovers at towers #10→#9



Case A3 : flashovers at towers #10→#9→#11



Case A4 : flashovers at towers #10→#9→#11→#8

PW voltage (SS-A) PW voltage (SS-B) Top of tower voltage GW current

Fig.7 Simulation results of lightning surges due to back flashovers on multiple towers for Case A : lightning to #10 tower

IV. THEORETICAL ANALYSIS

A lightning surge due to a back flashover is calculated by the travelling wave method. In this section, the calculation case is the section Ⅲ.B of this paper. Fig.8 illustrates a simplified equivalent circuit for the travelling wave method. The conditions are as follows.

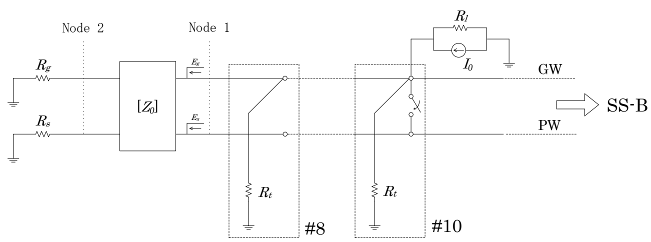


Fig.8 Simplified circuit for theoretical analysis

$[Z_0]$: transmission line characteristic impedance

$$[Z_0] = \begin{bmatrix} Z_{gg} & Z_{ga} \\ Z_{ga} & Z_{aa} \end{bmatrix} = \begin{bmatrix} 280 & 197 \\ 197 & 397 \end{bmatrix} [\Omega]$$

R_t=121.3[Ω]: Tower surge impedance

R_g=5[Ω]: Grounding resistance

R_s=2.52[Ω]: Substation resistance

R_l=400[Ω]: Lightning resistance

I_0=100[kA]: Lightning current

The lightning current is divided into a tower, left-and-right ground wires and flows. However, the lightning surges are calculated with time domain when a reflection from right side does not come back from lightning struck tower (No.10), and only the reflection from left side is considered.

Two ground wires are united into one, and only an upper phase wire where a back flashover occurs is considered. In addition, the lightning current is assumed to be a step wave function, and the propagation speed of the travelling wave is assumed to be the velocity of light.

A. Voltage on top of the lightning struck tower

This section investigates voltage on the top of the lightning struck tower. A flashover is expressed by closing a switch, connected between ground wire and phase wire, at the time when arc-horn voltage reached the flashover voltage. A switch is closed at t=0 as the lightning wave current is step function. At that time, total impedance Z judged at the lightning point is given as impedance of the parallel circuit consisting of lightning impedance, tower surge impedance, ground wire and phase wire.

$$\frac{1}{Z} = \frac{2}{Z_{gg}} + \frac{1}{R_l} + \frac{1}{R_t} + \frac{2}{Z_{aa}} \qquad \therefore Z = 43.62[\Omega] \qquad (1)$$

Therefore, the following gives the voltage on the top of the lightning struck tower:

$$V = ZI_0 = 4362[kV] \qquad (2)$$

The results agree well with the EMTP simulation results (4037kV). Therefore, the voltage on the top of the lightning struck tower is easily calculated by the travelling wave method.

B. Arc-horn voltage

Similarly, arc-horn voltage (No.8) is calculated by the travelling wave method. A refraction coefficient matrix from transmission line to substation is considered. The matrix is shown in the following.

$$[\lambda_2] = 2[Z_s]([Z_s]+[Z_0])^{-1} = 2\begin{bmatrix} R_g & 0 \\ 0 & R_s \end{bmatrix}\left(\begin{bmatrix} R_g & 0 \\ 0 & R_s \end{bmatrix} + \begin{bmatrix} Z_{gg} & Z_{ga} \\ Z_{ga} & Z_{aa} \end{bmatrix}\right)^{-1} \qquad (3)$$

$$= \frac{1}{\Delta}\begin{bmatrix} 2R_g(R_s+Z_{aa}) & -2R_gZ_{ga} \\ -2R_sZ_{ga} & 2R_s(R_g+Z_{gg}) \end{bmatrix} = \begin{bmatrix} 0.053 & -0.026 \\ -0.013 & 0.019 \end{bmatrix}$$

$$where \quad \Delta = (R_g+Z_{gg})(R_s+Z_{aa}) - Z_{ga}^2 = 75054$$

By substituting the conditions

$$E_g = 50[kV], \quad E_a = 1800[kV],$$

the voltage at Node2 is given as

$$\begin{bmatrix} V'_g \\ V'_a \end{bmatrix} = [\lambda_2]\begin{bmatrix} E_g \\ E_a \end{bmatrix} = \begin{bmatrix} 0.053 & -0.026 \\ -0.013 & 0.019 \end{bmatrix}\begin{bmatrix} 50(t-\tau) \\ 1800(t-\tau) \end{bmatrix} \qquad (4)$$

$$= \begin{bmatrix} -44.15(t-\tau) \\ 33.55(t-\tau) \end{bmatrix}[kV] \qquad time-delay : \tau = 8[\mu s]$$

From the above solutions, it is considered that approximately 2% of the left travelling wave E_a at the substation is transmitted and residual 98% of travelling wave goes to Node1 as a reflected wave. When this reflected wave comes in Node1 the following solutions (E'_g, E'_a) are obtained

$$E'_g = 50-(-44.15) = 94.15[kV] \qquad (5)$$

$$E'_a = 1800-33.55 = 1766.45[kV]$$

The arc-horn voltage is given as

$$V_{arc} = E'_a - E'_g = 1672.3[kV] \qquad (6)$$

The result agrees well with the EMTP simulation result at t=20[μs]=2τ (1650[kV]). Therefore, the arc-horn voltage is easily calculated by the travelling wave method. If only the maximum resultant voltage is investigated, it is considered that a theoretical analysis by 2 circuits model is effective.

V. CONCLUSIONS

This paper has investigated a possibility of back flashovers at multiple towers of an EHV transmission line based on EMTP simulations and theoretical analysis by the travelling wave method. From the investigations in the paper the following remarks are made.

(1) When the tower footing resistance is greater than and equal to 20Ω, it is quite possible that a back flashover occurs at towers near the lightning struck tower. In other words, it is possible that such a phenomenon is caused by a tower located in mountain site, which meets the above conditions.

(2) In this system, it is clear that lightning surges due to back flashovers are distributed symmetrically with regard to the lightning struck tower regardless of its location.

(3) As back flashovers occur sequentially at multiple

towers, phase wire voltages, arc-horn voltages and ground wire currents become smaller. There are no differences in voltages on top of the towers.

(4) The lightning surge due to back flashovers is easily calculated by the travelling wave method. If only the maximum resultant voltage is investigated, it is considered that a theoretical analysis by 2 circuits model is effective.

In this paper, the tower surge impedance is fixed to be 121.3Ω. A back flashover is dependent on the surge impedance, and thus its effect will be investigated in the next step of this research.

VI. References

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