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# Modeling of a 500kV Transmission Tower for Lightning Surge Analysis

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**Abstract**

Modeling of transmission towers is an essential part of the traveling analysis of lightning surges in overhead power transmission lines. In this paper, an equivalent distributed constant line model of the transmission tower is developed. The model consists of three parts: main poles, lattices and crossarms. The surge impedance of each part is expressed by the functions of their dimensions and geometries. This tower model is applied to the 500kV transmission tower of which surge performance characteristics are measured. It is found that the tower voltage wave shapes calculated from this model closely agree with the measured ones. This proves that the authors' proposed tower model well simulates the surge performances of an actual transmission tower.

## 1. Introduction

Most of the accidents that occured on the transmission line are caused by lightning strikes on the transmission tower. Modeling of transmission towers is an essential part of the analysis of the flashover characteristics of the towers. Theoretical studies of tower surge performance 1)-4) are very useful in understanding the phenomena. However, since those analyses were made for simple configurations, it is difficult to extrapolate their results to a complex-shaped actual transmission tower. Experimental studies for actual transmission towers 5)-7) and scale model towers 3), 4), 8), 9) can give the direct surge response characteristics of the towers. The recent experimental work by Ishi et al. 7) has developed the new multistory tower model for a transmission tower that produces close surge response to the actual 500kV transmission tower. However, though this model is very useful in the analysis of surge performances of 500kV transmission lines, it is not clear how widely the model can be used for other transmission lines.

The aim of this paper is to develop a more general representation of a transmission tower model. The authors had previously analyzed the surge response characteristics experimentally in the cylindrical tower 10), cylindrical tower with

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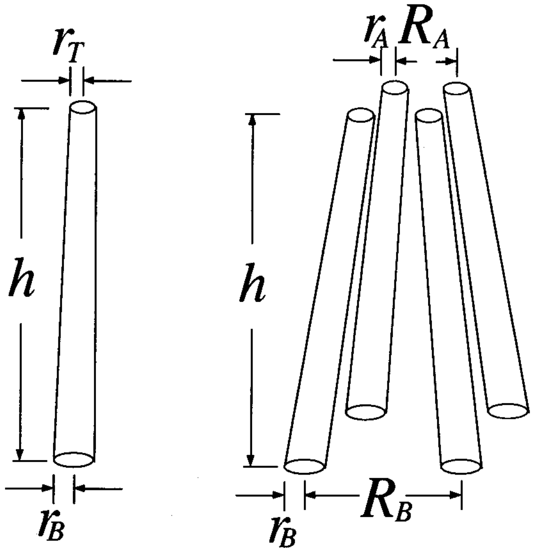
a crossarm 11) and multi-pole tower 12) and had developed the empirical formulas of surge impedance for them. In this paper, based on the results obtained from the above works, the authors develop a transmission tower model of which parameters are given by the functions of tower dimensions and geometries.

The surge response characteristics of the real size 500kV transmission tower are measured. The tower model parameters are calculated for this transmission tower by substituting the sizes of the tower into the functions. The surge responses are calculated from this tower model and are compared with the measured ones and the model is examined for whether it is applicable to the actual tower.

## 2. Pole tower model

*The model of a cylindrical tower*

In the previous paper 12), the surge response characteristics were measured for various radii and heights for the cylindrical tower shown in Fig. 1(a) and the empirical equation of the surge impedance for the cylindrical tower was derived as a function of its radius and height. It is shown by the following equation:




(a) single conductor (b) four conductors

Fig. 1. Configuration of the tower consists of single conductor or four conductors.

$$Z_T=60\left(\ln\frac{2\sqrt{2h}}{r_e}-2\right) \tag{1}$$

where, $h$ is the height of the cylindrical tower and $r_e$ is the equivalent radius of the tower,

$$r_e=r_T^{1/3}r_B^{2/3} \tag{2}$$

in which $r_T$ and $r_B$ are the radius at the top and the base of the cylindrical tower, respectively.

*The model of a tower consisted of four cylinders*

The surge responses of the tower consisted of four slanted cylinders, whose configurations were illustrated in Fig. 1 (b), were measured for various pole distances. The semi-empirical equation of the surge impedance for the four-pole tower was derived as follows,

$$Z_T=60\left(\ln\frac{2\sqrt{2h}}{2^{1/8}r_e^{1/4}R_e^{3/4}}-2\right) \tag{3}$$

where, $h$ and $r_e$ are the height and the equivalent radius of each cylinder, respectively and $R_e$ is the equivalent distance between the cylinders;

$$R_e=R_T^{1/3}R_B^{2/3} \tag{4}$$

in which $R_T$ and $R_B$ are the distance between two adjacent cylinders at the top and base of the tower, respectively.

## 3. Transmission tower model

*The model of main conductors*

In this section, we will derive the distributed constant line model of the transmission tower whose configurations and geometries are given in Fig. 2. We express the model by the circuit of distributed constant lines shown in Fig. 3. In the figure, $Z_T$ corresponds to the main conductors, $Z_L$ to lattice conductors and $Z_A$ to crossarms. For a tower higher than about 50 m, the main conductors are divided into four sections, namely, $Z_{T1}$, $Z_{T2}$, $Z_{T3}$ and $Z_{T4}$, each of which is given by

$$Z_{Tk}=60\left(\ln\frac{2\sqrt{2h}}{2^{1/8}r_{ek}^{1/4}R_{ek}^{1/4}}-2\right) \quad (k=1,2,3,4) \tag{5}$$

where,

$$r_{ek}=\begin{cases} r_{Tk}^{1/3}r_B'^{2/3} & (k=1,2,3) \\ r_{Tk}^{1/3}r_B^{2/3} & (k=4) \end{cases} \tag{6}$$

$$R_{ek}=\begin{cases} R_{Tk}^{1/3}R_B'^{2/3} & (k=1,2,3) \\ R_{Tk}^{1/3}R_B^{2/3} & (k=4) \end{cases} \tag{7}$$

in which $h_k(k=1,2,3,4)$, $r_{Tk}(k=1,2,3,4)$, $R_{Tk}=(1,2,3,4)$, $r_B$, $r'_B$, $R_B$, $R'_B$ are the lengths of the parts indicated in Fig. 2. The length of each line is set equal to the real conductor length.

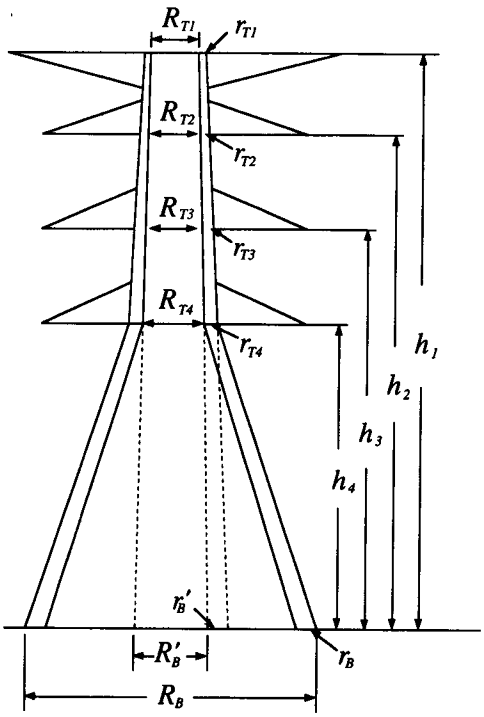



Fig. 2. Schematic diagram of the transmission tower.

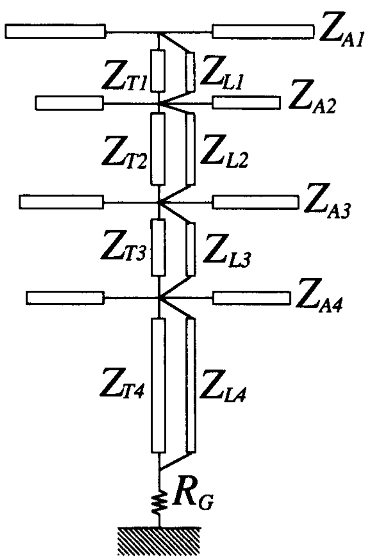



Fig. 3. Equivalent distributed constant line model of the transmission tower.

*The model of lattice conductors*

The surge responses of the two sets of four conductors with and without lattice are obtained and compared. It is found that the surge impedance is reduced about 10% by adding the lattice. Therefore, we express the lattice by the line $Z_{L1}$, $Z_{L2}$, $Z_{L3}$ and $Z_{L4}$ which are added parallel to the main line as shown in Fig. 3. The surge impedance of each part is given by

$$Z_{Lk}=9Z_{Tk} \quad (k=1,2,3,4) \tag{8}$$

The length of each lattice line is set 1.5 times larger than that of the main conductor.

*The model of crossarms*

We express the crossarms by the lines $Z_{A1}$, $Z_{A2}$, $Z_{A3}$ *and* $Z_{A4}$ branched at the junction point as shown in Fig. 3. They are expressed by the following equations:

$$Z_{Ak}=60\ln\frac{2h_k}{r_{Ak}} \quad (k=1,2,3,4) \tag{9}$$

where, $h_k(k=1,2,3,4)$ and $r_{Ak}(k=1,2,3,4)$ are the height and the equivalent radius of the $k$-th crossarm, respectively. Here, $r_{Ak}$ is chosen as 1/4 of the width of $k$-th crossarm at the junction point.

## 4. Application of the model to the 500kV transmission tower

*Selection of model parameters for 500kV transmission tower*

In this section, the tower model proposed in the previous section is applied to the real size transmission tower. The surge response characteristics of the real size 500kV transmission tower are measured. Impulse currents of 200nsec rise time are imposed on the top of the tower whose geometry is shown in Fig. 4. The imposed current wave shape is measured at the top of the tower and

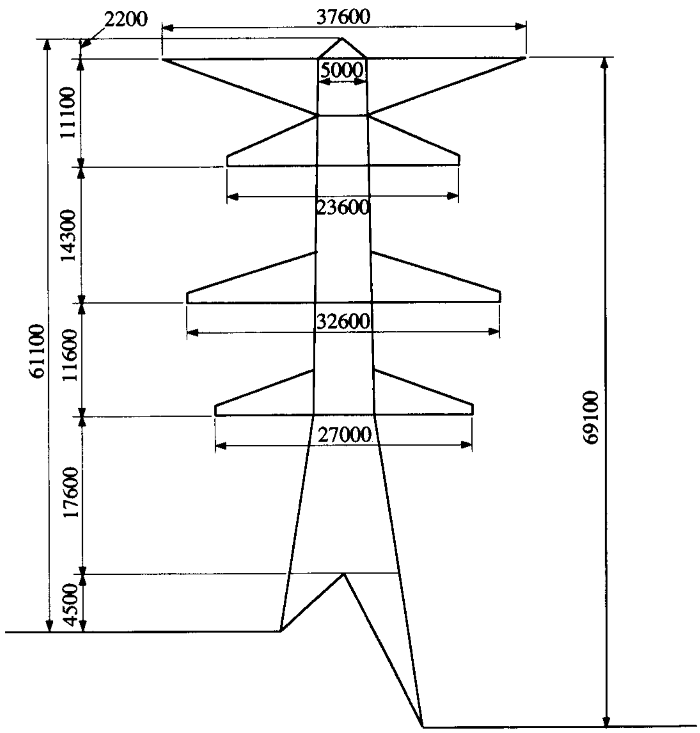



Fig. 4. Configuration and dimensions of the 500kV transmission tower (unit: mm).

the wave shapes of the induced tower voltage are measured at the tip of the four arms, i.e., the ground wire, the upper phase, and middle phase and the lower phase arm.

The dimensions of this tower in Fig. 2 are given as follows:

$$\begin{array}{llll} h_1 = 59\,\text{m}, & h_2 = 47.2\,\text{m}, & h_3 = 33.6\,\text{m}, & h_4 = 22\ \text{m}, \\ r_{T1} = 0.07\,\text{m}, & r_{T2} = 0.08\,\text{m}, & r_{T3} = 0.16\,\text{m}, & h_{T4} = 0.178\ \text{m}, \\ \text{R}_{T1} = 5.00\,\text{m}, & R_{T2} = 5.45\,\text{m}, & R_{T3} = 6.03\,\text{m}, & R_{T4} = 6.50\ \text{m}, \\ r_B = 0.203\,\text{m}, & r'_B = 0.178\,\text{m}, & R_B = 12.55\,\text{m}, & R'_B = 7.40\ \text{m}, \end{array}$$

Substituting those values into Eqs. (5), (6) and (7), the surge impedances of four sections of main conductors are obtained as follows:

$$\begin{aligned} Z_{T1} &= 129\ \Omega \\ Z_{T2} &= 113\ \Omega \\ Z_{T3} &= 88\ \Omega \\ Z_{T4} &= 45\ \Omega \end{aligned} \tag{10}$$

The surge impedances of four sections of lattice conductor part $Z_{L1}$, $Z_{L2}$, $Z_{L3}$ and $Z_{L4}$ can be obtained by putting the value of $Z_{T1}$ to $Z_{T4}$ in Eq. (10) into Eq. (8). Next, the surge impedances of the ground wire arm, the upper phase arm, the middle phase arm and the lower phase arm are also calculated from Eq. (9) by using the values of $r_{A1} = 2.95$ m, $r_{A2} = 2.67$ m, $r_{A3} = 2.60$ m, and $r_{A4} = 2.25$ m. Those are as follows:

$$\begin{aligned} Z_{A1} &= 221\ \Omega \\ Z_{A2} &= 215\ \Omega \\ Z_{A3} &= 195\ \Omega \\ Z_{A4} &= 178\ \Omega \end{aligned} \tag{11}$$

*Comparison between measured and calculated wave forms.*

The wave shapes of the voltages at the tip of the four arms; the ground wire, the upper phase, the middle phase and the lower phase arm, are calculated from the model shown in Fig. 3 giving the imposing current the same as the measured ones. Fig. 5 compares the calculated voltage wave shapes with the measured ones. It can be seen from Fig. 5(a) and (b) that the calculated wave shapes of the ground wire and upper phase arm agree with the measured ones not only at the maximum point but also in the wide range of the wave shapes. The calculated voltage wave shapes of the middle and the lower phase arms (Fig. 5(c) and (d)) agree with the measured ones except at the latter half of the wave shapes. This disagreement in the latter part is due to the difference of foot lengths of the main conductors. In general, however, the obtained results from the proposed tower model sufficiently agree with the measured ones. These results show that the four sections model is able to express the surge performances of the real size transmission tower.

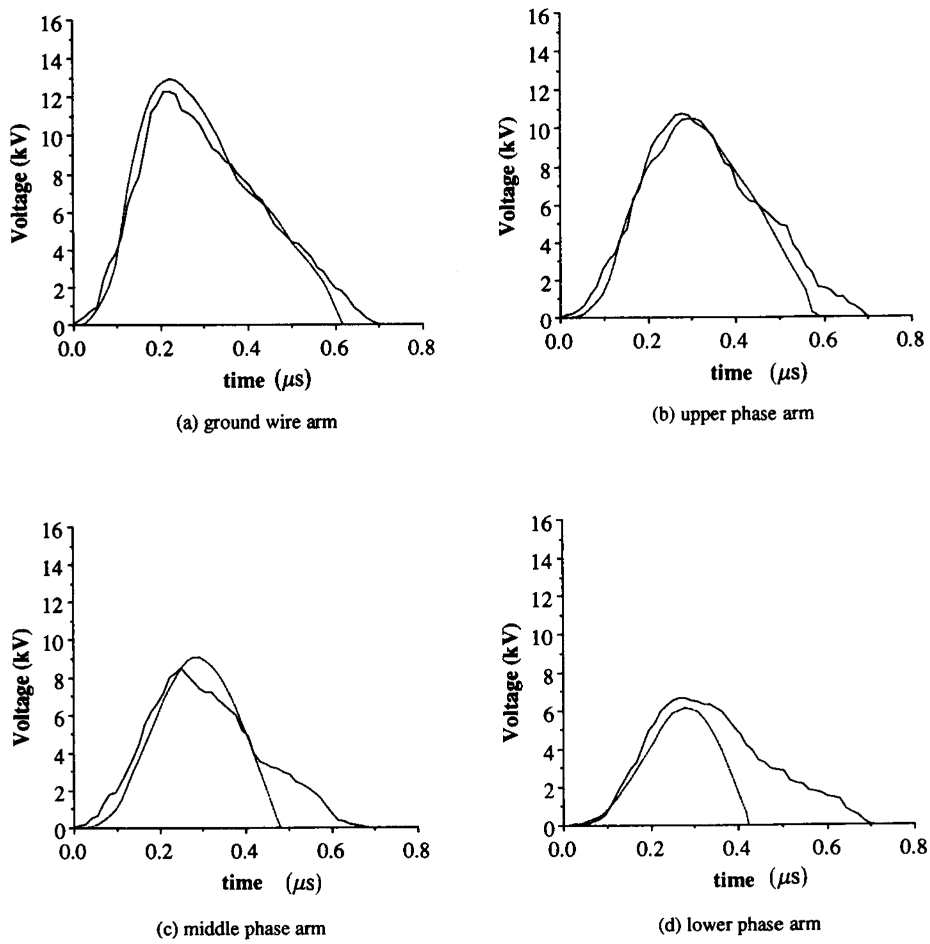



Fig. 5. Comparison between measured and clculated voltage wave shapes at various points on the tower.
(Four sections model,———measured,———calculated)

$Z_{T1}$ for one section model is determined by putting the values of $h=59$ m, $r_T=0.07$ m, $r_B=0.203$ m, $R_T=5.0$ m and $R_B=12.5$ m into Eq. (5), as

$$Z_T=111\,\Omega \tag{12}$$

The surge impedance of the lattice conductors is given by $Z_L=9Z_T$ and those of the four arms are chosen as the same values as of the four sections model given in Eq. (11).

The voltage wave shapes of the transmission tower calculated from this one section model are shown in Fig. 6 together with the measured ones. By comparing these results with the one obtained by the four sections model shown in Fig. 5, one section model does not simulate so well the measured wave shapes. Namely, the calculated voltages of the middle and the lower phase arm are somewhat larger than the measured ones. Neither the voltage wave shapes on the ground wire and the upper phase arm do not exactly agree with the measured ones in the latter half portion.

*The crossarm model*

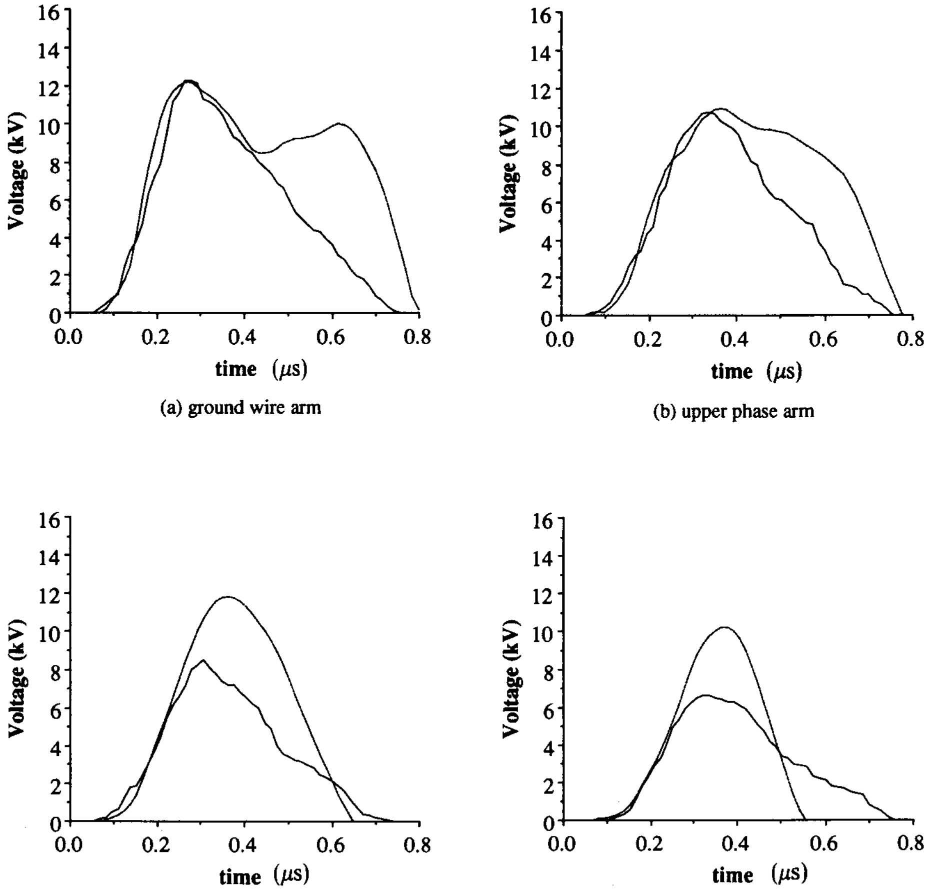
The tower model without crossarms is investigated. The voltage wave shapes of the 500kV tower are obtained from the armless model and are shown in Fig. 7. It is seen from this figure that the armless model produces considerably different responses from the actual ones. It is found by comparing these results with the ones of the full tower model shown in Fig. 5, that the armless tower model is not sufficient to simulate the tower surge performances.

*The surge propagation velocity*

In all the calculations done in the previous sections, the propagation velocity along the tower is set equal to that of light. In order to check the effect of surge propagation velocity, the tower voltages are calculated assuming that the propagation velocity is 80% of the speed of light, and are shown in Fig. 8. It is found from this figure that the light velocity model gives closer voltage wave forms with the measured ones than the reduced propagation velocity model.

## 5. Conclusions

(1) An equivalent distributed constant line model of the transmission tower is developed. The model consists of three parts: main conductors, lattice conductors and crossarms. The surge impedance of each part is given by the




(a) ground wire arm
(b) upper phase arm
(c) middle phase arm
(d) lower phase arm

Fig. 6. Comparison between measured and clculated voltage wave shapes at various points on the tower.
(One sections model,———measured,———calculated)

functions of its dimension and geometry.

(2) The model proposed is proved to provide the surge response characteristics close to that of the actual transmission tower.

(3) For such a tower higher than about 50 m, a one section tower model is not sufficient to express the real surge performances and a four story tower model affords the better performances.

(4) By adding the arm model to the armless model, the tower model is made

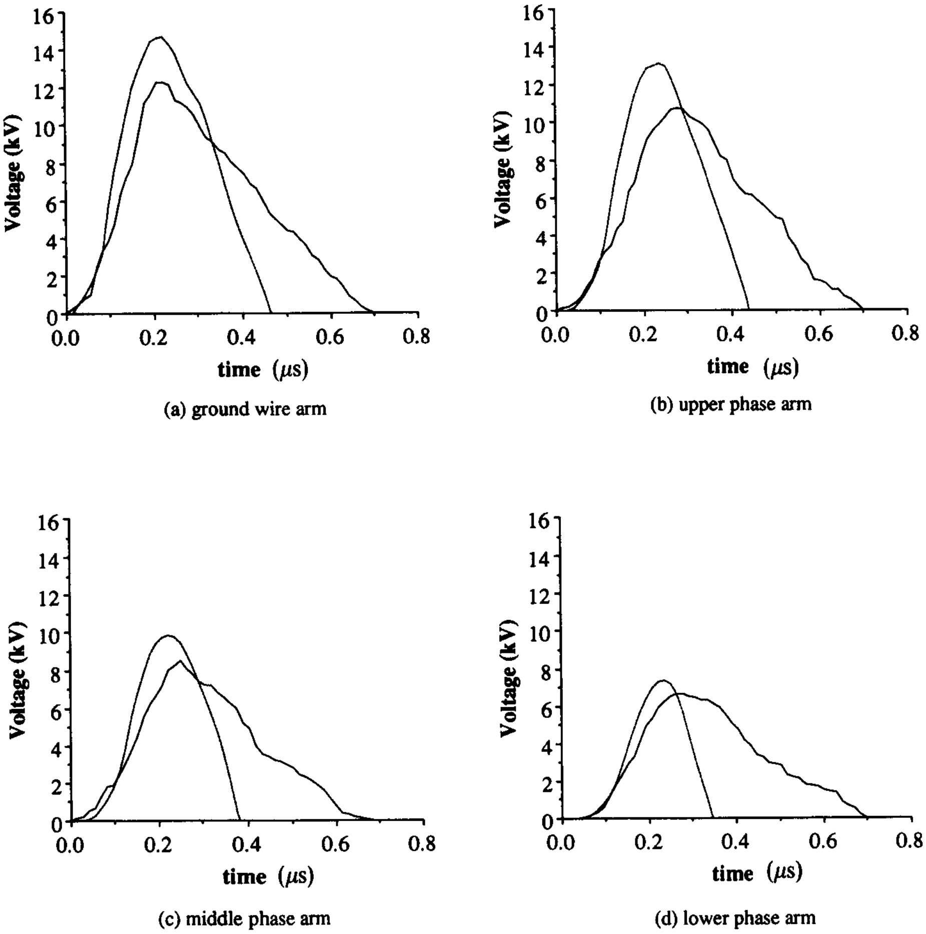



Fig. 7. Comparison between measured and clculated voltage wave shapes at various points on the tower.
(Armless model,———measured,———calculated)

to provide performances closer to the measured ones.

(5) The surge propagation velocity along the tower is proved to have the velocity of light.

In order to get more general conclusions, comparisons of surge performances obtained from model calculations with ones from measurements for several transmission towers should be made.

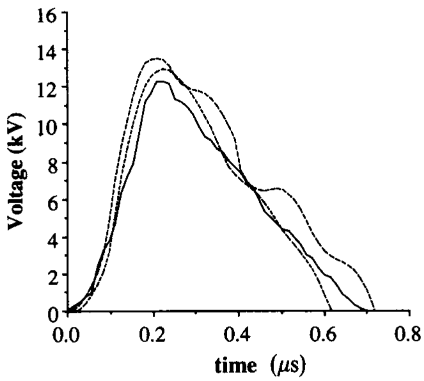



Fig. 8. Calculated wave shapes of the tower top voltage by two different propagation velocities.
(——measured,——light velocity, ——80% of the light velocity)

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