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DIGITAL COMPUTER STUDIES OF THE SURGE RESPONSE OF A TRANSMISSION LINE TOWER

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Abstract—In this paper, the transmission line tower response and behaviour are described when a lightning stroke terminates on the tower apex. The accompanied overvoltages on different points on the tower and under different conditions are covered. The effect of tower representation and modelling on the overvoltages produced and the tower travel time is also included.

Electrical power systems   Transmission line tower modelling   Lightning surges

INTRODUCTION

Overhead power lines are inevitably subject to disturbances from lightning on a considerable scale. These disturbances are the strongest and most dangerous in open line networks. The lightning overvoltages in power systems depend on many parameters, and a comprehensive and relatively complicated model is necessary to perform reliable calculations. An important element in such calculations *is the surge response characteristics of towers and lines.* In fact, many studies have been done on the behaviour of transmission line towers under lightning surge conditions. In most of these studies, *the tower* is represented simply by a single surge impedance. The accurate representation of the transmission tower is a difficult problem and has been the subject of much discussion. For HV and EHV systems, it is generally accepted that *the tower response model has a large influence on the final result.* In this study, the *transient behaviour of a specific tower under onerous lightning strokes is investigated.* Particular attention is paid to the tower modelling. Instead of simply representing the tower as a single surge impedance terminated to earth by a tower footing resistance, *each major limb is treated as a distributed parameter element in its own right.* That is, surge impedances and travel times are defined for each major member, so that the tower is defined by 10 interconnected propagation paths.

TOWER MODELLING

There are different approaches in representing the tower:

Tower as a Lumped Inductance

The tower was represented in many early studies by an inductance (L) terminated by the tower footing resistance (TFR). This is a rough approximation, but it is used usually for short tower structures in some calculations. For tall tower structures, however, the wave of lightning stroke current takes a finite time to travel down the tower structure to the earth. It is more accurate in such cases to represent the tower by an effective surge impedance and wave transit time rather than a lumped inductance.

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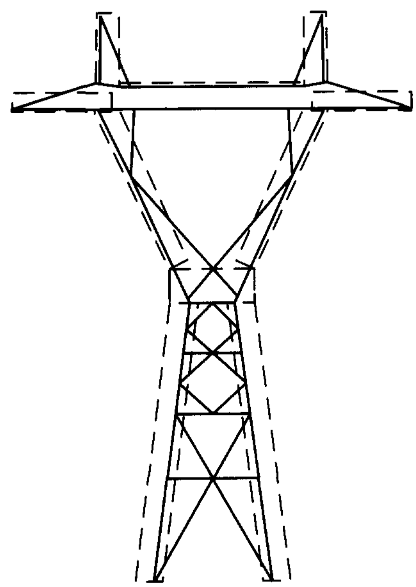

Fig. 1. Tower configuration.

Tower as a Single Propagation Path

This is the common representation of the tower. It consists of two parameters: *tower surge impedance and tower travel time*. Several attempts have been made to measure experimentally and theoretically calculate the tower impedance and tower travel time on full-scale towers [1–10].

Tower as many Interconnected Propagation Paths

Each major limb of the tower can be treated as a "*distributed parameter*" in its own right, instead of simply representing the tower as a single surge impedance terminated to earth by a "TFR". That is, surge impedances and transit times are defined for each crossarm or major member so that the tower is defined by many interconnected propagation paths. Figure 1 shows such a tower with 10 elements. This representation of the tower is, of course, more complicated than the previous one. It requires many more calculations, *but it can give more accurate results for the surge response of the tower* [11–15].

OVERVOLTAGE INVESTIGATION USING FULL TOWER REPRESENTATION

Stroke on Tower Apex

If a tower connected by a ground wire to its neighbour is hit by a *lightning stroke*, a large current flows to earth. If the *effective surge impedance* of the tower struck or the amplitude of the stroke current is *sufficiently high*, a voltage may be produced which is sufficient to cause *a back flashover*.

The voltage waves produced by the current flowing along the earth wire will travel along the earth wire in both directions from the tower struck. On reaching the neighbouring towers, waves are partly reflected and refracted (transmitted). The reflected surge will arrive back to the tower struck after a time equal to the wave transit time of one span of the transmission lines.

In this study, attention will be paid to the voltage conditions at tower T_1 when a stroke current *of abnormally high amplitude and high rate of front rise hits the tower* T_2 (Fig. 2). The effects of tower footing resistance (TFR), tower surge impedance and the length of the crossarms on the overvoltage magnitude will be investigated.

Method of calculation

One method that can be used for evaluating the resultant voltage wave at the tower is to consider all discharge paths to be replaced by their surge impedance and to construct a *space–time lattice diagram*.

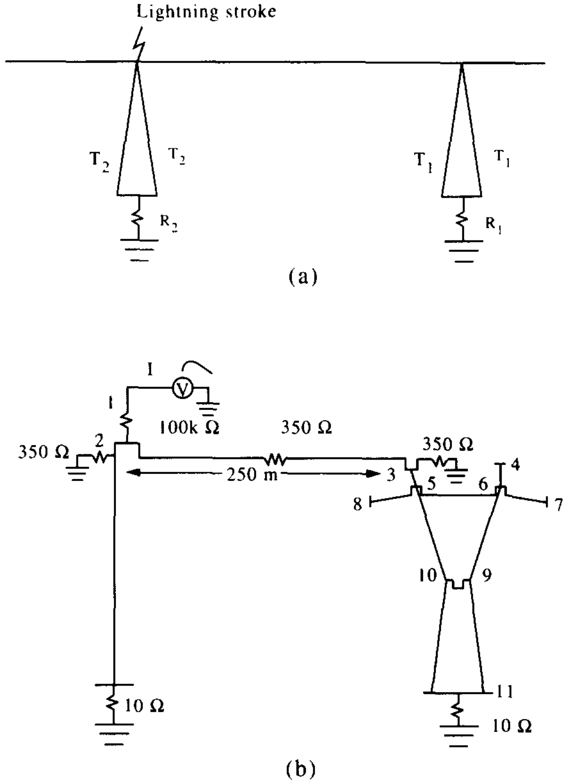

Fig. 2. Lightning stroke at tower T_2. System configuration: (a) schematic diagram; (b) system layout.

The description of this method can be found in Bewley's book [12]. It is basically *a graphical method* for calculating the voltage variation with time at any point on a line due to the propagation of voltage surges along the lines and cables. In the lattice diagram method, all circuit elements are represented by transmission lines with distributed parameters. The basic data required by the method consists of the lengths of the lines comprising the network and their surge impedances. *A basic time interval* "θ" must be chosen for each transient calculation and should have a value which is less than the travel time of the shortest line to be represented. More recently, the lattice diagram method has been used with a digital computer [13] for the solution of the power circuits. When using the method with the digital computer, the lattice diagram itself is dispensed with and is replaced by *a Branch timetable*, which records the progress of each particular wave along the circuit elements which comprise the system. Such a *timetable* can be found in Ref. [14], where illustrations are given about this matter.

(a) Transmission lines and tower modelling. Each major limb of the tower T_1 is considered as a stub of a transmission line. There are 10 such elements in the tower T_1. Each element is considered to have a surge impedance of 100 Ω. Figure 3 shows the length of each element of the tower. The surge impedance of the earth wire is assumed to be 350 Ω, and the length span between two adjacent towers is taken to be 250 m. Tower T_2 is represented in these investigations by a single surge impedance and a travel time equal to the height of the tower (31.33 m) divided by the velocity of light (300 m/μs). One reason for not modelling tower T_2 fully is that the attention is mainly focused on the voltage variations on different parts of the tower T_1 for a severe stroke on the tower T_2 apex.

(b) Stroke current simulation. A stroke current is usually simulated by a current source, but since in the computer program only voltage sources can be used, the current source is simulated by a voltage source with a series resistance.

(c) Basic time interval (θ). The shortest line to be represented in the system is 3.89 m. It has a travel time $= 3.89\ \text{m}/300\ \text{m}/\mu\text{s} = 0.01296\ \mu\text{s}$.

A basic time interval of 0.01 μs is chosen in carrying out this work.

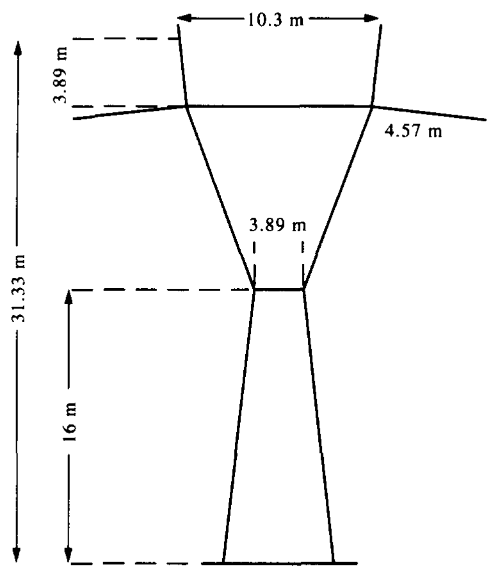

Fig. 3. Tower dimension.

System data

Tower dimension as shown in Fig. 3, surge impedance of the stubs (Z_t) = 100 Ω, surge impedance of the earth wire (Z_e) = 350 Ω, voltage base = 400 kV = 1 p.u., basic time interval = 0.01 μs, observation time = 2 μs.

Lightning waveshape representation

Among the few facts that are universally accepted at the present time is the double exponential nature of the lightning wave. The investigation in this work will, therefore, take the double exponential wave as typical of lightning strokes. The rate of rise of this wave, however, is subject to contention. Here, only waves of very *steep front* will be considered. In general, the rate of rise is important because it determines the flashover rate of the line external insulation. This wave is defined as:

$$i(t) = I_0(\epsilon^{-\alpha t}\epsilon^{-\beta t})$$

where, I_0 = peak current magnitude, and (α, β), are constants depending on the rate of rise and time to half value. The crest value, $I_c = I_0(\epsilon^{-\alpha k}\epsilon^{-\beta k})$, occurs at time to crest,

$$k = \frac{\ln \beta/\alpha}{\beta - \alpha}.$$

At any junction of the system, the magnitude of *the transmitted or reflected surge* depends linearly on the magnitude of the incoming surge. If V_i, V_r and V_t represent the *incoming*, *reflected* and *transmitted surges*, respectively, the following relations hold:

$$V_r = K_r V_i$$

and

$$V_t = K_t V_i$$

where

$$K_r = \frac{Z_t - Z_i}{Z_i + Z_t},$$

$$K_t = \frac{2Z_t}{Z_i + Z_t}$$

and Z_t, Z_i are surge impedances and K_r, K_t are reflection and refraction coefficients [12–14].

Voltage waveforms at tower T_1

Figure 4 shows the voltage variations at five points of the tower T_1 for a 320 kA, 1.2/50 μs stroke on tower T_2. The footing resistance of both towers is 10 Ω. A rough demonstration for the wave-forms of the overvoltages will be given.

When the stroke hits the tower T_2, a portion of the stroke current surge (S_1) travels along the earth wire towards tower T_1 in time T equal to the length of a span divided by the velocity of light (300 m/μs), thus T is

$$= \frac{\text{a span length}}{\text{velocity of light}} = \frac{250}{300} = 0.833\ \mu\text{s}.$$

The main portion of the stroke current goes through tower T_2, where successive reflections and refractions take place. When arriving at the tower base and due to the TFR, the surge reflects back and reaches the tower (T_2) top, where a portion of it again travels along the earth wire towards (T_1) top, where a portion of it again travels along the earth wire towards T_1, *lagging* the first surge by a time "t" equal to twice the travel time of the tower,

$$t = \frac{2 \times 31.33\ \text{m}}{300\ \text{m}/\mu\text{s}} = 0.209\ \mu\text{s}$$

(experimentally, t is found to be 0.26 μs, as the tower represented by this many interconnected propagation paths model [11]).

This second surge (S_2) is comparable in amplitude to the first surge because of the low footing resistance of tower T_2 (10 Ω), which permits the surge reaching the base to reflect back to the top with a reflection coefficient (K_r) close to 1,

$$K_r = \frac{Z_t - R}{Z_t + R}$$

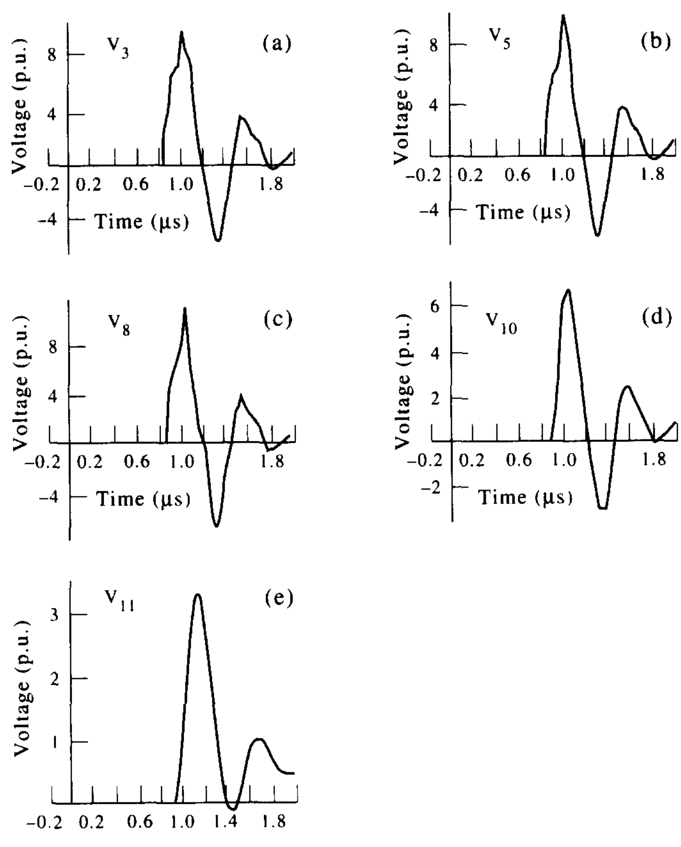

Fig. 4. Voltage at different points of the tower T_1 for a 320 kA, 1.2/50 μs stroke at tower T_2.

where Z_t = effective surge impedance of the tower, and R = tower footing resistance. If $Z_t = 100\,\Omega$ and $R = 10\,\Omega$, then $K_r = 0.82$. The same process continues, and a series of reflected surges from the base of tower T_2 travel along the earth wire and reach the tower T_1 in a cyclic manner. The time between two successive surges is $t = 0.26\,\mu$s. In examining the voltage waveforms of Fig. 4, the overvoltages start to build up at $t = 0.84\,\mu$s [Fig. 4(a)] when the first surge (S_1) reaches tower T_1. The crest occurs 0.26 μs later. After that, the voltage starts to *decrease steeply* due to the arrival of two surges at the same time with *different polarity* from the initial surge. The *first surge* is the reflected surge from the base of the tower T_1 of the initial surge (S_1). The *second* is the surge corresponding to that entering tower T_2 and coming back along the earth wire (S_2) to reach T_1 in a time $(T + t) = 1.093\,\mu$s. Because of the high rate of front rise of the lightning stroke, these surges are able *to reduce* the overvoltages *sharply and even dominate over* the initial surge and *turn the polarity* of the overvoltage into negative.

At time $(T + t)$, another pair of surges reach the tower top, but this time with a polarity similar to that of the initial surge. The overvoltage magnitude *starts then to drop in the negative region*, reaches zero and goes up to a new crest value, but this time of magnitude is less than that of the first crest. This process continues in an oscillatory manner. The period of these oscillations is 0.26 μs.

Effect of TFR on voltage magnitude

Broadly speaking, low tower footing resistance (TFR) has the following beneficial results:

(1) It reduces the potentials on the ground wires, on the line wires and the potential across the insulators.
(2) It limits the disturbance to a few spans.
(3) It shortens the duration of dangerous voltages.

In this section of the study, the effect of TFR on the voltage conditions at tower T_1 will be considered for a stroke current of 320 kA, 1.2/50 μs wave ($\alpha = 0.0143$ and $\beta = 4.876$) at tower T_2. Low tower footing resistances are considered here because it is assumed that towers T_2 and T_1 are close to a certain substation. Table 1 shows the positive peak and negative peak of the overvoltages at different nodes of tower T_1 for different values of the tower footing resistances R_1 and R_2 (where R_1 and R_2 are the footing resistances of towers T_1 and T_2, respectively).

The first positive peak of the voltage waveform at the points of the tower is independent of the TFR value. It depends mainly on the steepness of the initial stroke current surge. However, the negative peak of the voltage waveform *increases in magnitude when the tower footing resistance becomes lower*. Figures 5 and 6 show the voltage waveforms at the tower top and the crossarm, respectively, for different values of the tower footing resistance. It is seen that, *when the reflected surges (S_1 and S_2) from the base of towers T_1 and T_2 reach the tower top, the voltage starts to decrease*, reaches the zero value and becomes negative. For lower footing resistance of either tower T_1 or tower T_2, the reflected surge from the corresponding tower base has a large amplitude accompanied with a reduction in the positive region and an increase in the negative peak. The steepness of the voltage waveform becomes sharper for lower TFR, as seen in Figs 5 and 6.

Table 1. Maximum overvoltages at different points of tower T_1 for a 320 kA, 1.2/50 μs stroke on tower T_2 (Fig. 2)

R_1 (Ω)	R_2 (Ω)	V_3 (p.u.)	V_5 (p.u.)	V_7 (p.u.)	V_8 (p.u.)	V_9 (p.u.)	V_{10} (p.u.)	V_{11} (p.u.)
10	10	9.64	9.75	9.16	10.97	6.52	6.81	3.31
		−6.41	−6.32	−5.68	−6.90	−3.27	−3.31	
5	10	9.64	9.72	9.14	10.90	6.01	6.24	1.81
		−8.71	−8.61	−7.95	−9.26	−4.85	−4.97	
1	10	9.64	9.68	9.12	10.83	5.69	5.79	0.40
		−10.90	−10.80	−10.12	−11.51	−6.36	−6.55	
1	5	9.64	9.68	9.12	10.783	5.69	5.79	0.40
		−11.85	−11.85	−11.12	−12.54	−6.93	−7.16	

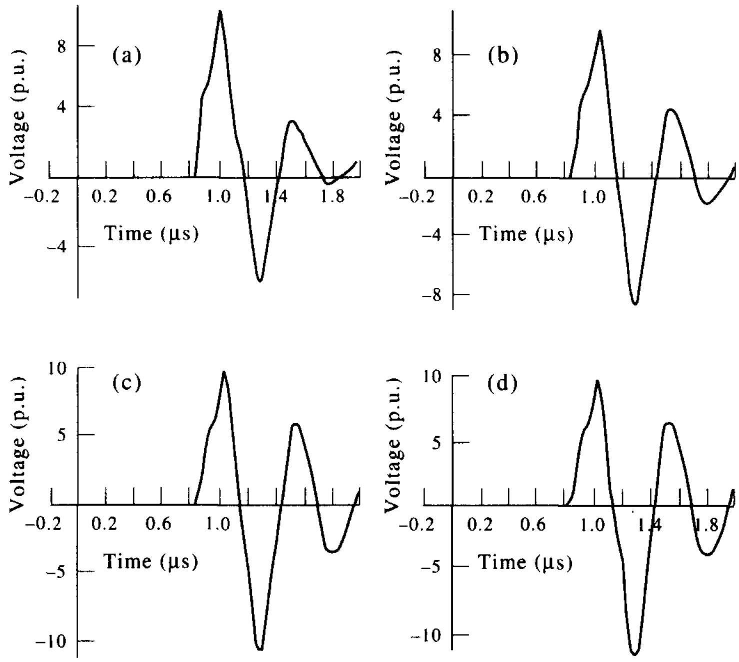

Fig. 5. Tower (T_1) top potential (V_5) for a 320 kA, 1.2/50 μs stroke at tower T_2: (a) $R_1 = R_2 = 10\,\Omega$; (b) $R_1 = 5\,\Omega$, $R_2 = 10\,\Omega$; (c) $R_1 = 1\,\Omega$, $R_2 = 10\,\Omega$; (d) $R_1 = 1\,\Omega$, $R_2 = 5\,\Omega$.

For the same reason, the second positive peak has a larger magnitude when the TFR becomes lower.

It can be concluded that, *for a stroke current of abnormally high amplitude and steepness, a lower TFR tends to increase the first subsequent peaks of the voltages at different nodes of the tower, except at the base, where the maximum overvoltage drops considerably.*

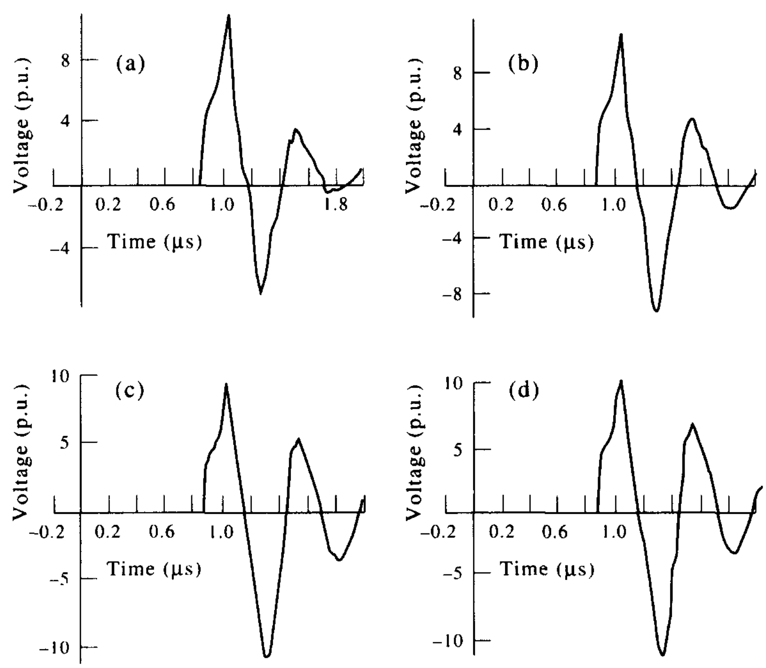

Fig. 6. Voltage at tower (T_1) crossarm (V_8) for a 320 kA, 1.2/50 μs stroke at tower T_2: (a) $R_1 = R_2 = 10\,\Omega$; (b) $R_1 = 5\,\Omega$; (c) $R_1 = 1\,\Omega$, $R_2 = 10\,\Omega$; (d) $R_1 = 1\,\Omega$, $R_2 = 5\,\Omega$.

Table 2. Maximum overvoltage at different points of the tower T_1 for a stroke current of 355 kA, 1.2/50 μs on tower T_2

Z_t (Ω)	V_3 (p.u.)	V_5 (p.u.)	V_7 (p.u.)	V_8 (p.u.)	V_9 (p.u.)	V_{10} (p.u.)	V_{11} (p.u.)
100	10.7	10.75	10.12	12.02	6.32	6.43	0.44
200	17.76	17.86	17.09	19.76	10.57	10.78	0.37
300	22.77	22.99	22.17	25.20	13.64	14.00	0.32
400	26.51	26.87	26.03	29.26	15.94	16.48	0.28

Effect of Tower Surge Impedance on Voltage Magnitude

Tower T_1 is represented by 10 interconnected stubs of transmission lines. Each one of these elements has a surge impedance of 100 Ω. The surge impedance of the tower elements (Z_t) is modified to investigate its effect on the overvoltage magnitudes on the tower. Table 2 shows the maximum overvoltages at different points on the tower for different values of Z_t. In this investigation, it is assumed that a stroke current of 355 kA, 1.2/50 μs waveshape ($\alpha = 0.0143$ and $\beta = 4.876$) hits tower T_2. The footing resistance of tower T_1 is 1 Ω and that of tower T_2 is 100 Ω. Figure 7 shows the voltage variation on the tower top for four different values of Z_t.

The effect of the surge impedance Z_t on the voltage conditions is clear from Fig. 7 and Table 2; the higher the tower surge impedance, *the larger the overvoltage magnitude*. This is because, when the initial surge coming along the earth wire towards tower T_1 reaches the tower, it splits into two portions; *one* travels along the extension of the earth wire, and *the other* goes through the tower itself. *The greater the surge impedance of the tower, the higher the transmitted surge into it, and consequently, larger overvoltages are expected to be produced.*

Effect of crossarms length on voltage magnitude

The tower considered in the previous investigations has crossarms 4.57 m long. In practice, some towers have longer crossarms. Two more towers are examined for crossarms of 7 and 10 m, respectively. The voltage conditions at different points of the tower are recorded. It is found that *the voltages corresponding to a tower of a crossarm length of 7 m are almost the same as that of 4.57 m crossarm length.* However, a crossarm 10 m long will *change the voltage* at the different

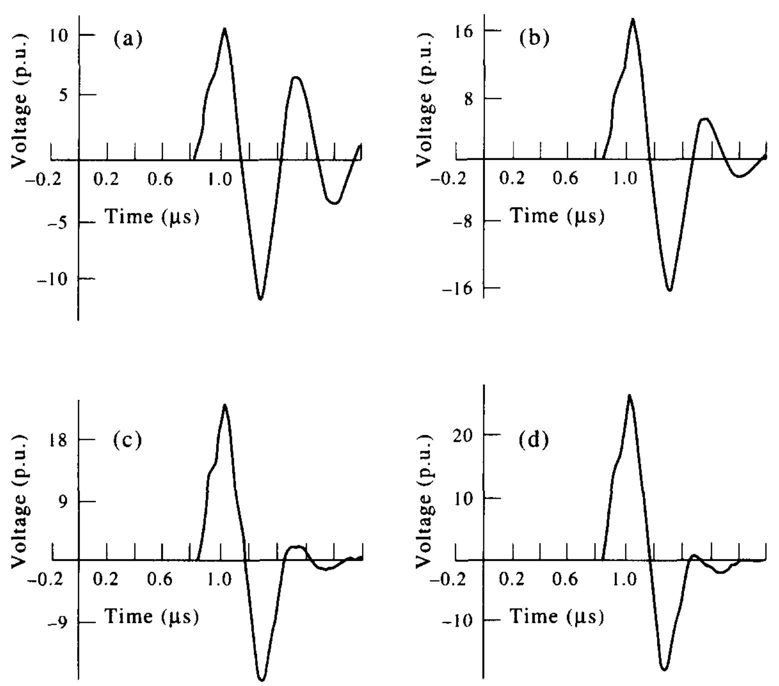

Fig. 7. Tower (T_1) top potential (V_5) for different tower surge impedance Z_t for a stroke at tower T_2: (a) $Z_t = 100\,\Omega$; (b) $Z_t = 200\,\Omega$; (c) $Z_t = 300\,\Omega$; (d) $Z_t = 400\,\Omega$.

Table 3. Positive and negative peaks of the overvoltages at different points of the tower T_1

Crossarm length (m)	V_3 (p.u.)	V_5 (p.u.)	V_7 (p.u.)	V_8 (p.u.)	V_9 (p.u.)	V_{10} (p.u.)	V_{11} (p.u.)
4.57	10.7	10.75	10.12	12.02	6.32	6.43	0.44
	−12.1	−11.99	−11.23	−12.78	−7.06	−7.27	
10	9.40	9.22	10.78	10.89	6.14	6.20	0.43
	−11.13	−11.06	−12.25	−11.88	−6.99	−6.74	

points of the tower. A *reduction* in the maximum overvoltages is obtained. This reduction appears mostly at the crossarm and tower top. Table 3 summarizes the situation.

The effect of crossarm length has a second interesting feature. The tower travel time value can be obtained from the repetition of multiple reflections seen in the tower top voltage. For crossarms 10 m long, the tower travel time is found to be longer than that corresponding to crossarms 4.57 m long. There is a time lag of 0.01 μs in the tower travel time. This corresponds to about 7.7% of the tower travel time.

CONCLUSION

In this study, one type of tower has been covered. The tower has been covered. The tower was represented by 10 *interconnected* "distributed parameter" *elements.* Transit time and surge impedance were defined for each element. *The transient behaviour on the tower* when severe lightning strokes terminate on the *apex of the tower* have been covered in the study.

Many parameters and factors are changed and modified to observe their effect on the *overvoltages on different points of the tower.*

For very steep fronted waves, the tower top potentials vary in an *oscillatory manner.* The first peak of these *oscillations is positive,* whereas the second peak is negative. It is found that, when a lower tower footing resistance is used, the negative peak *is higher in magnitude* and so are the *subsequent peaks of the oscillations.*

The effect of the tower surge impedance on the overvoltages produced at different locations on the tower was also investigated. The lower the surge impedances of the tower elements, the more the reduction in the overvoltages produced.

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