Study the Induced Voltage Caused by Lightning Flash to Overhead Power Lines Tower

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Abstract*- To estimate overhead lines lightning performance, the back flashover critical current computation of insulators is important. There are two methods at present. One method counts for the surge response at cross-arm and shielding wires, also shielding wires inducing voltage on phase lines. The other method not only considers the above components, but also counts for the lines induced voltage caused by the lightning electromagnetic field. The two methods produce great differences for the same lines. Many studies have proved that overhead lines induced voltage caused by lightning flash to their nearby ground be high, the biggest induced voltage reaches to or exceeds its operation voltage a few times. As lightning flash to tower, because the lightning return stroke channel or lightning striking point is near to the considering lines, its induced voltage will be accordingly higher than that produced by indirect lightning striking to nearby ground. This paper analyzes the lightning current distribution in the lightning channel and the transmission tower when lightning flash to a tower top. It is found that the great lightning current is reflected to the lightning channel because of the reflection effect at the tower top. When the tower is higher, the lightning striking point is far away from the ground. Based on the electromagnetic field theory, the induced voltage on the same height overhead lines is small since big lightning current is far away on the tower top. Using numerical electromagnetic code and its coupling to lines modeling, the overhead lines induced voltages are computed. The simulation results show that, sameness to the indirect lightning, the influence action of lightning striking distance is transformed to the tower up-leader height. That is, the lines induced voltage caused by lightning striking to tower top not only relates to the lines height, but also relates to the tower height.

I. INTRODUCTION

Lightning flash to the tower of an overhead power line produces a transient voltage across the insulator strings from which the phase conductors are suspended. Insulators will flash over if the transient voltage exceeds their withstand voltage level. This is called back flashover [1],[5][12],[13],[14]. At present, there are two methods to estimate these back flashover outage rate of overhead lines [18],[19]. One counts for the surge response at cross-arm and the shield wire inducing crosstalk coupling voltage on the phase lines, but neglecting the induction effects of the lightning channel The other not only considers the above two components, but also counts for the phase lines induced voltage caused by the lightning return stroke channel electromagnetic field and tower travelling current producing magnetic field [15],[17]. These two methods produce great differences for estimating the lightning performance of the same overhead lines, so the engineering cost of the power lines designed by the two methods are also different. Although this discrepancy is quite significant, the statistic status of lightning phenomenon and the environment conditions cause the engineers to overlook this issue. And practically when the lines insulation being designed, the estimation results must be amended according to the lines discharge test and the foretime accumulated lines operation experience which makes the induced voltage study be ignored.

Although the significance of the indirect lightning induced voltages is well known, owing to the higher withstand voltage level of the power transmission lines, the induction effects caused by the lightning strokes to nearby ground are neglected in estimation of lightning outage rates of power transmission lines[16]. But the lightning channel and tower are very close to the phase conductors when lightning strikes the tower. Since the lines were not connected with lightning channel, the lines induced voltage predicatively exists and is different from the nearby ground lightning stroke induced voltage. Therefore, the electromagnetic fields of the lightning channel and the tower travelling currents along with their inducing voltage must be discussed separately.

Based on the wave travelling characteristic analysis and the numerical electromagnetic code computation, this paper first analyzes the current distribution along the lightning channel and the struck tower. Then it simulates the lightning electromagnetic field around the tower. Thirdly it computes the induction voltages on perfect conductor phases. The results show that the induction effect of the lightning channel electromagnetic fields is very big, and it is greatly different from the induction effects caused by lightning strikes to nearby ground. The induction voltage of the same height phase conductor is dependent on the tower height. In a word, this paper will discuss the insulator voltage consisting components, overhead lines induced voltage, and the tower height influence to the induced voltage. Finally, the analysis is validated by simulation computation.

II. INSULATORS VOLTAGE

Fig.1 illustrates a transmission tower, which simulates a lightning stroke hitting a tower. The lightning current splits into the tower and the shield wire, and those currents will produce surge responses on cross-arms and shield wires. Due to the electromagnetic field induction effect, the phase lines suspended on strings would induce voltage. The transient voltage across the insulators string will be the difference between the cross-arm surge response and the phase induced voltages [13],[15]. Not considering the instantaneous AC voltage on phase lines, this voltage has several components: i) Cross-arm surge responses: the lightning current flowing through the surge impedance of the tower and footing resistance raises the cross-arm voltage. This produces a voltage across the insulator strings. This is called surge response component. ii) Phase conductors crosstalk voltage: the lightning current flowing through the shielding wire induces a voltage on phase conductors by the electromagnetic crosstalk coupling between the parallel lines. This also produces voltage across insulator strings. This is called crosstalk coupling component. The coupling potential polarity of the lines is the same to the lightning current. iii) The lightning channel induction voltage on lines: because the lines are not connected with lightning channel and tower, just like the crosstalk coupling from shield wires, the lightning channel electromagnetic fields must induce voltage on the lines, and so is the magnetic field induction effect due to the travelling currents along the tower. This is called induction component. The induction potential polarity is opposite to the lightning current which can increase the total voltage across the insulator [15]. Since the lightning channel and the tower are only a few meters away from the phase conductor, this component will be significant [2],[13].

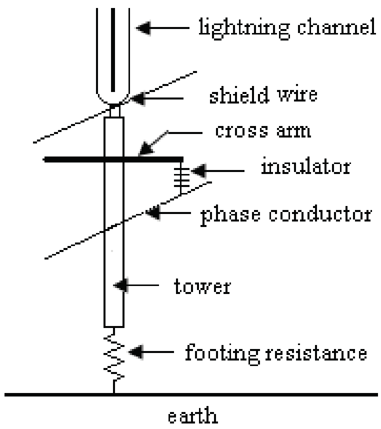

Fig. 1. Sketch map of the lightning strike to transmission tower

It has been proved that when we only consider the traveling effects of lightning current along the tower, the estimating veracity by using traveling wave method and the equivalent R-L circuit are similar on the whole. And a realistic simplification of the problem is also affected by the limited precision of the lightning stroke itself. And representation of the lightning response of transmission tower by lumped resistance-inductance circuits has distinct advantages in that the traveling wave equations are eliminated and voltage solutions may be determined by conventional circuit analysis.

Here, we use the equivalent R-L circuit shown in Fig. 2. To compute the cross-arm surge response, V_c, of lightning flash to tower, the tower was assumed a uniform inductance; the tower footing resistance was assumed to be constant, R_{tf}; L_s is the equivalent inductance of shield wires; V_{in} is the voltage across the insulator; V_{top}, V_p are respectively the surge voltage on the tower top and phase conductors; Z_p is the impedance of phase conductor; i, i_t, i_s, i_p are respectively the current following through the lightning channel, the tower, the shielding wire, and the phase conductor.

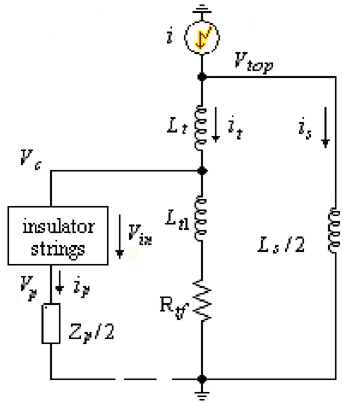

Fig.2. Equivalent R-L circuit of a transmission tower

Supposing the lightning current is a ramp function (in estimating lines lightning performance, this function is the common used waveshape), that is, $i = \alpha t$ strokes to the tower top. The lightning current will shunt into two portions: one flows through the tower and the footing resistance to ground, i.e. i_t; the other flows through the shield wires to adjacent towers i_S. If the tower current shunt coefficient with shield wire is β (according to the field test and analysis, β is a constant from 0.8 to 0.9), then the current that flows through the tower is

$$i_t = \beta i = \beta \alpha t \tag{1}$$

The cross-arm voltage, V_c of suspending insulator is the sum of the tower-footing resistance voltage and the corresponding height inductance voltage of the tower

$$V_c = R_{tf} i_t + L_{t1} \frac{di_t}{dt} \tag{2}$$

The phase conductor voltages are depended on both the cross-talk coupling voltage from shielding wires and induction voltage from lightning channel and the traveling current flowing in the tower together. The cross-talk coupling voltage on the phase conductor would reduce the voltage across the insulator. The overall effect of the induction voltage is to increase the insulator-string voltage.

The cross-talk coupling voltage of the phase conductor V_p is equal to kV_{top}. Where the k is the mutual cross-talk coupling coefficient between the shielding wire and the phase conductor. The tower-top voltage V_{top} was computed following the same procedure as for V_c. If the induction voltage on the phase conductor was neglected, the transient voltage across the insulator strings is

$$V_{in} = V_c - V_p \tag{3}$$

Induced Voltage

The induction voltage computation method will be discussed by using static-electric image method. Its rationality will be validated using the numerical electromagnetic code.

In computation, given that: i) the charges are distributing uniformity along the lightning channel, the charge density is λ. The electric field is produced by the lightning channel charge; ii) the lightning channel is vertical to the ground without considering its embranchment. Figure 3 gives the computation sketch. In Figure 3, the distance between the lightning strike point projection ***O*** and the phase conductor projection ***C*** on the ground is y. The electric field intensity at any point ***A*** just below the phase conductor denotes as E_{zA}. Supposing the whole channel charge exist at the same time, according to the relation between the charge and electric field intensity in static-electric field, the electric field intensity E_{zA} can be deduced as[14],[15]

$$E_{zA}=\frac{\lambda}{4\pi\varepsilon_0}\left[\int_{h-z}^{h_c-z}\frac{z'dz'}{\left(z'^2+y^2\right)}+\int_{h+z}^{h_c+z}\frac{z''dz''}{\left(z''^2+y^2\right)}\right]$$

$$=\frac{\lambda}{4\pi\varepsilon_0}\left[-\frac{1}{\sqrt{(h_c-z)^2+y^2}}+\frac{1}{\sqrt{(h-z)^2+y^2}}-\frac{1}{\sqrt{(h_c+z)^2+y^2}}+\frac{1}{\sqrt{(h+z)^2+y^2}}\right] \quad (4)$$

where, h_c is the cloud height, *m*; h is the upward leader height, *m*; z' is the vertical distance between the lightning channel charge segment $\lambda dz'$ and the computation point ***A***, *m*; z'' is the underground image of the z', *m*; z is the height of computing point A, *m*; ε_0 is the air dielectric constant; h_p is the height of the phase conductor, *m*.

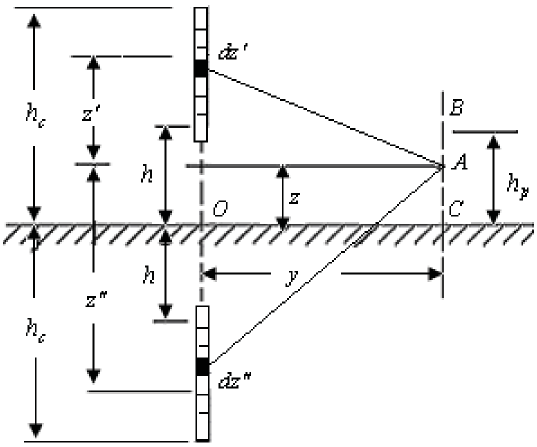

Fig.3. The phase conductor induction voltage computation

As to the lightning flash to the ground, supposing no upward leader progressing, $h=0$, and due to the condition of $h_c >> h$, in the electric field computing range $0\le z\le h_p$, the equation (4) can be transformed to

$$E_{zA}=\frac{\lambda}{2\pi\varepsilon_0}\frac{1}{\sqrt{z^2+y^2}} \quad (5)$$

where y is the horizontal distance perpendicular to the lines direction between lightning striking point and the computing field point .

Then, according to the relation between the potential and the electric field strength, the maximum induced voltage, V_{mpi}, of the lines caused by indirect lightning is

$$V_{mpi}=\int_0^{h_p}E_{zA}dz=\frac{\lambda}{2\pi\varepsilon_0}\ln\left[\frac{h_p}{y}+\sqrt{\left(\frac{h_p}{y}\right)^2+1}\right] \quad (6)$$

As to lightning flash to the ground, having the $y^2>>h_p^2$, by using the Taylor series disposing method, the equation (6) will be simplified as

$$V_{mpi}=\frac{\lambda}{2\pi\varepsilon_0}\ln\left[\frac{h_p}{y}+1\right]\approx\frac{\lambda}{2\pi\varepsilon_0}\frac{h_p}{y} \quad (7)$$

The lightning current I has a relation $\lambda v=I$ with the charge density. Where v is the lightning leading discharge speed. The concision equation can be attained

$$V_{mpi}=\frac{1}{2\pi\varepsilon_0 v}\frac{Ih_p}{y}=K\frac{Ih_p}{y} \quad (8)$$

where K is the constant computation coefficient defined by considering the lightning current magnetic induction effect. This is agreement with Rusck induced voltage computing formula derived from the wave traveling analysis method of transmission lines [3],[4][5],[6],[9],[13].

As to lightning strike to tower, y is small. Supposing $y=0$, taking into account that $h_c>>h_p$, at the range of $0\le z\le h_p$, equation (5) can be simplified as

$$E_{zA}=\frac{\lambda}{2\pi\varepsilon_0}\frac{h}{h^2-z^2} \quad (9)$$

Therefore, the maximum induction voltage on the phase conductor is

$$V_{mpi}=\frac{\lambda}{2\pi\varepsilon_0}\ln\frac{h+h_p}{h-h_p} \quad (10)$$

We can deduce to one simple induction computation formula as following

$$V_{pi}=12.5I\ln\left(1+\frac{h_p}{h}\right)\approx 25\frac{Ih_p}{h} \quad (11)$$

In equation (11), the upward leader height is the sum of the upward leader length and tower height. From the equation, we can see that the induction voltage on phase conductor caused by direct lightning stroke to power tower is direct proportional to the lightning current and conductor height, inverse proportion to the upward leader height. But upward leader height of the tower relates not only to the tower height, but also relates to the lightning current magnitude.

III. Tower Height Influence Analysis

A. Analysis of Lightning Currents Distribution in the Lightning Channel and Tower

When a lightning flashes to the tower, the equivalent surge impedance circuit for computing tower top voltage is shown in Fig. 4(a). Where, the tower was assumed to be a vertical transmission line having fixed surge impedance; the tower top was attacked by the lightning channel with constant surge impedance and the ground impedance equals to the footing resistance[12].

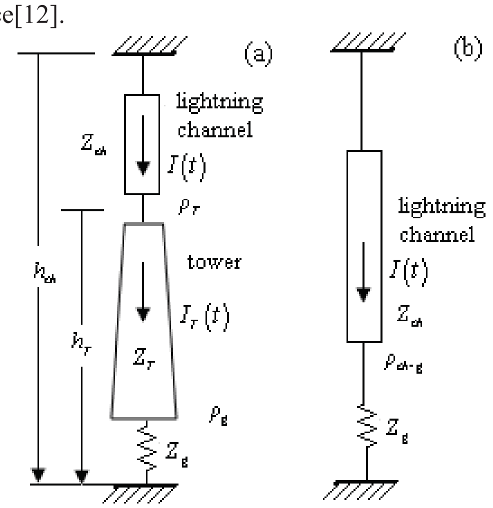

Fig. 4. Equivalent circuit for current distribution (a) lightning flash to tower (b) lightning flash to ground

Before computation the current distribution, the classical current reflection coefficient of the tower top and the tower base must be defined. Taking the tower and lightning channel as transmission line model, given the lightning channel, the tower and the ground impedance respectively are Z_{ch}, Z_T, Z_g, following the wave propagation theory, the lightning current will reflect or refract at the tower top and tower base because of their impedance being different.

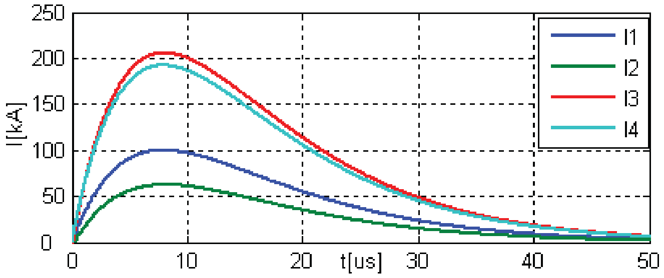

Fig.5. Lightning current distribution in return stroke and tower

The current reflect coefficient on the tower top is

$$\rho_T = \frac{Z_T - Z_{ch}}{Z_T + Z_{ch}} \tag{12}$$

The current reflect coefficient on the tower base is

$$\rho_g = \frac{Z_T - Z_g}{Z_T + Z_g} \tag{13}$$

For comparison, the case of lightning flash to ground is given in Fig. 4(b). As lightning flash to the ground, the ground current reflection coefficient is

$$\rho_{ch-g} = \frac{Z_{ch} - Z_g}{Z_{ch} + Z_g} \tag{14}$$

Given the lightning current is

$$i(t) = 3.4251 \times 10^5 \left(e^{-0.1259t} - e^{-0.126t}\right) \ \text{(kA)} \tag{15}$$

The lightning current distribution results are computed in Fig.5. In the figure, I1 is the striking source current, I2 is the tower top lightning channel current, I3 is the ground surface lightning channel current, I4 is the tower body flowing current. Fig. 5 shows that, with the 100kA exponent current incidence on tower top, the reflection effect doubles the lightning channel current of the original approximately and the tower body flowing current only 1/2 of the incidence current. If there is not a tower, the ground surface current will approach to 200kA.

From the comparison of the current distribution in Fig. 5, we can find that the tower impedance having the function of transforming the impulse current from ground to the tower top when there stands a tower. The higher the tower is, the further is the big lightning current away from the ground. Even though the tall tower having attraction lightning effect, its lower surge impedance causes a light flash current in the tower being low. If the shunting effects of the shielding wires are working, the tower body lightning current will be lower. So, according to the antenna theory, the electromagnetic field of the space around the tower is smaller than that of no tower. As to the induced voltage protection, it makes the space under the tower more firm ground. The tower height will influence the lines induced voltage in evidence. This is agreement with the analysis in equation (11). Then we will discuss the lightning electromagnetic field of the two cases.

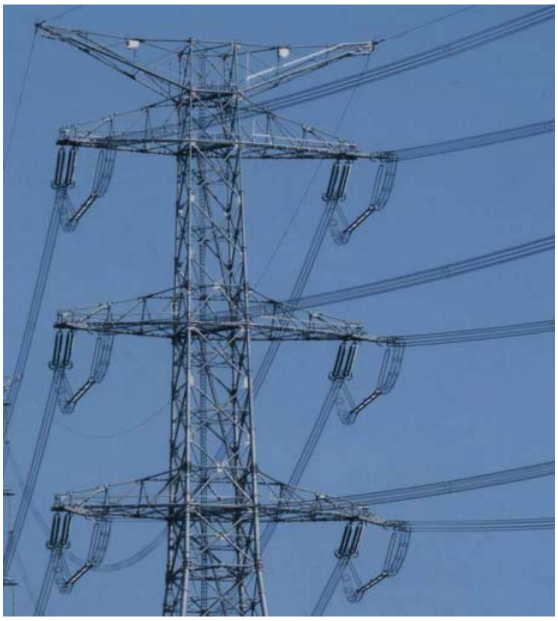

Fig.6. The Computed Metal Structure Tower

B. Analysis the Tower Height Influence to Lightning Electromagnetic Field

For the numerical simulation of the lines induced voltage caused by lightning flash to a tower, the numerical electromagnetic code (NEC) is employed [7],[8]. And the numerical electromagnetic code is a widely used three-dimensional electromagnetic modeling code based on the method of moments in the frequency domain. It particularly effective in analyzing metal structures composed of thin wires

[7],[8]. The modern transmission tower largely constructed from metal thin wire, its lightning current incidence producing electromagnetic field can be calculated simply by using it.

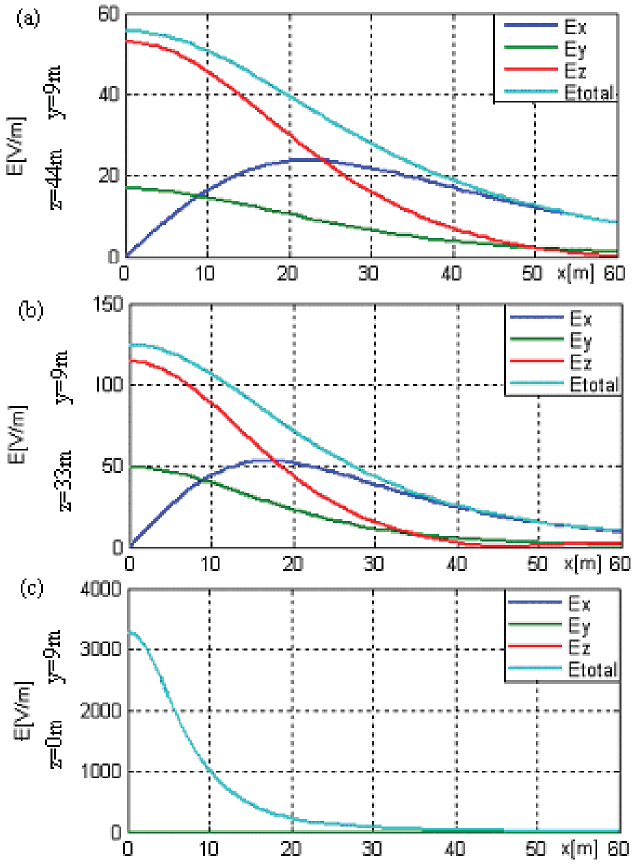

Fig.7 Lightning electric field strength nearby the channel as the lightning striking to ground

For the computed tower shown in Fig. 6, the tower structure was modeled and divided into many line segments or short cylinders. In the computation, it is assumed as bellow: the lightning current is a 1 A, 100kHz sine wave injecting on tower top; the tower material and ground all be perfect conductor; the tower centre on ground is the coordinate origin; the lightning channel is modeled as a 2000m long perfect conductor and also it is divided to segments; lastly, the current source is on the striking point.

Fig.7 shows the electric field of three places concerned without the tower, i.e. the electric fields are caused by the current incidence on the coordinate origin on ground. Fig. 8 gives the computed fields strength corresponding caused by the current incidence on tower top. In the figures, the abscissa is the transmission lines direction and the ordinate is the electric field strength distribution along the lines. In the three-dimensional space, y is the distance of the lines away the origin (the cross-arm one side length), z is the lines height being placed.

From comparing the computed field strength of the three concerned points, we can find that the tower existing makes the electric field of the ground surface lower. But the field strength of the other two points are bigger than that of caused by without the tower gradually. Without the tower, the computed peak value of the field strength E_z at points (0, 9, 0), (0, 9, 33) and (0, 9, 44) respectively is 3200V/m, 120V/m, and 52 V/m. While there is a 60m height tower, the same magnitude current producing electric field strength E_z is 27 V/m, 60 V/m, and 80 V/m at the three points. The peak value of E_z is at the point of (5, 9, 33) in Fig.8 (b). This is because of the cross-arm dispersion effect of the computing tower. Similarly, the peak value of the electric field E_z in Fig. 8 (a) is at the point of (5, 9, 44).

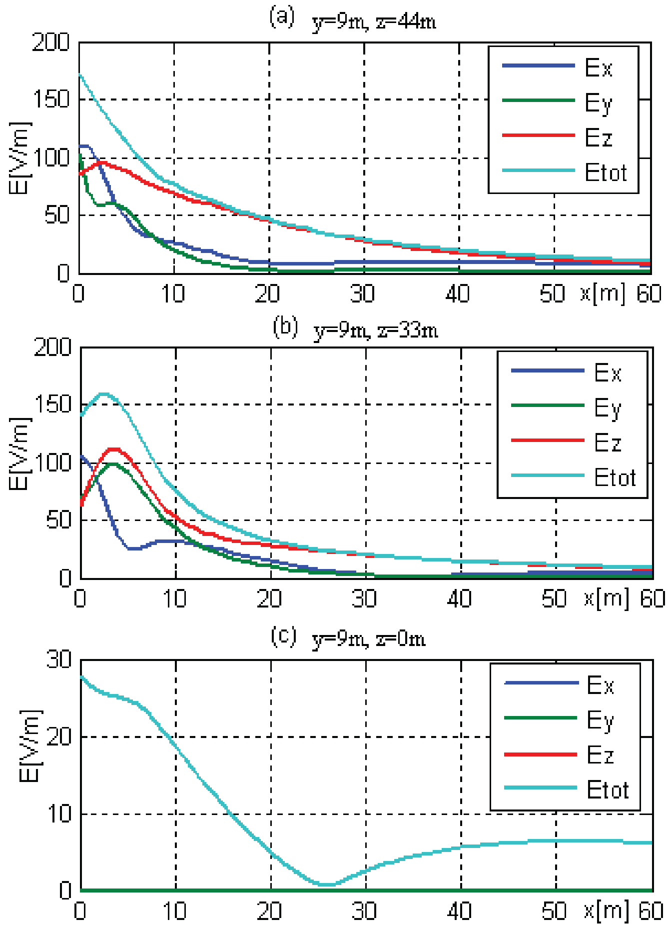

Fig. 8 Lightning electric field nearby the tower as the lightning flash to the tower

The field computation results are agreement with the antenna radiate theory. The tower height makes the distance between source point and field point longer, and reduces the field strength correspondingly.

IV. Induced Voltage Simulation

For computing the overhead lines lightning induced voltage, the Fourier transform and inverse Fourier transform must be used because of the lightning current time varying and the transient characteristic of the electromagnetic field. Even if the induced voltage on lines being considered when using the equation (2), but without reflecting the tower height influence, the designed lines insulation will be very irrational. Certainly, this will result high cost on the lines insulation construction.

Supposing the lightning current is exponent function, such as the I_1 in Fig. 5, with the front time 2.6 μs and half tail value time

$5\ \mu s$, striking to the tower top of Fig. 6, following the NEC computing steps, we can compute the transient electric filed around the tower. Applying the induction voltage computation equation (6), the lines induced voltage can be roughly computed under condition of the varying upward leader height [10]. The results were given in Fig. 9, Fig.10, Fig. 11, which the upward leader heights are respective 65m, 120m, and 150m.

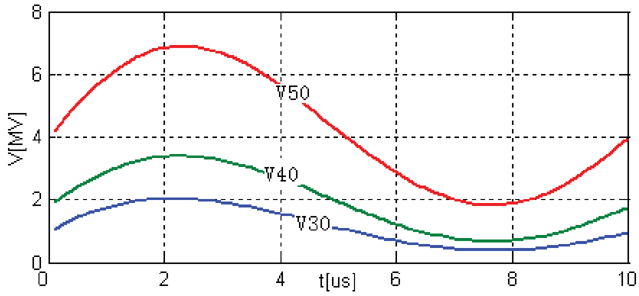

Fig. 9 Lightning induced voltage of overhead lines as $h = 65m$

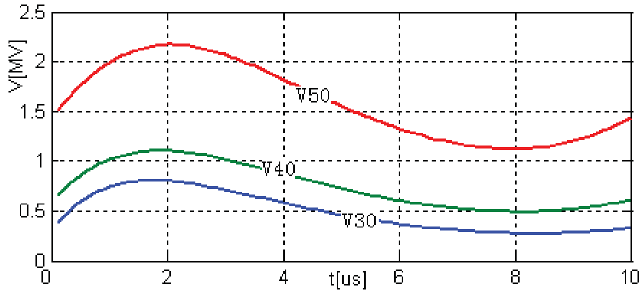

Fig. 10 Lightning induced voltage of overhead lines as $h = 120m$

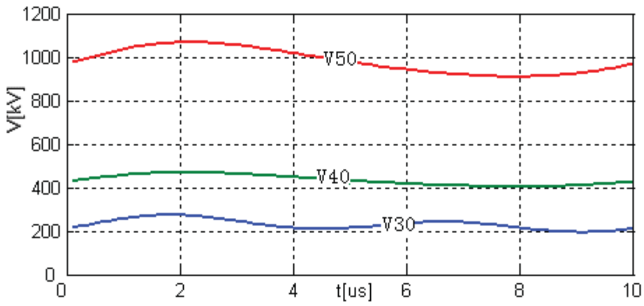

Fig. 11 Lightning induced voltage of overhead lines as $h = 150m$

In those figures, the signs V30, V40 and V50 respectively indicate the induced voltage on the 30m, 40m and 50m height lines. From the computation results we can find that the tower height and the tower upward leader height both play an important role in determining the lines lightning induced voltage. Moreover, as the lightning flash to a tower top, the lightning channel electromagnetic field induces a great voltage on the perfect conductor lines. No matter how the tower upward leader changes, the lines induced voltage is significant. Neglecting this component in estimating the overhead lines lightning performance is not rational. Although the lightning performance estimation is a rude prediction, and there also exist no most rigour method, the estimation method must not be contradicted.

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