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STUDY ON THE TRANSIENT ELECTROMAGNETIC EFFECT OF THE LIGHTNING PROTECTION SYSTEM OF A BUILDING BY NUMERICAL CALCULATION

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Abstract. *Aiming at the problem of electromagnetic interference caused by lightning stroke, the numerical calculation method for the transient electromagnetic phenomena in buildings is designed. Based on the theory of equivalent transmission line, the whole building Lightning Protection System (LPS) is equivalent to the transmission line network, and next calculate the current in the frequency domain. The time-domain current is obtained by Inverse Fast Fourier Transform (IFFT). Then the numerical calculation technique of a semi-analytical difference method is used to obtain the magnetic fields distribution inside the LPS. In order to verify the accuracy of the method, the simulation results of the same problem by the proposed method are compared with the results by the method in "IEC62305". The comparison shows that the accuracy of our numerical calculation method meets the IEC standard. The paper provides a new idea for the optimization design of building LPS, and it puts forward some suggestions on the design and construction of building LPS.*
Keywords: Transient electromagnetic effect, Lightning protection system of building, Transmission line model, Fast Fourier Transform (FFT), The difference method

1. Introduction.

In recent years, with the rapid development of information technology and the emergence of intelligent buildings, direct and indirect economic losses caused by lightning disasters become more and more serious [1-3]. When the building is struck by lightning, the strong lightning current is injected into the building Lightning Protection System (LPS) through the strike point and transmitted along the respective down conductors until it flows into the ground. In this process, there will be a strong transient electromagnetic effect, which will exert serious electromagnetic interference on the indoor electronic equipment, threatening its safe and reliable operation. Therefore, in the design of the LPS, the key areas of lightning protection must be firstly determined, and the lightning electromagnetic environment should be calculated.

There are two main methods to calculate the lightning transient electromagnetic phenomena of building lighting protection: analytic method and numerical method. In the documentations [4-6], the transient electromagnetic distribution in the building is calculated by the analysis method, but the calculation is complicated when the coupling relationship between the conductors is taken into account. There are three branches of the numerical method: the Moment Method (MOM) [7-9], the Finite Difference Time-Domain (FDTD) method [10-12], and the Finite Element Method (FEM) [13,14]. When using the numerical method to solve the transient electromagnetic environment in the lightning building, the model is complex and the instantaneity is poor, especially for large buildings. Therefore, this paper designs a semi-analytic method: difference method to solve the problems which is written directly according to the Maxwell differential equation and allows the establishment of a detailed model. Relative to analytic method and numerical method, the calculation of complex electromagnetic environment is particularly effective by using difference method.

This paper discusses the evaluation of the surge current distribution and transient electromagnetic fields based on the theory equivalent to the transmission line, the whole building Lightning Protection System (LPS) is equivalent to the transmission line network, and next the current distribution is calculated in the frequency domain. The time-domain current is obtained by Inverse Fast Fourier Transform (IFFT). Then the difference method is used to obtain the electromagnetic field distribution inside the LPS. In order to verify the accuracy of the method, the simulation results of the same problem by the proposed method are compared with the results by the method in IEC62305-4 [15]. The comparison shows that the accuracy of our numerical calculation method meets the IEC standard.

2. Development of Numerical Model.

2.1. LPS model of building based on transmission line. The LPS of building consists of a set if straight interconnected conductors forming a cage. The single conductor of the LPS can be treated by using the transmission line model [16,17]. Take the kth single conductor as subject for study, the single transmission line model is equal to a two-port circuit as shown in Figure 1, and the transmission line equation is presented by (1):

$$\begin{bmatrix} I_k^l \\ I_k^r \end{bmatrix} = \begin{bmatrix} y_k^{ll} & y_k^{lr} \\ y_k^{rl} & y_k^{rr} \end{bmatrix} \begin{bmatrix} U_k^l \\ U_k^r \end{bmatrix} \tag{1}$$

I_k^l, I_k^r, U_k^l, U_k^r in (1) are the current and voltage of the left and right ports of the kth transmission line, and y_k^{ll}, y_k^{rr}, y_k^{lr}, y_k^{rl} are the elements in the admittance matrix of the two-port network. Each conductor of LPS is modeled by a transmission line, which comprises resistance, inductance and capacitance and all elements are considered to be coupled together. Thus the whole LPS of building can be equivalent to a transmission line network made of a number of coupled transmission line.

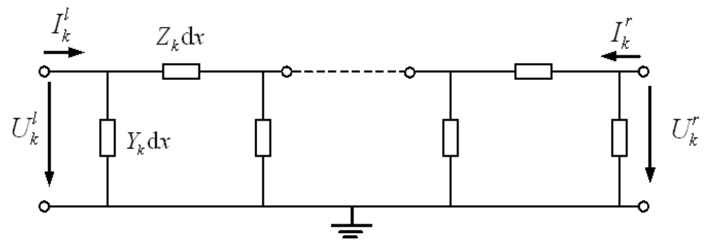


FIGURE 1. Two-port circuit of a single transmission line

2.2. Calculation of transient current in branch conductor of building LPS. By using the node voltage calculated in the previous step, the frequency response of the current distribution along the branch conductor can be obtained. For the kth conductor, the $I_k(\omega)$ at x in the local coordinate is given as (2), and the equivalent circuit of the kth conductor is shown in Figure 2.

$$I_k^{(x)}(\omega) = \frac{U_2(\omega)}{Z_k} \cdot \frac{\cosh(\gamma_k l - \gamma_k x)}{\sinh(\gamma_k l)} - \frac{U_1(\omega)}{Z_k} \cdot \frac{\cosh(\gamma_k x)}{\sinh(\gamma_k l)} \tag{2}$$

In (2), γ_k is the propagation constant of the transmission line. Z_k is the characteristic impedance of the transmission line, and l is the length of the branch conductor. After

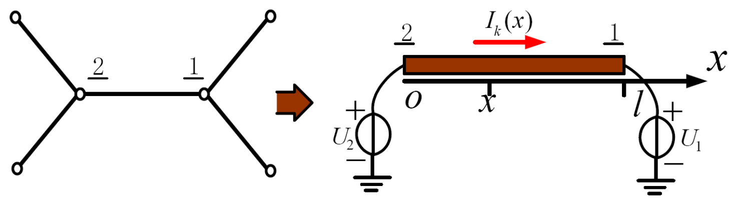


FIGURE 2. Schematic diagram of calculation of transient current in branch conductor

obtaining the current frequency response along all the conductors, the Inverse Fast Fourier Transform (IFFT) can be used to obtain the transient current in time domain.

2.3. **Calculation of electromagnetic fields in the building LPS.** The coupling of the lightning channel with the conductive branches of the gridlike structure is disregarded, the earth is considered as perfect conductor and the structure is earthed ideally. According to the current distribution along the branch conductor calculated in the previous step, the current density $\boldsymbol{J}(r', t)$ can be calculated. In the space V', the general result of dynamic magnetic vector function $\boldsymbol{A}$ is

$$\boldsymbol{A}(r,t) = \frac{\mu}{4\pi}\int_{V'} \frac{\boldsymbol{J}\left(r', t - R/c\right)}{R} dV' \tag{3}$$

The volume element dV' is located at r'. R is the distance from the position of the volume element to a point in the field, and $R = |r - r'|$. c is the speed of light in the free space. After calculating the dynamic magnetic vector function $\boldsymbol{A}$ of any point in space according to (3), the magnetic induction intensity $\boldsymbol{B}$ at any point in space can be obtained from (4).

$$\boldsymbol{B}(x,y,z,t) = \nabla \times \boldsymbol{A}(x,y,z,t) \tag{4}$$

In the Cartesian coordinate system, the components on the three directions of the magnetic induction intensity $\boldsymbol{B}$ can be calculated by the following formulas

$$\boldsymbol{B}_x \approx \frac{\boldsymbol{A}_{4z} - \boldsymbol{A}_{3z}}{2h} - \frac{\boldsymbol{A}_{6y} - \boldsymbol{A}_{5y}}{2h} \tag{5}$$

$$\boldsymbol{B}_y \approx \frac{\boldsymbol{A}_{6x} - \boldsymbol{A}_{5x}}{2h} - \frac{\boldsymbol{A}_{2z} - \boldsymbol{A}_{1z}}{2h} \tag{6}$$

$$\boldsymbol{B}_z \approx \frac{\boldsymbol{A}_{2y} - \boldsymbol{A}_{1y}}{2h} - \frac{\boldsymbol{A}_{4x} - \boldsymbol{A}_{3x}}{2h} \tag{7}$$

In Formulas (5) to (7), $\boldsymbol{A}_{ix}$, $\boldsymbol{A}_{iy}$ and $\boldsymbol{A}_{iz}$ $(i = 1, 2, \ldots, 6)$ represent the dynamic magnetic vector potential function of 6 points that are equidistant from point P in the x, y, z positive and negative directions. h is the step size (the 6 points' distances to P). The 6 points around P are shown in Figure 3. The magnetic field at any point in the space can be calculated using the difference method.

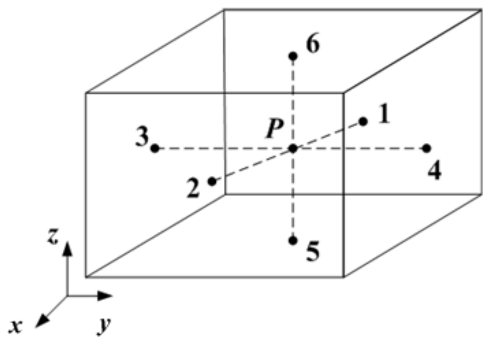


FIGURE 3. The distribution of the six points around the P point in the difference method

2.4. **The calculation flow of transient electromagnetic effect of LPS.** The lightning current $I(\omega)$ in the frequency domain is obtained by Fast Fourier transform (FFT) which is as excitation source, at each frequency point, the transmission line network equations of the whole LPS of building are solved, the frequency response of every nodal voltage at this frequency point can be obtained, and the frequency response of every branch's current at the frequency point can be obtained by the transmission line formula. The time domain response of the nodal voltage and the current can be obtained by IFFT. And then, the interior space of the building is divided into grids with unit length, and the difference method is used to calculate the transient magnetic fields distribution in LPS. The flow chart of transient electromagnetic effect is shown in Figure 4.

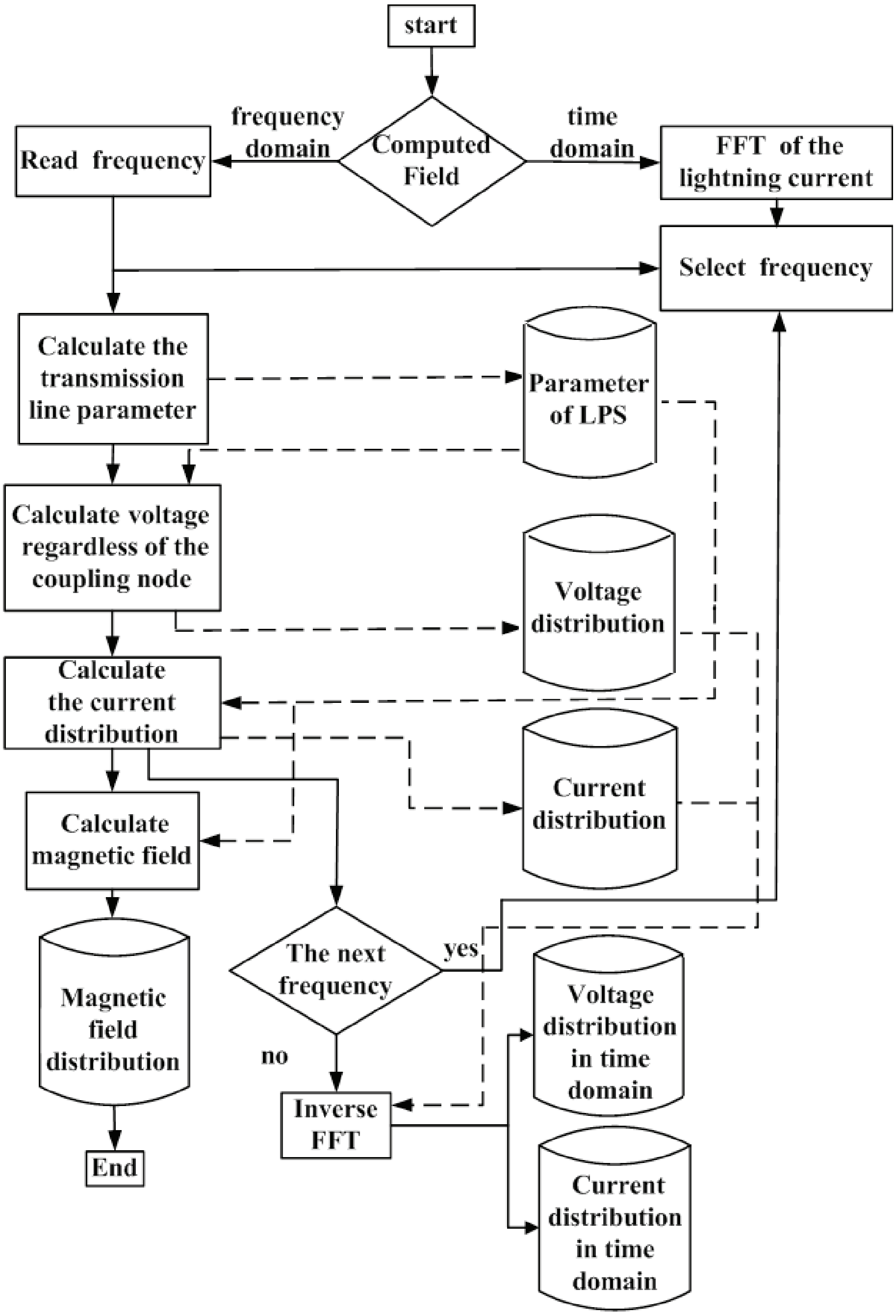


FIGURE 4. The flow chart of transient current and magnetic fields calculation

3. Numerical Examples.

3.1. Comparison with IEC standard. To verify the results computed by the proposed method, a comparison is carried out between the results calculated by the method in IEC62305-4 [15] and those calculated by the method proposed in this paper. Figure 5 shows typical geometry LPS of building with dimensions of double $24\text{m} \times 12\text{m} \times 12\text{m}$. For simplicity, the grounding system of the LPS is simulated by a set of lumped ground resistors connected to the down conductors directly, shown as R_g. The lightning current is applied to a node of the LPS as an ideal current generator, and point 1 and point 2 are selected as lightning points due to the symmetry. The peak value of the lightning current is assumed 100A and its waveform is $1/40\mu$s. In order to analyze the changing trend of lightning magnetic fields in different points of the building, $Q_1(12, 6, 6)$, $Q_2(24, 6, 6)$ and $Q_3(36, 6, 6)$ are selected as observation points of the magnetic field. The time-domain waveform of the magnetic induction intensity $\boldsymbol{B}$ at points Q_1, Q_2, Q_3 can be calculated with injection of the lightning current to point 1. At the lightning peak time, the magnetic field distribution at the height of (1m, 2m, 3m, 4m, 5m, 6m, 7m, 8m, 9m, 10m) is displayed when the lightning current injects into the building LPS from the point 1 and the point 2.

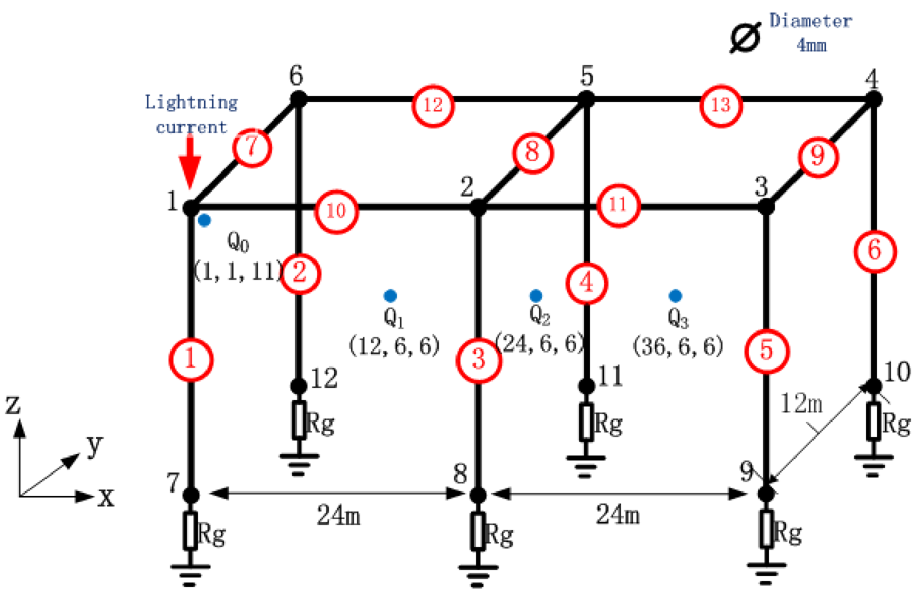


FIGURE 5. The model of building LPS

The calculation formula defined by the International Electrotechnical Commission (IEC) of the magnetic field generated by the grid-type shielding system around the building of lightning strike is [15]:

$$B_{\max} = \mu_0 H_l = \frac{\mu_0 K_H I_0 w}{d_w \sqrt{d_r}} \tag{8}$$

Figure 6 shows the magnetic induction intensity waveform in time domain. Within the entire building LPS, as the distance between the sensing point and the lightning current main drain channel (conductor 1) increases, the attenuation of magnetic field in space is severe. From Figure 7, the area which has the stronger magnetic induction intensity is mainly distributed around the metal conductor near the point of strike, and the bigger the shunt coefficient is, the stronger the magnetic field generates around the conductor.

In Formula (8), μ_0 is the vacuum permeability; d_r is the shortest distance between the point to be calculated and the top of the LPS; d_w is the shortest distance from the point to be calculated to the side wall of LPS; I_0 is the maximal amplitude of the lightning current; K_H is the shape factor, the typical value of which is 0.01, w is the width of the

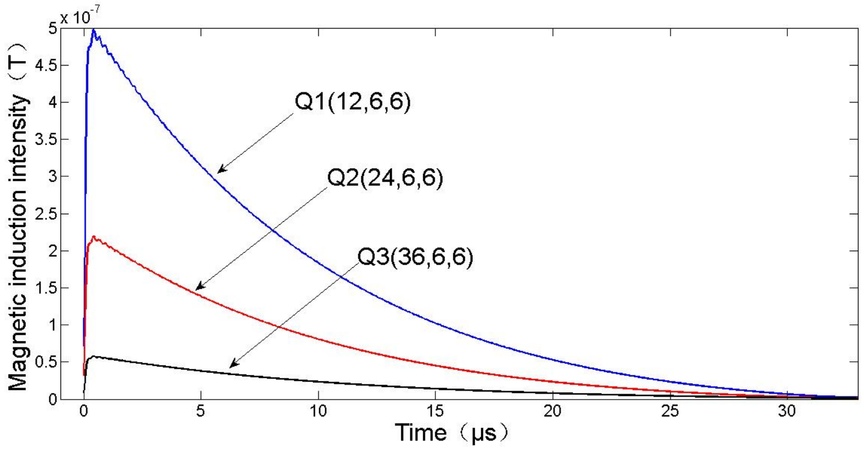
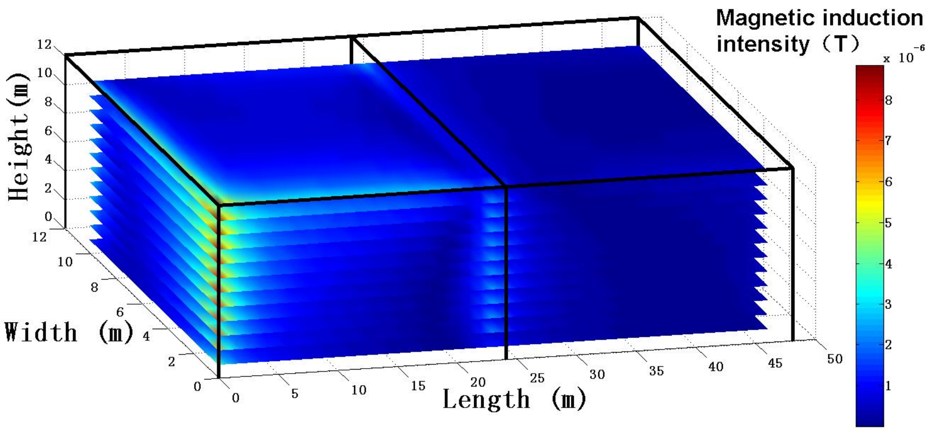
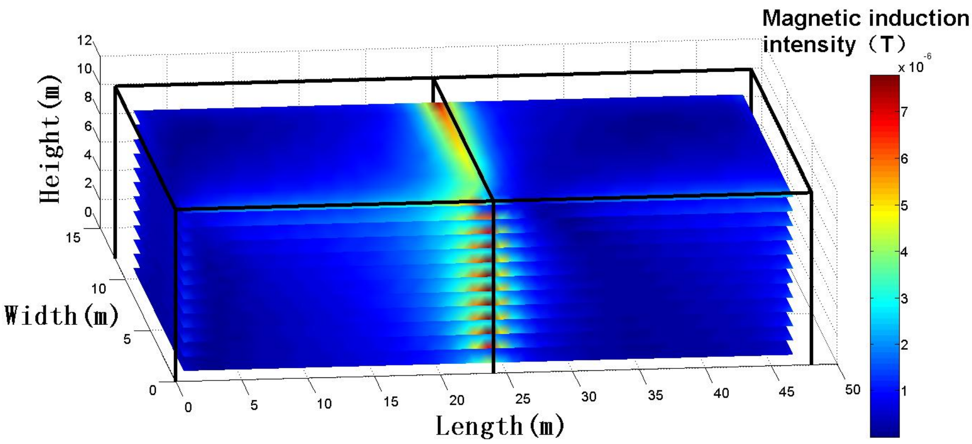


FIGURE 6. The magnetic induction intensity waveform in time domain



(a) Lightning injected into the corner node (point 1)



(b) Lightning injected into the mid-edge node (point 2)

FIGURE 7. The magnetic induction intensity distribution at different heights in the building

mesh of LPS. In the paper, three kinds of conductive structure of LPS models (10 × 10 × 10, 50 × 50 × 10, 10 × 10 × 50) are established according to the reference given in IEC62305-4. The maximum magnetic induction intensity $B_{\max}$ of the $Q_0(1, 1, 11)$ near the lightning point is calculated and compared with the results obtained by the IEC method. Then the relative errors can be obtained.

Table 1. Comparison of $B_{\max}$ under different LPS structures between IEC standard and calculated results

Conductive structure (m)	$B_{\max}$ (IEC) (T)	$B_{\max}$ (This paper) (T)	error (%)
$10 \times 10 \times 10$	2.25×10^{-4}	2.31×10^{-4}	2.75
$50 \times 50 \times 10$	0.45×10^{-4}	0.48×10^{-4}	6.67
$10 \times 10 \times 50$	1.01×10^{-4}	1.08×10^{-4}	6.93

It can be seen from Table 1 that the error of the result is kept within 10%, which is in the allowable error range of the engineering application; thus the method can meet the engineering requirements.

4. **Conclusions.** In this paper, a coupled transmission line network model is used to calculate the surge current distribution and difference method is proposed to obtain the transient magnetic field distribution in building LPS due to direct lightning stroke. The main advantage of the proposed model is its rather low computational demand especially for full size buildings, wind turbines and transformer substations. The reasons are as follows. The number of unknown quantities is less than that in the traditional analytic method and numerical method, which leads to a low rank equation system at each frequency.

The validation of the proposed model has been carried out with computed samples available in IEC standard, and engineering acceptable agreement has been demonstrated. It is worth mentioning that the present study does not take account of the coupling effects between any two conductors. In addition, the grounding system of the LPS is simulated by a set of lumped ground resistors connected to the down conductors for simplicity, which is not according with the true condition of grounding system, and those are the main limitations of the proposed method, which may be improved in future, and reported in an upcoming paper.

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