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FDTD analysis of the effects of indirect lightning on large floating roof oil tanks

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ABSTRACT

Lightning is one of the major hazards for large floating oil tanks. In order to research the effect of indirect lightning on floating roof oil tanks, this paper proposes a numerical procedure based on finite difference time domain (FDTD) method to analyze the electric field strength distribution on large floating oil tanks and calculate the lightning discharge radiation power. The impacts of lightning current amplitude, strike position and soil resistivity on the electric field strength are analyzed. The calculation results show that it may trigger oil tanks ignition if the lightning strikes within a dangerous distance with certain lightning current amplitude. And it is dangerous for electronic equipment on oil tanks when the lightning strikes within 500 m from the oil tank. The electric field strength gets higher with the lightning current amplitude and the soil resistivity increasing; decays with the distance increase between the stroke point and the oil tank. For the convenience and simplicity in engineering analysis, the fitting curves representing the relationship among lightning current amplitude, stroke distance and electric field strength is deduced.

1. Introduction

Fire is a serious disaster for large oil tanks, which could lead to great losses and severe consequences both economically and politically [1]. According to the statistical data, there are 61% of tank fire accidents are attributed to lightning [2], even though the oil tanks have already adopted proper lightning protection measures, such as proper tank grounding, electrical connection between the tank wall and the floating roof, and installing conductive sheet on the secondary seal plate etc. [3,4]. Both direct lightning and indirect lightning may cause oil tanks ignition. A lot of investigations have been carried out through theoretical and experimental ways to give suggestions for oil tank protection from direct lightning [5–8], while the effect of indirect lightning on the floating roof oil tank is not thoroughly investigated. In common situation, lightning strokes in the vicinity of oil tanks occurs more frequently than direct strokes. And the magnetic and electric fields caused by indirect lightning may also lead to oil tank fires. The Huangdao oil tank fire occurred in China in August 1989 is one of the typical examples that were identified as caused by indirect lightning [9]. More attentions should be paid to oil tanks protection from indirect lighting.

In recent years, more and more large external floating roof oil tanks are built in China [10]. Most of the large floating roof oil tanks' diameters are in the range of 80–100 m and are more easily to be affected by indirect lightning [11]. The existence of oil and gas mixture between the primary seal and the secondary seal of the oil tank is the main reason that lightning may ignite such oil tank fire accidents. When the oil gas concentration is greater than 1%, an electrical spark whose energy is above 0.2 mJ is powerful enough to ignite the fire [12,13]. The ignition of the electrical spark depends on the electric field strength distribution on the oil tanks, so the analysis of the electric field distribution on such tanks caused by indirect lightning is important.

The finite difference time domain (FDTD) method is an effective method to solve such complex problems as the electric field distribution on large floating roof oil tanks caused by indirect lightning. The FDTD method directly and numerically solves Maxwell's equations. Compared with the conventional methods, the FDTD-based calculation is superior in terms of the modeling of inhomogeneous ground parameters, 3-D structures, and grounding systems [14–17]. To calculate the electric field strength distribution on large floating roof oil tanks caused by indirect lightning, this paper adopts MTLE (modified transmission-line model with exponential current decay with height) model to describe the lightning current propagation along the lightning channel. A three-dimensional model of large floating roof oil tank and the lightning channel are proposed

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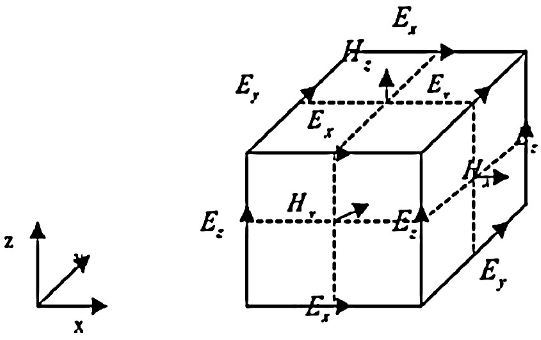

Fig. 1. The Yee cell with labeled field components.

to analyze the electric field strength between the floating roof and the tank wall and calculate the lightning discharge radiation power. The impacts of strike position, lightning current amplitude and soil resistivity on the field strength distribution are analyzed. Based on the calculation results, this paper deduced the dangerous distance of lightning stroke for large floating roof oil tanks.

2. FDTD analysis

2.1. The FDTD method

The FDTD method solves the electromagnetic problems in time and space domain and rapidly becomes one of the most effective methods since it is proposed by Yee [18]. For solving the Maxwell equation, the electromagnetism vector can be expressed in time domain in a rectangular coordinate system [19]. In the FDTD approach, both the space and the time are divided into discrete segments. The space is segmented into box-shaped cells. The electric fields are located on the edges of the box and the magnetic fields are positioned on the faces, respectively, which is shown in Fig. 1.

The time is quantized into small steps, and each step represents the time required for the field to travel from one cell to the next. According to Courant's stable condition, the time step should be set within a certain range.

The three-dimensional volume of the problem is divided into many FDTD cells, turning into an FDTD grid or mesh. Each FDTD cell will overlap its edges and faces with its neighbors and have three electric field components that begin at a common node corresponding to it. The electric fields begin at the other seven nodes of the FDTD cell will belong to other, adjacent cells. Each cell will also have three magnetic field components originating on the faces of the cell adjacent to the common node of the electric fields, as shown in Fig. 1. The medium of the analysis space is isotropic and nondispersive. Based on a leapfrog algorithm, Eqs. (1) and (2) are used to update the electric and magnetic fields, respectively [18].

$$E^{n+1} = E^n + \frac{\Delta t}{\varepsilon}\nabla \times H^{n+1/2} - \frac{\Delta t}{\varepsilon \Delta s^2} I^{n+1/2} \tag{1}$$

$$H^{n+3/2} = H^{n+1/2} - \frac{\Delta t}{\mu}\nabla \times E^{n+1} \tag{2}$$

where Δt is the time step. Δs is the size of the cell (space step). The superscripts n represents the iteration steps at time $n\Delta t$.

2.2. Lightning current and channel model

Cloud-to-ground (CG) flash is the most dangerous lightning to oil tanks and over 90% of lightning flashes are downward negative lightning [20]. Considering the strokes in CG flashes, the first return stroke is the most dangerous to oil tanks [21]. Therefore, only the first return stroke of downward negative flash is considered in the calculation model. In the lightning channel model, the assumption of channel length affects both the calculation accuracy and time consumption. According to the existing literature [22,23], a channel length of 3000 m is high enough for the calculation of induced effect in an area less than 1000 m away from the lightning channel. The following hypotheses are adopted in the lightning channel model,

Table 1
The parameters of the lightning current.

Waveform	τ_{1i} (s)	τ_{2i} (s)	n_i
1	0.25	2.1	2
2	2.5	230	2

(a) Only the first return stroke current is considered;
(b) The lightning channel is perpendicular to the ground and without branches, as the shape of the channel has little influence on the near field electromagnetic field distribution [24];
(c) The lightning current channel is modeled as a monopole antenna of 3000 m height.

The MTLE model is employed for the description of the current propagation along the lightning channel. The return stroke velocity is assumed to be $v = 1.3 \times 10^8$ m/s.

The MTLE model describes the lightning current propagation along the channel. The lightning current $i\,(z', t)$ is presented as,

$$i(z', t) = i\left(0, \frac{t - z'}{v}\right) e^{-\alpha z'} \tag{3}$$

where the current decay constant, α, is 0.6(1/km). $i(0, t - z'/v)$ is the channel base current. v is the current–wave propagation speed. The channel base current model can be described as Heidler model with two added Heidler functions, which is presented in the following equations:

$$i(0, t) = \sum_{i=1}^{2} \frac{I_{0i}}{\eta_i} \frac{(t/\tau_{1i})^{n_1}}{1 + (t/\tau_{2i})^{n_1}} e^{-t/\tau_{2i}} \tag{4}$$

$$\eta_i = \exp\left[-\frac{\tau_{1i}}{\tau_{2i}}\left(n_i \frac{\tau_{2i}}{\tau_{1i}}\right)^{1/n_i}\right] \tag{5}$$

The lightning current waveform parameters adopted in the simulation are shown in Table 1.

The frequency spectrum of such Heidler model described lightning current is illustrated in Fig. 2.

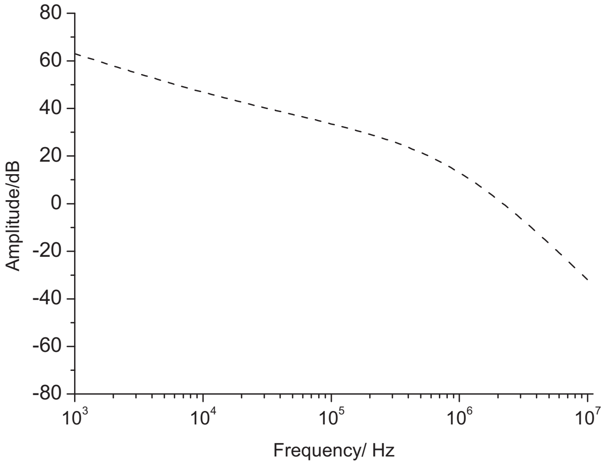

Fig. 2. The frequency spectrum of Heidler model described lightning current.