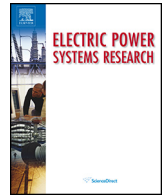




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FDTD analysis of the effects of indirect lightning on large floating roof oil tanks

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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.

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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 lightning.

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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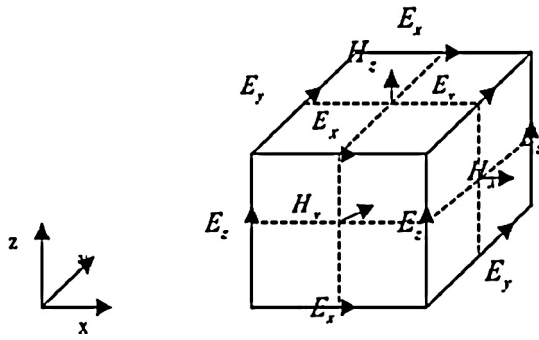


Fig. 1. The Yee cell with labeled field components.

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].

$$E^{n+1} = E^n + \frac{\Delta t}{\epsilon} \nabla \times H^{n+1/2} - \frac{\Delta t}{\epsilon \Delta S^2} I^{n+1/2} \quad (1)$$

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

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

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

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,

- Only the first return stroke current is considered;
- 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];
- 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,

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

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:

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

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

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.

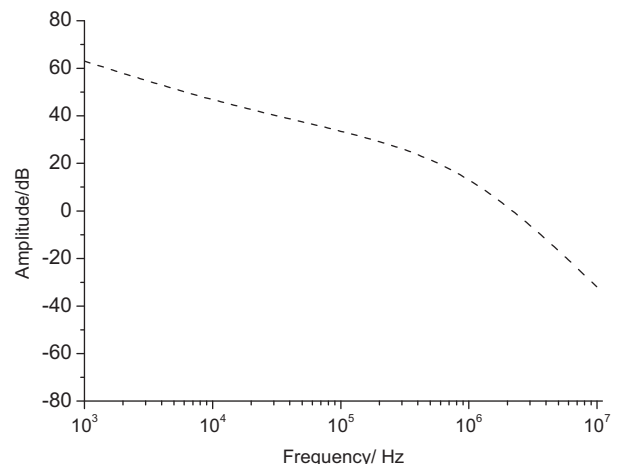


Fig. 2. The frequency spectrum of Heidler model described lightning current.

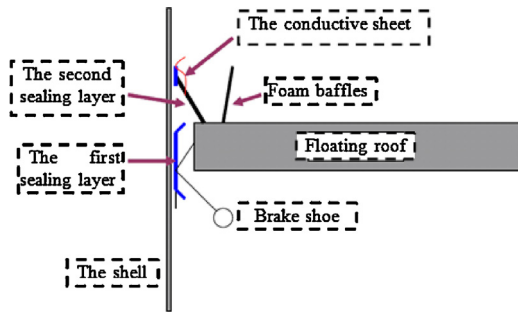


Fig. 3. The sealing and conductive connection structure of a floating roof oil tank.

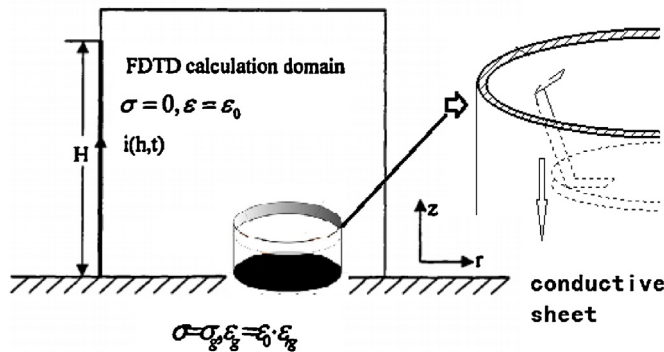


Fig. 4. The FDTD model for the simulation of indirect lightning effect on floating oil tanks.

2.2.1. The simulation model

A floating roof oil tank is consisted of the floating roof, the tank body including the tank bottom and the tank wall, and the sealing connection components between the wall and the roof. The sealed connection generally includes four components: (a) the first sealing layer; (b) the second sealing layer; (c) the conductive sheet; and (d) the fixing device, as shown in Fig. 3. Oil gas will exist between the first and the secondary seal layer during the operation of the oil tank. The spark occurs between the conductive sheet and the tank wall and may cause explosion under lightning situations [8].

In the simulation model, the diameter of the oil tank is 80 m, and the height of the tank is 22 m. The thickness of the tank shell is 45 mm. The situation when the floating roof is at the highest position is considered as the worst electrical field distribution case in the simulation. The gap distance between the tank wall and the edge of the floating roof is 250 mm. 84 even distributed contact sheets of 150 mm width are laid out to consist the charge transfer channel between the floating roof and the tank wall, which is in accordance with the tank design standard [8]. The sealing substance and the brake shoe, which has no impact on the tank surface electric field distribution [13], is ignored in the model.

The absorbing outer boundary setting and seven perfectly matched layers (PML) setting is adopted in the simulation. The developed FDTD model for the analysis of indirect lightning effect on the large floating roof oil tank is shown in Fig. 4. Considering that the main range of the lightning electromagnetic spectrum is distributed in 10^2 – 10^6 Hz, the outer dimension of the oil tank is in an order of about 100 m and the thickness of the tank wall is in an order of about 50 mm only, the global grid and local fine grid combined subdivision method was employed.

As shown in Fig. 5, the IEC standard suggested protecting angle method is adopted to estimate the range in which lightning strike to ground is effectively protected by the tank itself [25]. Under a protecting angle of 45° , the protected range is 22 m, which means that when considering the indirect lightning effect, the nearest lightning

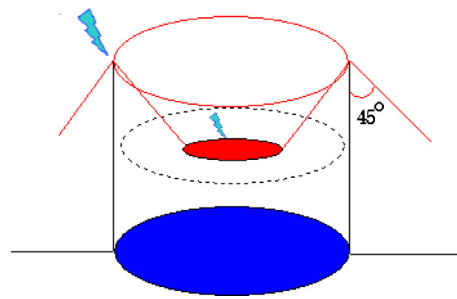


Fig. 5. The protection angle method for estimating the direct strike protected area of the oil tank.

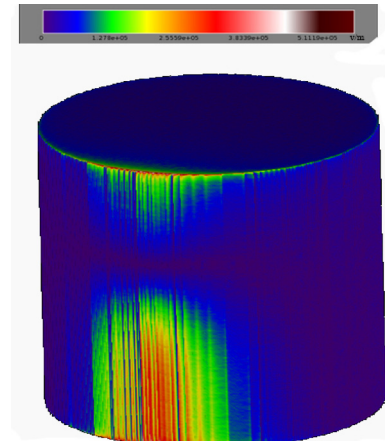


Fig. 6. The electric field distribution on the oil tank under lightning current amplitude 30 kA, 22 m distance.

Table 2

The maximum electric field strength under different lightning current amplitude.

Lightning current amplitude I (kA)	Electric field strength (kV/m)
10	158.5
30	344.5
50	612.7
70	903.5
100	1235.4
130	1576.2
160	1895.2
200	2423.2

strike point need to be considered is 22 m. In the simulation, cases with strike points of 22 m, 40 m, 80 m, 120 m, 160 m and 200 m are calculated under ground conductivity conditions of infinity and 0.001 S/m, respectively.

3. The simulation results

3.1. The impact of lightning current amplitude on the electric field distribution

The lightning current amplitude has important impact on the induced electric field distribution on the tank. Under the situation of 30 kA lightning current amplitude, 22 m strike point distance, and infinity ground conductivity, the calculated induced electric field distribution (maximum amplitude) on the tank is shown in Fig. 6. The maximum electric field strength at the top of the tank wall is 344.5 kV/m.

The maximum electric field strength on the top of tank wall under different lightning current amplitudes from 10 kA to 200 kA at 22 m distance also, is given in Table 2.

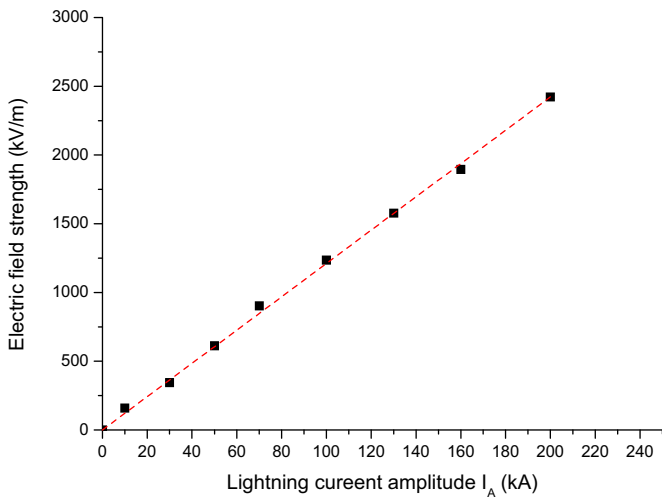


Fig. 7. The fitting curve for the relationship between the lightning current amplitude and the maximum electric field strength on the tank.

Table 3
The electric field strength under different lightning stroke distance.

Lightning stroke distance (m)	Electric field strength (kV/m)
22	344.5
40	98.7
80	46.5
120	20.8
160	11.5
200	7.2

From the simulation results, it is concluded that, the field strength is increasing linearly with the increase of the lightning current amplitude. For the convenience and simplicity of engineering application, the fitting curve of the relationship between the lightning current amplitude and the maximum electric field strength is shown in Fig. 7. The fitting equation is expressed as,

$$E = 12.112I_A \quad (6)$$

where E is the maximum electric field strength at the top of the tank wall, kV/m. I_A is the lightning current amplitude, kA.

3.2. The impact of strike position on the induced electric field

The maximum electric field strength on the top of the tank wall decreases with the strike point distance. The most dangerous situation is when the strike point is at the nearest possible strike to ground point, i.e., 22 m from the oil tank. Under the lightning current amplitude of 30 kA, the maximum electric field strength is 344.5 kV/m. From 22 m to 200 m distance, also under 30 kA lightning current amplitude, the calculated maximum induced electric field on the top of the tank wall is shown in Table 3.

For the convenience and simplicity of engineering application, the fitting curve for the relationship between the strike distance and the induced electric field strength is shown in Fig. 8. The fitting equation is expressed in the following equation as:

$$E = 59599.97d^{-1.681} \quad (7)$$

where E is the maximum electric field strength at the top of the tank wall, kV/m. d is the stroke distance, m.

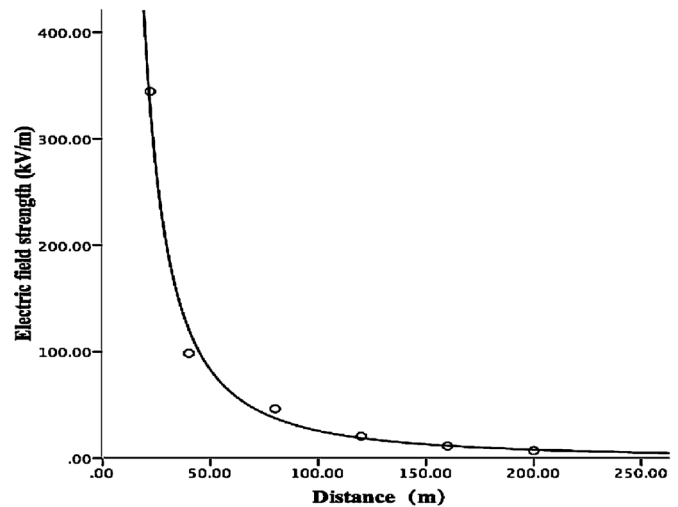


Fig. 8. The fitting curve between the lightning stroke distance and the electric field strength.

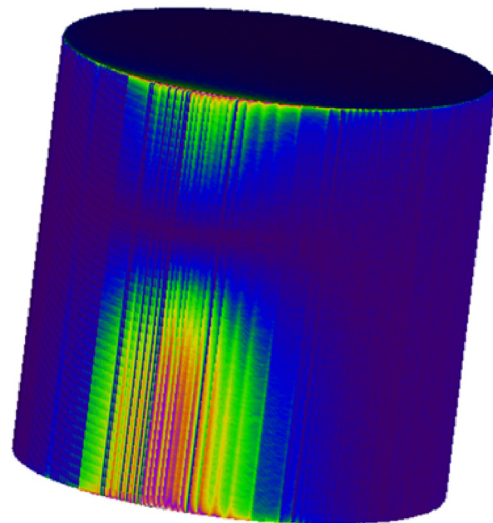
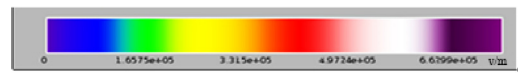


Fig. 9. Electric field distribution on the tank with ground conductivity 0.001 S/m, 22 m distance.

3.3. The impact of soil resistivity on the induced electric field

Two cases are compared, as shown in Figs. 6 and 9, representing the considered infinity ground conductivity and 0.001 S/m ground conductivity, respectively.

From the above result, it is concluded that, under 0.001 S/m ground conductivity condition, the maximum electric field strength is 393.6 kV/m, which is 14.3% higher than under infinity ground conductivity condition.

3.4. The lightning radiated impulse power

For the protection of the electronic equipment on the oil tanks from lightning, it is necessary to calculate the radiation power of the indirect lightning discharge. The lightning discharge radiated power a current amplitude of 30 kA under different distances is show in Table 4.

Table 4
The electromagnetic radiated power of lightning under different distances.

Distance r (m)	Electric field strength (kV/m)	Radiated power (W)
1.0	1632.254	23,589.297
10.0	348.742	1076.832
20.0	235.622	491.553
50.0	38.259	12.960
100.0	22.657	4.545
500.0	4.352	0.167
1000.0	2.225	0.043
2000.0	0.825	0.006

Table 5
The calculated dangerous distance under different lightning current amplitude.

Lightning current amplitude I (kA)	Dangerous distance (m)
10	17.2
17	22.0
30	30.0
50	40.0
70	48.4
100	59.4
130	69.2
160	78.1
200	88.9

4. Discussion of the dangerous distance of the tank from the lightning

According to an existing report, when the field strength at the conductive sheet reaches 200 kV/m [26], it is possible to ignite a spark and may probably trigger an oil tank fire. It is shown that the electric field strength decays with the distance between the strike point and the oil tank. The dangerous distance is defined as a distance from the tank to the lightning strike point under certain lightning current amplitude when the maximum induced electric field strength on the tank may exceed 200 kV/m. The calculated dangerous distance under different lightning current amplitude is shown in Table 5.

From the above calculation results, it is concluded that a nearby lightning stroke with current amplitude less than 17kA is free of threaten for large floating roof oil tanks.

The electronic devices on the oil tank will be affected if the electric field strength in the area of the device exceeds 1.15 kV/m [27,28]. From the above results we can conclude that it may be dangerous if a 30 kA lightning current strikes at the ground in less than 1200 m far from the oil tank. So it is almost always necessary to take measures to protect the electronic equipment on the oil tanks.

The field strength gets higher with lightning current amplitude increasing and decays with the distance between the strike point and the oil tank. For the convenience and simplicity of engineering application, a fitting curve considering both the impact of lightning current amplitude and the impact of strike distance is proposed and shown in the following equation:

$$E = 1998.11d^{-1.66}I_A \quad d \geq 22 \quad (8)$$

where E is the maximum field strength on the tank, kV/m. d is the strike distance, m. I_A is the lightning current amplitude, kA.

5. Conclusion

The electric field distribution on an example large floating oil tank with 80 m diameter and 22 m height under nearby lightning strike situations is analyzed base on the proposed FDTD model. From the case study of such example, it is concluded that,

- (a) The maximum electric field strength on the oil tank increases linearly with the increase of the lightning current amplitude.

The maximum induced electric field strength on the tank under different nearby lightning current amplitude can be estimated by a fitting equation. A lightning current amplitude exceeds 17kA may threat the oil tank.

- (b) The maximum electric field strength on the oil tank decays with the distance between the strike point and the oil tank exponentially. A fitting equation for the estimation of the dangerous distance under different lightning current amplitude is proposed.
- (c) For the convenience and simplicity in engineering application, a fitting equation simultaneously considering the impact of the lightning current amplitude and the stroke distance on the maximum electric field strength on the oil tank is also proposed.
- (d) Considering the lightning discharge radiated electromagnetic power, it is almost always necessary to take measures to protect such devices from nearby lightning strokes.

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