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Evaluation of power in bypass conductors in hydrocarbon storage tanks with external floating roof when a lightning current flows

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***Abstract*— This article analyzes the electrical power dissipated in the bypass of an external floating roof tank when a lightning current flows. Two cases are analyzed: the first for the bypass without curves and the second case for the bypass with curves. Finally, it is concluded which of the two configurations dissipates more electrical power in the bypass when a lightning current of 30 KA flows. For this analysis, the FEKO software was used.**

Keywords*— *lightning; floating roof tank; bypass.

I. INTRODUCTION

This article focuses on external floating roof tanks, analyzes the effect of lightning impacts directly in the context of atmospheric electrical activity in Colombia. Studies of fires in hydrocarbon storage tanks [4] indicate the high probability of fires that occur with the direct impact of lightning on a tank that stores hydrocarbons; The biggest risk is in the external floating roof tanks.

It is analyzed which bypass configuration dissipates the least amount of energy when a lightning strikes the tank wall directly.

Using the FEKO software, the electric and magnetic fields are calculated in the bypass for two study scenarios.

II. ELECTRIC AND MAGNETIC FIELD CAUSED OF LIGHTNING

A. Electric dipole technical

To calculate the radiated electromagnetic fields product of a variable current source in the time, two analytical methodologies are used, one is the electric dipole technique and the other is the electric monopole technique. The dipole technique is widely used for the calculation of the electromagnetic fields radiated by antennas and by lightning.

The Figure *1* shows the structure of the electric dipole oriented on the *z* axis in spherical coordinates, the measuring point of the electromagnetic fields (**E**, **B**) is located, the conductor of the channel is assumed to be perfect and only electric current flows, for calculating the radiated field at point *p* calculates the vector potential **A**.

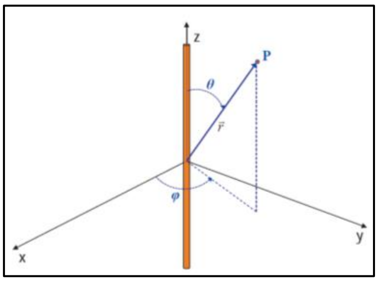

Figure 1. *Electric dipole on* z *axis*

$$\boldsymbol{A}(x,y,z) = \frac{\mu}{4\pi}\int \boldsymbol{I_e}\,(x',y',z')\,\frac{e^{-jKR}}{R}\,dl' \tag{1}$$

Where,

A, is the magnetic potential.
(x, y, z), source point.
(x', y', z'), measurement point.
I_e, current vector.
R, distance between measurement point and source point.
K, is the wavelength

Assuming that the radius of the dipole is much smaller than the wavelength and that the current I_e=I_o is considered constant and that there is only propagation in the z-axis, the expression can be reduced to:

$$\boldsymbol{A}(x,y,z) = \hat{z}\,\frac{\mu I_0 l}{4\pi r}\,e^{-jkr} \tag{2}$$

$$R = \sqrt{(x-x')^2+(y-y')^2+(z-z')^2} \approxeq r = \sqrt{(x)^2+(y)^2+(z)^2} \tag{3}$$

The Lorentz condition [11] is used to find the scalar potential φ.

$$\varphi(r_s,t) = -\frac{1}{\mu\varepsilon}\int_{-\infty}^{t} \nabla \cdot A dt' + \varphi(t=-\infty) \quad (4)$$

The electric field **E** is calculated using **A** and φ.

$$E = -\nabla\varphi - \frac{\partial A}{\partial t} \quad (5)$$

Finally, the magnetic field **B** is calculated using **A**

$$B = \nabla \times A \quad (6)$$

With the above approach, the fundamental analytical bases necessary for the calculation of the electromagnetic field radiated by an electric current in a linear beam channel are left.

To determine the values of electric and magnetic field on the surface of the storage tank that can give rise to ignitions, it is necessary to apply the concepts of the calculation of the electromagnetic field radiated on the surface of the tanks and the following general considerations must be taken into account:

The ignition of flammable materials by lightning can occur by four mechanisms [8] [16].

1. Due to fast lightning current pulses of up to 30 KA, the associated speed changes in magnetic fields are able to induce voltages and currents in circuits and structures. Next, sparks from grounded points with sufficient energy can be produced to ignite a flammable mixture.
2. An electrical discharge on a metal plate could give sufficient local temperature such that the vapor on the other side of the plate reaches a temperature above the spontaneous ignition temperature.
3. By direct entry into a vapor space.
4. When generating currents that are conducted through the pipes and generate sparks in the flanges because they are not at the same electrical potential.

To perform the analysis of the direct impact of a beam on the external floating roof tank, all numerical calculations will be performed only considering the impact of a lightning on the tank wall, the most likely point of the direct impact [3].

III. MODEL OF LIGHTNING CURRENT AND CALCULATION OF ELECTROMAGNETIC FIELD

For the analysis of the direct impact of lightning in an external floating roof hydrocarbon storage tank, the magnitude of the first return current will be modeled using an engineering model [8] equation (7).

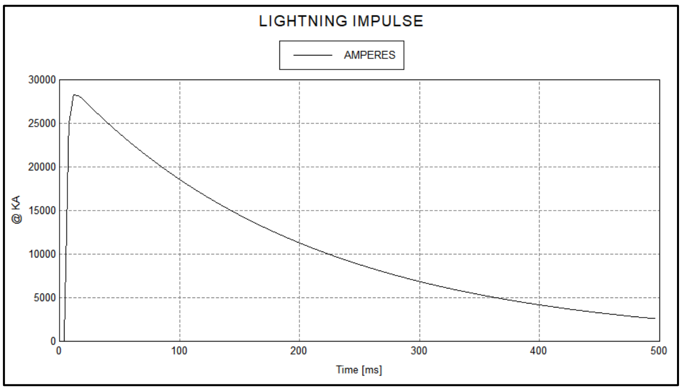

Figure 2.Double exponential model of lightning current for 30kA. FEKO Software Source

$$\mathrm{I(t)} = I_0 \; [\mathrm{e}^{-\mathrm{at}} - \mathrm{e}^{-\mathrm{bt}}] \quad (7)$$

For the analysis of the behavior of the direct impact of lightning on the roof of the tank and determine the values of **E**, **B** (electric field, magnetic field), it is necessary to solve Maxwell's equations [23] [29, p. 567].

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial \mathrm{t}} + \mathbf{J} \quad (8)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathrm{t}} - \mathbf{J} \quad (9)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (10)$$

$$\nabla \cdot \mathbf{D} = \rho \quad (11)$$

The constitutive equations:

$$\mathbf{B} = \mu\mathbf{H} \quad (12)$$

$$\mathbf{D} = \varepsilon\mathbf{E} \quad (13)$$

Where,
E, the electric field
H, the magnetic field
J, current density
ε, electric permittivity
μ, magnetic permeability

The solutions of the Maxwell equations for the particular case of this article were developed by means of numerical analysis of the finite difference time domain (FDTD) method.
According to Baba [23], the method of finite differences is based on a simple procedure presenting a simple programming, has the ability to analyze complex and non-homogeneous geometries, can incorporate nonlinear elements as well as can develop in the time domain and the frequency.

The Ampere law is expressed:

$$\nabla \times \boldsymbol{H}^{n-\frac{1}{2}} = \varepsilon \frac{\partial \boldsymbol{E}^{n-\frac{1}{2}}}{\partial t} + \boldsymbol{J}^{n-\frac{1}{2}} = \varepsilon \frac{\partial \boldsymbol{E}^{n-\frac{1}{2}}}{\partial t} + \boldsymbol{\sigma} \boldsymbol{E}^{n-\frac{1}{2}} \quad (14)$$

Where:
E = the electric field strength [V / m].
H = the magnetic field strength [A / m].
J = the current density [A / m2].
σ = the electrical conductivity [S / m].
J = σE = the law of ohm.
ε = the electric permittivity [F / m].
n-1/2 = are the numeric steps of time.

Faraday's law is expressed:

$$\nabla \times \boldsymbol{E}^{n} = -\mu \frac{\partial \boldsymbol{H}^{n}}{\partial t} \quad (15)$$

Where:
E = the electric field strength [V / m].
H = the magnetic field strength [A / m].
μ = magnetic permeability [H / m].
n = are the numeric steps of time.

For this article the model of the return discharge was developed, assigning a direct impact on the roof of the tank and calculating the electric, magnetic fields.

IV. CALCULATION RESULT

The storage tanks of hydrocarbons of external floating roof are those that present the highest probability of a fire [7] by atmospheric electric discharges, API-RP-545 standard [10] presents a particular development in analysis and approach to protection for this type of tanks. Before 2009, the tank's own protection systems were developed in the shunt systems as an equipotential element between the tank roof and the tank wall, these equipotential elements were built above the floating roof. The following table 1 summarizes the protection elements used in floating roof tanks before 2009 and after 2009.

Two particular cases are analyzed: the first case for the bypass without curvatures in its disposition and a second case with the bypass with curves. From the analyzed cases, it can be concluded which configuration dissipates more energy at the moment of a lightning impact on the wall of the external floating roof tank.

TABLE 1 TANK PROTECTION ELEMENTS BASED ON API-545 STANDARD.

External floating roof tank	
Analysis API-RP-545 standard	
Before 2009	After 2009
Use of the norm API-2003	Use of the norm API-545
Use of Shunt above the floating roof. Equipotential elements	Shunt immersed in the liquid at least 30 cm. Equipotential elements canceling the oxygen component before a possible spark produced by lightning.
External protection with the rolling sphere method.	Bypass conductors connected between the top of the tank and the roof of the tank.
Does not apply	Electrical insulation of more than 1kV between the elements of the roof of the tank and the wall of the tank (seals, springs, scrapers.)

A. Case I

For the effects of the simulation, the equipotentialization of the whole roof with the whole structure of the tank was performed and a direct impact of the first return discharge of 30kA of magnitude was made. Bypass conductors were added between the top of the tank wall and the floating roof. The selected conductor is equivalent to a 120 mm2 copper cable, to simulate the bypass conductor. For the simulated tank of 16 meters in diameter and 12 meters in height, 4 bypass conductors were located.

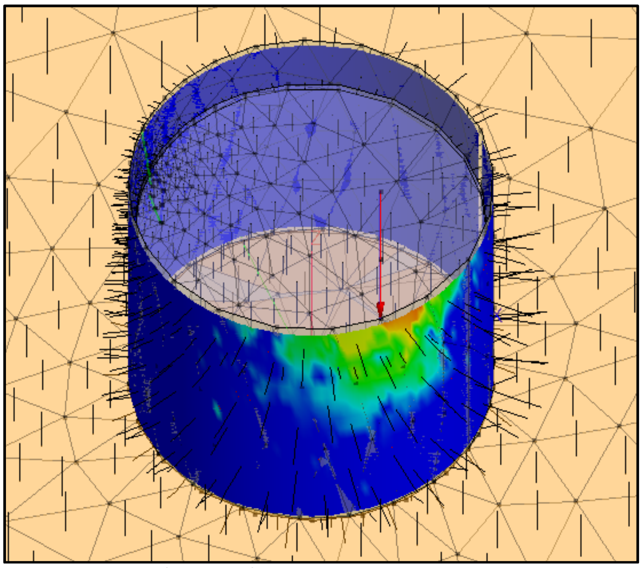

Figure 3. Point of impact of lightning with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

Next, a comparison will be made between the magnitudes of the electromagnetic fields that are obtained when the beam directly impacts the roof of the tank that is considered the most critical scenario. Table 2 shows the most relevant parameters with which the tank is modeled.

TABLE 2 MODELING TANK PROPERTIES

	Modeling tank properties.	
Diameter [ft.]	**Height [ft.]**	**Roof height [ft.]**
40	60	45
carbon steel	carbon steel	carbon steel
Relative permeability	**Conductivity[s/m]**	**Magnetic loss tangent**
1	1e7	0

Figure 4, Figure 5, Figure 7, shows the behavior of the intensity of the electromagnetic fields at the point of impact and the equipotential bond between the roof of the tank and the wall with the bypass conductors.

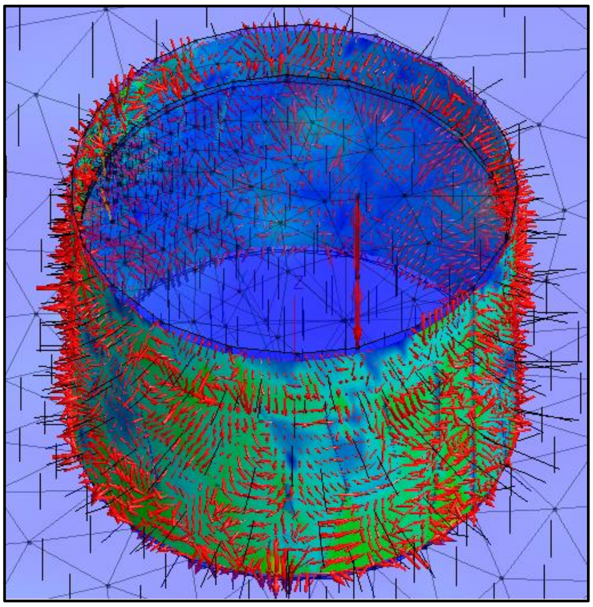

Figure 4. Magnetic field strength [A/m] with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

The highest intensities occur in the wall of the tank at the high point and in the equipotential bonding between the wall and the tank at the bottom point where the beam is impacting. According to the reference of 200kV / m as maximum potential [30] in which sparks can be presented at points at different potentials, the following results obtained in the simulation are analyzed. At the junction between the roof and the wall is where there is the highest probability that flammable gases and vapors are present and that is where potentials of < 200kV/m. According to these results, for equipotential shunt elements, adding a bypass conductor to a discharge of 30kA has values below 200kV / m, values that represent a considerable decrease in the probability of starting a fire in the face of an atmospheric electrical discharge. And in the presence of flammable vapors.

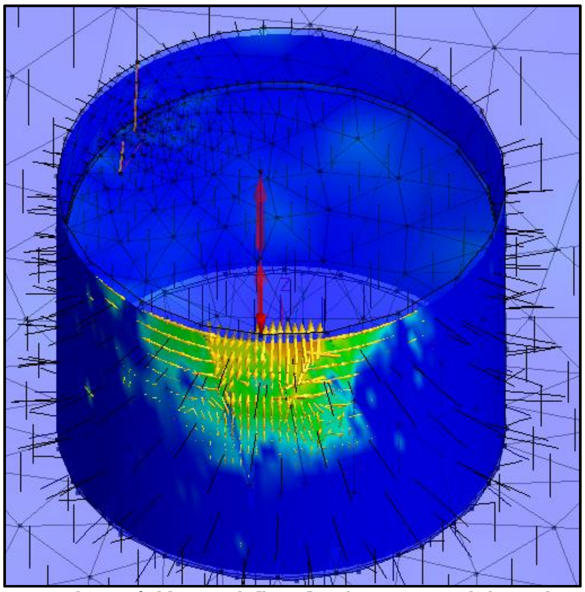

Figure 5. Electric field strength [kV/m] with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

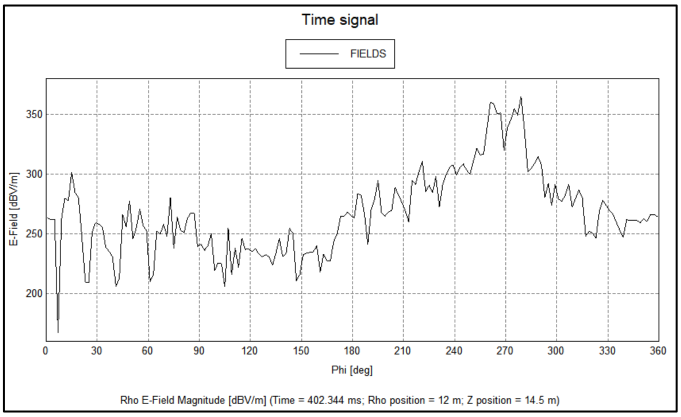

Figure 6. Electric field strength [kV/m] with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

In conclusion of the simulation carried out, results are shown that indicate that using only shunt equipotential is not sufficient in terms of protection because they have values of more than 200kV / m, which represents a high probability of starting a fire. By adding bypass conductors, the values of electric field are in values lower than 200kV / m, which decrease the probability of sparks in elements that are not at the same potential.

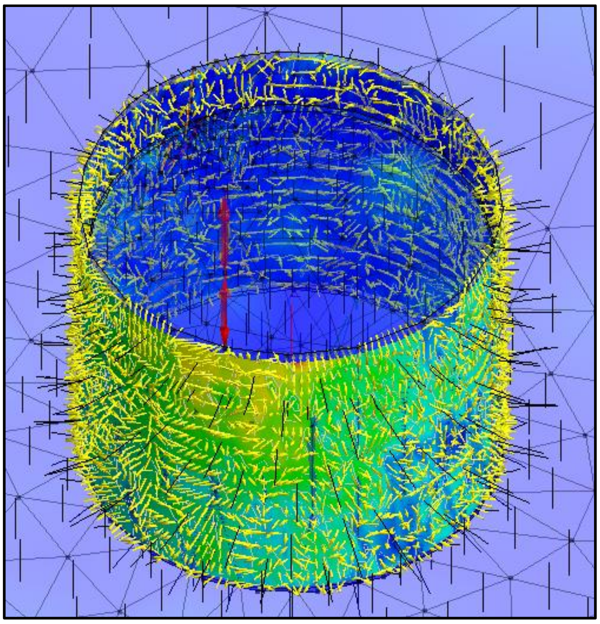

Figure 7. Poynting vector [W/m²] with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

B. *Case II*

In case 2 it is shown that both for the straight-line cable and for the cable with a curve, the behavior of the current is very similar Figure 8. In the Figure 6, Figure 9, Figure 10 shows the behavior of the intensity of the electromagnetic fields at the point of impact and the equipotential bond between the roof of the tank and the wall with the bypass conductors. Figure 11 shows the value of the electric field calculated in the ring that forms the roof and the wall of the tank, values higher than 200kV/m are shown, which represents a high probability of a fire occurring in the tank ring.

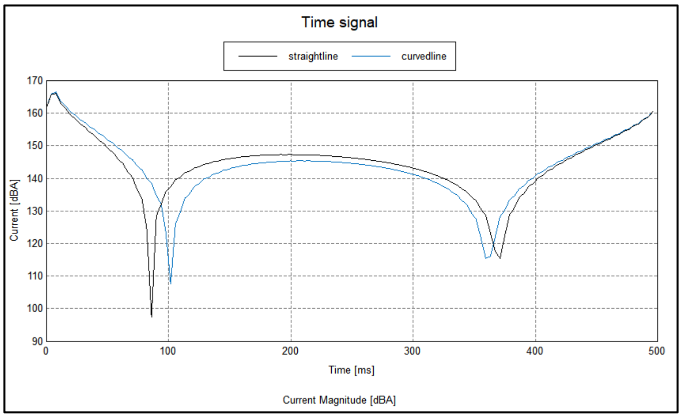

Figure 8. Ampere [A] . for bypass cable with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

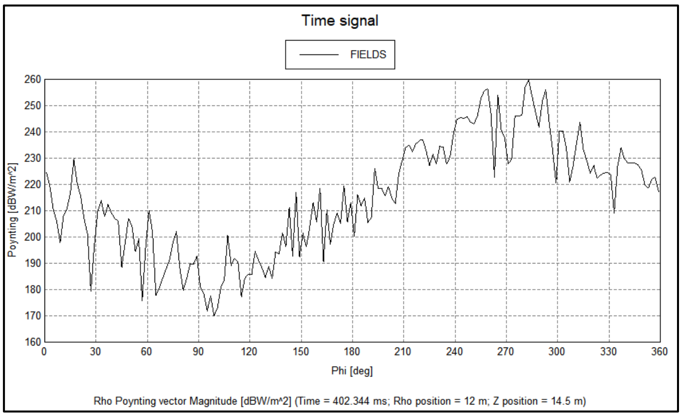

Figure 9. Poynting vector [W/m²] with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

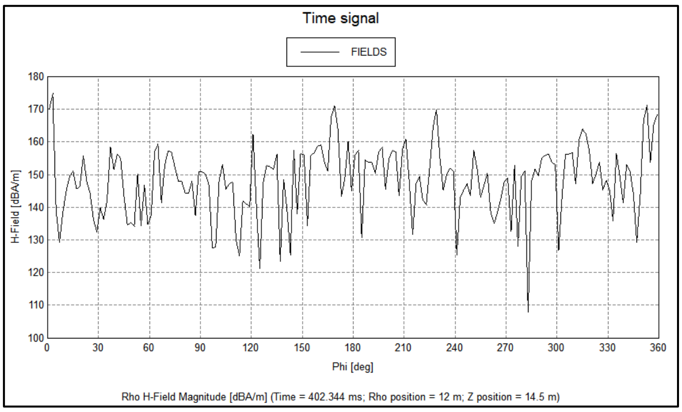

Figure 10. Magnetic field strength [A/m] with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

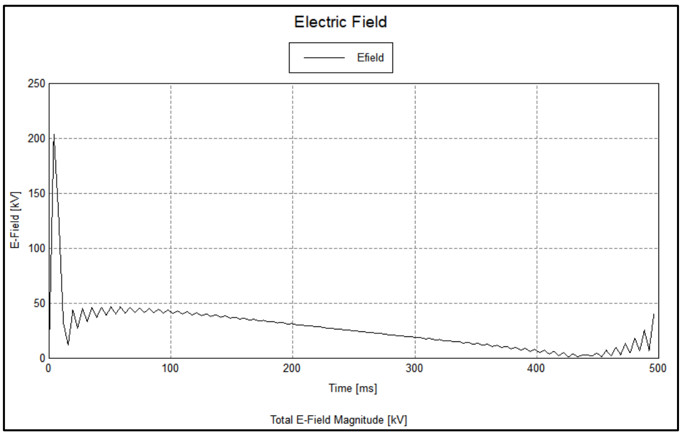

Figure 11. Electric field in the ring that forms the roof and the wall of the tank [kV/m] with equipotential shunt+ bypass, isometric view. Source. Adaptation from the FEKO software

V. CONCLUSIONS

For the external floating roof tanks, it was shown by simulations that for the equipotential shunt both immersed in the flammable liquid and located above the floating roof, the electric field values exceed 200kV/m [210kV/m, Figure 11] at the junction of the roof and the immediately lower wall to the point of impact of the beam.

The equipotentialization cables behave very similar to the moment of the passage of the lightning current driving impacting the wall of the tank.

It is concluded that the electric equipotentialization cables must be maintained in good mechanical conditions to avoid electric potential increases above values of 200kV/m.

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