LIGHTNING STEPPED LEADER NUMERICAL SIMULATION

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Abstract: A lightning stepped leader model is developed. To predict the stepped leader is important to protect installations at ground against lightning. The numerical technique TLM (Transmission-line matrix) is applied.
Key words: stepped leader, lightning, TLM, numerical simulation, protection.

1. Introduction

The protection systems against lightning are projected based on the stepped leader propagation toward the victim. The calculation technique used was obtained many decades ago. This simple process does not give enough precision for the modern industrial installations [1,2]. Many of these installations have been struck by lightning although there were "well" protected. A process to verify the efficiency of the lightning protection systems depends on a more detailed model of the lightning formation. This modeling is a numerical and computational simulation of the stepped leader.

Thus, this research has a large application on the industry (telecommunication, microelectronics, installations, power systems, etc.), allowing larger system reliability and fewer interruptions due to storms.

Firstly, it is described the stepped leader phenomenology [2,3,4,5,6]. From there, the leader computational model is developed in three parts. The first is one-dimensional model, making use of the TLM (Transmission Line Method) technique [3]. The leader is modeled as transmission line. The two other parts are the cloud model and the earth model.

A better return stroke model will be possible combining a stepped leader model and the return stroke model [7].

2. Phenomenology

The lightning stepped leader environment is divided into three parts: the cloud, the channel and the earth. These parts are discussed below.

2.1 Cloud

The cloud is charged with positive and negative charge and the exact charge distribution is not known. Electric field measured at ground level gives that there are charge regions roughly spherical inside the cloud [8,9]. Negative charges are at the bottom and positive charges are at higher altitude [10].

The cloud electric field measured at the leader initiation is approximately 10kV/m. This value is reasonable since the breakdown value for dry air at sea level between parallel plates is 30kV. Inside the clouds there are ice crystals, low pressure and water drops which contributes to decreases the air critical strength.

2.2 Earth

The earth influence is important for the stepped leader propagation. This is because of the earth permittivity, conductivity and charge distribution at ground level. The earth surface geometry, roughness and soil layers have also influenced the electric field between cloud and ground.

2.3 Stepped Leader

The stepped leader begins after the preliminary breakdown inside cloud. This allows a charge flow toward earth that increases the electric field at the bottom. As soon as the electric field is higher than the air strength a new breakdown takes place. This opens a 50m, approximately, path toward earth [9]. New charge from the cloud comes to this new open channel. Again the electric field is strong enough to open a new path toward earth. This process repeats util the cloud charge is sufficient to feed the channel or util the ground is not reached [11], see fig. 1. The time between two steps is approximately 50,0μs [9].

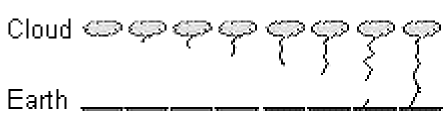

Figure 1: Stepped leader propagation toward earth.

2.4 Corona Build Up

The stepped leader corona begins with the first step. The corona enlarges as the stepped leader propagates. As the cloud charge flows towards the newest step it also flows toward the corona limits. This creates conditions for a new breakdown transversal to the lightning channel. Thus, at each new step the corona around the channel is larger and with more charge. At stepped leader end the corona has a conical shape with several meters of diameter [9], see fig. 2.

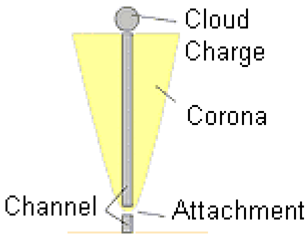

Figure 2: Lightning discharge at the end of the stepped leader.

4. Modeling

4.1 Stepped Leader Model

The stepped leader is modeled as a vertical transmission line. The line length varies as the leader propagates toward earth. At the top is the source that is a charged capacitance in series with a resistance, see fig 3. At the other end there is a capacitance in series with a large resistance. The current passes through an ionized channel except for the newest step that is opened as the current is propagating. The parameters for the newest step are different for the others steps.

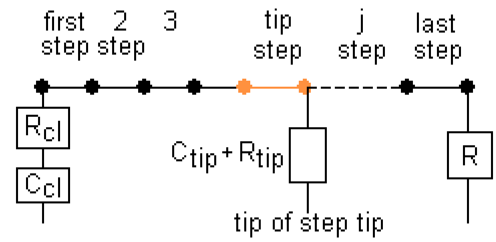

Figure 3: Lightning stepped leader model.

At the initial condition there is already the first step, see fig. 4.

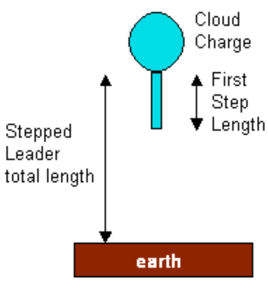

Figure 4: First step representation.

4.2 Cloud Capacitance

The cloud charge is thought to be in a capacitor. This capacitor can be estimated from [9].

$$C = Q_{cl}/V \quad \textbf{(1)}$$

where V – cloud voltage to ground;
Q_{cl} – cloud charge.

To do so, the cloud charge is considered uniformly distributed into a sphere few kilometers above ground level. The ground is thought an infinite plane with perfect conductivity.

4.3 Cloud Resistance

The cloud resistance is estimated to be the channel resistance inside the cloud, which has length equal to the cloud charge radius. This radius is gotten from the distance between the cloud charge center to a point where the electric field is E_c = 10kV/cm. At this value the air breakdown takes place [9]. This value was use before for return stroke simulation [12,13].

4.4 Geometrical Capacitance

This is the capacitance formed by the channel and the soil surface. This capacitance is calculated by the following equation [14].

$$C(h) = \frac{2\pi\varepsilon h}{\ln\left(\frac{2h}{d}\sqrt{\frac{4s+h}{4s+3h}}\right)} \quad (2)$$

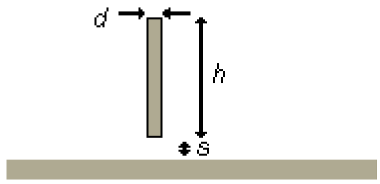

Figure 5: Lightning stepped leader geometry.

The leader diameter is assumed 1m due to photographic measurements.

4.5 Geometrical Inductance

$$L(h) = \frac{1}{\sqrt{v^2 C(h)}}$$, where v is the light speed.

4.6 Transmission Line Impedance

This impedance is obtained from the minimum geometrical inductance and from the minimum geometrical capacitance

$$Z(h) = \sqrt{\frac{\min(L(h))}{\min(C(h))}} \quad (3)$$

4.7 Step Length

This length is obtained from the striking distance [15]

$$S_d = 10\left(10.6 q_{ch}{}^{0.7}\right)^{0.65} \quad (4)$$

4.8 Corona Capacitance

The equation (2) is also used to calculate the corona sheath capacitance, *Ccor*, for each height. The diameter is obtained from the critical electrical breakdown *Ec* distance to the leader channel. Considering a perpendicular cross section. The corona capacitance for the newest step is taken 5 times *Ccor* as it has been observed in power transmission lines transient with corona [16].

4.9 Critical Electric Field

The transmission line corona breakdown varies with high, cable roughness, temperature and other factors. All these features are included in the following equation

$$E_C = 30 m_r \gamma \left(1 + \frac{0.301}{\sqrt{a\gamma}}\right) \qquad (6)$$

where

$a = d/2$ corona radius;

air density $\gamma = \dfrac{3.92b}{273 + T}$ (7)

3.92 °C/cm of Hg, 273 °C, T is temperature [°C], m_r=0.72 (roughness), b is the barometric pressure [cm de Hg], which is gotten from Halley's equation:

$$\log(b) = \log 76 - \frac{A}{18336} \qquad (8)$$

where A is the altitude in meters.

Ec is at the limit between the corona sheath and air, see fig. 6.

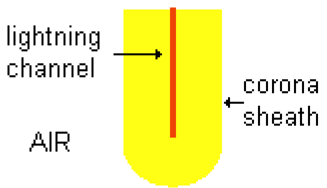

Figure 6: Corona effect around the lightning stepped leader channel.

4.10 Channel Resistance

The channel resistance is not linear and behaves as Braginskii's equation [17].

$$R(t) = \frac{\Delta h \left(1.29 \times 10^{-3}\right)^{1/6}}{0.93 \times 10^{-2} i^{1/3} \sqrt{t}} \qquad (10)$$

This equation takes into account the channel expansion due to heat. Braginskii's equation is not applied for the newest step simulation which has a constant resistance of 100Ω/m.

4.11 Electric Field

This field is calculated for static conditions.

4.12 Tip Capacitance (at tip step tip)

At the Stepped Leader tip there is a capacitance. This *Ctip* is at the end of the new added step.

This capacitance is to model the corona charge at the tip.

4.13 Tip Resistance (at tip step tip)

At the stepped leader tip there is a very large resistance. This *Rtip* is at the end of the new added step.

5. TLM Model

Each transmission line segment is modeled as in fig. 7. This circuit is solved for each transmission line node and for every time step.

C_{cp}

This is the difference between the geometrical capacitance and the minimum geometrical capacitance.

L_{cp}

This is the difference between the geometrical inductance and the minimum geometrical inductance.

Lcp and *Ccp+Ccor* are stub lines and *Z* is a series line [3].

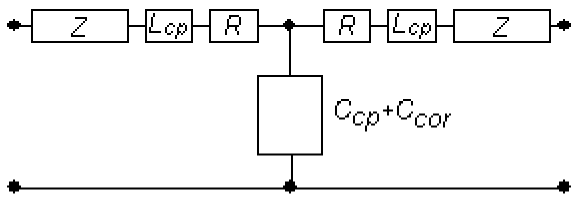

Figure 7: Stepped leader channel circuit model.

6. Results

6.1 Case 1

This simulations considers the following input data:

cloud height = 3000m

cloud charge = 30C

cloud resistance = 1 Ω

segment size =14.989625 m

time step = 0.05 μs .

At fig. 8 the channel current for each step at cloud level and at tip level are shown. As the stepped leader approaches earth the current decreases. The calculated time between each lightning step is about 50μs.

The final channel charge is 6.85 C within the expected value [9,15].

The fig. 9 shows the steps lengths that are in agreement with the measure values [9,15].

This simulation was repeated with cloud charge equal to 5C. The step length is shown on fig. 9. It is possible to compare the leader propagation for the two cloud charges. For a bigger cloud charge the stepped leaders have fewer steps and longer than the cloud with lower charge.

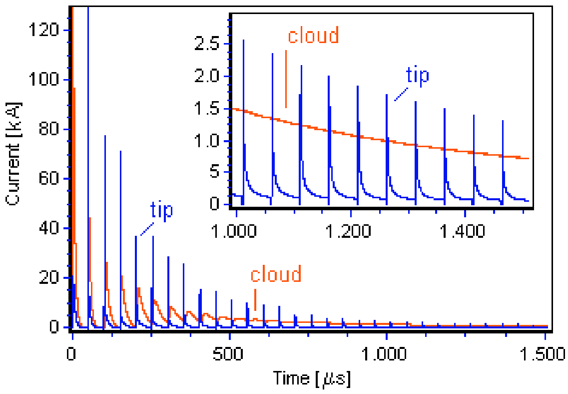

Figure 8: Channel current at cloud level and at tip level, and detail of the channel current at cloud level and at tip level. Cloud charge 30C.

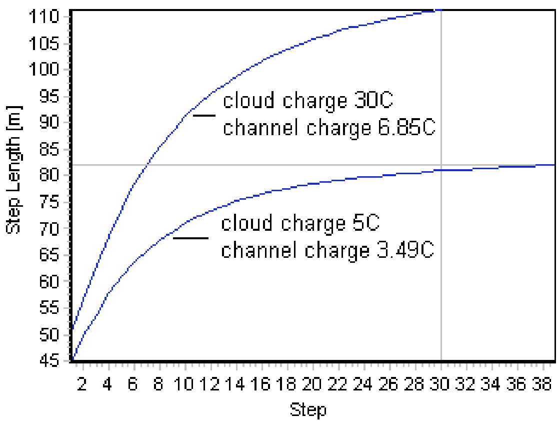

Figure 9: The step length increases as the stepped leader approaches ground.

7. Conclusion

A lightning stepped leader model was developed from the physical aspects with good agreement with observed data [15], step length, current peak, current rise time and time between steps. The Transmission-Line Matrix method was used successfully.

The investigation is under way in order to bring more physical features into this model. The new propose is to have a three dimensional model. Including the upward stepped leader.

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