Protection of Trees against Lightning Strikes as a Measure to Prevent Fires and Loss of Human Life

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***Abstract*--Lighting strikes have been the catalyst of massive uncontrolled fires in areas of combustible vegetation. In some regions, lightning strikes may be a relatively unusual occurrence (e.g., California), but instead they seem to have become a major contributor to the propagation of wildfires, as a byproduct of climate change. Given such unusual weather, wildfires originating from lightning are an increasing threat.**

In this paper, the authors discuss the withstand capability of trees against lightning and introduce a proactive approach to prevent wildfires by the deployment of tree lighting protection systems (TLPS) to protect forested areas, where deemed necessary by the tree risk assessment.

***Index Terms*--collection area, density, flash density, form factor, lightning, resistivity, trees.**

I. Introduction

Lightning strikes have been the catalyst of massive uncontrolled fires in areas of combustible vegetation. In some regions, lightning strikes may be a relatively unusual occurrence (e.g., California), but instead they seem to have become a major contributor to the propagation of wildfires, as a by-product of climate change. Given such unusual weather, fires originating from lightning are an increasing threat.

Reference [1] projects that the number of lightning-ignited fires will increase by 19.1% by 2020 to 2049 and the annual area burned at high severity will increase by 21.9%. These projections depict a scenario where climate-induced bushfires may become a serious threat to persons and assets.

In the landscape, tall trees are the most receptive elements of lightning strikes, especially those growing on hills. Lightning striking a tree causes the circulation of an intense electrical current, which flows to ground through the trunk and the roots. The tree can catch on fire, and so can the neighboring vegetation, with the risk of initiating a spreading catastrophic wildfire.

A proactive approach to prevent the ignition of forested areas and mitigate the propagation of wildfires may be the deployment of lighting protection systems (LPS) to protect:

1. trees that are likely to be hit by lightning per applicable standards, and
2. trees that are likely to catch on fire, or present a fire hazard to the surrounding, based on their physical characteristics.

Not all trees in forested areas belong simultaneously to the two sets above.

This approach would involve the installation of air terminals, possibly integrated in trees, connected to grounding systems via down conductors.

The authors believe that the above strategy would prevent the ignition of trees by allowing the safe discharge to ground of the energy from these more often occurring lightning strikes, and therefore decrease the risk of wildfire.

While the authors understand that this solution may be relatively expensive for a wide deployment, they also believe that the cost would pale in juxtaposition to the life, economic, and environmental price associated with wildfires.

II. Withstand Capability of a Tree

During a lightning discharge, the thermal energy W generated in the trunk is the product of its ohmic resistance R and the specific energy of the lightning flash conveyed by the lightning current i (1).

$$W = R\int i^2 dt \tag{1}$$

The lightning current has a very brief duration, therefore the thermal exchange by convection or radiation between the tree and the environment is not significant. The phenomenon is therefore to be considered adiabatic, and the heat trapped in the trunk will raise its temperature.

If the trunk has a minimum cross-sectional area sufficient to avoid the superheating of the moisture in the tree, which could cause the splintering of the tree, and present a fire hazard to the surroundings, wildfires may be avoided.

Equating the thermal energy W provided by the lightning to the heat accumulated in the trunk, which is determined on the physical size and makeup of the wood, the minimum cross-sectional area S (in m2) of the trunk, which allows the tree to withstand the lightning current without posing a fire hazard to the surroundings, can be calculated with (2) [2] [3] [4].

$$S \geq \sqrt{\frac{\frac{W}{R}\rho \cdot \alpha}{\gamma \cdot c \cdot \ln[\alpha \cdot (T_M - T_0) + 1]}} \tag{2}$$

where:

- W/R is the specific energy of the current impulse (J/Ω). It represents the energy dissipated by the lightning current in a unit resistance;

- ρ is the electric resistivity of the wood at 20˚C (Ωm);
- α is the temperature coefficient of resistance of wood (1/K);
- γ is the wood density (kg/m^3);
- c is the wood thermal capacity (J·kg^{-1}·K^{-1});
- T_M is the critical temperature that the trunk could reach after the expiration of the lightning current, which poses a fire hazard to the surroundings, herein 523 K (or 250˚C) [5];
- T_0 is the wood temperature wood before the lightning strike, herein 293 K (or 20˚C).

A. Resistivity and temperature coefficient of resistance α

Dry wood is an excellent electrical insulator, with a resistivity of about 10^{15} - 10^{16} Ω·m at ambient temperature. However, the resistivity dramatically decreases as the moisture content of the wood increases. For a tree at fiber saturation, the resistivity becomes 10^3-10^4 Ω·m [6] [7]. The fiber saturation denotes the point at which wood cannot absorb any more water (i.e., 30% moisture content). In this condition, the conductive behavior of the trunk may be characterized by a value α for the temperature coefficient of resistance of 0.004 K^{-1}, which is typical of conductors.

The maximum temperature rise (T_M - T_0) to which the tree may be subjected as consequence of the lightning strike has been herein assumed to be 80 K.

B. Wood density γ

For wood, both mass and volume depend on moisture content, therefore, the wood density γ to be used in (1), at a given percentage moisture content m, may be determined with (3) [7].

$$\gamma = 1{,}000 \cdot G \cdot (1 + \frac{m}{100}) \tag{3}$$

G is the specific gravity of wood, defined as the ratio of the density of dry wood to the density of water at a specified reference temperature, typically 4°C, where the density of water is 1,000 kg·m^{-3} [7].

The specific gravity G ranges between 0.3 and 0.7, depending on the type of tree (e.g., White Ash). Thus, according to (3), for a moisture content of the wood of 30%, γ ranges between 390 kg·m^{-3} and 910 kg·m^{-3}.

C. Wood thermal capacity

The wood thermal capacity c is defined as the amount of energy necessary to increase one unit of mass (in kg) by one unit in temperature (in K).

c does depend on the temperature and moisture content of the wood but is virtually independent of its density or type and can be calculated with equations (4), (5) and (6) [7].

$$c = \frac{c_0 + 0.01 \cdot m \cdot c_{h20}}{1 + 0.01 \cdot m} + A \tag{4}$$

$$A = -619.1 \cdot 10^{-4} \cdot m + 2.36 \cdot 10^{-4} \cdot m \cdot T - 1.3 \cdot 10^{-4} \cdot m^2 \tag{5}$$

$$c_0 = 0.1031 + 0.003867 \cdot T \tag{6}$$

m is the moisture content, which is assumed at fiber saturation (i.e., 30%); T is the wood temperature (K); c_0 is the thermal capacity of dry wood, which is 1.24 kJ·kg^{-1}·K^{-1} at T = 293 K (20˚C); c_{h20} is the thermal capacity of water (4.18 kJ·kg^{-1}·K^{-1}). In the above conditions, the wood thermal capacity c is about 2 kJ·kg^{-1}K^{-1}.

D. Specific energy of the current impulse

Reference [8] tabulates values of lightning current parameters and lists the cumulative frequency distribution of the specific energy W/R (Table I).

TABLE I
TABULATED VALUES OF *W/R*

	***W/R* (kJ/Ω)**		
Type of stroke	**95%**	**50%**	**5%**
First negative stroke	6	55	550
First positive stroke	25	650	15,000

The above calculated and tabulated parameters have been used in equation (2) to determine the values of the trunk radius below which the tree will sustain damage and may catch on fire. Both calculated minimum and maximum values of wood density γ have been used, for both first negative and positive strokes of the lightning current. The results are shown in Figs. 1 and 2 as a function of the probable values of the ratio W/R.

The calculations show that the worst-case scenario occurs at the occurrence of the first positive impulse stroke with a specific energy W/R of 15 MJ/Ω, for a wood density γ of 390 kg·m^{-3}. In this scenario, trees with trunk radius less than 3.3 m would not withstand a lightning strike and might ignite the surrounding vegetation.

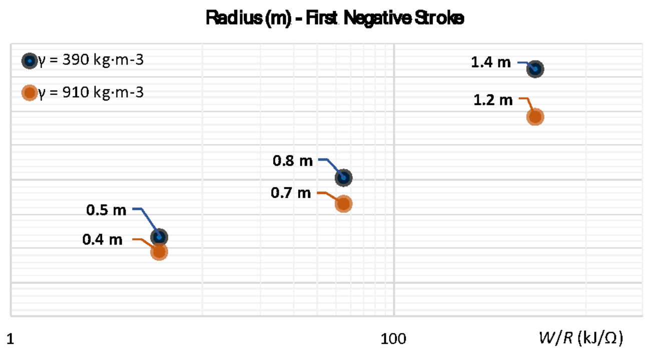

Fig. 1. Minimum trunk radius below which the tree may catch on fire due to the first negative strike.

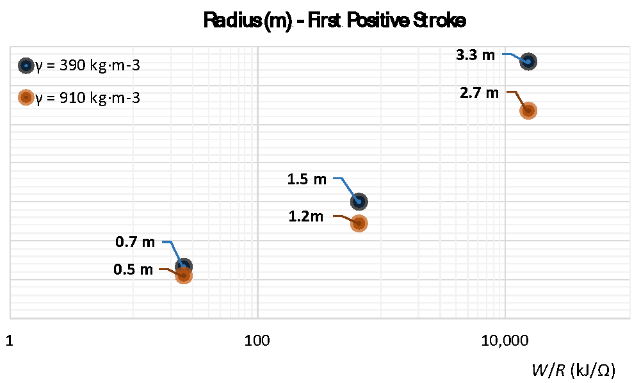

Fig. 2. Minimum trunk radius below which the tree may catch on fire due to the first positive strike.

III. Equivalent Collection Area of a Tree

According to [8] and [9], the vulnerability of a structure to lightning involves the evaluation of the *equivalent collection area* A_D of the structure and the flash density for the area in which the structure is located.

In our case, A_D is the equivalent area at the ground level, having the equivalent lightning flash vulnerability as the tree.

The collection area is defined by the intersection between the earth surface and a straight line with 1/3 slope which passes from the top of the tree of height H and rotates around it (Fig. 3).

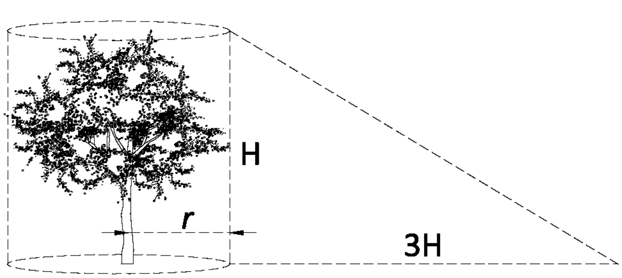

Fig. 3. Equivalent Collection Area of a tree

Based on the above, A_D (m^2) can be calculated with (6).

$$A_D = \pi(3H+r)^2 \tag{6}$$

where r is the maximum length of the tree canopy.

A_D must be adjusted to include the effect of the location of the tree, by multiplying it for the location factor C_D. The location factor accounts for the topography of the site where the tree is growing and any objects located within the distance 3H from it, which may affect the collection area (Table II).

TABLE II
LOCATION FACTOR, C_D

Relative location	C_D
Tree surrounded by higher objects	0.25
Isolated tree: no other objects in the vicinity	0.5
Tree surrounded by objects of the same height or smaller	1
Isolated tree on a hilltop or a knoll	2

The greater is the adjusted collection area, the greater is the expected annual threat occurrence for that tree. The tree in question is, therefore, more likely to be hit by lightning than other neighboring objects and becomes a natural air terminal.

Thus, protecting a tree against lightning also defends neighboring objects, whose own collection area is completely included within the tree's adjusted collection area.

In this paper, we have assumed H ranging between 3 m and 30 m, and r ranging between 1.5 m and 15 m.

To take into account different shapes of trees in collection areas calculations, the form factor $\kappa = H/r$ is herein introduced (Fig. 4).

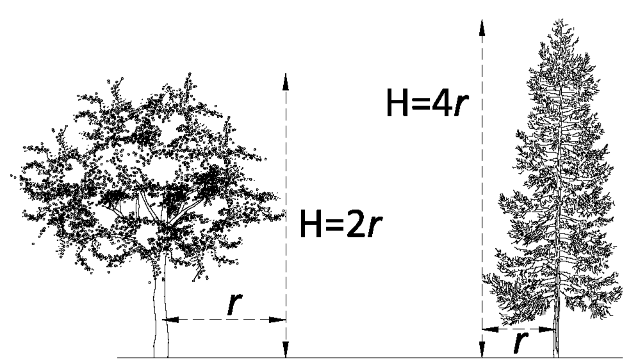

Fig. 4. Form factor H/r

The expected annual number of dangerous events N_D (y^{-1}) due to lightning flashes striking a tree can be calculated with (7) [8][9].

$$N_D = N_G \cdot A_D \cdot C_D \cdot 10^{-6} \tag{7}$$

where N_G is the annual lightning ground flash density [$km^{-2} \cdot y^{-1}$]; A_D is the collection area of the structure (m^2); C_D is the location factor of the structure.

N_G depends on the thunderstorm activity of the region where the tree is located, and its values may be reported in lightning flash density maps. For instance, in 2019, in the state of Florida (U.S.), 88 lightning events per square kilometer were observed [10], whereas [9] reports only 0.5 to 1 flash per square kilometer per year in the state of California.

Unusual weather events, however, such as the *dry thunderstorms* occurred in California the month of August 2020, produced over 12,000 lightning strikes in four days over Northern California, which spiked 585 wildfires [11]. The above events caused a lightning ground flash density well above the value indicated in applicable standards.

IV. Risk Assessment of direct flashes to trees

The risk assessment of direct flashes to trees compares the annual threat occurrence R for the tree, which is based on N_D, to the tolerable risk R_T (y^{-1}).

Typical values of tolerable risk are given in Table III [8].

TABLE III
TOLERABLE RISK, R_T

Types of loss	R_T (y^{-1})
Loss of human life or permanent injuries	10^{-5}
Loss of cultural heritage	10^{-4}
Loss of economic value	10^{-3}

The annual risk R may be expressed by equation (8).

$$R_x = N_D \times P_x \times L_x \tag{8}$$

P_x is the probability of damage (to a tree or to persons), and L_x is the consequent loss (human life or physical damage to a tree). Protection measures will be required if $R_x > R_T$.

Lightning striking trees may endanger the environment creating a fire risk R_B, but also threaten the public if located in areas with continuous presence of persons (e.g., national parks). The lightning strike may in fact cause dangerous touch and step voltages [12] around the tree; therefore, the risk R_A of loss of human life and injury to living beings by electric shock must be considered.

In addition, trees may be considered monumental for historical reasons, aesthetic value, but also for their role in preserving rare and endangered species [13]. In this case, the risk of loss of cultural heritage R_B must also be evaluated.

A. Risk of loss of human life and permanent injury to living beings

The risk R_A of loss of human life and permanent injury to living beings may be determined with equation (9).

$$R_A = N_D \times P_A \times L_T \times r_t = N_D \times 10^{-4} \tag{9}$$

P_A is the probability that the lightning flash will cause shock to living beings around the tree. If the tree is not protected and grows in a crowded area, P_A=1.

L_T is the relative numbers of victims injured by electric shock, which is assumed to be 10^{-2} [8]. r_t is a factor reducing the loss of human life thanks to the agricultural soil around the tree (i.e., low resistivity), which is also 10^{-2} [8].

B. Risk of loss of cultural heritage

The risk R_B of loss of cultural heritage may be determined with equation (10).

$$R_B = N_D \times P_B \times \frac{c}{c_t} \times r_f = 0.1 \times N_D \tag{10}$$

P_B is the probability of a physical damage occurring to the tree due to lightning flash. If the tree is not protected by a lighting protection systems (LPS), P_B =1.

c is the mean value of the possible loss, and c_t is the value of the tree. In the case of lightning strike, the tree may be completely destroyed, therefore the ratio c/c_t equals 1.

r_f is a factor reducing the loss due to physical damage depending on the risk of fire, which for a tree is high; therefore, r_f = 0.1.

V. Lightning Protection Assessment

The value of the height H above which a tree needs protection against lightning strikes can be studied as a function of κ, N_G and C_D. Eq. 11 identifies the height $H^{(RA)}$ above which the risk of loss of human life is greater than the tolerable value of 10^{-5} y^{-1}.

$$H^{(R_A)}(\kappa, N_G, C_D) = 178\frac{\kappa}{3\kappa+1}\sqrt{\frac{1}{N_G C_D}} \tag{11}$$

Equation 11 is graphed in Fig. 5 and Fig. 6, for κ = 2 and κ = 4, respectively.

It can be clearly seen that increasing values of N_G, decrease the height of trees above which protection against the hazard of touch and step voltages due to lightning is required. Increasing values of C_D cause the same effect.

In the case of unusual weather events (i.e., $N_G \geq 90$ $km^{-2}y^{-1}$), the height of the trees above which protection against lightning is required to lower the risk of loss of human life is below 4 m.

Eq. 12 identifies the height $H^{(RB)}$ above which the risk of loss of cultural heritage is greater than the tolerable value of 10^{-5} y^{-1}.

$$H^{(R_B)}(\kappa, N_G, C_D) = 17.8\frac{\kappa}{3\kappa+1}\sqrt{\frac{1}{N_G C_D}} \tag{12}$$

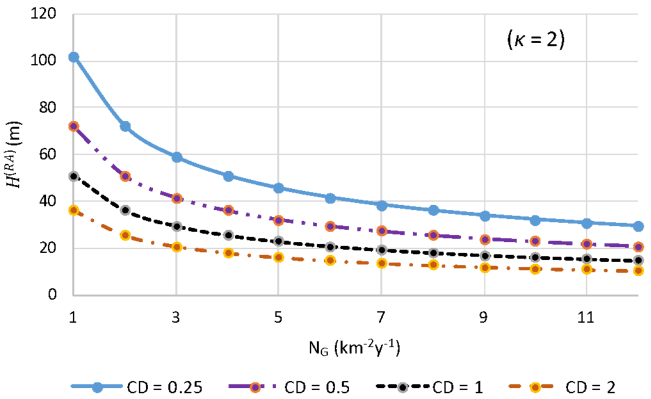

Fig. 5. Maximum $H^{(RA)}$, for $\kappa = 2$.

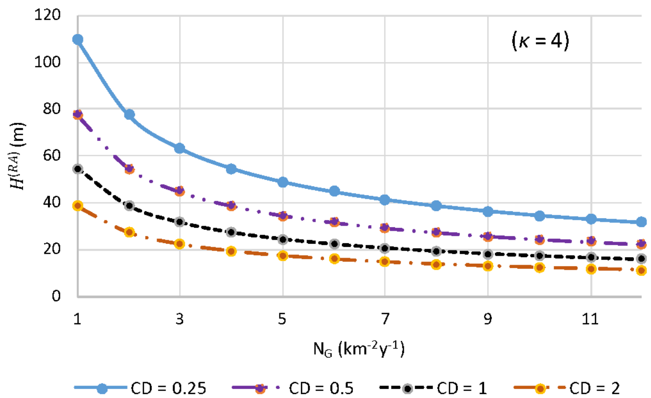

Fig. 6. Maximum $H^{(RA)}$, for $\kappa = 4$.

Equation 12 is graphed in Fig. 7 and Fig. 8, for κ = 2 and κ = 4, respectively.

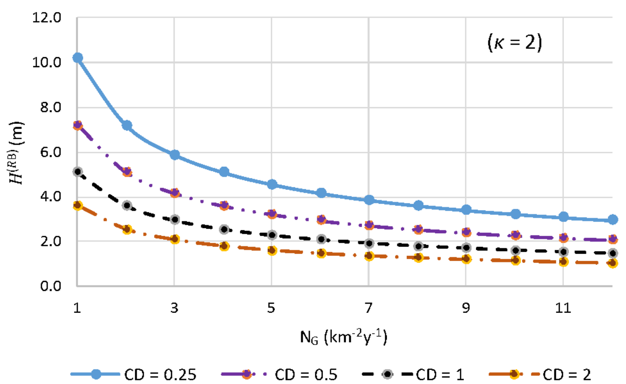

Fig. 7. Maximum $H^{(RB)}$, for $\kappa = 2$.

The trend of the height $H^{(RB)}$ for increasing values of N_G is similar to that of $H^{(RA)}$. The critical heights $H^{(RA)}$ and $H^{(RB)}$ in the case of an isolated tree on a hilltop (i.e., $C_D = 2$) and of unusual lightning events (i.e., $N_G = 90$ km^{-2}y^{-1}) are shown in Fig. 9, for $\kappa = 2$ and $\kappa = 4$.

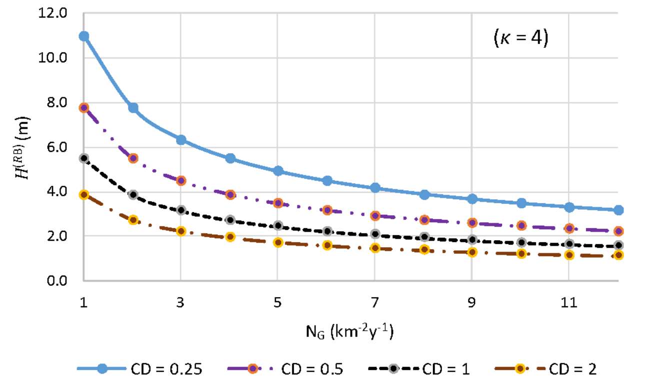

Fig. 8. Maximum $H^{(RB)}$, for $\kappa = 4$.

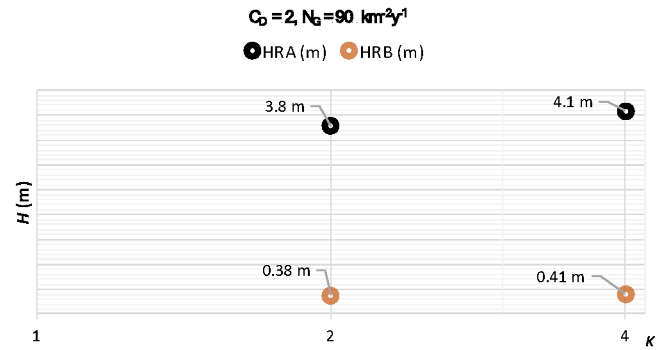

Fig. 9. Critical heights for $\kappa = 2$ and $\kappa = 4$.

VI. Tree Lightning Protection System

The goal of tree lightning protection systems (TLPS) is to provide a preferred point for the lightning attachment and an avenue the lightning currents to dissipate to earth. This path reduces the risk of fire for the struck tree, as well as for neighboring trees due to side flash. The components of a TLPS embedded in a tree are depicted in Fig. 10.

Aluminum wires or accessories should not be used on trees due to overall strength and corrosion resistance issues; only materials made of copper and bronze alloys should be used [14]. The down-conductors are attached to the tree by means of fasteners, hammer driven through the bark and into the tree; fasteners must be placed at not more than 2 m apart. Wires are flexible to allow for the swaying of the trunk and branches, and components are adjustable to allow for the growth of the tree. The ground electrode should be located at least 3.6 m from the trunk to avoid root damage [14]. The air terminal tip may be sharp or blunt.

An economic alternative to a TLPS for each single tree may be an overhead ground wire (OHGW), typical of transmission lines. The OHGW may be mechanically supported by the tallest trees (Fig. 11a), and locally grounded. If the tree is not deemed able to withstand the mechanical load imposed by the OHGW, grounded metal poles may be used (Fig. 11b). The solution with metal poles may add additional costs to this protective configuration, which does not use the tree as a mechanical support; however, the cost is still offset by the economy of scale created by the simultaneous protection of multiple trees. The presence of the OHGW prevents the flow of the impulse current through the tree down-conductor of Fig. 10, which would occur in the case of a TLPS embedded into a tree; this further reduces the risk of fire.

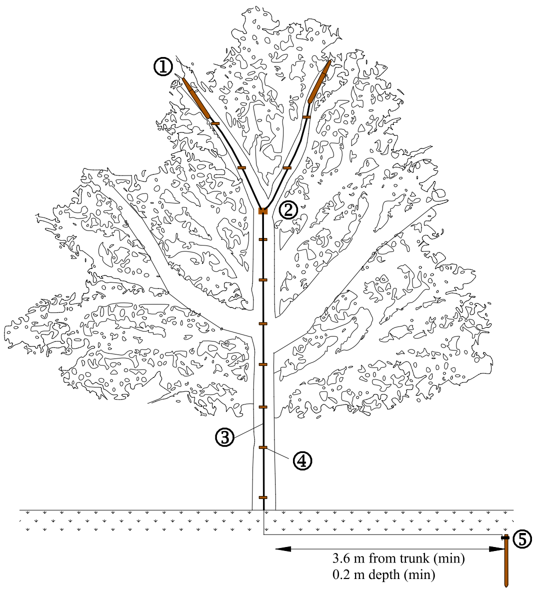

Fig. 10. Tree Lightning Protection System components. ① air terminal (typ.); ② side-by-side connector; ③ down-conductor; ④ tree drives (typ.); ⑤ ground rod and clamp.

VII. Conclusion

Lightning strike induced fires have become a concerning world issue, even in locations where a very low flash density has been so far assumed. As a byproduct of the climate change, lighting strikes have been the catalyst of massive wildfires, threating persons and assets.

In this paper, the authors have discussed the lightning strike withstand capability of trees, by analytically identifying the minimum trunk radius that allows the tree to sustain the first positive and negative strikes without igniting the surrounding vegetation. A first positive impulse stroke with a specific energy of 15 MJ/Ω (5% probability of occurrence) may ignite a wildfire if the tree's radius is 3.3 m or less.

The critical heights $H^{(RA)}$ and $H^{(RB)}$ above which trees must be protected against lightning strikes to prevent loss of human life and cultural heritage, respectively, have been analyzed as a function of the tree form factor κ, the ground flash density N_G and the location factor C_D.

Critical heights $H^{(RA)}$ and $H^{(RB)}$for an isolated tree on a hilltop, in the case of the more frequent unusual lightning events, have been identified and shown in Fig. 9.

Tree lightning protection solution have been proposed, which include TLPS embedded in trees, and overhead ground wires to protect group of trees. In further studies, economic aspects of a large-scale deployment of TLPSs in forested areas will be presented.

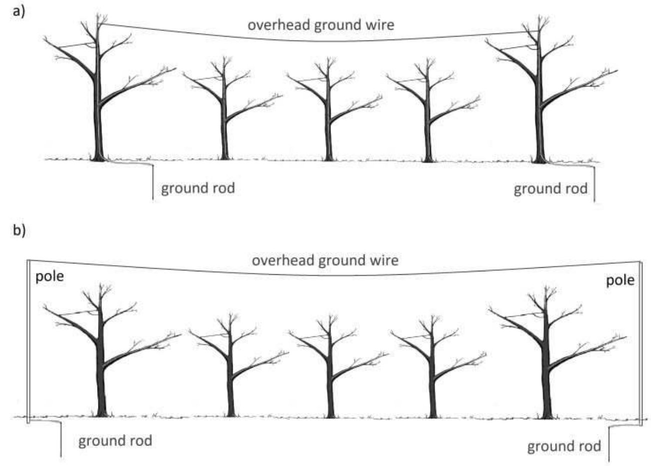

Fig. 11. TLPS for groups of trees.

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