Experimental Performance of Induced Voltage on Power Line due to Lightning Discharge to nearby Tree

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Abstract— **With continually increasing emphasis on the reliability of power systems, further understanding of the main causes of lightning faults in medium voltage lines is required for effective protection. Lightning-induced voltage on power distribution lines or telecommunication lines has been a subject that has received critical attention in the literature for years. However, very few investigations have been carried out on the influence of very close and tall structures, such as trees, buildings and other high structures on the lightning performance of power distribution lines. Recent measurements have revealed that a tree can intersect a lightning stroke in the vicinity of a power line, but not in all situations. In addition, induced voltage exists even when the power line is perfectly shielded by the nearby tree. This paper presents the results of experimental findings on the induced voltages existing between a lightning-struck tree and a power distribution line. The effects of; tree-to-line clearance, change in lightning time characteristics and polarities on the induced voltages are investigated.**

Keywords- Induced voltage; lightning voltage; tree; power line; electrostatic field

I. Introduction

Lightning overvoltages are the cause of a high number of faults to power distribution lines. Overvoltage build-up from lightning interaction with power circuits takes two forms, namely; the overvoltage produced by direct strokes to lines and the induced flashovers from indirect strokes to nearby distribution lines. Most lightning disturbances on power lines are due to indirect strokes to the ground [1, 2, 3] or to the high structures within the vicinity of the lines [1-5]. Some literature have reported the benefits of locating power lines around forest areas. The analytical study [6], simulation studies [7] and experimental studies [5, 8, 9] have proved that power lines that traverse through forests are naturally protected by the nearby trees. Main reason is that the lightning will strike the trees instead of the lines because of the higher attractiveness of the trees to the lightning strokes. However, in the event that a stroke is directly terminated on a tree, the resulting overvoltage from this stroke can be high enough to create flashover(s) on the power lines which can possibly lead to permanent fault. This study aims at reporting the results of recent experiments in search of the performance of induced voltage on a power line due to a direct stroke to a tree within the vicinity of the line. Induced voltages on the line are examined with change in tree-to-line clearance, change in lightning time characteristics and polarities of the indirect lightning strokes. The arrangement of the paper is as follows; Section II discusses the concept and practicality of perfect shield by tree, Section III presents the experimental setup, Section IV provides measurement results and discussions and Section V concludes the study.

II. Power Line Electrostatic Shield by Trees

Concept of perfect shield by tree

The concept of electrostatic shield is briefly adapted from [10] to explain how electrostatic shielding of power lines by trees may be provided. According to the situation of Figure 1(a), electrostatic field from the lightning, L can be perfectly shielded by the grounded tree, T, if the attractive area of the tree is large enough to overshadow the striking area of the conductor, C. The equivalent mutual capacitance circuit of the Figure 1(a) is shown in Figure 1 (b). Thus the expression for the electrostatic charges on the lightning, L, the tree, T and the conductor, C, are given in (1)

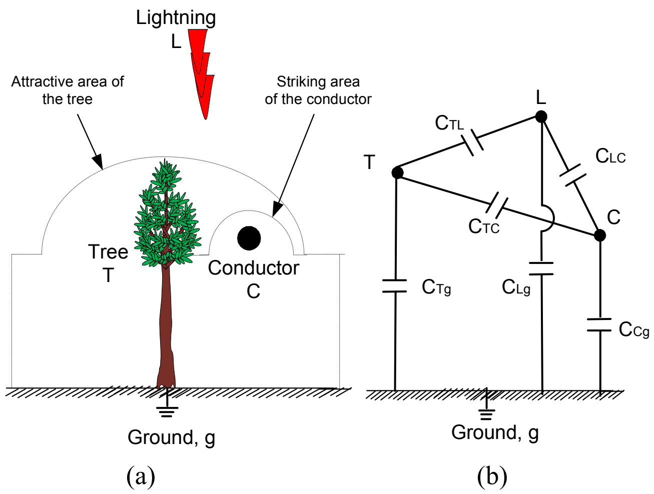

Figure 1. (a) Schematic of a perfect electrostatics shielding of a conductor by a tree. (b) Schematic of equivalent coupling capacitance between the objects (lightning, tree, conductor) and the ground.

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$$Q_C = (C_{Cg} + C_{CT} + C_{CL})V_C - C_{CT}V_T - C_{CL}V_L \quad (1a)$$

$$Q_T = -C_{CT}V_C + (C_{Tg} + C_{CT} + C_{TL})V_T - C_{LT}V_L \quad (1b)$$

$$Q_L = -C_{CL}V_C - C_{TL}V_T + (C_{Lg} + C_{CL} + C_{TL})V_T \quad (1c)$$

From (1a), by setting the lightning voltage, V_T, on the tree to $V_T = 0$, then

$$Q_C = (C_{Cg})V_C - C_{CT}V_C - C_{CL}(V_C - V_L) \quad (2)$$

For perfect shielding, the charge, Q_L, around the conductor will be $Q_L = 0$; hence the conductor and the tree will have the same potential, i.e $V_C = V_T = 0$. This implies that the coupling capacitance C_{CL} between the conductor and the lightning leader must vanish, since V_L is arbitrary. This shows that the presence of V_L will not affect the charge, Q_C, on the conductor. This term explains why perfect electrostatic shielding by tree is assumed for the case of power lines and lightning discharges. In reality, voltages and charges that exist on a nearby lightning-struck tree can create some electromagnetic fields which can induce voltages on power lines near trees. Also, the above expression is often not the situation in reality because of the contributions of weather condition, tree's high resistance/ surge impedance and conductor's surge impedance and characteristics of lightning strokes. Hence this study is made to investigate the performance of these induced voltages on power lines from nearby lightning-struck trees.

Effect of tree on shielding

Here, the experimental background on the lightning shield by tree in is briefly discussed. Shielding effect of a grounded structure on direct lightning strokes to distribution conductors can be examined from the length of exposure-arc of the conductor to the incoming lightning stroke. Considering the position of lightning stroke, the tree and the conductor in Figure 2, the tree will hardly provide a perfect shield on the bare conductor due to the exposure-arc (a_1-a_2), the possible areas at which the lightning stroke may hit the conductor is this exposure-arc (a_1-a_2). Thus, to achieve a perfect shielding, the tree must be positioned so as to eliminate the exposure-arc in the figure. Perfect shielding is achieved if the length, a_1-a_2, vanished, otherwise the possibility of direct stroke to the conductor exists.

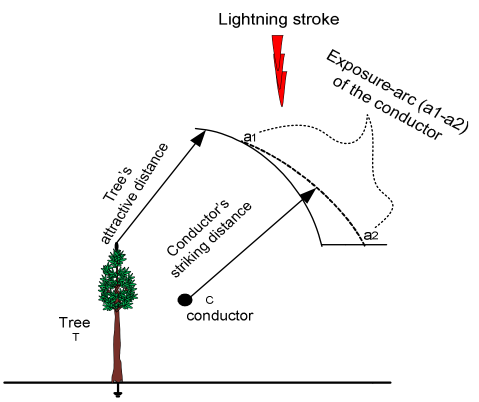

Figure 2. Exposure-arc of conductor shielded by tree to lightning stroke [5].

III. EXPERIMENTAL SETUP

An experiment was conducted to examine the contributions of lightning impulse parameters (magnitude, polarity, rise time) and tree-to-line clearance to induced voltages on a power line. The experiment was conducted under the atmospheric condition: T = 21 °C, RH% = 15 and P = 1011 hPa. Figure 3 gives the configuration of the experimental setup. The experiment was carried out in the Electrical Engineering department, Aalto University, Finland. The configuration was a full-scale representation of a Finnish 20 kV medium voltage lines around trees in Finland. The line, having a length of 16 m, a height of 8 m was terminated with characteristic impedance of 400 Ω at both ends. The height of the tree was around 9.5 m. The tree was equidistance from the line termination and was at 1m from the center of the line. This distance was varied in one of the experimental cases reported. The schematic of tree and bare conductor arrangement is shown in Figure 4. Two measurement channels were utilized for measuring the applied impulse voltage on top of the tree and the resulting induced voltage on the bare conductor. Channel one was for the applied voltage, while channel two for the induced voltage measurements.

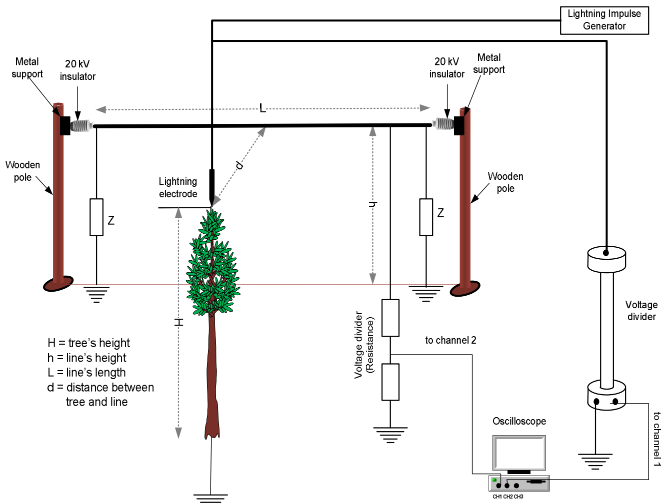

Figure 3. Experimental configuration

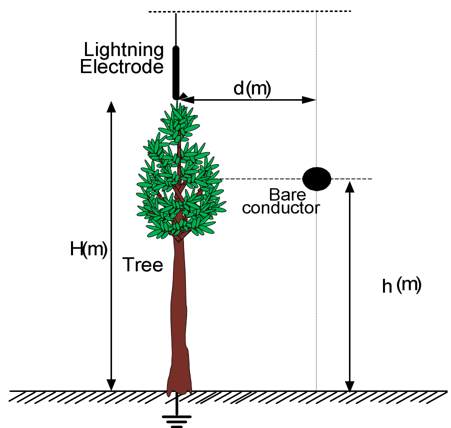

Figure 4. Schematic of the tree and the MV bare conductor

IV. MEASUREMENT RESULTS AND DISCUSSIONS

Induced voltages were recorded on the 20 kV overhead distribution conductor of Figure 4 when the lightning was applied on top of the tree. The performances of induced voltages were examined with variations in; lightning voltages, tree-conductor clearance and time characteristic, polarity of the lightning waveforms. The measurements were carefully recorded and examined in all the cases considered.

A. Magnitude and shape of induced voltage from nearby tree

Shown in Figure 5 is a 400 kV, standard lightning impulse applied on top of the tree at 1 m distance to the center of the conductor (see Figure 4), and the resulting induced voltage recorded on the conductor is given in Figure 6. Judging by the figures, the induced voltage waveform was characterized by faster rise-time and shorter duration with regards to the originating lightning impulse waveform on the tree. It can be seen from the figure, the presence of the tree has made a great influence on the resulting overvoltage on the conductor by limiting the induced voltage by a factor of 29 (i.e. 400 kV / 14 kV); the induced voltage has smaller amplitude in comparison with the direct voltage amplitude on the tree. However, the existence of the induced voltage has again revealed that perfect shielding by tree is unrealistic. The induced overvoltage may be higher than this in real situation due to the wetness of the air insulation, as lightning activities occur during rainfall, rainstorms and other natural phenomena [11]. Also, higher lightning impulse magnitude on a tree can induce much higher overvoltages or create flashovers that can be greater than the insulation level of the line, and this may lead to flashover(s) between phases and between phase and earth. Apart from the high transient overvoltages which can illuminate the surrounding objects from the lightning struck-tree, the high current flowing through the tree with sufficiently high resistance can generate enough heat to start fires.

B. Effect of lightning voltage class on induced voltage

Induced voltages on the conductor from different applied voltage magnitudes on top of the tree are shown in Figure 7. It can be seen that the induced voltages on the conductor are practically proportional to the direct voltages on top of the tree. Increasing the voltage amplitude and keeping the time characteristics at 1.2 / 50 µs, increases not only the induced voltages but also the time characteristics of the induced voltages.

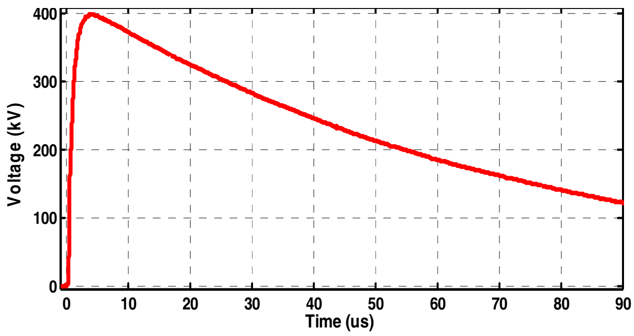

Figure 5. Lightning impulse applied on top of the tree close to the bare conductor (1.2 / 50 µs).

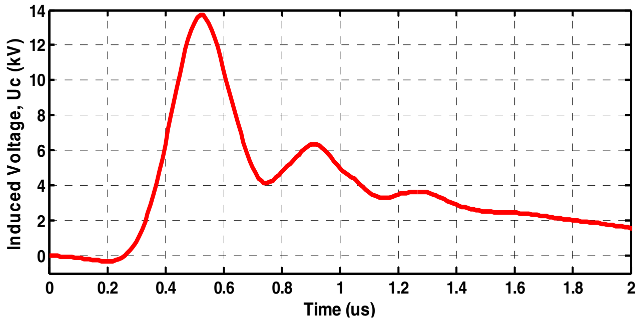

Figure 6. Measured induced voltage on the conductor. Tree height , H = 9.5 m, conductor height h = 8 m and clearance, d = 1 m.

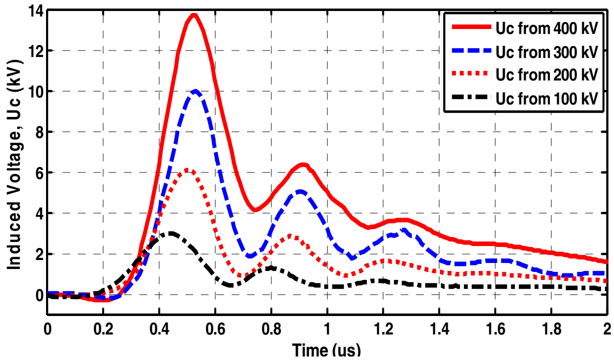

Figure 7. Measured induced voltages on the conductor as a function of the applied impulse on the tree. Tree height, H = 9.5 m, conductor height, h = 8 m and tree-conductor clearance, d = 1 m.

C. Effect of tree-to-line clearance on induced voltage

For the impulse voltage of Figure 6 on the tree, the resulting induced voltage on the conductor are shown Figure 8 with increasing the clearance between the tree and the line, i.e. from 1 m to 3 m. It can be deduced from this figure that the induced voltage on the line decreases marginally by increasing the clearance. The result is in agreement with [7] that a change in tree-to-line clearance does not influence greatly the induced voltage performance on power lines. Therefore it is expected that, in reality, the variation in the clearance between trees and medium voltage lines would have limited effect on the induced voltage performance of the lines.

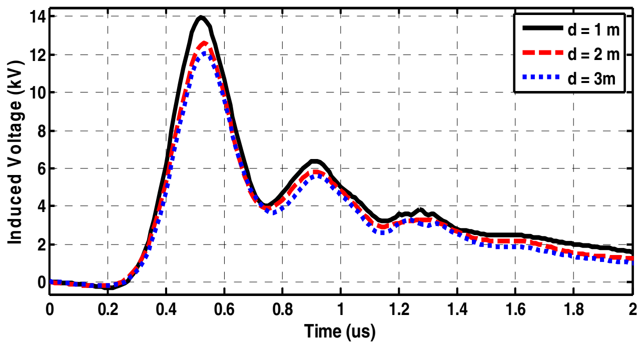

Figure 8. Measured induced voltages on the conductor as a function of the tree-conductor clearance. Tree height, H = 9.5 m, conductor height, h = 8 m and clearance, with the applied impulse of Figure 6.

D. *Effect of lightning steepness on induced voltage*

As it can be seen clearly from this section, the induced voltage illuminating the power lines at some distance from the lightning-struck tree is greatly dependent on the steepness (front-time) of the nearby lightning discharge. For different time characteristics of the lightning impulse of Figure 9 on the tree, i.e. 1.2 / 50 µs and 2.4 / 50 µs, the resulting induced voltages on the measured on the conductor are given in Figure 10. It is revealed from the figure that the time to crest (0.56 and 0.5 µs) and the time to half (0.67 and 0.61µs) of the induced voltages are very short compared to the applied impulses. Regarding the peak values of the induced voltages, by the decreasing the front-time by a factor of 2, the magnitude of the induced voltage increases by a factor of 1.63. Thus, a direct stroke with different time characteristics on a tree can induce different magnitude of overvoltages on a power line within the vicinity of the tree. As the rate of voltage increase in a real lightning voltage discharge often exceeds several hundreds of megavolts per second, the discharges with shorter front-time will produced larger voltage difference across the air insulation causing "side flashes" to nearby power lines, which can subsequently damage the equipment connected to the lines.

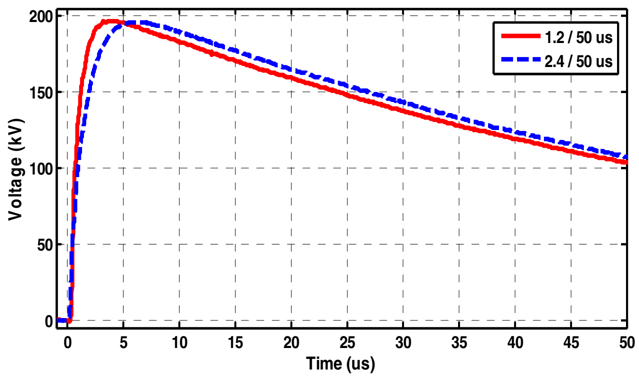

Figure 9. Lightning impulse with different time characteristics applied on top of the tree close to the bare conductor.

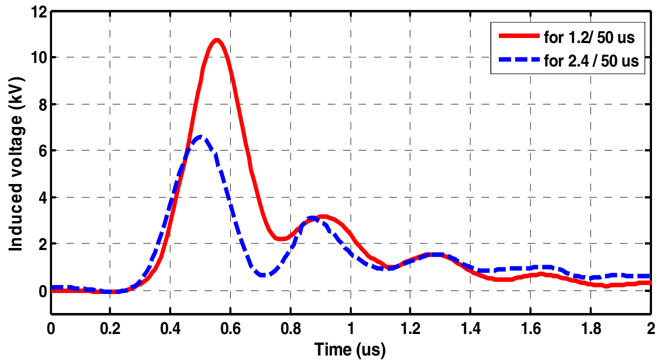

Figure 10. Measured induced voltages on the conductor as a function of time characteristics of the applied impulse (see Figure 10) on the tree. Tree height, H = 9.5 m, conductor height, h = 8 m and clearance, d = 1 m.

E. *Effect of lightning polarity on induced voltage*

An attempt was made to determine the contribution of the polarity of a stroke to a nearby tree on the induced voltage illuminating a conductor within the vicinity of the stroke. With the same configuration of Figure 4, a standard lightning impulse (200 kV) (see Figure 11) with positive and negative polarities, were applied on top of the tree at 1 m from the conductor. Here, the induced voltage for the positive lightning impulse was more than doubles the induced voltage for the negative lightning impulse. The line insulation could be more stressful for the positive lightning impulse than the negative one. However, higher oscillation was observed on the negative induced voltage waveform, this may be harmful also to the equipment which are closer to the stroke location.

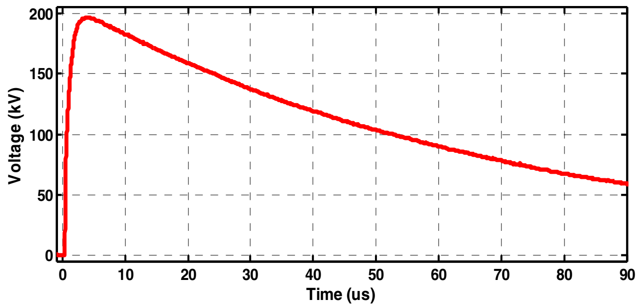

Figure 11. Lightning impulse voltage applied on top of the tree close to the bare conductor (1.2 / 50 µs).

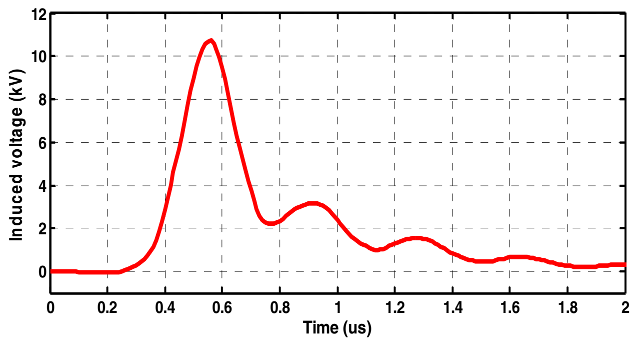

Figure 12. Measured induced voltage on the conductor as a function positive polarity of the applied impulse (see Figure 11) on the tree. Tree height, H = 9.5 m, conductor height, h = 8 m and clearance , d = 1 m

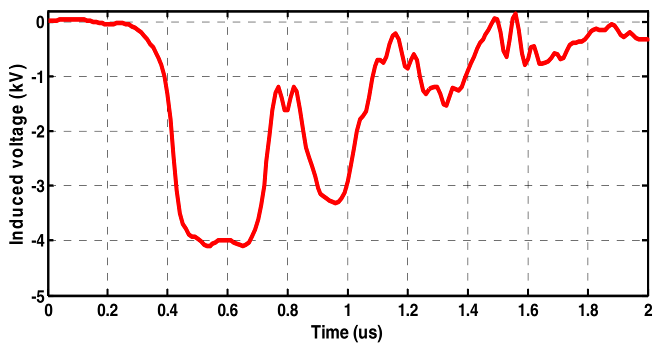

Figure 13. Measured induced voltages on the conductor as a function of negative polarity of the applied impulse (see Figure 11) on the tree. Tree height, H = 9.5 m, conductor height, h = 8 m and clearance , d = 1 m.

V. CONCLUSIONS

Lightning has higher tendency of striking high structures like trees than the ground surface. In some cases, trees can help to intercept direct strokes to power lines. However the resulting induced overvoltage on the lines due to the shielding by the trees can be sufficient to disrupt power supply and reduce power quality. Higher lightning stroke to a tree can induce much higher overvoltage on an overhead power line situated in the vicinity of the tree. For the same value of the direct strokes to tree, there was a significant increase in the induced voltages on the conductor by reducing the front-time of the strokes on the tree. The polarity of the applied impulse also contributed to the performance of the induced voltage, where the positive lightning polarity poised more threat on the line than the negative polarity of the applied impulse voltage. In general, important factors that can contribute to the performance of induced voltages are; the magnitude, polarity, time characteristics of the lightning waveform and the tree height above the ground. A study, dealing with the influence of weather conditions on the performance of the induced voltages between a lightning-struck tree and a power line, is in preparation.

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