Aalto University
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Report

Modelling and Analysis of the Lightning Performance of Air Distribution Cables

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Abstract

This report presents theoretical analysis and digital modelling of lightning performance air distribution cables and possible protection methods against the lightning faults. The analysis was made with reference to international standards for evaluating and improving the lightning performance of power distribution lines. The digital modelling was made using Alternative Transient Program- Electromagnetic Transient Program (ATP-EMTP) and careful consideration of different modelling guidelines in the lightning literature. The first part of the work deals with the theoretical estimation of lightning faults on distribution cables and the protection improvement options against the faults. Further, the second part of the study considered the used the ATP-EMTP to examine digitally the lightning faults on distribution cables and the protective options. The performance and protection of the lightning overvoltages and lightning flashover phenomena are analyzed and simulated using typical Finnish distribution cable designs. With series of laboratory tests, practical examination of lightning hazard to air cables is conducted, and the need for shield wire protection is established. This report is expected to answer some questions regarding the possible methods and techniques for the protection of Finnish medium voltage lines against lightning and other weather-related phenomena. The research will strive to provide the information, engineering methods, and decision-making support to help Finnish electricity companies achieve the most effective protection of power infrastructures, which may potentially reduce electricity rates to end-use customers.

Contents

1. Background

The fast increase in global climate change has been associated with a high rise in global lightning distributions and frequencies around the world. The implication is that electricity distribution lines and equipment will continue to be vulnerable to this natural phenomenon if proper care is not taken. Lightning has been identified as the major cause of faults on medium voltage distribution lines [1-4]. In Finland, yearly reports of faults in all distribution lines have shown that lightning-related faults take the lead over other faults, despite substantial surge protection. In December 26th, 2011, more than 250,000 homes were affected by blackouts in the wake of the rainstorms, snowstorms and other natural phenomena. This calls for a deep understanding of lightning electromagnetic interaction with different distribution line designs and the provision of adequate surge protection schemes for the total mitigation of lightning-caused faults in all medium voltage distribution line types, which include air cables and covered conductors.

Although the introduction of air cables has brought about numerous benefits to the utilities and the end-use customers, service reliability of the air cables in our exposed climate is not quite clarified. Among other weather-related hazards, the ability of air cables to withstand conductor burn-down and insulation damages (holes in jackets) caused by lightning is uncertain. Lightning performance of the air cable can be influenced by: surrounding trees and other high structures, ground resistance, presence of shield-wire, earthed or unearthed poles, BILs of cable jackets, Lightning struck points (i.e. messenger or poles),distance between protective devices on lines, characteristics of lightning currents, and line span.

The lightning performance and overvoltage protection of air medium voltage cables and covered conductors are problems of increasing importance as a large number of these expensive feeders are being installed in Finnish distribution systems. Also, other motivation behind the protection is the use of sensitive electronic devices in the power systems (circuit breakers, control and protection circuits and disconnectors) and, in parallel, by the increasing demand by customers for good quality in electricity supply. Lightning strokes to the neighbouring objects, such as trees, poles or messenger can create flashovers to the air cables and subsequently make holes to the cable jackets. Although, there may be no immediate fault, problems can occur with time. Therefore, the protection of cable's insulation against hole created by lightning flashovers is the most critical question with air cables. Due to lightning strokes, the cable failures can occur within a few meters of the locations where the cable's screen and cable's messenger were bounded and grounded. This naturally raises a question regarding the feasibility of bonding and grounding the screen and messenger at locations other than the ends of the cable line. In order to understand the lightning performance of air cable, some questions regarding the effects of the presence of surrounding trees (other structures), installation of shield wire, the increase in insulation level of distribution cable, the frequency of grounding of the cable's screen and messenger as well as the values of grounding resistances, must be explained. Knowing the effect of replacing wooden poles with steel towers, for many reasons, may be valuable.

1.1 Research objectives:

This report investigates the lightning faults in air distribution cables and possible improvement options for mitigating the faults. The following highlights the main objectives of the work:

- To estimate the lightning performance level of the current Finnish air distribution cable design and investigate the improvement options using real lightning statistics and Finnish distribution cable configuration.
- To model and simulate the lightning performance of Finnish air cable design and investigate various improvement options using the Alternative Transient Program- Electromagnetic Transient Program (ATP-EMTP).

2. Analyses of the Lightning Performance of Air Distribution Cables

Power system interruptions are obviously caused by lightning overvoltages and these may be in three different forms; direct strokes, which terminate on the poles and air cables and indirect strokes, which may likely result into induce overvoltages or flashovers to the cables. This section is expected to estimate the number of direct and indirect flashovers which may be experienced by air distribution cable based on medium voltage configuration in Finland.

Thus, the following are the required tasks which are expected to be carried out in this section:

- To investigate the probability of having lightning strokes enough to make such holes in air cable's jacket in real cases.
- To estimate the lightning performance level of Finnish air distribution cables in open ground and within forest areas.
- To assess the degree of proneness of the cable designs to lightning failure from direct strokes and lightning induced flashovers.
- To discuss and recommend improvement options for the lightning protection of distribution cables

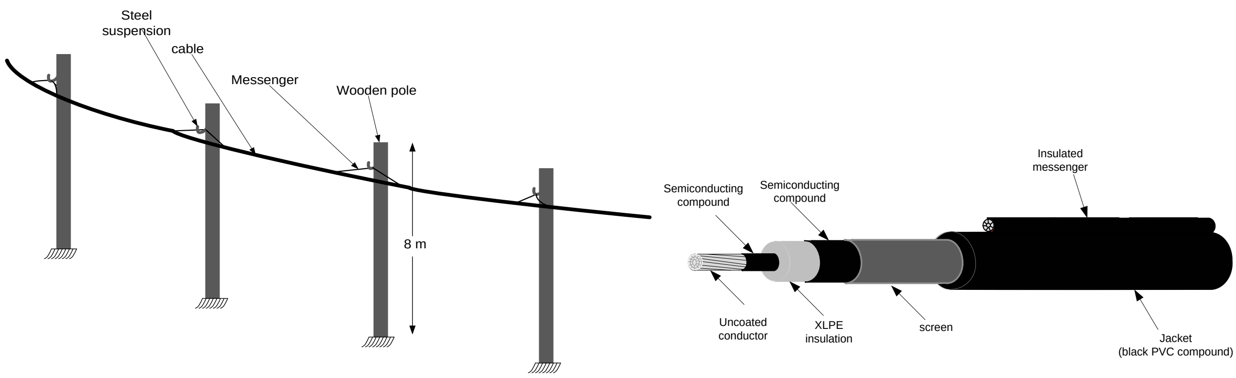


Figure 1.1: Configuration and installation of air distribution cables.

2.1 Lightning statistics in Finland

An understanding of lightning activities in an area where lightning protection is required is very important for the assessment of lightning performance level and improvement recommendation of the power network. The lightning data used in this work were made available by the Finnish Metrological Institute (FMI). The surface area of Finland, excluding the open waters of the Baltic Sea, is about 377,000 square kilometres [5]. The long-term (1960 - 2007) average annual ground flash density (GFD) is 0.393 flashes/km^2 (0.786 strokes/km^2 with average of 2 strokes per flash) , which corresponds to about 150,000 ground flashes. Thus, the field data analysis has shown that the cumulative distribution of lightning stroke magnitudes $P(I_p)$ can be represented as shown in Figure 1.2. After careful analysis, the probability distribution of lightning current peak in Finland is given by Equation (1.1) [6]. Hence, typical stroke in any lightning flash is expected to comply with Equation (1.1) and Figure 1.2 where the mean lightning stroke, $I_{50,}$ is about 15 kA.

$$P(I_p) = \frac{1}{1+\left(\frac{I_p}{I_{50}}\right)^{3.09}} \tag{1.1}$$

where;

$P(I_p)$ = Probability that any peak return-stroke in any given flash will exceed I_p,

I_p = Lightning peak current (kA),

I_{50} = 50% lightning current, (15 kA is the mean lightning current in Finland).

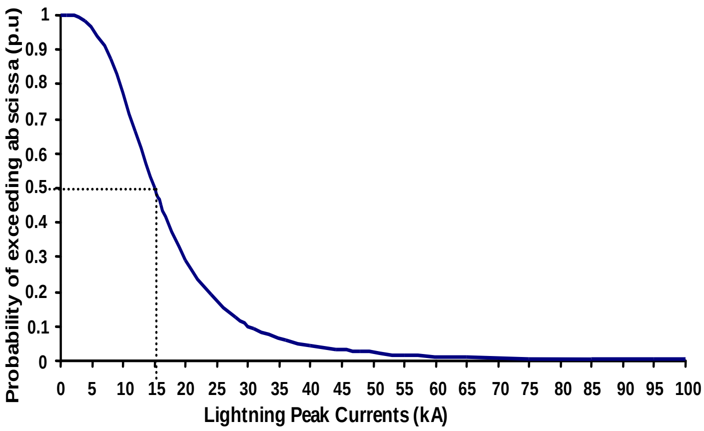


Figure 1.2. Cumulative distribution of lightning peak current in Finland according to lightning data collected from the Finnish Meteorological Institute (FMI) [6].

2.2 Direct strokes to open air distribution cables (without shielding trees or shield wire)

Lightning may have a significant effect on the reliability of air distribution cable, most especially if the height of the distribution installation is higher than the surrounding terrain. Under this condition, more flashes will be collected by the taller installation [1-2]. With reference to Figure 1.3a, the flash/strokes collection rate N in an open ground (without trees and structures) can be determined by Eriksson's equation [1]:

$$N = N_g\left(\frac{28h^{0.6} + b}{10}\right) \tag{1.2}$$

where,

h = the height of the cable above ground level (m)

b = the cable structure width (m)

N_g = the ground flash density (flash/ square km/year)

N = the flash collection rate (flash/ 100km/year)

Note: for all distribution lines types, the line structure width factor, *b*, is negligible ($b \approx 0$)

Thus, by using the Equation (1.2), the average Ground Flash Density, Ng, of 0.786 stroke/ km^2/year and the average height of the air distribution cables, *h*, of 8 m within Finland, the number of direct stroke to air distribution cable in an open ground (Figure 1.3a) can be estimated as

$N = 0.786[28 \text{ x } (8^{0.6}) + 0]/10 = 7.7$ strokes/ 100km/yr.

Note: Based on the probability distribution of lightning current peak in Finland, in Section 2.1, , a direct stroke with average value of 15 kA to wooden pole or cable insulation is assumed to damage the cable regardless of the cable arrangement or grounding, unless it is protected with shield wire. This damage may occur at any point along the distribution feeder.

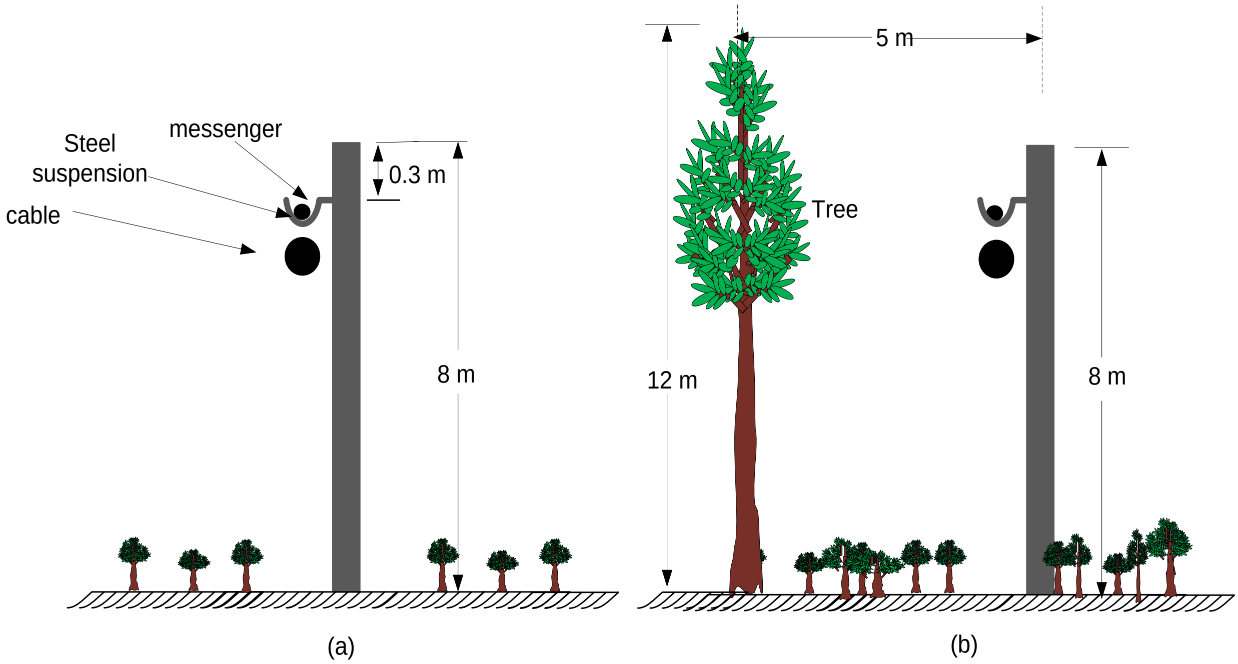


Figure 1.3: Typical Finnish 20kV air distribution cable arrangements in bare land (a), and forested land (b).

2.3 Analysis of shielding factor using electro-geometric model

The protection of distribution lines against surge are normally achieved with surge arresters, shield wire and insulation enhancement [6]. However, naturally, distribution equipment can be protected from direct strokes when sited around high and grounded structures, such as buildings, masts and trees [6]. The expected overall failure rate can be minimized by the shielding objects [6], though the induced flashovers due to the nearby strokes will increase considerably when such a situation arises [6]. The shielding effect of a tree on a direct lightning stroke to nearby distribution lines can be explained with the *Electro-geometric model*, as discussed in [6]. The heart of the electro-geometric model is the striking distance of the lightning stepped leader to a grounded object. According to the model, the striking distance is a function of the peak return stroke current; the higher the lightning current, the longer the striking distance. The theory of this model has been extensively addressed in the literature, as explained in [6]. A simple illustration of the model will be used for an understanding of this study. From Figure 1.4a, with a known value of striking distance r_g, an arc a_1-a_2 of a cylinder can be drawn by taking the centre point from the conductor. The line b_1-b_2 parallel to the ground surface is then drawn with the striking distance, r_g, separating the ground and the line. Now, the arc is intercepted at points a_1 and a_2 by the straight line b_1-b_2. Thus, if there is any stroke tip within the exposure-arc a_1-a_2, it will hit the conductor. For a lightning stroke to ground, a parallel plane at a distance, r_g, above ground shows a boundary which when crossed by a lightning stroke, I, will signal the final jump of the stroke to ground. Thus, for a distribution cable that traverses forest area, as in Figure 1.4b, perfect shielding of a tree on the lightning stroke, I, to cable must appear in such a way that the cylinder of radius, r_g, around the conductor must be entirely covered by the corresponding cylinder of the tree and by plane distance, r_g, from ground (see Figure 1.4b).

For the purpose of analysis, a fundamental principle of electro-geometric model is that a power line or other structure has a certain attractive radius that increases with height, and also the attractive radius is dependent on the current magnitude in the lightning stroke [1]. There have been quite a number of models used in the literature for the estimation of shielding factors. Here, the equation used for calculating the striking distances is based on Equation (1.3a), as expressed by Whitehead, which is also adopted in the IEEE Working Group Report [1]. The equation expressed the striking distance r_s as a function the return-stroke current, I. Moreover, the report also adopted the relationship between the striking distance r_s and the striking distance to ground r_g has been given in the Equation (1.3b) [1].

$$r_s = 10I^{0.8} \tag{1.3a}$$

$$r_g = 0.9r_s \tag{1.3b}$$

where

I is the peak of lightning stroke (kA)

rs is the striking distance to the tree (m)

r_g is the striking distance to the distribution line (m)

The aim of this study is to estimate the shielding effect of trees on lightning strokes to the distribution cable in terms of *Shielding Factor*. Here, the shielding factor, SF, is defined as the per-unit portion of a cable shielded by a nearby tree [1]. This task was performed by using Equation (1.3b) for the estimation of the shielding factor of trees on distribution cables, using different magnitudes of lightning strokes and different height of trees, for various distances between the tree and the cable. Shown in Figure 1.5a is the shielding factor of a tree on a lightning stroke of different magnitudes to a nearby distribution cable. The figure reveals that the tree will automatically provide perfect shield to the cable for a direct lightning stroke of 100 kA, if the separation distance between the objects is not more than 15 m. It is also important to know that, at this separation distance of 15 m, any stroke above 100 kA will be intercepted by the tree. However, lightning strokes below this value will not be perfectly intercepted by the tree. Therefore, for emphasis, if the cable is shielded for a lightning stroke, I, it will by all means be automatically shielded for any stroke greater than I. Lightning strokes smaller than I will have chance to penetrate the shielding and hit the conductor. Also, the effect of shielding by the tree gradually decreases as the distance between the tree and the cable increases. Figure 1.5b gives the effect of tree height on the shielding effect of the tree for a lightning stroke of 15 kA to distribution cable for different tree-to-line separation distances. It is shown that there is a significant contribution of tree height on shielding effectiveness of a tree on distribution cable due to direct strokes. For a 15 kA stroke, it is shown here that the best shielding is provided if the tree height doubles the height of the distribution cable and the two are separate by clearance of not more than 5 m. Any increase in the tree height above this value is inconsiderable to the shielding effect. The figure also indicates lower performance of the nearby tree on the shielding effect of the cable when the tree height is the same with the cable (8m) and when it is lower (5m).

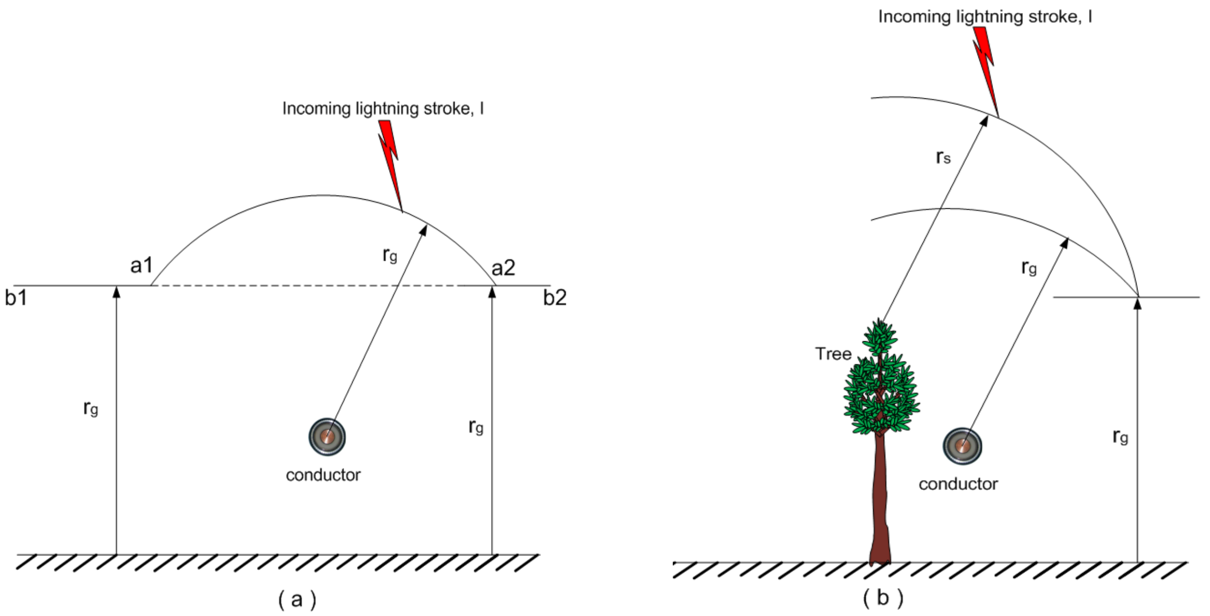


Figure 1.4. (a): Electro-geometric model for estimating the least distance of ground strike. (b) Electro-geometric model of shielding of cable by nearby tree.

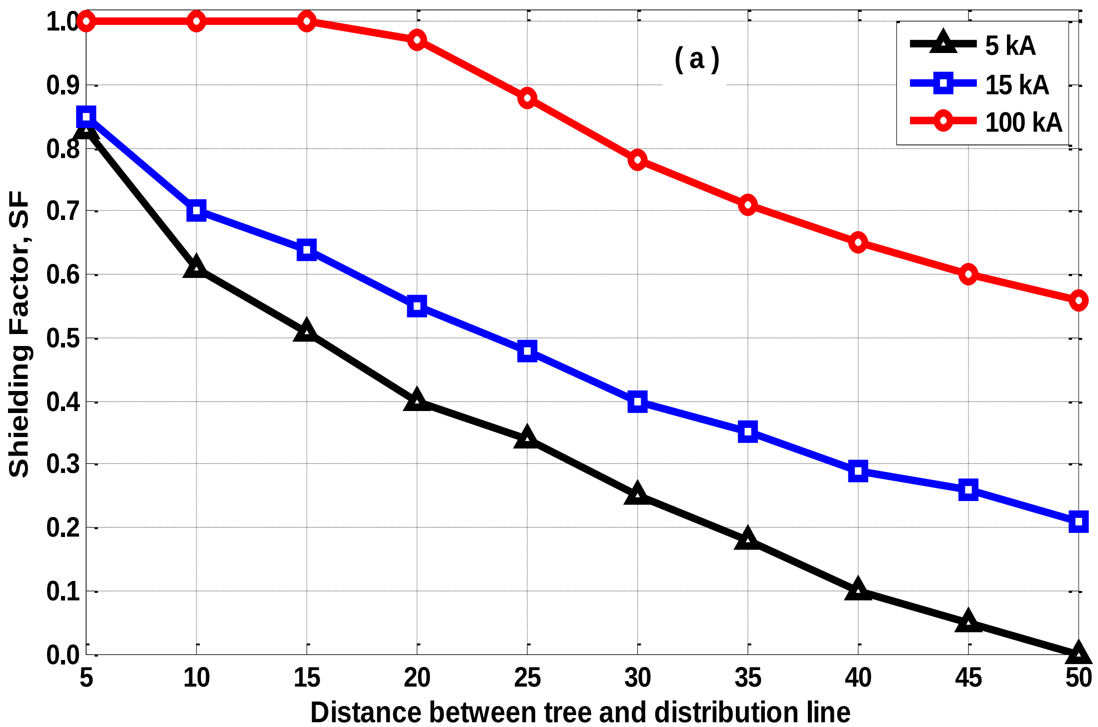


Figure 1.5a: Shielding Factor as a function of tree-to-cable distance for different lightning strokes. Tree height is 12 m, cable height is 8 m and direct lightning strokes are 5kA, 15kA and 100kA.

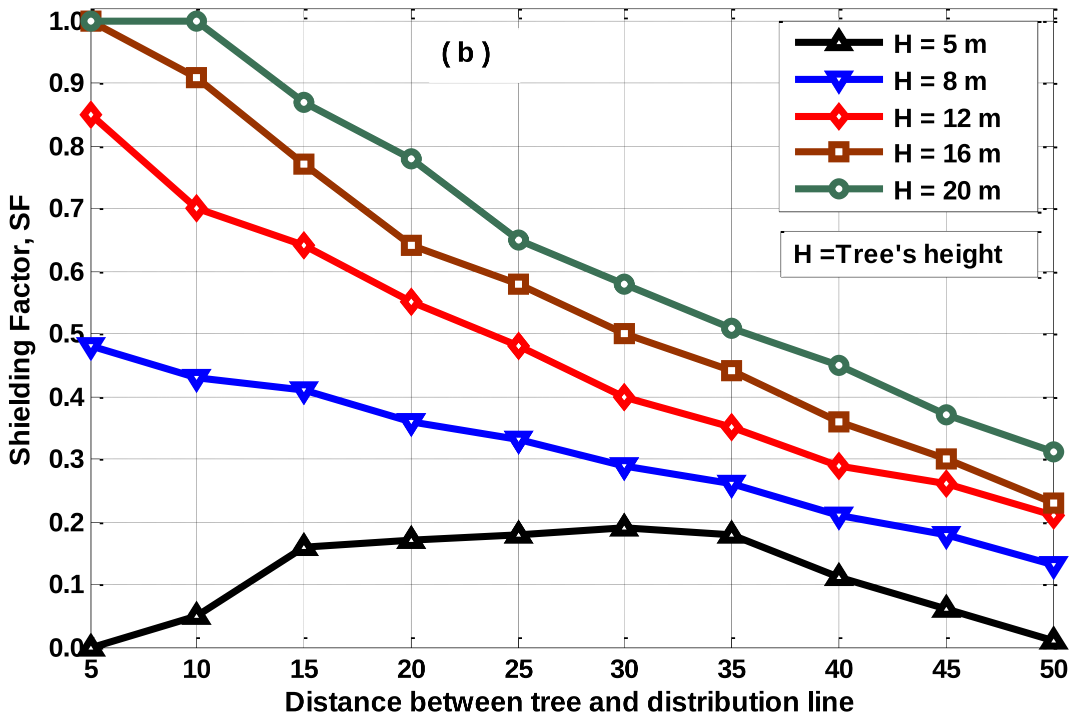


Figure 1.5b: Shielding Factor as a function of tree-to-cable distance for different height of the tree. Cable height is 8m, lightning stroke magnitude is 15 kA and tree heights are 5m, 8m, 12m,16 and 20m.

2.4 Shielding of distribution cable by nearby trees and structures

Trees, nearby tall buildings and other high structures can play important role in intercepting direct strokes which may possibly strike air distribution cables [1-4, 6]. The shielding effects of these objects should be taken into consideration in calculating the numbers of direct strokes to open distribution cables. Thus, direct strokes to an air cable shielded by nearby trees, as in Figure 1.3b, can be calculated by [1],

$$N_s = N * (1\text{-}SF) \qquad (1.4)$$

where SF is the shielding factor and it is defined as per-unit portion of the distribution cable shielded by the nearby objects.

Considering a lightning stroke of 15 kA, on a 12 m high tree having a separation distance of 5 m from a nearby 8 m high cable, as shown in Figure 1.3b, Figure 1.5b gives the calculated shielding factor SF = 0.85. As shown in Figure 1.3b, the calculated number of direct strokes to the cable with the shielded trees will decrease to;

$$N_s = (7.7) * [1 - (0.85)] \qquad = \underline{1.15\ strokes/100km/yr}$$

2.5 Induced flashovers of from nearby tree to cable

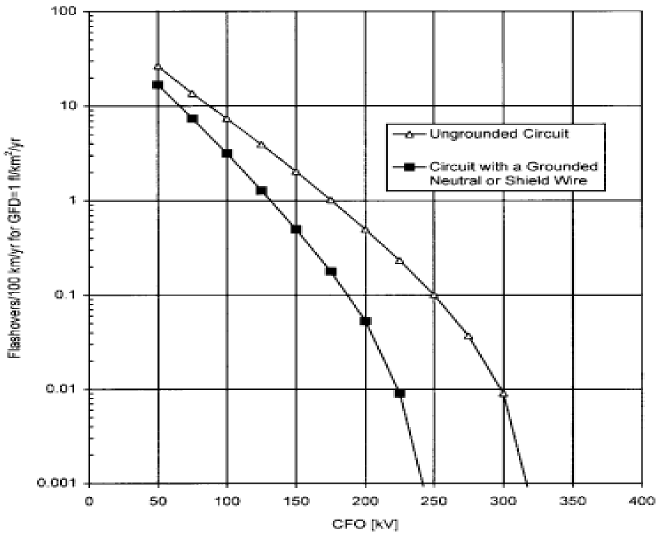
As explained in Section II.4, much of the distribution cable is shielded (surrounded by trees, e.g., SF = 0.85). Also, larger magnitudes of lightning strokes that hit the cable structure (e.g. wooden pole) can also initiate induced flashovers to the cable. Thus, the presence of shielding objects (e.g. nearby trees) will increase the total number of induced flashovers to the cable. The numbers of induced flashovers may be known by scaling the '*Induced flashover curve*' of Figure 1.6 [1-2] by taking the CFO path of 145 kV with a direct-hit flashover to the pole (0.3 m x 65kV/m = 20kV for wooden pole, 0 kV for steel suspension [1-2] and 125 kV for 20kV cable)

$$I_p = \frac{2 * CFO}{Z_O} \qquad [7]\ (1.5)$$

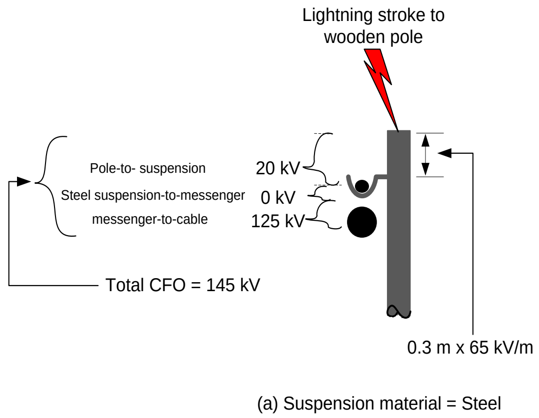
Ip = the mean lightning peak current

Z_O = the characteristics impedance of the line.

CFO = the insulation level of the distribution line under consideration



(a)



(b)

Figure 1.6: (a) Number of induced-voltage flashovers versus distribution-line insulation level [1]. (b) CFO of ungrounded 20kV cable design. Direct strokes to wooden pole may lead to induced flashovers on air cable

From Figure 1.6a [1], induced flashover rates on an open ground of an ungrounded cable may be traced and scaled out with known Ground Flash Density (GFD), since, Ng is directly proportional to the flashover rate for a given height h of the line, therefore;

2 flashovers/100km /yr is proportional to Ng of 1 stroke /square km/yr for h = 8m

1.57 flashovers/100km /yr is expected for Ng of 0.786 strokes/km^2/yr for h=8m

Induced flashovers (open ground) = 1.57 flashovers/100km/yr.

According to the calculation done in Section 2.3, much of the distribution cable is shielded by tall trees which make it to have a SF of 0.85. It is possible for larger strokes drawn close to the cable, without terminating directly to the cable. If such situation happens, the induced flashover increases (it was assumed to be twice the flashovers in the open ground in [1]). Thus,

Induced flashovers (shielded cable) = 2 induced flashovers (open ground) = 3.14 flashovers/100km/yr*

Since all flashovers are considered to cause faults on the line, therefore the total fault can be estimated as follows:

Total faults on the cable = Fault due to direct strokes + Faults due to induced flashovers

Total faults on the cable = 1.15 + 3.14 = **4.29 faults/100km/yr.**

Based on lightning data (Section 2.1), configuration of the distribution cable configuration, and the recommendations in the lightning literature standards, the analytical estimation of failure rate of air distribution cable has been made. The following provides the improvement options to be taken into consideration as so to reduce the total lightning fault on air distribution cables.

2.6 Improvement options for reducing faults on distribution cables

The proposed improvement options for the cable design are not expected to be too much expensive and they should also be very easy to implement. Due to the nature of the distribution networks in Finland, where more than 86 % of land is covered with forests and most of the lines traverse the forests, the most significant part of the total faults will occur as a result of induced flashovers to the cable. However, it is suggested to increase the CFO [pole-to-suspension-to-cable insulation = 145 kV] of the cable by replacing the *steel suspension* with *insulator suspension*. The use of shield wire with good grounding scheme can also provide some appreciable improvement.

a. Replacement of steel suspension (CFO≈ 0) with insulator suspension (CFO≈ 105 *kV*)(Figure 1.7) :

One good improvement option is to consider changing the conducting steel suspension with insulator suspension. This would improve the lightning performance of the distribution cable by increasing the pole-to-cable insulation as expressed below:

***Direct stroke*:** = 1.15 strokes/100km/yr (from Section 2.4)

Induced flashovers: The arrangement will increase the CFO to 250 kV [(wooden pole 0.3 m x 65 kV/m = 20 kV) + (insulator =105 kV) + (cable insulation = 125 kV)] [1] (see Flashover VS CFO in Figure 1.6a**)**. This will lower the total faults from 4.29 to 1.31 faults/ 100km/yr as expressed below and shown in Figure 1.7 (for shielding factor SF= 0.85).

0.1 flashovers/100km /yr is proportional to Ng of 1 stroke /square km/yr for h = 8m

0.08 flashovers/100km /yr is expected for Ng of 0.786 strokes/km^2/yr for h=8m

Induced flashovers (open ground) = <u>0.08 flashovers/100km/yr.</u>

Induced flashovers (shielded cable) = 2* induced flashovers (open ground) = <u>0.16 flashovers/100km/yr</u>

Total faults on the cable = 1.15 + 0.16 = **<u>1.31 faults/ 100km/year</u>**

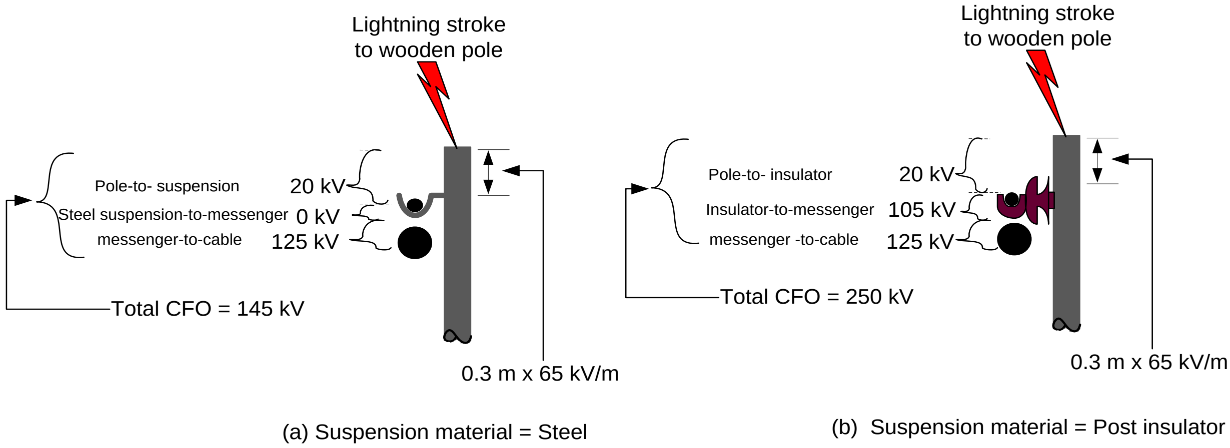


Figure 1.7: Replacement of steel suspension with porcelain insulator suspension for better lightning performance of the cable.

b. Use of grounded shield wire (SW) at every pole placed directly above the air cable (see Figure 1.8):

The following analysis demonstrates the improvements in the lightning performance of air distribution cables by adding shield wire above the cables and grounding the shield wire at every pole. With this method, lightning stroke will be intercepted by the shield wire and flows directly to the ground without causing any problem to the cable insulations or burning the wooden poles. Otherwise, without a shield wire, lightning current flowing through the pole ground impedance will cause a potential rise which will result to high voltage difference between the ground lead and the air cable. The difference in the voltage may lead to flashover across the cable's jacket and damage to the cable [1]. Based on the CFO estimated in Figure 1.8b, it is understandable that the ground lead should be electrical insulated from the cable to avoid flashovers. In doing so, fiberglass standoffs insulator (with CFO =500 kV/m) should be used to insulate the ground lead from the cable [1]. The fiberglass insulators of about 0.5 m long attached to the other side of the cable installation side would be suitable.

By placing shield wire at 0.5 m above the wooden pole and grounded at every pole, the installation will increase the CFO to 325 kV [(shield wire post insulator = 180 kV) + (wooden pole 0.3 m x 65 kV/m = 20 kV) + (steel suspension = 0 kV) + (cable insulation = 125 kV)] (see Figure 1.8b). This will lower the induced flashover from 4.29 to 0.58 faults/ 100km/yr as expressed below and shown in Figure 1.10 (for shield factor SF= 0.85).

***Direct stroke*:** The height of the grounded shield wire above the ground is assumed to be 8.5 m while the line structure width factor, *b*, is negligible ($b \approx 0$). Using Equation (1.2), the number of direct strokes in open ground is

$N = 0.786[28 \text{ x } (8.1^{0.6}) + 0]/10 =$ <u>7.7 strokes/ 100km/yr.</u>

Direct stroke to the shield wire, using (4) and SF = 0.85 (with surrounding trees), is

$N_s = (7.72) * [1 - (0.85)]$ = <u>1.15 strokes/100km/yr</u>

With the assumption that the shield wire is grounded with a resistance of 100 Ω at each pole, all the direct strokes to cable will be intercepted by the grounded shield wire. Thus, the flashovers to the distribution cable may be made roughly estimated by adopting 350 kV CFO plot from Figure 1.9 [1]:

Flashovers to cable = Direct stroke to shield wire * % direct stroke causing flashovers to cable

= 1.15 strokes/100km/yr * 50% flashover rate

= <u>0.58 flashovers/100km/yr</u>

***Induced flashovers*:** Since the new arrangement of the cable circuit with adding shield wire has increased the CFO to 325 kV, the cable can be assumed to be protected from induced flashovers, as shown in Figure 1.8b. Thus, all flashovers to the cable to the cable are assumed to occur from direct strokes to the shield wire and results into faults which has been estimated as

Total faults = direct stroke to shield wire = **<u>0.58 faults/100km/yr</u>**

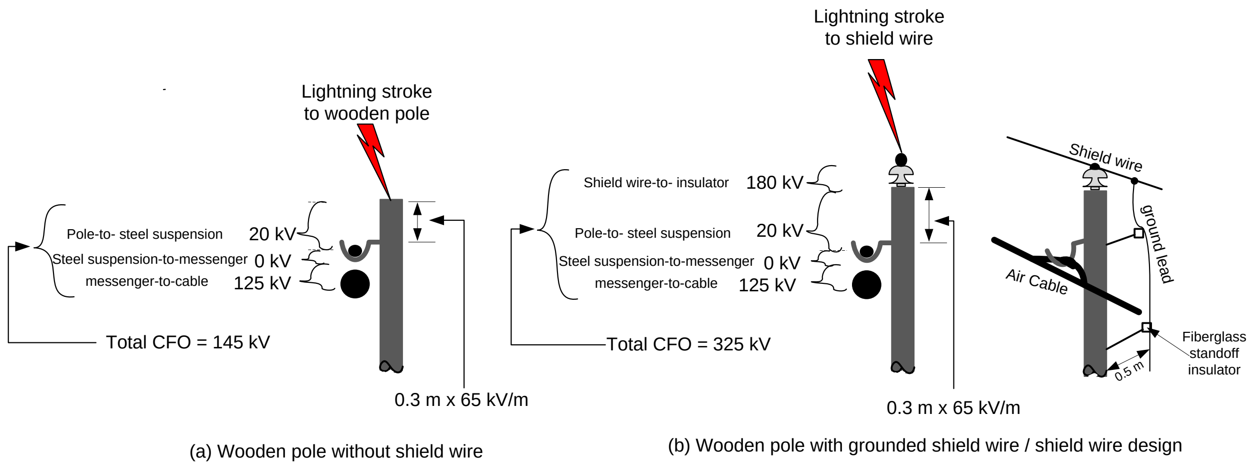


Figure 1.8: Installation of grounded shield wire on top of the wooden pole for better lightning performance of the cable.

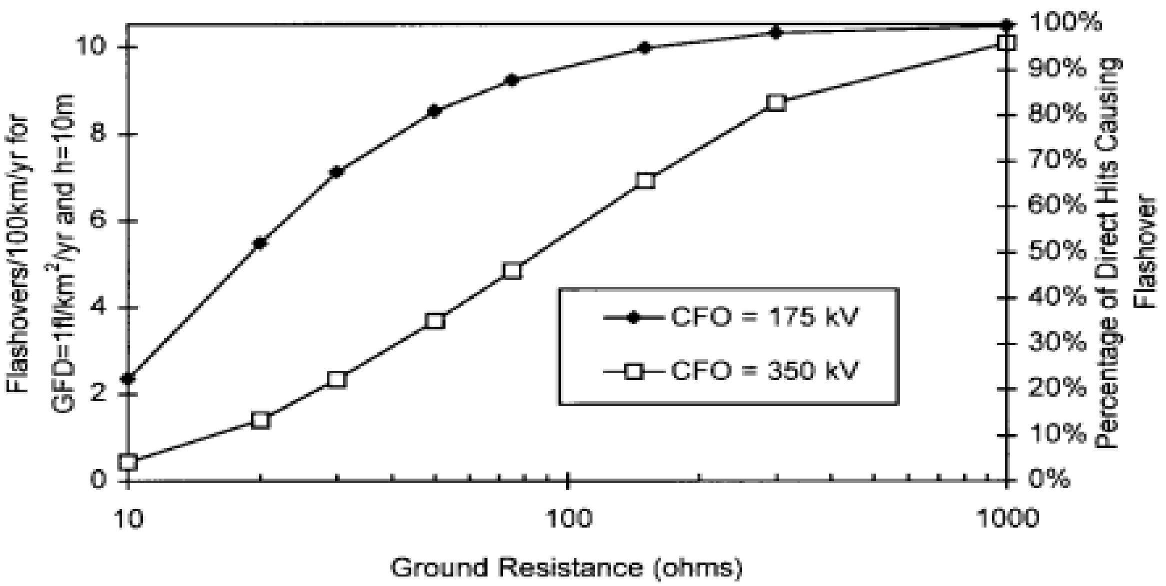


Figure 1.9: Effect of grounding resistance on shield-wire performance (direct strokes) from the IEEE guide [1].

c. Improving the grounding resistance:

As previously estimated, a shield wire directly above a distribution cable will lower the lightning related faults by 86.5% (from 4.29 to 0.58 faults/ 100km/ yr) if the shield wire is grounded at ever pole with a grounding resistance of 100 Ω . For the analyzed curve in Figure 1.11, a better flashover performance of the distribution cable may be achieved by lowering the grounding resistance. For instance, by increasing the grounding resistance from 100 Ω to 1000 Ω, the flashover rates will increase from 0.58 faults/100km/yr to 1.09 faults/100km/yr (47% increase). In order to achieve very good flashover performance of distribution cable with the use of shield wire, a very good grounding must be taken into consideration. Although there would be increase in the cost of the distribution cable construction, this cost should be weighed against the reduced cost of faults caused by lightning flashovers. In spite of the cost and problems associated with shield wire, some utilities have implemented the design in their distribution systems with better performance and great success [1-2].

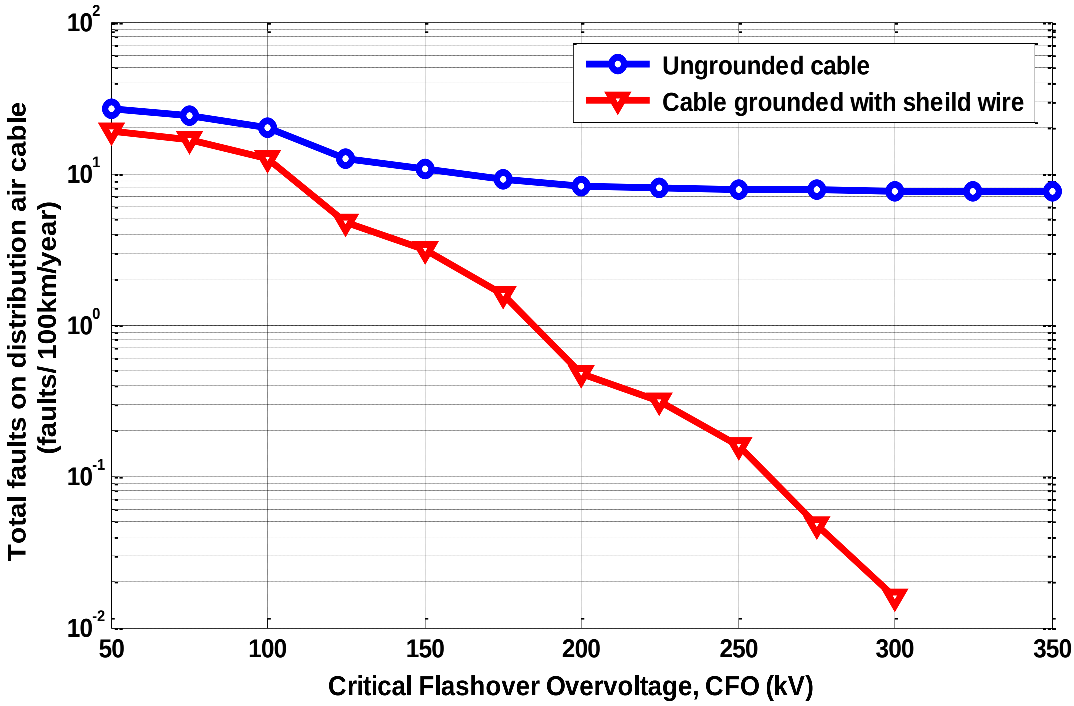


Figure 1.10: Total faults on 20 kV air distribution cable for different insulation level.

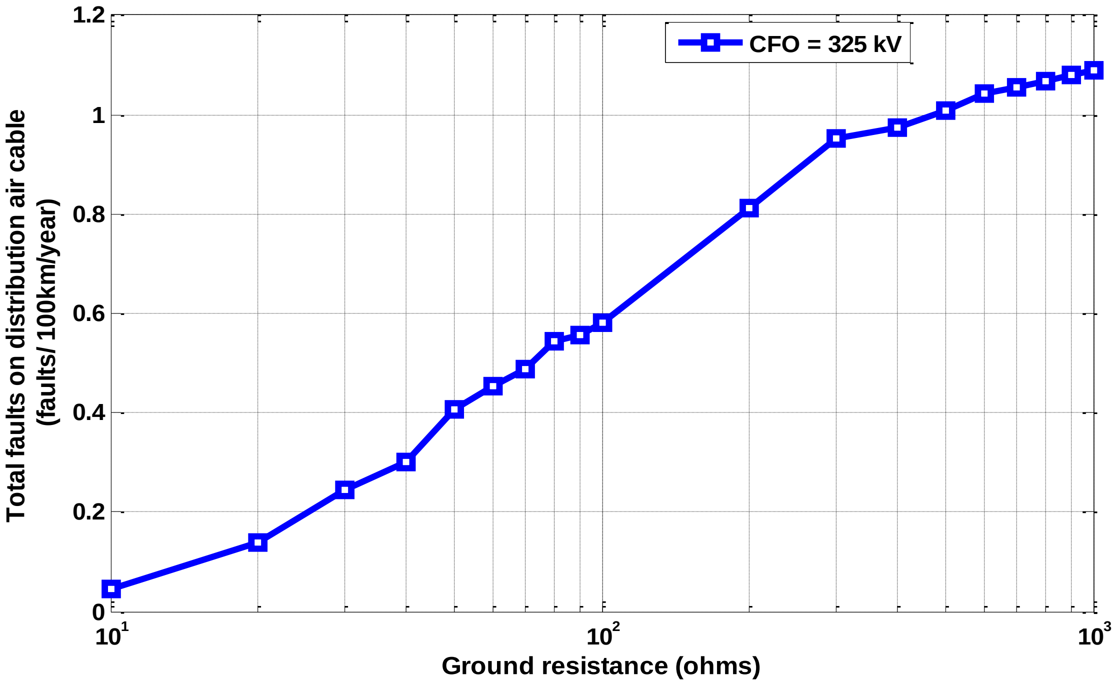


Figure 1.11: Effect of the grounding resistance of shield wire on the lightning performance of distribution cable (total fault =direct strokes + induced flashovers).

3. Modelling of the Lightning Performance of Air Distribution Cables

This section addresses the modelling of lightning performance of air distribution cable using Alternative Transient Program - Electromagnetic Transient Program (ATP-EMTP). By means of simulation using digital models and Transient Analysis Control System (TACS) features developed within the ATP-EMTP program, the investigation of lightning overvoltage on the air cables is analyzed. The analyses are made under the influence of direct strokes to wooden poles, to messenger wires or to nearby trees. The simulation includes adequate models of distribution air cables, messenger wires, tree and distribution poles while also considering the other factors which are the frequency dependence of the cable parameters, models of porcelain insulation, shield wire, steel tower and grounding systems including impulse resistance characteristics. An adequate flashover model was used to examine the flashovers over air and solid insulations. This model is not only useful for producing overvoltage waveforms and predicting their crest values throughout the distribution line, but also important for assessing the accurate effect of providing improvement options for the air cable protection. Based on the simulation results, practical recommendations are made for improving in the lightning performance of air distribution cables. The required task here is to simulate the lightning performance of Finnish air cable design and investigate various improvement options by means of digital modelling and simulation (ATP-EMTP program).

3.1 Modelling guidelines of air distribution cables for lightning studies

In this task, the ATP-EMTP was used to model the power systems components and the lightning phenomena for the lightning simulation studies. For each of the components, the important model parameter was described, and typical values were provided with reference to some lightning standards and also, from the previously conducted experimental tests. With the ATP-EMTP, the representation of all air distribution cable components which are relevant for lightning overvoltage studies, were provided. In addition, its TACS features provide for the study of air and solid insulation flashover mechanisms.

3.1.1 Components of the air distribution cable

The main part of the ATP- EMTP model of a typical Finnish air distribution cables for this lightning studies contains blocks depicting a number of spans, or line section, terminated by wooden poles or steel towers that act as supports for the cables, messenger wires and shield wires of the MV line. A typical configuration of the air cable system that was studied is shown in Figure 2.1. In addition to the accurate frequency-dependent model of the cables and wooden poles, other components such as accurate frequency-dependent model of shield wires, porcelain insulator, tree, steel towers and footing resistance, which are the subjects of consideration in other case studies, are represented well in the ATP-EMTP model. Flashovers models are represented as a combined voltage controlled switch and dynamic models that reproduce the real behaviour of the components under lightning-surge condition. Details of the model of each of the components, as in Figure 2.1, are given as follows. Also, Table A (in Appendix) provides the modelling parameters and simulated conditions of all the components considered in this study.

Thus, as indicated in Figure 2.1, the illustration of the air cable systems is represented in the ATP-EMTP as follow:

- Components (1) and (2) give the model of wooden pole as a parallel combination of pole resistance, pole capacitance and dynamic flashover model represented with flashover switches (SW1 and SW2) to simulate the flashovers on across the wooden pole
- Component (3) shows the model of air cable steel suspension as an inductive element (lumped inductance, Ls3)

- Component (4) give the model of cable's screen-to-messenger insulation as a capacitor (C4) in parallel with dynamic flashover model represented with flashover switch (SW4) to simulate screen-to-messenger insulation flashover mechanism.

a. Distribution cable

The main components for the lightning analysis are the messenger and cable. These were modelled as a multi-phase model *Jmarti* frequency-dependent model with distributed parameters [7-8]. The *J. Marti* settings were that of a 3 phase cable in air, with 8 decades and 10 points per decade. A steady state frequency of 50 Hz and frequency matrix of 500 kHz, default fitting was used. The ground resistivity was taken to be 2300 Ωm and the lower frequency as 0.5 Hz. The distribution cable was modelled with 100 m segments (or spans) since the flashover model to be introduced is part of each pole. A total of 10 spans were used and to avoid complications in terms of reflections a distributed parameter (Clarke) having characteristic impedances of 400 Ω was added to both the beginning and end sections of the line [7], for all the simulation cases.

b. Lightning Stroke

Lightning current of 15 kA was considered for this study, this is the mean lightning current in Finland (see section 2.1). The positive polarity stroke with the lightning impulse characteristics was represented using a single-stroke, Heidler-type [7] current source. The equation of the current source is given in Equation (3.1). This equation is represented with a characteristics of τ_f/τ = 1/70 µs [10]. In the ATP- EMTP, the source was connected in parallel lightning channel surge impedance of 400 Ω [3, 7].

$$i\,(t\,)=\frac{I_p}{\eta}\frac{(t\,/\,\tau_f)^{n}}{\left(1+(t\,/\,\tau_f)^{n}\right)}e^{-t/\tau} \qquad (3.1)$$

Where I_p is the peak current, η is a correction factor of the peak current, n is the current steepness factor, τ_f, and τ are the time constants determining current rise and decay time, respectively

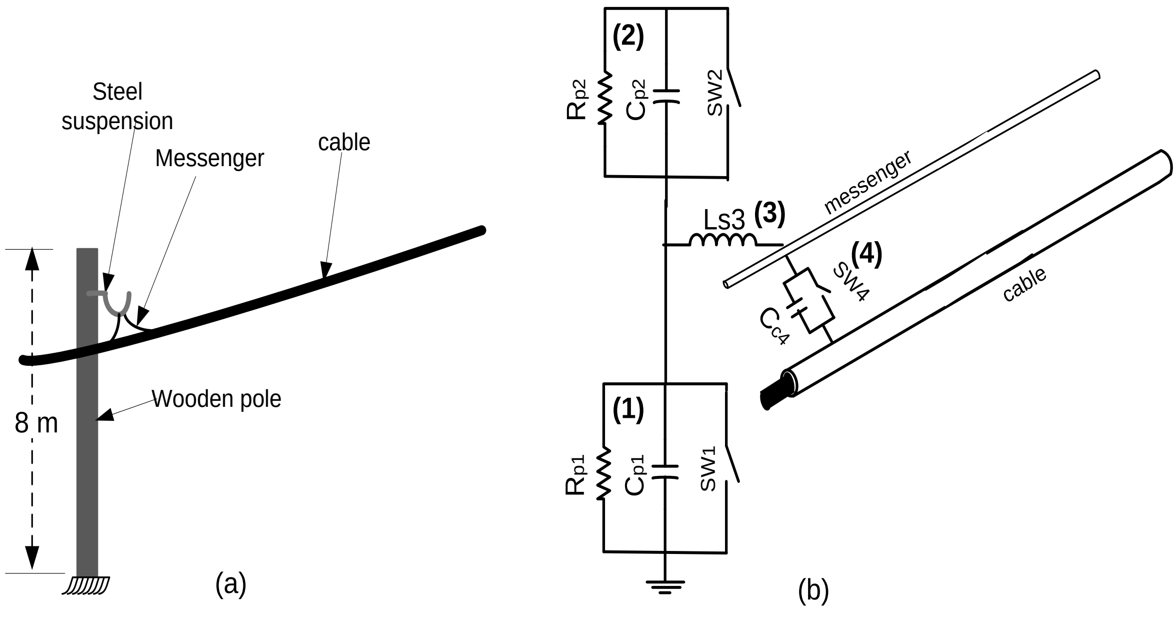


Figure 2.1: (a) Configuration of a typical Finnish air distribution cable system and (b) Circuit elements for EMTP modelling for wooden pole, categorized as Components (1) to (4).

c. Distribution wooden pole and insulators

The wooden pole used for the lightning studies was represented as a parallel combination pole resistance (Rp1 and Rp2), capacitance (Cp1 and Cp2) and flashover switches (SW1 and SW2). In [13], a 12.5 m wooden pole was represented with a parallel resistance of 7.5 MΩ (or 600 k Ω/ m for 12.5 m) and capacitance of 3.5 PF. Thus, the pole components of Fig. 2 were calculated, based on parallel-plate capacitor expression, as Cp1 = 5.68 pF, Rp1 = 4.62 M Ω for 7.7 m length of wooden pole *components (1)* and Cp2 = 146 pF, Rp2 = 0.18 M Ω for the remaining length, 0.3 m, of wooden pole *components (2)*.The steel suspension was assumed to have a radius 1.3 cm and length of 20 cm and was represented by its inductance, Ls3 = 0.19 µH using Equation 3.4.

d. Dynamic arc model for flashover over solid and air insulations

Flashovers over the wooden pole components (1) and (2), and the messenger-to-cable insulation *component (4)* of Figure 2.1 were considered with bilateral interaction between TACS and the ATP- EMTP software. Flashovers in air between components and over the surfaces the wooden pole components were modelled with '*flashover switches*', SW1, SW2 and SW4 in parallel with their coupling capacitances, Cp1, Cp2 and C4. The realization of the flashovers in ATP-EMTP is shown in Figure 2.2a. The figure consists of a voltage controlled switch in series with a dynamic arc model [6]. The switch is in normally off position. Thus, the switch closes and activates the dynamic arc model whenever the node voltage, V(t), is greater than the specified '*critical insulation flashover voltage*, (CFO)', Vb, of any component under consideration, at any time. Different Vb, that were considered from the IEEE std 1410™ 2004 [1] are; Air (600 kV/m), Wooden pole (330 kV/m), Porcelain insulator (180 kV). The capacitance, C, in the Figure 2.2 is represented as either the mutual capacitance between *components* (e.g. screen and messenger) or the capacitance within *components* (e.g wooden pole, porcelain insulator). The capacitance, Cc4, is calculated inside ATP-EMTP program by specifying the configuration of the *'REKA air cable'* as in the Appendix, in Equation 3.3.a The dynamic arc resistance, Rarc (1/g), has been experimented and modelled previously in [6]. Experimental study was conducted to measure the V-I characteristics of lightning-arcs between trees and nearby distribution conductor [6]. The dynamic arc model was used, with the help of TACS, to model and simulate the experimental V-I characteristics. The steps for the calculation of the arc conductance with ATP-EMTP and its TACS features are shown in Figure 2.2b. The dynamic arc resistance (Rarc) value was varied based on the arc dynamics Equations (3.3b) and (3.3c).

$$C = \frac{2\pi\varepsilon}{\ln(b/a)}, \text{ F/m} \qquad (3.3a)$$

where a is the inner conductor diameter, b is the inner diameter of outer conductor, ε is the dielectric permittivity between the conductors.

$$g = \int \frac{1}{\tau}(G - g)dt \qquad (3.3b)$$

$$\tau = Ae^{Bg} \qquad (3.3c)$$

$$G = |i| / U_{arc} \qquad (3.3d)$$

$$U_{arc} = (U_o + r|i|)l \qquad (3.3e)$$

where t is the time and g is the time varying arc conductance. G is the stationary arc conductance, where $|i|$ is the absolute value of the arc current, U_{arc} is a constant arc voltage parameter, U_o is the arc voltage gradient, r is the arc resistance per unit length and τ is the arc time constant which influences the arc voltage-current characteristic, and A and B are two fitting coefficients and they can help to accurately track the arc nature.

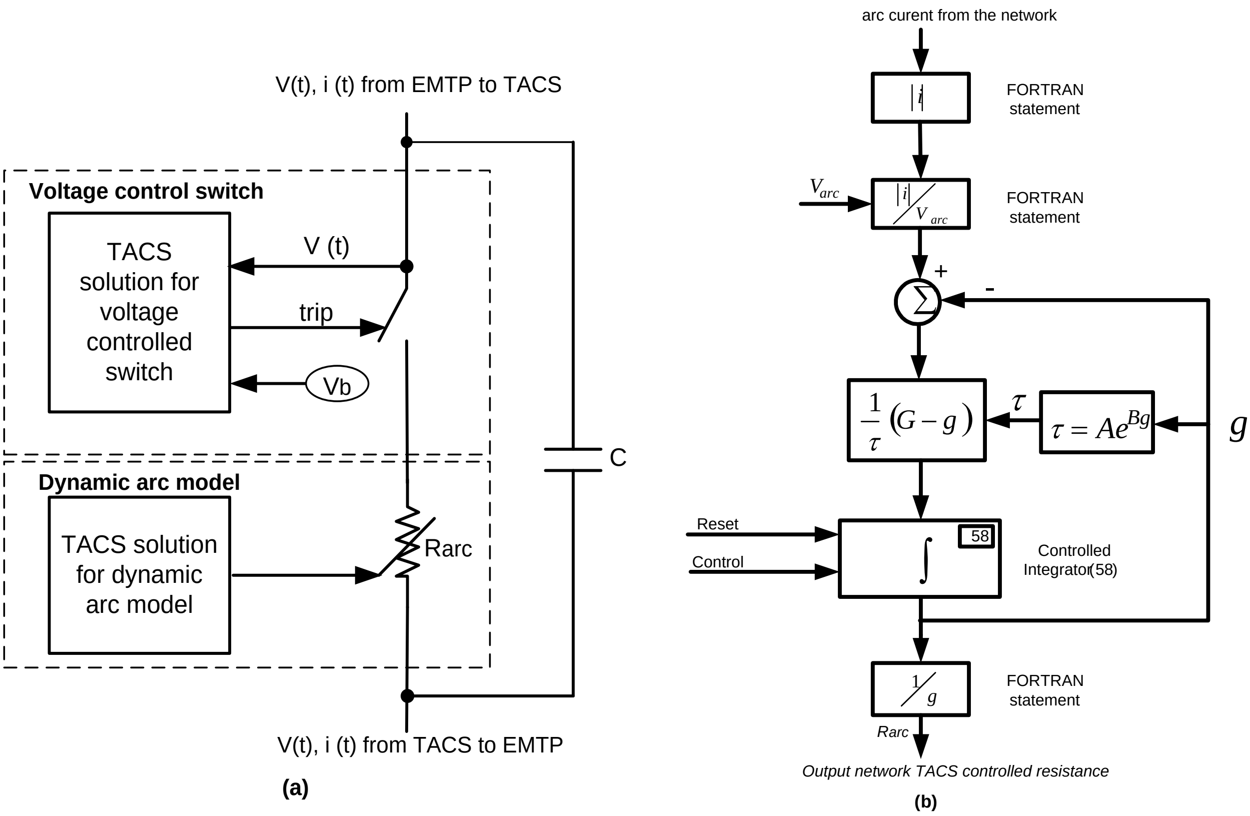


Figure 2.2: (a) Realization of flashover model in ATP-EMTP program, (b) Equations flowchart for dynamic arc model [6].

3.2 Case studies and simulation results

The ATP-EMTP modelling guidelines described above (also detailed in Table A1 of the Appendix) were applied to air distribution cable installation for lightning surge analysis. The installation consists of 1 km long air distribution cable (cable and messenger) on 11 poles, 10 spans. The main objectives of the study are to assess the severity of lightning overvoltages on the distribution cable, and to establish the importance of overvoltage protection for the improved lightning performance of the cable. The overvoltage protection assessments are; the role of messenger grounding in the lightning protection of air cable; the effect of bonding and grounding of both messenger and screen on overvoltage performance of the cable; the effect of shield-wire in intercepting possible lightning strokes to the air cable; the effect of shield-wire grounding resistance on cable's overvoltage suppression; the effect of insulation level on lightning performance of the cable. Table 1 gives details of the cases considered for simulation study.

Table 1: Simulated Cases

Case 1	Lightning overvoltage waveforms on cable at stroke point and adjacent poles
Case 2	Role of messenger grounding on overvoltage performance of cable
Case 3	Effect of bonding and grounding of both messenger and screen on overvoltage performance of cable
Case 4	Lightning performance of cable by replacing wooden pole's steel suspension with insulator suspension
Case 5	Role of messenger insulation on the lightning overvoltage performance of cable
Case 6	Effect of shield-wire in intercepting possible lightning strokes to cable
Case 7	Effect of shield-wire grounding resistance on overvoltage suppression on cable
Case 8	Lightning performance of cable by replacing wooden poles with steel towers
Case 9	Lightning performance of cable with installation of shield wire on steel tower
Case 10	Lightning stroke to tree and coupling overvoltage or flashover to nearby cable

CASE 1: Lightning overvoltage waveforms on cable at stroke point and adjacent poles

The important reason for performing this particular case is to assess the lightning overvoltage waveforms on the distribution cables and the hanging messenger wire at the point where a lightning stroke hit the pole (pole 6) and the adjacent poles (pole 5 and 7). Thus, the cable is not protected from a lightning current of 15 kA that was simulated on the pole number 6 (middle pole), which has equal distance (500 m) from both ends of the line. Figure 2.2 provides the simulation condition and the overvoltage waveforms at various calculation points. The simulation results are shown in terms of plots of voltage waveforms for the important line components, such as voltage on the poles, voltage on messenger wires and voltage on the cable. It is observed in this that the insulation level of the line is exceeded and the cable can damage if such situation would exist in reality.

When the lightning stroke is assumed to hit a messenger wire directly, overvoltage waveforms are expected to be different from those in Figure 2.2. Thus, Figure 2.3 reveals the influence of the lightning struck point on the lightning overvoltage performance of the cable. It can be seen that there is a lower induced flashover overvoltage peak (1620 kV) on the cable from the stroke to the wooden pole as against the overvoltage peak (2120 kV) when the stroke hit the messenger. Thus, air distribution cables can be relieved of some amount overvoltage stress if direct strokes to messenger wires can be avoided.

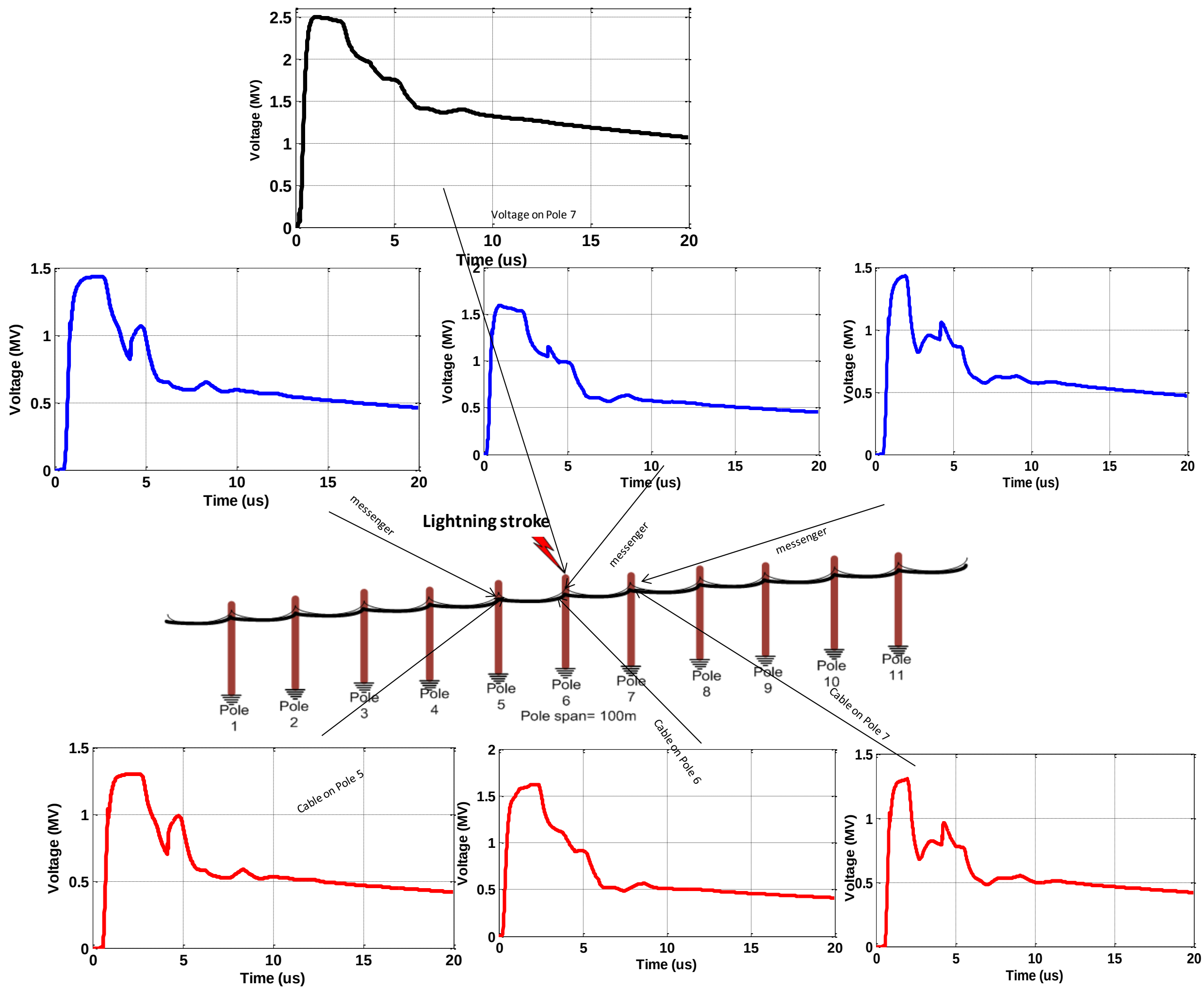


Figure 2.2: Voltage waveforms on cable and messenger wire due to a lightning stroke of 15kA on wooden pole. Both the poles and the messenger are ungrounded.

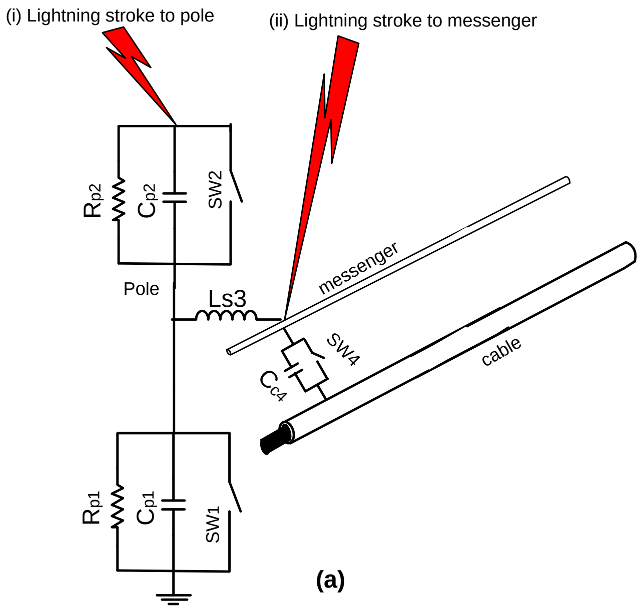


Figure 2.3a: Model description of a direct lightning current (15 kA) to either a distribution pole or ungrounded messenger wire.

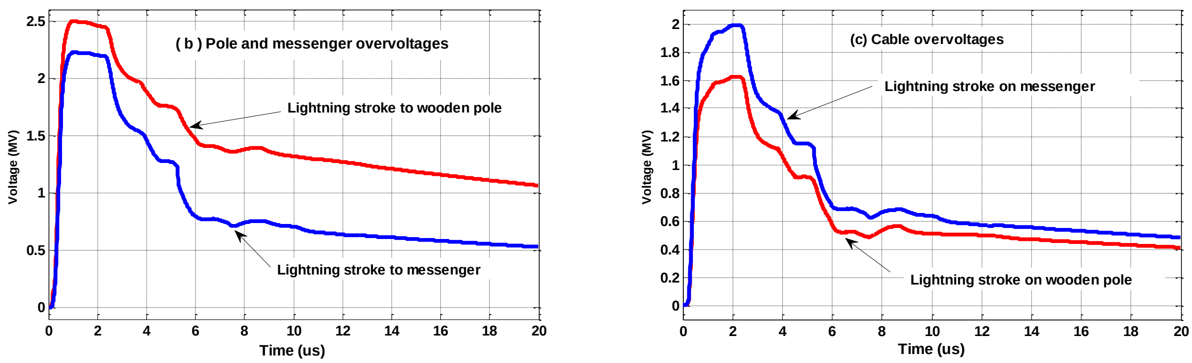


Figure 2.3: Overvoltage waveforms on struck points (wooden pole/ messenger) and distribution cable due to a direct stroke to wooden pole/ messenger

CASE 2: Role of messenger grounding on overvoltage performance of cable

Distribution systems are usually grounded to suppress fault currents into the ground, which can be caused either by internal faults or by external sources, such as lightning. In the literature, grounding of distribution line has been proved to be effective against direct and indirect lightning strokes by bypassing the energy of the lightning discharge into the ground [6, 9-12]. Therefore, the effectiveness of grounding messenger wire of the cable in order to minimize the overvoltage stress caused by a lightning stroke to distribution pole was simulated here. Recalling that the all the resulting overvoltages due to a direct lightning stroke on the distribution pole/ messenger, in *Case 1,* are much more than the insulation level, *BIL* (125 kV), of the cable. Thus, in real situation the overvoltage on the pole will flash over and make a hole in the cable's jacket as long as the overvoltage exceeds the withstand voltage level of the line. However, much of this overvoltage on the pole can be minimized if there is flashover from the pole to the messenger and the messenger is effectively grounded. To observe this condition, a simulation was carried with the same configuration as in *Case 1* but with the messenger wire connected to the ground at every pole (see Figure 2.4a). The grounded wire was modelled with a single inductance using Equation 3.4.

$$Lg = 0.2l\left[\ln\left(\frac{2l}{r}\right) - 1\right] \qquad [6], (3.4)$$

where the length of grounding wire, l = 8 m and radius of the wire, r_g= 1.3 mm, hence, the inductance was estimated to Lg =13.5 μH.

The grounding resistance of the wire was taken as 10 Ω. Thus, with a lightning stroke of 15 kA on pole 6, the *Case 1* was simulated with the messenger grounded at every pole (all 11 poles). Figures 2.4b and 2.4c give the resulting overvoltage waveforms on the distribution line (pole, messenger and cable) for ungrounded and grounded messenger respectively, at the lightning struck point (pole 6).It can be observed that the grounding of the messenger was very effective; the overvoltages were suppressed accordingly at the pole 6, the messenger and the cable. This shows that, in real situation, the grounding of the messenger will reduce the effective surge impedance of the cable. In a situation where a lightning hit a pole directly, the overvoltage developed on the cable at the struck point will be lowered than the cable without messenger grounded. Figure 2.4d gives the overvoltage comparison on the cable when the messenger is grounded and ungrounded. The figure indicates the possibility of suppressing the overvoltage peak by 88% with the grounding of messenger at every pole. However, the closeness of the messenger and cable can allow overvoltage stress that may create holes in the cable's insulation.

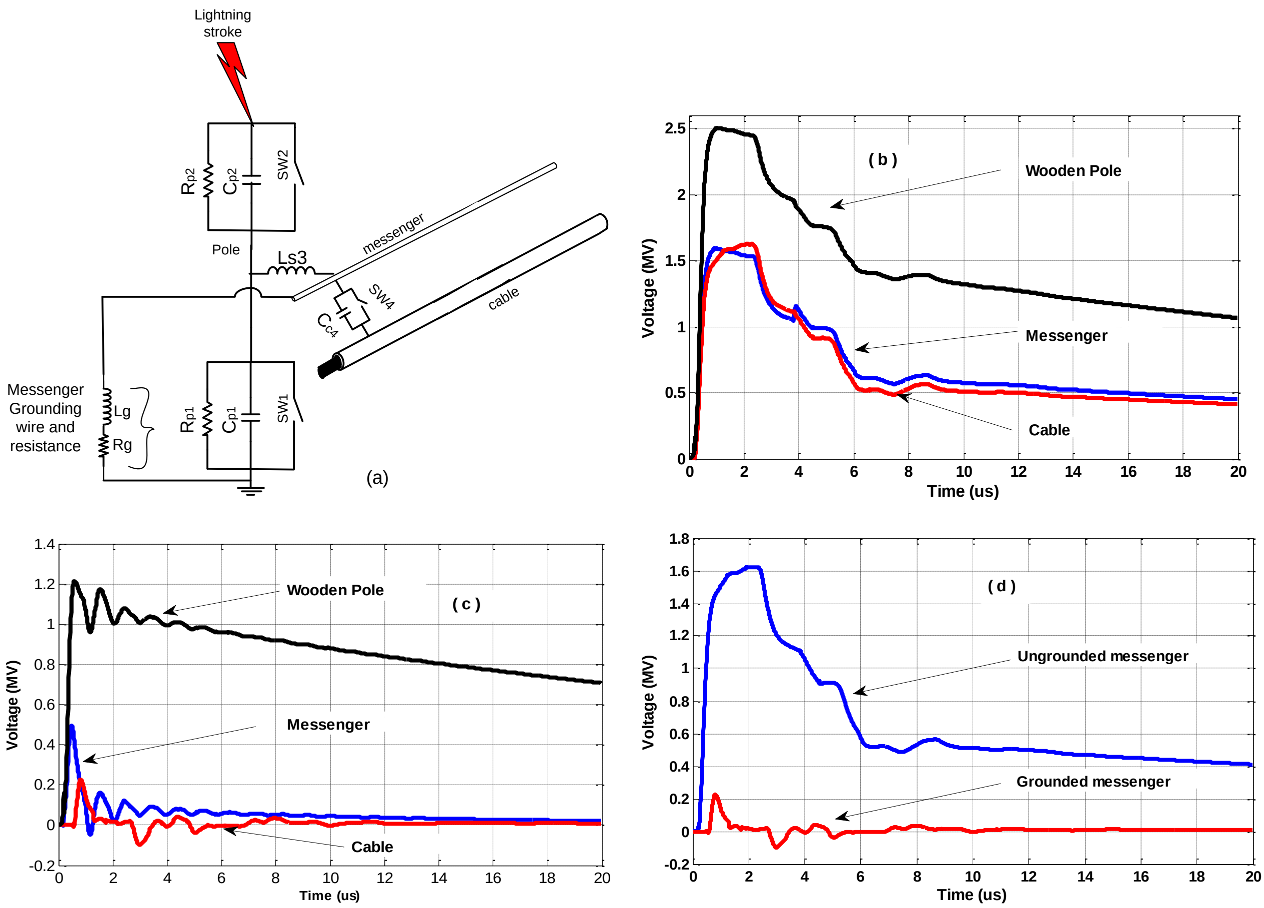


Figure 2.4: (a) Model description of the distribution pole struck by lightning current (15 kA), the grounded and ungrounded messenger wire and cable. (b) Overvoltage waveforms on the wooden pole, messenger wire and cable without grounding messenger wire. (c) Overvoltage waveforms on the wooden pole, messenger wire and cable with messenger wire grounded at every pole with grounding resistance Rg =10 Ω. (d) Overvoltage waveforms on the cable for grounded and ungrounded messenger-wire due to a lightning stroke of 15 kA on wooden pole.

Case 3: Effect of bonding and grounding of both messenger and screen on overvoltage performance of cable

The aim of observing this case is to assess the effect of bonding and grounding of cable's screen and messenger on cable's overvoltages. Therefore, a simulation was performed in which a variation in the bonding and grounding of the messenger and cable's screen were made as follows: (i) the screen and the messenger were neither bonded nor grounded, (ii) the screen was bonded with the messenger at every pole, (iii) both the screen and messenger were bonded and grounded at every pole and (iv) the screen was not bonded messenger while the messenger is grounded at every pole. Accordingly, a lightning stroke of 15 kA was applied to the pole 6 at the idle of the line (shown in Figure 2.2) as in *Case 2*. Figure 2.5 gives the resulting overvoltage waveforms on the cable for the simulated conditions.

From Figure 2.5a, it can be observed that the two overvoltage waveforms are too identical to the extent that they appear in one waveform. This suggests that the bonding of the messenger wire and the screen is unnecessarily when neither the screen nor messenger is grounded. On the other hand, Figure 2.5b gives the effect of grounding the arrangement of the screen and the messenger on the cable's overvoltage. Surprisingly, there was a slight difference of about 10% of the first overvoltage peaks on the cable for these conditions. The figure reveals that bonding of the screen and messenger, at any point on the line, does not substantially affect the cable voltage at the point where a lightning stroke hits the line.

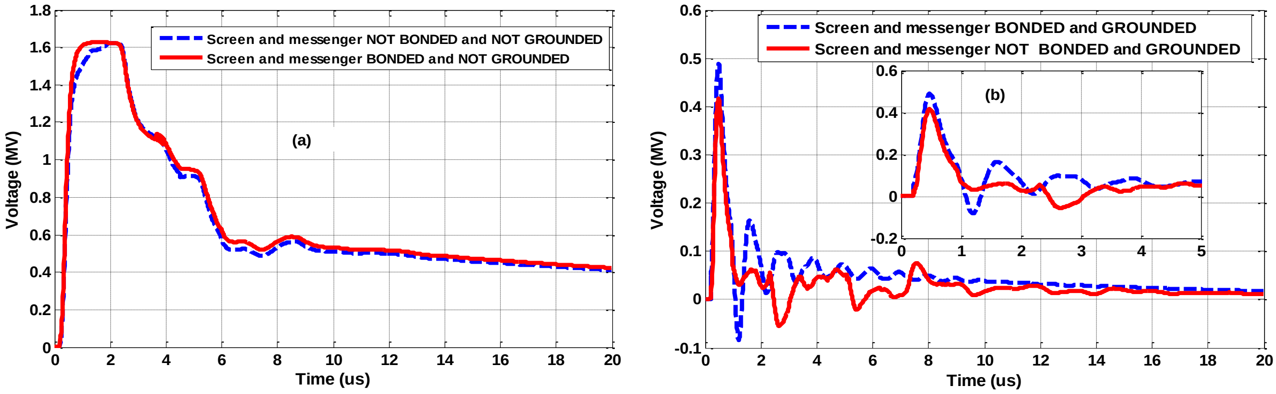


Figure 2.5: (a) Overvoltage waveforms comparison on cable with messenger and screen not bonded and not grounded *and* bonded but not grounded, *(b) Overvoltage waveforms comparison on cable with messenger and screen* bonded and grounded *and* not bonded and grounded. *Grounding resistance of Rg= 10 Ω.*

Case 4: Lightning performance of cable by replacing steel suspension of wooden pole with insulator suspension

An option was considered to increase the lightning-impulse strength of the air distribution cable insulation by replacing the steel suspension (CFO =0kV) with a porcelain insulation suspension (CFO =105kV).By doing so, it is expected that the pole-to-cable impulse insulation level (BIL) would be increased for better lightning performance. Thus, this simulation case took into consideration the effect of increasing insulation level of the line for the purpose of suppressing the overvoltage stress due to direct strokes to the wooden pole. Accordingly, the simulation was done as in *Case 1* but with the replacement of the steel suspension having a CFO of 0 kV (see Figure 2.6a) with a porcelain insulator having a CFO of 105kV (see Figure 2.6b). The insulator was represented in the simulation as a capacitor, Cc6, in parallel connection with a flashover model, as in Figure 2.6b. This flashover model was represented in the same way as in Figure 2.2. The insulator was connected between the messenger and all the 11 wooden poles. The range values of the capacitance which are adequate for modelling porcelain suspension insulation are 50- 80 pF [13-15], thus, a value of 50μF was used in this case. The resulting overvoltages on *pole 6* and cable from the average lightning stroke of 15kA (average in Finland) to a *Pole 6* is shown in Figures 2.6c and 2.6d. The figures reveal that adding insulator suspension will not appreciably reduce the overvoltage on the cable due to direct stroke to the pole. This is because of the magnitude of the simulated lightning current which resulted into a flashover across the insulator when the current hit the wooden pole.

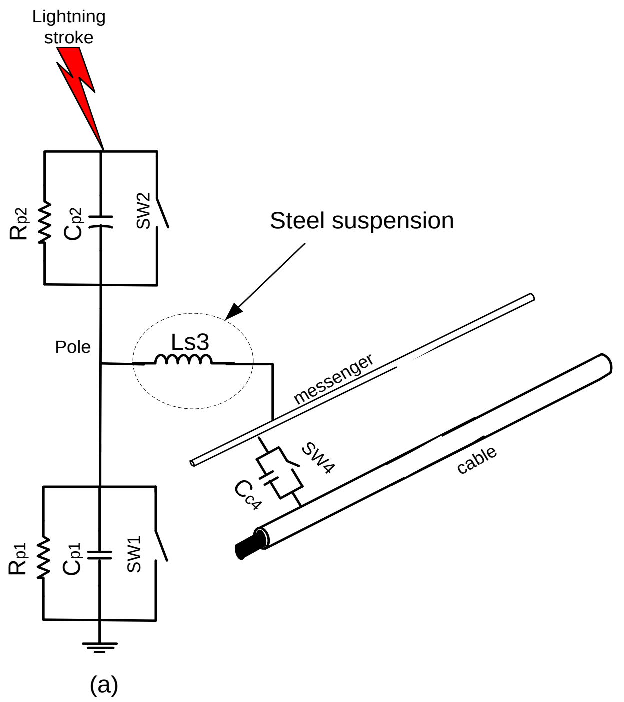


Figure 2.6 (a and b): Model description of a lightning current (15 kA) on distribution pole with different suspension components, (a) steel suspension modeled with inductance Ls3 = 6.98 µH, (b) insulator suspension modeled with capacitance Cc6 = 50 pF [13-15] in parallel with dynamic arc model SW6.

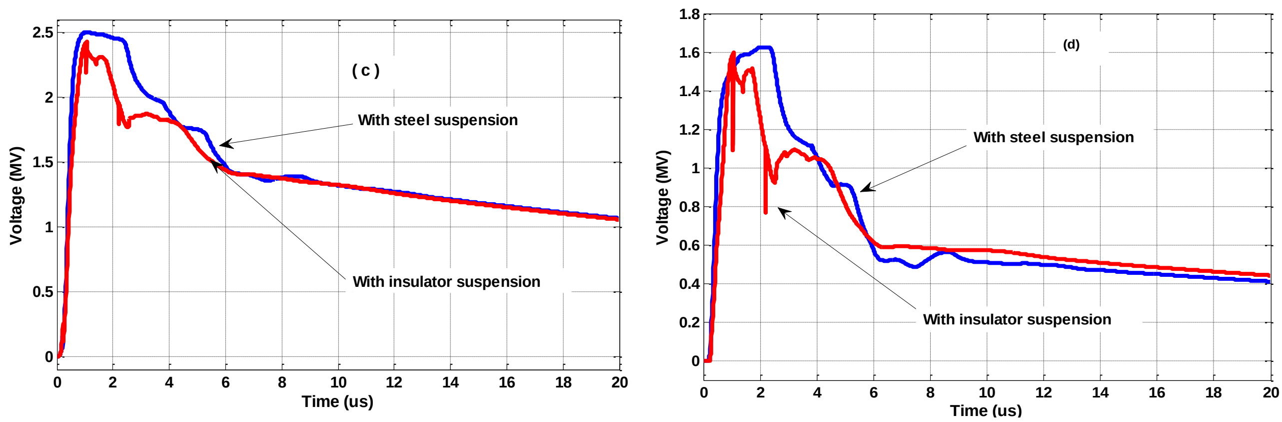


Figure 2.6 (c and d): Comparison of overvoltage waveforms on the pole in (c) and cable in (d) with steel suspension and insulator (porcelain) suspension, (c) and (d) represents overvoltage waveforms by considering flashover model across the line components.

Case 5: Role of messenger insulation on the lightning overvoltage performance of cable

Another simulation was carried out to determine the contribution of messenger insulation to the lightning performance of the cable installed on wooden poles. Thus the model description of the pole, messenger and cable is the same as in Figure 2.6a, except that the messenger wire was considered to have XLPE insulation as in the Appendix B. In the ATP-EMTP simulation, a capacitance of 55 pF was calculated using Equation (3.2a). It was represented as a capacitance between the steel suspension and the bare messenger wire, by considering the configuration of the messenger wire of the universal cable (see Appendix B). Figure 2.7 shows the overvoltage waveforms on the wooden pole and cable as a comparison between the insulated and bare messenger for the simulated case. The figures reveal that insulating messenger may not provide appreciable improvement on the lightning performance of the cable, for the kind of stroke simulated in this study.

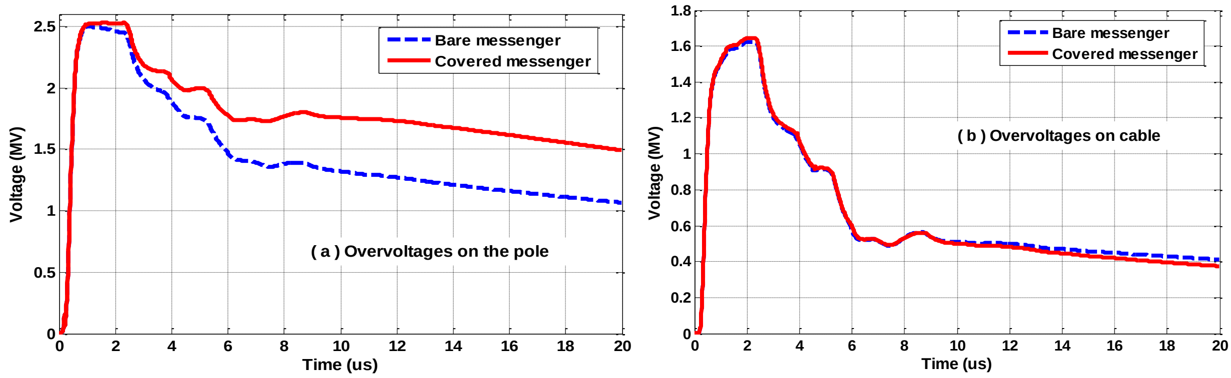


Figure 2.7: Comparison of overvoltage waveforms on wooden pole and cable for the bare messenger wire and covered messenger wire.

CASE 6: Effect of shield-wire on intercepting possible lightning strokes to cable

In order to protect the simulated line in Case 1 from direct strokes to the pole, messenger or cable, a shield wire was placed 1 m above the pole (see Figures 2.8a and 2.8b) for the purpose of intercepting lightning strokes that would otherwise hit the distribution line. To assess this condition, a shield wire was modelled with the length l = 9 m and radius of the wire, rg= 1.3 mm, hence, the inductance was estimated to Lg =15 μH (from Equation 3.4) and grounded at every pole with resistance Rg = 10 Ω. Figures 2.8c and 12.8d give the resulting cable's overvoltages from a stroke of 15 kA on pole 6 as comparison between the simulated line with and without shield wire. It is evident that the overvoltage reduction of about 75% can be achieved by installing a shield wire above the distribution cable.

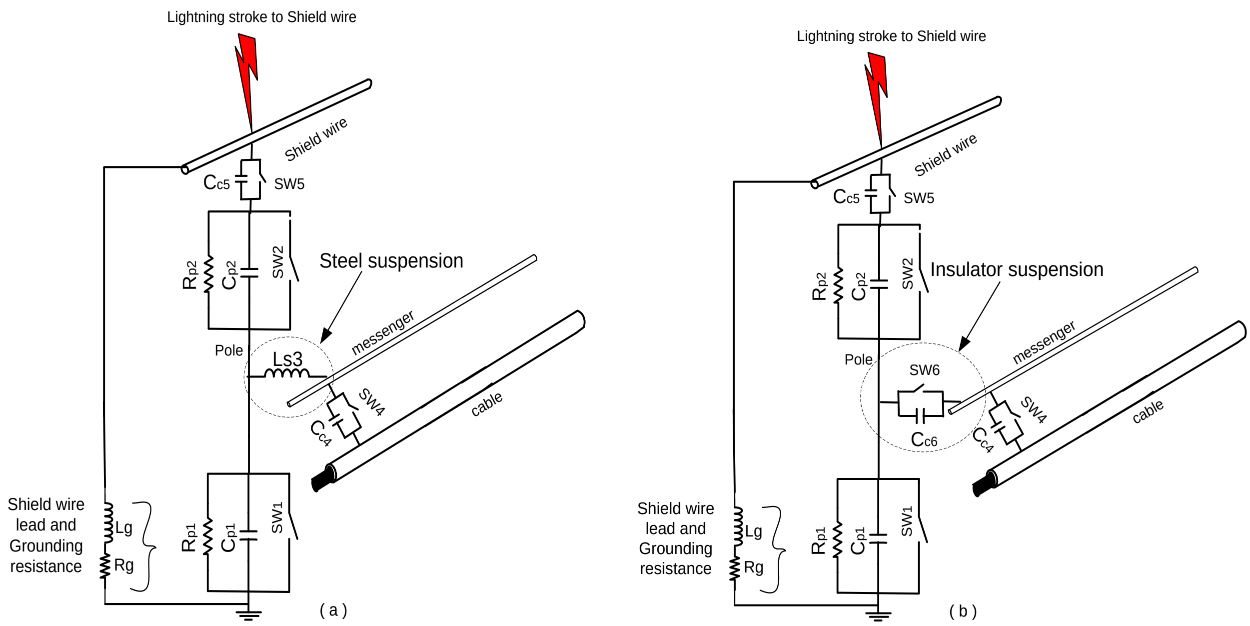


Figure 2.8 (a and b): (a) Model description of a lightning current (15 kA) intercepted by shield wire and messenger hanging on steel suspension. (b) Model description of a lightning current (15 kA) intercepted by shield wire and messenger hanging on insulator suspension.

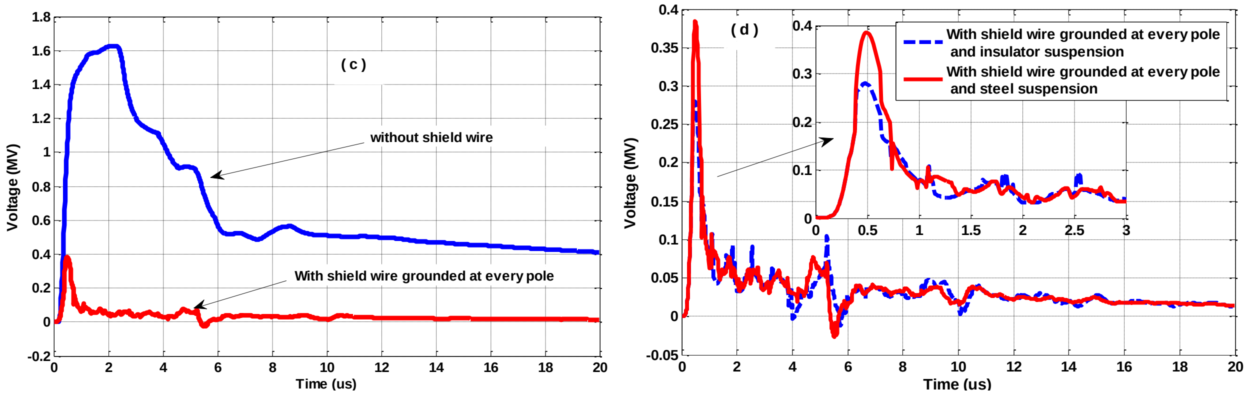


Figure 2.8 (c and d): (c) Overvoltage on the cable with and without shield wire grounded at every pole, (d) Overvoltage comparison on the cable with shield wire when messenger is hanging on steel suspension and insulator suspensions. Rg =10 Ω.

Case 7: Effect of shield-wire grounding resistance on overvoltage suppression on cable

The dependence of shield wire on grounding resistance was simulated in this case by varying the grounding resistance of *Case 6.* As shown in Figure 2.8, shield wire effectiveness is greatly dependent on grounding resistance. As seen from the previous case, the shield wire was able achieve a 75% (1600 kV to 400 kV) reduction in the resulting overvoltage on the cable at the lightning struck point, when the grounding resistance was 10 Ω. Therefore, the remaining overvoltage can still make flashover and create a hole on the cable if this situation occurs in reality. Thus, if hazards from direct strokes are to be completely eliminated, low ground resistance should be designed for the type of distribution line which has a CFO of about 325 kV (as calculated in Section 2.5).

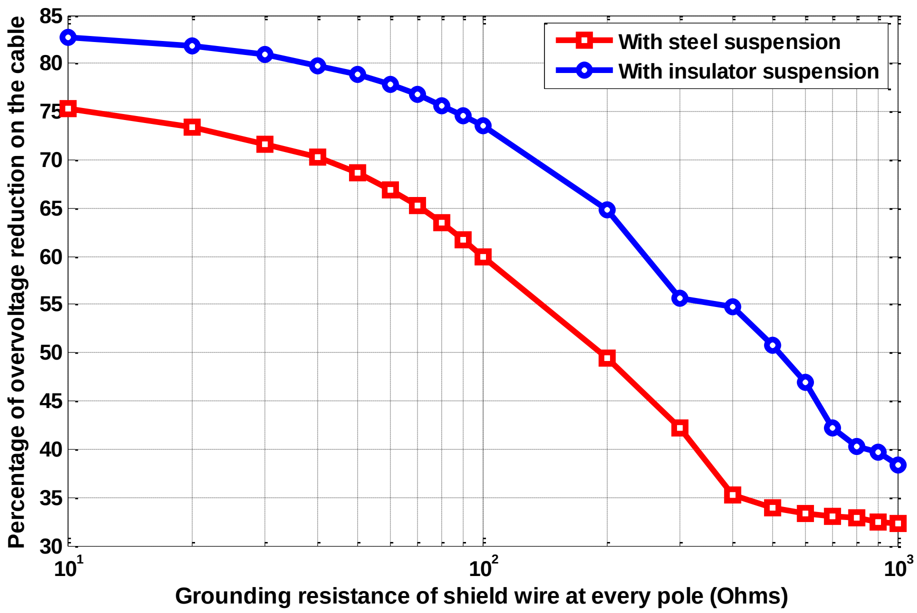


Figure 2.8: Percentage of overvoltage reduction on the cable (screen-to-conductor) with increasing grounding resistance of shield wire. Lightning current simulated is 15kA (average in Finland) and the stroke was applied to the shield wire at the pole 6 in Figure 2.2.

CASE 8: Lightning performance of cable by replacing wooden poles with steel towers

In this case, a simulation was made to compare the lightning performance of cable installed on wooden pole with the cable installed on steel tower. As shown in Figures 2.9a and 2.9b, the wooden pole was modelled and simulated as in the previous cases while the steel tower is introduced as follows. The tower was assumed to have a cylindrical shape, thus its surge impedance, Z_c , was calculated using Equation 3.5 as derived by [16].

$$Z_c = 30\ln\left(\sqrt{2}(2h/r)\right) - 60 \tag{3.5}$$

where h and r represent the height and radius of the tower, respectively. Thus with the height, h, of the tower as to be 8.1m and its radius, r, taking as 0.25 m, the surge impedance, Zc =169 Ω. In order to take into consideration the nonlinear behaviour of footing resistance of a steel tower struck by a lightning struck, the footing resistance, was represented in the ATP- EMTP, with a nonlinear ground by using Equation 3.6 [1]

$$R_i = \frac{R_o}{\sqrt{1+\dfrac{2\pi R_o I}{E_g \ell}}} \tag{3.6}$$

where R_o is the normally measured low-current footing resistance, Ri is the tower footing resistance that is a function of the current flowing through the footing resistance, E_g is the soil ionization gradient which is about 300 kV/m [1] and ℓ is the soil resistivity in Ωm and I is the current flowing through the footing resistance. The nonlinear resistance, R_i, was used for all the 11 steel towers that were considered in this simulation case. Therefore, in the ATP-EMTP program, the tower's surge impedance, Z_c, and nonlinear footing resistance, R_i were represented by distributed parameters *(Clarke)* and a nonlinear TACS-controlled resistor (TYPE 91), respectively. The simulation was carried as in *Case 1* with a direct lightning stroke of 15 kA on middle tower (*tower 6*).

Figures 2.9c and 2.9d show a comparison between the overvoltages measured at the point of stroke contact and the cable. It is observed in the figures that the used of steel towers, instead of wooden poles, has decreased the overvoltages at the point of stroke contact and on the cable by 46% and 44%, respectively. The simulation reveals that a better lightning performance of the cable can be realised by using steel towers instead of wooden poles. The reason for this improvement is the surge impedance of the steel tower which is much lower than the resistance of the wooden pole. Thus, an improvement option to take into consideration is the use steel towers instead of wooden poles.

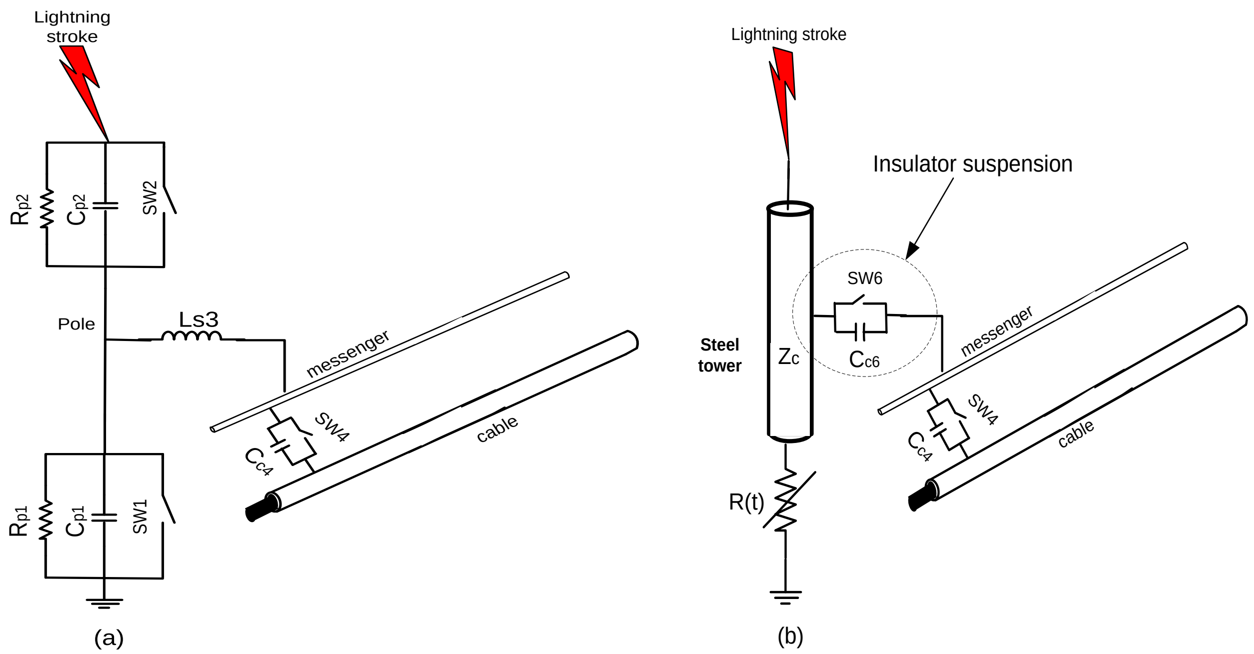


Figure 2.9 (a and b): Model description of a lightning current (15 kA) distribution wooden pole and steel tower of height 8 m. (a) wooden pole (b) steel tower

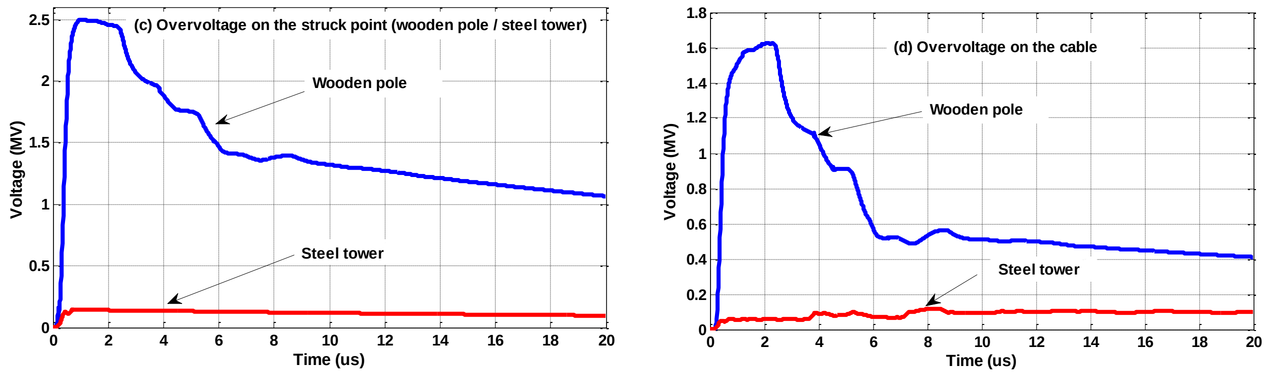


Figure 2.9 (c and d): Comparison of overvoltage waveforms on wooden pole and steel tower; (c) overvoltage waveforms at struck point with wooden poles installed and with steel tower installed; (d) overvoltage waveform on the cable with wooden poles installed and with steel tower installed.

Case 9: Overvoltage performance of cable with installation of shield wire on steel tower

The following scenario considered the impact of shield wire installation on steel tower on cable's overvoltage suppression. The same configuration of shield wire in Figure 2.8b was employed for this case study (see Figure 2.10b) except that there was shield wire was connected directly to all the 11 steel towers under consideration. Thus, Figures 2.10a and 2.10b give the model description of the tower for simulation with a direct lightning stroke of 15 kA on steel tower 6. Figures 2.10c and 20.10d compare the overvoltage at the point of lightning stroke (steel tower/ shield wire) and on the cable. The simulation has revealed the significance of installing shield wire above steel towers; as shield wire can intercept any direct hit that may damage the cable's insulation, and eliminate overvoltage increase due to reflections on the tower struck by lightning. Figure 2.10e gives sensitivity of overvoltage peaks on the grounding resistance of the steel towers, with and without shield wire. As shown in Figure 2.10e, the installation of shield wire on steel tower gave better lightning performance of the cable with higher grounding resistance.

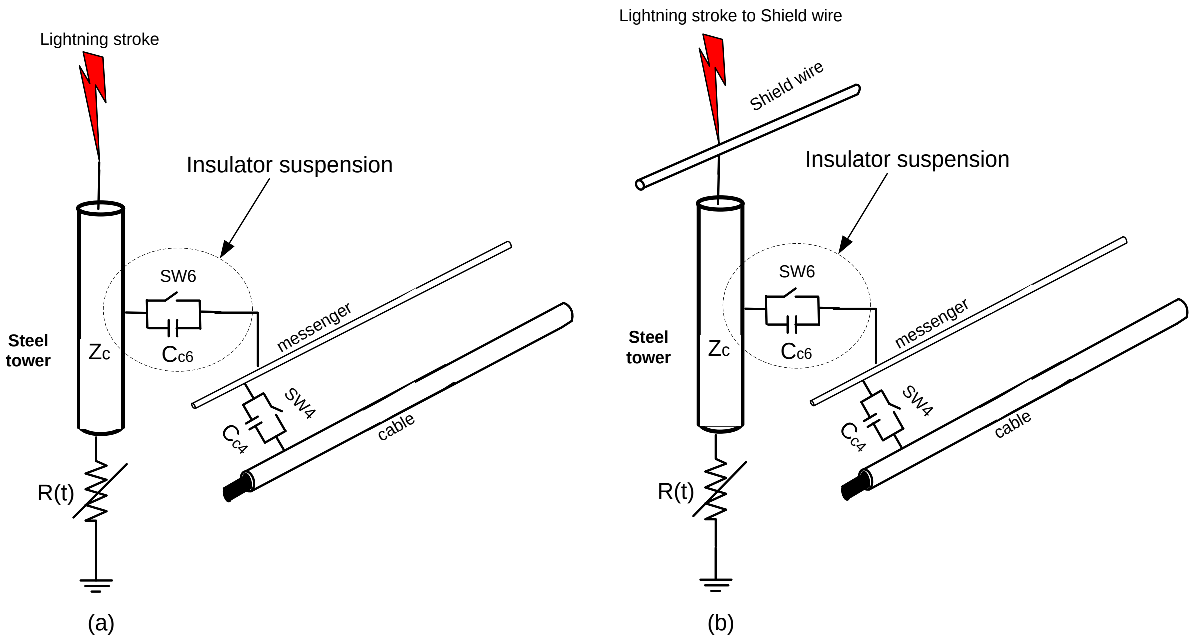


Figure 2.10 (a and b): Model description of a lightning current (15 kA, and steel tower (a) without and (b) with shield wire

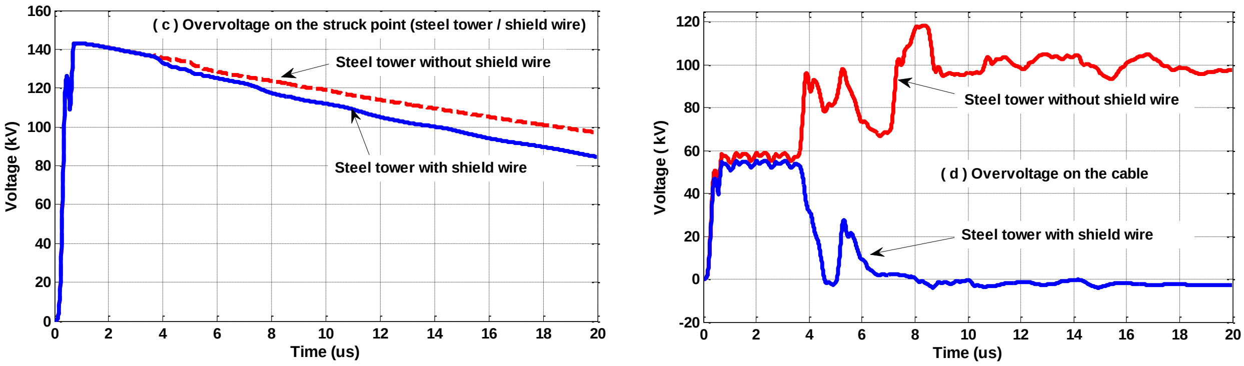


Figure 2.10 (c and d): Comparison of overvoltage waveforms on steel tower with resistance $R_o = 10\ \Omega$*; (c) overvoltage waveforms at striking point without (d) overvoltage waveforms on the cable with wooden poles installed and with steel tower installed.*

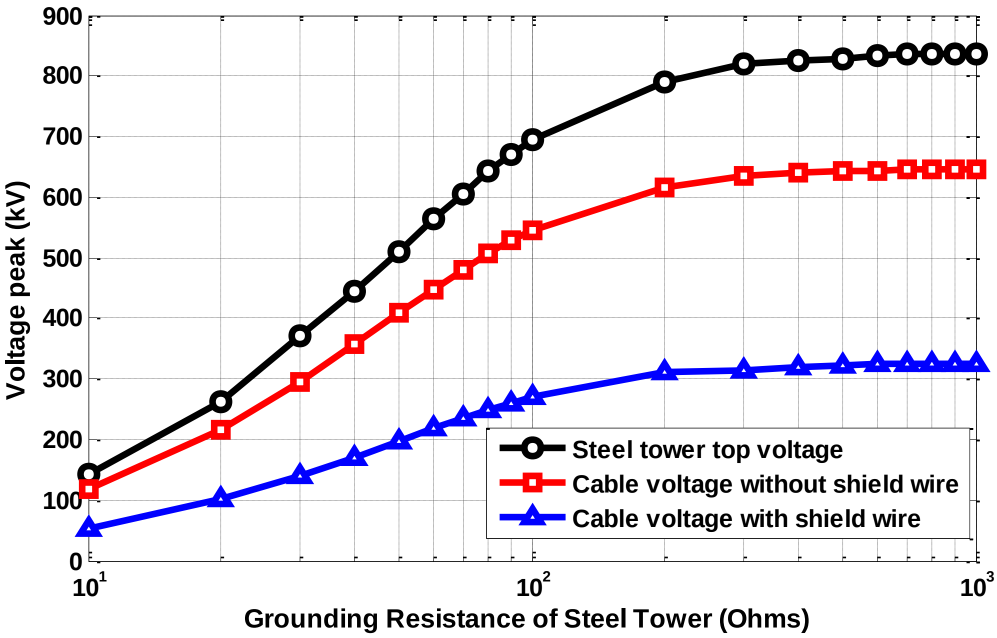


Figure 2.10 e: Calculated overvoltage peak on steel tower top and cable with and without installation of shield wire at the top of the steel tower for different grounding resistance of the steel tower.

CASE 10: Lightning stroke to tree and coupling overvoltage or flashover to nearby cable

When a lightning current of 15 kA with a surge impedance of 400 Ω hit a tree or other object of higher resistance, the surge voltage from the lightning is expected not to be more than 6 MV. Therefore, with regards to 600 kV/m field strength of air [1], a separation distance of less than 10 m between the lightning-struck tree and the cable will lead to a flashover on the cable. Thus, above 10 m separation distance, only induced voltage can be expected to illuminate the distribution cable. In order to understand the problem of lightning coupling overvoltage and flashover to nearby cable, two different simulation scenarios were considered.

In the first scenario, lightning stroke of 15 kA was assumed to hit a tree located at distance of 11 m to the distribution cable. Thus, the resulting coupling overvoltage on the cable was computed, for the ungrounded messenger, grounded messenger and grounded shield wire shown in Figures 2.11a and 2.12a, without taking into consideration a flashover. Accordingly, the lightning stroke to the tree was 15 kA as in the previous cases. The configuration of the air cable, in Figures 2.11a and 2.12a, was the same as in the previous simulation conditions with the steel suspension and wooden poles. As it was derived by experiment and subsequently modelled in [6], any tree can be adequately represented by a capacitance and a resistance in parallel, as in Figure 2.11a. Thus, the tree shown the figures is represented by a resistance, Rt = 830 kΩ and a capacitance, Ct = 4.32 pF [6]. The electrical interaction between the tree and the cable, was presented by an experimentally verified mutual capacitance, Cc6 = 10 pF (for 11 m tree-to-line clearance).

Thus, Figure 2.11b show the resulting coupling overvoltages on the cable for ungrounded messenger and grounded messenger, while Figure 2.12b produced resulting coupling overvoltages on the cable for ungrounded messenger and grounded shield wire. The simulation results show that about 69 % of coupling overvoltage can be suppressed if messenger is grounded at every pole, and about 72 % can be suppressed if shield wire is installed and grounded at every pole. Apart from the substantial coupling overvoltage suppression with the grounding of messenger or shield wire, the installation of shield wire also has the advantage of intercepting possible direct strokes or side flashes from the nearby tree. This advantage is taken into consideration in the next scenario.

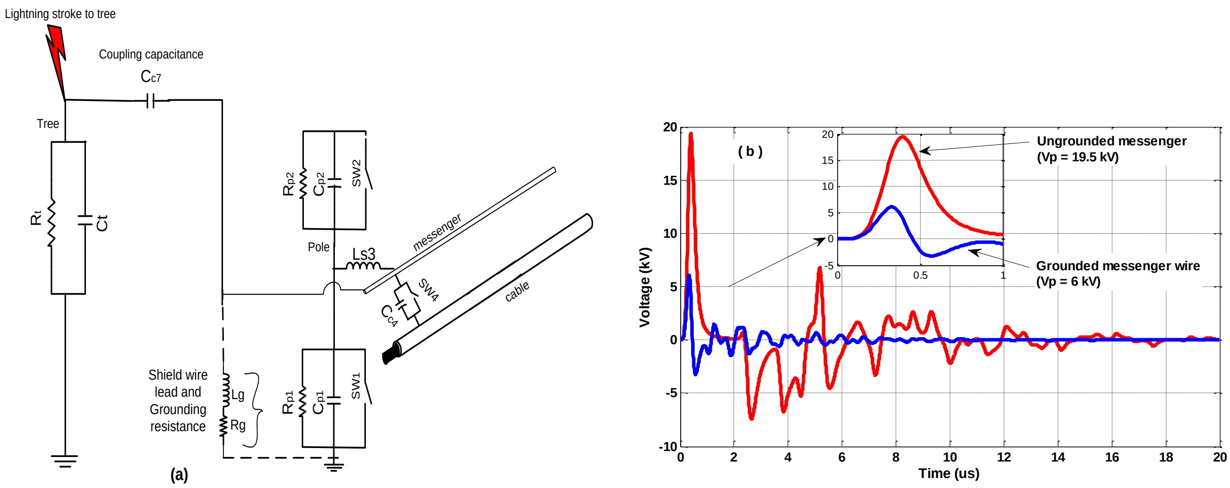


Figure 2.11(a and b): (a) Model description of a voltage induction from a lightning –struck tree at 11 m distance from nearby air distribution cable structure. (b)Comparison of induced overvoltage waveforms on distribution cable

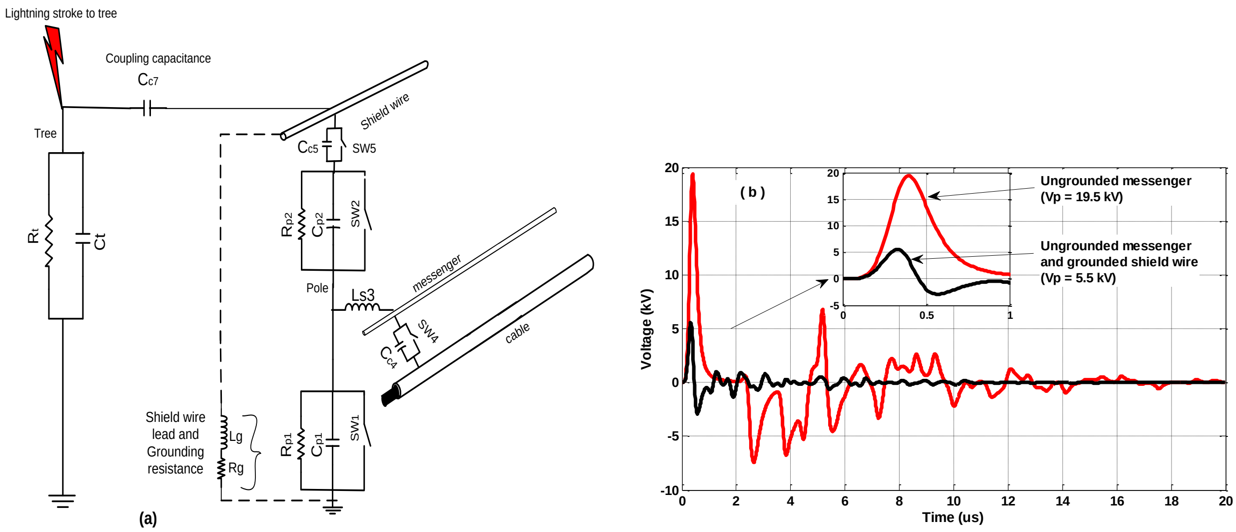


Figure 2.12(a and b): (a) Model description of a voltage induction from a lightning –struck tree at 11 m distance from nearby air distribution cable protected with shield wire. (b)Comparison of induced overvoltage waveforms on distribution cable

In the second scenario, a separation distance of 1 m was assumed between the lightning-struck tree and the cable; hence, lightning flashover was assumed to occur to the nearby the cable, as in Figures 2.13a and 2.14a. Thus, a simulation was carried out to investigate the lightning performance of the cable due to a flashover from the nearby tree. The induced flashover overvoltages on the messenger and cable were calculated when the messenger was grounded and not grounded. The electrical interaction between the tree and the cable, was presented by an experimentally verified mutual capacitance, Cc6 = 110 pF (for 1 m tree-to-line distance), and a 'flashover switch', SW7 [6]. The SW7 was a combine model of TACS voltage controlled switch and a dynamic model which have been explained in Section 3.1.1. The switch was modelled by taking into consideration the CFO of 600 kV/m of the air insulation between the tree and the distribution cable having a separation distance of 1 m. The distribution pole and air cable (ungrounded messenger and cable) grounding configurations, as shown in Figure 2.13a, were the same as in Figure 2.6a. Thus, for a lightning stroke of 15 kA on the simulated tree, the resulting flashover overvoltages on the nearby messenger and the induced flashover overvoltages on cable are given in Figures 2.13b and 2.13c, respectively, for the case of ungrounded and grounded messenger. The simulation has also proved that the grounding of messenger could provide substantial improvement in the lightning performance of air distribution cable by limiting the overvoltage stress on the cable insulations.

Further, it was considered that the tree is located at the same distance to a distribution cable being protected with shield wire, as indicated Figure 2.14a. The shield configuration was the same as in Case 6. The, flashover from the tree to the shield wire and the flashovers between the distribution components were modelled as previously done in this case study. For a lightning stroke of 15 kA on the simulated tree, the resulting flashover overvoltages on the nearby shield wire and the induced flashover overvoltages on cable are shown in Figures 2.14b and 2.14c, respectively, for the case of grounded and ungrounded shield wire. By proving adequate grounding for the messenger at every pole, the overvoltage peaks in the flashover were reduced by 74% and 83% on the messenger and cable, respectively. With installation and grounding of shield wire at every pole, the overvoltage peaks in the flashover were reduced by 68% and 71% on the shield wire and cable, respectively. Figures 3.14d and 2.14e give the calculated overvoltage waveforms on the shield-wire/ messenger and the cable as a comparison between the grounded messenger (Figure 2.13a) and grounded shield wire (Figure 2.14a). It can be observed that the overvoltage peak on the shield wire is marginally higher than the overvoltage peak on the messenger by 5.5 % and the resulting induced flashover overvoltage on the cable from the shield wire is also marginally higher than the resulting induced flashover overvoltage on the cable from the messenger by 5.8%. Thus, for the average lightning stroke in Finland that has been simulated, the grounding of messenger will not eliminate the puncture on cable insulation jacket due to flashovers from the surrounding trees. However, if a shield wire is installed above the cable with the same grounding scheme, it is expected to intercept side-flashes from nearby trees or other objects hit by direct lightning strokes. This will relieve the cable and other electrical components from excessive energy input and will adequately protect the cable insulation from puncture.

As revealed in Figure 2.8, a shield wire with grounding resistance of 10 Ω will suppress the lightning overvoltage peak on a cable, with steel suspension, by 75 %. However, if the lightning stroke is intercepted by a tree and resulted into a flashover to the shield wire (as in Figure 2.14a), the percentage of overvoltage peak suppression will increase to 83% (as in Figure 2.14c). This reveals the contribution of trees and other high structures to the improvement in lightning performance of the cable. Thus, trees may intercept and equally suppress lightning strokes that otherwise would have hit a distribution line. The effectiveness shield wire can greatly rely on the insulation provided on the distribution cable and the grounding resistance [1]. Thus, the percentage of overvoltage peak suppression on the cable with increase in grounding resistance is show in Figure 2.15. Another factor that was considered in this case is the replacement of the steel suspension with porcelain insulation suspension. This effect is also shown in Figure 2.14 for the case of the steel suspension and the porcelain insulation suspension by increasing the grounding resistance. This also yielded a positive result for improvement in the lightning performance of the cable.

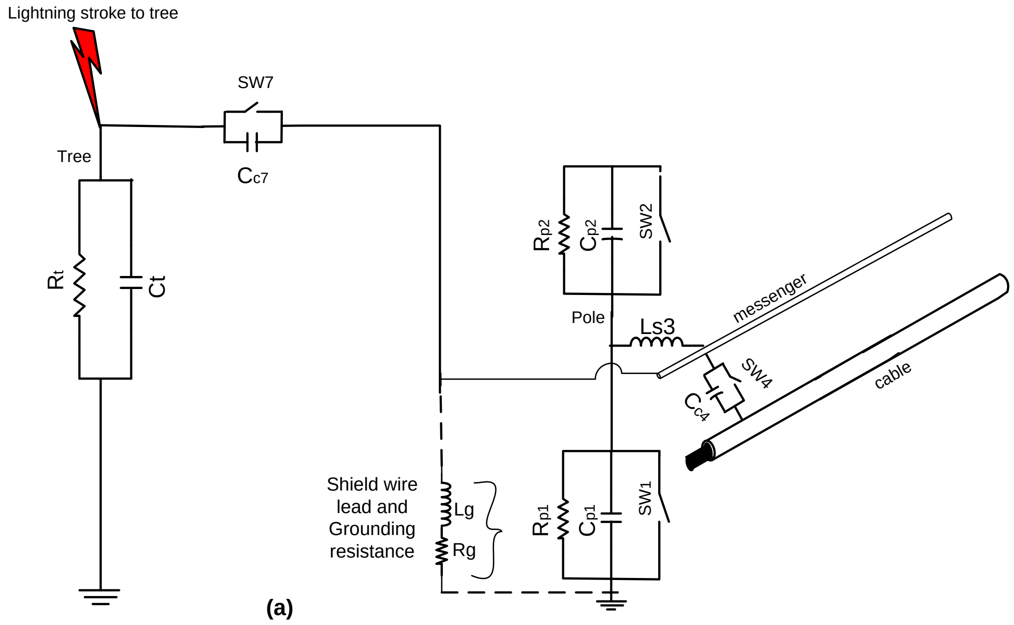


Figure 2.13 (a): Model description of a lightning stroke (15 kA) to tree at 1 m distance from nearby air distribution cable structure.

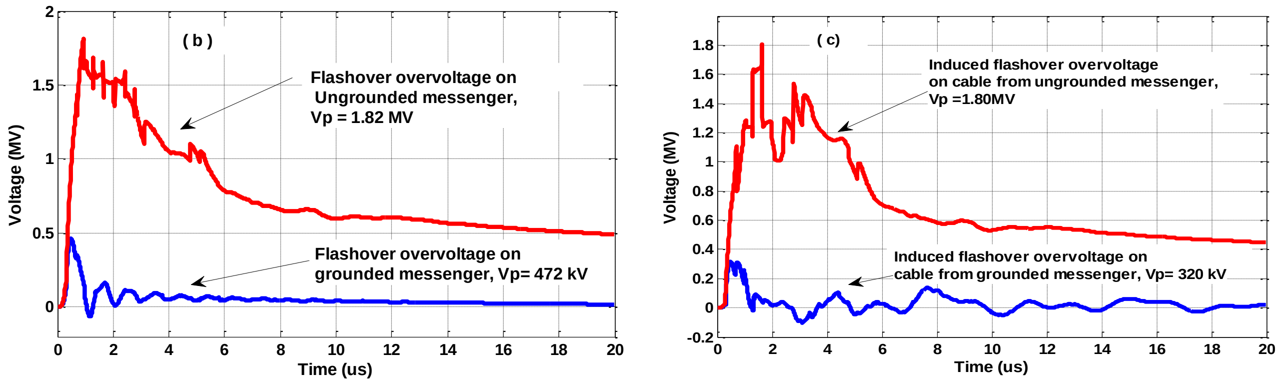


Figure 2.13 (b) and (c): Comparison of flashover overvoltage waveforms on distribution messenger wire in (b) and cable in (c), from a lightning stroke (15 kA) to the nearby tree, with messenger wire grounded and not grounded. Grounding resistance, Rg= 10 Ω.

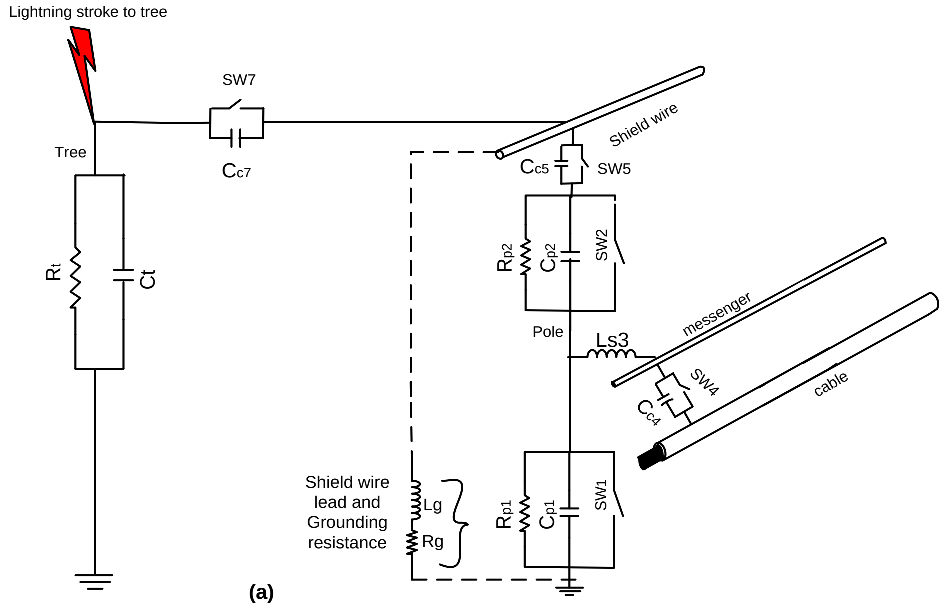


Figure 2.14 (a): Model description of a lightning stroke (15 kA) to tree at 1 m distance from nearby air distribution cable having a shield wire.

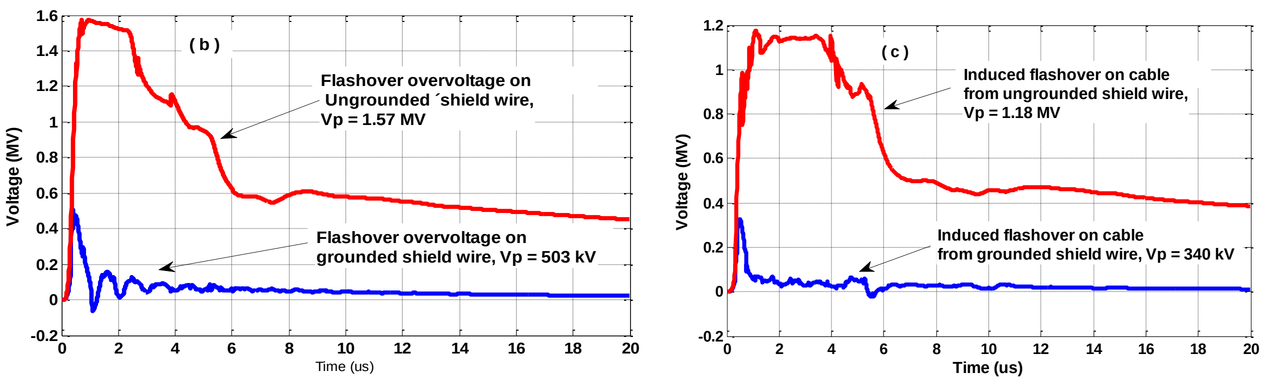


Figure 2.14 (b and c): Comparison of flashover overvoltage waveforms on shield wire in (b) and cable in (c), from a lightning stroke (15 kA) to the nearby tree, with shield wire grounded and not grounded. Grounding resistance, Rg= 10 Ω.

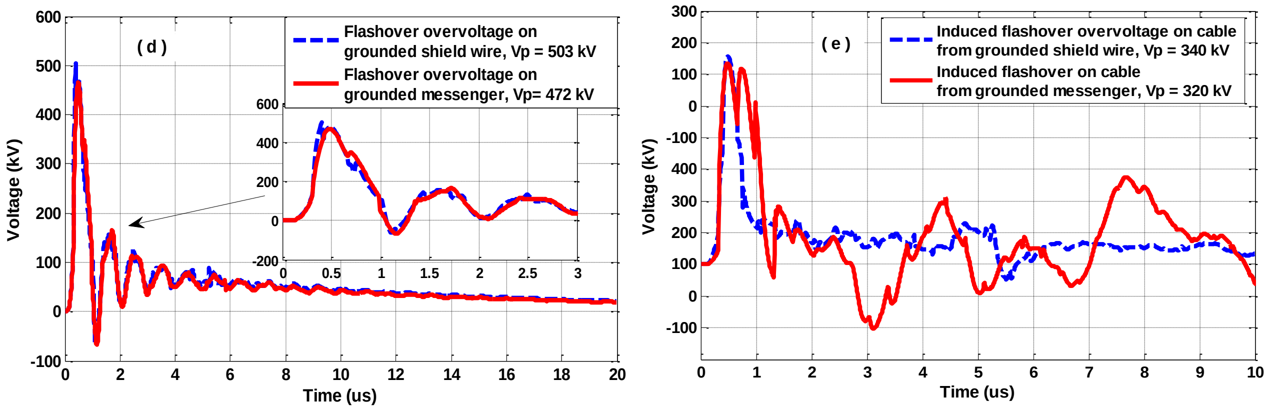


Figure 2.14: Comparison of flashover overvoltage waveforms on grounded messenger and grounded shield wire from a lightning stroke (15 kA) to the nearby tree. (d) Calculated overvoltage on the shield wire/ messenger and (e) Calculated overvoltage on the cable. Grounding resistance, Rg= 10 Ω.

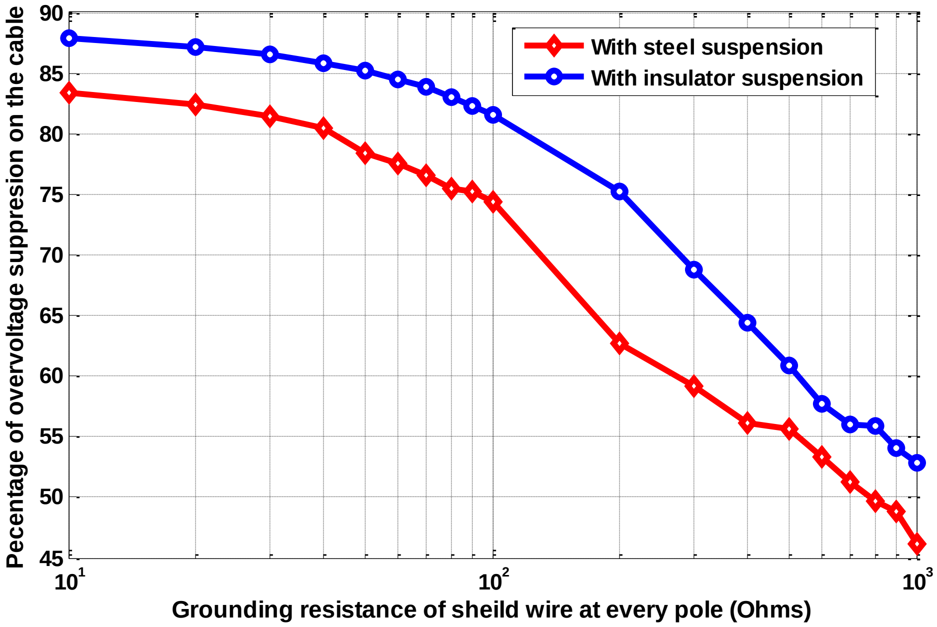


Figure 2.15: Percentage of overvoltage reduction on cable protected with shield wire when a lightning strokes (15kA) a nearby tree, flashovers to a shield wire and messenger hanging on steel suspension and insulator suspension.

4. Experimental Verification of Shield Wire Protection of Air Cable

This section reports the experimental results which show the performance of air cables and the evidence of lightning hazards to air cables without protection. The results also provided the proof of shield wire protection of the cable when it is directly above the shield wire installation. The experiment is expected to further the understanding of lightning performance and protection of air cable. It will also validate the analysis and simulation results that have been previously reported in this report.

4.1 Laboratory Configuration and Approach

The laboratory test was classified as *CASE A* for coupled overvoltage tests and *CASE B* for flashover overvoltage tests on the cable. The experimental configuration was a full-scale air cable design which is a typical representation of 20 kV air distribution cables around trees in Finland. The air cables having a length of 35 m and height of 8 m, consisted of three pieces of cable and one messenger wire. The diameter of cable's conductor and sheath were 5.6 mm and 25 mm respectively. The diameter over messenger and sheath were 10 mm and 12.5 mm respectively. The height of the tree was 9.5 m. The tree was equidistance from the cables termination and was varied from 1 m to 5 m from the center of the cables. The schematic of tree and cable arrangement is shown in Figure 3.1. In the case of coupled voltage test on the cable, the messenger wire was ungrounded (or grounded) while the cables were left hanging at both ends. An impulse generator was employed to supply repetitive standard voltage (1.2/ 50 μs) directly on top of the tree. The test was carried out under the atmospheric condition as follows; Temperature of 20 ^{o}C, Relative humidity of 21.4 % and Pressure 1001 hPa.

4.2 Test Results

CASE A: Coupled voltages were recorded on the 20 kV air distribution cable of Figure 3.1 when the lightning of 300 kV (1.2/ 50 μs) (see Figure 3.2a) was applied on top of the tree. The performances of cable were examined; with grounded and ungrounded shield wire, with tree-to-cable distance of 1 m and 5 m, and with and without the installation shield wire. The measurements were carefully recorded and examined in all the cases considered. Figure 3.2b gives the coupled voltages on the cable from an impulse voltage of 300 kV (Figure 3.2a) on top of the tree when the messenger with grounded and ungrounded. It can be seen that there is a significant different between the coupled voltages on the cable, with peak voltage of 34 kV for ungrounded messenger wire and 8.2 kV for grounded messenger wire. Figure 3.2c gives the resulting coupled voltage on the cable (ungrounded screen and messenger) with increasing the clearance between the tree and the line, i.e. from 1 m to 5 m. It can be deduced from this figure that the induced voltage on the cable decreases marginally by increasing the clearance, with a peak voltage of 35 kV for 1m tree-to-cable clearance and 27.8 kV for 5 m (21 % difference). Thus, a change in tree-to-cable clearance does not influence greatly the coupled voltage on cable. Therefore it is expected that, in reality, the variation in the clearance between trees and air cable would have limited effect on the coupled voltage from a nearby stroke.

CASE B: An attempt was made to determine the effect of the shield wire on both the coupled overvoltage and flashover overvoltage from nearby lightning-struck tree. In the case of shield wire protection against the coupled overvoltage and induced flashover from nearby strokes, as revealed in Figure 3.4, an iron bar of length 20 m was installed 1 m directly above the air cable and connected to the ground with a copper sheath. The impulse voltage of 300 kV was applied on the tree for the tests and the coupled overvoltages were measured on the cable with and without the installation of shield wire. Figure 3.2 d reveals the coupled overvoltages on the cable with a voltage peak of 35 kV without shield wire and a voltage peak of 25 kV with shield wire (29 % difference). For the protection against induced flashover, the impulse voltage peak on the tree was increased from 300 kV until flashover occurred at about 700 kV. A digital camera, operating in "frame-mode", was carefully used to capture the flashover between the lightning-struck tree and the cable/ shield wire. The tests were conducted to reveal the information, such as, the nature of flashovers from nearby tree to cable, and the influence of grounded shield wire on flashovers to the cable. With the installation of shield wire, as shown in Figure 3.3, the applied impulse voltage of about 700 kV on the tree resulted into a flashover to the grounded shield wire. The figure shows the path through which the lightning flashover passed from the lightning-struck point to the shield wire. When the shield wire was removed, as indicated in Figure 3.4, the flashover went directly to the to the air cable. This reveals that placing grounded shield wire directly above air cable will not only protected the cable from direct strokes and induced flashovers, but also from coupled overvoltages from nearby structures.

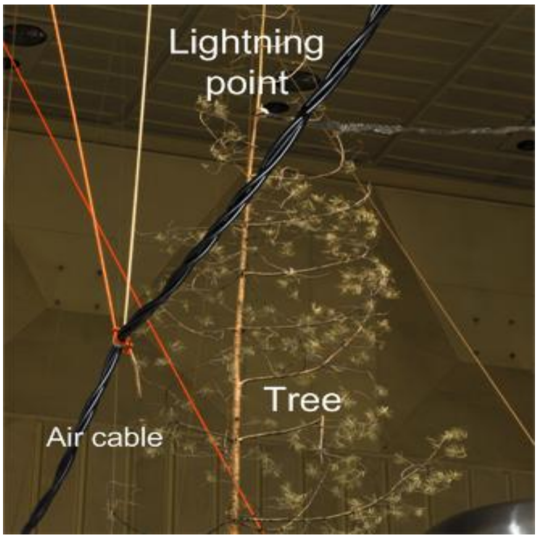


Figure 3.1. Experimental arrangement of tree, air cable and lightning attachment to the tree.

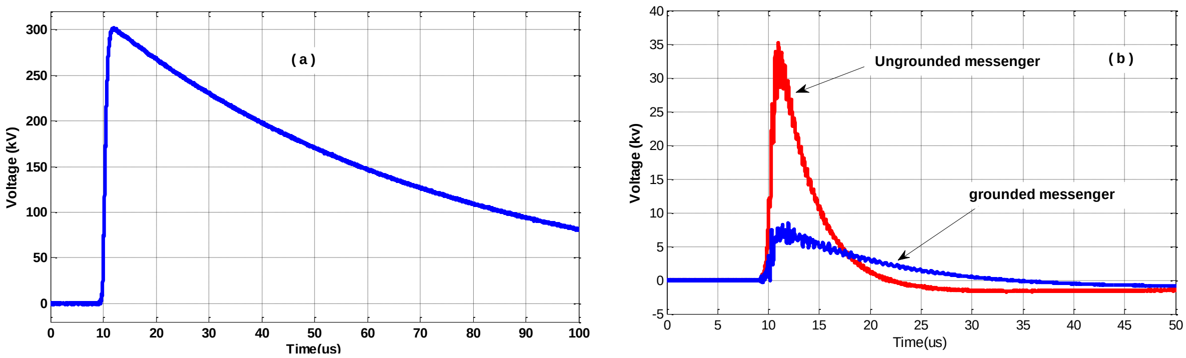


Figure 3.2: (a) Lightning impulse voltage applied on the tree (300 kV). (b) Coupled overvoltage on the cable for grounded and ungrounded messenger-wire due to a lightning impulse voltage of 300 kV on a tree, for tree-to-cable distance of 1m.

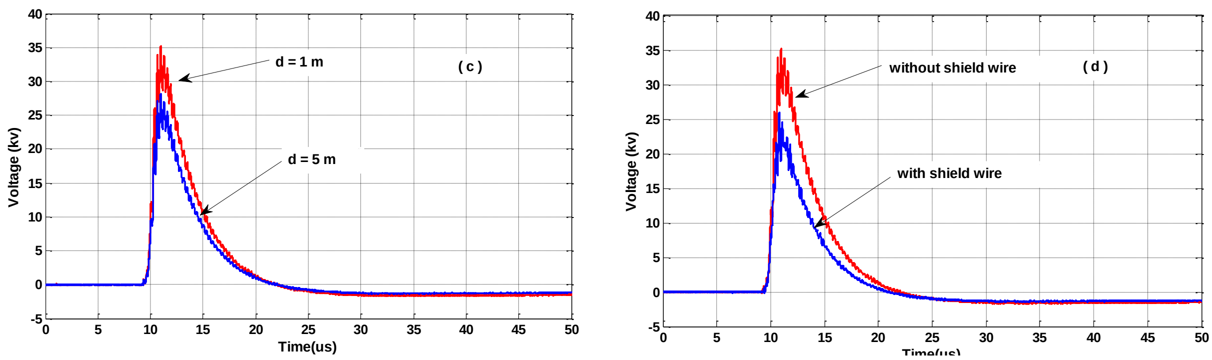


Figure 3.2: (c) Coupled overvoltage on the cable due to a lightning impulse voltage of 300 kV on a tree, for tree-to-cable distance of 1m and 5m. (d) Coupled overvoltage on the cable due to a lightning impulse voltage of 300 kV on a tree, with and without shield wire installation, and tree-to-cable distance of 1m.

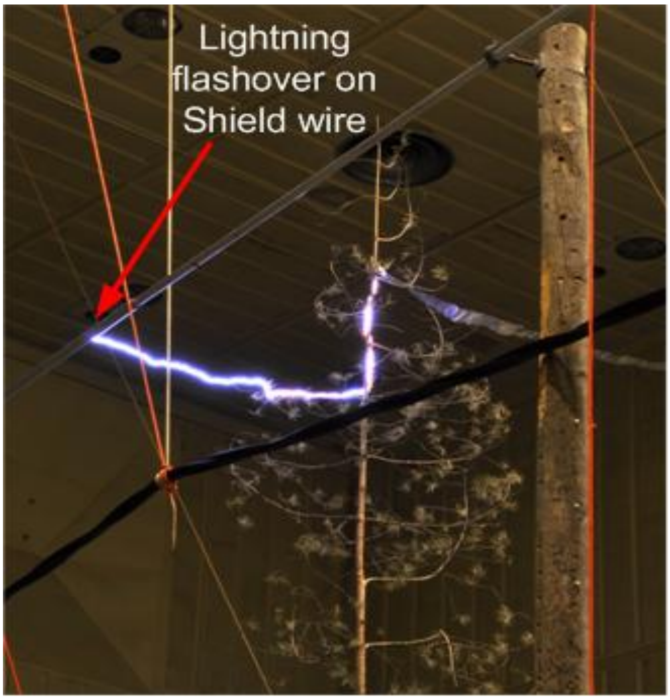


Figure 3.3. Lightning flashover to shield wire from the lightning-struck tree.

Figure 3.4. Lightning flashover to air cable from the lightning-struck tree

5. Conclusions

In this report, new knowledge has been introduced in terms of the lightning performance and protection of air distribution cables using analysis and digital modelling. In Finland, the average magnitude of lightning stroke is about 15 kA and this has been taken into consideration in the analysis and ATP- EMTP simulations. The results have revealed some lightning performance of air cables in bare land and forest areas in real situations. The following provide some conclusions from the study:

1. By means of electro-geometric model, information about the shielding effect of trees on lightning performance of distribution cable has been provided. It has been shown that there is a significant contribution of tree height, lightning stroke magnitude and clearance on the shielding of distribution cable from direct stroke. Specifically, trees will automatically provide perfect shield on a line for direct lightning stroke of 100 kA (highest in Finland), if the separation distance between the objects is less than 15 m. Also, at this separation distance of 15 m, any stroke above 100 kA will be intercepted by the trees. For a stroke of 15 kA, best shielding is provided if the height of a tree doubles the height of the distribution cable and they are separated by a clearance of not more 5 m.
2. Further analysis showed that lightning damage may occur on air cable due to locale damage at the point where direct lightning strokes hit the cable or pole. In case of shielding by nearby objects, lightning strokes to the neighboring objects, such as trees, poles or messenger can create flashovers to the cables and subsequently make holes to the cable jackets (screen).
3. After careful analysis of the lightning problems in distribution cable, various options provided for the improvements in lightning performance of the cable are:
    a. Replacement of the steel suspension with porcelain insulation suspension: The total lightning fault on the cable has been estimated to 4.29 faults/100km/yr for the steel suspension, as against 1.31 faults/100km/yr for porcelain insulator suspension. Thus, replacement of steel suspension with insulator suspension can limit the total lightning fault by about 70%
    b. Installation of shield wire above the cable: The analysis revealed the improvements in the lightning performance of air distribution cables by adding shield wire above the cables and grounding the shield wire at every pole. Thus, by placing shield wire on porcelain insulation of length 0.5 m, above the wooden pole and grounded at every pole with a grounding resistance of 100 Ω, the installation will increase the CFO to 325 kV. Hence the total lightning fault will reduce from 4.29 faults/100km/yr to 0.58 faults/100km/yr **.** The installation of shield wire directly above a distribution cable will lower the lightning related faults by 87%**.** Thus, it is worthwhile to have a shield wire install above the cables for the purpose of intercepting the incoming strokes and possibly suppressing the excessive lightning energy into the ground.
    c. Improvement in grounding systems: In order to achieve a very good lightning performance of distribution cables with the use of shield wire, good grounding scheme must be taken into consideration. For instance, this study shows that a decrease in grounding resistance from 1000 Ω to 100 Ω will be reduce the total lightning faults on the cable from 1.09 faults/100km/yr to 0.58 faults/100km/yr. This translates to about 47% reduction.
4. The ATP- EMTP simulation study has established that a lightning hit of an average lightning stroke in Finland (about 15 kA) to the wooden pole of distribution cable can create flashovers to the messenger and screen of the cable, thereby causing damage to the cable insulation.
5. Adequate grounding of the messenger wire will improve the lightning performance of the cable. However, the remaining overvoltage in excess of the cable's BIL can lead to a flashover on the cable and subsequently damage its insulation.
6. Direct bounding of cable's screen and messenger does not yield considerable reduction in the overvoltage stress on the air cable. A significant difference in the overvoltage stress was achieved when the bonded screen and messenger was grounded at every pole. There was only a marginal difference in the overvoltage stress when they were bonded and grounded and when they were grounded and not

bonded. It is therefore important to know that bonding of cable's screen and messenger is unnecessarily when the messenger is grounded.

7. By simulation studies, conditions of a direct lightning strokes to tree and flashovers to nearby cable with and without shield wire have been examined. It is revealed that the shielding by nearby trees is beneficial but not sufficient to subdue totally the lightning overvoltage stress on distribution cables. The study shows that the overvoltage performance of the cable can be affected more positively by the presence of the tree and grounding of messenger. However, great improvement in the surge performance of the cable can be achieved with the installation of shield wire above the cable so as to intercept the lightning strokes and suppress overvoltage stress to the ground.
8. Under the simulation conditions, the presence of a shield wire above the pole can protect the cable from direct and induced flashover from nearby trees/buildings /masts. Since the performance of shield wire is dependent in the grounding resistance, effort should be made to design low resistance grounding for the improved performance of the shield wire.
9. High surge impedance of the wooden pole can contribute to the higher overvoltage stress on the cable. For instance, the simulation study has shown that there could be a significant overvoltage stress reduction, of about 44%, on the cable by using a steel tower as against a wooden pole.
10. Much more overvoltage stress can be achieved by installing a shield wire on steel towers. Shield wire can intercept any direct hit that may damage the cable's insulation, and eliminate overvoltage increase due to reflections on the tower struck by lightning
11. Experimental study has been conducted and it was practically shown that lightning strokes to the neighboring objects, such as trees can create flashovers to the cables and subsequently make punctures in the cable jackets. Thus, lightning damage may occur on the cable insulation due to puncture at the point where there is a flashover from the nearby tree to the cable. In case of shielding by nearby objects, lightning strokes to the neighboring trees can create flashovers to the cables and subsequently make holes to the cable jackets (screen). Thus, enhancement in the insulation strength of the cables and the provision of adequately grounded shield wires can offer some significant improvements in the lightning performance of air distribution cables.

References

[1] IEEE working group on lightning performance of Electric Power Overhead Line, 2004, IEEE Guide for improving the Lightning Performance of Electric Power Overhead Lines, IEEE Std 1410TM- 2004, NY, 2004.

[2] Draft guide for improving the lightning performance of electric power overhead distribution lines, IEEE P1410 TM/D7, NY, 2010.

[3] P.Chowdhuri, Electromagnetic transients in power systems, (Research studies Press Ltd, Somerset, England, (1996)

[4] CIGRE Working Group 33.01 (Lightning), "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines" CIGRE 21 rue d' Artois – F-75008 Paris, October 1991.

[5] J. T. Tapio, M. Antti, Lighnting Observations in Finland, Report of Finnish Metrological Institute, Helsinki, No. 6, 2006

[6] M. A. Omidiora, Modeling and experimental investigation of lightning arcs and overvoltages for medium voltage distribution lines, Published doctoral thesis dissertation, Aalto University, Finland, 2011.

[7] S. Meyer, T. Liu, Alternative Transient Program (ATP) Rule Book, Canadian/American EMTP User Group, EMTP Center, USA.

[8] J. R. Marti, "Accurate Modelling of Frequency- Dependent Transmission Lines in Electromagnetic Transient Simulations," IEEE Trans. Power Apparatus and Systems, Vol. 101, pp. 147-155, 1982.

[9] A. Ametani, K. Matsuoka, H. Omura, Y. Naga "Surge Voltages and Currents into a Customer Due to Nearby Lightning", Electric Power Systems Research. Vol. 79, pp. 428–435, 2009.

[10] A. Ametani, T. Kawamura "Method of a Lightning Surge Analysis Recommended in Japan using EMTP", IEEE Transactions on Power Delivery, Vol. 20 No. 2, pp. 867-875, 2005.

[11] T. Noda, M. Sakae, S. Yokoyama "Simulation of Lightning Surge Propagation from Distribution Line to Consumer Entrance via Pole-Mounted Transformer", IEEE Trans on Power Delivery, Vol. 19, No. 1, pp. 442-444, 2004.

[12] F. E. Menter and L. Grcev, "EMTP-based model for grounding system analysis", IEEE Transactions on Power Delivery, Vol. 9, No. 4, October 1994, pp. 1838-1849.

[13] I.M. Dudurych, T.J. Gallagher, J. Corbett and M. Val Escudero, "EMTP analysis of the lightning performance of a HV transmission line", IEE Proceedings Generation *Transmission* and Distribution, Vol. 150, No.4, 2003.

[14] IEEE working group report: "Modeling guidelines for fast front transients". IEEE Trans. on Power Delivery,1996, Vol. 1, pp. 493-506.

[15] M. Darveniza, G.J. Limbourn, and S.A. Prentice, "Line design and electrical properties of wood". IEEE Trans. on Power Apparatus System,1967. 86. pp. 1344-1353.

[16] M. A. Sargent, M. Darveniza, "Tower surge impedance", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-88, No. 5, May 1969.

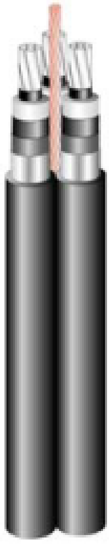
6. Appendix

Table A1
Conditions of the Simulated System in ATP-EMTP

20 kV distribution cable	Cables	2 phase covered conductor in air for Messenger and cable representation, and 3 phase covered conductor for Shield wire and Messenger and cable representation , with length 1000 m, 10 spans of 100 m segments on 11 wooden poles / steel towers)
		3 phase *Jmarti* frequency-dependent model with Freq.matrix, 500kHz, Steady state freq., 50 Hz. A soil resistivity of 2300 Ωm was assumed.
	Line termination	3 Single phase distributed parameter (*Clarke*) with Z = 400 Ω
	Cable suspension model	Steel suspension (radius 1.3 mm and length of 20 cm) represented with inductance, Ls3 = 6.98 nH.
		insulator suspension modeled with capacitance Cc6 = 50 pF [13-15] in parallel with flashover model, SW6
	Wooden pole model	Height, 8 m. Modelled with Parallel combination of Resistance, Rp , Capacitance, Cp and flashover switches (SW1 and SW2). Cp1 = 3.69 pF, Rp1 = 4.62 M Ω for 7.7 m length and Cp2 = 4.57 pF, Rp2 = 0.18 M Ω for the remaining length,0.3 m
	Steel tower model	Height, 8.1 m, radius, 0.25 m, model as single phase distributed parameters, *Clarke* with Zt = 169 Ω, and non linear footing resistance *Ri* as in Equation 3.6 [1].
	Shield-wire model	1 m above phase B, modeled with the MV lines.
		Grounded at every pole with inductance, L =15 µH and resistance, Rg = 10 Ω [6]
Tree	Parallel RC model with frequency dependent characteristic impedance, Z_c, such that R_{dc} = 830 kΩ and C = 4.18 pF at f = 1 MHz [11]	
Lightning stroke and flashover phenomena	Lightning current	15 kA (mean current in Finland [6]), positive polarity, with 1/ 70 µs wave characteristics, modeled with positive single-stroke Heidler-type [6]. Impedance of 400 Ω in parallel with lightning surge current [6], [14]
	Lightning positions	On the wooden pole/messenger wire/shield wire / steel tower/ At the top of the tree
	Flashover switch	As in Figure 2.2a, flashover switch (i.e. SW1, SW2, SW4, SW6, SW7) is a series combination of TACS' Voltage controlled switch and dynamic arc model.
	Dynamic arc model	Experimental arc parameter: arc length, l = 230 cm), U_o = 4.1 kV/cm, r = 0.0085/cm, A = 9 x 10^{-6}, B = 50000.
	Flashover points	Over wooden pole (SW1 & SW2), cable insulation (SW4), insulator suspension (SW6), from tree to messenger/shield wire (SW7)
Critical insulation flashover voltage (CFO) components under consideration	Air (600 kV/m), Wooden pole (330 kV/m), Porcelain insulator (180 kV), Cable insulation (125kV)	

REKA CABLES

DRYREX



Medium voltage cable AHXAMK-W

12/20 (24) kV
SFS 5636; HD 620-5F
For fixed outdoor installations

Conductor	Watertight, Circular, stranded aluminium
Special property	Longitudinal and radial waterproof
Fire class	F1 –
Conductor screen	Semiconducting compound
Insulation	PEX-compound
Insulation screen	Semiconducting compound
Watertightness	Semiconducting waterswellable tape against longitudinal water penetration.
Metallic screen	Aluminium/plastic laminate, which acts also as a radial water barrier.
Individual sheath	Black Weather resistant PE-compound
Earthing conductor	Circular, stranded copper
Twisting	Three sheathed phase conductors laid-up together with copper earthing conductor.
Min.handling temperature °C	-20
Max. conductor temperature °C	+90
Conductor shortcircuit temperature 5 s °C	+250

Product number	Size	Diameter [mm]	Weight [kg/km]	Maximum allowed bending radius in installation [cm]	Maximum allowed bending radius in final installation [cm]
06 224 31	3x70+35	65	2670	52	39
06 224 32	3x95+35	69	3050	55	41
06 224 33	3x120+35	73	3420	58	44
06 224 34	3x150+35	76	3780	61	46
06 224 35	3x185+35	80	4280	64	48
06 224 36	3x240+35	86	5440	69	52

Size	Maximum allowed bending radius in installation, phase conductor [cm]	Maximum allowed bending radius in final installation, phase conductor [cm]	Maximum allowed pulling force when pulling from conductors [kN]	Maximum allowed pulling force when pulling with cable stocking [kN]	Maximum DC-resistance of phase conductor +20 °C [ohm/km]
3x70+35	34	24	10.5	3.2	0.443
3x95+35	36	25	14.3	4.3	0.32
3x120+35	39	27	18	5.4	0.253
3x150+35	41	29	20	6.8	0.206
3x185+35	44	31	20	8.3	0.164
3x240+35	47	33	20	8.5	0.125

REKA CABLES

DRYREX

Medium voltage cable AHXAMK-WP

12/20 (24) kV
HD 620 S1/A2 Part 5F
For fixed outdoor installations

Conductor	Watertight, Circular, stranded aluminium
Special property	Longitudinal and radial waterproof
Fire class	F1 »
Conductor screen	Semiconducting compound
Insulation	PEX-compound
Insulation screen	Semiconducting compound
Watertightness	Semiconducting waterswellable tape against longitudinal water penetration.
Metallic screen	Aluminium/plastic laminate, which acts also as a radial water barrier.
Individual sheath	Black Weather resistant PE-compound
Earthing conductor	Circular, stranded copper
Twisting	Three sheathed phase conductors laid-up together.
Min.handling temperature °C	-20
Max. conductor temperature °C	+90
Conductor shortcircuit temperature 5 s °C	+250

Product number	Size	Diameter [mm]	Weight [kg/km]	Maximum allowed bending radius in installation [cm]	Maximum allowed bending radius in final installation [cm]
06 224 28	3x25	55	1565	44	33

Size	Maximum allowed pulling force when pulling from conductors [kN]	Maximum allowed pulling force when pulling with cable stocking [kN]	Maximum DC-resistance of phase conductor +20˚C [ohm/km]	Induktance, cables in triangle [mH]	Induktance, cables on level [mH]
3x25	3.8	1.1	1.2	-	-

Size	Operating capasitance [µF/km]	Current carrying capacity in soil, conductor +65˚C [A]	Current carrying capacity in air, conductor +90˚C [A]	Thermal shortcut current of conductor, 1 s, [kA]	Packing [m]
3x25	0.14	110	125	2.3	1000 K26

DRYREX

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