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Effect of the Time-Varying Soil Resistivity on the Performance of the Protective Devices under the Electromagnetic Fields from Lightning

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Abstract

Background/Objectives: Transients in the overhead power lines due to lightning events can be caused by both direct and indirect strokes. Both direct and indirect events can cause severe issues in the power system. **Methods/Statistical Analysis:** The frequency of the indirect lightning return strokes is more when we consider the lightning studies on the overhead lines considering the height of the present distribution and transmission lines. Lightning-induced voltages on the overhead transmission lines have been computed using the finite-difference time-domain method. A source of lightning surge wave on power transmission lines is modelled as a double exponential wave using Modified Transmission Line with Exponential current decay (MTLE) model. Computation of overvoltage caused by lightning waves is calculated for single conductor lines with and without considering the soil reflections taking into account the dynamic characteristics of soil under lightning conditions. **Findings:** Computations are carried out for the various configurations of multi-conductor transmission lines. The effectiveness of the protective devices such as shield wires is also studied here. The surge arrester modelling is carried out and the design parameters for these protective devices are finalised after optimization. MATLAB and PSCAD software are used for simulation. Triangular configuration gave a better response to lightning than the horizontal and vertical configuration. **Applications/Improvements:** A 3D approach on the problem with use of COMSOL will give a better insight on the field pattern.

Keywords: Kaizen, Manufacturing Organizations, Manufacturing Performance, Total Productive Maintenance (TPM), Total Quality Management (TQM)

1. Introduction

The phenomenon of lightning is explained as a discharge of the cloud to the ground. The cloud and the ground form the two parallel plates of a gigantic capacitor and air in between acts as the dielectric medium. The lower part of the cloud has negative charges and hence it forms the negative plate of the capacitor. The earth forms the positive plate as its gets positively charged due to induction. The puncture of the dielectric medium, air is required for the lightning discharge to reach the ground. For the breakdown of air, the critical electric field required is 30 kV/cm peaks at Standard Temperature and Pressure (STP) conditions. But an electric field of 10 kV/cm is sufficiently enough for the breakdown of air because of the higher altitudes (low pressure) and moisture content. So, the objective of a good line design is to reduce the number of outages or faults caused due to lightning discharges.

The accurate computation of the lightning induced overvoltages is essential for overhead transmission lines

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for evaluation of the lightning performance of these lines and for the optimization of the characteristics, number and location of the protective devices (shield wires, surge arresters, etc.).[1]

Transients in overhead transmission lines occur due to either direct or indirect lightning strokes. Since the frequency of the indirect strokes are more for these lines, the paper focuses on indirect lightning return strokes in spite of the high probability of flashover of the insulation when a direct lightning strike occurs.

The computations on a section of a 110 kV single phase lines are done and the studies are further extended considering the soil parameters. Various three phase configurations are also taken for the study. The paper also deals with the presence of the lightning protective devices and also designs the optimal characteristics for them. The paper is organized as follows. Section II describes the models for the lightning stroke, transmission line and soil respectively. Section III illustrates the lightning effects on the transmission lines and their analysis. Section IV depicts the performance improvements in the presence of lightning protection devices such as the shield wires and surge arresters. This section also calculates optimal design parameters for shield wires and surge arrester.

2. Modelling of Lightning Stroke, Transmission Line and Soil

2.1 Lightning Return Stroke Modelling

Transient is a transient high current electric discharge whose effects can be in kilometre range. Lightning discharges are of many types like those which occur between clouds, within the cloud, cloud and ground, and cloud and upper atmosphere. Practically the study of cloud to ground discharge is of utmost significance as this can cause human injuries, death, disturbances in the communication and power networks, etc.). Lightning return strokes have the highest electromagnetic field associated with it generally. Only the return stroke associated with the cloud to ground lightning has been considered in this paper.

There are four models available for the modelling of lightning impulse namely gas dynamic model, electromagnetic model, distributed circuit model and engineering model. The engineering model is chosen for the lightning return stroke modelling as this is the most suitable for return strokes. The MTLE model is described by (1). Here the return stroke current magnitude decreases exponentially while propagating up the channel. The lightning current is given by (2), the Heidler's surge equation.

$$i(z',t) = i\left(0, t - \frac{z'}{v_p}\right) e^{\frac{-z'}{\lambda}}; z' \le v_p t$$

$$i(z',t) = 0; z' \ge v_p \qquad (1)$$

$$i(0,t) = \frac{I_p \left({}^{t}/_{\tau_1}\right)^n}{\eta\left(1 + \left(\left[{}^{t}/_{\tau_1}\right)\right]^n\right)} e^{-t/\tau_2} \qquad (2)$$

Here, I_p is the peak amplitude of the channel-base current, τ_1 is the front time constant; τ_2 is the decay time constant. n is the exponent which varies between 2 to 10.v_p is the velocity of propagation of the return-stroke. λ is the decay constant which allows the current to reduce its amplitude with height. η is the amplitude correction factor given by (3).

$$\eta = e^{\left[-\left(\frac{\tau_1}{\tau_2}\right)\left(n\frac{\tau_2}{\tau_1}\right)^{(1/n)}\right]} \qquad (3)$$

A standard lightning impulse current of 34kA 8/20μs with a return stroke velocity of 2x10[8] m/s is modelled using the MTLE equation as shown in Figure 1.

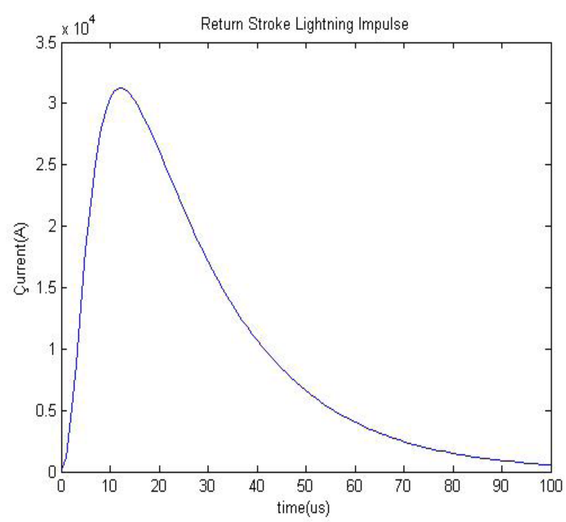


Figure 1. Lightning impulse current of 34kA 8/20μs with a return stroke velocity of 2x10[8] m/s.

2.2 Transmission Line Modelling

Electric power transmission is the bulk transfer of electrical energy from generating power plants to the electrical substations located near the load demand regions. The interconnection of the transmission lines becomes the transmission network. Transmission lines may be single phase AC, three phases AC or DC. It can be laid underground or overhead. An overhead transmission line f 110 kV is modelled here using the distributed model of the transmission lines since lumped parameter approach is not feasible for long transmission lines. The transmission line is modelled using series resistance, series inductance, shunt capacitance and shunt conductance. The factors affecting the transmission line parameters are voltage level, line length, type of conductor used, number of conductors, spacing of the conductors, etc. The transmission line parameters are obtained by solving the transmission line equations (4). The distributed parameter model of the transmission line is as shown in Figure 2.

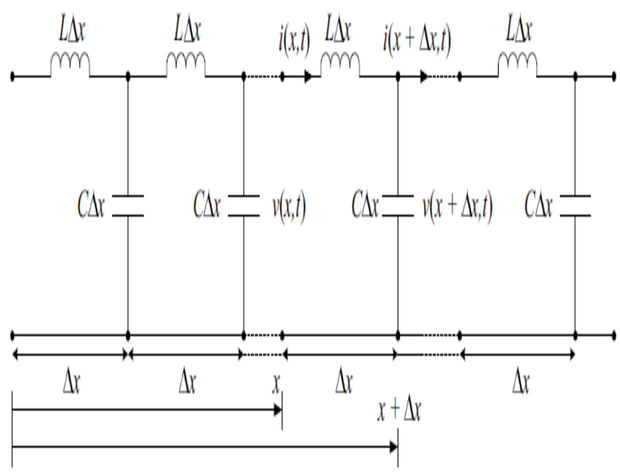


Figure 2. Transmission Line Model.

$$\frac{dV}{dz} = ZI$$
$$\frac{dI}{dz} = YV \tag{4}$$

The computations of the voltages and currents at different points on the line necessitate the line to be discretized into several sections. Since the voltages are to be found at different instants time discretization will be advantageous. Finite Difference Time Domain (FDTD) method can be used for obtaining the solutions of such problems. FDTD method is a convenient method to solve electromagnetic coupling equations in time domain.[2] Here, discretization in time (1μs) and space (20 m) is done on the 110 kV transmission line.

2.3 Soil Modelling

When the lightning strikes the ground and if the electric field produced by the lightning current in the soil is greater than the critical electric field of the soil, soil ionization takes place. As the injected current increases, the soil resistivity decreases and hence the soil resistance decreases with the increase of current till the current reaches its peak. This proves the dynamic characteristics of the soil. The non linear characteristics of the soil is described by the three zones namely the ionization one, the deionization zone and the non ionization zone as shown in Figure 3. Region (1) represents the ionization region, region (2) represents the deionization region and region (3) represents the non ionization region. Ionization zone is the area around the point where the lightning strikes and ionization takes place. The soil tries to retain its original state when the current decreases from the peak value. This region is known as the deionization region.[3]

Variable geometry and variable resistivity methods can be used for the modelling of soil. Variable resistivity method has been used here. In the variable resistivity model, the resistance of the soil decreases for increasing current value with decrease of soil resistivity if the electric field goes beyond the soil critical breakdown field. The value of the soil critical electric field varies between 300 kV/m and 1000 kV/m depending on the nature of the soil. The resistivity of the ionized region decays exponentially. The ionization process is actually independent of the field intensity. Only the starting of the ionization occurs with the field intensity. The ionization process is governed by its own dynamics above a critical value of current density J_c. This results in the decrease in the soil resistivity with time being independent from the local electric field. The total resistance of the soil is given by (5).

$$R_g(t) = R_{dc}(t) + R_{ion}(t) + R_{deion}(t)$$
$$R_{dc}(t) = \frac{\rho_0}{2\pi r_{max}}$$
$$R_{ion}(t) = \frac{\rho_{ion}(t)}{2\pi}\left(\frac{1}{r_0} - \frac{1}{r(t)}\right)$$
$$R_{deion}(t) = \frac{\rho_{deion}(t)}{2\pi\left(\frac{1}{r(t)} - \frac{1}{r_{max}}\right)} \tag{5}$$

Here, R_{dc} is the DC resistance of the soil, R_{ion} is the ionization resistance and R_{deion} is the deionization resistance. ρ_0, ρ_{ion}, ρ_{deion} are the non ionized soil resistivity, ionized soil resistivity and the de-ionized soil resistivity respectively.

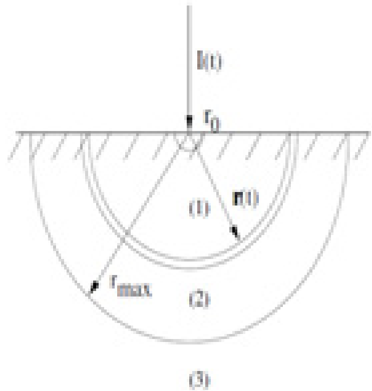


Figure 3. Soil Ionization.

3. Results and Analysis

3.1 Single Phase

A 110 kV transmission line is struck by a return stroke lightning pulse of 34 kA peak. The front time and the tail time are 8 microseconds and 20 microseconds respectively which are the specified front and tail time for a standard lightning current impulse. The return stroke velocity of the impulse is 2×10^8 m/s. This pulse on striking the line induces an overvoltage of 64 kV as shown in Figure 4. The end to end reflections along the line are not considered as only a section of the line is under consideration. Reflections from the soil are taken into account by considering soil of finite conductivity.[4] For various current peaks, different values of over voltages are obtained and the trend followed is in the increasing order with the increase in the current value. This is evident from Table 1.

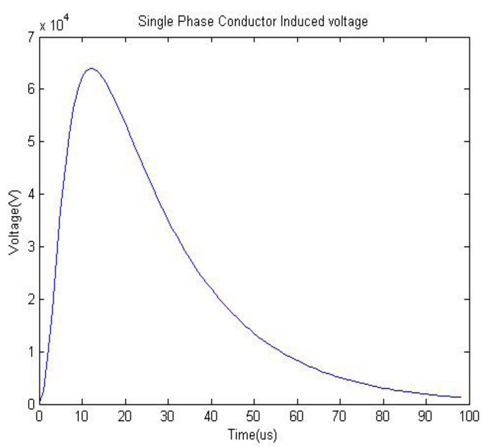


Figure 4. Induced overvoltage on a 110kV single conductor transmission line on application of a 34kA lightning impulse.

Table 1. Induced overvoltage's for different current peaks

Current Peak (kA)	Peak Induced Voltage (kV)
34	64
25	47
10	19

The dynamic resistance of the soil changes the characteristics obtained without considering the ionization effects of soil. Dynamic resistance calculation is done using (5). The reflection coefficients are computed so as to obtain the first reflection and the significant subsequent reflections which add to the total induced voltage on the line. The voltage is obtained from the field calculations done at different points on the line and ground. The total induced voltage has a second peak after the time taken by the lightning pulse to travel twice the distance as the height of the transmission line. This happens because of the first reflection which is highly significant. The second peak has a significant value of overvoltage which gets neglected when the soil reflections are not considered. The effect of these reflections decreases as time passes.

On the point of striking on the ground, the highest value of electric field is obtained and the peak value is 3.3×10^5V/m as shown in Figure 5. A portion of this gets reflected and strikes on the transmission line. The amount of reflection depends on the vertical reflection coefficient of the soil. At the point of striking of the line, there will be incident field and its subsequent reflections from the soil. The subsequent reflections have their respective time delays depending upon the height of the transmission lines. Here, the incident field on the line is found to have a peak value of 1.6×10^5V/m. The first reflection from the ground strikes the line after a certain time delay as it has to travel twice the height of the transmission line. The subsequent reflections have lesser values of electric fields and they have lesser contribution towards the total electric field at a point. Figure 6 shows the total field at the point of striking on the line considering all the soil reflections.

The electric fields at different points on the line can also be obtained as a 2D plot. To plot the electric fields at different points on the line at different time instants, 3D plots have been useful. 3D plot of the total fields on the line at different points and different time instants are also obtained Figure 7a. The plots for the incident and reflected fields on the line are also obtained in Figure 7b and Figure 7c.

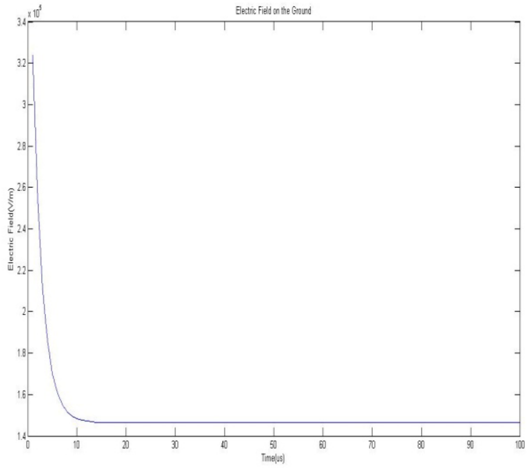


Figure 5. Electric Field on the point of striking on the ground.

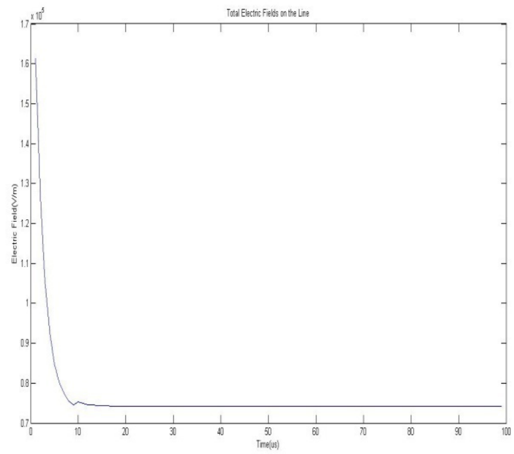


Figure 6. Total field on the line.

3.2 Three Phase

For three phase AC transmission lines, various configurations say, vertical, horizontal and triangular configurations are implemented here and they are made to be struck by the return strokes. In three phase lines, the effect of coupling between the conductors should also be taken into account as in the reported article.[5] Here also, 34 kA, 8/20 µs lightning return stroke with a return stroke velocity of $2x10^8$ m/s is applied.

3.2.1 Horizontal Configuration

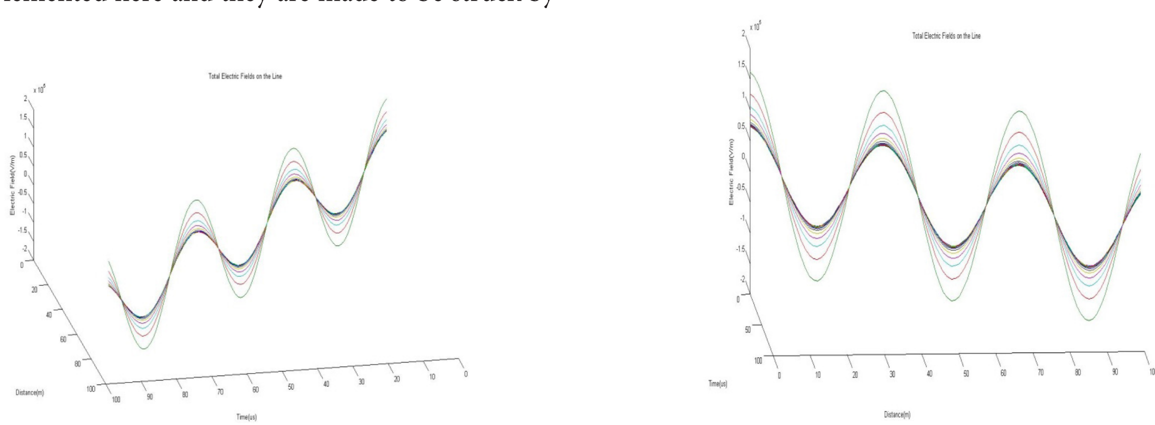
Three conductors are equally spaced and they all lie in the same horizontal plane. Here, the height of the conductors is 20 m and the spacing between them is 11m. The overvoltage obtained on the conductors in this configuration has a peak value of about 87 kV as in Figure 8.

3.2.2 Vertical Configuration

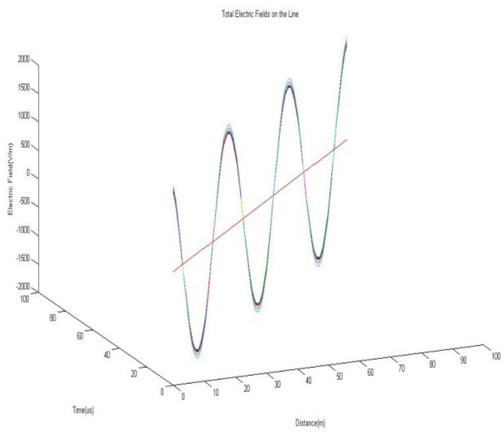
Three conductors are spaced equally in a vertical plane. The heights of the conductors considered here are 20 m, 27.2 m and 34.4 m. When the lightning strikes on the lowest conductor in this configuration, an overvoltage of peak 69 kV is found Figure 9.

3.2.3 Triangular Configuration

Three conductors are placed such that two conductors are at the same height and the third conductor which lies in between the other two conductors is placed at a lower height. The spacing of the middle conductor with the top two is same. The heights of the conductors considered here are 20 m, 12 m and 20 m. The spacing between the conductors is 11 m. When the middle conductor in this configuration is subjected to the lightning surge, an overvoltage having a peak value of 37 kV is obtained as is evident in Figure 10. This configuration has anatural shielding better than the other configurations. Hence, the overvoltage calculated here is the minimum in comparison with the overvoltages of conductors in other configurations.



(a) (b)



(c)

Figure 7 **(a).** 3D plot of the total fields (b). 3D plot of the incident field (c). 3D plot of the first reflected fields at different points at different time instants on the line.

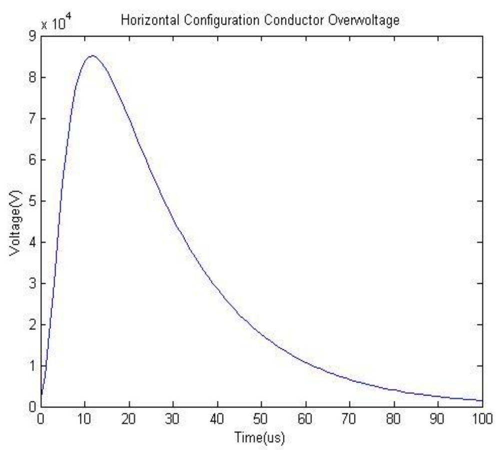


Figure 8. Horizontal Configuration Conductor over voltage.

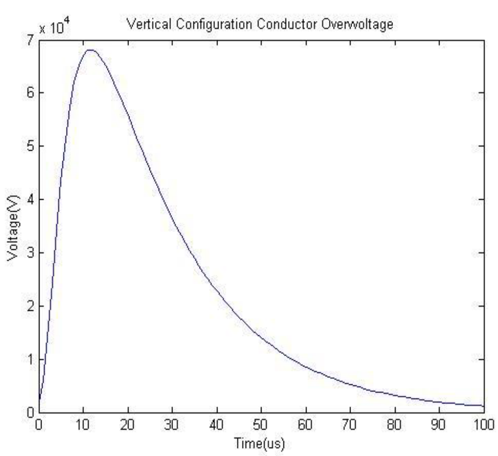


Figure 9. Vertical Configuration lowest conductor over voltage.

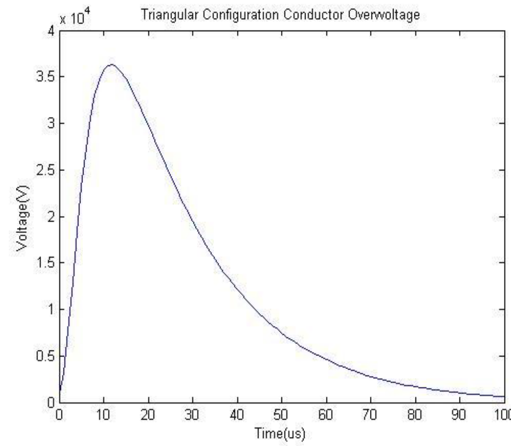


Figure 10. Triangular configuration middle conductor over voltage.

4. Effect of Protective Devices

A typical power system consists of power plants, power grid (power network) and the power consumers. Lightning constitutes to a significant cause of power system fault. When the lightning strikes on a phase conductor of the transmission line, the lightning current encounters the surge impedance of the conductor which results in development of overvoltage on the conductor. This overvoltage propagates to the substation along the transmission line in wave form. This wave can damage the electrical equipments and facilities in substation. Line flashover can also take place. Shielding failure and backstroke events happen due to direct lightning stroke on HV, EHV and UHV transmission lines. A wide range of protective devices are used for the protection of the power system. A lighter conductor called the shield wire is placed above the main power conductors in high tension power transmission lines which is a protective device. Lightning protection arresters are installed at places where wires enter a structure so that it prevents damage to the electronic equipments inside and also ensuring the safety of the individuals near these equipments.

4.1 Shield Wires

Shield/ground wires are installed at proper positions to act as lightning protective devices for the overhead transmission lines. They suppress the surge voltages across the transmission lines. The effects of these shield wires are more effective in the three phase configurations.For a vertical configuration a shield wire is installed at a particular height above the highest conductor. Horizontal conductors are shielded by two shield wires placed above the conductors at a particular angle. The placement of these protective wires significantly reduces the peak overvoltage's induced by the lightning wave.

Optimisation of the shield wire constraints are done so as to achieve maximum effectiveness in cost and performance. A set of shielding constraints are derived so that it achieves effective shielding against lightning for all of the phase conductors of an overhead transmission line in relation to earth-wire placement. The shielding constraints are obtained such that after the determination of the earth-wire position for a critical lightning stroke current, the shielding of phase conductors should still be maintained for lightning stroke currents greater than the critical value. In the optimal shielding design procedure, the cost function relating to earth-wire position(s) is minimised subject to shielding constraints and specified clearance constraints. The optimisation is carried out as in the article.[6] The cost function is given by (6).

$$CE(d_0,\theta_0)=C_0\,[d_0\cos(\theta_0) + XD_{P0} - d_0\sin(\theta_0)] + F_0 \quad (6)$$

Here, P_0 is the phase conductor nominated for defining the shielding angle θ_0, D_0 is the distance between P_0 and earth wire, C_0 is the cost coefficient relating to the earth-wire positions, and XD_{P0} is the perpendicular distance from phase conductor *Po* to the centre line of the tower. From this cost minimization function, the results for the optimal shielding design for the horizontal and vertical configuration of three phase conductors which are considered previously are obtained.

4.1.1 Horizontal Configuration

Two wires are placed above the conductors at a particular angle for shielding. The optimal design calculations for horizontal configuration results in a shield wire height of 28.2 m and shield wire spacing of 14.47 m with a shielding angle of 24.3°. With this shielding design, the overvoltage has reduced to 44 kV peak from 87 kV peak without the shielding Figure 11.

4.1.2 Vertical Configuration

A single shield wire conductor is placed on the top of all the other conductors for shielding in vertical configuration. From the optimal design computations for the vertical configuration of conductors, the single shield wire is placed above all the phase conductors at a height of 40.4 m so that the peak overvoltage has reduced from 69 kV without shielding to 52 kV on account of shielding. This is shown in Figure 12.

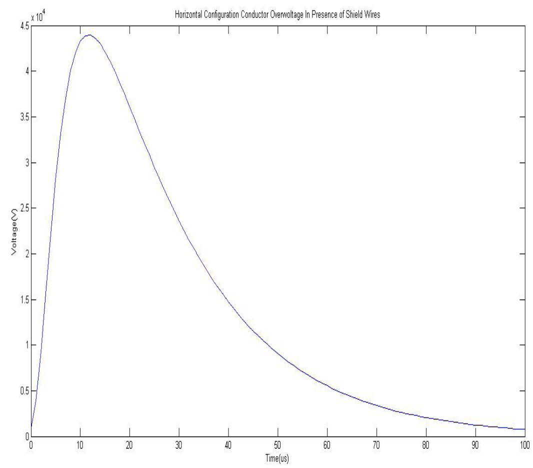


Figure 11. Horizontal Configuration conductor over voltage in the presence of shield wire.

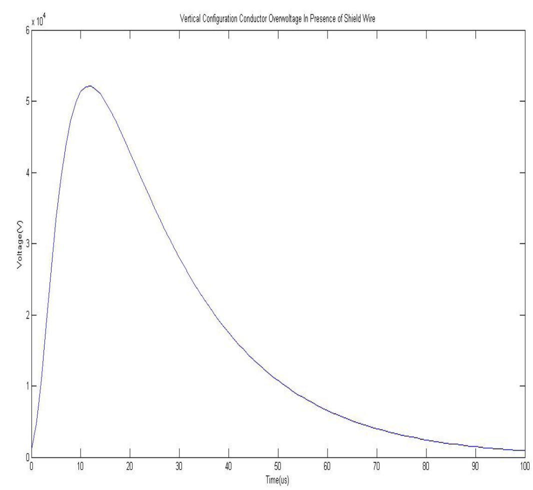


Figure 12. Vertical configuration lowest conductor overvoltage in the presence of shield wire.

4.2 Surge Arrester

The surge arrester is a protection device which diverts the surge current to ground and limits the surge voltage on the system so that the system remains unaffected by the surges. The IEEE lightning model of the surge arrester[7] is as shown in Figure 13.

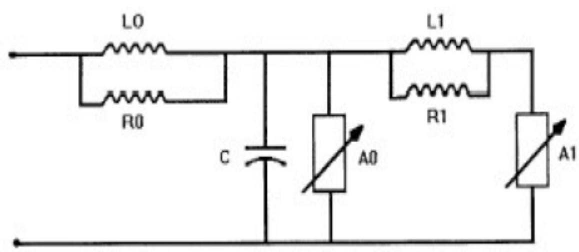


Figure 13. IEEE Model of Surge Arrester.

This is a frequency dependent model which has two sections of non linear resistance A_0 and A_1 which are separated by an R-L filter. It offers low impedance for slow surges. A_0 has a higher voltage for a given current than A_1. L_0 is the inductance associated with the magnetic field in the immediate vicinity while R_0 avoids the numerical instability.

The selection of the surge arrester is based on the type of equipment to be protected, the location of the equipment and the expected duty of the surge arrester. The two major steps in selecting a surge arrester are to match the electrical characteristics and the mechanical characteristics. The major consideration for selecting the surge arrester type is the voltage rating of the arrester. This also includes the overvoltage factors. The voltage across the arrester increases as the time to the peak of arrester current reduces for fast front transients. The voltage reaches its peak before the current peak. Arrester with higher rating improves the Temporary OverVoltage (TOV) capacity and system voltage stress handling capacity. But, it reduces the margin of protection provided by the arrester for a given protective level. A compromise is required between the protective levels, temporary overvoltage capacity and energy absorption capability. Hence, optimisation of the surge arrester parameters is necessary.

The design equations for the surge arrester are given by (7).

$$L_0 = {}^{0.2d}/_{n}\ \mu H$$
$$R_1 = {}^{65d}/_{n}\ ohms$$
$$L_1 = {}^{15d}/_{n}\ \mu H$$
$$C = {}^{100n}/_{d}\ pF \tag{7}$$

Here, n is the number of columns and d is the estimated height.[7] The optimization for these design parameters are carried out and the values are L_0= 0.5 micro henries, L_1 = 30 micro henries, R_1 = 165 ohms and C = 38 pico farads.

5. Conclusion

FDTD simulation of a transmission line struck by a return stroke lightning channel at different points considering the reflections is done and the results are obtained. Studies are carried out for different current peaks. The computation of lightning induced overvoltages on the overhead transmission lines are of importance since these overvoltages can cause a lot of issues in the system. Lightning return stroke is modelled as an upward propagating wave. Reflections are taken into account considering soil of finite conductivity. It has been found that the induced voltage on the line increases with the increase in the peak value of the lightning current. Induced voltages are calculated for different three phase configurations as well.

Effect of shield wires and surge arresters are also studied. Optimal shielding design is obtained for the different three phase configurations of conductors and the induced voltages have considerably reduced in the presence of the shield wires. Surge arrester modelling and optimisation are also carried out.

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