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Calculation of Surge Voltages on the Overhead Lines Due To Direct and Indirect Lightning Impulse

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ABSTRACT:-The purpose of this thesis is to describe how surge magnitudes are calculated. In the transmission line systems due to direct and indirect lightning strokes. In order to identify the magnitude of voltage due to direct lightning source, we have some formulae which provides the approximate value. For the magnitude value due to indirect lightning strokes, we use two methods namely RBF-FDTD METHOD which uses deep learning techniques in order to study the detailed concept of coupling between field to transmission lines and the other method is the Modelling of simulation system in which the coupling system Approximations are taken and considered as a block at the time of simulation. This thesis also describes about the calculation of outage rate and its Geometrical analysis.

KEYWORDS: Surge magnitude, Radial basis function, Finite difference time domain

I. INTRODUCTION

1.1 Origin of Overvoltage

There are two types of overvoltage in a power system: lightning impulse and switching impulse. Switching impulses are triggered by changes in the system's operation. When lightning strikes power system equipment, it causes lightning impulses.

Negative and positive lightning are the two forms of lightning that can be triggered based on the type of electrical discharge, with the latter being about 10 times greater than the former. Cloud to Ground (CG), Ground to Cloud (GC), and Cloud to Cloud (IC) are the three general classifications based on charge flow. Direct lightning strikes on power systems are triggered by CG and GC, while induced lightning effects in power systems can be caused by any kind of lightning.

1.2 Lightning Stroke expected points in a system

Since the effects of lightning strokes can be seen in the power system equipment, earthing of all power system equipment, including transmission line poles, is needed. The transmission line poles' footing resistance and the earth mat of the substations should be held at low values to achieve better protection from lightning.In order to achieve maximum protection, the earth resistance is usually kept below 10Ω.The earth resistance is maintained about 1-2Ω in some high altitude areas.Transmission cables, poles, overhead lines near the substation, and the substation itself are the places where lightning strikes are most likely to occur.

1.2.1 Transmission Line

Electrical transmission system is adopted to transfer electricity from generating station to the load centres, electricity travels around hundred to thousands of kilometres through these transmission lines. Here the voltage is raised 400kv or other high value with the help of power transformers to reduce the losses.Lightning strikes transmission lines in both direct and indirect (induced) ways. The fig 1.5 represents the 500kv transmission line system and earth resistance at their respective places.

$R_{E,P}$ is the earth resistance with at the transmission line pole

$R_{E,S}$ is the resistance of earth at sub-station level

1.2.2 Pole Top

Poles are used to link transmission cables from the source to the destination. There's a risk that lightning could strike the tops of poles, inducing lightning surges in the phase conductors.The poles must be grounded in order to prevent the transients in the system. The

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conduction between the pole and the overhead line cables is stopped with the help of high insulations which prevents the cables from direct contact to the pole

1.2.3 Overhead lines near to substation

The worst-case scenario for a lightning strike is this. Both the substation and the transmission are damaged when lightning hits overhead lines near the substation. If the lightning protection systems fail to stop it, it has the potential to cause significant damage to the system equipment. The magnitude of the surge current is divided into two parts and drives into the system.

1.2.4 Sub-station

Lightning protection systems have been installed in the substations. To divert the direction of surge to the ground, all of the equipment in the substation is grounded. In order to divert surges to ground, various forms of earthing and grounding practises are used. In fig 8 the lightning rod is taken as a lightning protection scheme.

II. INDIRECT LIGHTNING STROKE MAGNITUDE CALCULATION

2.1 Modelling of simulation system

Inorder to identify the Induced effect of lightning on the transmission line system we have to identify the effect of electromagnetic fields in the overhead cables

Cloud to cloud(IC) lightning often serves as an indirect lightning stroke in certain high-altitude regions, influencing system parameters.

2.1.1 Calculation of EMF across the line

Inorder to calculate the electromagnetic fields(EMF) the current channel is considered as a function of altitude and time I(z',t). The Induced lightning current is a function of current obtained on the basis of current channel I(o,t) As it is the only form of current which can be measured directly

$$i(0,t)=I_0\left(e^{(-\alpha t)} - e^{(-\beta t)}\right)$$

I_0 – magnitude of surge currents produced due to Induced effect of lightning

α, β are constants

$$i(z',t) = i(0, t - z'/v)e^{(-z'/\lambda)}$$

The model that describes the relationship between indirect lightning and phase line fields is used to calculate the emf equation of the lightning return stroke.We must consider the Maxwell theory in both scalar and vector potentials in order to obtain the horizontal and vertical components of the emf equation.

$$\varphi = \frac{1}{4\pi\varepsilon_0}\int_{(V)} \frac{t-R/C}{R} dV$$

$$\bar{A} = \frac{\mu}{4\pi}\int_{(V)} \frac{\bar{J}(t-R/C)}{R} dV$$

When there is a known potential in the system, the electric field is calculated by using the following equation

$$\bar{E} = -\text{grad}\ \varphi - \frac{\partial \bar{A}}{\partial t}$$

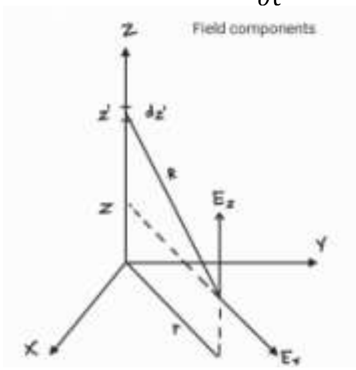

Fig: Field component coordinate system

By considering the ground as an reference conductor, we derive the equations of electromagnetic fields of horizontal and vertical dipoles. the overall fields consists of three different components of fields they are

Electrostatics: it consists of the field effects of static charged particles and it is directly proportional to integral of current

Electrostatics ∝ ∫ current

Induction: this effect changes with the change in currents of the system

Induction ∝ current

Radiation: this effect changes with the rate of change of current with respect to time

Radiation $\propto \frac{\partial(\text{current})}{\partial t}$

The overall vertical dipole EMF (E_Z) is written as

$E_z = E_{z1} + E_{z2} + E_{z3}$

Where

$$E_{z1}(r,z,t) = \frac{1}{4\pi\varepsilon_0}\int_{-z'}^{z'}\left(\frac{2(z-z')^2-r^2}{R^5} e^{(-z'/\lambda)}.\int_0^t i(0,\tau - z'V - Rc)d\tau\right)dz'$$

$$\mathrm{E}_{z2}(\mathrm{r},\mathrm{z},\mathrm{t}) = \frac{1}{4\pi\varepsilon_0}\int_{-z'}^{z'}\left(\frac{2(z-z')^2-r^2}{cR^4}e^{(-z'/\lambda)}.i(0,t - z'/V - R/c)\right)dz'$$

$$E_{z3}(r,z,t) = \frac{1}{4\pi\varepsilon_0}\int_{-z'}^{z'}\left(\frac{r^2}{c^2R^3}e^{(-z'/\lambda)}.\frac{\partial i(0,t-z'/V-R/c)}{\partial t}\right)dz'$$

For E_r, the EMF of horizontal dipole is written as

$E_r = E_{r1} + E_{r2} + E_{r3}$

Where

$$E_{r1}(r,z,t) = \frac{1}{4\pi\varepsilon_0}\int_{-z'}^{z'}\left(\frac{3r(z-z')}{R^5}e^{(-z'/\lambda)}.\int_0^i i(0,\tau - z'/V - R/c)d\tau\right)dz'$$

$$E_{r2}(r,z,t) = \frac{1}{4\pi\varepsilon_0}\int_{-z'}^{z'}\left(\frac{3r(z-z')}{cR^4}e^{(-z'/\lambda)}.i(0,t - z'/V - R/c)dz'\right.$$

$$E_{r3}(r,z,t) = \frac{1}{4\pi\varepsilon_0}\int_{-z'}^{z'}\left(\frac{r(z-z')}{c^2R^3}e^{(-z'/\lambda)}.\frac{\partial i(0,t-z'/V-R/c)}{\partial t}dz'\right.$$

Where i(0,t) is the current at channel base

C = 3×10^8m/s (speed of light)

R=$\sqrt{(r^2+(z-z')^2)}$

The value of z is altitude(taking ground as reference) where the field is calculated (z=h)

In order to obtain the value of time t we integration limit is set w.r.to z

$$z'/v + \sqrt{(r^2+(z-z')^2)}/c = t$$

2.1.2 Identification of overvoltage magnitude using EMF

Inorder to design a coupling system whichcalculates the induced overvoltages due to indirect lightning we have to project the components of Er on the x-Er axis. This is done by the following equation which provides relation between Ex and Er.

$$E_x(r,z,t) = E_r(r,z,t)\,(L/2 - x)/r$$

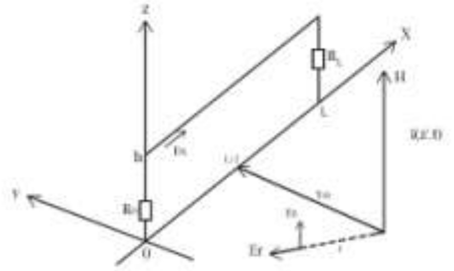

Fig: Geometry of surge calculations

The field parameters are calculated for ground with high conductive property with the steps

Step 1: vertical parameters of the field

Step 2: freq domain vertical components using DFT

Step 3: freq domain horizontal components using transfer function

$$W(j\omega) = \frac{E_r(j\omega)}{E_z(j\omega)} = \left(\varepsilon_r + \frac{\sigma_{gr}}{j\omega\varepsilon_0}\right)^{-\frac{1}{2}}$$

The above equation includes permittivity and conductivity of the ground

Step 4: time domain horizontal components using IDFT

The induced voltage due to indirect lightning stroke is calculated with the help of modifications in the normal form of travelling wave equation, this considers only a certain portion of the transmission line, this makes a modification in the system basic equations

$$\frac{\partial u^s(x,t)}{\partial x} + L'\frac{\partial i(x,t)}{\partial t} = E^i{}_x(x,h,t)$$

$$\frac{\partial i(x,t)}{\partial x} + C'\frac{\partial u^s(x,t)}{\partial t} = 0$$

The equation in time domain are as follows

$$u^s(t,x) = v(t-\tau_x) + w(t-\tau_{l-x})$$

$$Z_c i(t,x) = v(t-\tau_x) - w(t-\tau_{l-x}) + Z_c\frac{1}{L}\int_0^t E^i{}_x(t)dt$$

The surge calculation is done in MATLAB which intakes the following parameters as an input to the code

(1) Io – magnitude of current channel , alpha and beta , damping constant
(2) H – height of surge channel, Yo, L, h, r

$$r = \sqrt{Y_0{}^2 + \left(\frac{L}{2} - (p-1).\frac{L}{N}\right)^2}$$

(3) N – number of sections of partition line, description line
(4) T – time required to calculate the parameters
(5) Calculation of magnitude of overvoltage

It take the numerical value of sections present in the transmission line system

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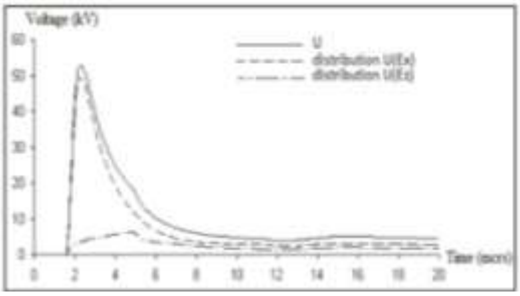

Fig: the induced voltages at x=0m

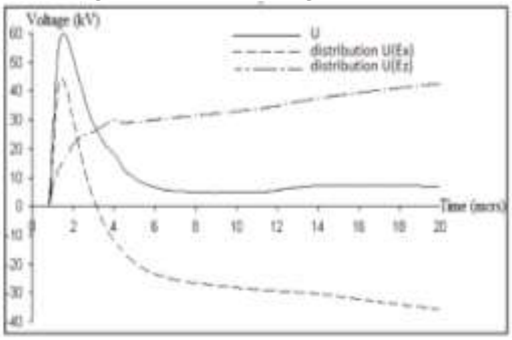

Fig: The induced voltage at x=250m

2.2 Direct formula for magnitude of induced voltage

(refer fig 2.1) whenever an indirect lightning strikes nearby the transmission line system, the surge Ui will be injected into the system due to the coupling of magnetic field H. there is a direct formula which provides us with the approximate value of the induced voltage surge, it was given by Rusck.

$$U_{max,i} = Z_0 i_b \frac{h}{x}$$

Where
Z_0 – mutual impedance (between line and strike point)
h – height of line with respect to the ground
x – displacement between line and strike point
i_b– surge current induced in the transmission line
Modified version of this formula is given as

$$U_{max} = \frac{z_0 I_0 h}{d}\left(1 + \frac{1}{\sqrt{2}}\frac{v}{c}\frac{1}{\sqrt{1-\frac{1}{2}\left(\frac{v}{c}\right)^2}}\right)$$

where
d – displacement between line and strike point
v – return stroke velocity
c = 3×10^8m/s (speed of light)

2.3 RBF-FDTD method

This approach is used to solve the numerical equations in the coupling of the field produced by the lightning to the transmission line model. This method's output is the precise value of the lightning-induced overvoltage.The radial basis function and the finite difference time domain method are integrated in this method.It provides comprehensive data on electromagnetic coupling in different phases of the power system (distribution and transmission phase).

2.3.1 Introduction to FDTD assumptions

The Maxwell's equations are used in the finite difference time domain system to formulate the upcoming electric and magnetic field values. Based on the initial parameters, these formulae are used to predict the upcoming electric and magnetic field values.
The initial x-t plane must be used to construct a finite difference grid, which divides the overall plane into equipotential grids of steps, respectively $\Delta x$and Δt.By considering The first and second order spatial derivatives of the function f(x,t) at a grid point, as well as the second order estimates of centred difference, are provided below.

$$\frac{\partial}{\partial x} f(x,t) = \frac{f_{k+1}^{n} - f_{k-1}^{n}}{2\Delta x}$$

The second derivative of the above equation is given as

$$\frac{\partial^2}{\partial x^2} f(x,t) = \frac{f_{k+1}^{n} - 2f_k^n + f_{k-1}^{n}}{\Delta x^2}$$

The first order time related derivative is given as

$$\frac{\partial}{\partial t} f(x,t) = \frac{f_k^{n+1} - f_k^{n-1}}{2\Delta t}$$

2.3.2 RBF FDTD formulation

The m^{th} order derivative of a function with respect to x, at a point x_i, is approximated by the summation given below

$$\frac{d^m f}{dx^m}|_{x_i} = \sum_{j=1}^{n} w_{i,j}^m f(x_j)$$

The radial basis function is given as

$$f(x) = \sum_{j=1}^{n} \lambda_j \phi(\|\underline{x} - \underline{x}_j\|) + \beta$$

Which includes RBF, $\|.\|$ is considered to be the norm.
We use multiquadric RBF to get the derived approximations in a one dimensional (1D) domain.

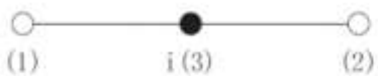

Fig: Support points for i in 1D domain
The first and second order spatial derivatives of finite difference and the first order derivative of temporal finite difference are given as

International Journal of Advances in Engineering and Management (IJAEM)
Volume 3, Issue 6 June 2021, pp: 421-432 www.ijaem.net ISSN: 2395-5252

$$\frac{\partial}{\partial x} f(x,t) = k_x^1 (f_{k+1}^n - f_{k-1}^n)$$

$$\frac{\partial^2}{\partial x^2} f(x,t) = k_x^2 (f_{k+1}^n + f_{k-1}^n - 2f_k^n)$$

$$\frac{\partial}{\partial t} f(x,t) = k_t^1 (f_k^{n+1} - f_k^{n-1})$$

The approximations of the radial basis function corresponding to the geometrical parameters of c are

- Spatial Domain

$$k_x^1 = \frac{\Delta x}{(\sqrt{4\Delta x^2 + c^2} - c)\sqrt{\Delta x^2 + c^2}}$$

$$k_x^2 = \frac{\frac{c^2}{\left(\sqrt{\Delta x^2 + c^2}\right)^3} - \frac{1}{c}}{3c - \sqrt{\Delta x^2 + c^2} + \sqrt{4\Delta x^2 + c^2}}$$

- Temporal Domain

$$k_t^1 = \frac{\Delta t}{(\sqrt{4\Delta t^2 + c^2} - c)\sqrt{\Delta t^2 + c^2}}$$

This method will provide the same approximations as of those in FDTD method when c tends to ∞. In order to select a parameter for the spatial domain, we consider different values which provide a better result than the FDTD method.

We consider the coupling equation FTL(field to transmission lines(lossless))

$$\frac{\partial V^s(x,t)}{\partial x} + L\frac{\partial}{\partial t} I(x,t) = E_x^i(x,t)$$

$$\frac{\partial I(x,t)}{\partial x} + C\frac{\partial}{\partial t} V^s(x,t) = 0$$

Where $V^s(x,t)$ and $I(x,t)$ are the surges induced into the line due to FTL coupling.

L and C are the inductance and capacitance(per unit length)

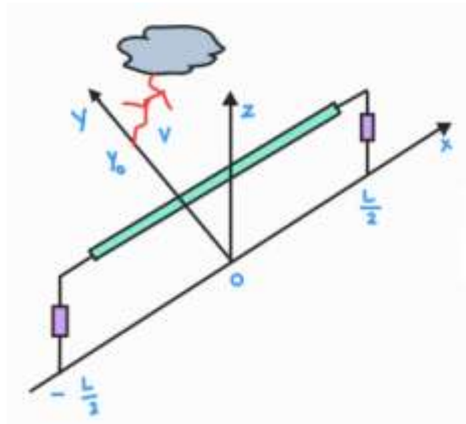

Fig: Induced voltage calculation geometry

By differentiating the above equations with respect to x, we get the second order equations as shown below

$$\frac{\partial^2 V^s(x,t)}{\partial x^2} - LC\frac{\partial^2 V^s(x,t)}{\partial t^2} = \frac{\partial E_x^i(x,t)}{\partial x}$$

$$\frac{\partial^2 I(x,t)}{\partial x^2} - LC\frac{\partial^2 I(x,t)}{\partial t^2} = -C\frac{\partial E_x^i(x,t)}{\partial t}$$

By considering the Taylor series for the surges generated in the system up to second order is given as

$$V^s(x,t) = V^s(x,t_0) + \Delta t\frac{\partial V^s(x,t)}{\partial x} + \frac{\Delta t^2}{2!}\frac{\partial^2 V^s(x,t)}{\partial t^2} + O(\Delta t^3)$$

$$I(x,t) = I(x,t_0) + \Delta t\frac{\partial I(x,t)}{\partial x} + \frac{\Delta t^2}{2!}\frac{\partial^2 I(x,t)}{\partial t^2} + O(\Delta t^3)$$

By substituting the values of first and second order derivatives of surges(time based domain)

$$V^s(x,t) = V^s(x,t_0) - \Delta t C^{-1}\frac{\partial I(x,t)}{\partial x} + \frac{\Delta t^2 (LC)^{-1}}{2}\left(\frac{\partial^2 V^s(x,t)}{\partial x^2} - \frac{\partial E_x^i(x,t)}{\partial x}\right) + O(\Delta t^3)$$

$$I(x,t) = I(x,t_0) - \Delta t L^{-1}\left(\frac{\partial V^s(x,t)}{\partial x} - E_x^i(x,t)\right) + \frac{\Delta t^2 (LC)^{-1}}{2}\left(\frac{\partial^2 I(x,t)}{\partial x^2} + C\frac{\partial E_x^i(x,t)}{\partial t}\right) + O(\Delta t^3)$$

By representing the above equations in the spatial and time related derivatives using RBF-FDTD approximation are given as

$$V_k^{n+1} = V_k^n - \Delta t C^{-1} k_x^1 (I_{k+1}^n - I_{k-1}^n) + \frac{\Delta t^2 (LC)^{-1}}{2} [k_x^2 (V_{k+1}^n + V_{k-1}^n - 2V_k^n) - k_x^1 (E_{k+1}^n - E_{k-1}^n)]$$

$$I_k^{n+1} = I_k^n + \Delta t L^{-1} \left(E_k^n - k_x^1 (V_{k+1}^n - V_{k-1}^n)\right) + \frac{\Delta t^2 (CL)^{-1}}{2} [k_x^2 (I_{k+1}^n + I_{k-1}^n - 2I_k^n) + C k_t^1 (E_k^{n+1} - E_k^{n-1})]$$

The approximations are given as

$$V_k^n \equiv V^s\left((k-1)\Delta x, n\Delta t\right)$$

$$I_k^n \equiv I\left((k-1)\Delta x, n\Delta t\right)$$

Where $\Delta x, \Delta t$ are spatial and time steps(equal grid steps)

k,n are k^{th} and n^{th} integral steps(k is spatial and n is temporal)

The conditions to the boundaries of the surge voltage with a load at two line closing is given as follows

$$V_1^n = \int_0^h E_z^i(0,0,t)dz - Z_0 I_1^n$$

$$V_{Nx+1}^n = \int_0^h E_z^i(L,0,t)dz - Z_L I_{Nx+1}^n$$

Where E_z^i refers to the incident electrical field (with respect to vertical field lines)

Z refers to the impedance of the termination of boundary lines

The terminating conditions are designed in order to avoid the reflected waves on the boundaries.

The overall surge voltage induced into the transmission line system due to the indirect lightning stroke is given as a sum of the voltage scattered and the incident vertical electric field with an finite integral ranging from 0 to h

$$V^T(x,t) = V^s(x,t) - \int_0^h E_z^i(x,h,t)dz$$

The above equation can be expressed as the sum of scattered and incident voltage

$$V^T(x,t) = V^s(x,t) + V^i(x,t)$$

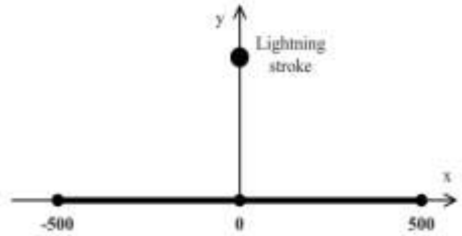

Fig: Distance between line and stroke

A perpendicular is drawn from the point of incidence of lightning to the transmission line considering the observation point at 500m, the 1D varies in the range[-500,500]

The results of magnitude of surge voltage due to lightning is shown in the below 3D surface plot

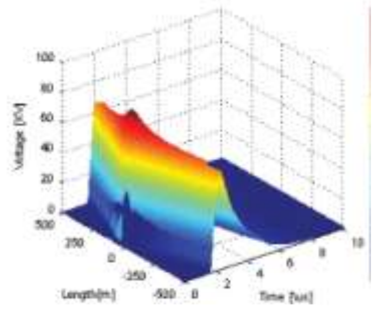

Fig: Induced voltage plot

III. DIRECT LIGHTNING STROKE MAGNITUDE CALCULATION

3.1 Magnitude of Overvoltages

Direct lightning stroke is a case where the lightning directly come in contact with the power system equipment, in a transmission line system this case is considered if the lightning directly hits the cables or transmission line poles. If no proper protection system is equipped the it will cause a severe damage to the system. In order to protect the system from these strokes we employee different protection schemes.

The surge current flows in both the directions, the overall magnitude of the current is divided into two equal parts. By knowing the value of surge impedance, we can find the overvoltage magnitude of the lightning stroke.

Let's consider that the surge current Induced here is i_b = 30kA

The surge impedance Z = 200 ohms

Then the surge voltage

U = Z × i_b

U = 200 × 30 = 6000kV

For the above, the surge voltage Induced in transmission line due to direct lightning is 6000kV

When a direct lightning strikes on the top of Pole or on earth Wire (shielding protector) under

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ideal conditions(zero Pole resistance)the complete surge current will be moved directly into the ground. But in practical conditions the Pole resistance can never be zero, so the surge is produced in the Pole, the surge produced is more than the withstand value of insulation which leads to a generation of flash between the Pole and the phase conductor .

Let's consider that the surge current Induced here is
$i_b = 30kA$
The pole resistance $R_{E,P} = 100$ ohms
Then the surge voltage
$U = R_{E,P} \times i_b$
$U = 100 \times 30 = 3000kV$

The value of surge obtained is higher than the withstand value of insulation which resulting in addition of surge into the phase wire due to back flash mechanism. In order to avoid this we have to maintain the least possible resistance of the pole and we should maintain high withstand value insulation in the transmission line system.

3.2 Lightning voltage sensing

In order to absorb the surges raised in the system due to the lightning effect we employee voltage sensing equipment which helps in identifying the magnitude of surges in the system.

3.2.1 Direct lightning stroke voltage sensor

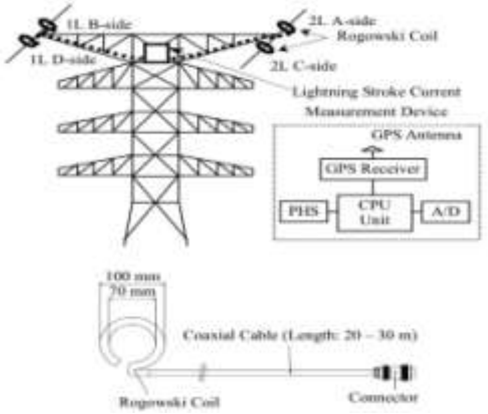
The voltage sensing part has a stray capacitanceC_1 between the conductor and tank and a potential divider capacitance C_2 in the pre amplification stages. We can also predict whether the surge formed due to direct or indirect lightning stroke with the help of polarities of the surges. The surge polarities are constant in all the phases for the Induced lightning effect but in the direct lightning effect the polarities differ in all the phases. These are arranged at the switching substation's and the surges can be recorded by the continuous monitoring of the phase lines of the transmission line. The magnitude of voltage across the line is measured with the help of the impact dividers(voltage dividers capacitance) and stray capacitance and the value is enhanced in the further procedure in order to get the accurate value of the magnitude of the surges encountered by the system

3.2.2 UHV transmission line design to identify surge magnitudes

In order to perform the study on lightning strike effects on transmission line we employee certain instrumentation in the transmission line which helps to identify the Amplitude of the surges encountered in the system. This is known as an observatory system. In the UHV lines we employee the observatory system in order to study the surge that encountered in the earth Wire of the transmission line.

Fig:Observatory system for UHV TL

This system analyse the potential in the earth Wire with the help of Rogowski coil arranged at both the sides of the earth Wire shield. The recorded data is transmitted with the help of GPS to the personal handset(PHS) and we do have analog to digital converter in order to obtain the value of the surge current due to lightning stroke on the ground Wire.



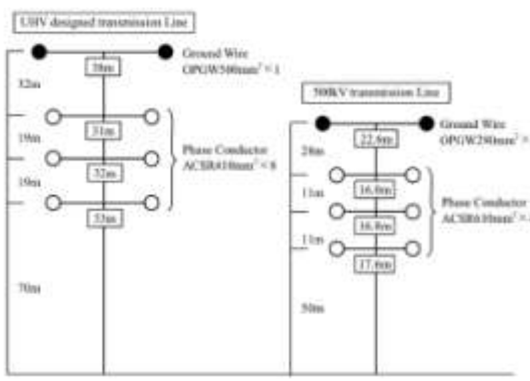


Fig: conductor positioning in the UHV transmission lines

These arrangement plans are designed to reduce the effect of lightning and to increase the probability of lightning to fall on the earth Wire shielding in order to reduce the chances of high surges generated in the phase wires of the UHV lines .

IV. LIGHTNING OUTAGE RATE CALCULATION

4.1 Introduction to outage rate

Outage rate gives the relation between the lightning shielding success and its failure. It mostly describes about the shielding success in the transmission line system. If the lightning shielding works efficiently, outages can be eradicated from the system. The lightning outage in a transmission line system causes back flashover voltages.

4.2 Outage rate calculation

The IEEE standards provide us with the formulae applied to find the lightning density on the ground.

$$N_g = 0.04{T_d}^{1.25}$$

$$N_g = 0.054{T_h}^{1.1}$$

Where N_g is the Lightning density on the ground(GLD)

T_d is the count of thunderstorm days

T_h is the count of lightning hours

For every 100 kilometres line being hit by lightning surges each year is described as

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

$$N = N_g\left(\frac{4{h_p}^{1.09}+b}{10}\right)$$

$$N = N_g\left(\frac{38{h_p}^{0.45}+b}{10}\right)$$

Where N is the count of lightning strikes

h_p- height of line with respect to ground

H_T- tower height with respect to ground

b – ground wire spacing

4.2.2 Amplitude of surge

The function of return stroke current is given as

$$f_i(I) = \left(\frac{1}{\sqrt{2\pi}\sigma_{ln} I}\right) e^{\frac{-(\ln I/\bar{I})^2}{2\sigma_{ln}^2}}$$

Where $\sigma_{ln} = 1.33$ for current less than 20kA

$\bar{I}$ is the reference current

If the amplitude of the return stroke > the collective, requires $f_i(I)$

The probability can also be given as

$$P(I_f > I) = \frac{1}{1+\left(\frac{I}{\bar{I}_{first}}\right)^{2.6}}$$

4.2.3 Geometrical Analysis

In order to understand the concept of lightning strike in the transmission line environment, we consider the geometrical analysis which provides the protection angle value in order to increase the shielding efficiency. This analysis is known as Electrical shielding geometry. We use this model in order to analyse the failure in shielding which consists of ground wire on the top of the tower and reference ground component. Let us consider, α as a protection angle, the striking distance is given by S and its factor is given as β.

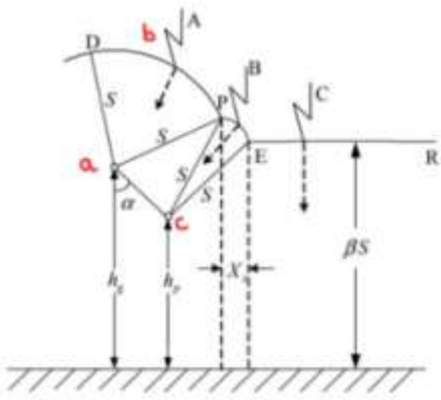


Fig: Geometrical model ($X_s \neq 0$)

Where DPER- path of lightning pilot

a– line of lightning

b – point of lightning strike

c – describes the phase line

Due to increase in the magnitude of surge current(due to lightning) the distance of striking will also increase. Due to this, the distance PE will gradually decrease and becomes 0 eventually.

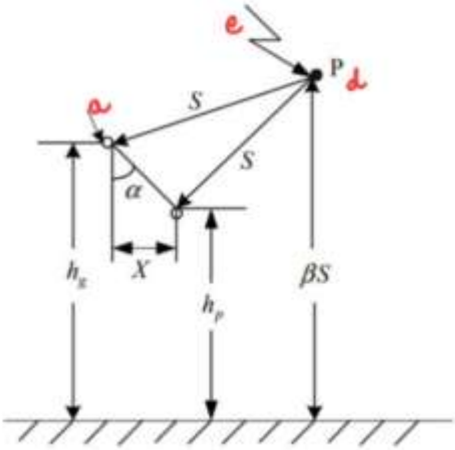


Fig: Geometrical Model ($X_s = 0$)

Where, point P is known as critical point
At this point, the conductor is completely shielded due to maximum surge current shielding and maximum strike distance.
We do observe sag in the conductor which results in the new height of the phase line with respect to the ground. We need to identify the average height of the phase line which is provided by the given formula

$$H_p = h_p - \frac{2}{3}S_{ap}$$

Where S_{ap} denotes sag observed in the phase line
If the strike distance is identified and the product of the strike distance factor and the strike distance is less than the height of phase line(considering sag)

$$X_s = S[\cos\theta + \sin(\alpha_s - \omega)]$$

$$\theta = \sin^{-1}\left(\frac{\beta S - H_p}{S}\right)$$

$$\omega = \cos^{-1}\left(\frac{\sqrt{(x_p - x_g)^2 + (H_p - H_g)^2}}{2S}\right)$$

$$\alpha_s = \tan^{-1}\left(\frac{x_p - x_g}{H_g - H_p}\right)$$

These are obtained with the help of horizontal coordinates of phase and ground wires. Under this condition

$$X_s = S[1 + \sin(\alpha_s - \omega)]$$

Whenever there is a minimum amount of surge current the exposure distance is maximum and the exposure distance is 0 corresponding to maximum surge current.

$$N_{SF} = 0.1\, N_g \frac{X_s}{2}(P_{min} - P_{max})$$

Where P_{min} is the probability of the surge current amplitude being above I_{min}
P_{max} is the probability of the surge current amplitude being above I_{max}
In HV transmission lines, whenever a direct lightning strikes on the top of the pole it produces a back flash if the insulation failure occurs.
Let us consider a voltage calculation model with respect to resistance and inductance

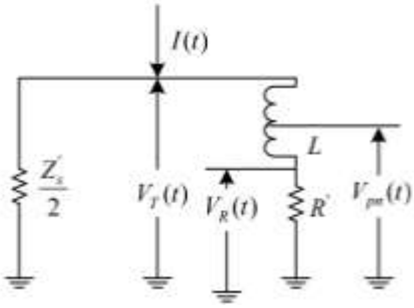


Fig: Electrical circuitry of tower

In the above figure, we have considered tower or the pole as a transmission line
Where

$$Z_S' = \frac{2Z_s Z_T}{Z_s + 2Z_T}$$

$$R' = \frac{RZ_T}{Z_T - R}$$

By considering the time of propagation and the attenuation coefficient we get the values

$$Z_W = \frac{2Z_T Z_S{}^2}{(2Z_T + Z_s)^2}\frac{Z_T - R}{Z_T + R}$$

$$\psi = \frac{2Z_T - Z_S}{2Z_T + Z_s}\frac{Z_T - R}{Z_T + R}$$

Where ψ is the coefficient of attenuation
With these parameters, we can find out the total inductance of the tower

$$L = \left(\frac{Z_S' + 2R'}{Z_S'}\right)\frac{2Z_w \tau_T}{(1-\psi)^2}$$

We use volt time characteristics of lightning current to calculate the value of voltage at which the critical breakdown takes place.
Whenever the lightning strike takes place, we have to calculate the voltage on the insulation at only two points. Let us consider the time divisions as 2-6 micro seconds. Let's consider two cases in calculating the value of voltage at insulator.
Case 1 – Non reflective case

$$V_{T2} = \left[Z_1 - \frac{Z_w}{1-\psi}\left(1 - \frac{\tau_T}{1-\psi}\right)\right] I$$

The impedance is given as

$$Z_i = \frac{Z_s Z_T}{Z_s + 2Z_T}$$

Case 2 – Reflective case

$$V_{T2}{}' = \left[Z_1 - \frac{-4KV_{T2}}{Z_s}\left(1 - \frac{\tau_T}{Z_s}\right)\right](1 - \tau_s)$$

This includes the coefficient of attenuation (considering $K_s = 0.85$ in this case)

International Journal of Advances in Engineering and Management (IJAEM)
Volume 3, Issue 6 June 2021, pp: 421-432 www.ijaem.net ISSN: 2395-5252

If the current propagation time is greater than one microsecond then it come under a non reflective case(at time = 2 micro seconds). When the propagation time is less than one microsecond

$$V_{T2} = V_{T2} + V_{T2}'$$

The grounding voltage at time is equals $2+\tau_T$is given as

$$V_{R2} = \left[\frac{\alpha_1 Z_1}{1-\psi}\left(1 - \frac{\psi\tau_T}{1-\psi}\right)\right] I$$

$\alpha_1 = \frac{2R}{Z_T+R}$(grounding current related)

$$V_{pn2} = V_{R2} + \frac{\tau_T - \tau_{pn}}{\tau_T}(V_{T2} - V_{R2})$$

τ_{pn} is the time of transmission from pole top to the n bars of magnitude of surge current.

The voltage of the n^{th} number phase line is given as the difference between the voltage of insulator strings to the phase voltage

$$V_{sn2} = V_{pn2} - K_n V_{T2}$$

At a time, t = 6 micro seconds, the pole has lost its impact resistance as the peak of surge current has passed. So the voltage is given as

$$V_{T6} = \left(\frac{Z_s R}{Z_s + 2R}\right) I$$

For a reflecting case, the voltage expression is given as

$$V'_{T6} = -4K_s Z_s \left(\frac{R}{Z_s + 2R}\right)^2 \left(1 - \frac{2R}{Z_s + 2R}\right) I$$

The insulator voltage is given as

$$V_{sn6} = [V_{T6} + V'_{T6}](1 - K_n)$$

The voltage of insulators at two microseconds and 6 microseconds is given as

$$V_{I2} = 820l$$

$$V_{I6} = 585l$$

Where l is the length of insulation

The flash over currents are given as

$$I_{cn2} = \frac{V_{I2}}{V_{sn2}}$$

$$I_{cn6} = \frac{V_{I6}}{V_{sn6}}$$

Fig: Examples of Lightning outage at different conductors

V. IMPLEMENTATION OF SCADA

5.1 SCADA interface block diagram

Our idea is to monitor the two port network of the Transmission line system by using SCADA, this helps in monitoring the system and to identify the faults and we can also record the data regarding the faults occurred in the system

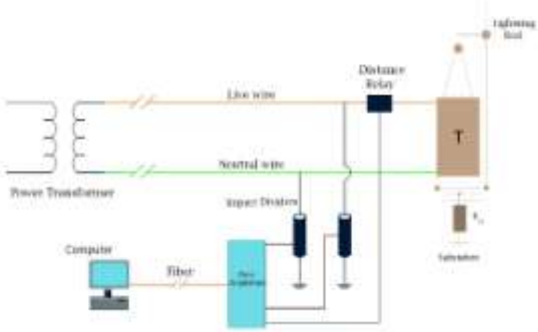


Fig: SCADA interface diagram

Our idea deals with the recording and monitoring the surges in the transmission line system and to determine the location of fault using distance relay. we have to identify the fault Parameters and analyzethe electrical stress encountered by the insulation at the position of fault.

We have to employee a long range distance relay in between the power transformer of the generating station and primary distribution station to analyze The UHV lines.

We have build an algorithm that identifies the places where more faults occurred and we have to calculate the electrical stress on the insulation installed at that particular place based on the

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Volume 3, Issue 6 June 2021, pp: 421-432 www.ijaem.net ISSN: 2395-5252

previous data recorded. This helps in identifying the insulation strength by which we can predict the survival of that insulation in further fault cases and analyze if replacement is needed or not inorder to reduce the probability of lightning outage and insulation failure at the time of lightning strike, this helps inreducing the faults entering into the phase Wires of the transmission line.

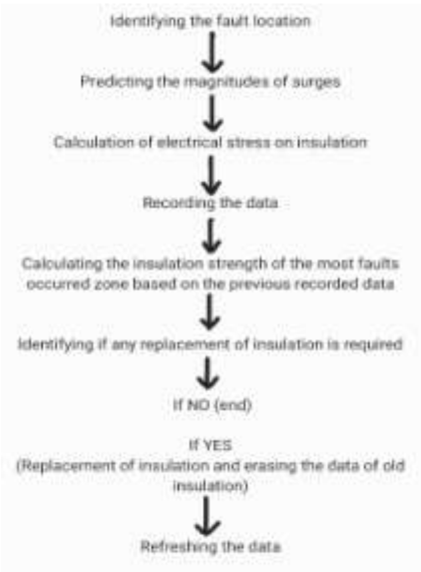

Fig: Algorithm of the proposed idea

In order to record and save the data in the server we use SCADA system and we employee certain communication systems in order to achieve the required conditions. The data cables which comes from the distance relay are given to the RTU(remote terminal unit)just as the IED (Intelligence Electronic Device) and this data communication is taken place. The recorded data must me made available to the compiler which runs the code to calculate the dielectric strength of the insulation in the transmission lines.

5.1.1Communication System:

The communication systems are connected to the RTU of the substation. so, we are going to place the distance relay near to the sub-station and the RTU of the primary distribution sub-station will accept the data regarding the distance relay. The data is also collected from the impact dividers which provide more detailed information regarding the surges generated, but mostly impact dividers are reliable when there is a short transmission path. A distance relay can be considered after the generating station with a long range so that tracking the faults will become easy and efficient. The communication is done mostly in two ways, which are mentioned below

- **MPLS (Multiprotocol Label Switching)**
- **GPRS (General Packet Radio Service)**

Both the MPLS and GPRS, the data is transferred in the form of packets

MPLS :

In this communication system, the output of the RTU is given to the MPLS with FO (**F**iber **O**ptic) cables. This sends the data to the control center. It adds a MPLS label to the data which allows the IP packets of the data to pass at switching level, without being passed up to the routing level, by which the transmission is done faster when compared to the packet data transfer.

GPRS :

This is the secondary option for communication, where the Router will be installed with a SIM card and it transmits the signal through 3G network in case of FO breakdown condition. This data gets transmits through the MPLS communication system.

Working of MPLS:

IP address of data before MPLS label

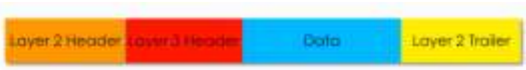

Fig: IP before MPLS

In routing level, the IP of the data is checked at the each stage of transmission through router.

Fig: IP address of data after the MPLS label

Now, the routers only look at the MPLS label, and never check the IP address till the receiver level. This label creates a pre-defined path to the data from transmitter to the receiver, which makes the data to travel more fast when compared to routing level.

MPLS creates an end-to-end path that act like a circuit switched condition.Since layer-3: routing function is made to act like layer-2: switching function the MPLS is also called as **2.5 layer protocol.**

MPLS in SCADA

The MPLS and GPRS are employeed and by default we use the MPLS communication, in case of any failure or disconnection in the Fiber Optic cable the MPLS will not work and the data transfer is achieved using the GPRS communication. The fig shows the data transfer using the MPLS and GPRS .

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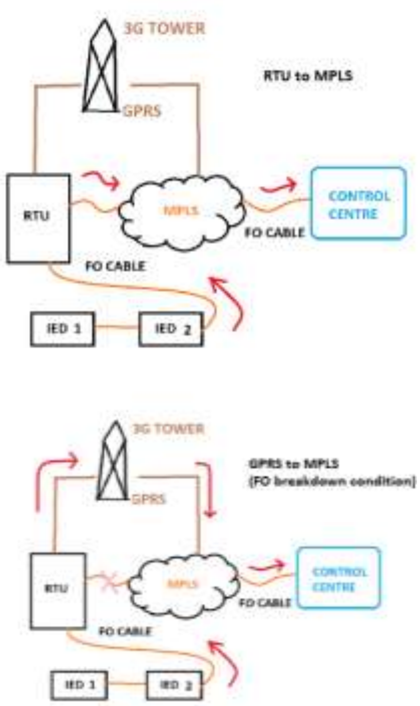

Fig: MPLS and GPRS communication

VI. CONCLUSION

In this thesis, the methods used for identifying the magnitude of surges due to different types of lightning strokes can also be used for the brief study of Electro-magnetic coupling in the system and it provides high accurate values than the initial methods due to integration of deep learning techniques into the system

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