JEAS

Journal of Engineering and Applied Sciences 5 (2010)

JOURNAL OF ENGINEERING

AND

Effects of lightning transients on electric power system

O.A. Ezechukwu

Department of electrical engineering, Nnamdi Azikiwe University, Awka.

Abstract

This paper tries to explain the phenomenon called 'lightning stroke'. It discusses the break down mechanisms for the cloud; from the stepped leader to the return streamer and up to the dart leader, and its effect on the insulator and the associated line conductors. The effects of the direct and indirect strokes are also discussed and this led to the development of expressions for over voltage on the line as a result of these strokes. At the end an approach is made towards analysing the transient circuit with the aid of a new formula called 'Ezechukwu's reduction formula'.

Key words: Lightning, potential difference, transient, charges.

Introduction

Lightning phenomenon occurs when charged particles of the cloud discharge to ground; and this can be likened to a large capacitor, with its air dielectric, being subjected to voltage higher than the insulation level; thus causing a flash-over or short circuit across its terminals. The development of this high (break down) voltage can be caused by some atmospheric disturbances like the thunderstorm, which impresses high voltage on the upper plate (the cloud), resulting in short circuit with its lower plate (the ground). During thunderstorm, there is air current separating the positively charged upper layer constituting of ice crystals and negatively charged lower layer constituting of rain/mist. As this continues, there is more concentration of positive charge at the top and more negative charge at the lower part of the cloud and as this increases, the electric field across the plates increases too and a point is reached when there is a flash-over across the 2 plates and therefore, causing a spark which is given off as lightning. The potential difference between these plates may range between 100 and 1000 MV. The lightning, always trying to discharge through the ground, carries only small fraction of this voltage while the rest is consumed in inter-cloud activities. As the lower layer of the cloud gets more negatively charged, the ground, by induction, gets more positively charged by Lenze's law. As said earlier the flashover or lightning across the two plates, the cloud and the ground, is caused by the breakdown of the air dielectric between the two plates. Only 10KV/cm is required for this breakdown as against 30KV/cm required at standard temperature and pressure, because this breakdown is done at high altitude with lower pressure. The mechanism of this breakdown is depicted in fig.1.

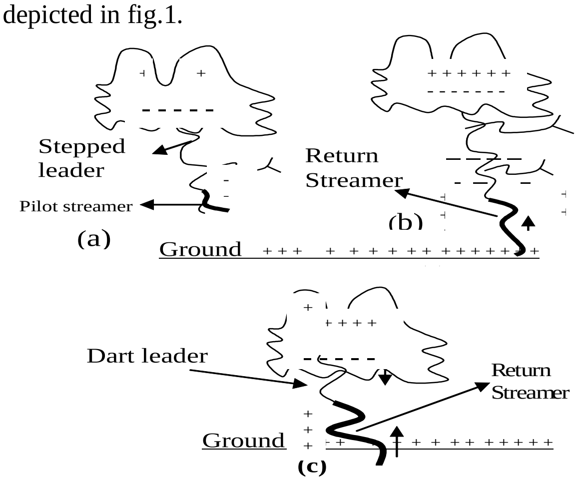


Fig1: The Lightning

At about 10KV/cm, the ambient air of the cloud ionizes and this gives way to the first stage of lighting discharge. At this point, a pilot streamer starts from the cloud and moves towards the ground without being visible. About 100Amps is involved in this process at the frequency of about 150m/s.The pilot streamer could be branched as shown in fig.1 (a) depending on the ionization level; and the pilot streamer could also be in stepped form, hence it is called “stepped leader” with each step being about 50m in length. The propagation velocity is about 16% of the velocity of light ($0.5x10^8$m/s). Some of the ionized charges from the centre of origin are spread along the temporary conducting paths. The process continues until one of the leaders strikes the ground and returns very brightly as a ‘return leader’ (fig.1 (b)) tracing its original path while the charges around it discharge to the ground. The current varies between 1000A and 200KA at a velocity of about $0.3x10^8$ m/s. At this stage the negative charge of the cloud is being neutralized by the ground positive (induced) charge and the lightning flash begins to manifest and can be seen with the naked eyes.

Should there be need for further discharge after the neutralization of the initial charge on the cloud, it should emanate from another charge centre near the already neutralized charge centre, making use of the already existing ionized path, and consequently having a single discharge branch with large amount of current. This repeated discharge is called the ‘dart leader’ (fig.1(c)). The dart leader is more devastating than the return leader. Its velocity is in the neighborhood of 3% of the velocity of light.

The dart leader is also called ‘hot lightning stroke’ because even when the current in this leader is relatively small it contains more energy since it continues for some milliseconds. On the other hand, the return streamer’s current is large but since it lasts for few microseconds, the energy is smaller than the dart leader. The return streamer is also called the ‘cold lightning stroke’.

Thundercloud may consist of more than 30 separate charge centers, which give rise to heavy lightning strikes. When a lightning stroke takes place at any point along the high voltage line, the current associated with it induces a voltage on the line, which is in form of a traveling wave. The expression for the induced current on the line is; I_L= 20chIo/x - - -(1)

Where c = constant of value 1.3

h = height of the line from ground

Io= lightning current and

x = distance from the stricken point

Lightning may discharge heavy current, Io, in the range of 10-100KA within a very short time, which consists of the front time, Tf and tail time, Tt, in microseconds. Tf is the time taken by Io to discharge to half of its peak value (some times called the half time). The values of the frequency components, F_1 and F_2, depend on Tf and Tt.

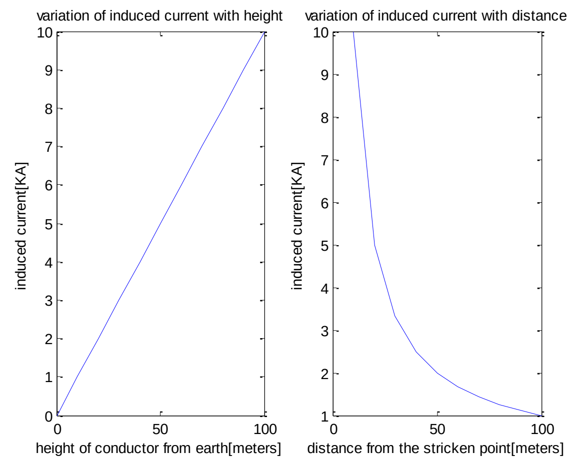


Fig2(a); Variation of induced current with position

Thus;

$$\left.\begin{array}{l} F_1 = \dfrac{1}{2TF} \\ F_2 = 1/4(T_t - T_f) \end{array}\right\} \quad - - - \; (2)$$

The voltage, because of lightning, has traveling wave of very steep wave front. The voltage, Vo, due to lightning stroke is given by

$$Vo=V(e^{-at}-e^{-bt}) \quad - - - - - - (3)$$

Where a and b are constants which determines the shape. Vo is the magnitude of the steep voltage and V is the peak or crest value of the impulse voltage wave. The wave shape of this type and the current is shown in fig.2. Note that;

Tf = about 3μs in fig2(b) and

Tt = about 13μs.

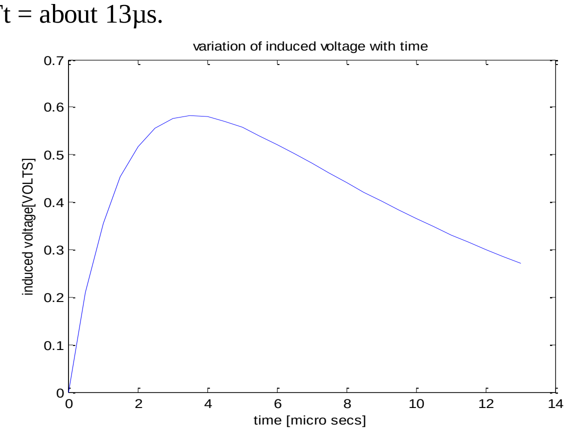


Fig.2(b); variation of induced voltage with time

The effects of variation in height, h, and distance, x, of the conductor are shown in fig. 2(a)

OVER VOLTAGES DUE TO LIGHTNING

Two types of voltage surges are caused by lightning; the first, by direct stroke on a line conductor while the other, indirect stroke, is as a result of dissipation of bound charges on a structure or object near the line conductor.

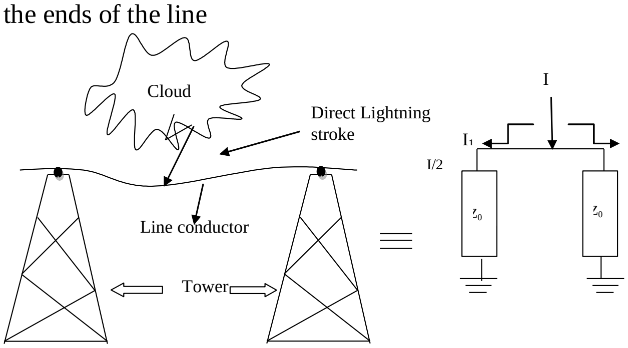
The direct stroke is the most devastating because it produces the highest surge voltage for a given stroke current. This stroke current is usually not affected by the voltage induced between the power line and the ground. Therefore, the direct lightning stroke can be considered as a constant current source. When lightning strikes a line conductor, (say at the middle of the span) two currents, I_1 and I_2 moving backwards and forward respectively, will flow from the stricken point (in both directions) as shown in fig. 3.

The over voltage, V_s, at the stricken point can be expressed as

$V_s=I_0Z_o/2$----- - -   -   (4)

Where Z_o is the surge impedance of the line.

This over voltage appearing on the power line as a result of the stroke usually moves as a traveling wave towards the ends of the line



(a) (b)

Fig.3:Mechanism of lightning .

conductor and the effect can be reduced by corona charge - Perhaps this is one of the advantages of corona charge.

The effect of direct lightning stroke on the insulation range between total damage to minor cracking and depends on so many factors like; the magnitude and shape of the induced current, I_0, the tower footing resistance, the earth lead or electrode resistances, the shape of potential wave at the top of the tower etc. The potential difference across the insulator due to direct stroke,

V_d, is given as $V_d = I_0R_T$ - - - --   - (5)

Over-voltage

Where R_T is the total (parallel) resistance of the earth electrode, Re_1, earth lead, Re_2 and tower footing, R_f.

If tower inductance is taken into account,

$V_d = I_0R_T + Ldi/d_{t----}$(6)

Where L = inductance of the tower and di/dt = rate of change of current due to direct lightning stroke.

For indirect strokes, positive charges are induced on a line conductor near the negatively charged cloud causing the line conductor potential to rise to

$V_{ind} = E.h$ ----------------   (7)

Where E = mean electric field strength near the earth surface under thunder cloud (usually between 0.5kv/cm to 2.8kv/cm) and h = the height of the line conductor above the earth.

Thus in a situation where both direct and indirect strokes are involved, the total overvoltage developed is $V_{T.}$

$V_T = I_0R_T + L^{d1}/_{dt} + Eh$ Volt-- --(8)

From equation (8) it is seen that R_T is an important factor in determining the value of V_T. It is therefore recommended that R_T should be kept as low as possible; and not more than 10 ohms.

If I_1 be forward traveling wave and I_2, the backward traveling wave as shown in fig 3(b), then when $I_1 = I_2$, total current, I_T = O but $V_1 = V_2$ gives total voltage, $V_T = V/2$.

Direct and indirect strokes give lot of troubles to sub-transmission lines below 33KV because their insulators are small in size and have weaker dielectric strength**.**

ANALYSIS OF TRANSIENT CIRCUIT

Towers or pylons carrying power across the river, swampy area, vegetations, etc., lend themselves to the development of static charges; such that under lightening conditions the effects of phase to phase and line to ground capacitances developed become more pronounced. The equivalent circuit is shown in fig 4.

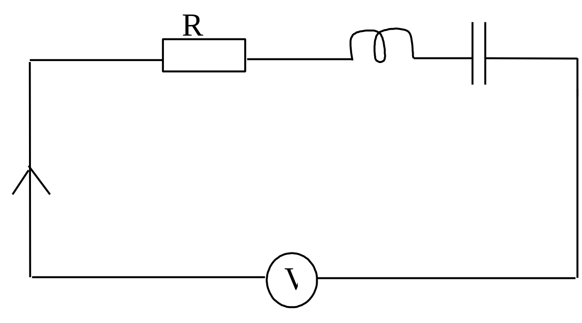


Fig 4: Equivalent circuit of a double energy transient network

If R, L and C represent total resistance, inductance and capacitance respectively, of the network, the transient current, $I_{(t)}$, can easily be found by the application of laplace transform method.

$Z(s) = R + Ls + 1/Cs$

$= \frac{RCs + LCs + 1}{Cs}$

$I(s) = V/s \div Z(s)$

$= \frac{V}{s} \cdot \frac{sC}{s^2LC + sRC + 1}$

$$I(s) = \frac{VC}{s^2LC + sRC + 1} \quad \text{- - -(9)}$$

Dividing equation (9) by LC : $I(s) = \frac{V/L}{s^2 + Rs/L + 1/LC}$ - - - - - (10)

Equation (10) can produce four conditions depending on the cases:

From [3], case 1: If R = O the circuit becomes **undamped** and can be expressed as

$$I = \frac{V/L}{\sqrt{LC}} \text{ Sin } \sqrt{(1/LC)}t \text{ Amps}$$

Now if $\sqrt{LC} = w$ then,

$I = V/wL \text{Sin } \omega t$ Amps -- - - -(11)

Case 2: $R^2/4 << L/C$; the circuit becomes **under damped** and the expression of current,

$I = V/wL. e^{-Rt/2L}\text{Sin } wt$- -- -(12)

Case 3: $R^2/4 = L/C$; the circuit is **critically damped** and assumes an expression;

$I = (V/L)t\, e^{-Rt/2L}$ ---------- (13)

Case 4: $R^2/4>>L/C$-The circuit is **over-damped** and assumes the expression;

$I=(2V/R)e^{-Rt/2L}\text{Sinh}(Rt/2L)A$--(14)

When the values at Eqn (10) are large, solution could be more cumbersome, but by using Ezechukwu's reduction formula, solution can be simplified thus;

Equation (10) can be given in form of

$$\frac{A}{S^2 + Xs + y} \quad \text{- - - -.(15a)}$$

Where x = R/L, y = 1/LC and A = the numerator, V/L

This can be simplified by Ezechukwu's reduction to;

$$\frac{\sqrt{(y - x^2/4)}}{(s+x/2)^2+(\sqrt{(y - x^2/4)})^2} \cdot \frac{A.}{\sqrt{(y - x^2/4)}} \quad \text{- - - (15b)}$$

See[4] for Proof of Equations (15a/ 15b)

So for case No1: lossless circuit (**undamped)** where R = O

Then x = 0 and equation (15b) becomes; $I_{(s)}$ =

$$\frac{\sqrt{y}}{S^2 + (\sqrt{y})^2} \cdot \frac{A}{\sqrt{y}}$$

which is in form of

$$C \cdot \frac{K}{S^2+K^2}$$

Where $C=A/\sqrt{y}$.

From the inverse transform,

$I_{(t)} = C.\text{sin}kt$ - - - - - (16a)

Putting back the values,

$I_{(t)}=(V/L)/(1/LC)^{1/2}\text{Sin}(1/LC)^{1/2}t$

$I_{(t)}=V/wL \text{ Sin}(wt)$ Amps. - - (16b)

Case No2: $R^2/4<<L/C$ or $(R/2L)^2<<1/LC$ implying that $x/2<<y$: which is the condition for **under-damped circuit**. Returning to eqn.(15b),

$A/\sqrt{y} = C$ and

$$\frac{\sqrt{(y)}}{(S + x/2)^2+ (\sqrt{y})^2} \Rightarrow \frac{K}{(S+a)^2+ K^2}$$

Thus eqn.(15b)becomes

$$C. \frac{K}{(S+a)^2+K^2}.$$

Where $K=\sqrt{(y)}$ and $a=x/2$ Therefore from inverse transform, $I_{(t)}=C.e^{at}\text{Sin}kt$---(17a) Substituting values in eqn(17a) $I_{(t)}=V/L(1/LC)^{1/2}.e^{Rt/2L}\text{sin}(1/LC)^{1/2}t$

$I_{(t)}=(V/wL)e^{Rt/2L}\text{sin}wt$Amps--(17b)

as in eqn(12).

CaseNo3:$R^2/4=L/C$ or $(R/2L)^2=1/LC$ (**Critically damped condition**);

Eqn.(15b) degenerates to; $I(s)= \frac{A}{S+(x/2)^2}$ since $y-(x/2)^2 =0$.

.The inverse transform therefore is; $I_{(t)} = Ate^{-xt/2L}$ - - (18a)

Now substituting values in eqn(18a);$I_{(t)}=(Vt/L).e^{-Rt/2L}A$-(18b)

Case4:$R^2/4>>L/C$ or $(R/2L)^2>>1/LC$,**overdamped condition**,and eqn(15b) becomes;

$$\frac{\sqrt{(-x/2)^2}}{(S+x/2)^2+(\sqrt{(-x/2)^2}} \cdot \frac{A}{\sqrt{(-x/2)^2}}$$

$$\Rightarrow C.\frac{K}{(S+a)^2+K^2}$$

Where $K=\sqrt{(-x/2)^2}$, $a=x/2$, $A=V/L$.

From the inverse transform and substituting values

$I_{(t)}=(A/K).e^{-Rt/2L}\sinh Rt/2L$ Amps;
$I_{(t)}=(2V/R)e^{-Rt/2L}\sinh Rt/2LA$---(19)
Again this is the same as eqn(14).
Note: the results obtained using Ezechukwu's reduction formula [4], eqns(18-19) correspond to eqns(11-14) obtained through analytic approach.

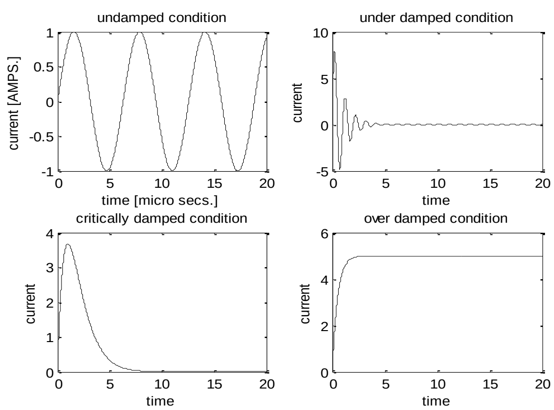


Fig 5(a): The 4 conditions plotted separately at an extended time of 20 μs

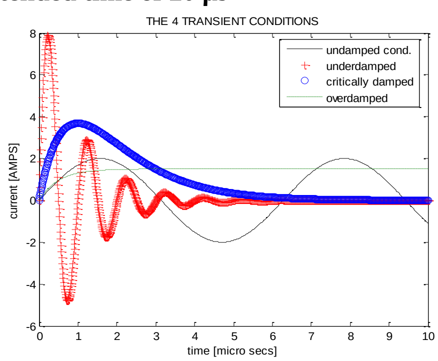


Fig.5 (b);The 4 conditions plotted together for comparison.
(i) undamped,(ii) under damped, (iii)critically damped and
(iv) over damped conditions.

REMEDY

High voltage induced by lightning can cause damage to insulations and equipment. Therefore it is necessary to protect the lines and equipment with sensitive over-voltage and over current devices.
There are many methods of earthing, viz; the aerial method, the peripheral method and the Protective Multiple Earthing (PME), etc. The aerial method seems to be more effective since the aerial wires receive the stroke before it gets down to the equipment.
However no matter the method used, the earth resistance of 10 ohms must not be exceeded. Where, due to the nature of the soil or/and environment, it is not possible to achieve that, the protective multiple earthing should be applied in addition.

CONCLUSION

Lightning phenomenon occurs when a charged particle of the cloud discharges to ground and this is similar to a short put across the terminals of a charged large capacitor. The potential difference developed as a result of lightning strike ranges between 100 to 1000MV while the induced current may range between 10 to 100KA within few micro seconds. The potential difference across a line insulator, due to lightning stroke is dependent on the magnitude and shape of the induced current, the total parallel resistances of the earth lead, earth electrodes, the tower footing resistances, and also the shape of the potential wave. It is more devastating to line insulators with low dielectric strength.
The induced current of a double energy transient can be easily found using Ezechukwu's reduction formula.

REFERENCES

Badri Ram, Vishwakarma DN 1995 Power system protection & switchgear-Tata McGrawhill, New Delhi 402

Nagrath IJ, Kolhari DP – Power System Engineering Tata McGrawhill New Delhi

Shepherd J, Morton H, Spence LF 1970 Higher Electrical Engineering Pitman Pub.(T)London pg 186 – 190

Ezechukwu OA 2000 – Signals and Systems Unpublished lecture note – Nnamdi Azikiwe university – Awka

Bajpai AC, Mustoe LR, Walker D 1982 Advanced Engineering. Mathematics John Willy & Sons Chichester 293.

Kalunta FO, Okafor DN 2007 Lightning Electromagnetic pulse and GSM base stations in tropical environment-NIEEE Proceedings of ICEPT's international conference, Abuja App 150..

Vahidi A, Nassab R S June2006 Ferroresonant overvoltage investigation in Wye-Wye transformer in transmission system IEEE J 20 06.

Buhmann L.J, McDaniel J, Stanek E.K 1993 Lightning arrester failures and ferroresonance on a distribution systems-IEEE transactions on industry application, Vol.29,No6 1189.

Walling R.A, Barker K.D1993 Ferroresonant overvoltages in grounded star-star padmount transformer with low loss silicon cores-IEEE transactions on power delivery,Vol.8,No 3 1647

Marungsri B, Boonpoke S Study of tower grounding resistance, back flashover to transmission line using ATP/EMTP International journal of Electric power and Energy systems Engineering. Vol.2,97-103.