International Journal of Applied Engineering Research ISSN 0973-4562 Volume 14, Number 22 (2019) pp. 4126-4135

Improving Overhead HV AC Line Performance using Line Surge Arrestors under Lightning Conditions with Economic Analysis

Eddie Singh [1], Innocent E. Davidson [2]

[1] *Eskom Distribution, Newcastle, KZN 2940, South Africa.*

[2] *Department of Electrical Power Engineering, Durban University of Technology, South Africa.*

Abstract

In areas with high occurrence of lightning, lightning strokes play an important role in the performance of overhead HV AC lines. A single stroke can lead to back flashovers and the resultant surge on the conductor results in the protective devices operating to extinguish the power surge. This operation of the protective devices leads to consumer interruptions on the network, thus leading to a loss of production and negatively impacting the economy. Line Surge Arrestors are devices that can drain the power surge to ground, if placed adequately and in sufficient numbers. This paper determines the relationship between the magnitude of the lightning stroke, the tower top voltage and hence the back-flashover voltage that would appear on the line, which would lead to power interruptions. Surge arrestors were modelled, using the MATLAB software, and the required number of surge arrestors per phase is thus determined that is required to drain the surge current down to earth and prevent power interruptions. Simulated results are presented in this paper.

Keywords Surge Impedance, Electrodes, Lightning strokes, Line surge arrestors, Over voltages.

I. INTRODUCTION

LIGHTNING tend to terminate on the earth wire and/or tower of HV AC overhead lines. Factors such as the conductor/tower/soil impedance and magnitude of the strike, play a critical role in determining the possibility of a flashover across the insulator. This is actually a short circuit that is formed with high current. This current splits and propagates along the line until it is extinguished by the impedance of the line or the line breaker operates. The movement of the current tends to 'damage' and reduce the life span of associated equipment such as breakers, transformers and negatively impacts network performance. Should breakers operate, the resultant short duration outage and/or dips, would impact negatively on customers. Those customers with sensitive equipment such as electric motors would come to a halt and production would stop, thus negatively affecting the economy.

For transmission systems, the current practice is to have tower footing resistance below a threshold value. This allows the lightning surges to be dissipated through the earthling systems. On an 88kV line, the tower footing resistance should Ideally be less than 30 ohms. The introduction of Fault Analysis and Lightning Location System (FALLS) program and database enables [1] one to determine the magnitude and position of the lightning stroke more accurately. Preliminary analysis indicates that only a portion of the strokes can be withstood by the current line design.

This leads to poor performance of the line under lightning conditions. (Previously the actual magnitude of the lightning strokes was not known). A lightning mitigating devices called Line Surge Arrestor (LSA) can be placed in existing transmission systems to improve system performance. Surge counter can be attached onto the LSA to obtained information such as the date, time and magnitude of the current that flowed through the LSA. The LSA reduces/or eliminates the high magnitude power surge arising from back flashovers. This may assist in preventing the network breaker from operating and improving security of supply and power quality. Analyzed data from installed devices revealed that lightning strokes results in both the surge arrestor and breaker operating and in some cases just the surge arrestors. This is dependent on the placement and number of LSA and other line parameters such as the magnitude of the associated lightning stroke. Figure 1, indicates the process that can be followed to determine the power surge on the phase conductor and hence the required number of surge arrestors to drain the surge to ground.

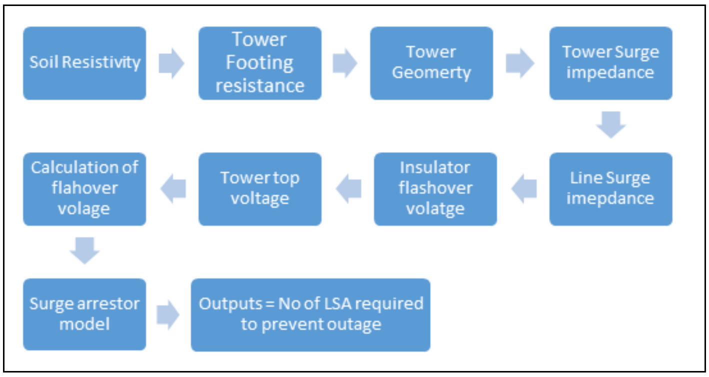

Fig 1: Process flow diagram to determine required number of surge arrestors to prevent power interruptions.

II. TOWER FOOTING RESISTANCE

The resistance offered by the metal parts of the tower combined with the ground resistance to the dissipation of current is known as Tower Footing Resistance. Should the tower footing resistance value be low, less voltage stresses across the line insulation would be experienced. A lightning stroke to the tower would result in high currents flowing into the ground through the tower footing. This gives rise to soil ionization and thermal effects. This causes the ground resistance of the tower base to decrease by an amount depending on the soil resistivity, the current magnitude and tower footing construction [2], [3], [4], [5]. To prevent line back flashovers and to maintain the ground potential rise within safety tolerance limit, the tower footing resistance value should be as low as possible. The lower the tower footing resistance, the more negative reflections are produced from the tower base towards the tower top. This assists in lowering the tower top peak voltage.

There are two key factors that affect the tower footing resistances. These are:

(i.) Electrode configuration

(ii.) Soil Resistivity

1. *Electrode Configuration*

The earth electrode is usually a metal plate, pipe or conductors electrically connected to earth and are usually made of copper, aluminum, mild steel or galvanized steel. The following factors influence the earthing resistance. [6] [7],

(i.) Resistance of an electrode or group of electrodes.

(ii.) Composition of soil in the immediate vicinity.

(iii.) Temperature of the soil.

(iv.) Moisture content of the soil.

(v.) Depth of the electrode.

2. *Soil Resistivity*

Soil resistivity can be defined as the resistance of a cube of soil of 1 m size measured between any two opposite faces and is expressed in Ohm-meter. This is one of many factors in determining the resistance of the charging electrode and the depth, which it should be planted to obtain low resistance. The resistance of the soil fluctuates between the wet and dry seasons and differs from sandy to rocky areas. The following factors determine the levels of soil resistivity. [6] [8]:

(i.) Moisture

(ii.) Minerals

(iii.) Dissolved salts

The higher the soil resistivity, the more the number of electrodes required to achieve the desired earth resistance value. Furthermore, an additional factor that should be considered is the layer thickness. For areas with gentle gradients, the soil environment can be considered as an upper layer and a more conductive lower layer [6]. In mountainous areas the opposite is true; the top layer can consist of fertile conducting soil and the deeper layer can consist of low conductive boulders or rock. Normally the grid or the electrode is buried in the upper layer. Detailed modelling is required to determine the soil resistivity for multi-layer and depth of soil.

Furthermore, practical testing was done on two sites within the Durban area in South Africa. These sites were the Durban University of Technology (DUT) and Kwa - Makhutha Comprehensive High School (KCHS) [9]. The results showed that the soil resistivity under dry conditions is 1862 ohms' meters and that under wet conditions is 200 ohms' meter. This is for soil depth of 0.5 meters as shown in figure 2 and 3.

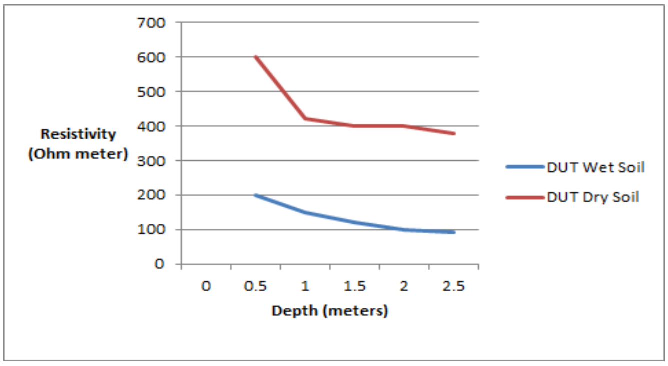

Fig 2: Soil Resistivity tests at DUT

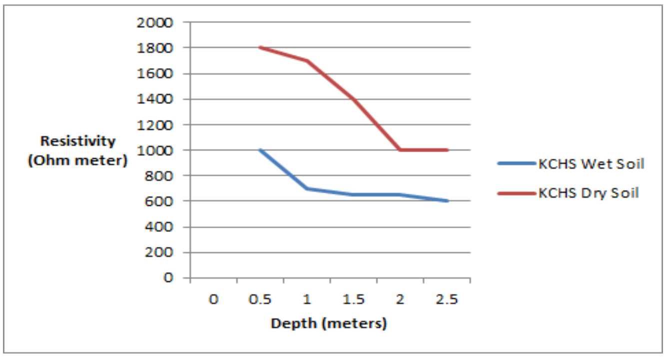

Fig 3: Soil Resistivity test at KCHS

III. EARTH METHODS AND CONFIGURATION

There are different types of earthling methods and configuration available for improving tower footing resistance. There are different types of earth electrodes [10]. These are:

(i.) Vertical electrode (Driven rod)

(ii.) Horizontal electrode

(iii.) Earthling grid

(iv.) Ring electrode

Utilizing the MATLAB software, genetic models were developed to calculate tower footing resistance based on the following formulae. The programming was developed using the following formula [6], [8] Driven Rod:

$$R = \rho \frac{\left[\ln\left(\left(\frac{L}{\alpha}\right)+\left((r-1)D\right)\right)\right]}{2rL\rho} \quad (1)$$

Horizontal Electrode (crow's foot):

$$R_g = \frac{\rho\left(\ln\left(\frac{4L}{\sqrt{dh}}\right)-1\right)}{\pi L} \quad (2)$$

Radial Conductors:

$$R_g = \frac{\rho\left(\ln\left(\frac{4L}{\sqrt{dh}}\right)-1+N(n)\right)}{n\pi L} \quad (3)$$

Where,

r = number of rods

R = Tower Footing Resistance in ohms

ρ = Soil Resistivity in ohm-meter

L = Length of conductor in meters

α = Radius of conductor meters

D = distance between rods in meters

L = Buried length of the electrode in meters

d = Diameter of the electrode in meters

h = Buried depth of the electrode in meter

n = Number of radials (number)

For the purposes of the MATLAB program the variables are inputs to the program and the tower footing resistance values obtained is the output*. The soil resistivity is assumed to be uniform [5] and was varied for wet conditions (less than 200 ohm meter) and dry conditions (~ 1800 ohm meters). Results obtained from the four case studies are displayed in Table 1

Table 1: Tower Footing Resistance for different soil conditions

	Case Study 1	Case Study 2	Case Study 3	Case Study 4
Upper Level (ohm m)	1862	1000	600	200
Lower Level (ohm m)	500	500	200	50
Depth of upper level (m)	7	7	7	7
Overall Soil Resistivity (ohm m)*	1025	763	375	105
Tower footing resistance (ohm)*	143	107	52.5	14.7

For HVAC lines the overall tower footing resistances needs to be less than 30ohms. Case study 1, 2 and 3 displays values in excess of 30 ohms. To reduce the values to that below 30 ohms, either the number of rods or conductor length can be increased.

The calculated values are shown in tables 2, 3 and 4. These conditions are simulated for case study 1, 2 and 3. Case study 4 is below 30 ohms. Table 2 shows the various configurations, in terms of length and number of conductors

Table 2: Radial Conductors required to obtain a Tower Footing Resistance value of less than 30 ohms.

Radial Conductor						
	Case Study 1		**Case Study 2**		**Case Study 3**	
No of conductors	**Length (m)**	**Resistance (ohms)**	**Length (m)**	**Resistance (ohms)**	**Length (m)**	**Resistance (ohms)**
2	50	24.94	30	29.12	20	20.09
3	30	28.87	30	21.67	10	27.33
6	30	24.15	20	25.96	10	23.24
8	20	28.41	20	21.33	10	19.41
12	20	25.54	20	19.18	10	17.66
13	20	23.15	20	17.38	10	16.25

Arising from case study 1, the best combination is 13 conductors with a length of 20 meters each will provide a TFR of 23.15 ohms. The total conductor length would be 260 meters. For case study 2, the same combination will result in the lowest tower footing resistance, which is 25% less than the value obtained in case study 1.

Case study 3 will require 13 conductors with a length of 10 meters each to obtain a tower footing resistance value of 16.25. These results are expected as the soil resistivity decreases from case study 1 to 3. From case study 3, to obtaining a tower footing resistance of 23.24, it would require 6 conductors of 10 meters each. This material length of 60 meters is much less than that of case study 1. Again this can be attributed to the better soil conditions. It must be note that any of these combinations would suffice to give a tower footing resistances less than 30 ohms.

Table 3 explores the Driven Rod option. The model varies the number of rods and hence the length of the conductor required in obtaining a TFR value of less than 30 ohms for each case study. The number of rods is user specified.

Table 3: Relationship between rods, length and tower footing resistance

Driven Rod												
	Case Study 1				Case Study 2				Case Study 3			
No of Rods	1	2	3	4	1	2	3	4	1	2	3	4
Length (m)	22	17	16	15	17	13	12	11	8	7	6	6
Resistance	30	30	28	29	29	29	28	29	30	26	28	26

The length of the rods required to reduce the tower footing resistance to less than 30 ohms decreases as the soil resistivity values decreases. Table 4 shows the results obtained for the crow's foot option

Table 4: Crows Foot

	Crows Foot	
	Rg(Ohms)	Length(m)
Case 1	27.3	90
Case 2	29.1	60
Case 3	25.6	30

Table 4 illustrates the length of conductor needed to reduce the tower footing resistance to a value less than 30ohms. The sub routine created in MATLAB would then compare the results from all three methods and would display the technical solution that would provide the lowest tower footing resistance as shown in table 5.

Table 5: Method with lowest tower resistance values.

	Method	Tower footing resistance value
Case 1	Radial	23.4
Case 2	Radial	17.3
Case 3	Radial	16.25
Case 4	All values less than 30 ohms	

IV. PEAK LIGHTNING CURRENT

At the strike point on an overhead line earth wire, the injected current is equally split between the earth wire ends connected to the towers. Therefore, the impedance Z as seen from Fig. 4 shows the lightning strike is a parallel circuit of earth wires Z_{ew} and tower impedances Z_t plus the ground impedance Z_e.

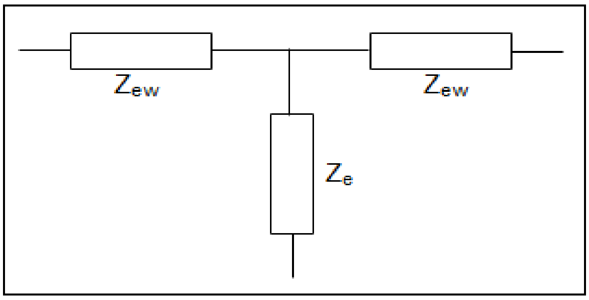

Fig. 4: Three-way current split based on impedance

If the lightning channel impedance is 3000Ω, the earth wire impedance is 500Ω, tower impedance is 200Ω and ground impedance is 50Ω, the equivalent impedance seen by the lightning stroke calculates to 334Ω resulting in the injection of approximately 90% of the strike current at the strike point. Thus a 30-kA strike to the earth wire would result in a 14-kA surge going in each direction towards the towers. The surge would travel to the pole top (a point of impedance change). At this point there will be a reflected and transmitted component. The pole top junction has several paths available for the current and voltage waves and the surge current will split according to the inverse ratio of the surge impedances of the routes available – say ~200Ω down the tower route and ~500Ω for the continuing earth wire. The 14 kA surge would therefore split approximately 5/7 down the tower i.e. 10 kA.

V. BACK FLASHOVER

Lightning strokes has the capacity to discharge hundreds of Kilo-Amperes with low-rise time. The strokes can strike the towers, phase conductor or overhead earth wires and can produce over-voltages of sufficient energy to cause flash over across the insulators. Back-flashover is the situation when the potential difference between the tower top and cross-arm exceeds that of the phase insulator voltage.

Since most of the stroke current flows into the ground, the tower footing resistance has a major impact on the over voltages generated. The back flashover causes a line to ground fault that will be cleared by a circuit breaker. The opening of the circuit breaker will result in a power outage to the customers supplied by that line, until the circuit breaker is reclosed.

This would last for a few milli-seconds depending on the speed of the protection operations. The back-flashover-generated surge has a very sharp wave front as the arc causes the phase wire to jump in less than 1μs from an induced voltage level (from the surge along the earth wire) to virtually the full lightning surge voltage as present on the tower cross-arm (the arc itself will drop a few hundred volts only).

VI. TOWER MODEL

By ignoring the tower resistance and allowing for the low precision, the tower can be equivalent to the lumped inductance model [11]. The equation of the lumped inductance model is given by:

$$Z_T = 60 \ln\left[cot\left(0.5 \tan^{-1}\left(\frac{r_{avg}}{Ht}\right)\right)\right] \qquad (4)$$

Where,

$$r_{avg} = \frac{r_1 h_1 + r_2(h_1 + h_2) + r_3 h_1}{h_1 + h_2}$$

Z_T = average tower surge impedance

r_1 = tower top radius

r_2 = tower mid-section radius

r_3 = tower base radius

h_1 = height from base of tower to mid-span

h_2 = height of mid span to top

The surge impedance model may be considered to be a transient wave proceeding across the tower. In the surge impedance models, tower over voltage is the result of superposition of the lightning over voltage and the reflected voltage wave from the tower bottom. The calculation principle of the single-surge impedance of tower is regarded as a cone [11].

VII. INSULATOR FLASHOVER VOLTAGE

Normally the insulator withstand voltage is prescribed as part of the specifications. The voltage time characteristics as been proposed by CIGRE is given in (5) and is used for the simulations [10], [12]

$$V_{flashover} = K_1 + \frac{K_2}{t^{0.75}} \qquad (5)$$

Where,

K_1 = 400 L

K_2 = 710 L

L = Length of insulator in meters

t = Elapsed time after lightning stroke in micro seconds.

Fig 5 illustrates the insulator flashover voltage for different insulator lengths. As expected the insulator flashover voltages increases for increasing insulator length. The expected peak flashover voltage for a 1.0-meter insulator (88kV) is 549kV. This is for a lightning waveform of 8/20 microsecond.

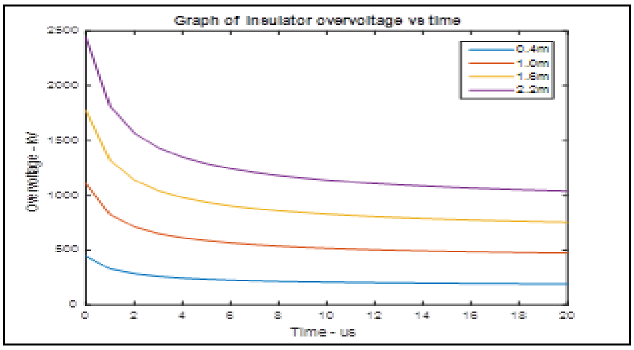

Fig 5: Graph of insulator overvoltage vs time

VIII. TOWER TOP VOLTAGE

The resulting lightning stroke terminating on the tower, earth wire or directly onto the phase conductor will result in current flowing through the tower to ground. The tower has some resistance and along with the ground resistance will result in a potential difference between the top of the tower and ground. Normally if the tower top voltage is greater than the flashover voltage of the insulator, there will be a flashover across the insulator. Hence, to calculate the voltage produced by the current and charge fed into the tower and ground wires, conventional traveling-wave theory should be used. However, the proper values of surge impedances need to be used.

There are a number of tower surge impedances that appear in various literatures; hence a specific equation justified by theory is an important result of this analysis. An estimation of the tower top voltage may be given by [13]. Fig 3 shows the relationship between top tower voltage and lightning strokes.

$$V_t = Z_1 I - Z_W\left(\frac{I}{(1-\omega)} - \frac{\Delta I}{(1-\omega)^2}\right) \qquad (6)$$

Where,

$$Z_1 = \frac{Z_s Z_T}{Z_s + 2Z_T}$$

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

$$\omega; = \left(\frac{2Z_T - Z_s}{2Z_T + Z_s}\right)\left(\frac{Z_T - R}{Z_T + R}\right)$$

$$\Delta I = \left(\frac{2T_t}{T_0}\right) I$$

Z_1 = Intrinsic impedance at the tower top (Ω)

Zs = Surge impedance of the line (Ω)

Z_t = Surge impedance of the tower (Ω)

Z_W= Wave impedance of the tower (Ω)

R = Tower footing resistance (Ω)

ω = Damping constant for all the travelling Waves

Tt = Wave travel time on the tower (ms)

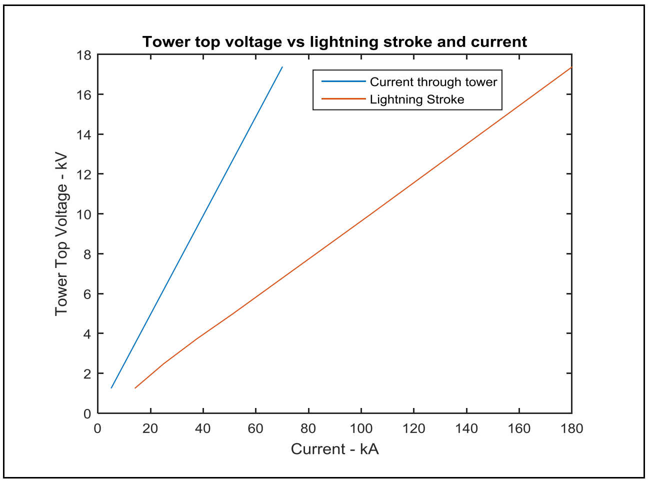

Fig 6: Tower Top voltage vs lightning stroke

With the magnitude of the lightning stroke been the only variable, Figure 6 would indicate a linear relationship. Of importance is the magnitude of the tower top voltage corresponding to that lightning current that flows through the tower. Due to the current splitting, 15kA of a 37.5kA stroke would flow through the tower. This would give a peak overvoltage 3720kV as shown in figure 7. This is based on 8/20 micro second lightning waveform. Figure 8 provides the over voltage curves for different tower footing resistance and lightning strokes.

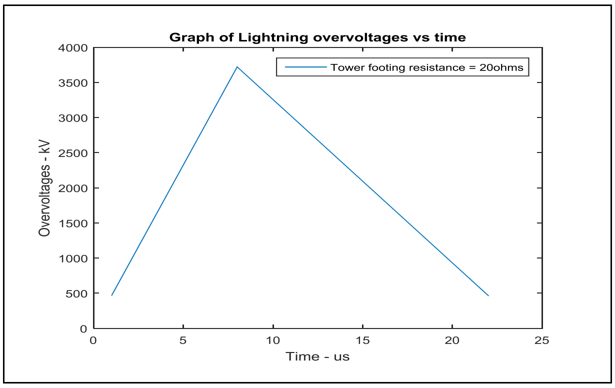

Fig 7: Over voltages caused by a 37.5kA lightning stroke

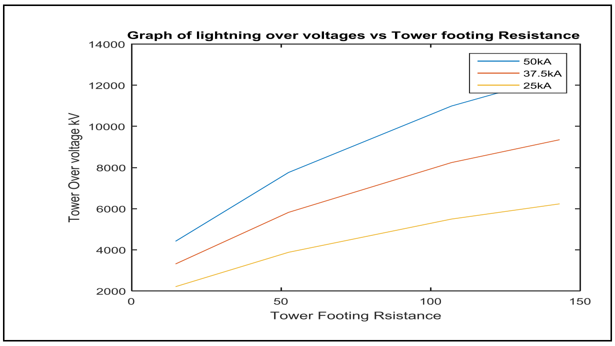

Fig 8: Tower Top Voltage variation vs Tower Footing Resistance

With a constant lightning stroke magnitude, the tower voltage top would increase with an increasing tower footing resistance. No earthling enhancement is considered for the earthling values used as per figure 8. Utilizing earthling enhancement techniques as shown in Tables 2, 3 and 4, reduces the tower footing resistance to a value less than 30ohms, the graph shown in figure 9 is obtained.

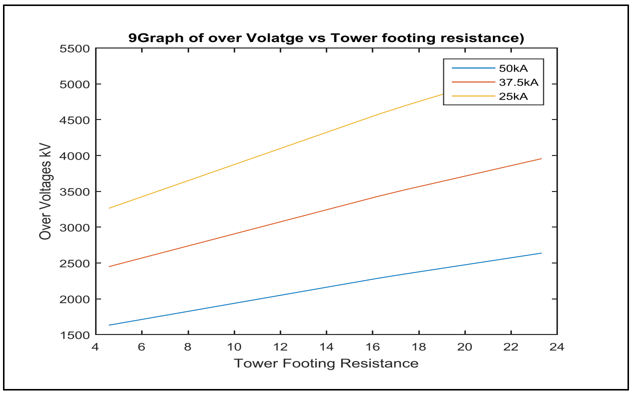

Fig 9: Enhance earthling (less than 30ohms) vs over voltages

The Tower Top Voltage in figure 9 shows a substantial reduction in the tower top voltage compared to that in figure 8. It is almost halved. This highlights the need to have acceptable tower footing resistance. It may be costly to reduce the footing resistance to single digit figures.

IX. SURGE ARRESTOR MODELS

The dynamic characteristics that Metal-oxide surge arresters have are significant for over voltage coordination studies involving fast front surges. There are a number of models that have an acceptable accuracy, which have been proposed to simulate this frequency-dependent behaviour. The calculation and adjustment of the model parameters can be difficult and in instances iterative procedures are required, in other cases the necessary data are not reported on manufacturers' datasheets.

A simplified model for zinc oxide surge arresters has already been developed, on the basis of the frequency dependent model recommended by the IEEE WG.3.4.11. The non-linear characteristic of the line arrester is modelled as recommended by the IEEE W.G 3.4.11, which is metal oxide surge arrester [14]. The IEEE line arrester model has been chosen because the Toshiba surge arrester uses nonlinear resistor metal oxide elements as the main component.

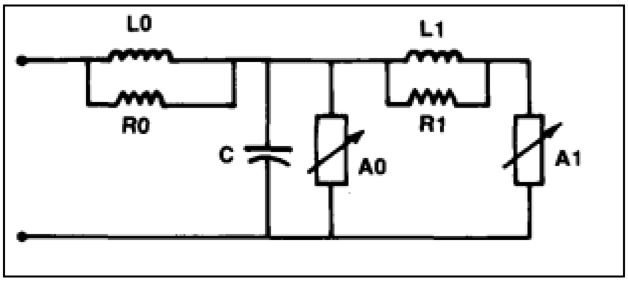

Fig 10: IEEE frequency-dependent model line arrester

The frequency-dependent model consists of two non-linear resistors, A0 and A1, which are separated by an R-L filter, as shown in Fig. 10. Fig. 11 shows the V-I characteristics of A0 and A1 obtained from 8/20 µs impulse data, which is supplied by the manufacturer.

The nonlinear resistors, and, may be modelled in the Electromagnetic Transient Program (EMTP) as a piecewise linear V-I curve. The characteristics can be defined point by point. The number of points selected to represent the nonlinear resistance depends on the smoothness desired. In this example, approximately a dozen points ranging from 10A to 20kA were selected [12] [14]. Fig. 11 is used to determine the initial characteristics of the nonlinear resistors Ao and Ai. Each of the V-I points for the nonlinear resistors is found by selecting a current point and then reading the relative IR

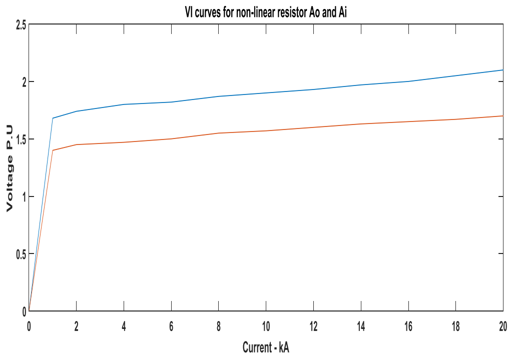

Fig 11: V-I non-linear characteristic for A_0 and A_1

The nonlinear resistors, A_0 and A_1, may be modelled in the Electromagnetic Transient Program (EMTP) as a piecewise linear V-I curve. The characteristics can be defined point by point. The number of points selected to represent the nonlinear resistance depends on the smoothness desired. In this example, approximately a dozen points ranging from 10A to 20kA were selected [12] [14]. Fig. 11 is used to determine the initial characteristics of the nonlinear resistors Ao and Ai. Each of the V-I points for the nonlinear resistors is found by selecting a current point and then reading the relative IR in p.u. from the plot. This value is then multiplied by $\frac{V_{10}}{1.6}$ to determine the model discharge voltage in kV for the associated current. This scaling from p.u. to actual voltage is done by the application of the following formula to the "Relative IR" p.u. voltage obtained for that current as shown in Fig 11:

For A_0, the discharge voltage

$$V_d = B_o \frac{V_{10}}{1.6} \quad (7)$$

Likewise, for A_1,

$$V_d = B_1 \frac{V_{10}}{1.6} \quad (8)$$

$where\ V_d = Discharge\ voltage$

$B_o = Relative\ IR\ in\ pu\ for\ A_0$

$B_1 = Relative\ IR\ in\ pu\ for\ A_1$

For the above arrester, the associated V-I voltage for a l0kA current for the nonlinear resistor, A_0 is determined by reading the "Relative IR" for a 10kA current from Fig 11. Examination of the plot shows that the "Relative IR" for a 10 kA current is 1.9pu. The operating voltage for the 8/20us 10kA surge arrestor specification is 249kV. This value is obtained from the associated surge arrestor data specifications, which is available from the manufacturers. Therefore, the discharge kV for associated with l0kA is:

$$V_d = \frac{1.9 * 249}{1.6} kV \ldots\ldots\ldots (9)$$

X. DISSIPATION OF POWER SURGE ON PHASE CONDUCTOR USING SURGE ARRESTORS

At this stage the power surge caused by the lightning stroke would either be completely drained to ground via the tower or a back flash over would occur. The number of surge arrestors required is thus a simple process of deducting the overvoltage on the phase conductor (remember that this splits into two) by the V_d calculated value, until the power surge is completely eliminated. This would indicate the required number of surge arrestors.

For a current stroke of 25kA and Tower Footing Resistance of 17.38ohms, four 88kV surge arrestors connected in parallel would be required to completely dissipate the lightning stroke and hence preventing the line breaker from operating and causing small duration outages. The connectivity of the surge arrestors is shown in figure 12.

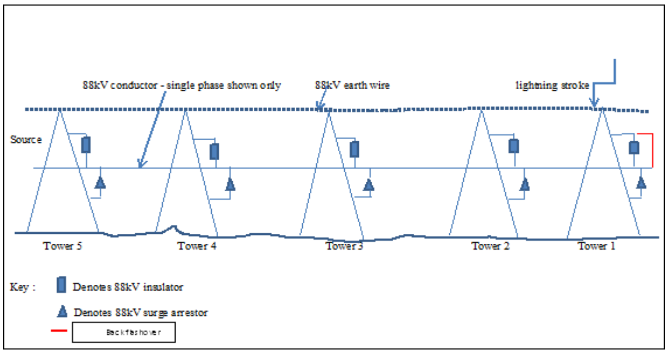

Fig 12: Surge arrestor connected on a parallel on a number of towers

Figure 13 illustrates the reduction of the over-voltage caused by a 25kA lightning stroke. Surge arrestors of the same rating were used and the tower footing resistance used is 17.38 ohms.

Table 6a-d illustrates the number of surge arrestors required to drain the over-voltages caused by lightning strokes of different magnitude and for different soil parameters. The soil parameters are taken from case studies 1 to 4.

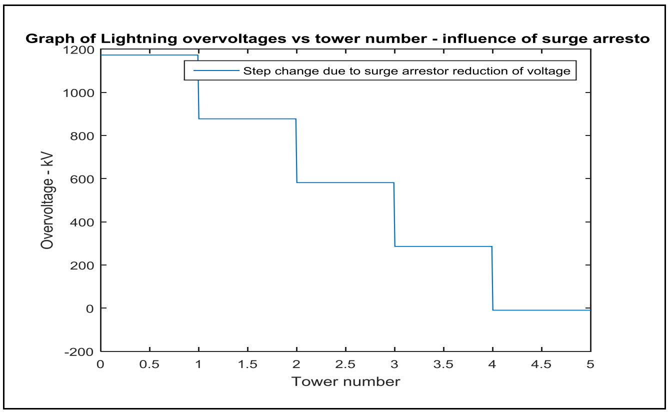

Fig 13: Lightning over voltages vs tower number – influence of surge line arrestors

Case Study 1

Table 2a: Tower Footing resistance of 23.1 and different lightning strokes

Lightning current – kA	Insulator Voltage kV	Tower Footing Resistance	Tower top Voltage kV	Back Flash over	Phase Voltage	Required SA
12	3296	4.56	804	No	402	0
25	3296	4.56	1609	No	805	0
37.5	3296	4.56	1415	No	1107	0
50	3296	4.56	3119	No	1609	0
98	3296	4.56	6194	Yes	3147	3

Table 6a-d illustrates the number of surge arrestors required to drain the over-voltages caused by lightning strokes of different magnitude and for different soil parameters. The soil parameters are taken from case studies 1 to 4.

Case Study 1

Table 6a: Tower Footing resistance of 23.1 and different lightning strokes

Lightning current kA	Insulator voltage kV	Tower footing resistance	Tower top voltage -kV	Back flash over	Phase voltage	Required SA, to prevent outage
12	849	23.2	1318	yes	659	1
25	849	23.2	2636	yes	1318	5
37.5	849	23.2	3955	yes	1978	7
50	849	23.2	5273	yes	2637	9

Case Study 2

Table 6b: Tower Footing resistance of 17.4 and different lightning strokes

Lightning current kA	Insulator voltage kV	Tower footing resistance	Tower top voltage -kV	Back flash over	Phase voltage	Required SA, to prevent outage
12	849	17.38	1173	yes	587	1
25	849	17.38	2346	yes	1113	4
37.5	849	17.38	3510	yes	1760	6
50	849	17.38	4693	yes	2346	8

Case Study 3

Table 6c: Tower Footing resistance of 16.3 and different lightning strokes

Lightning current kA	Insulator voltage kV	Tower footing resistance	Tower top voltage -kV	Back flash over	Phase voltage	Required SA, to prevent outage
12	849	16.3	1144	yes	571	1
25	849	16.3	2288	yes	1144	4
37.5	849	16.3	3431	yes	1716	6
50	849	16.3	4578	yes	2288	8

Case Study 4

Table 6d: Tower Footing resistance of 4.56 and different lightning strokes

Lightning current kA	Insulator voltage kV	Tower footing resistance	Tower top voltage -kV	Back flash over	Phase voltage	Required SA, to prevent outage
12	849	4.56	816	No	408	0
25	849	4.56	1632	yes	816	3
37.5	849	4.56	2449	yes	1225	5
50	849	4.56	3265	yes	1633	6

It is interesting to note that even with a low tower footing resistance and lightning strokes greater than 25kA will still cause a back flash over. These cases would require line surge arrestors to drain the power surge to earth.

The following two profiles show the lightning strokes experienced by an 88kV 49km overhead line. The graph in figure 14 shows the count per lightning stroke category and figure 15 shows the accumulative count of strokes per lightning strength category [15].

Almost 85% of the recorded strokes are less than 25kA and over 95% of the strokes are below 50kA. This implies, with correct tower footing resistance (less than 30ohms) and utilizing 9 sets of surge arrestors, the outages resulting from these lightning strokes should be substantial reduced.

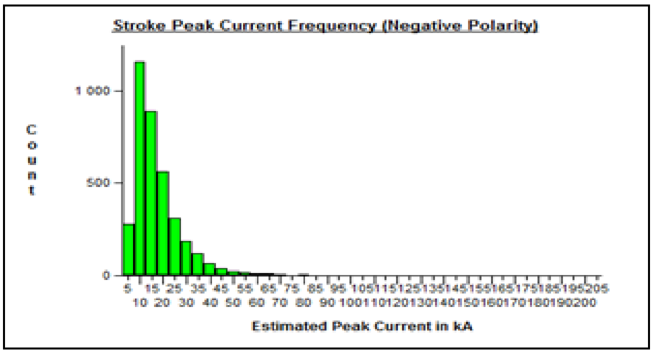

Fig 14: The count per lightning stroke category

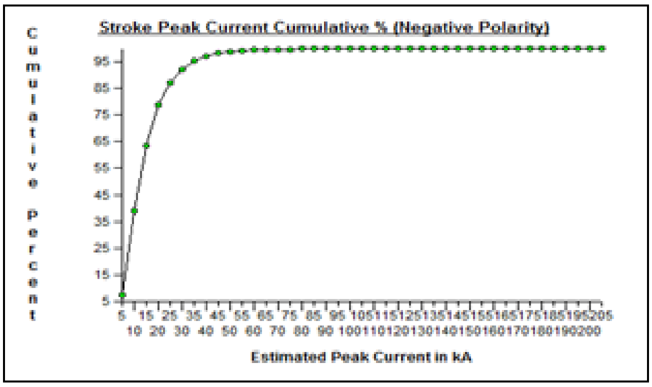

Fig. 15: The accumulative count of strokes per lightning strength category

Figure 16 illustrates the number of breaker interruptions over a 4-year period [15]. All these interruptions resulted from lightning strokes within a diameter of 1km of the line. The corresponding stroke magnitude for the breaker interruptions time was obtained from the FALLS system [1].

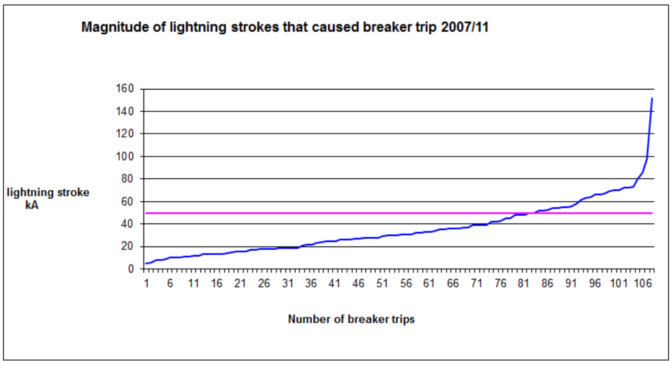

Fig 16: Incident of breaker interruptions vs stroke magnitude

Analysis of the data revealed that there were 106 lightning induced breaker interruptions over a four storm cycle period. 83 of these interruptions resulted from lightning strokes less than 50kA. This is about 78% of the interruptions. Hence by installing 9 sets of surge arrestors, we can prevent these 83 interruptions. This would be an average of 21 per year. To overcome more lightning related breaker interruptions additional surge arrestors maybe required.

XI. FINANCIAL EVALUATION

a) Annual expected number of voltage dips and momentary outages due to lightning. Performance monitoring of a sub transmission overhead line revealed that for a period between 2007 and 2011, there was 106 lightning induced momentary interruptions. This is an average of 26 lightning related interruptions per year.

b) Estimate the cost associated with voltage dips and momentary outages. A study undertaken by Nzimande [16] revealed that lightning related dips lead to losses of between US $5357 and US $35714 per annum for 10 storm related dips, and average of between US$535.7 and US $3571 per dip.

c) The cost for the installation of 27 surge arrestors to effectively militate against breaker operation is shown in table 7

Table 7: illustrating the costs to install 27 surge arrestor

Item	Year 1018
Cost of a surge arrestor and counter	$ 35 760
Cost of 17 surge arrestor and counters	$ 96 564
Labour and transport	$ 31 060
Total	$127 623

Figure 17 shows that it will take 12 years to recover the capital invested in the surge arrestors to mitigate against dips. The inflation rate is assumed to be 10%.

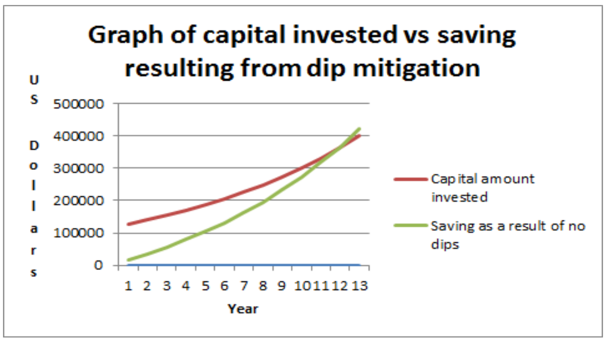

Fig 17: Break-even point occurs in year 12

XII. CONCLUSION

The tower top voltage is a function of the lighting stroke, line and tower surge impedance and the earth resistance. Using earthling enhancement techniques such as additional conductors, not only reduces the tower footing resistance, but also reduces the tower top voltage by almost 50%. Hence it is important that the tower footing resistance be kept to values less than 30 ohms.

Should the insulator flashover voltage be exceeded, this will give rise to a flashover. The same tower top voltage level will be present on the live side of the surge arrestor.

Lightning surges travel at the speed of light. This waveform does not stay at the node of the surge arrestor for durations long enough for the surge arrestor to dissipate the voltage to ground. Hence additional surges arrestors are required.

The placement of the surge arrestor should be in parallel to each other and placed after the operating device, which would be used to clear the fault. This should prevent the device from operating and any short during outages.

Mitigation against a lightning stoke of 50kA will require 9 surge arrestors per phase. For this amount of surge arrestors, the break-even point will be 12 years. Mitigation against high lightning strikes would require more surge arrestors.

REFERENCES

[1]. Global Atmospherics Inc,, "Vaisala-GAI fault Analysis and Lightning Location Systems (FALLS) Version 3.2.4," Tucson, Arizona, USA, 2002.

[2]. T. Hayashi, Y. Mizuno and K. Naito, "Study on Transmission – Line Arresters for Tower with High Footing Resistance," IEEE Transaction on Power Delivery, vol. 23, no. 4, pp. 2456-2460, October 2008.

[3]. C. Li-Hsiung, C. Jiann-Fuh, L.Tsorng-Juu and W. Wen-I, "Calculation of ground resistance and step voltage for buried ground rod with insulation lead," Electric Power Systems Research 78, p. 995– 1007, 2008.

[4]. "High Voltage Surge Arrestors," WWW.ABB.COM.

[5]. E. Singh, I.E. Davidson, G.K. Venayagamoorthy, "Methodology for measuring and enhancing Tower Footing Resistance for Lightning Protection for an 88kV line," in Saupec Conference, Stellenbosch, February 2017.

[6]. O.E. Gouda, G.M.Amer and T.M El-Saied, "Factors Affecting the Apparent Soil Resistivity of Multi-Layer Soil," in Proceedings of the XIVth International Symposium on High Voltage Engineering, 2005.

[7]. I. E. Davidson, "A Mathematical Algorithm for Investigating Soil Resistivity," in Proceedings of the 6th Southern African Universities Power Engineering Conference. University of the Witwatersrand, Johannesburg, 1996.

[8]. G.A, Adegboyega and K.O. Odeyemi, "Assessment of Soil Resistivity on Grounding of Electrical Systems: A case study of North-East Zone, Nigeria," Journal of Academic and Applied Studies, vol. 1(3), pp. 28-38, September 2011.

[9]. S.C Malanda, E. Buraimoh, I.E.Davidson and E. Singh, "Analysis of Soil Resistivity and its Impact on," in SAIEE Power Africa Conference , Cape Town, June 2018.

[10]. Mohd Z.A Ab Kadir, Zawati Mohd Nawi and Junainah Sardi, "Numerical Modeling and Simulation in Electro Magnetic Transient Program for Estimating Line Back Flashover Performance," November 2010.

[11]. C.F. Wagner and H.R. Hileman, "Lightning Performance of Transmission lines 3," AIEE Power Apparatus and Systems, p. 903, November 1960.

[12]. G. Radhika, M. Suryakalavathi and G. Soujanya, "Effective Placement of Surge Arrestor during Lightning," International Journal of Computer Communication and Information System, vol. 2, no. 1, pp. 167-172, 2010.

[13]. M. Dekker, "Lightning Surge Analysis http://197.14.51.10:81/pmb/ informatique/computer%20aid%20analys/0824706994/ PDFs/DK1913_CH13.pdf.," 2012. [Online].

[14]. N.H.N. Hassan, A.H.A. Bakar, H. Mokhlis and H. A. Illis, "Analysis of Arrestor Energy for 132kV Overhead Transmission Line due to Back Flashover and Shielding failure," Proceedings Of the 16th IEEE International Conference on Power and Energy, pp. 683-688, December 2012.

[15]. E. Singh, "“Fault Mitigation and Performance Improvement of an 88kV line using Line Surge Arrestors and Counters," Durban, 2016.

[16]. Nzimande, T.M., "Voltage Dip Performance Analysis," Master of Science Thesis, pp. 90-96, 2009.

[17]. Johnson and Arnold Ivan., "Methods of measuring soil moisture in the field," US Government Printing Office, 1962.

[18]. Black C.A., "Methods of Soil Analysis: Part I Physical and mineralogical," American Society of Agronomy, Madison, Wisconsin, USA, 1965.

[19]. IEEE Working group 3.4.11, "Modeling of metal oxide surge arrestors," IEEE transaction on Power Delivery, vol. 7, no. 1, pp. 302-309, January 1999.

[20]. “Earthing Fundamentals” Lightning and Surge Technologies:, "www.lightningman.com.au," [Online].