

# Utilization of Line Surge Arrestors to Improve Overhead EHV DC Line Performance under Lightning Conditions

Eddie Singh <sup>1</sup>, Innocent E. Davidson <sup>2</sup>

<sup>1</sup> Eskom Distribution, Newcastle, KZN 2940, South Africa.

<sup>2</sup> Department of Electrical Power Engineering, Durban University of Technology, South Africa.

## Abstract

In high lightning areas, lightning strokes play an important role in the performance of overhead HV DC lines. A single stroke can lead to back flashovers and the resultant surge on the conductor usually results in the protective devices operating to extinguish that power surge. This operation of the protective devices leads to consumer interruptions and loss of industrial production, which negatively affects the economy. Devices such as Line Surge Arrestors that can drain that power surge to ground are available. This paper examines 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. The network and surge arrester installations were modelled using MATLAB software. The required number of surge arrestors per phase is thus determined that is required to drain the surge current down to earth, thus preventing power interruptions; and the results obtained from tests and simulation are presented and discussed.

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

## I. INTRODUCTION

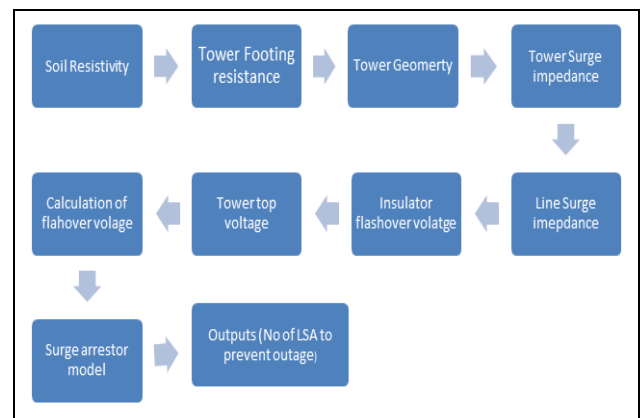
Lightning strokes tend to terminate on the tower or earth wire of Extra High Voltage (EHV) DC overhead lines. Depending on factors such as the conductor type, tower, soil impedance and magnitude of the strike, it will result in flashover across the insulator. The resultant fault surge will propagate along the line until it is extinguished or until the breaker operates. This movement of the surge tends to ‘damage’ and reduce the life span of associated equipment such as breakers, transformers, and impacts network performance adversely. Should the breaker operate, the resultant short duration outage or dips, would negatively affect customers. Customers with sensitive equipment such as motors would halt and production would stop – negatively affecting production.

For DC systems, under phase to earth fault conditions, the current flow to earth produces potential gradients within and around the grounding system. Arising from these situations, dangerous voltages may develop between ground structures or electrical equipment frames. To prevent this situation a safe grounding design must consider the following:

- The resistance of the ground of the system to remote earth.
- The magnitude and position of the maximum step voltage that may result at the earth’s surface
- The surface voltage where individuals are standing whilst their hands are in contact with some structure

In any transmission system, the current practice is to have tower footing resistance below a certain value. This would allow the lightning surges to be dissipated through the earthing systems. The introduction of Visalia-GAI Fault Analysis and the Lightning Location System (“FALLS”) Version 3.2.4, enable us to determine the magnitude and position of the lightning stroke more accurately [1]. Preliminary analysis indicates that only a portion of the strokes can be withstood by the current line design.

These lightning’s strokes contribute to the poor line performance. Previously, the magnitude of the lightning strikes was not known. Lightning mitigating devices called Line Surge Arrester (LSA) can be used on existing HVDC lines to improve system performances. Installing surge counters onto the LSA would enable us to obtain information such as the date, time and magnitude of the current that flowed through the LSA. Figure 1 shows 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:** Flow chart to determine required number of surge arrestors to prevent power interruptions.

1. Earthling Electrode

There are many possible configurations for designing an earth electrode. These include:

- a) Vertical electrode (Driven rod)
- b) Shallow horizontal electrode
- c) Deep well electrode
- d) Ring electrode

Genetic models were developed in MATLAB to calculate the tower footing resistance bases on the following formulae. This was developed based on the following formula [2], [3]

The Driven Rod:

$$R = \rho \frac{\left[ \ln\left(\frac{L}{d}\right) + ((r-1) \times D) \right]}{2 \times r \times L \times \rho} \tag{1}$$

For horizontal Electrode (crow's foot):

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

For Radial Conductors:

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

where,

r = number of rods

R = Tower Footing Resistance in ohms

ρ = Soil Resistivity in ohm-meter

L = Length of conductor in meters

r = 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).

2. Ground Rod

The ground rod is one of the more popular grounding systems used. It is installed by the driven and the buried rod method. The rod is driven into the soil with its upper end at the soil level. The buried rod results in the upper level been below the soil level. Research has shown that the ground resistance, earth's surface voltage and step voltage of the driven ground electrode exceed that of the buried rod. Hence, the buried rod is used to ground the system. A ground rod of radius r (m), length L (m) can dissipate a current I (A) in a soil with an

apparent resistivity of ρ (Ω-m) and a depth of T (m) as illustrated in figure 2.

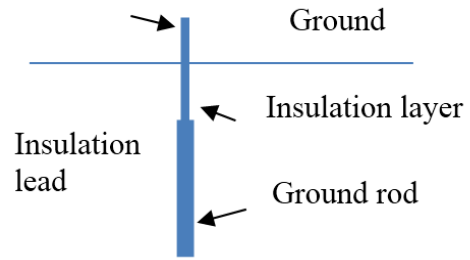


Fig 2: Buried ground rod with insulated lead

It is assumed that the linear leakage current over the surface of the ground rod is uniform, the end effect of the ground rod is negligible and the voltage on the ground rod is kept constant. The method of average potential was used to determine the value of the voltage on the surface of the ground rod. The ground resistance of the ground rod can be obtained by the equation:

$$R(r) = \frac{V_{av}}{I} = \frac{\rho F(r)}{2\pi L} \tag{4}$$

Where

$$F(r) = \ln \frac{L}{r} \left[ 1 + \sqrt{1 + \left(\frac{r}{L}\right)^2} \right] + \frac{r}{L} - \sqrt{1 + \left(\frac{r}{L}\right)^2} +$$

$$\ln \left[ \frac{2(L+T) \left[ 1 + \sqrt{1 + \left(\frac{r}{2(L+T)}\right)^2} \right]}{(L+2T) \left[ 1 + \sqrt{1 + \left(\frac{r}{(L+2T)}\right)^2} \right]} \right] +$$

$$\frac{T}{L} \ln \left[ \frac{2(L+T) \left[ 1 + \sqrt{1 + \left(\frac{r}{2(L+T)}\right)^2} \right] (2T) \left[ 1 + \sqrt{1 + \left(\frac{r}{(2T)}\right)^2} \right]}{\left[ (L+2T) \left( 1 + \sqrt{1 + \left(\frac{r}{(L+2T)}\right)^2} \right) \right]^2} \right] -$$

$$\left( 1 + \frac{T}{L} \right) \sqrt{1 + \left[ \frac{r}{2(L+T)} \right]^2} + \left( 1 + \frac{2T}{L} \right) \sqrt{1 + \left( \frac{r}{L+2T} \right)^2} -$$

$$\frac{T}{L} \sqrt{1 + \left( \frac{r}{2T} \right)^2}$$

The earth surface voltage Vz can at any point be written as:

$$V_z = \frac{\rho I}{2\pi L \ln} \frac{(L+2T) + \sqrt{(L+2T)^2 + z^2}}{2T + \sqrt{2T^2 + z^2}} \tag{5}$$

The step voltage, which can be defined as the difference between the surface voltages, that a human would experience

that, bridges a distance of 1 meter with the feet without contacting any other grounded object.

$$V_{step} = \frac{\rho l}{2\pi l} \left[ \ln \frac{(L+2T) + \sqrt{(L+2T)^2 + T^2}}{2T + \sqrt{2T^2 + T^2}} - \ln \frac{(L+2T) + \sqrt{(L+2T)^2 + (Z+1)^2}}{2T + \sqrt{2T^2 + (Z+1)^2}} \right] \quad (6)$$

The maximum permissible step voltage is 8.5 volts. This is based on a body current of 6mA and a 70 ohm-m uniform soil resistivity.

$$E_{MAX} = I_b(1000 + 6p_s) \quad (7)$$

$E_{MAX}$  = Permissible voltage

$I_b$  = Body current

$p_s$  = soil resistivity

Hence, the design of the earth electrode must satisfy both the step voltage and the ground resistance conditions. The ground resistance is the resistance offered by the metal parts of the tower combined with the ground resistance to the dissipation of current. The significance of a low value of ground resistance results in less voltage stresses across the line insulation. A lightning strike to the tower results in high currents flowing into the ground through the tower footing. This gives rise to soil ionization and thermal effects. Hence, the ground resistance of the tower base decreases by an amount depending on the soil resistivity, the current magnitude and tower footing construction [2], [3], [4], [5].

To maintain the ground potential rise within safety tolerance, the ground resistance value needs to be as low as possible. This would also assist in preventing line back flashover. 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 peak voltage at the tower top.

## II. ELECTRODE DESIGN

Five key factors that affect the design of an electrode [5], namely:

- Safety.
- Physical design criteria and constraints.
- Potential environmental impact.
- Potential influence of electrode operation on other facilities.
- Practicality of building an electrode at the site.

In this paper, the following two factors are of importance and discussed.

### 1. Safety

The design of the electrode should not result in animals or humans been harmed by the operations of the electrode. The operational conditions man falls into two main areas. These are:

- Continuous conditions that persist for 10 seconds or longer

- Transient conditions which would persist for less than 10 seconds

In the case of the DC transient line fault, the transient overcurrent should persist for only about 50 ms, until the current line protection and current controller will reduce the fault current to zero. The criteria for these two timeframes are different since the tolerance of the human body to current is time dependent. Table 1 shows the tolerance of the human body to dc current.

The criteria that are selected for used in safety design limits for the earth electrodes are superimposed on Figure 2. Acceptable levels of current within the body are generally considered currents that are above the threshold of perception, but which are below the let-go current level and well below the current that would result in fibrillation of the heart. These current magnitudes may be large enough to cause annoyance to the person or animal, but would not be sufficient to endanger life or cause injury.

**Table 1:** Human body tolerance to dc current

Bodily Effect	Men/Women	Direct Current (mA)	60 Hz AC (mA)	10 kHz AC (mA)
Slight sensation felt at hand(s)	Men	1.0	0.4	7
	Women	0.6	0.3	5
Threshold of pain	Men	5.2	1.1	12
	Women	3.5	0.7	8
Painful, but voluntary muscle control maintained	Men	62	9	55
	Women	41	6	37
Painful, unable to let go of wires	Men	76	16	75
	Women	60	15	63
Severe pain, difficulty breathing	Men	90	23	94
	Women	60	15	63
Possible heart fibrillation after 3 seconds	Men and Women		500	100

Generally, the safety criteria for electrodes are defined using acceptable levels of dc current within the body. An exception is consideration of the maximum transient electrode fault current that has a short duration. This is characterized as an ac current or pulse current superimposed on a dc level. The tolerance of the body to current flow is a function of the frequency of the current. The acceptable values of dc current in the body are higher than the corresponding values of power frequency ac current [6].

It should be noted that the sensitivity of adults to dc current has been studied and tested, but there is very little data concerning children. It is known that the threshold of perception and let-go currents are lower in women than in men, and children are expected to be slightly lower than women [7] are. In most cases, 6mA is the acceptable level of current that a body threshold used to design the electrode.

## 2. Safety Metrics and Criteria

Safety of humans and animals at an electrode site is of concern primarily within the area where the surface potential rise and the associated surface potential gradients resulting from electrode operation are high. This is applicable to areas where there are bodies of water and the currents that can enter the human and animals that enter or are present in the water.

Safety can be defined in terms of the following quantities (using the definitions from IEEE Std. 80, modifying them to reflect the special character, and operating characteristics of HVDC ground electrodes)

- a) Step Voltage
- b) Touch Voltage
- c) Metal-to-Metal Touch Voltage
- d) Transferred Voltage or Transferred Potential
- e) Potential gradient in water

These need to be evaluated when considering the safety of the earth electrode installation. Note: The acceptable values are not based on voltage but rather on acceptable levels of currents within the human and animal bodies as discussed in (a).

However, for convenience in electrode design, it is usually desirable to be able to work with voltage limits or limits on potential gradients, which can be more easily calculated and verified by measurements. Safe or acceptable values of voltages and potential gradients are determined by working backwards from the acceptable levels of current in the body using assumed conservative values of contact resistance and body resistance.

The two criteria, which may extend for significant distances into publicly accessible areas, are:

- Transferred potential,
- Voltage gradient in water

Step voltages approaching the limits would normally be confined to within the areas of the earth electrode sites. It is advising that these areas be located behind locked fences, as the public cannot be protected from the effects. An earth electrode is a metal plate, pipe or conductor electrically connected to earth. They can be made up of either copper, aluminum, mild steel or galvanized steel. Some of the factors that influence the earthing are [6], [7]:

- a) Resistance of the electrode or group of electrodes.
- b) Composition of the soil in the immediate neighborhood.
- c) Temperature of the soil.
- d) Moisture content of the soil.
- e) Depth of the electrode.

## III. TOWER FOOTING

MATLAB program was developed to calculate tower footing resistance for four case studies. These models are based on equations 1, 2 and 3. 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 [4] and was varied for wet conditions (less than 200 ohm meter) and dry conditions (~ 1800 ohm meters) [8]. The results obtained from four case studies are displayed in Table 2

**Table 2:** 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	1025	763	375	105
Tower footing resistance (ohm)*	143	107	52.5	14.7

For EHVDC lines, the overall tower footing resistances needs to be less than 30 ohms. Case study 1, 2 and 3 displays values in excess of 30 ohms. To reduce the values to that below 30 ohms, either the can be obtained by increasing either the number of rods or conductor length. 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 3 shows the various configurations, in terms of conductor length and numbers.

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.

**Table 3:** 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

From case study 3, to obtaining a tower footing resistance of 23.2, it would require 6 conductors of 10 meters each. This material length is 60 meters is much less than that of case study 1. 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.

Arising from case study 1, the best combination is 13 conductors with a length of 20 meters each will provide a TFR of 23.2 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.

**Table 4.** 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.

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 5 illustrates the length of conductor needed to reduce the tower footing resistance to a value less than 30ohms

**Table 5:** Crows Foot

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

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 6.

**Table 6:** 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. SURGE IMPEDANCE OF THE LINE AND TOWER MODEL**

[9] give the surge impedance of the line:

$$Z_g = 60 \ln \frac{2h}{r_i} \tag{8}$$

where  $h$  is the ground-wire height,

$r_i$  = radius of conductor

By ignoring the tower resistance and permitting low precision, the tower can be equivalent to one inductance called lumped inductance model [9]. The formula of lumped inductance model is:

$$Z_T = 60 \ln \left( \cot \left[ 0.5 \tan^{-1} \left( \frac{r_{avg}}{H_t} \right) \right] \right) \tag{9}$$

Where

$$r_{avg} = \frac{r_1 h_1 + r_2(h_1 + h_2) + r_3 h_1}{h_1 + h_2} \tag{10}$$

$Z_T$  = average tower surge impedance

$r_1$  = tower top radius

$r_2$  = tower mid-section radius

$r_3$  = tower base radius

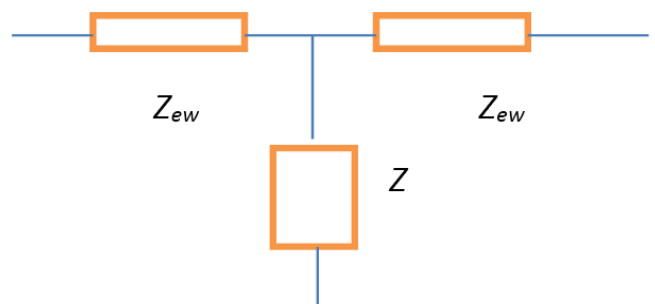
$h_1$  = height from base of tower to mid-span

$h_2$  = height of mid span to top

The surge impedance model can be considered as a transient wave process across the tower. In the surge impedance models, the tower over voltage is the results of superposition of the lightning over voltages and the reflected voltage wave from the tower bottom. The calculation principle of the single-surge impedance of tower is most regarded the tower as cone. [9].

**1. Peak Lighting Current**

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



**Fig 3:** Three-way current split based on impedance

Assuming that the lightning channel impedance is  $3000\Omega$ , the earth wire impedance  $500\Omega$ , tower impedances  $200\Omega$  and ground impedance  $50\Omega$ , the equivalent impedance seen by the lightning strike calculates to  $334\Omega$  resulting in the injection of approximately 90% of the strike current at the strike point

In round terms, therefore, a 30 kA strike to the earth wire will result in a 14 kA surge going in each direction towards the towers. The surge will travel to a point of impedance change (the pole top) at which there will be a reflected and transmitted component. The pole top junction has several routes 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  $\sim 200\Omega$  down the tower route and  $\sim 500\Omega$  for the continuing earth wire. The 14 kA surge will therefore split approximately 5/7 down the tower i.e. 10 kA

### 2. Back Flashover

Lightning strokes are of very high potential with the capacity to discharge hundreds of Kilo-Ampere with low-rise time. Back flash over will occur, should the difference between the tower top voltage and phase voltage exceeds that of the breakdown voltage of the phase insulator.

Since most of the tower stroke current flows into the ground during a lightning incident, the tower footing resistance has a major impact on the over voltages generated. The back flashover will cause a line to ground fault that should be cleared by a circuit breaker within a few milliseconds. This may result in a line outage or dips, until the circuit breaker is reclosed. The back-flashover generated surge has a very sharp wave front as the arc causes the phase wire to jump in less than  $1\mu s$  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).

### 3. Insulator Flashover Voltage

Normally the insulator withstand voltage is prescribed as part of the specifications. However, the voltage time characteristics as been proposed by CIGRE [10].

$$V_{flashover} = K_1 + \frac{K_2}{t^{0.75}} \quad (11)$$

where

$$K_1 = 400L, \text{ and } K_2 = 710L$$

Figure 4 illustrates the insulator flashover voltage for different insulator lengths.

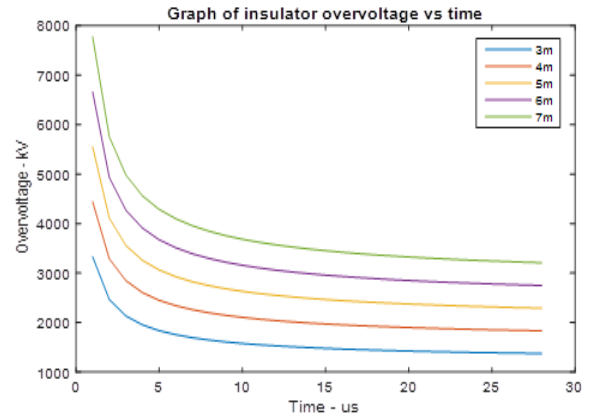


Fig 4: Graph of insulator overvoltage vs time

The calculated breakdown voltage for a 6-meter insulator (533kV) is 3296kV. This is for a lightning waveform of 8/20 microsecond. As expected the insulator breakdown voltages increases for increasing insulator length.

### 4. Tower Top Voltage

Arising from the direct lightning stroke that would terminate on the tower or earth wire, current would flow through the tower to earth. The tower would have resistance and along with the ground resistance will result in a voltage at the tower top with respect to ground. Should the tower top voltage be greater than the breakdown voltage of the insulator, there will be a flashover across the insulator.

One can use conventional traveling-wave theory to calculate the voltage produced by the current and charge fed into the tower and ground wires. The proper values of line and tower surge impedances must be used.

In view of the wide range of tower surge impedances that appear in various literatures, a specific equation justified by theory can be used. Hence, an estimation of the tower top voltage may be given by [11]

$$V_t = Z_I I - Z_W \left( \frac{I}{(1-\omega)} - \frac{\Delta I}{(1-\omega)^2} \right) \quad (12)$$

Where

$$Z_I = \frac{Z_s Z_T}{Z_s + 2Z_T} \quad (13)$$

$$Z_W = \left( \frac{Z_s^2 Z_T}{Z_s + 2Z_T^2} \right) \left( \frac{Z_T - R}{Z_T + R} \right) \quad (14)$$

$$\omega = \left( \frac{2Z_T - Z_s}{2Z_T + Z_s} \right) \left( \frac{Z_T - R}{Z_T + R} \right) \quad (15)$$

$$\Delta I = \left( \frac{2T_t}{T_0} \right) I \quad (16)$$

$Z_I$  = Intrinsic impedance at the tower top ( $\Omega$ )

$Z_s$  = Line surge impedance ( $\Omega$ )

$Z_T$  = Tower surge impedance ( $\Omega$ )

$Z_w$  = Wave impedance of the tower ( $\Omega$ )

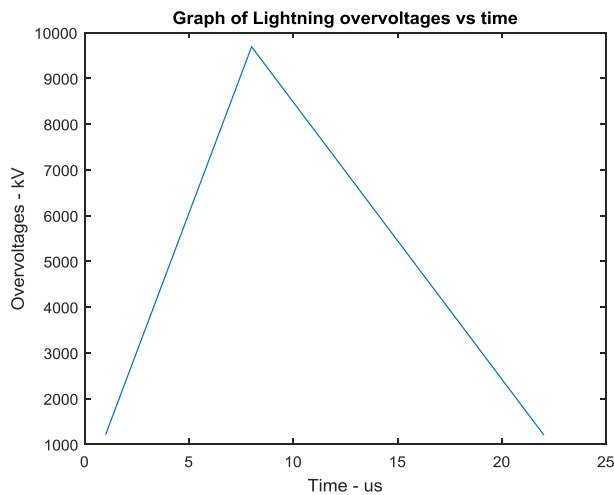
R = Tower footing resistance ( $\Omega$ )

$\omega$  = Damping constant for all the travelling

Waves

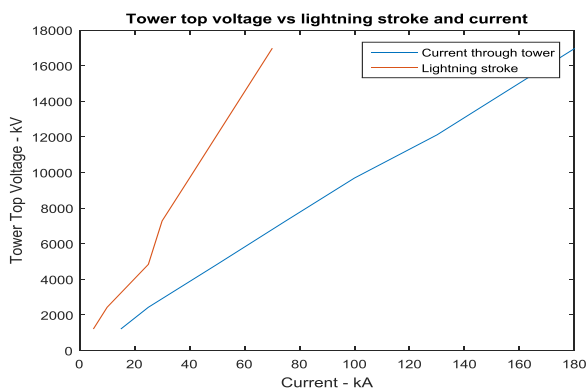
$T_t$  = Wave travel time on the tower (ms)

Figure 5 shows the Tower Top voltage vs lightning stroke. This is for a 100kA stroke on the tower and a tower footing resistance of 17.33ohms.



**Fig 5:** Tower Top voltage vs lightning stroke

Figure 6 was generated using various lightning stroke magnitudes

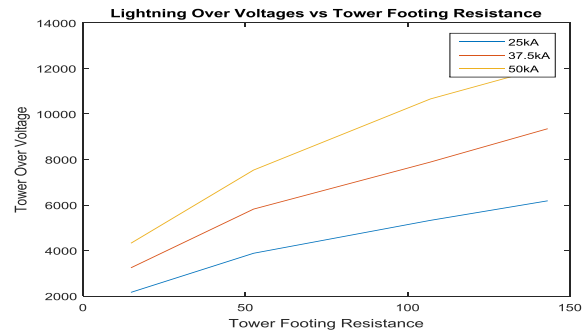


**Fig 6:** Tower top voltage vs lightning current through the tower

With the stroke current been the only variable, a 'linear' relationship with the tower top voltage is obtained. It must be noted that this over voltage is generated using the current flowing through the tower. This is due to the current splitting

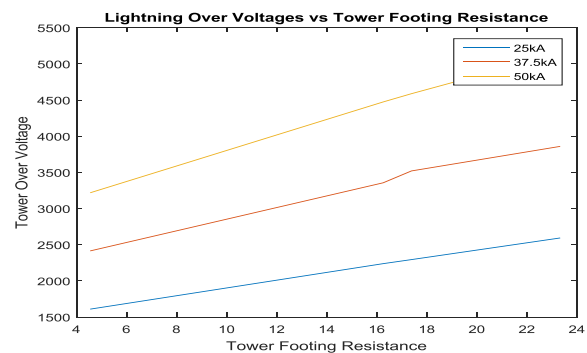
effect. From the above figure, a lightning stroke of 50kA would give rise to a short duration over-voltage of 4475kV.

Figure 7 shows the over voltage curves for different tower footing resistance. This is for different lightning strokes



**Fig 7:** Tower Top Voltage vs Tower Footing Resistance

With a constant lightning stroke magnitude, the tower voltage top would increase with an increasing tower footing resistance. No earthing enhancement is considered for the earthing values used in figure 7. Utilizing earthing enhancement techniques, such as increased conductor lengths, the tower footing resistance is reduced to a value less than 30ohms as shown in figure 8.



**Fig 8:** Tower Top Voltage Vs Modified Tower Footing Resistance

From figures 7 and 8, there is a substantial reduction in the tower top voltage, 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.

## V. SURGE ARRESTOR MODELS

Metal-oxide surge arresters have dynamic characteristics that are significant for overvoltage coordination studies involving fast front surges. Several models with acceptable accuracy have been proposed to simulate this frequency-dependent behaviour. Difficulties arise in the calculation and adjustment of the model parameters: in some cases, iterative procedures

are required, in others the necessary data are not reported on manufacturers' datasheets.

A simplified model for zinc oxide surge arresters has already been developed, based on 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 [13]. IEEE line arrester model has been chosen because the Toshiba surge arrester uses nonlinear resistor metal oxide elements as the main component.

The frequency-dependent model consists of two non-linear resistors, A0 and A1, which are separated by an R-L filter, as shown in figure 9. Figure 8 shows the V-I characteristics of A0 and A1 obtained from 8/20 μs impulse data, which is supplied by the manufacturer

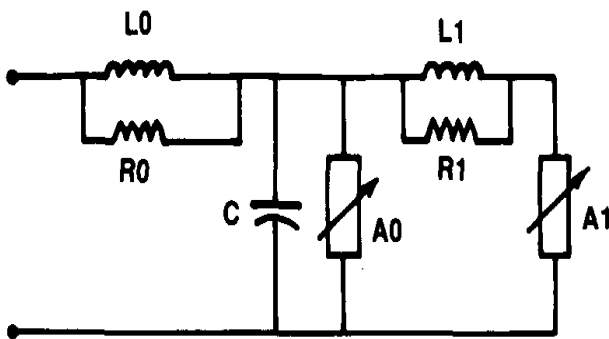


Fig 9: IEEE frequency-dependent model line arrester

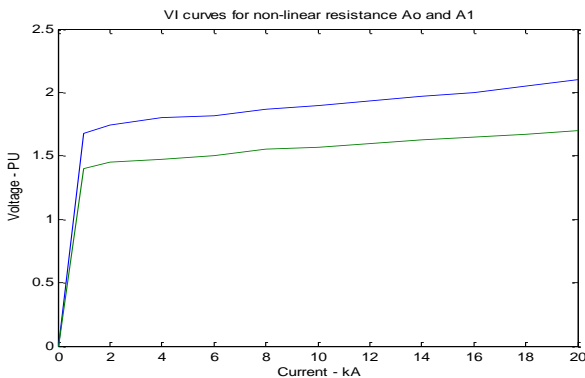


Figure 10: V-I non-linear characteristic for A0 and A1

The nonlinear resistors, Ai and Ai, can be modelled in the EMTP as a piecewise linear V-I curve with characteristics 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], [13].

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 10. This value is obtained from the associated surge arrester data specifications, which is available from the manufacturers.

For A0, the

$$V_d = B_0 \frac{V_{10}}{1.6} \tag{16}$$

Likewise, for A1,

$$V_d = B_1 \frac{V_{10}}{1.6} \tag{17}$$

where  $V_d =$  Discharge voltage

$B_0 =$  Relative IR in pu for A0

$B_1 =$  Relative IR in pu for A1

For the above arrester, the associated V-I voltage for a 20kA current for the nonlinear resistor, A0 is determined by reading the "Relative IR" for a 20kA current from Figure 6.

Examination of the plot shows that the "Relative IR" for a 20 kA current is 2.1pu. Therefore the discharge kV for associated with 20kA is:

$$V_d = \frac{2.1 \cdot 1014}{1.6} \text{ kV} = 1331 \text{ kV} \tag{18}$$

## VI. LIGHTNING PARAMETERS

Figure 9 illustrates the amount of lightning strokes that can occur within a corridor of an overhead EHVDC line. The strokes would be of different magnitude.

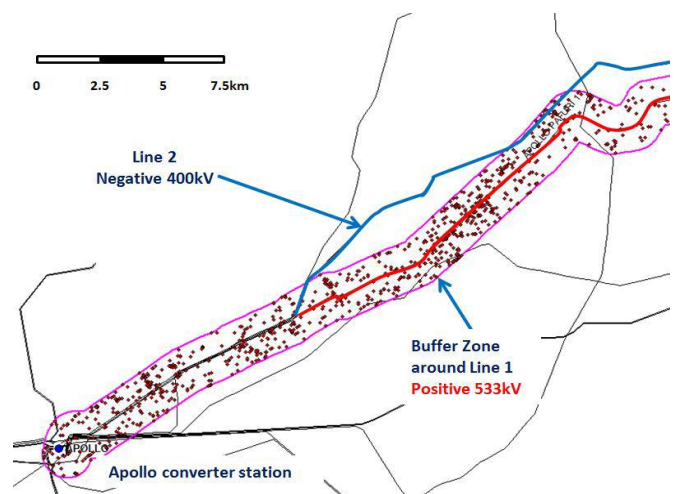


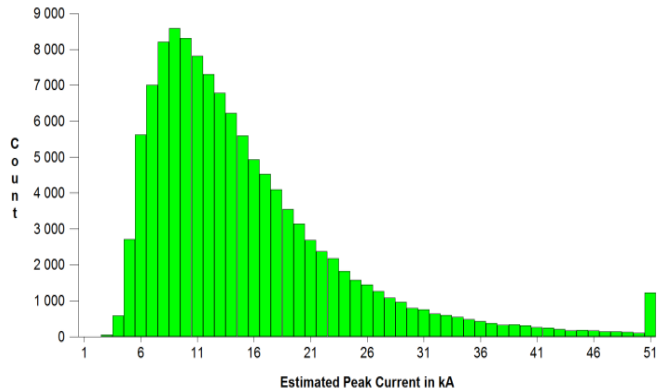
Fig 11: Lightning activity within the 1km buffer of the EHVDC line

In figure 12 and 13 the lightning strokes experiences by a 533kV DC line is shown. [14]. The first graph shows the peak

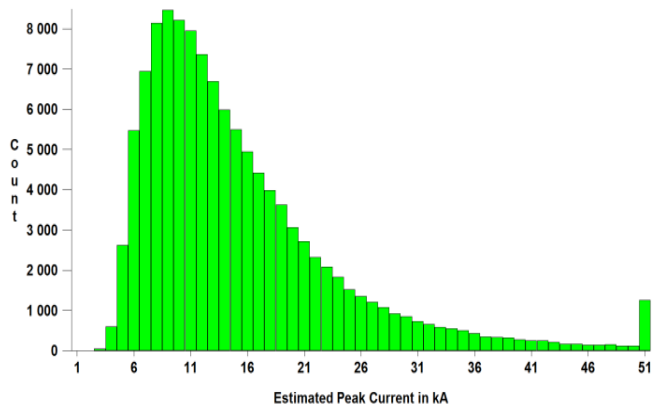


current frequency for the positive pole of the line and the second show same, but for the negative pole.

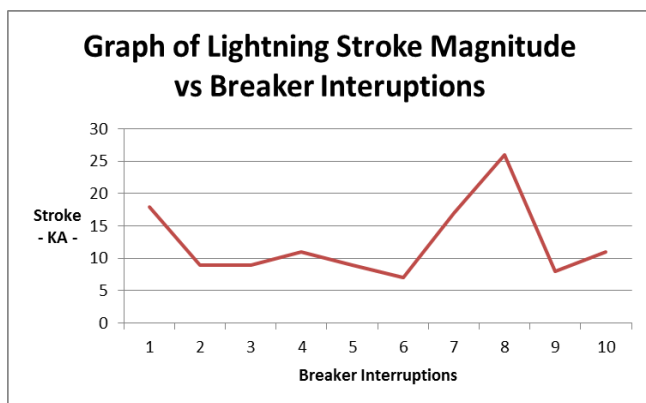
From figure 12 and 13, majority of the lightning strokes are less than 26kA. It is expected that for a line BIL and tower footing resistance, no back flash over would occur for a 25kA lightning stroke. However, there is a small percentage of strokes greater than 50kA. Breaker interruptions would be recorded for this lightning magnitude



**Fig 12:** Positive pole (Line 1) stroke peak current frequency for strokes of negative polarity



**Fig 13:** Negative pole (Line 2) stroke peak current frequency for strokes of negative polarity



**Fig 14:** Stroke magnitude vs breaker interruptions

Figure 14 shows the correlated breaker interruptions due to lightning for a 533kV EHVDC line for the 2009 calendar year. All these interruptions resulted from lightning strokes within a diameter of 1km of the line [14]. The corresponding stroke magnitude for the breaker trip time was obtained from the FALLS system [1].

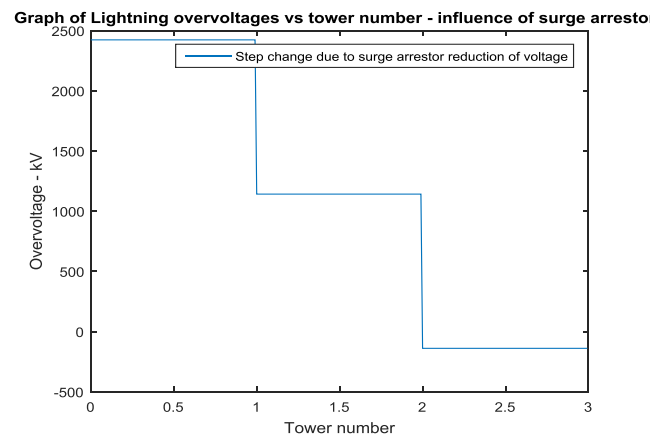
Analysis of the data revealed that that the peak lightning stroke that resulted in a breaker interruption was 26kA. There may have been a tower with high tower footing resistance, which would give a high Tower top Voltage and hence the subsequent trip.

## VII. REQUIRED SURGE ARRESTORS

Once a back flash over has occurred, the voltage seen on phase conductor is almost equal to the back flash over voltage. On the power surge will further split into two. Half would travel away from the source bus bar and the other towards the end of the line.

Should the surge arrester be placed at this node, a three-way power surge split would occur. This split would be based on the impedance of the line and the amount of energy the surge arrester may conduct in that short time interval, which is normally less than 1us. Depending on the magnitude of the overvoltage, a number of line surge arrester would have to be connected in parallel to dissipate the power surge and prevent a breaker operation.

For a current stroke of 50kA, three 500kV 20kA surge arrestors connected on parallel would be required to dissipate the lightning stroke to an extent to prevent the line breaker from operating and cause small duration outages. These surge arrestors may be connected as shown in the figure 15. Figure 15 shows the reduction of the over-voltage caused cause by a 50kA lightning stroke. Surge arrestors of the same rating were used.



**Fig 15:** Reduction of lightning over voltages due to the introduction of line surge arrestors

Table 2 a-d shows the required number of surge arrestors to drain the over voltages caused by lightning strokes of different magnitudes and different soil parameters. The soil parameters are taken from case studies 1 – 4.

**Table 2a:** Tower Footing resistance of 23.1 and different lightning strokes (Case Studies 1)

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 2d:** Tower Footing resistance of 23.15 and different lightning strokes.

Lightning current – kA	Insulator Voltage kV	Tower Footing Resistance	Tower top Voltage kV	Back Flash over	Phase Voltage	Required SA - Prevent outage
12	3296	23.15	1186	No	643	0
25	3296	23.15	2573	No	1286	0
37.5	3296	23.15	3859	Yes	1929	2
50	3296	23.15	5145	Yes	2573	2
98	3296	23.15	10290	Yes	5145	4

**Table 2b:** Tower Footing resistance of 16.25 and different lightning strokes

Lightning current – kA	Insulator Voltage kV	Tower Footing Resistance	Tower top Voltage kV	Back Flash over	Phase Voltage	Required SA - Prevent outage
12	3296	16.25	1118	No	559	0
25	3296	16.25	1134	No	1119	0
37.5	3296	16.25	3356	Yes	1678	2
50	3296	16.25	4475	Yes	1137	2
98	3296	16.25	8950	Yes	4475	4

**Table 2c:** Tower Footing resistance of 17.3 and different lightning strokes

Lightning current – kA	Insulator Voltage kV	Tower Footing Resistance	Tower top Voltage kV	Back Flash over	Phase Voltage	Required SA - Prevent outage
12	3296	17.33	1143	No	573	0
25	3296	17.33	2349	No	1174	0
37.5	3296	17.33	3440	Yes	1720	2
50	3296	17.33	4588	Yes	2294	2
98	3296	17.33	9175	Yes	4587	4

### VIII. FINANCIAL EVALUATION

- Annual expected number of voltage dips and momentary outages due to lightning. Performance monitoring of a 533kV overhead line revealed that in the year 2009 there was 124 momentary trips. Of these 10 was due to lightning. [14]
- Estimate the cost associated with voltage dips and momentary outages. A study undertaken by Nzimande [15] revealed that lightning (storm) related dips lead to losses of between US\$5357 and US\$35714 per annum for 10 storm related dips, an average of between US\$357 and US\$3571 per dip.

The following table illustrates the high level costing required to install 4x550kV surge arrestors, i.e. 2 surge arrestor per phase.

**Table 3** Illustrates the Cost Required to Mitigate against a 50ka Lightning Stroke

Item	Year 2019
Cost of a surge arrestor and counter	USD 38 835
Cost of 4 surge arrestor and counters	USD 158 700
Labour and transport	USD 4 601
Total	USD 163 302

The following figure 13 shows that it would take 14 years to recover the capital invested in the surge arrestors to mitigate against dips, providing the inflation is 5%. Should the inflation be 10%, the capital will be recovered after 23 years.

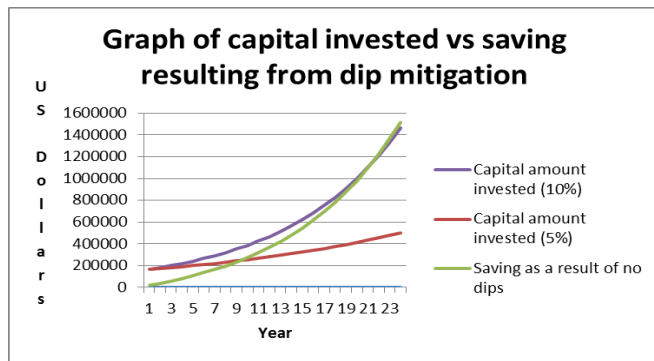


Fig 14: Break-even point occurs in year 14 (5% inflation rate)

## IX. CONCLUSION

Using earthing 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 to have the tower footing resistance below 30 ohms. The tower top voltage is a function of the lightning stroke, line and tower surge impedance and earthing resistance. Should the insulator breakdown 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 arrester. Lightning surges travel at the speed of light. This waveform does not stay at the node of the surge arrester for duration long enough for the surge arrester to dissipate the voltage to ground. Hence, additional surge arresters are required. The placement of the surge arrester 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 stroke of 50kA will require two surge arresters per phase. For this amount of surge arresters, the break-even point will be 14 years.

## REFERENCES

- [1]. Global Atmospheric 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*. Vol. 78, p. 995–1007, 2008.
- [4]. "High Voltage Surge Arrestors," [www.abb.com](http://www.abb.com).
- [5]. E. Singh, I.E. Davidson and G.K. Venayagamoorthy, "Methodology for Measuring and Enhancing Tower Footing Resistance for Lightning Protection in an 88KV Line". In *Proceedings of the 25<sup>th</sup> South African Universities Power Engineering Conference*, 30 Jan – 1<sup>st</sup> Feb 2017, Stellenbosch, South Africa, pp. 655-659.
- [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*, Tsinghua University, Beijing, China, Aug, 2005, pp. 25-29.
- [7]. I E Davidson. "A Mathematical Algorithm for Investigating Soil Resistivity". *Proceedings of the 6<sup>th</sup> Southern African Universities Power Engineering Conference (SAUPEC)*, University of the Witwatersrand, South Africa, January 1996, Vol. 6, pp. 279-282, 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 Malanda, I E Davidson, E Buraimoh and E Singh, "Analysis of Soil Resistivity and its Impact on Grounding Systems Design". *Proceedings of the IEEE Power Africa Conference*, 26 – 29 June, 2018, Cape Town, South Africa, pp. 522-527
- [10]. M.Z.A A Kadir, Z M Nawi and J Sardi, "Numerical Modeling and Simulation in Electro Magnetic Transient Program for Estimating Line Back Flashover Performance," November 2010. ." *Engineering Letters*, vol.18, no. 4, p351, 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 Arrester 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](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 Arrester Energy for 132kV Overhead Transmission Line due to Back Flashover and Shielding failure". In *Proceedings of the 16<sup>th</sup> IEEE International Conference on Power and Energy, (PECon)*, pp. 683-688, December 2012.
- [15]. E. Singh, "Fault Mitigation and Performance Improvement of an 88kV line using Line Surge Arrestors and Counters," Poster, University of KwaZulu-Natal, Durban, 2016.

- [16]. Nzimande, T.M., "Voltage Dip Performance Analysis," Master of Science Thesis, University of KwaZulu-Natal, 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](http://www.lightningman.com.au)," [Online].

*Mail your Manuscript to editor.ijaers@gmail.com*

---

i