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# Improved Lightning Protection on 132 kV Transmission Line Due to Indirect Stroke Using Line Meta-Oxide Surge Arresters

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## ABSTRACT:
*This research demonstrate an innovative improvement on Lightning protection to curb the catastrophic effect of Lightning on 132 kV Transmission line which have adverse effect on power companies and also causes a great inconvenience to energy users. Indirect lightning stroke on transmission lines results in back-flashover, a phenomenon which occurs when the lightning induced voltage exceeds the insulation gap thereby flashing the line. The use of overhead sky wire for protection against lightning, though could withstand the stroke, but lacks the capability of quickly damping the lightning overvoltage along the line especially for regions with high grounding resistance. Using PSCAD-EMTDC 4.5 to model and simulate the line with improved protection having Line Meta-Oxide surge arrester installed along the line, the lightning performance was found improved and the back-flashover from lightning overvoltage reduced to its barest minimum before getting to the substation which reduces line trip out and equipment damage leading to a more reliable and secured network.*

***Keywords***: Lightning Phenomenon, Meta-Oxide Surge Arrester, Overvoltage, 132kV, Transmission Line.

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## I. INTRODUCTION
Lightning stroke has been identified as the main cause of transmission line trip-out as more than fifty percent (50%) power system faults on transmission lines are caused by lightning stroke in most developing countries according to statistics (Hu *et al*., 2014, Sima *et al*., 2014). Transmission line lightning stroke failure causes a lot of damage to transmission equipment on one hand, line consecutive failures as a result of lightning stroke also is a major threat to the safe operation of the power grid, that adversely affects the growth of social economic activities. The Nigerian Power Sector experienced twelve (12) system collapses in 2018 and that the sum of ₦532 Billion Naira was lost due to insufficient power Supply (www.vanguardngr.com, 2018). This corroborates the opinion of Gabriel *et al*. (2018) which stated that the economic and social effects of the loss of electric service have huge impacts on both the energy providers and end user as well. Lightning protection of transmission lines is emphasized in power system, and scholars have conducted a lot of research. The protection level of key lines is relatively weak resulting to the above disadvantages, and generally lines have relative protection design which does not tend to reduce the lightning effect along the line before getting to the substation where equipment are mostly damaged and personnel endangered. Hence, it is obligatory to study the power transmission and transformation systems of lightning protection practice to ensure that reliability of electric network is guaranteed, and study the effect of lightning stroke failure on the security and dependability of power grid. Lightning disaster is an essential factor currently affecting safe operation of transmission lines. Transmission line overvoltage caused by back flashover is one of the vital reasons threatening safe operation of transmission lines and safety of electrical equipment (Mochen *et al*., 2017).

Nur *et al*. (2012) noted that to design adequate insulation for power system, it is of utmost importance to know the lightning behaviour.

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### 1.1 FREQUENCY OF LIGHTING STROKE ON TRANSMISSION LINES

Swati and Manoj (2014) stated that proper awareness of the regularity of occurrence of lightning strokes is quite important in the design of protection system against lightning. This frequency of lightning event is well known as the flashes that occur per unit area per year. This stroke result in various overvoltage effects on the line depending on the point the stroke hits the network. Generally, lightning overvoltages are refer to as Fast Front Overvoltage (Martinez-Velasco & Gonzalez-Molina 2015). The all-encompassing effect shall be discussed.

### 1.2 PROBABILITY OF LIGHTNING STROKE ON TRANSMISSION NETWORK

Lightning strike could be regarded as direct or indirect on the network depending on the point of impact during its occurrence. In each case, its effect poses a threat to the stability and reliability of the transmission network. For a transmission line with conventional shield wire protection, Figure 1 gives the likely probability of strike. Figure 1 explains transmission line protection using conventional sky wire alone and the different stroke to shield area covered. $r_s$ is the shield distance from the sky wire while $r_c$ is for the conductor. Between the stroke to Shield wire and Stroke to Ground is the Stroke to Pole conductor. Depending on the angle and position of sky wire above the conductors, the possibility of shielding failure exist.

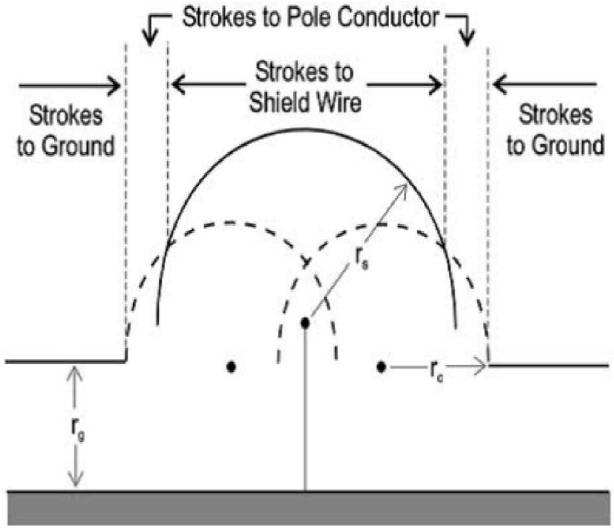


Figure 1: Zones of Attraction for a High Voltage Direct Current (HVDC) transmission line tower (Swati & Manoj, 2014).

### 1.3 Shielding Failure

HE *et al*. (2009) noted in their work on "Fractal Model of Lightning channel for simulating lightning strikes to transmission lines" that, after conducting the iterated simulations, they obtained statistical results, which shows that even if the transmission line fulfills the perfect shielding circumstance, shielding failure fault remains probable. Also, they calculated shielding failure fault degrees of a transmission line with different ground parameters and distribution of stroke points over the space between two towers along an Ultra High Voltage Direct Current (UHV-DC) line to find out the likely point of transmission-line lightning protection. Their work provides a hopeful approach for improving the lightning protection property of transmission lines by improving the configuration of shielding wires and phase or pole conductors.

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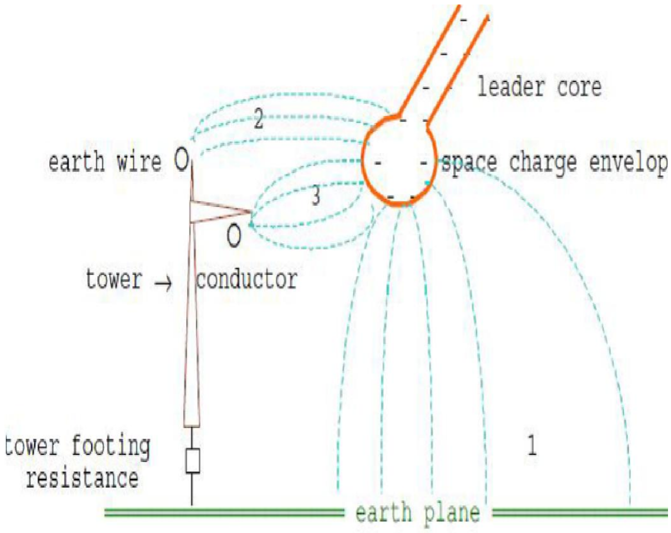


Figure 2: Lightning Leader Stroke Geometry on Transmission line (Swati & Manoj, 2014).

Figure 2 is a pictorial view of the lightning occurrence in a transmission line.
(a) considering path (1), that runs from the core of the leader of the lightning stroke to the earth, the capacitance between the earth and the leader is promptly discharged, and at the same time, the capacitances links the leader head to the earth wire and the line conductor are well discharged by the action of travelling wave, so that a voltage is developed across the string of the insulator. This voltage is called the induced voltage as a result of lightning stroke to nearby ground. It does not have any major factor in the lightning behaviour of transmission lines.

(b) The discharge on the second path (2) as seen is between the earth wire on top of the tower and the lightning leader. Its capacitance is discharged between these two points. The tower carries the subsequent travelling wave down and acting through its main impedance and then raises the potential of the tower top to a point whereby, the difference in the voltage level across is sufficiently large enough to result in flashover from the tower and the line conductor. This phenomenon is called the back-Flashover.

(c) Finally, the last mode of discharge in (3) as in Figure 2, is that between the phase conductor and the leader core. The capacitance is discharged between the phase conductor and the leader core and then, the main discharge current is injected into the phase conductor, and this result in developing a surge impedance voltage that goes across the insulator string. At moderately low current values, the strength of the insulation is suppressed and the path of discharge is completed to the earth through the tower. This process is called the shielding failure or direct stroke to the phase conductor. The protection of equipment and structure from this last mode of discharge by the use of lightning conductor or grounding wires is one of the oldest ways of lightning studies and still remain so.

## 1.4 Lightning Stroke to a Phase Conductor

Figure 2 shows a view of how the transmission line could directly receive the charged cloud and if the line is struck from a long distance from the station; the surge will flow in the network as shown in Figure 3. It will flow in both directions, (left, right and downward) along the tower shattering insulators, and in some cases destroying poles until all the surge is dissipated. In case the stroke hits the lines immediately adjacent to the transmission station, then there is a significant damage to equipment like transformers, circuit breakers etc. Since the time for the energy to dissipate is quite short, considering the fact that the lightning arrestor at the station may not be able to prevent damage to these equipment like transformer, circuit breaker, etc., without allowing part to affect them. Swati and Manoj (2014) noted that when lightning strike hits an overhead transmission line phase conductor, the magnitude of the discharge current and the nature of the high frequency of the stroke causes huge voltage to be transmitted in both directions beginning from the point of impart as demonstrated in Figure 3. The voltage surge and discharge current have wave shapes that are very similar. At the point of contact with the conductor, the discharge current split in either directions in equal magnitude that gives rise to a traveling wave of size E, as shown in Equation (1):

$$E = \frac{1}{2} \times Z \times i \times \left(e^{-\alpha t} - e^{-\beta t}\right) \quad (1)$$

Where Z is the phase conductor surge impedance, E is Magnitude of traveling wave, i is the current.

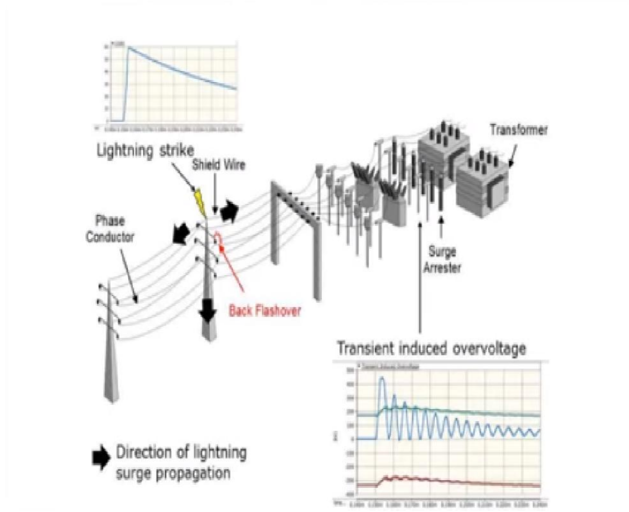


Figure 3: Schematic of Lightning Stroke on Transmission Lines (Swati & Manoj, 2014)

## 1.5 Lightning Stroke to a Tower with no Earth Wire

Fortunately, lightning stroke direct to phase conductors are not frequent in their occurrence as compared to side stroke whose effects are not so severe. If a lightning stroke hit the tower, the discharge current would run along the metal work of the tower from top to bottom thereby creating a potential difference. Figure 4 shows the capacitance buildup of the space between the cloud and the phase conductor in C3 and then capacitance buildup between the phase conductor and the ground in C1.

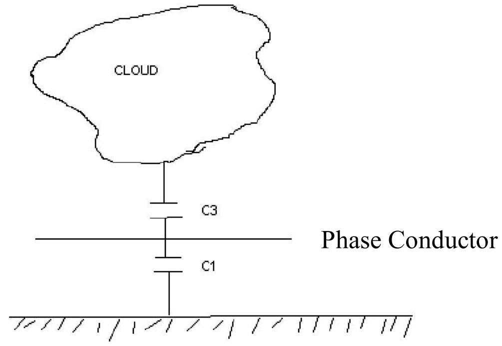


Figure 4: Capacitance of Unprotected Transmission Line

As currently practiced, if the earth resistance at the tower foot is reduced to say R (5 to 100Ω), and the lightning struck the network, then the potential that is build up on the tower top would be as given in Equation (2).

$$Ri + L\frac{di}{dt} \quad (2)$$

If ei is used to represent the voltage due to lightning that is induced on the conductor then the potential difference buildup across the tower and the conductor is given in Equation (3).

$$E = Ri + L\frac{di}{dt} + ei \quad (3)$$

In the event that values of Equation (3) exceeds the insulation strength of the line, then there is what is referred to as flashover between the tower and the phase conductor and this effect is called Back-Flashover.

Where R is resistance, i is current, L is line inductance, ei is the induced voltage, E magnitude of traveling wave.

## 1.6 LIGHTNING OVERVOLTAGES DUE TO STRIKE

Over-voltages are produced from lightning whenever it hits phase conductor called direct stroke or a point within the vicinity of the transmission/distribution network known as indirect stroke. The overvoltage could be impressed on the power system network also by atmospheric discharge and this is called lightning overvoltage or could be generated within the

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system by the connection or disconnection of the circuit elements or the initiation of fault interruption. The latter type is called temporary overvoltage if they are of power or harmonic frequency sustained and weakly damped or as switching overvoltages if they are highly damped and occurs for a short duration. Considering the common origin, both temporary overvoltage and switching overvoltage occurs together and their collective effect is very important for insulation design. The probability of the coincidental occurrence of switching and lightning surges on the other hand is very small and could be neglected. The likely magnitude of lightning surges appearing on transmission line are not much affected by line design; therefore, lightning performance tends to improve with the increasing insulation level, that is, the system voltage. On the other hand, the magnitudes of switching surges are considerably proportional to system voltage.

### 1.7 REVIEW OF PROTECTION AGAINST LIGHTNING EFFECTS.

Adequate protection against lightning would be achieved by first understanding their effect and behaviour on the various stroke targets in the power systems network (Nur *et al*., 2012). Various attempts have been put in place to protect against the devastating effects of lightning overvoltage in the delivery of power to end users. These are sky wire to lightning arrestors each for specific voltage level. Benjamin Franklin was the first to install a detector to warn on the approach of a thunder storm in the eighteenth century called the "lightning bell" which was based on electrostatic device called "electric chimes" But this warning sign neither tell of the effect of the stroke nor how to protect against the effect upon its impact. In the work of Kelechi and Idoniboyeobu (2013), they opined that effective lightning protection could be achieved by having devices that incorporate the attraction distance into its design.

This they noted that, increase in the attraction distance of the object to be protected will reduce the induced voltage surge of the return stroke. But transmission lines and towers are stationary equipment and their position could not be adjusted during a possible lightning strike. Also, excessive spacing of the line conductors because of lightning effect will lead to very tall and gigantic towers which will not be economically feasible and could also pose great danger to flight. Therefore, this research tends to analyze the effect of lightning stroke on 132 kV lines and then know how to mitigate its occurrence.

Martinez-Velasco and Castro-Aranda (2007), stated that transmission lines protection could be taken to a new level and be more significant by installing lightning arrestor in all three phases of a transmission line protected by a shield wire but this study was limited to a multistory tower with a single shield for a 400 kV Transmission line where the energy discharge of the Lightning Arrestor is a function of the tower model used. The study did not apply to 132 kV as in this research study and also did not analyze what could happen should the lightning stroke hit the shield or any of the phase conductors. Following the protection trend, Qi-Bin and Du (2016) noted in their work that earthing of an open track mask effectively reduces the voltage surge on the cable and that in the absence of a dedicated earthing for the mask, the bulk of the lightning current propagates through to the overhead wire. Though, this research was on DC, it also borders about lightning threats and same principle could as well be applied but does not involve towers connected together with lines.

## 2 MATERIALS AND METHOD

### 2.1 Modeling of Transmission Line and Tower

The transmission line and tower are modeled based on the standard 132 kV double circuit line geometry with tower configuration as shown in Figure 5 (Sardi *et al*., 2008).

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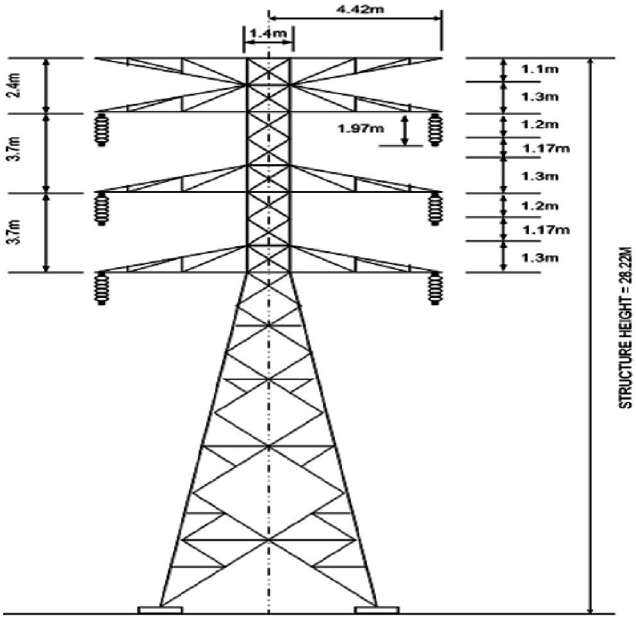


Figure 5: A 132 kV Transmission Line of interest

Figure 5 shows a typical double circuit 132 kV transmission line and their spacing.

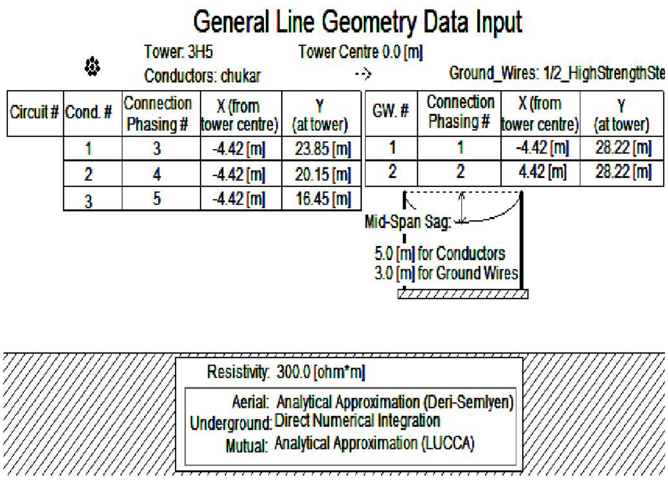


Figure 6: Modeling of 132kV Transmission Line configuration in PSCAD-EMTDC.

The transmission tower in Figure 5 is modeled in PSCAD-EMTDC as shown in Figure 6 with four spans of 300 m each using the distributed parameter model of transmission line characteristics for travelling wave. The general geometry is as shown in Figure 6 with the highest and lowest phase conductors having a height of 23.85 m and 16.45 m respectively above ground level. Note that the velocity of surge propagation is assumed equal to 85% of the speed of light according to (IEEE, 1985).

The computation of the surge impedance of tower can be achieved by using different formulae. For a single storey lattice in form of a truncated cone shown in Figure 5, the Surge impedance is modeled using Equation (4) (Chisiholm, 1985; CIGRE, 1991).

$$Z_{surge} = 60\, In\left[\cot\left\{0.5\tan^{-1}\left(\frac{R}{h}\right)\right\}\right] \quad (4)$$

$$R = \frac{r_1 h_2 + r_2 h + r_3 h_1}{h}, h = h_1 + h_2 \quad (5)$$

Figure 7 shows a four (4) span transmission network moving with two (2) sky wire above a single circuit of conductor A, B and C, from Generation through Transmission line to the load end. At the second tower (TL2), nodes where created as point of impact for lightning surge.

### 2.3 The Use of PSCAD EMTDC for Power System Modeling and Simulation

The Power System Computer Aided Design (PSCAD) Electromagnetic Transient and Direct Current (EMTDC) is a software that makes it easier

Where:

R: Equivalent radius of the tower in Figure 5 above

h: Tower height (m); h1: Tower height from base to midsection

h2: Tower height from midsection to top

r1, r2, r3: Tower top, midsection and the base radii, m.

$$V_{flashover} = K_1 + \frac{K_2}{t^{0.75}} \quad (6)$$

$K_1 = 400L$; $K_2 = 710L$;

L = Insulator Length in meters

t = time pass after lightning stroke in µs (CIGRE, 1991; Martinez-Velasco & Castro-Aranda, 2005).

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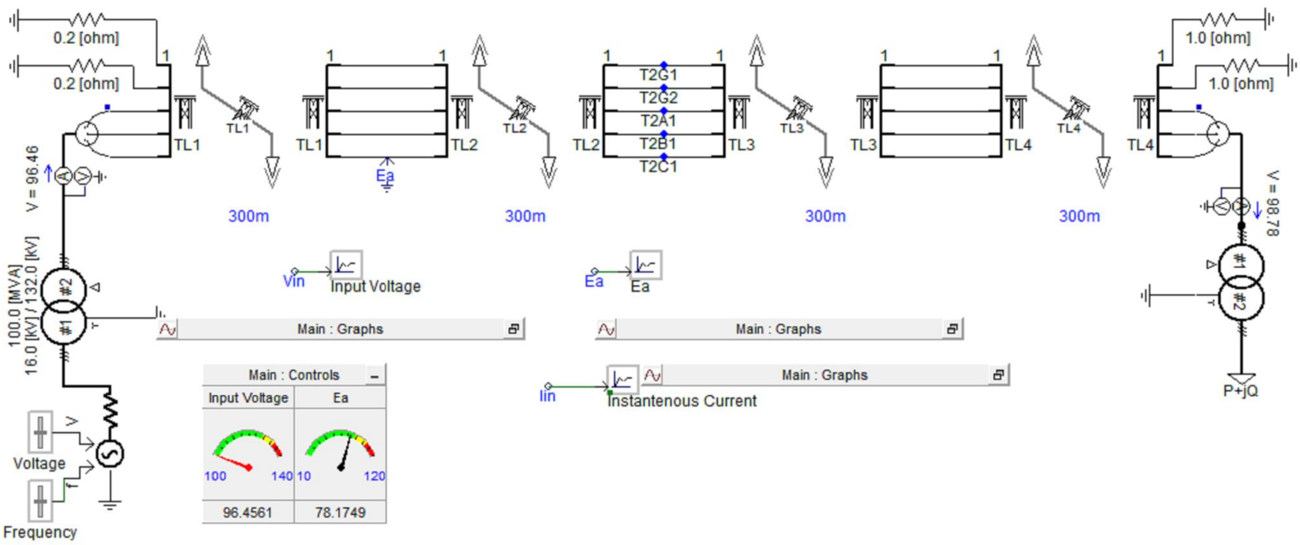


Figure 7: Four Span Transmission Lines of 300m each modeled in PSCAD-EMTDC

to implement power system networks at different operating conditions and simulate the results accurately as if it has been obtained actually from a real-life application which saves a lot time, money and it is much safer. Ali and Zulkuurnain (2016) highlighted the advantages of using PSCAD as compared to other simulation software. Nor *et al.* (2012) analyzed arrester energy for 132 kV Overhead transmission due to Back Flashover and Shielding failure using PSCAD and noted that their simulation result and computed theoretically values are in reasonable agreement. Christodoulou *et al*. (2014) worked on Simulation of Meta Oxide Surge Arresters Behaviour using PSCAD and noted that the various models function with satisfactory accuracy.

## 2.4 Modeling of String Insulator

The Insulator holding the conductor is modeled as a stray capacitance that is connected between the tower and the conductors. Also, the insulator provides mechanical support for the conductor during normal and transient operations. The Insulator voltage withstand capability is computed by using Equation (6).

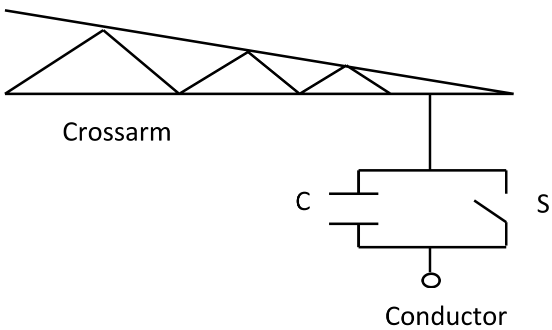


Figure 8: Flashover Model for Insulator String.

## 2.5 Modeling of Meta-Oxide Line Surge Arrester

Table 1: Arrester Characteristics

| | |
|---|---|
| Norminal Voltage (kV) | 120 |
| MCOV (kV rms) | 97.3 |
| Voltage (kV) for 8/20μs | 330 |
| Energy Absorption (kJ/kV) | 5 |
| Length of Arrester Column, d (m) | 1.485 |
| Number of Parallel column of disk, n | 1 |

Data from Toshiba arrester datasheet (132 kV)

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By using the estimated height of the arrester and the number of parallel plates as contained in Table 1, the parameters of the resistor, inductors and capacitor of the metal-oxide surge arrester are calculated using Equations (7) to (11):

$$L_1 = \frac{15 \times d}{n} \quad (\mu H) \qquad (7)$$

$$R_1 = \frac{65 \times d}{n} \quad (\Omega) \qquad (8)$$

$$L_0 = \frac{0.2 \times d}{n} \quad (\mu H) \qquad (9)$$

$$R_0 = \frac{100 \times d}{n} \quad (\Omega) \qquad (10)$$

$$C = \frac{100 \times n}{d} \quad (\mu F) \qquad (11)$$

Where d is the length of the arrester column in meters and n is number of parallel columns of meta-oxide disks as in Table 1.
Equation (7) to (11) is used to compute the value of the circuit parameter of internal circuitry of Meta Oxide Lightning Arrester shown in Figure 9.

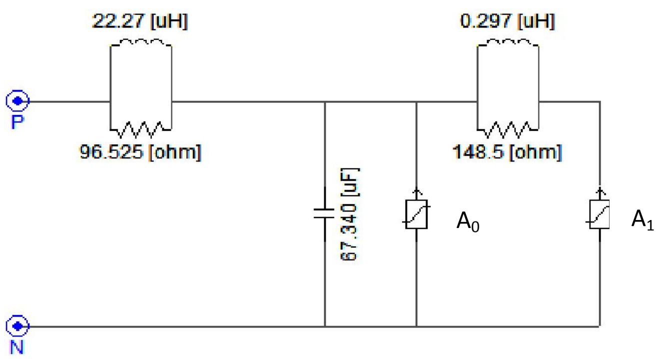


Figure 9: Internal Circuitry of the Meta-Oxide Lightning Arrester modeled in PSCAD

## 2.6 Modeling of Lightning Source.

The lightning source used in the study is modeled according to IEC triangular wave shape (Bakar *et al.*, 2010). This is shown in Figure 10. The impedance for the lightning path is modeled as a parallel resistance of 400Ω according to Bewly (1963). Different values peak current were used to investigate the back flashover phenomenon and the behaviour of the transmission line with line Meta-Oxide surge arrester.

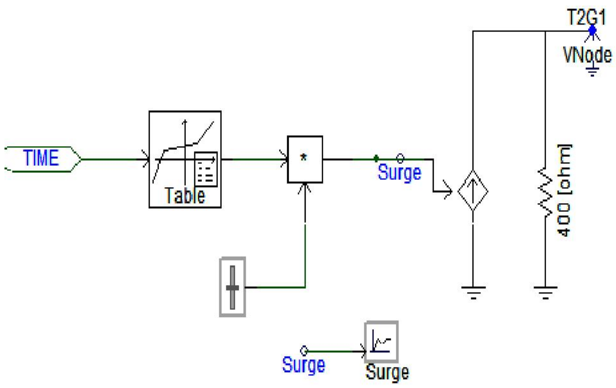


Figure 10: The Lightning source with path impedance Modeled in PSCAD-EMTDC

The Back-Flashover simulation was done using lightning source in Figure 10 with the first block as time, the second block is used to enter range of current values injected on the line. This enters a multiplier connected to slider to vary the values and to current generator named surge. The current is injected into the network at tower T2 on ground conductor G1, named T2G1. T2G1 shown in Figure 10 is also same point of impact in Figure 7.

## 2.7 Modeling of Arrester Energy.

The discharged energy by the line arrester, $W_A$, during occurrence of Back Flashover can be estimated using Equations (12) and (13).

$$W_A = i_A \times e_A \times \tau \qquad (12)$$

$e_A$ = the discharged voltage, V; $i_A$ = the arrester current, A; $\tau$ is time constant, s.

$$\tau = \frac{Z_g}{R_i} \times T_s \qquad (13)$$

Ts = Line span length divided by velocity of light; $Z_g$ = ground impedance, Ω; $R_i$ is the footing resistance, Ω;

## 3. RESULTS AND DISCUSSION

For this study, the lightning stroke was modeled as seen the Figure 10 and its effect is injected in the Transmission network in Figure 5, the resultant

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surge effect on the line is as shown in Figures 11 to 15. Upon stroke, the current magnitude is very high and dangerous and goes down gradually with time. If not mitigated, this causes harmful effect to equipment and personnel.

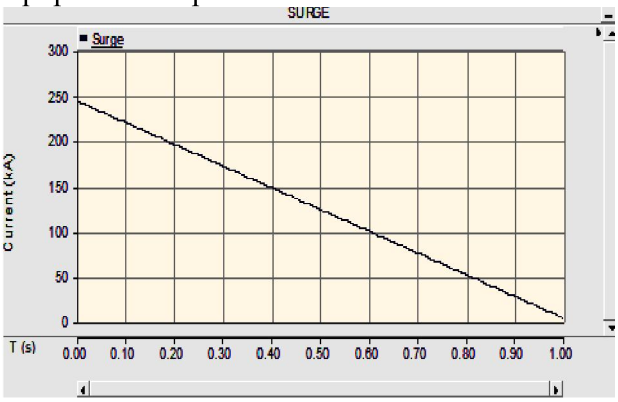


Figure 11: 30kA Stroke to ground wire causing Back-Flashover.

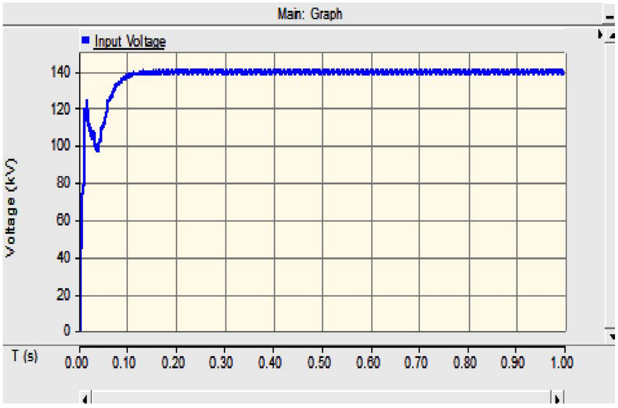


Figure 12: The Line Voltage initially distorted due to Back-Flashover

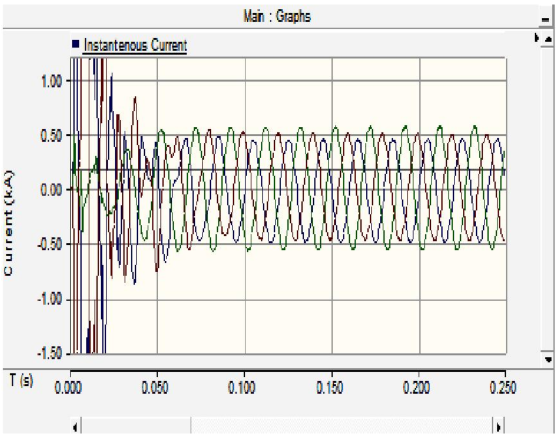


Figure 13: Three Phase current on the Line during and after the occurrence of Back Flashover

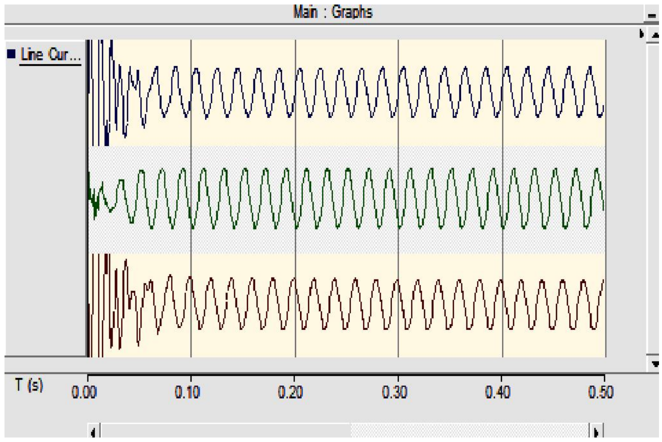


Figure 14: Behaviour of the Line current with the Upper most Line closest the ground wire receiving the most effect

Figure 11 shows the lightning source which dies out gradually due upon stroke. As seen in Figure 12 and 13, the input voltage and current was distorted at the instant of back flashover on the transmission line, but with the installations of MOSA along the line, this effect was gradually damped and the voltage immediately brought to normal behaviour and this help to prevent unplanned outages, power failure, equipment damage and ensure safe operations.

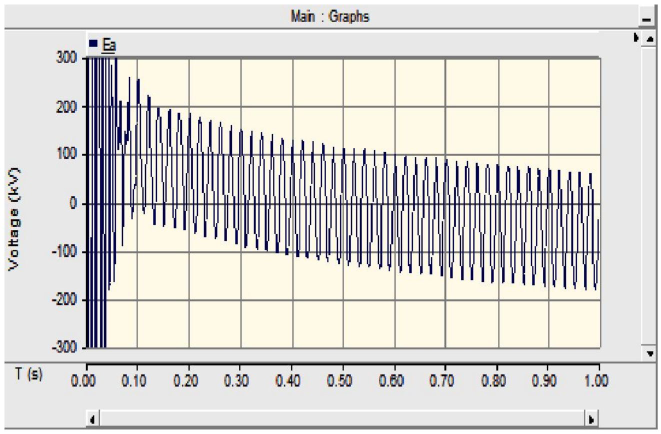


Figure 15: The Line to Ground voltage of the Transmission network during and after the back flashover effect

Figure 14 above also reveal that, for the truncated cone type of tower configuration of Figure 5, the phase conductor of height 23.85m as modeled in

Figure 6 and closest to the sky wire receives the highest effect of back flashover but the lines were normalized due to the damping power of the MOSA along the line.

Figure 15 shows the behaviour of the phase to neutral voltage upon occurrence of back flashover on the network which initially distorted but gradually restored to normal waveform.

## 4. CONCLUSION

Improved Lightning protection on 132 kV transmission line was carried out considering the negative effect of Lightning stroke on transmission lines and because the 132 kV Transmission Line is a network common to both developed and developing countries, the need for its optimal operation is of paramount importance. Back Flashover on transmission lines causes negative effect on the line, which results to unplanned outages and causes equipment failures, economics losses and customer distrust. But with Meta-Oxide Surge Arrester along the line, these negative effects of back flashover will easily be damped and reduced to its barest minimum and make the line function normally during lightning occurrence. This is an innovation to the conventional use of only sky wire on towers for lightning protection.

## 5. ACKNOWLEDGEMENT

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