Concept and Application of Lightning Arrester for 11kV Electric Power Systems Protection

Research Article

Received: 22 November 2019

Accepted: 27 December 2019

Published: 23 January 2020

Uche C. Ogbuefi¹, Cajetan M. Nwosu² & Cosmas U. Ogbuka³

^{1,2,3}Department of Electrical Engineering,
University of Nigeria, Nsukka, Enugu
State, Nigeria.

Corresponding Author

Author Email:

Uche.ogbuefi@unn.edu.ng

1. INTRODUCTION

Lightning is unpredictable and it is the most destructive of all elements associated with thunderstorms. It causes damage to many objects and systems such as electronic circuits, overhead

and underground electric power and communication systems, buildings, boats, and aircraft and launch vehicles in flight. It is the most frequent cause of over voltages on distribution systems [1, 2]. The voltage of a lightning strike may start at hundreds of millions of volts between the cloud and earth. Although these values do not reach the earth, millions of volts can be delivered to the buildings, trees or distribution lines struck [3]. Lightning is a direct transient current that has been recorded to be up to 260,000 amperes and last for duration of up to 200 microseconds making it very hard to study [4]. According to [5], lightning strikes and thunderstorms during rainfall are very likely to occur frequently and hence protection of equipment especially transformers, that can be affected by their occurrence should be treated with utmost priority [6].

Lightning as a physical phenomenon, occurs when the clouds acquire charge or become polarized, thus creating electric fields of considerable strength between the cloud and adjacent masses such as earth and other clouds [5]. However, it takes a very conductive atmosphere below/about 50 km owing to the presence of ions created by both cosmic rays and the natural radioactivity for lightning to be triggered [7]. Studies carried out by Mowete and Adelabu [8] indicates that in the early times, the destructive effects of lightning strikes were limited mainly to high voltage (HV) power supply lines, but with the

Abstract: The phenomenon of lightning is an exciting natural incident. However, its rate of occurrence can be as critical as it is electrifying. The magnitude of energy contained in lightning strikes is very high and can be destructive. In order to prevent electric power equipment from lightning, protection schemes like the use of lightning rods, ground wires and surge diverters are put in place to curtail its effects on electric equipment. This device is used for the protection of substations equipment against high travelling waves, by arresting the abnormal high voltage spike to the general mass of the earth devoid of affecting the continuity of supply. In this paper, a detailed design of surge diverter or lightning arrester for protection of electric power system is presented. SOLIDWORKS software was utilized in this study to access the performance analysis and application of an 11kV valve-type surge diverter modelled after the IEEE lightning arrester model. Different lightning arrester models are presented. By Slight variation to the IEEE model, a 92% reduction in the lightning-induced voltage was recorded. Thus, the modified model can be applied to the protection of 11kV power systems for more reliable and improved supply of power to customers.

Keywords: Electric Power Systems, IEEE Model, Surge Diverters, Lightning-induced Voltage, SOLIDWORKS Software, Lightning Arrester.

Nomenclature

R_1	=	Filter resistance
X_{L_1}	=	Filter inductive reactance
μH	=	Micro-Henry, sub unit of Inductance
Ω	=	Ohm, unit of Resistance
L_1	=	Filter inductance
C	=	Terminal-to-terminal Capacitance of Arrester
R_0	=	Stabilizing Resistance
L_0	=	Inductance associated with the magnetic field in the immediate vicinity of the arrester
LA	=	Lightning Arrester
MO	=	Metal Oxide
MCOV	=	Maximum Continuous Operating Voltage
V_s	=	System line-to-line voltage
C_e	=	Coefficient of Earthing
V_{max}	=	Maximum system voltage
V_p	=	Phase Voltage
ZnO	=	Zinc Oxide

advent of mobile telephony services, information technology infrastructure concern expanded to include the increase in equipment fatalities occasioned by the absence of lightning protective systems. The choice of protection depends on the criticality of the load, relative size of the transformer compared to the total system load and potential safety concerns. Percentage differential protection is the most widely used scheme for the protection of transformers rated 10 MVA and above [9, 10].

Lightning arresters are essential devices of serious importance in areas prone to lightning strikes hazards like losses due to equipment damage [11, 12]. They are used to prevent the disastrous effects of lightning on buildings, power and communication systems, and equipment in general. As a result, the reliability of an electric power system is greatly affected by lightning strikes to such effects as line design, the frequency of lightning flashes, the magnitude of the lightning over voltages and the failure statistics of power system components as a major cause of power outages worldwide [13, 14, 15]. This is because, lightning damages power system equipment and many times renders them inoperable thereby making the system very unreliable. For instance, in 2003 United States, Canada and Europe suffered a series of blackouts, attributed majorly to lightning strikes leaving more than 60 million people without electricity [15, 16].

In addition, according to [17] a direct lightning strike on a power line or an induced voltage from a nearby strike may lead to line “flashover” or failure of arresters, transformers, insulators, or other line hardware. Flashovers or equipment failure can result in an out-of-service line, which is a more technical term for an “outage” [18, 19].

Different types of lightning arresters exist and they differ in material construction. They operate almost on the principle to provide low resistance path for the surges to the general mass of the earth.

Their selection depends on the factors like the material makeup, current, voltage ratings they can withstand, their reliability mostly and others follow. There are the rod arrester, multi gap, metal oxide, horn gap, expulsive type, valve type lightning arresters. The issue with the rod lightning arrester is that once the spark occur, it may continue for some time even at low voltage. This is taken care of by the use of current limiting reactor in series with the rod. The presentation of the design of a valve type lightning arrester modelled after the IEEE model is the main concern of this work. Valve type of lightning arresters incorporate non-linear resistor. As the magnitude of lightning current/voltage is very high, the non-linear elements will offer a very low resistance to then passage of the surge which will rapidly go to the general mass of the earth instead of being sent back over the line. The non-linear resistors take up high resistance to stop the flow of current as the surge is over.

2. MODELS OF LIGHTNING DIVERTER

A number of good models have been proposed to describe the arrester behaviour for different kinds of stress [20]. There are mainly three lightning arrester models namely as presented in [21]:

i) IEEE model, ii) Pinceti model, and iii) Fernandez-Diaz model

Fig. 1(a) shows the model recommended by IEEE. It uses the non-linear V-I characteristic which is obtained by means of two non-linear resistors, represented by A_0 and A_1 and separated by an R-L filter. For slow surges, the filter impedance i.e. $R_1 \parallel X_{L_1}$ is extremely low and A_0 and A_1 are practically connected in parallel, with $R = R_1$ and L

$= L_1$ [20]. The corresponding inductive reactance, X_{L_1} is obtained by computing ωL_1 accordingly. A_0 and A_1 are non-linear resistors (varistors) whose values have already been defined experimentally by the committee of IEEE W.G. 3.4.11 [3]. Figure 1 and Table 1 summarize the results of the experiments. They are represented by the MOV blocks in Figure 8.

Figure 1: V-I characteristics of nonlinear resistors A_0 and A_1 . Source: [3, 4]

Table 1: V-I characteristics for A_0 and A_1 .

I [kA]	V [p.u.]	
	A_0	A_1
0.1	0.963	0.769
1	1.05	0.85
2	1.088	0.894
4	1.125	0.925
6	1.138	0.938
8	1.169	0.956
10	1.188	0.969
12	1.206	0.975
14	1.231	0.988
16	1.25	0.994
18	1.281	1
20	1.313	1.006

Using the details provided in Table 1, the non-linear characteristics of A_0 and A_1 can be obtained for any value of discharge current, bearing in mind that they are to be calculated to match the residual voltages for the lightning discharge currents of the protection V-I-characteristic provided by the manufacturer, which is the Crompton Greaves ZLA2007 Lightning arrester in this case (See Figure 7 and Table 2 [6]. Obtaining the values of A_0 and A_1 by hand would be quite laborious and laden with error. The use of the ATPDraw software however, simplifies this as when a nonlinear branch element like a metal oxide arrester (whose resistance is typified by A_0 or A_1) with MOV Type-92 component is specified in the ATPDraw software. ATPDraw accepts the current/voltage (V-I) characteristic and performs an exponential fitting in the log-log domain to produce the required ATP data format [7]. The Pinceti model shown in Figure 2(b) was proposed by Pinceti and Giannetoni in 1999. It is based on the IEEE model with some minor

differences [21] A_0 and A_1 are the non-linear resistors, L_1 , the filter inductance and R_0 the stabilizing resistance are used to avoid numerical oscillations [22, 23]. The model proposed by Fernandez and Diaz in 2001 is shown in Fig.

2(c). In this model A_0 and A_1 are in parallel and are separated by an inductor of inductance L_1 , which is the filter inductance, and has the most influence on the result.

Figure 2: Lightning Diverter Models

Among these models, the IEEE model is somewhat advantageous over the Pinceti and Fernandez-Diaz models because it involves the physical dimensions of the arrester which can be easily measured.

3. LIGHTNING ARRESTERS IN THE PROTECTION OF POWER LINES

Lightning discharges on transmission and distribution lines affect their efficiency and performance as the transient high voltages may cause flashovers on electrical equipment on the power line [16]. The protection of electric power lines from the destructive effects of lightning may be achieved by one or a combination of the following methods [17]. First is the use of the highest economically reasonable insulation levels, second is the use of overhead ground wires with good earth connections at the most closely spaced intervals physically possible and economically reasonable, and third is the use of lightning arresters between the phase conductors and the neutral, spaced as closely along the line as economically reasonable and at locations of sensitive line hardware. The role of lightning arresters in the protection of power lines cannot be overemphasized. [24], in their research on the lightning performance of unshielded transmission lines, posited that the installation of lightning arresters after four years of operation of the Narrabri-Moree line reduced the observed outage rate, buttressing the need for the protection of power lines against lightning.

Grounding Details

Earth rods are selected based on their ability to withstand corrosion, copper bond earth rods are selected for the earthing of the LPS [25]. Earthing systems must also, have an electrical resistance less than 10 ohms [26].

4. METHODS AND MATERIALS

In this work, 132/11kV transmission line system is chosen alongside SOLIDWORKS software being used. SOLIDWORKS software is a software that is used for the design of physical engineering structures. It allows the designer to separate the structure into its constituent components and then assemble them to realize the full structure. Designs in the SOLIDWORKS software are saved with the extension, **SLDDRW**. This software is used to test the designed arrester and know its performance. The software is also used for modelling of the overhead transmission line system. It can simulate overvoltage problem related to lightning phenomena and switching problem occurring in electric power systems.

However, in our paper, a quite different design methodology is proposed. This approach entails using MOV blocks that are bored and a 10 mm connecting metal (copper or aluminum) rod (main stud) passed through the bored holes in the stacked MOVs. This connecting rod is welded at both ends to a 10 mm hexagonal screw at the non-threaded end. The design is a little crude but is workable if the means were available. It is on top of this design that other steps taken in the conventional construction of lightning arresters can be made. It has also featured a comparison of the voltage levels for three different load cases under two system conditions.

a. Model Calculations

We employed the following equations in determining the parameters of the lightning arrester modelled after the IEEE model whose parameters are dependent of the physical properties of the lightning arrester.

The Stabilizing Resistance, R_0 , can be determined using Eq. 1:

$$R_0 = 100d/n \quad [\Omega] \quad (1)$$

Where $d = 445\text{mm}$ and

$n = \text{number of parallel columns of metal oxide} = 12 \text{ columns}$

$d = 445 \text{ mm}$, and

Substituting the variables into Eq. (1) gives $\Rightarrow R_0 \text{ as } 3.71 \Omega$

Hence, the stabilizing Resistance is 3.71Ω .

Also, the Magnetic Field Inductance, L_0 , is given by Eq. 2:

$$L_0 = 0.2d/n \quad [\mu H] \quad (2)$$

Where n and d are as defined earlier, thus, giving $L_0 \text{ as } 7.42 \times 10^{-3} \mu H$

Further, the Filter Resistance, R_1 is given by Eq.3

$$R_1 = 65d/n \quad [\Omega] \quad (3)$$

$\Rightarrow R_1 = 2.41 \Omega$.

The Filter Inductance, L_1 is given as

$$L_1 = 15d/n \quad [\mu H] \quad (4)$$

$\therefore L_1 = \cong 0.56 \mu H$.

The Terminal-To-Terminal Capacitance of The Arrester, C , can be determined from Eq. (5):

$$C = 100n/d \quad [pF] \quad (5)$$

$\Rightarrow$ Implies that $C \equiv 2.70 \text{ nF}$.

The Dimensions of One Zn-O Varistor of The Lightning Arrester can be calculated using Eq. 6:

$$h_v = \frac{h_c}{\text{Number of columns of ZnO}} \quad (6)$$

where h_v is the height of one varistor, $\Rightarrow h_v \cong 30.42 \text{ mm}$.

The Arrester Rated Voltage is given as:

$$V = 11 \text{ kV} + (10\% \times 11 \text{ kV}) \quad (7)$$

The lightning arrester designed is to be installed on a 11-kV transmission line i.e. a transmission line with system voltage of 11-kV (rms). So, by employing equation (7), the rated arrester voltage can be gotten as:

$V = 12.10 \text{ kV rms}$ i.e. adding in 10% voltage regulation, gives $V_p = 6.9 \text{ kV (rms)} = \text{Min. MCOV}$.

Arrester voltage got is $\cong 7.6 \text{ kV}$ but 9kV is chosen because it is the closest arrester rating available in the market. Which implies that MCOV, which is 85% of the chosen voltage is 7.65kV

For this study, a $10 \text{ mm} \times 365 \text{ mm}$ lightning arrester, to be installed on a 11 kV transmission line, is designed using the SOLIDWORKS software. The structure of the lightning arrester and the SOLIDWORKS design consist of the following four (4) main parts.

- A. The Column or Disc.
- B. The Main Stud.
- C. The Hexagonal Head Bolt (M10).
- D. Stack of Metal-Oxide Varistors e.g. ZnO varistors.

1. The Column or Disc

This is made of thyrite, porcelain, rubber or polymer and forms the exterior housing of the lightning arrester. It consists of a hollow, which is 16mm in diameter and a pair of circular discs, the top larger than the one at the bottom. The top is 96mm in diameter while the bottom is 83mm in diameter as shown in Figure 3. Twelve (12) of this pair makes the full length of the arrester body i.e. number of thyrite discs, $= 2 \times 12 = 24$. The hollow is the slot for the hexagonal (hex) bolt.

Figure 3: Dimensions of the Designed Lightning Arrester (in mm)

2. The Main Stud

This part of the arrester is 365 mm in length. It is made of metal like stainless steel and runs through the hollow inside the arrester main body comprising the discs. The hex bolt is welded to a 10 mm metal rod to form the main

stud as shown in Figure 4. The main stud is 10 mm wide in diameter. This metal stud holds the varistors together in place together with the springs. The connections to the transmission line on top of the lightning arrester are made using the hex bolt and nuts that are 10 mm in diameter. At the bottom of the lightning arrester, the hex bolt is connected to a disconnector, which is connected to a set of insulating brackets.

Figure 4 (a): The Rod joined to the Hex bolt to form the Lightning Arrester, (b): Cross-section of Lightning arrester with parts labelled.

3. Grounding Features

Earth rods are selected based on their ability to withstand corrosion, and as such, copperbond earth rods are selected for the earthing of the LPS. Earthing systems must also, have an electrical resistance less than 10 ohms. The earthing protection system chosen is a Type-A earthing protection system which consists of:

- Vertical copperbond earth rods (length – 2400 mm, weight – 3 kg, 0.254 mm thickness. IEC/BS EN 62561-2 & BS 7430 standards). It should have a steel core with electroplated nickel and copper plating.
- Steel driving stud (0.08 kg).
- Copper coupling (0.13 kg).
- Solid Copper earth plates (600×600×3 mm).

4. Stack of Metal Oxide Varistors

These are shown in Figure 5 and handle the conduction of the lightning current through the lightning arrester to the ground. The stack of the metal oxide varistors in the designed lightning arrester consists of twelve (12) identical metal-oxide varistors; one lodged in between a pair of discs or columns. Each MOV (metal-oxide varistor, ZnO) has an outer diameter of 40mm and an internal diameter of 12mm. The height of one MOV (Metal-Oxide Varistor) is 30.42

Figure 5: Full Lightning Arrester Design using SOLIDWORKS.

mm (see Calculations Section). Figure 5 shows the final arrester design as realized using SOLIDWORKS Premium software.

5. Lightning Waveform

Figure 6 represents the waveform of the first lightning stroke. It was simulated using ATPDraw using three shunt-connected ideal current sources of 10kA, 6kA and 4kA respectively. **Type-15** surge function (double exponential source [7]) was used for the first lightning stroke while **Type-13** ramp functions were used to simulate the second and third lightning strokes with magnitudes of 6kA and 4kA respectively; each having a duration of 0.5ms. Figure 6 is the lightning surge voltage waveform used in the analysis. It has the following characteristics viz:

- Front time, $t_f \cong 0.05 \text{ ms}$ ($50 \mu\text{s}$).
- Tail time, $t_T \cong 0.148 \text{ ms}$ ($148 \mu\text{s}$).
- Simulation Period = 0.6 ms .

6. Characteristics of the Lightning Arrester

For the simulation of the lightning arrester, MOV-Type 92 component is used. Crompton Greaves ZLA2007 surge arrester with Class 3 ZnO element i.e. the varistor possesses a hollow, is employed for the simulation on ATP. This arrester has the following characteristics shown in Table 2 below. Using these values, the VI characteristics of the chosen lightning arrester is plotted and is shown in Figure 7.

Table 2: Characteristics of Crompton Greaves Zla2007 Lightning Arrester

Maximum Continuous Operating Voltage	7.65			
Rated Voltage, kV (rms)	9			
Overall Height (mm)	470			
Residual Voltage at Specific	1.5 kA	2.5 kA	5 kA	10 kA
Discharge Current	21.5	22.5	23.2	24.5

Figure 7: Lightning arrester V - I characteristics.

Figure 7 is the residual voltage curve of the chosen lightning arrester (Crompton Greaves ZLA2007). It represents the V-I characteristics of the lightning arrester and gives the conductivity or resistance of the arrester's varistor. It is not used in the simulation but only serves as representational and explanatory purposes.

5. RESULTS

The performance of the designed lightning arrester, using the obtained results, is evaluated using the Alternative Transients Program (ATP). For analysis, the effect of lightning strike on a power system, a 132/11kV substation is modelled and simulated. Figure 8 shows the 132/11kV system in which the 11 kV is fed from the 132-kV system through a step-down transformer, T_1 .

Figure 8: Scheme of the Power Network

In this model, the line connecting the 132kV source to point 3 is “line 1” and it is around 50 km long and the length of its lateral branches is shown on Figure 8. The modelling of lightning flash was done by using three spikes of different values of magnitude. This includes first stroke duration of 0.7ms with about 10 kA lighting current while the second and third subsequent lightning strokes have durations of 0.5ms with 6 kA and 4 kA lighting current magnitude respectively.

Having considered the different models needed for the simulation, the following cases are considered in the analysis:

- I. When lightning strikes at the 132/11 kV substation secondary side of transformer T_1 on line 1. This is the first lightning strike.
- II. When lightning strikes at a point on line 1, 30 km away from the first point i.e. 30 km away from the secondary side of T_1 . This is the second lightning strike.
- III. When lightning strikes at the end of the first phase transmission i.e. at point 3 which is 50 km from the secondary side of T_1 or 9.5 km from Load 2 in the power network.

Since only the parameters for the IEEE model were calculated for this project, only the IEEE model is simulated using ATP-Draw. The parameters of the IEEE model are summarized in Table 3.

The model given in Table 3 is used to obtain the response of the surge arrester to the lightning waveform using ATP as shown in Figure 9. A lightning waveform $8 \times 20 \mu\text{s}$ with 10 kA is applied at the input terminals of the IEEE model circuit of Figure 2a and a graph of the voltage response is obtained. This is done to ascertain the behavior of the IEEE surge arrester model under the influence lightning

Table 3: Parameters of the IEEE Model

Model	$R_0 (\Omega)$	$L_0 (\mu\text{H})$	$R_1 (\Omega)$	$L_1 (\mu\text{H})$	$C (\text{pF})$
IEEE	3.71	7.42×10^{-3}	2.41	0.56	2.696×10^3

Figure 9: Response to lightning waveform $8 \times 20 \mu\text{s}$ - 10 kA.

As shown in Figure 10, the object which the lightning strikes is a pole. The MOV blocks represent lightning arresters installed on the line. From Figure 10, we can see that two lightning arresters are installed on line 1 while one arrester is installed for each line connecting a load i.e. one arrester for the line to Load 1, Load 2 and Load 3.

Figure 10: ATP-Draw Simulation for Case I.

Next, the voltage values obtained at the loads when arresters were installed and when they are not installed are compared. All graphs are plotted using the ATP-Draw software. Figure 11 shows the graph for the three cases for Load 1 without an arrester connected. It can be seen from Figure 11 that the maximum voltages at Load 1 for Case I, II, and III without lightning arresters are 32 kV, 25 kV and 20 kV respectively. Apparently, these values are very high because of the lightning and these voltages are very unhealthy for electric power system equipment as it exceeds insulation flashover levels.

Taking the maximum positive values from the figure above, one can see that the voltage value for Load 1, for the first case is slightly greater than 30 kV, that of case 2 is around 25 kV, while that of case 3 is 20kV. The same process is repeated for cases 2 and 3.

Having looked at the voltage values, without lightning arresters installed, it is important to discover the effect of the installation of the lightning

Figure 11. Voltage vs. Time for the Three Cases for Load 1 (without arresters).

arresters on the power system and how it affects supply to the loads. Figure 12 gives the effect of lightning arresters installation on the voltages at Load 1. From the graph, the maximum voltage for Case I, II and III are obtained as 11 kV, 10 kV, 8.0 kV respectively. Clearly, these values are way much lower than those obtained when lightning arresters were not installed and closer to the actual value which is 11 kV. Apparently, the installation of lightning arresters greatly reduces the voltages at Load 1. Using the same techniques, the voltages at Load 2 with lightning arresters installed are 15 kV, 13.5 kV and 11.25 kV respectively while those at Load 3 are 5 kV, 3.2 kV and 0.5 kV

Figure 12: Voltage Values at Load 1 with Lightning Arresters Installed.

Table 4: Voltage Values for Loads 1, 2, & 3 (For the Three Cases) Without Lightning Arresters

CASE	I (kV)	II (kV)	III (kV)
Load 1	32.00	25.00	20.00
Load 2	80.00	38.80	22.00
Load 3	12.00	8.00	6.00

Table 5: Voltage Values for Loads 1, 2, & 3 (for the Three Cases) With Lightning Arresters Installed.

CASE	I (kV)	II (kV)	III (kV)
Load 1	11.00	10.00	8.00
Load 2	15.00	13.50	11.25
Load 3	5.00	3.20	0.50

Comparing, the values in both tables, that is, the voltage values without the installation of arresters and the voltage value with arresters, one can infer that the installation of lightning arresters greatly reduces the voltages induced by the lightning on the loads therefore establishing the need for lightning protection. Considering Case III and Load 3, one can calculate the percentage reduction thus:

$$\% \text{ Reduction in Voltage} = \frac{6-0.5}{6} \times 100\%$$

$$\therefore \% \text{ Reduction in Voltage} = 91.67 \% \cong 92\%.$$

6. DISCUSSION OF RESULTS

The maximum voltage values at three different load points, i.e. Load 1, Load 2 and Load 3 were taken from graphs plotted by the same software under two conditions which were without the connection of lightning arresters on the line and with lightning arresters connected on the line. From the results obtained, it is evident that lightning strikes induce very high voltages on power lines as voltages as high as 80 kV were recorded when lightning arresters were not installed on the power lines. These results show how dangerous lightning is as the lightning-induced voltages are above insulation flashover levels for 11 kV equipment (11 kV/ 132 kV BIL- Basic Insulation Level). Three cases were studied, and results show that lightning-induced voltages are much higher at the start of a line than at its end. These voltages at the loads when there are no arresters installed on the lines are dangerous for distribution as they are capable of damaging household equipment. The results establish the need for lightning protection by employing lightning arresters. The installation of the lightning arresters greatly reduced the voltages at the loads. Clearly, this implies that lightning arresters are indispensable in power systems protection as they greatly reduce lightning-induced voltages in power systems.

It is evident that the operation of a power transmission or distribution network with no lightning protection, is very detrimental for system performance. Also, loads and system devices are exposed to unnecessary and very dangerous over voltages which may cause insulation flashovers and device failures. The installation of lightning arresters therefore is imperative as they help decrease the adverse effects resulting from the lightning strike on the line.

7. CONCLUSIONS

The primary consequence of the lightning is that it leads to overvoltages in a power system network which are harmful to both equipment and personnel. They can be greatly suppressed by lightning arresters. The designed lightning arrester performs optimally as it greatly reduces the lightning-induced voltages recorded at specific loads in a 132/11 kV power system network by about 92 % as can be seen in Table 5. A direct proportionality relationship exists between the system line-to-line voltage and the voltage rating of the arrester, and as such lightning arrester ratings should be selected based on the particular voltage of the system to be protected. Also, the voltage induced by the lightning on the line, from the results obtained, decreases along the line i.e. the voltage is lower at the end of the line than at the start of the line. From the results obtained also, the IEEE model of the lightning arrester also proved to be efficient. It has also featured a comparison of the voltage levels for three different load cases under two system conditions – with and without lightning arresters installed, plus a statement of the best percentage reduction in load voltage, which is Case III (in Table 5), thus affirming the advantage the IEEE model offers over other lightning diverter models [2].

REFERENCES

- [1] Williams, E.R., Rothkin, K., Stevenson, D and Boccippio, D.J (2000) “Global lightning variations caused by changes in thunderstorm flash rate and by changes in the number of thunderstorms,” *J. Appl. Meteor*, vol. 39, pp.2223–2230.
- [2] D. Guillén, H. Esponda, E. Vázquez, G. Idárraga-Ospina (2016) “Algorithm for transformer differential protection based on wavelet correlation modes,” *IET Generation Transmission & Distribution*, vol. 10, iss. 12, pp. 2871–2879.
- [3] Beaty H. W. (2006). “Standard Handbook for Electrical Engineers”, New York: McGraw-Hill Professional, 2006.
- [4] Burke J.J. (1994). “Power Distribution Engineering Fundamentals and applications,” New York: CRC Press, 1994.
- [5] Tobias J.M. (1993). “Lightning Protection System Design,” U.S. Army Communications- Electronics Command, CECOM Safety Office, Fort Monmouth, New Jersey, U.S.A., Tech. Report. AD-A261 900, Jan. 1993.
- [6] K. Inagaki, M. Higaki, Y. Matsui, K. Kurita, M. Suzuki, K. Yoshida, T. Maeda “Digital protection method for power transformers based on an equivalent circuit composed of inverse inductance”, *IEEE Trans. Power Deliv.*, 3 (1988), pp. 1501-1510, 1988.

- [7] Nweke, F.U., Nwofe, P.A., Akpan, B.U., Ukwu, C.N and Onah D.U. (2015) “Lighting Discharge on Power Lines- A Case Study of Afam Power Plant, Nigeria,” *International Research Journal of Pure and Applied Physics*, vol. 3, no. 1, pp.1-8.
- [8] Mowete, A. I and Adelabu M.A. (2009) “An Assessment of lightning and other electrostatic Disturbances along the coast of South West Nigeria,” In 19th International Conference on Electromagnetic Disturbances, 2009, p. 200.
- [9] E. Ali, H. Helal, H. Desouki, K. Shobl, S. Adelskader, and O.P. Malik, “Power Transformer differential protection using current & voltage ratio”, *Electric power system research*, Vol. 154, pp140 -150, January 2018.
- [10] S. Member, “A novel transformer protection method based on the ratio of voltage and fluxional differential current”, *Proceedings of IEEE Transmission Distribution Conf. Expo.* (2003), pp. 342-347.
- [11] Kerr J. (2003). “Protecting against Lightning strikes and their Secondary effects”, Technical Report. LEC-02-78, 2003.
- [12] Sugarman R. (1978), *New York City’s blackout: a \$350 million drain*. IEEE Spectrum 15, pp. 44–46, 1978
- [13] Madueme T.C. (1989). “The Effect of Lightning flashes on a distribution network,” *ResearchGate*, pp. 24-32, 1989.
- [14] Adepitan J.O and Oladiran E.O (2012). “Analysis of the Dependence of Power Outages on Lightning Events within the Ijebu Province, Nigeria,” *Research Journal of Environmental and Earth Sciences*, vol. 4, no. 9, pp. 850-856, 2012.
- [15] Andersson, G., Donalek, P., Farmer, R., Hatziaargyriou, N., Kamwa, I., Kundur, P., Martins, N., Paserba, P., Pourbeik, P., Sanchez-Gasca, J., Schulz, R., Stankovic, A., Taylor C and Vittal, V. (2005). “Causes of the 2003 major grid blackout in North America and Europe and recommended means to improve system dynamic performance,” *IEEE Transactions on Power Sys.*, vol. 20, no. 4: 1922-1928, 2005.
- [16] Izadi, M., Abd Rahman, M.S., Ab-Kadir, M.Z., Gomes, C., Jasni, J and Hajikhani, M. (2017) “The influence of lightning induced voltage on the distribution power line polymer insulators,” *PLoS ONE*, vol. 12, no. 2. [Online serial]. Available: <http://doi.org/10.1371/journal.pone.0172118>. [Accessed Nov.21, 2017].
- [17] Uman, M.A (2008). *The Art and Science of Lightning Protection*. Cambridge, UK: Cambridge University Press, 2008.
- [18] Uche C. Ogbuefi, Philip O. Okorodudu, Clinton O. Enwerem, and Theophilus C. Madueme, “Lightning Arrester Design for Protection of Electric Power Systems”, 2018 INTERNATIONAL CONFERENCE PROCEEDINGS: FACULTY OF ENGINEERING, UNIZIK, Pg. 931 to 941.
- [19] Rakov, V.A and Uman, M.A. (2003). *Lightning Physics and Effects*, UK: Cambridge University Press, 2003, p. 4.

- [20] Pinceti, P. and Giannettoni, P. (1999). "A Simplified Model for Zinc Oxide Surge Arresters," *IEEE Transactions on Power Delivery*, Vol. 14, No. 2, April 1999.
- [21] Ali, S.A (2013) "Design of Lightning Arresters for Electrical Power Systems Protection," *Power Engineering and Electrical Engineering*, vol. 11, no. 8, pp. 433-442.
- [22] Fernandez F and Diaz, R. (2001) "Metal oxide surge arrester model for fast transient simulations," *International Conference on Power System Transients*, Rio De Janeiro: Federal University of Rio de Janeiro, 2001, pp. 144-1 – 144-5.
- [23] A.G. Phadke, J.S. Thorp A new computer-based flux-restrained current-differential relay for power transformer protection, *IEEE Trans. Power Apparatus. Syst.*, PAS-102 (1983), pp. 3624-3629.
- [24] nVent ERICO, Lightning Protection Consultant Handbook, nVent, 2018.
- [25] Omega Red Group, Earthing and Lightning Protection Product Catalogue, Bulwell: Omega Red Group Ltd, 2015, pp. 1-64.