



MODELING OF EFFICACIOUS LIGHTNING PROTECTION SCHEME ON NIGERIAN 11-132 kV SUBSTATIONS USING CONE OF PROTECTION METHODS

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Abstract

This research aimed to model efficacious lightning protection scheme (MELPS) in Nigerian 11-132 kV substations using analytical models for evaluating both raw and derived data. Specific Transmission substations in the coastal area zone of Nigeria prone to lightning strike were selected as a case study. In order to assess the adequacy of protectiveness of 11 kV -132 kV existing substations, direct dimension of installations using measuring tape were carried out and installations were scaled down and modelled dimensionally using AutoCAD software in order to measure spatial parameters. In order to achieve a proposed desired protective cone of protection, each tower was increased. The results obtained show that there are significant improvements in protective efficacy of proposed protective scheme model (PPSM) for the existing 33/11 kV and 132/33 kV substations. Under the PPSM, all 23 and 33 elements of both 33/11 kV and 132/33 kV substations respectively are adequately protected against lightning strike by obtained coverage factor assessment values and volume of protection evaluation. The PPSM overcomes the ruinous effects of lightning discharge in accordance with lightning protection level standard (99% probability of lightning efficiency). The proposed lightning scheme model is costlier than the existing lightning schemes: 30% and 50% for 33/11kV and 132/33 kV substations respectively. However, juxtaposing the cost with obtainable cost of repair or restoration due to C-G LS, the latter outweighs the cost. It is recommended that the existing protective systems should be reviewed for upgrading that will incorporate a hybrid design comprising sky wire and spike schemes with adequate parameter values in order to mitigate reported failures being caused by lightning in the systems.

Keywords: Lightning, protection scheme, substation, cone of protection, discharge

Introduction

Lightning is a natural electrical discharge characterized by short duration of high voltage (1×10^9 V), high current electric pulses (4×10^4 A), temperature (2.8×10^4 °C), speed (3×10^8 ms⁻¹) and can occur without warning (Richard, 2010; Ronald, 2011). It is generated in the earth's atmosphere by cumulonimbus clouds and can strike anywhere on earth. Improper ejection of lightning fault currents to the ground on time may result in economic damage and loss of life (Melodi and Oyeleye, 2017; Adekitan and Rock, 2022).

Power outage is a function of lightning discharge. Lightning discharge correlates to power outage. The more frequent is lightning strike the more is power outage. Equipment damage, loss of life, enormous costs of equipment and power failures occur (Oyeleye, 2019; Cooper and Holle, 2019; Ikhazuangbe *et al.*, 2023).

It follows that for lightning to be effectively discharged from the cloud, a good 'arresting' of it is necessary. As a result of the arresting of the discharge, recommended protective angle of protection or cone of protection must be considered with respect to lightning discharge (IEC, 2006; Oyeleye, 2019). Thus recommended protective angles were considered in this work.

According to Leke and Gbenga (2013); Melodi and Oyeleye (2017), the coastal region of Nigeria is subjected to thunderstorm of 15flash/10⁶ m/year located at coordinates 6°35'N 3° 45'E and prone to lightning calamities. According to Oyeleye (2019), the existing 11-132 kV Transmission Substations (TS), Ikorodu, Nigeria were not adequately protected. The degree of protection for the 132/33 kV substation is 33.3% protection (eleven out of thirty-three elements) were unprotected. Also, for 33/11 kV substation, it is 50%, 42.9% and 40.75% for sky, spike, and combined sky and spike wire protection respectively. This

indicated that seven out of fourteen, six out of fourteen, and eleven out of twenty-seven were protected. This is a calamity to the stations and end users. The disasters include hurt to life, economic damage to property, disruption of power facilities and electrical related activities (Mowete and Adelabu, 2009).

This research aims at modeling efficacious lightning protection scheme (MELPS) in Nigerian 11-132 kV substations using cone of protection methods. This aligned with the recommendation and further research work for upgrading that will incorporate a hybrid design comprising sky wire and spike schemes with adequate parameter values (Oyeleye, 2019). This will mitigate reported failures and uncertainties in the system.

This work considered Cloud to Ground(C-G) direct lightning (DL) and indirect lightning (IL) strike on designated 11- 132 kV installations in Ikorodu Transmission Substation. The choice of Ikorodu municipality is as a result of outstanding concentration of high voltage (HV) supplies set-up involving large HV power transmission substations, significant industries, communication systems, intense lightning occurrence, and unpleasant lightning damages in this region.

The substations that were inadequately protected were used in this work using similar methodologies. The negative effects of the inadequate protection were overcome in this work. The net results show that the inadequate protective substations were adequately protected in this research. IT substations began operation in 1976 and transmit voltage at 132 kV to significant transmission distribution systems (Oyeleye, 2019; Mowete and Adelabu, 2009).

This work embraces the science of electrical engineering lightning discharge interception for protection, and dissipation into the ground. Also, embraced are the effective methods of preventing power supply systems from lightning. The operational Lightning protective system (LPS) is the most proficient way to protect electrical installations and edifice from damages caused by lightning disastrous current (Saju, 2010; Cooper and Holle, 2019).

Air Terminal System (Interception)

Oyeleye (2019); Adekitan and Rock (2022) stated that the main and most effective protection measure intended for protection of structures against mechanical damage, fire and explosion danger and life hazard due to direct flashes is the lightning protection system (LPS). Properly designed air termination system (ATS)

considerably decreases the probability of lightning stroke current penetrating the structure (Oyeleye, 2019; Daḡa *et al.*, 2021). Air terminals usually located on the top-most part of a structure because top of a structure is usually characterised with highest electrical field where the striking point of the upward leaders is found. The air termination system can compose of spike, catenary nerve, mesh conduction or sky wire often called overhead ground conductor (Oyeleye, 2017).

The materials used for the LPS shall be of good electrical conductivity for flowing of the current and mechanical strength suitability in order to withstand the electromagnetic stresses caused by the high peak values of the current and a good resistance against the corrosion due to atmospheric environment.

The materials usually adopted are iron, copper, and aluminum depending on cost, corrosion, soil resistivity and ability to dissipate fault current to ground but copper material is recommended because of its better conductivity and mechanical efficacy where cost is less considerate (Oyeleye, 2017). Steel and galvanized materials can also be used (Daḡa *et al.*, 2021).

Lightning Cone of Protection Method (LCPM)

Conventional lightning protective methods are Rolling Sphere Method (RSM), Faraday Electro-Geometrical Method (FEMG) and Mesh Method (MM). Any of one or combination of the two methods can be used to prevent lightning damage. From FEMG and RSM equivalent protective angle method ((PAM) was derived. Protective angle method is applied in this research.

High Voltage substation (HVS) uses Overhead Ground Wire (OGW) to form LCPM in order to capture the lightning discharges and grounded lightning discharges to earth. In the past, 33 kV 11 kV substation and lines hardly use OGW. The use of OGW or spike or combination of the two methods are becoming popular for effective protection on 33/11 kV substation projects (Oyeleye, 2017).

Cone of Protection and Mesh Method

Four types of Lightning Protection Scheme (LPS) namely level I, II, III, and IV are defined as a set of construction standards corresponding to lightning protection level (LPL). Each set is level dependent. The level dependent is a function of methods of protection and level independent which is a function of cross sections, materials etc. construction rules. According to Cooray (2010), cone and mesh methods were developed for over one hundred and eighty years (180years). Development of cone or Zone of Protection and Mesh Method of Protection is presented in Table 1.

Table 1: Zone of Protection and Mesh Method (Adapted from Cooray, 2010)

No.	Name	Year	Cone	Cylinder/Mesh
1	Gay- Lussac	1823		100m x 400m
2	DeFonville	1874	63 ⁰	
3	Paris Commission	1875	60 ⁰	
4	Chapman	1875		100 m x 100m
5	Adams	1881	45 ⁰	
6	Wagner <i>et al</i>	1941	20 ⁰ - 70 ⁰	
7	Wagner <i>et al</i>	1942; 1996	30 ⁰ - 45 ⁰	
8	IEC Standards	1990; 1995; 2006	25 ⁰ - 55 ⁰	5m x 5m- 20m x 20m

The cone angle varies from 20° – 70°. Minimum values of lightning current(I) and related rolling sphere radius(R) corresponding to the lightning

protection level [LPL] of LPS, protection angle corresponding to LPL, percentage of probability of lightning strike is presented in Table 2 (Cooray, 2010; Oyeleye, 2017).

Table 2: Lightning Protective Level, Lightning Current and Related Rolling Sphere Radius, Mesh Width, Protection Angle, and Percentage of Probability of Lightning Strike (Cooray, 2010)

LPL	Probability of Lightning Efficiency	of Rolling Sphere Radius	Mesh Width	Protection Angle Method For Different Heights (M) Of Terminals:				Minimum Peak Lightning Current
				20	30	45	60	
LPL	$p(LE)$	R, m	D, m	α (°)				I, kA
I	99%	20	5	25				3
II	94%	30	10	35	25			5
III	91%	45	15	45	35	25		10
IV	84%	60	20	55	45	35	25	16

The protection measures defined by the LPL specified for design is effective against lightning current parameters in the Table 2. The efficiency of a protection measure is assumed equal to the probability in which lightning current parameters fall. In addition to Table 2, protective zone offers by 45° is used for height ≤ 10m (Cooray, 2010; Oyeleye, 2019). Level I protection is considered for the sky and spike wire in this report because it offers best protection. Appropriate protective angle for different heights is applied in this research.

Volume of Protection

The cone of protection defines the volume of protection, Figure 1. Volume of space protected is proportional directly to the angle of protection. Any object within the volume of protection is adequately protected from lightning strike.

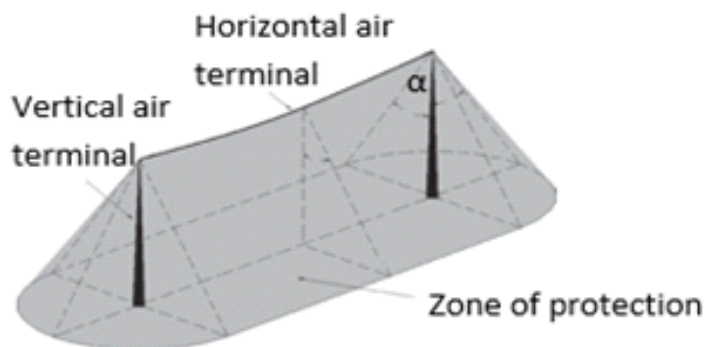


Figure 1: The volume of space protected according to the angle-of-protection method by a horizontal conductor connected to two vertical conductors at the ends (Cooray, 2010)

Negative Lightning Effects

Lightning could unleash potential damage on plants and built structure. The destructive natures of lightning on built structures include hazard for human body, loss of life and economic loss (Saju , 2010). On power supply systems, lightning produces overvoltage which can be minimized but they cannot be eliminated, This overvoltage resulting in insulation break down of power apparatus associated with power outages or damage to equipment. Although lightning is responsible for more deaths and property loss than tornadoes, hurricanes and flood combined, it is the only one we can economically afford to protect ourselves against (Francis, 2010).

Recent brunt of lightning presented in Figure 2 and Figure 3.



Figure 2: Damaged 132/33 kV 60MVA transformer (Tx)

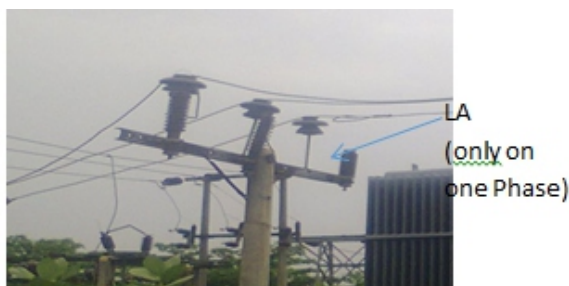


Figure 3: Damaged LA on 33/11 kV substation

Positive Lightning Effects

Lightning may be frightful to life, property and electrical installations but it also serves an important function. It helps in provision of our daily need of the element nitrogen which must be renewed continual for human use. The great electrical energy of lightning converts Nitrogen (N₂) to Triozo-Nitrate (NO₃). According to Donald (2015) , Pickering (2014) and Oyeleye (2017), up to one-half of all usable nitrogen in the soil is made useable by the lightning energy. Nitrogen and its compounds are used as fertilizers, energy-stores, in production of fabric, dyes “super”

glue, pharmacological drug including [antibiotics](#), fertilizers and energy-stores (Willem *et al.*, 2008; Chen *et al.*, 2017; Ogienko *et al.*, 2022; Wang *et al.*, 2022).

Materials and Methods

This research methodology adopted Oyeleye (2019) methodology closely. This is due to the fact that this research wishes to provide solution to the inadequate lightning protection in the previous work.

Data Collection

In order to assess the adequacy of protectiveness of 11 kV -132 kV substations, direct dimension of dimensions of installations were carried out and scaled models of installations were created in AutoCAD. Also, direct dimensions of existing protective devices and the associated lines were carried out in attempt to evaluate the protectiveness of 11 kV -132 kV substations. Physical dimensions (using a measuring tape) of available one number of 132/33 kV substation and four numbers of 33/11 substations in the studied region were carried for the assessment.

Assessment of LPS for Substation and Lines Using Cone and Volume of Protection Methods

Cone of protection (protective angle) method was used to assess the LPS for substation and associated lines in Ikorodu zone. The lightning protective system for substation and lines were assessed by model substation and tower using measured real life dimensions. Using the AutoCAD work space model scaled dimension of the modelled substation and tower, angle of protection is obtained. For this method, theoretically, the following criterion is established for evaluation or appraisal of existing designs for protection against direct lightning strike. Let protection angle of protected element to normal of LPS device be termed θ_{el}

$$\theta_{el} \leq \theta_{std} \quad \text{Oyeleye (2017)} \quad (1)$$

where θ_{std} is the standard maximum coverage angle of LPS device with respect to normal, θ_{el} .

For angular evaluation in this study, the LPS and protected network were assessed using AutoCAD software. Using this criterion, an analytical coverage factor (CF) is proposed for measuring the degree of protective coverage, as in Equations (2).

$$CF = 1 - \theta_{el} / \theta_{std}; 0 \leq CF \leq 1 \quad (2)$$

Design of Proposed Efficacious Lightning Protective Scheme (PELPS)

In order to overcome the inability of the measured angles of existing elements with the standard to offer the necessary protection, coupled with analytical CF for the substations element (Oyeleye, 2019), there is a need to re-design the existing substations for effective protection. In order to achieve this, each tower height,

H_{mt} , is increased for adequate protection as given by Equation (3).
 $H_{mt} > H_{et}$ (3)

where H_{et} is existing height of a tower.

For 132/33 kV, the substation tower height is increased from 13m to 20m; and 16m to 25m for adequate protective angle. 25mH (maximum) is used because of the existing tower height in the study country due to

aviation regulation. For 33/11 the mounting height of the sky wire and spike increased from 8.5m to 16m and 10.5m to 20m respectively for adequate protective angle.

Results and Discussion

Design and Model of PELPS

Results obtained from measurements and evaluations of all elements considered by standard angle of protection requirement, are presented in Figures 4 and 5.

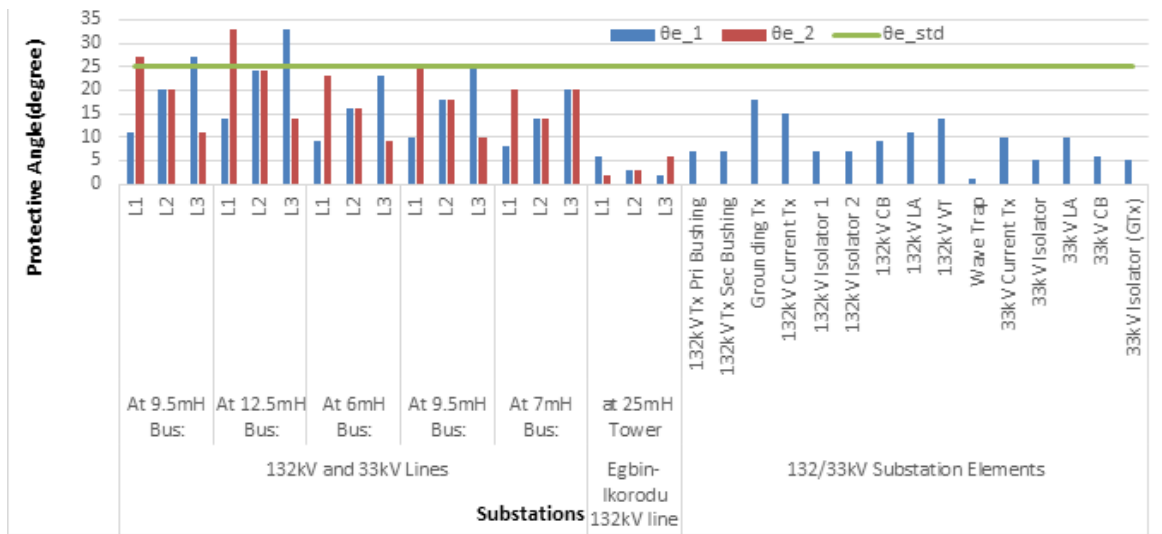


Figure 4: Model of protection angles with respect to standard provided by adjacent OGWS 1 and 2 for 132/33 kV Ikorodu substation

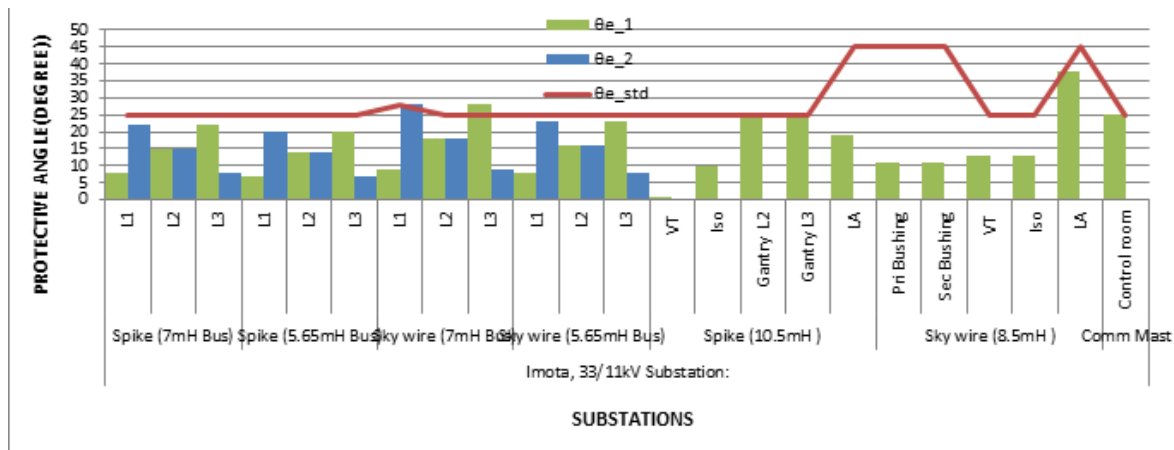


Figure 5: Model of protection angles with respect to standard provided by adjacent OGWS 1 and for 33/11 kV Imota substation

The results show modelled proposed efficacious lightning protective scheme for DLS for elements with values of θ_{e1} and θ_{e2} above θ_{std} for 132/33 kV substation and 33/11 kV substation respectively. For a particular element, one of the two protective angles protects at least the particular element. The results

show that both 33/11 kV and 132/33 kV substations are adequately protected against lightning strike: for the 132/33 kV substation elements, 31/31 (100%) of elements are protected; and for 33/11 kV substation elements, 23/23 (100%) of elements are protected. These values correspond to the coverage factor assessment values presented in Figures 6 - 7.

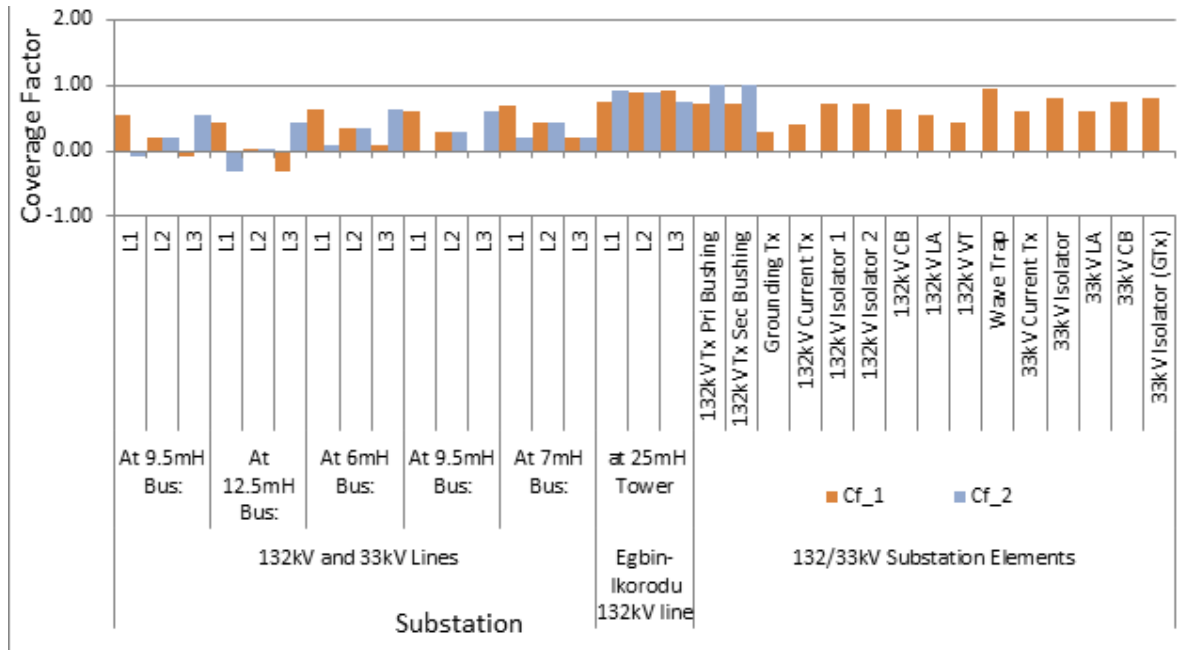


Figure 6: model of coverage factors from adjacent OGWs 1 and 2 for each protected installation in 132/33 kV Ikorodu transmission substation

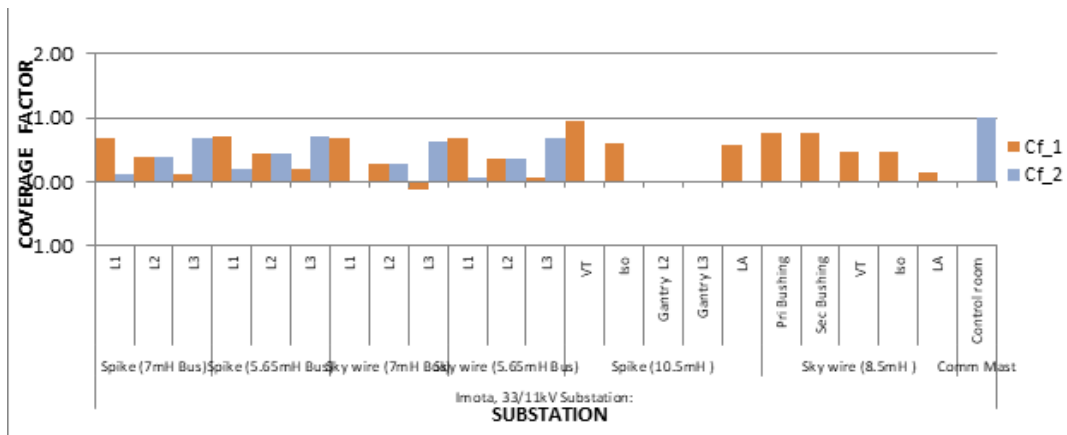


Figure 7: Model of coverage factors from adjacent OGWS 1 and 2 for each protected installation in 33/11kV Imota distribution substation typical to other four studied 33/11kV distribution substations

Cost of Modelled PELPS

The cost of modelled PELPS in comparison with the existing substation is presented in Table 3.

Table 3: Bill of Engineering Measurement and Evaluation

S/N	Substation	Unit Price(N)	Ratio - Model:Existing	Cd/beapps
33/11 kV				
Existing				
1	33/11 kV Modeled	4,394,501.80		₦1.3m
2	33/11 kV	5,694,799.30	1.3	
132/33 kV				
Existing				
3	132/33 kV Modeled	199,319,343.50		₦107m
4	132/33 kV	306,034,343.50	1.5	

N.B: CDBEAPPS –Cost of difference between existing and proposed protective scheme

From Table 3, the cost of a model for 33/11kV and 132/33 kV substation is 30% and 50% higher than 33/11kV and 132/33 kV substation the existing one respectively.

Conclusions

This work was carried out by proposing and using analytical models for evaluating both raw and derived data of the existing installations for effective lightning protections. Installations were scaled down and modelled dimensionally using AutoCAD software in order to measure spatial parameters.

From the analyses of the results, the following conclusions were made:

- i. There are significant improvements in protective efficacy of Proposed Efficacious Lightning Protective Scheme (PELPS)
- ii. Under the proposed lightning protective scheme, all 23 and 33 elements of both 33/11 kV and 132/33 kV substations respectively are adequately protected against lightning strike.
- iii. The PELPS overcomes the ruinous effects of lightning discharge in accordance with lightning protection level standard (99% Probability of Lightning Efficiency).
- iv. The proposed lightning scheme model is costlier than the existing lightning schemes: 30% and 50% for 33/11kV and 132/33 kV substations respectively. However, juxtaposing the cost with obtainable cost of repair or restoration due to C-G LS, the latter outweighs the cost.

It is recommended that the existing protective systems should be reviewed for upgrading that will incorporate a hybrid design comprising screen, sky wire and spike schemes with adequate parameter values. This will mitigate reported failures being caused by lightning in the system. Further Studies should be carried out on the various size of air terminal, down conductor and earthing employed in lighting network.

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