Evaluation of Lightning Protection Efficacy On Nigerian Installations High Voltage Installations Using Screen and Cone of Protection Methods

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***Abstract*—This study evaluated lightning protective system efficacy on 11kV-132kV substation-power line installation in Ikorodu, Lagos State, Nigeria with reference to cloud to ground(C-G) lightning strike (LS) events. It focusses on interception of lightning strikes and its protection with reference to direct lightning strike (DLS) and indirect lightning strike (IDLS). Data were collected from Ikorodu 132/33 kV Transmission Substation and its four major injection stations. This work was carried out using physical measurement of raw data obtained from the high voltage substation. Installations were scaled down and modelled dimensionally using AutoCAD software in order to measure spatial parameters in order to measure the screening of the existing substations and connected lines, as well as the existing cone angles of protection. Probability of lightning efficiency of lightning protective level (LPL) are used for screening evaluation while spike and sky wire angle of protection are used for cone of protection evaluation. Physical measurement of six substations (33/11 kV and 132/33 kV substations) in the studied area were also carried out to evaluate the effectiveness of the installed lightning arresters with respect to the protected devices using applicable standard. The results under the prevailing lightning protective system, LPS, (screening method), revealed that the existing 33/11 kV and 132/33 kV substations are not adequately protected against lightning strike; 132/33 kV substation is more vulnerable to lightning strike than 33/11kV substation and that the incoming 132kV power lines to the substation are adequately protected. The evaluation of the installed distances of all lightning arresters are within standard range and would adequately protect substation transformers against travelling waves (Indirect Stroke) events. The installed lightning arresters (LAs) would adequately protect substation transformers against travelling waves (Indirect Stroke) events. The adequate protection should be reinforced with proposed design scheme in further study in order to mitigate the disastrous effects of lightning strike. Any proposed design of protective system for electric power installations in Nigeria should be simulated using computer aided design software for scaled validation of dimensional and spatial design values in order to mitigate reported failures and uncertainties in identifying causes of observed failures in the system**

***Index Terms*—Substation Power Line, AUTOCAD Software, Lightning Strike, Lightning Protection, Lightning Efficiency Probability, Interception, Air Termination.**

I. INTRODUCTION

Lightning is electrical discharge generated in the earth's atmosphere by cumulonimbus clouds, volcanic eruptions, dust storms and snow storms [1]. This research is confined to cumulonimbus clouds. [1] reported that lightning discharges are known to be characterized by short duration of high voltage(1GV), high current electric pulses(40kA), temperature (27.8 x 10^4), speed (3 x 10^8 ms $^{-1}$) and can occur at any time [1], [2]. Lightning is an unpredictable event that can strike anywhere on earth. When the faulty currents are not effectively discharged to the ground, malfunction of valuable equipment or systems, equipment damages and life loss are experience. [1], [3].

The definite objectives of this study is to evaluate the adequacy of existing protection system on the selected 11-132 kV installations in Ikorodu Transmission Substation (ITS) with reference to direct lightning strike (DLS) and indirect lightning strike (IDLS). The choice of Ikorodu town is due comparatively high concentration of HV supplies infrastructure comprising HV power transmission substations, substantial industries, numerous communication networks, and obvious high lightning activity, disastrous lightning strike event in this region. Ikorodu Transmission Substation (ITS) began operation in 1976. The station transmits voltage at 132 kV to Maryland and Sagamu transmission stations, and supplies power to Ikorodu Distribution Systems. The science of lightning interception and protection, discharge and dissipation into the ground from the engineering point of view are reviewed. Also, the effects and effective methods of preventing power supply systems from lightning are also reviewed.

Lightning protective system (LPS) is the most efficient way to protect electrical installation and building from damages caused by lightning stroke [4]. The control of lightning discharge therefore calls for an effective protective system to minimize or remove the adverse effects of loss of life, economic damage to properties, disruption of power facilities and other activities. Lightning detecting system (LDS) nowadays combine with on line monitoring of circuit breakers, relays and or substation alarms to improve operation and minimize damage in electrical utilities. Feeder lockouts during lightning strike can be opened and can be reclosed after lightning strike in order to avert damage to the system or building structure. Conventional lightning protective methods like protective angle methods, faraday electro-geometrical method (EMG), rolling sphere method (RSM) and mesh (screen) method can be used to prevent lightning damage. Faraday electro-geometrical method (EMG) and rolling sphere method (RSM) were modified to obtain equivalent protective angle methods [5]. Protective angle method and mesh methods are applied in this research. High tension (HT) substations and power line (500 kV to 132 kV) uses mainly lightning arrester(LA) and overhead

Published on July 9, 2019.
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ground wire grounded to earth as LPS while 33 kV 11 kV substation and lines rarely use OGW [6]. Nowadays in Nigeria, the use of OGW or spike or combination of the two methods are used on 33/11 kV sub stations project.

Ikorodu town is located in coastal region hence the transmission station is located in this region and thus prone to LS and its associated effects and damages which needs to be mitigated. [7], [8] and [9].

II. Literature Review

A. Overvoltages, Lightning and Characteristics

Voltage above rated maximum allowable voltage is referred to as overvoltage. One of the cause of overvoltage in power systems is lightning strikes (LS). It can be direct lightning strike (DLS) or indirect lightning strike (ILS). ILS is more frequent but generate smaller overvoltage (OVs) than DLS [[10].

According to [9], maximum permissible voltage on lines / electrical installations for distribution is ±6% of the rated voltage whereas for a transmission line, voltage variation can be up to 10% or even 15% due to variation in load. However, the voltage is always ±5% of the supply voltage while frequency is kept within ±0.05Hz.

According to [3], a lightning current can travel for long distances on overhead power lines and cable to do a damage. Lightning current is in above 40kA, induced temperature equal to 27.8 x 10^4 ^oC and speed closed to 1 x 10^8 ms $^{-1}$. It occurs either within a large cumulonimbus cloud (cloud-to-cloud, C-C) or between the cloud to ground (C-G). According to [9], thunder storm occurrence varies with location.

B. Types of LS with Respect to Power Installations

The transmission and distribution lines together with their substation are in the open and directly exposed to lightning strike, [9]. Lightning strikes (LSs) are classified as direct lightning strikes (DLS) and indirect lightning strikes (ILS). A direct lightning strike is a lightning discharge which is directly from the cloud to the subject equipment like an overhead line, tower or earth wire [10] and [9]. Indirect direct lightning strike result from electrostatically induced charges on the conductors due to the presence of charged cloud. Majority of the surge in a transmission line are caused by indirect lightning strike. Lightning strike can be harmful to life and equipment; and there are significant downtime and outage-related revenue losses due to equipment damage associated with it.

C. Lightning Protection

Thunderstorms are natural phenomena and there are no devices and methods capable of preventing discharges [11]. [12] reported that there is particularly no protection against the direct lighting stroke but protective devices will limit the damage and prevent the resulting waves affecting the power lines and generating stations as far as possible. According to [13], 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).

Protective method used in HV (132 kV, 33 kV) lightning protection network includes (1) interception (air terminal system -ground wire); (2) conduction (down conductor - earth connecting wire) and (3) dissipation [12]. Adequate insulation structures must be provided so that the discharge can drain to ground without affecting the conductors. This research focus on interception of lightning strikes and its protection. Due to lightning strike exposure, it is therefore necessary to protect: Power station or substation; Overhead transmission and distribution lines; and electrical equipment, especially power transformer.

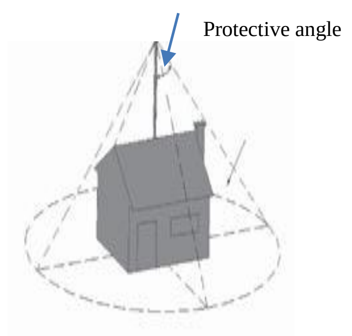
D. Development of Lightning Protection

Lightning protection science was first conceived by Benjamin Franklin in 1749 [14]. New theories, results of observations and statistical results followed [15]. Early observation about the LPS or LP network shown effectiveness (45^o protective angle) and the failure of angle of protection (outside 45^o to 64^o protective angle). This resulted in limitation of early Franklin iron rod. Later, development of protective zone aided the birth of rules and standards in 1800s and subsequently code in 1904 that established a set of rules for those who installed LPSs in Britain.

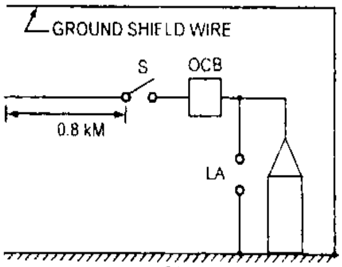
For decades, a sort of lightning protection system (LPS) has been devised at arresting potential lightning strikes and diverting surge currents to the ground [16]. Lightning protection devices properly designed and installed, collect and dissipate these charges and protect from catastrophic damage [14]**.** [5] stated that lightning protection relies upon the application of some of the principles of electricity and the physics of electrical discharges to mitigate the effects of direct and electromagnetic fields generated by lightning discharges. They are protective angle method, the electro-geometrical method, the rolling sphere method, and the mesh method.

E. Lightning Protection against Lightning Strikes

Known lightning protection devices (LPD) for protections against surges, include: Earthing screen; Overhead ground wire; Lightning arresters, Insulation level coordination, and Surge modifiers [10], [17] [12]; [18]. OGW is used in cone of protection method (Fig. 1a) and earthing screen method (Fig. 1b). Lightning arrester(Fig.1c) is required due to the inadequate of OGWs to providing protection against travelling waves which may reach the terminal equipment and sufficient enough to cause damages).



(a)



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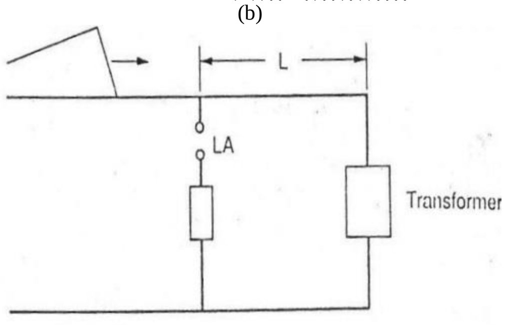

(c)

Fig. 1: (a) Protective Angle Method, (b) Shielding method, (c) Location of Lightning Arrester to Transformer (Adapted from [5] [12] and [7] respectively)

According to [12], Overhead Ground Wires (OGWs)is used to protect DLS in transmission stations and lines while lightning arrester (LA**)** is used due to the inadequate of OGWs to providing protection against travelling waves which may reach the terminal equipment and sufficient enough to cause damages). According to [18]), OGWs are the most effective for providing protection to transmission lines against DLSs. The OGW also reduces IDLS voltage (electrostatically or electromagnetically induced in the conductors). The combination of the two methods provides better protection, [19], [20]. This combination is used in Japan Distribution Power Industry [19]. Overhead ground wire (OGW) are used for voltages 110 kV up to 500 kV lines According to [6] and [11], only shielding (screening) has a possible protection against lightning electromagnetic fields.

Practically, voltage lower than 35 kV is affected by induced overvoltage, Induced overvoltages are much more frequent than direct strokes [6]. For a line of 35 kV or more, induced overvoltages are practically harmless and DLSs are dominant hence a protecting wire is useless in low voltage transmission lines of lower than 35 kV. However, this is contrary to Nigeria Independent Power Project (NIPP) in Lagos state, as OGW is used on their main 33/11 kV injection substations. The degree of protection provided by OGWs depends upon the footing resistance (Re) of the tower and the shielding angle α, the lower the shielding angle position of protected element, the greater is the protection [18].

In practice, one ground wire is usually used. This reduces the intensity of overvoltage and presents less or reduced over voltage to lightning arrester (LA) connected to the system. Two ground wires may be installed on tower in case of lines subject to serve lightning

There are many types of lightning arrester which are used to protect the power system. The commonly used arresters are Thyrite, Metal oxide and expulsion type (protector tube) lightning arresters [12], [10]. What is used in the studied case installation? According to Nagrath and Kothari (2003, the building up of voltage at the transformer is a function of the time of travel and or distance between the transformer and LA. The smaller the distance L the smaller the transformer voltage builds up. LA should be located as close as possible to the transformer [17] and [12]. Improved protection of transformer is achieved if LA is installed at a short distance to transformer [21] and [20]. [22] defined the maximum permissible distance of LA to a transformer as 10m.

Failure of overhead ground conductors in substations can result in costly substation damages and long-lasting supply outages. This rare event has been witnessed within [23]. As a result of this failure, Screening method may be combined with overhead ground conductor as a backup.

F. Development of Cone of Protection and Mesh Method of Lightning Protections

Four types of LPS (I, II, III, and IV) are defined as a set of construction rules, based on the corresponding lightning protection level (LPL). Each set includes level-dependent (e.g. rolling sphere radius, mesh width etc.) and level-independent (e.g. cross sections, materials etc.) construction rules.

According to [5], cone and mesh methods were developed from 1823 to 2006. The cone of protective angle varied from 20o - 63o while the mesh method varied from 5m x 5m to 100m x 400m.

However, 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 I [7].

TABLE I: LIGHTNING PROTECTIVE LEVEL, LIGHTNING CURRENT AND RELATED ROLLING SPHERE RADIUS, MESH WIDTH, PROTECTION ANGLE, AND PERCENTAGE OF PROBABILITY OF LIGHTNING STRIKE 97

LIGHTNING PROTECTION LEVEL	**PROBABILITY OF LIGHTNING EFFICIENCY**	**ROLLING SPHERE RADIUS**	**MESH WIDTH**	**PROTECTION ANGLE METHOD FOR DIFFERENT HEIGHTS (M) OF TERMINALS:**				**MINIMUM PEAK LIGHTNING CURRENT**
LPL	*p(LE)*	*R*, m	*D*, m	à (º)				*I*, kA
				20	30	45	60	
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 are effective against lightning whose current parameters are in the range defined by the LPL assumed for design. Therefore, the efficiency of a protection measure is assumed equal to the probability with which lightning current parameters are inside such range. However, protection angle of 45 degree of cone is used for height less than or equal to 10m (Cooray, 2010). Level I protection is considered for the sky and spike wire in this report.

A lightning-rod has a better chance of intercepting lightnings if it has a greater height above the object located within this zone, the greater the protection reliability required, the more pointed is the zone.

According to Cooray (2003), protection zones can be built with sufficient validity only for two types of lightning rods -rods and wires. 45 degree of cone is applied for main injection distribution substations in Ikorodu, Ikorodu 33kV Distribution Substation (2010) and Table I is applied to other heights in this research.

G. Conventional Protection Systems and Non-Conventional Protection Systems

CPSs are basically composed of three elements: 1)" air terminals" at appropriate points on the structure to intercept the lightning, 2) "down conductors" to carry the lightning current from the air terminals toward the ground, and 3) "grounding electrodes" to pass the lightning current into the earth (Uman and Ravok, 2002). He reported that non-conventional lightning protection system for ground-based structure generally falls into two classes namely (1) "lightning elimination, recently otherwise called dissipation array (DAS) or called charge transfer system (CTS) or (2) early streamer emission (ESE).

However, the conventional lightning protection techniques has proven its effectiveness scientifically and practically to larger scientists than the non-conventional system and that non-conventional protection system is not better than conventional protection system [24].

III. Research Methodology

A. Data Collection

Direct measurement of dimensions of installations were carried out in order to evaluate the protectiveness of 11 kV - 132 kV substation-line. Scaled models of installations were produced in AutoCAD in order to measure the screening of the existing substations and associated lines and also the existing cone angles of protection evaluation. Direct measurement of dimensions of installations, screening of substations and associated lines; and existing protective devices were carried out in attempt to evaluate the protectiveness of 11 kV -132 kV substation-line. Physical measurement (using a measuring tape) of six substations (33/11 kV and 132/33 kV substations in the studied area were carried out to evaluate the installation of lightning arrester within a distance of 10m to the transformer being protected.

B. Assessment of Lightning Protective System (LPS) For Substation and Lines in Ikorodu Zone

Two methods were used to assess the LPS for substation and associated lines in Ikorodu zone: screen method, and cone of protection (protective angle) method.

Assessment of Lightning Protection (LP) for Substation and Lines Using Mesh Method

In this study, the LPS for substation were assessed by model substation using measured real life dimensions. Using the AutoCAD work space model, scaled dimension of the modelled mesh width (W) and length (L) is obtained. The area, A^2, m) of the mesh is determined as

$$A = W \times L \tag{1}$$

Using known p (LE) rating scale obtained in Cooray (2010) and as shown in Table I, the substations p (LE) for installed mesh is obtained based on A. That is D=20 m, p (LE) = 84%

For irregular shape of substation land area, method or concept of division of total mesh area into N regular shapes is applicable:

$$A = \sum_1^N a_n \tag{2}$$

Where a_n is n-th regular shape area obtainable from total irregular mesh area A of substation.

However, with the mesh of modelled 33/11 kV and 132/33kV substation in AutoCAD worksheet, the mesh areas of the substation can be measured using the software's planimeter tool.

C. Assessment of LPS for Substation and Lines Using Cone of Protection Method

In this study, 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. In this method, from theoretical analyses, 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}. Then the following criterion-expression must hold for LPS to be effective for the given element:

$$\theta_{el} \leq \theta_{std} \tag{3}$$

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

In this study, the LPS and protected network were assessed using AutoCAD software for angular evaluation.

Based on this criterion, an analytical coverage factor (CF), and protected volume of installation (PVI), volume protected substation (VPS) are proposed for measuring the degree of protective coverage, as in (4) and (5) respectively.

$$\mathrm{CF} = 1 - \frac{\theta_{el}}{\theta_{std}};\ 0 \leq CF \geq 0 \tag{4}$$

$$V_{PVI} = \frac{V_p}{V_T} \tag{5}$$

where, V_p is the protective volume of the installation; and V_T is the total volume of the installation. The scaled models of installations were produced in AutoCAD in order to measure the angles θ_{el} and areas in the substations. The result of CF for existing substations are presented in Fig. 8 to Fig.11.

D. Assessment of Lightning Arrester for Transformer Protection

In this study, the location of lightning arrester to a transformer is assessed by physical measurement using measuring tape. From theoretical analyses, the following criterion is established.

In this study for evaluating the existing designs for protection of transformer against indirect lightning strike

(ILS). Let distance of protected transformer to the location of lightning arrester (LA) be termed L_d. The following criterion must hold for transformer to be effectively protected:

$$L_d \leq L_{std} \quad (6)$$

where, L_{std} is the standard maximum distance from a transformer to the protective element (LA).

Based on this criterion, an analytical distance protective factor (PF) is proposed for measuring the degree of protective distance, as in (7).

$$PF = \frac{L_{std}}{L_d};\ PF > 1 \quad (7)$$

IV. Results

For mesh method, coverage adequacy of existing LPS on 11-132kV substations are presented in Fig. 2 and 3 respectively.

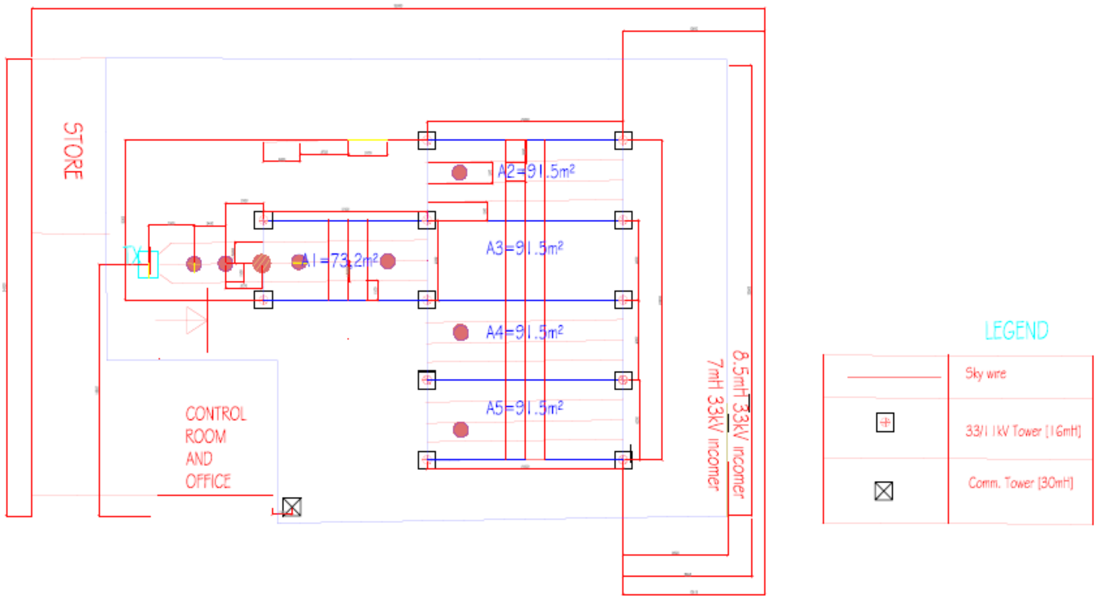

Fig. 2: Plan View of Imota, Ikorodu 33/11kV Substation, showing Mesh Method of Screening Substation Elements Typical to Ijede, Ebute and Igbogbo Substation

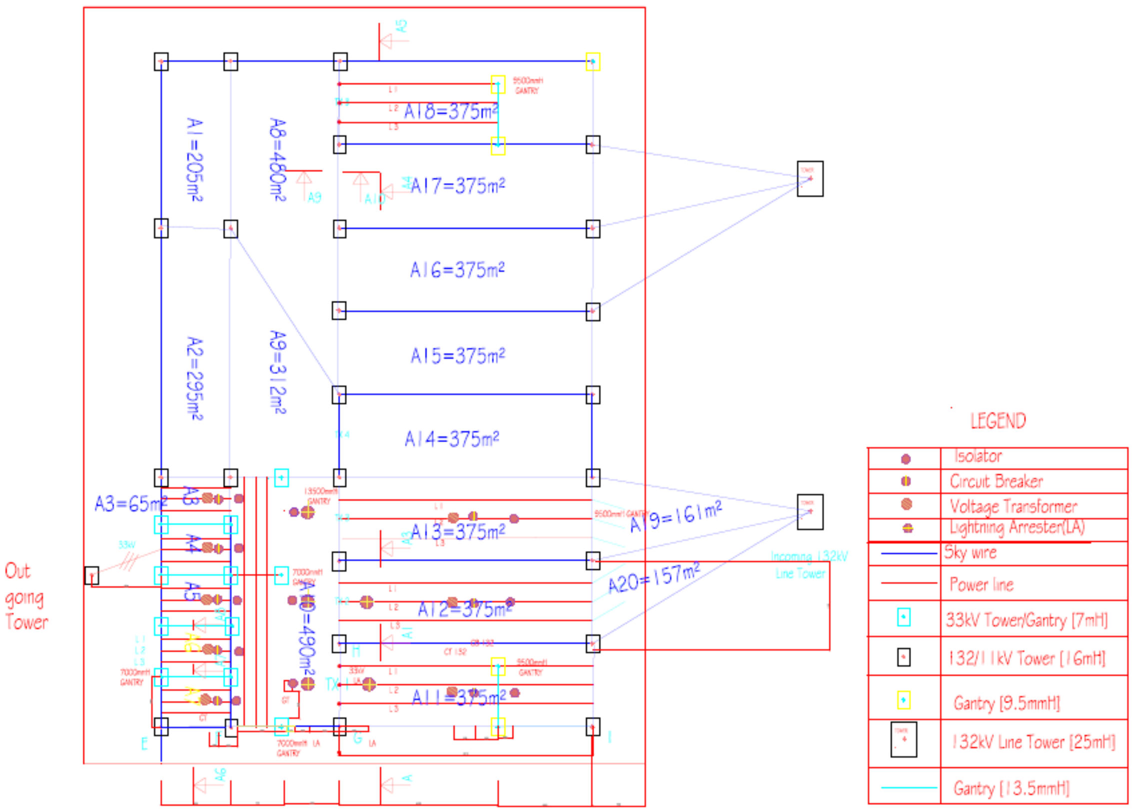

Fig. 3: Plan View of Ikorodu 132/33 kV Substation, showing Mesh Area of Ikorodu Transmission Substation Using Mesh Method

The screen method of protection results show that the spatial subdivisions of 33/11kV substation are all level II protected, corresponding to 94% probability of lightning efficiency(pLE); while the spatial subdivisions of 132/33 kV substation exhibit level II (pLE) to Level IV (pLE) and above level IV (less than pLE) protection scenarios. It shows that 132/33 kV substation is more vulnerable to lightning strike than 33/11kV substation.

Results obtained from measurements and evaluations of all considered lightning protective system (LPS) by standard angle of protection requirement, are presented in Fig. 4 to 7.

The results show that both 33/11 kV and 132/33 kV substations are not adequately protected against lightning strike: for the 132/33 kV substation elements and lines, 11/33 (33.3%) of elements are unprotected; and for 33/11 kV substation elements and lines, sky wire: 7/14 (50%), spike 6/14(42.9%, sky and spike 11/27(40.7%) of elements are unprotected. These values correspond to the coverage factor assessment values, which are as shown in Fig. 8 – Fig. 11.

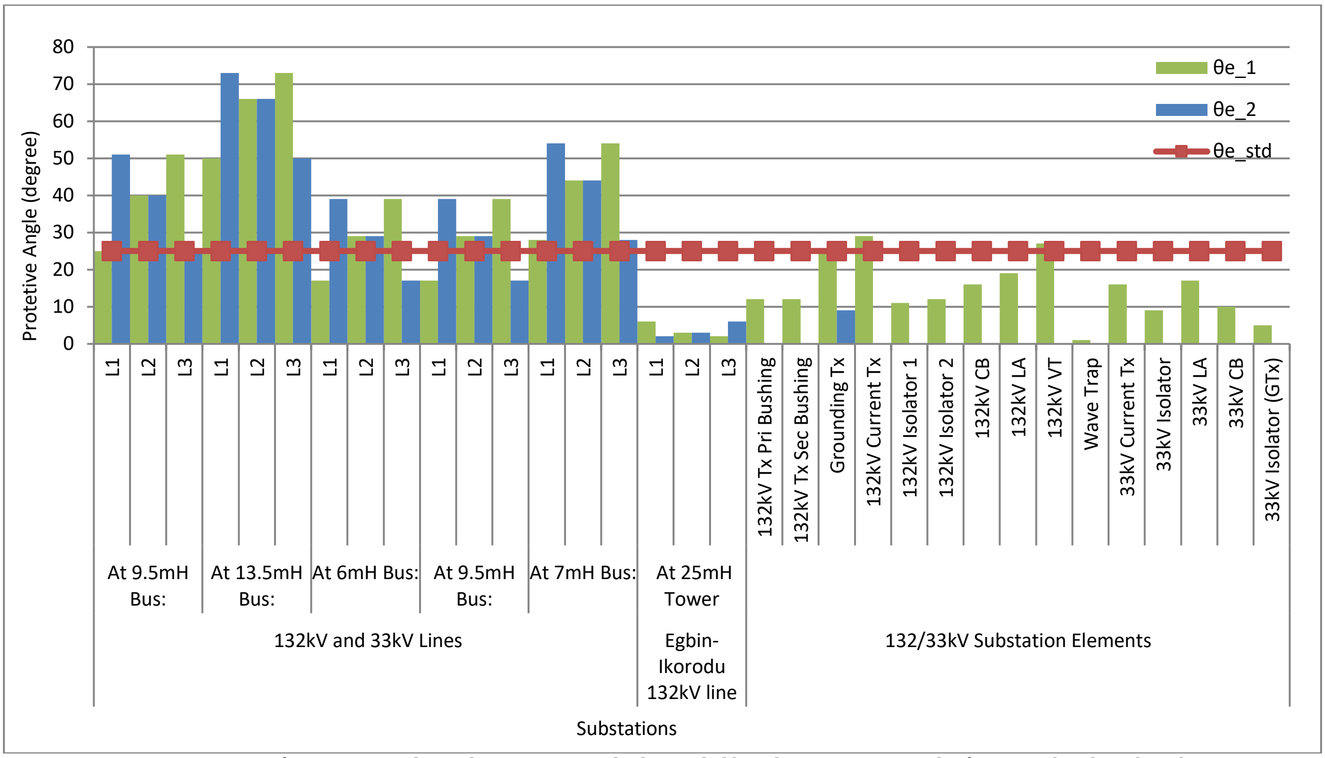

Fig. 4: Measurements of protection angles with respect to standard provided by adjacent OGWs 1and 2 for 132/33kV Ikorodu Substation

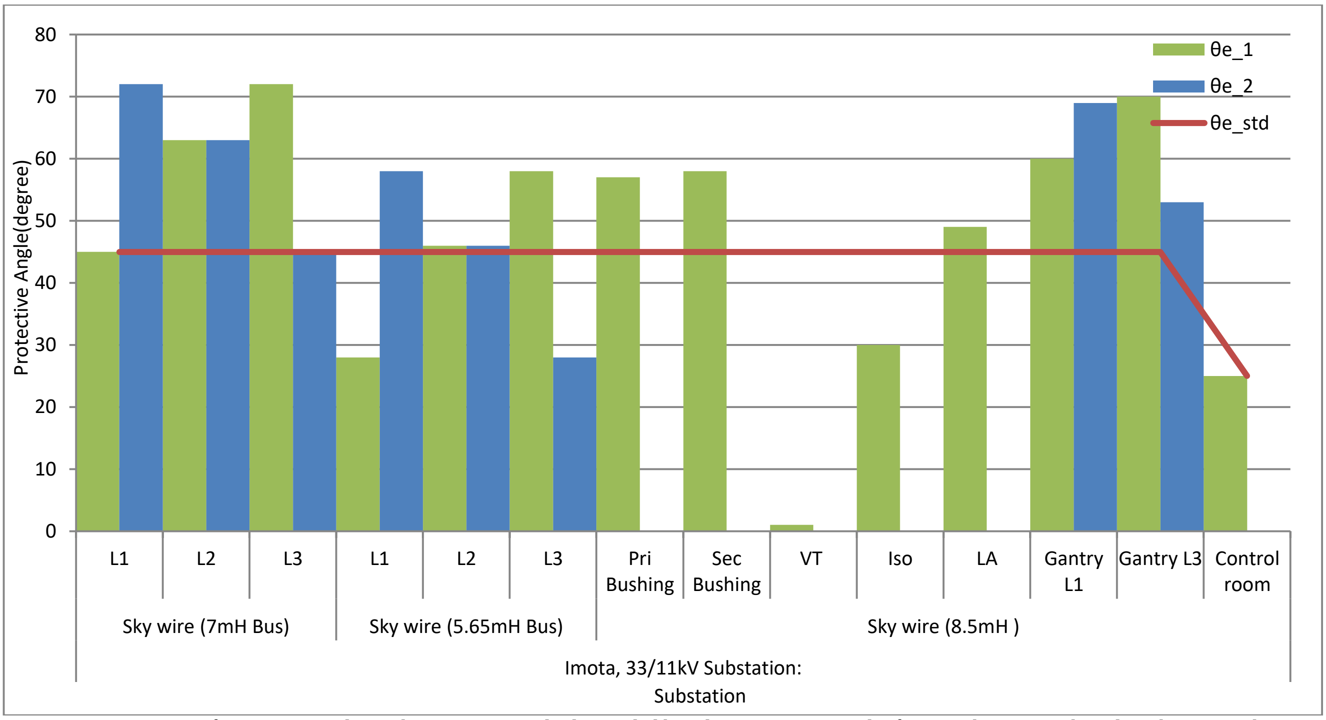

Fig. 5: Measurements of protection angles with respect to standard provided by adjacent OGWs 1and 2 for 33/11kV Imota, Ikorodu Substation -Sky wire

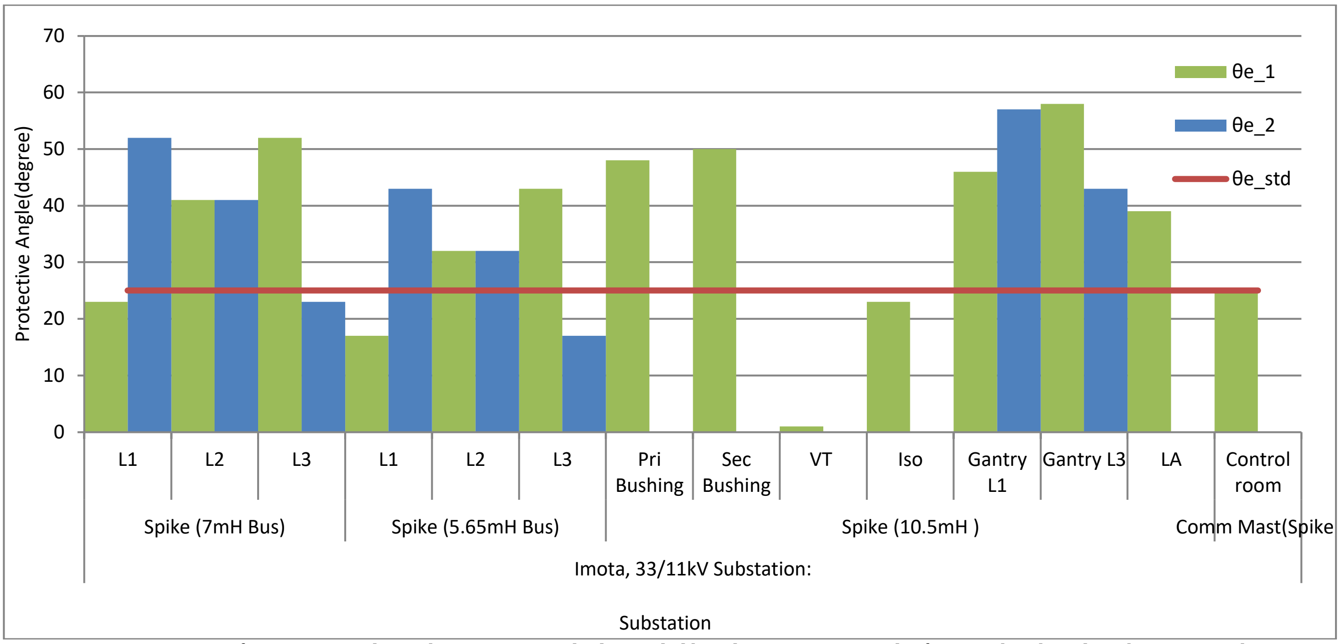

Fig. 6: Measurements of protection angles with respect to standard provided by adjacent OGWs 1and 2 for 33/11kV Ikorodu Substation –Spike wire

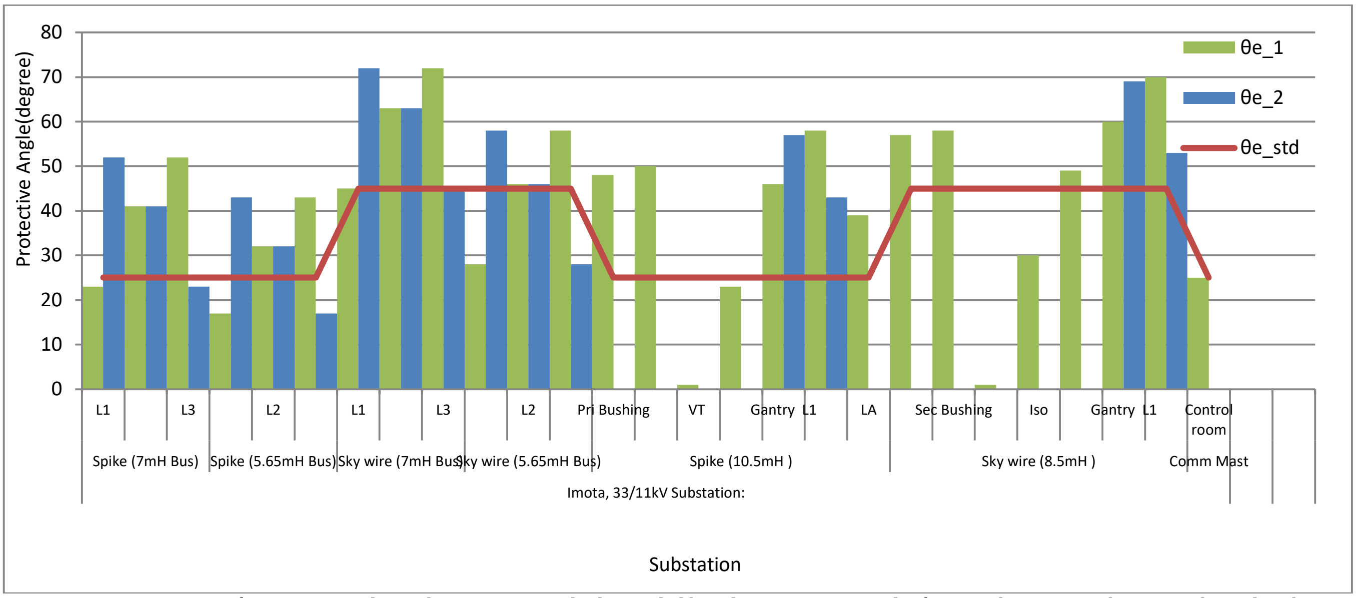

Fig. 7: Measurements of protection angles with respect to standard provided by adjacent OGWs 1and 2 for 33/11kV Imota Substation -Sky and Spike

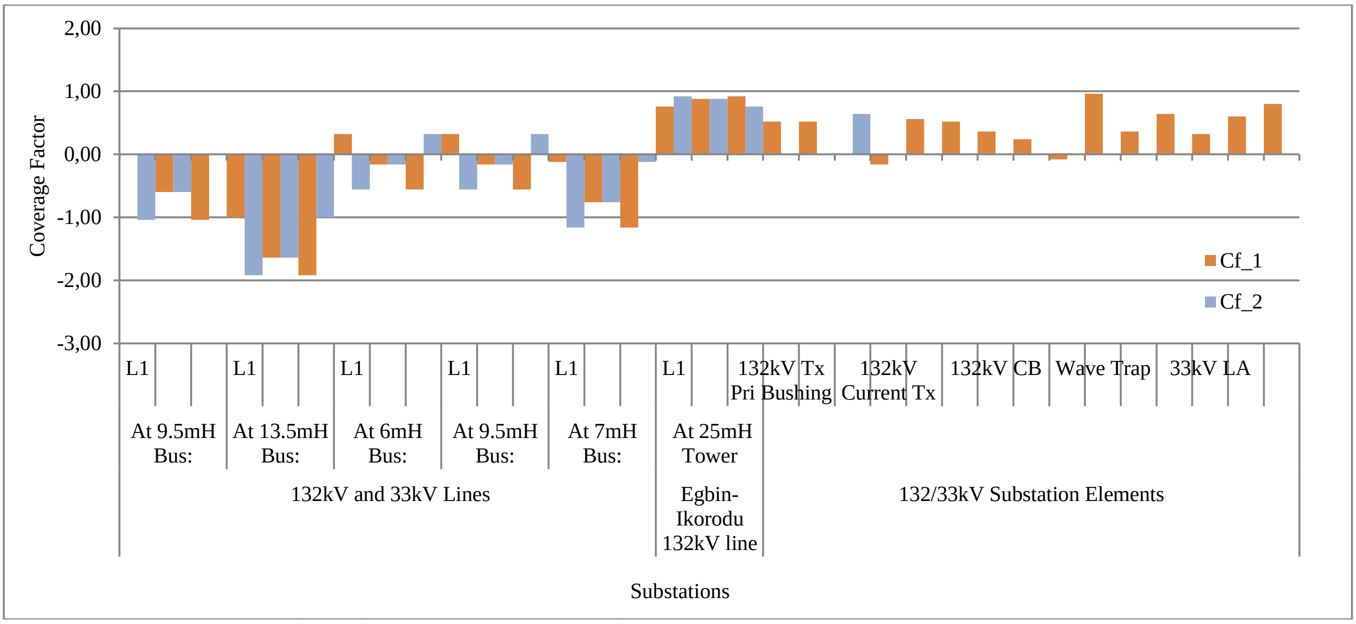

Fig. 8: Coverage factors from adjacent OGWs 1 and 2 for each protected installation in 132/33kV Ikorodu Substation – sky

DOI: http://dx.doi.org/10.24018/ejers.2019.4.7.1401

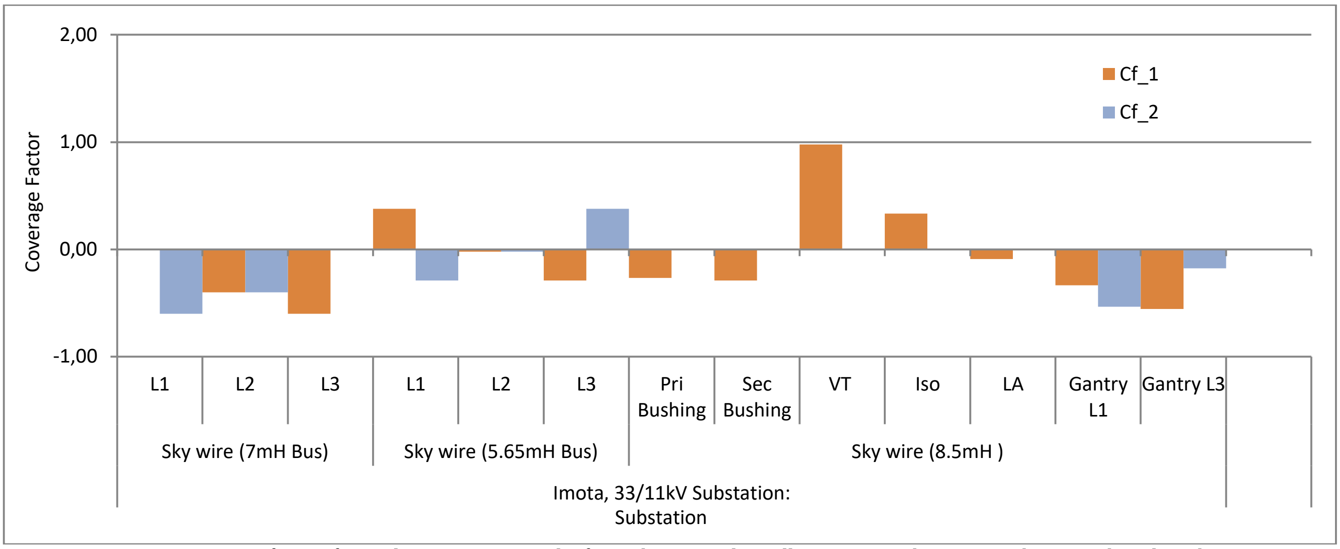

Fig. 9: Coverage factors from adjacent OGWs 1and 2 for each protected installation in 33/11kV Imota Substation, Ikorodu - Sky

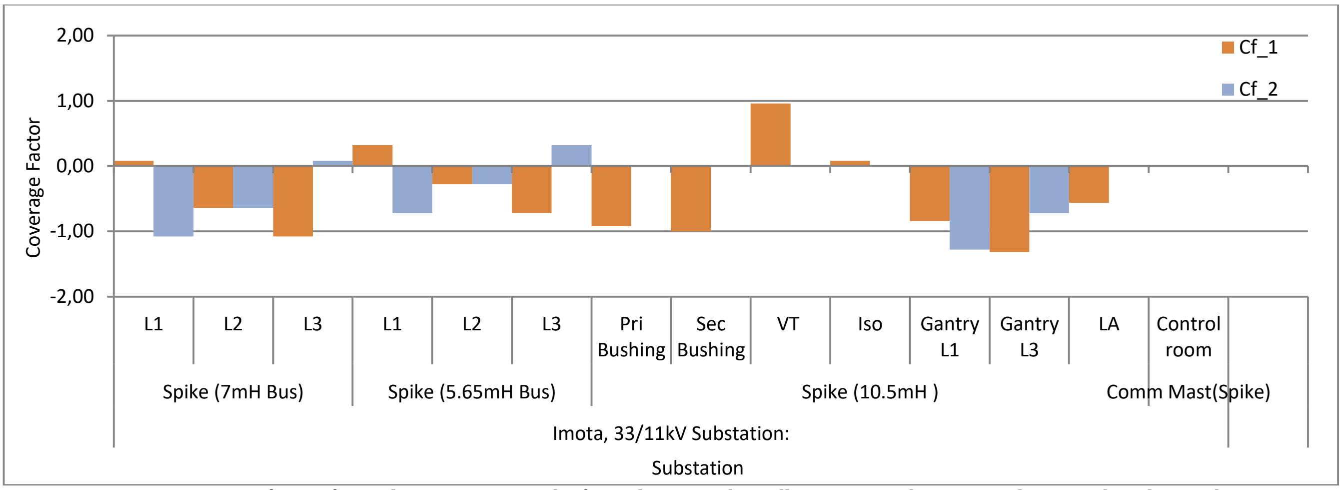

Fig. 10: Coverage factors from adjacent OGWs 1and 2 for each protected installation in 33/11kV Imota Substation, Ikorodu – Spike

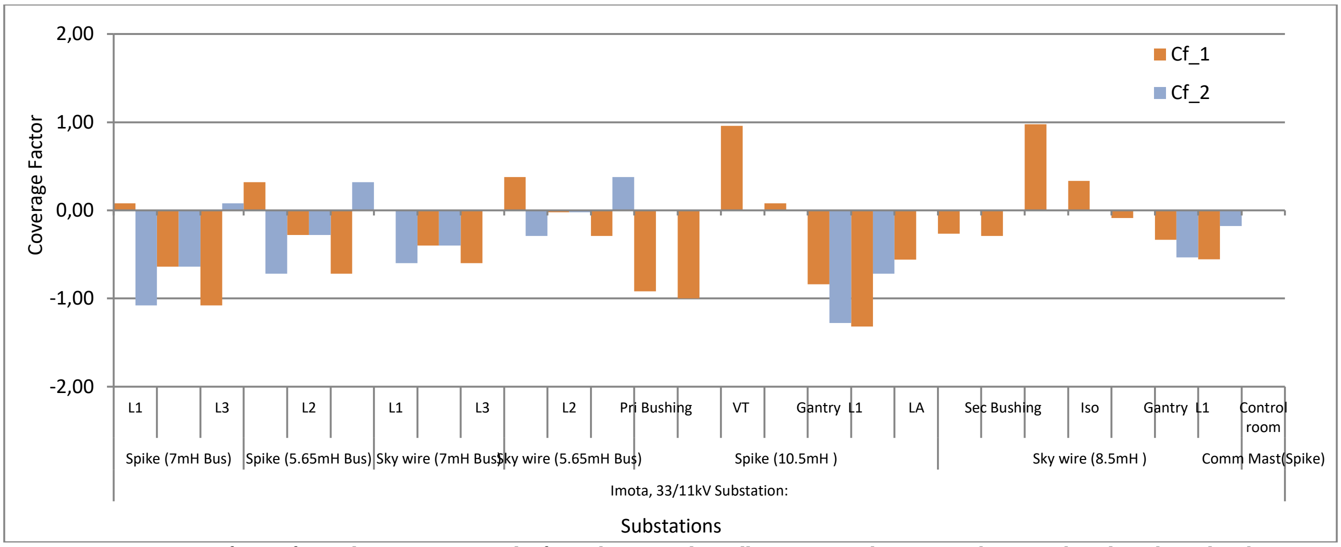

Fig. 11 Coverage factors from adjacent OGWs 1and 2 for each protected installation in 33/11kV Imota Substation, Ikorodu - Sky and Spike

The volume of protection adequacy of the existing installations is presented in Table II.

TABLE II: EXISTING SUBSTATIONS AND POWER LINE PROTECTION VOLUME ON 132 - 11 KV SUBSTATION, IKORODU

SUBSTATION	PROTECTIVE INSTALLATION	PROTECTED VOLUME (%)
132 kV Substation	Sky wire	51.7
	Spike	66.4
	Tower	277
33 kV Substation	Sky wire	40.8
	Spike	29.6

Table II shows that the coverage volume of existing LPS is 52% for sky wire in 132/33 kV substation; 277% for transmission line towers along the lines, 40.8% for sky wire in the 33/11 kV substation, and 29.6% for spike in 33/11 kV substation.

The results show that the incoming 132kV power lines to the substation are adequately protected; 132/33 kV and 33/11 kV substations are not adequately protected.

Evaluation of LA adequacy by standard distance to transformer is presented in Fig. 12. The results show the installed distances of all lightning arrester are within standard range and would adequately protect substation transformers against travelling waves (Indirect Stroke) events.

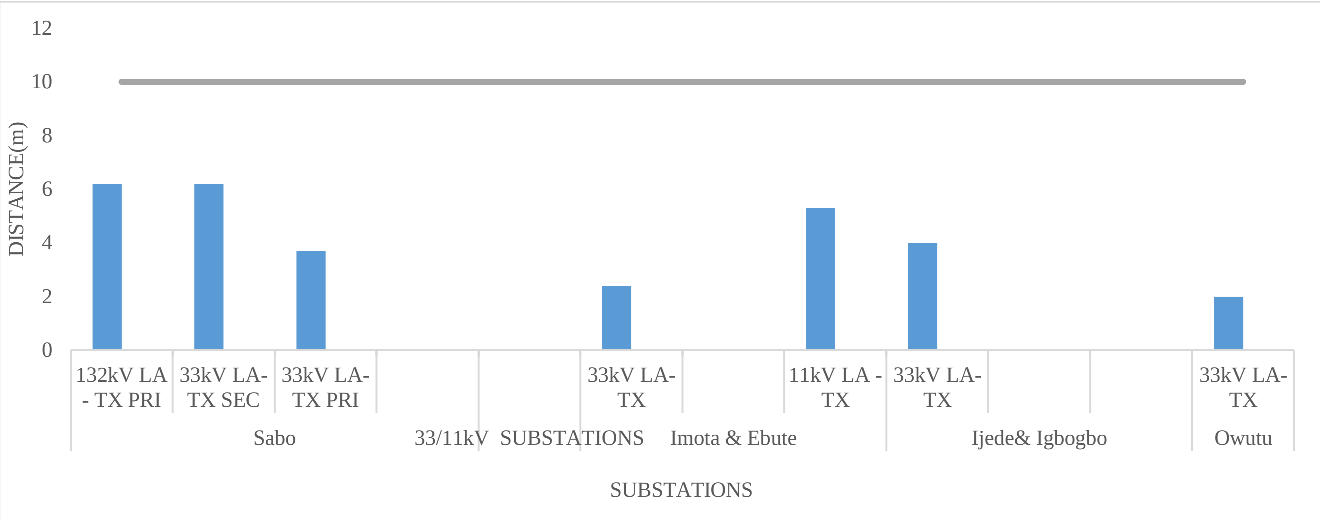

Fig. 12: Measurements of Lightning Arrester Distance to Transformer on 132 kV-11kV Ikorodu Substation

V. Conclusions and Recommendations

A. Conclusions

This work was carried out by using analytical models for evaluating both raw and derived data. Installations were scaled down and modelled dimensionally using AutoCAD software in order to measure spatial parameters.

i. Under the prevailing lightning protective system, LPS, (screening method), 132/33 kV substation is not adequately protected;
ii. 132/33 kV substation is more vulnerable to lightning strike than 33/11kV substation;
iii. 132/33 kV lines are adequately protected (277%) by OGW.
iv. With installed cone of protection scheme, the existing 33/11 kV and 132/33 kV substations are not adequately protected against lightning strike: for the 132/33 kV substation elements and lines, 11/33 (33.3%) of elements are unprotected; and for 33/11 kV substation elements and lines, sky wire: 7/14 (50%), spike 6/14(42.9%, sky and spike 11/27(40.7%) of elements are unprotected.
v. The installed lightning arresters (LAs) would adequately protect substation transformers against travelling waves (Indirect Stroke) events. For effective lightning surge control, the lightning arrester (LA) distance protection factor is greater than or equal to 1.

B. Recommendations

132/33 kV substation should be reinforced for adequate protection to avoid the dangerous lightning effects earlire stated in this research. Dimension of HV substations using AutoCAD software in order to measure spatial parameters is highly recommended. Further study should be carried out using recommended cone of protection by [5] and installation LA to transformer by [22].

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