



LIGHTNING PROTECTIVE SYSTEM: SIZING OF INTERCEPTION, DOWN CONDUCTOR AND EARTHING NETWORKS ON NIGERIAN 11-132 KV SUBSTATIONS

Oyeleye M.O and Melodi A. O.

Department of Electrical and Electronics Engineering, Federal University of Technology, Akure, Ondo State, Nigeria

**Corresponding Email: mooyeleye@futa.edu.ng*

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ABSTRACT

This research focused on the lightning protective system (LPS) elements, most especially grounding using the elements of LPS as interceptor, down conductor and ground. Grounding is defined as a system of electrical fault save linkage to the earth and as a total set of measures used to connect an electrically conductive part to earth for equipment and life safety. The choice of Ikorodu town is informed by high voltage (HV) power transmission substations and heavy industries located in coastal area being affected by apparent disastrous lightning strike. The methodology used include collection of LPS network cross section sizes from 5 numbers of 33/11 kV distribution substations and one number of 132/33 kV Transmission substation in the study area. Also, the earthing resistance values of all the substations elements were collected. Physical measurements and existing design formula of previous work were used to evaluating the existing LPS network. Conductor size compliance ratio was also used for cross sectional area of down conductor, lightning electrode and air terminal adequacy. Appropriate equation was established and used to determine the safe grounding resistance (R). The result shows that the 95 mm² conductors (or less) for LPS network is not adequate for LPS network especially when lightning magnitude is not available. The bonding to the earthing terminal should conform to designed protective device size. 161 mm sq. is proposed for LPS conductors of any power system in order obtain an effective protection, the absence of lightning current magnitude data. A model of air terminal, down conductor and lightning electrode is proposed in this research. In order to obtain an effective LPS, 11-132 kV substations and associated lines LPS elements conductor size should conform to 161 mm² cross sectional area.

Keywords: *Lightning Protective System, Network, Interceptor, Coastal Area, Grounding*

INTRODUCTION

Grounding is defined as a system of electrical linkage to the earth (Samadinab *et al.*, 2017). According to Ahmadi (2015), earthing system is the total set of measures used to connect an electrically conductive part to earth.

According to Gomes and Abkadir, 2014; NESIS, 2015; Omorogiuwa and Oboh, 2018, the objectives of earthing are essentially for equipment and life safety. One of the electrical hazards in substations is ineffective earthing system on substations (Oyeleye, 2019a; Omorogiuwa and Oboh, 2018). Electrical fault can flow from the utility or lightning strike source or both. Electrical fault can be any form of short circuit in power utility system. Lightning fault is defined as electrical discharge generated by cumulonimbus clouds, volcanic eruptions, dust storms or snow storms in the earth’s atmosphere (Cooray, 2010). It is capricious, random and unpredictable event that can strike any point on earth with enormous current of over 40kA, induced temperature approximated to 300 k °C and speed approaching one third the speed of light (Richard, 2010; Oyeleye, 2019a) Also, lightning discharges are known to be characterized by short duration of high voltage, high current electric pulses.

Lightning protective system (LPS) is the most efficient way to protect electrical installation and building from damages caused by lightning stroke (IEC 61024, 2003; Saju, 2010). Lightning transient voltage on lines, towers, substations and generating stations on account of direct strokes to phase conductors, towers, earth wires and other utility equipment is not electrically friendly (Oyeleye, 2019a); Cooray, 2010; and Meliopoulos, 2006).

Voltage in excess of rated maximum permissible voltage is referred to as overvoltage. A 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 generates smaller overvoltage (OVs) than DLS (Nagrath and Kothari, 2006). According to Gupta (2013), overvoltage due to DLS is function of tower footing resistance. Overvoltage due to electrostatic, U , is a function of grounding rod. According to Lakervi and Holmes (1989), maximum permissible voltage on lines / electrical installations for distribution is $\pm 6\%$ 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 $\pm 5\%$ of the supply voltage while frequency is kept within $\pm 0.05\text{Hz}$ (Federal Republic of Nigeria Official Gazette, No 3, 1996).

The resulted overvoltage is usually far above these specified tolerance for power systems. Protective method used in High Voltage, HV, (33 kV -132 kV),

lightning protection network includes interception (air terminal system -ground wire); conduction (down conductor -earth connecting wire) and dissipation (earthing network - R_e), Figure 1 .

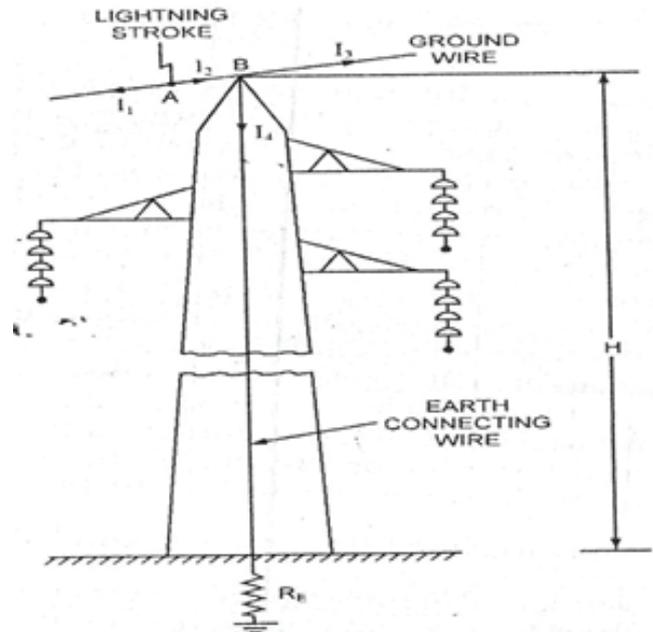


Figure 1: Interception, Down Conductor and Earthing Network (Adapted Gupta, 2013)

Properly designed air termination system considerably decreases the probability of lightning stroke current penetrating the structure. The protective angle coverage offered by over ground wire (sky wire or spike or both) or the area around a protector which would be reliably protected is called zone of protection (Bazelyan and Razer, 2000; Oyeleye 2017).

Lightning discharge passes through the down conductor to the earth. Side effects of un-controlled lightning pulse discharge to the ground network include earth failures, frequent tripping of feeders, falling of tree on line, pole damages, soaking of soil, disc and pot shattering, transformer damages, substation damages, short of revenues, consumers’ dissatisfaction and loss of life. These losses are of high impact in wet season especially for cloud-ground (CG) lightning flash (Melodi and Oyeleye, 2017; Mowete and Adelabu, 2009). The case study of this work is Ikorodu town which houses 11-132 kV Ikorodu Transmissions Stations (ITS), comprising 132/33 kV Ikorodu Transmissions Station (ITS) and five numbers of 33/11 kV Ikorodu Distribution Substation (TDS). The choice of Ikorodu town is informed by high voltage (HV) power transmission substations and heavy industries located in coastal area being affected by apparent disastrous lightning strike.

Lightning Specific Energy, Median Lightning Return Stroke (MLRS) and Peak Current

Lightning consists of flash specific energy which is the highest values of the statistical distribution. It is important for the selection of a conductor for the ‘protective system’ aimed at preventing damage due to thermal effects and for setting up a suitable “earthing system” in order to prevent its associated hazards. Available median lightning return stroke (MLRS) and peak current data estimates (PCDE) in the world for lightning parameters varies from 14kA to 44kA as in Table 1.

Table 1: Median Lightning Return Stroke and Peak Current Data (Cooray, 2010; IDS, 2010; Carpenter and Drabkin, 2010; IDS, 2010; Sulaimani, 2011)

PARAMETER	FIRST STROKE LIGHTNING CURRENT (kA)	REFERENCES	LOCATION
Lightning Current	13.5 kA	Saba <i>et al.</i> (2006)	
	25 kA	33kV IDS (2010)	Ikorodu, Lagos, Nigeria
	31.1 kA	Anderson and Eriksson (1980)	South Africa
	31.6 kA	Oyeleye (2017)	N/A
	30 kA	Berger <i>et al.</i> ; Bazelyan and Razer(2000)	N/A
	33 kA	Garbagnati (2004)	Northern Italy
	40 kA	Richard (2010)	N/A
	44 kA	Takami and Okabe; Eriksson (1979)	Kanto, Italy
	45 kA	Visacro <i>et al.</i> , (2004)	N/A
Peak Current Derivative	14.3 kA/μs	Carpenter and Drabkin (2010)	
	> kA/μs	Anderson and Eriksson (1980)	South Africa
	20 -30 kA/μs	Cooray (2010)	Africa// Europe
	14 kA/μs	Garbagnati (2004)	Northern Italy
	19.4 kA/μs	Visacro <i>et al.</i> , (2004)	N/A
	18.9 kA/μs	Takami and Okabe; Eriksson(1980)	Kanto, Italy

According to Nagrath and Kothari (2006), lightning current path may be over the insulator down the pole to the ground. Indirect lightning strike occurs when a thunder cloud passes over ground objects (Figure 2). Direct stroke is the most severe and rare form of stroke. Indirect direct lightning strike results 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 and the unprotected equipment connected to electrical supply are prone to damage hence need to pass the pulse to earth (Carpenter and Drabkin, 2010; Melodi and Oyeleye, 2017).

Lightning Protection Devices

Known lightning protection devices (LPD) for protections against surges include: Earthing screen; Overhead ground wire; Lightning arresters or surge diverters, and Surge absorber or modifiers (SM) (Gupta, 2013; Oyeleye, 2017). The earthing screen is properly connected to earth on at least two points through low impedance (Mehta and Mehta, 2013). All the aforementioned lightning protection devices are connected electrically to the ground.

Principles of Design Earthing Termination System (ETS)

All literatures on earthing agreed that LPS earth termination system must be able to disperse lightning current into the ground without causing any danger to people or damage to the installations inside the protected structure. ETS must be designed for effective dispersion of lightning current to the ground without endangering people. Soil resistivity is needed to design a proper sized grounding system (GS) for effective discharging of lightning current into the ground. Also, the GS will also serve as grounding of the LPS (Technical Manual No. 5-811-3, 1985; Oyeleye, 2017).

Earthing system of different materials shall not be used in order to avoid corrosion. According to the IEC 61024-1(2003; Oyeleye (2017), for earth termination systems, two types of earth electrode arrangement are to be used, namely:

- i. type a: arrangement which comprises of horizontal and vertical earth electrodes connected to each down conductor and
- ii. type b: arrangement which comprises either a ring conductor external to the structure in contact with the soil (80% of total length) or a foundation earth electrode; the earth electrode may also be meshed shall be employed.

Towers are grounded by ground rods and counterpoise wires connected to tower legs at its foundation but nowadays, each tower is grounded on its own.

Earthing Termination System Materials, Dimensions and Earthing Resistance Value

The materials used for the LPS shall be of good electrical conductivity, mechanical strength and electromagnetic stresses caused by the high peak

values of the current. Also, good earthing resistance is necessary against the corrosion due to atmospheric environment. The materials are usually iron, copper, and aluminum depending on cost, corrosion, soil resistivity and ability to dissipate fault current to ground.

According to Gupta (2006; Oyeleye, 2019), the earth rod is usually 16mm² and the mat (copper) is usually 600mm x 600mm x 3mm and earthing lead 2.9mm² min and 70mm² max. However, new substations by National Independent Power Project (NIPP) in Ikorodu used 95mm² (IDS, 2010). Copper earthing material is recommended because of its better conductivity and mechanical efficacy where cost is less considerate. International standard on the materials, configuration and cross sections of air terminal and down conductor and corrosion effect varies from 50 to 70mm²

According to Gupta (2006), earthing mat is used generally to ground the general mass of a substation and placed at a 0.5m to 3m depth to the soil. National Electric Utility(NEU) uses 2m depth for her 132 kV transmission while National Independent Power Plant (NIPP) uses 0.5m depth for 33/11 kV substations. In design, earthing rod or mat is best located on the most reachable conductive part of the soil layer base on geophysics report. In practice, research shows that earth rod or mat or combination of both are used for lightning discharging into the soil. The rod is linked with earth mat for more effective grounding. Earthing rod is located 1.5m to the building (Gupta (2006). Popham Walter Odusote used earthing value of maximum 1Ω (PWO (2009), IEC recommended max of 4Ω, and British Standard (BS) recommended max of 10Ω. 0.05Ω is a practice in Ikorodu Transmission System and 5Ω in Ikorodu Distribution system for earthing and LPS grounding (ITS, 2010; Oyeleye, 2017).

The earthing system and LPS are to be interconnected (NFPA-70, 1996; Chandima, 2014). In some practice, earthing and LPS earthing and LPS earthing are electrically separated to limit the spreading of lightning surge likely to caused problem, even, at earthing resistance of 10Ω (Chandima, 2014). Chandima suggested the review of the 10Ω standard. Bonding is usually 35mm² to 150mm² to the earthing mat or lightning electrode and mat conductor is 70mm². In practice, 95mm² is used in some cases on 132/33kV substation instead of 150mm² (ITS 132/11 kV, 2013) and 75 mm² for distribution substation. From Table 3; Bazelyan and Razer (2000); Ikorodu 33kV Distribution Substation Earthing System Design (2010); Cooray (2010), Table 2 is computed in order to size Down Conductor and Earthing Grid. Table 2: Down Conductor and Earth Mat Design Data

S/N	PARAMETER	VALUES
1	Standard lightning current (I _f)	30 kA
2	Duration of Fault (t _c)	1 Sec
3	Ambient Temperature (T _a)	40 Deg. C
4	Maximum Allowable Temp. Rise ((T _m)	1084
5	Thermal Capacity Factor(T _{cap})	3.42
6	Thermal Coefficient of resistivity at (α)	0.00381
7	Reference Temp. for Material Constant (T _p)	20
8	$K_o = \frac{1}{\alpha} - T_r = \frac{1}{T} - 20$	242
9	Resistivity of Ground Conductor at Tr (pr)	1.78Ω-m

MATERIALS AND METHODS

Raw data of down conductor, air terminal and earthing size of all the substations elements were collected from 5 numbers 33/11 kV distribution substations and one number of 132/33 kV Transmission substation in the study area. Also, the earthing resistance values of all the substations elements were collected.

Assessment of Sizing Adequate Air Terminal, Down Conductor and Lightning Ground Electrode

In this study, evaluation of down conductor and earthing mat was carried out using direct measurement of air terminal (sky wire), conductor and ground electrode sizes population in the system.

The method used here is by applying equation (1) from IEEE 80-2000 to various lightning currents in Table 3 to ascertain the area of the conductor size adequacy (IDS, 2010).

$$A(I_f) = I_f \times \frac{1}{\sqrt{\frac{T_{cap}}{t_c \times T_r \times P_r} \ln \frac{K_o + T_m}{K_o + T_a}}} \dots\dots(1)$$

Where A(I_p) is the minimum required area of electrode for lightning current I_f, t_c is the duration of fault, T_a is the ambient temperature, T_r is the thermal coefficient of resistivity of conductor, T_m is the maximum allowable temperature rise, thermal capacity factor is the T_{cap}, K_o is the resistivity and material constant.

From theoretical analyses, the following criterion is established in this study for evaluating the area of existing down conductor and earthing grid mat size. Then the following criterion-expression must hold for area of down conductor or earthing grid to be adequately protected.

$$R_c = \frac{A_{amp.i}}{A(I_f)} ; R_c \geq 1 \quad \dots\dots\dots(2)$$

Where R_c is the Conductor size compliance ratio for area of down conductor or lightning electrode size, $A_{amp.i}$ is the size of installed i th down conductor(mm^2),

Then,
 $\{ A_{amp.}, i \} \geq A(I_f) \quad \dots\dots\dots(3)$

From equation (3), R_c is calculated. Assessment of Adequacy of Earthing Resistance

Value
 In this study, according to ITS (2013), the safe grounding resistance R is as given in equation (4)
 $R \leq 0.1 \Omega \quad \dots\dots\dots(4)$

The grounding resistance test (measurements) of 128 Transmission Substation elements of the study area was carried out with the company’s authorized maintenance team.

RESULTS AND DISCUSSION

The result of air terminal, down conductor and lightning ground electrode sizing is presented in Table 3, Table 4 and Figure 4.

Table 3: Sizing of Air Terminal, Down Conductor and Earthing Rod

ith	SUBS. (kV)	SYMBOLS															A(I _f), mm ²												
		I _f (kA)											T _{amb} (°C)	Ko	Tm	tc (Sec)	Tr	Pr	Ta	1	2	3	4	5	6	7	8	9	10
1	132/33 SS	13.5	25	30	30	31.1	31.6	33	40	44	45	3.42	242	1084	1	20	1.78	40	48	89	107	107	111	113	118	143	157	157	161
2	33/11 SS	13.5	25	30	30	31.1	31.6	33	40	44	45	3.42	242	1084	1	20	1.78	40	48	89	107	107	111	113	118	143	157	157	161
3	132 LINE	13.5	25	30	30	31.1	31.6	33	40	44	45	3.42	242	1084	1	20	1.78	40	48	89	107	107	111	113	118	143	157	157	161
4	33 LINE	13.5	25	30	30	31.1	31.6	33	40	44	45	3.42	242	1084	1	20	1.78	40	48	89	107	107	111	113	118	143	157	157	161

Table 4: Conductors Area and Conductor Size Compliance Ratio

Am(mm ²)	Rc										
	1	2	3	4	5	6	7	8	9	10	11
95	1.97	1.06	0.88	0.88	0.85	0.84	0.80	0.66	0.60	0.60	0.59
95	1.97	1.06	0.88	0.88	0.85	0.84	0.80	0.66	0.60	0.60	0.59
95	1.97	1.06	0.88	0.88	0.85	0.84	0.80	0.66	0.60	0.60	0.59
95	1.97	1.06	0.88	0.88	0.85	0.84	0.80	0.66	0.60	0.60	0.59

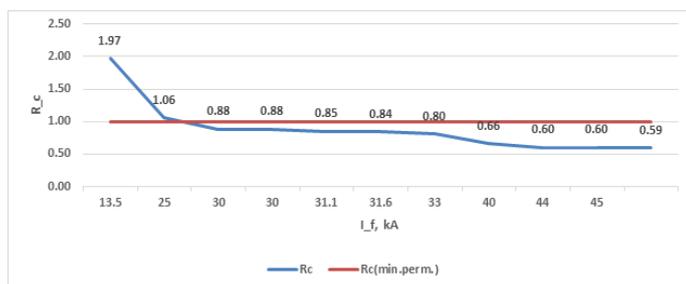


Figure 4: Sizing of Air Terminal, Down Conductor and Lightning Earthing Electrode

This result shows that when the conductor size compliance ratio is greater than 1, the lightning current is between 13.5 kA – 25 kA and when the conductor size compliance ratio is below 1, the lightning current is 25 kA-45 kA. From the result, 95 mm² conductors (air terminal, down conductor, and earthing rods) is adequate only if lightning current does not exceed 25 kA. This implies that the down and earthing conductors are inadequate in case of instances of over

25 kA lightning currents. The earthing, down and air terminal conductors must be aligned in term of their cross section. It therefore follows that the earthing, down and air terminal conductors are inadequate in case of instances of over 25 kA lightning currents.

The bonding to the earthing terminal should conform to designed protective device size. 161 mm sq. is proposed for LPS conductors of any power system in order obtain an effective protection, especially, where the lightning current magnitude data is not available. It means that in order to obtain an effective LPS, LPS elements, conductor size of not less than 161 mm² should be proposed on 11-132 kV substations and associated lines and depicted in Figure 5.

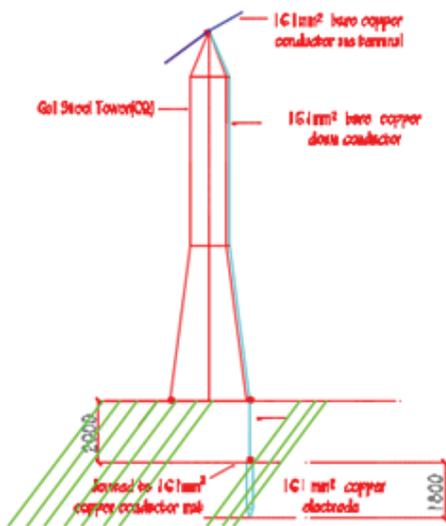


Figure 5: A Model of Air Terminal, Down Conductor and Lightning Electrode

CONCLUSION

It was established in this research that the prevailing earthing system conductor size of 95 mm² or less

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should be discouraged to avoid inadequate LPS. Generally, this work was carried out by proposing 161 mm sq. for the proposed LPS for any power system in order obtain an effective protection, especially, where the lightning current magnitude data is not available Modelled of Lightning Protective System Elements (Air Terminal, Down Conductor and Lightning Electrode) is also proposed for 11-132 kV substations and associated lines. It is recommended that 161 mm sq. for the proposed LPS for any power system should be used in order obtain an effective protection, especially, where the lightning current magnitude data is not available.

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