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DIRECT STROKE LIGHTNING PROTECTION DESIGN

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Abstract:

This guide includes methods that have been utilized for decades as well as some that have been developed more recently. The general nature of lightning is discussed, and the problems associated with providing shielding from direct strokes are described. Tables, formulas, and examples are provided to calculate whether substation equipment is effectively shielded from direct lightning strokes.

Keywords: Direct Strokes, Lightning, Shielding, Strokes.

I. Introduction:

Direct strokes from lightning can damage substation equipment and bus work. To protect equipment, substation engineers can install direct stroke lightning shielding. This guide is intended to provide engineers with information pertaining to the interception of damaging direct lightning strokes to outdoor substations.

Because of the unpredictability of lightning and the costs associated with damage from direct lightning strokes, research into lightning phenomenon is ongoing. This guide includes descriptions of four non-conventional modeling methods for lightning interception, as well as a review of active lightning terminals. The four non-conventional methods are in various stages of development and are presented as a sample of the continuing research in direct lightning stroke shielding. These methods have potential to be used as design models for substation direct lightning stroke shielding in the future.

II. Terminology associated with DSLP:

For the purposes of this document, the following terms and definitions apply. The IEEE Standards Dictionary Online should be consulted for terms not defined in this clause.

2.1 Critical Stroke Amplitude

The amplitude of the current of the lightning stroke that, upon terminating on the phase conductor, would raise the voltage of the conductor to a level at which flashover is likely. The critical stroke amplitude can flow from the first stroke or any of the subsequent strokes in a lightning flash.

2.2 Dart Leader

The downward leader of a subsequent stroke of a multiple-stroke lightning flash.

2.3 Effective Shielding

That which permits lightning strokes no greater than those of critical amplitude (less design margin) to reach phase conductors. Effective (100% reliable) shielding cannot be achieved in substations because subsequent strokes can flow in the same channel established by the first stroke in a flash, and the models of first-stroke termination of flashes rely on statistical relationships among lightning parameters.

2.4 Electrogeometric Model (EGM)

A geometrical representation of a facility that, together with suitable analytical expressions correlating its dimensions to the current of the lightning stroke, is capable of predicting if the first return stroke of a lightning flash will terminate on the shielding system, the earth, or the element of the facility being protected.

2.5 Electrogeometric Model Theory

The theory describing the electrogeometric model together with the related quantitative analyses including the correlation between the striking distance and the electrical parameters, such as charge and peak current, of the prospective first return stroke.

2.6 Ground Flash Density (GFD)

The average number of lightning flashes per unit area per unit time at a particular location.

2.7 Isokeraunic Lines

Lines on a map connecting points having the same keraunic level.

2.8 Keraunic Level

The average annual number of thunderstorm days or hours for a given locality. A daily keraunic level is called a thunderstorm-day and is the average number of days per year in which thunder is heard during a 24-hour period. An hourly Keraunic level is called a thunderstorm-hour and is the average number of hours per year that thunder is heard during a 60-minute period.

2.9 Lightning Flash

The complete lightning discharge, most often composed of leaders from a cloud followed by one or more return strokes.

2.10 Lightning Mast

A column or narrow-base structure containing a vertical conductor from its tip to earth, or that is itself a suitable conductor to earth. Its purpose is to intercept lightning strokes so that they do not terminate on objects located within its zone of protection.

2.11 Negative Shielding Angle

The shielding angle formed when the shield wire is located beyond the area occupied by the outermost conductors.

2.12 Positive Shielding Angle

The shielding angle formed when the shield wire is located above and inside of the area occupied by the outermost conductors.

2.13 Rolling Sphere Method

A simplified technique for applying the electrogeometric theory to the shielding of substations. The technique involves rolling an imaginary sphere of prescribed radius over the surface of a substation. The sphere rolls up and over (and is supported by) lightning masts, shield wires, fences, and other grounded metal objects intended for lightning shielding. A piece of equipment is protected from a direct stroke if it remains below the curved surface of the sphere by virtue of the sphere being elevated by shield wires or other devices. Equipment that touches the sphere or penetrates its surface is not protected.

2.14 Shielding Angle

(A) (Of shield wires with respect to conductors): The angle formed by the intersection of a vertical line drawn through a shield wire and a line drawn from the shield wire to a protected conductor. The angle is chosen to provide a zone of protection for the conductor so that most lightning strokes will terminate on the shield wire rather than on the conductor.

(B) (of a lightning mast): The angle formed by the intersection of a vertical line drawn through the tip of the mast and another line drawn through the tip of the mast to earth at some selected angle with the vertical. Rotation of this angle around the structure forms a cone-shaped zone of protection for objects located within the cone. The angle is chosen so that lightning strokes will terminate on the mast rather than on an object contained within the protective zone so formed.

2.15 Shield Wire (Overhead Power Line or Substation)

A wire suspended above the phase conductors positioned with the intention of having lightning strike it instead of the phase conductor(s).

2.16 Stepped Leader

Static discharge that propagates from a cloud into the air. Current magnitudes that are associated with stepped leaders are small (on the order of 100 A) in comparison with the final stroke current. The stepped leaders progress in a random direction in discrete steps from 10 to 80 m in length. It is not until the stepped leader is within striking distance of the point to be struck that the stepped leader is positively directed toward this point.

2.17 Striking Distance

The length of the final jump between the downward stepped leader and the grounded structure, as the electric field in this gap exceeds the electrical breakdown strength. The length of the final jump is a function of the leader potential, the associated charge, the rate of change of electric field, and the geometry of the gap. The first peak return stroke currents of negative downward lightning flashes are reasonably correlated with the respective impulse charge values.

2.18 Surge Impedance

The ratio between voltage and current of a wave that travels on a conductor.

2.19 Thunder

The sound that follows a flash of lightning and is caused by the sudden expansion of the air in the path of electrical discharge.

2.20 Thunderstorm Day

A day on which thunder can be heard, and hence when lightning occurs.

2.12 Thunderstorm Hour

An hour during which thunder can be heard, and hence when lightning occurs.

III. Types of strokes:

There are a number of different types of lightning strokes. These include strokes within clouds, strokes between separate clouds, strokes to tall structures, and strokes that terminate on the ground. The positive and negative strokes terminating on the ground are the types of most interest in designing shielding systems and the following discussion will be confined to those types.

(A) Stepped leaders

The actual stroke development occurs in a two-step process. The first step is ionization of the air surrounding the charge center and the development of stepped leaders, which propagate charge from the cloud into the air. Current magnitudes associated with stepped leaders are small (in the order of 100 A) in comparison with the final stroke current (Wagner [B142]). The stepped leaders progress in a random direction in discrete steps from 10 to 80 m in length. Their most frequent velocity of propagation is about 0.05% the speed of light, or approximately 150 000 m/s (Anderson [B7]). This produces electric fields near ground with rise times on the order of 100 to 500 microseconds. Electric fields of 250 microseconds from switching surge overvoltages tend to produce the minimum electrical strength of large air gaps compared to 1.2/50 microsecond lightning overvoltages. It is not until the stepped leader is within striking distance of the point to be struck that the leader is positively diverted toward this point. Striking distance is the length of the last step of leader under the influence of attraction toward the point of opposite polarity to be struck.

(B) Return stroke

The second step in the development of a lightning stroke is the return stroke. The return stroke is the extremely bright streamer that propagates upward from the earth to the cloud following the same path as the main channel of the downward stepped leader. This return stroke is the actual flow of stroke current that has a median value of about 24 000 Ampere and is actually the flow of charge from earth (flat ground) to cloud to neutralize the charge center (Mousa and Srivastava [B109]). The velocity of the return stroke propagation is lower than the speed of light and varies with atmospheric conditions; an approximate value can be 10% of the speed of light (Rakov and Uman [B126]).

The amount of charge (usually negative) descending to the earth from the cloud is equal to the charge (usually positive) that flows upward from the earth. Since the propagation velocity of the return stroke is so much greater than the propagation velocity of the stepped leader, the return stroke exhibits a much larger current flow (rate of charge movement). The various stages of a stroke development are shown in Figure 2. Approximately 55% of all lightning flashes consist of multiple strokes that traverse the same path formed by the initial stroke.

IV. Calculation:

The calculation is carried out in various method like

- Fixed Angle
- Empirical Curves
- Whitehead's Electro-Geometric-Model
- Mousa's Electro-Geometric-Model
- Eriksson's Electro-Geometric-Model
- Razevig Method

Out of which fixed angle is conventionally popular. Circular Sphere (Mousa's EGM) and Razevig are most commonly used methods these days. Let's see both of these methods.

4.1 Circular Sphere/ Rolling Sphere Method:

Nomenclature used in the calculations when using mast protection:	
Symbol	**Description**
S	Sphere radius
H	Mast height
A	Bus height
W&C	Horizontal distance from origin of sphere (OOS) to bus
T	Maximum separation from mast to bus for protection
Y	Minimum phase to steel clearance
Z	Horizontal distance between OOS and line drawn between two masts
L	Half the separation between two masts
X	Maximum separation between two masts
D	Elevation difference between mast and bus
E	Elevation difference between mast and OOS
J	Horizontal distance between OOS and mast

K	Diagonal distance between masts when four masts support the sphere
P	Distance between masts when four masts support the sphere
Q	Distance between masts when three masts support the sphere

GIVEN DATA				
Sr. no.	**Description**	**Notations**	**Unit**	**Value**
1	Nominal System Voltage	V_s	kV	220
2	System Frequency	F_s	Hz	50
3	Rated Lightning Impulse Withstand Voltage	V_c	kV	1050
4	Limiting Corona Gradient	E_o	kV/m	1500
5	Strikes on shield wire	k	---	1
6	Types of conductor	Single Moose ACSR		
7	Diameter of conductor	d	m	0.03177
8	No. of conductor	---	No.	1
9	Sub-Conductor Spacing	1	m	0
10	Heights of Installation above FGL	A	m	9
11	Heights of shield wire	H	m	18.2

CALCULATION OF DSLP BY CIRCULAR SPHERE PROTECTION FOR TRANFORMER

I. FIND CORONA RADIUS :-

$$R_c \times \ln\left(\frac{2 \times h}{R_c}\right) - \frac{V_c}{E_o} = 0$$

Where,

R_C is the corona radius in meters ~ 0.164473265

H is the average height of the conductor in meters

V_C is the allowable insulator voltage for a negative polarity surge having a 6 μs front in kilovolts (V_C = the BIL for post insulators)

E_0 is the limiting corona gradient; this is taken equal to 1500 kV/m

Above Equation can be solved by trial and error using a programmable calculator. (An approximate solution can be obtained)

Hence, **Rc ≈ 0.188085896**

II. SURGE IMPEDANCES UNDER CORONA :-

$$z_s = 60\sqrt{ln\left(\frac{2\times h}{R_c}\right)\times ln\left(\frac{2\times h}{r}\right)}$$

Where,

H is the average height of the conductor

R_C is the corona radius (use Equation as appropriate)

R is the metallic radius of the conductor, or equivalent radius in the case of bundled conductors

Hence, **Zs = 387.8073 Ω**

III. PROTECTION BY MASTS :-

$$I_s = \frac{BIL \times 2.2}{Z_s}$$

Hence, Is **= 5.9565671 kA**

Assuming, K = 1.2

$$S = 8 \times K \times I_S^{0.65}$$

Hence,

S = 30.62094984

$$C = \sqrt{S^2 - (S - A)^2}$$

Hence,

C = 21.68356744

Also, *C = S - T*

Therefore, T = S - C

T = 8.937382393

IV. MAXIMUM DISTANCE BETWEEN TWO MASTS FOR SIDE STROKE :-

$$W = \sqrt{S^2 - (S - A)^2}$$

W = 21.68356744 m

Here,

Y = 1m (Assumption)

Therefore,

Z = W - Y

Z = 20.68356744 m

Similarly,

$$L = \sqrt{S^2 - E^2}$$

L = 22.57947313 m

Hence,

X = 2 x L

X = 45.15894625 m

V. MAXIMUM DISTANCE BETWEEN MASTS FOR VERTICAL STROKE SPHERE SUPPORTED BY FOUR MASTS :-

D = H - A

D = 9.2 m

E = S - D

E = 21.42094984 m

$$J = \sqrt{S^2 - E^2}$$

J = 21.88116718 m

K = 2 x J

K = 43.76233435 m

$$P = \frac{K}{\sqrt{2}}$$

P = 30.94464338 m

$$Q = 2\cos\left(\frac{30\ \pi}{180}\right)J$$

Q = 37.89929328 m .

However, Q shall not be Greater than X

Thus, Condition is satisfied.

4.2 Razevig Method:

Nomenclature for DSLP protection by Razevig Method for **Transformer Protection**		
Symbol	**Description**	**Unit**
h	Height of Lightning Spikes	m
h_x	Height of Live part to be Protected	m
h_o	Midway Point Protective Height Between Two LM's	m
P	Coefficient for the LM Height	-
s	Allowable Distance Between Two LM's	m
b_x	Midway Point Protective Distance Between Two LM's	m

Given data remains the same as used in above example.

CALCULATION OF DSLP BY RAZEVIG METHOD FOR TRANFORMER PROTECTION

I. <u>GIVEN DATA:</u>

Height of Lightning Spikes (h) = 18.2 m
Height of Live Part to be Protected (h_x) = 5.5 m

II. FORMULAE'S USED:

I. Protective Radius (r_x):-

If, h_x <= (2/3) h and h > 30m:-

$$r_x = 1.5h \times \left(1 - \frac{h_x}{0.8h}\right) \times P \qquad \text{m}$$

If, h_x <= (2/3) h and h <= 30m:-

$$r_x = 1.5h \times \left(1 - \frac{h_x}{0.8h}\right) \qquad \text{m}$$

We use Second Formula as that Satisfies Our Condition

Therefore, r_x = 16.9875

II. Co-efficient for the Lightning Mast Height :-

For h > 30m P = $5.5\sqrt{h}$ m

For h <= 30m P = 1 m

III. Allowable Distance Between Two LMs :-

S = 7 x h_a x P m

h_a = 12.7 m (Where h_a = h - h_x)

Hence,

S = 88.9 m (Allowable)

Actual Distance between Two LMs:-

S = 24.42

IV. Midway Point Protective Height (Ho) and Midway Point Protective Distance (bx) :-

$$h_o = h - \left(\frac{S}{7 \text{ x } P}\right)$$

h_o = 14.71142857

If hx < (2/3) h_o and h_o > 30 m:-

$$b_x = 1.5\, h_o \times \left(1 - \frac{h_x}{0.8\, h_o}\right) \times P$$

If hx > (2/3) h_o and h_o < 30 m:-

$$b_x = 1.5\, h_o \times \left(1 - \frac{h_x}{0.8\, h_o}\right)$$

If hx > (2/3) h_o and h_o < 30 m:-

$$b_x = 0.75\, h_o \times \left(1 - \frac{h_x}{h_o}\right)$$

In our case hx = 9 > (2/3) 14.711 and 14.711 < 30

Hence,

$$b_x = 1.5 \times 14.71142857 \times \left(1 - \frac{9}{0.8 \times 14.71142857}\right)$$

$$b_x = 11.75464 \quad m$$

V. Conclusion:

Direct stroke lightning protection calculation was henceforth done to prevent the system from surge and protect the equipment from damage. It's evidence that all devices are inside the protected zones. Thus, the calculated heights of the masts are satisfactory. Obviously, if the mast heights were decrease, the protective zones would be narrowed. However, since those figures, if the protective zones were narrowed, they couldn't cover whole devices. Therefore, the economical criterion is satisfied. In addition, if there are some masts with certain heights and the user wants to use those masts for lightning protection, the user can use this method to calculate the required mast heights. The heights of existing masts are then compared with the calculated mast heights. The user will know that which installed masts can be salvaged and which masts must be freshly installed.

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