ENGINEERING PRACTICE

EP-4020-C

Substation Lightning Protection Requirements

July 2, 2014

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TABLE OF CONTENTS

Subject Page

1.0 Scope....4
2.0 Purpose....4
3.0 References....4
4.0 General....4
5.0 Shielding System Design....5
5.1 Design Criteria....5
5.1.1 System Data....6
5.1.2 Shield Wire Use....6
5.1.3 Structures....7
5.1.4 Grounding of Poles, Masts, and Dead End Structures....7
5.2 Typical Lightning Shielding Design Process....7
6.0 Shield Poles
6.1 Standards for Steel Poles....8
6.2 Shield Pole Loading....8
6.3 Shield Pole Height....9
6.4 Dead End Structures....9
7.0 Sample Design Of Substation Shielding
7.1 345 kV Switching Type Substation....9
8.0 Summary....11
9.0 Attachments
9.1 Surge Arrester Energy Capability....12

9.2 Determining the Critical Strike Radius 13

9.3 Rolling Sphere and EGM Shielding Techniques-Shield Wires 15

9.4 Shielding Using Masts 22

9.5 Lightning Strike Probabilities 25

9.0 Development history 28

1.0 Scope

This document contains the recommended practices for the design of lightning shielding systems at Exelon substations.

2.0 Purpose

This purpose of this document is to define the required protection of substation equipment from direct stroke lightning flashes. It also lists practical information to assist the design engineer.

3.0 References

EP-4019E Substation Surge Arrester Requirements

EP-2130-E Overhead Transmission Line Conductor and Static Wire Motion - Design for Aeolian Vibration, Galloping, and Sub-Conductor Oscillation

PJM TSDS Technical Requirement V.N Insulation Coordination and Surge Protection

IEEE998 IEEE Guide For Direct Lightning Stroke Shielding of Substations

IEEE1313.2 IEEE Guide For the Application of Insulation Coordination

4.0 General

The use of lightning protection at substations is part of the insulation coordination principle. This principle identifies several “zones of protection” for surge waveforms, and coordinates these zones with the ability of the substation insulation systems to withstand the surges.

Substation shielding is designed to protect equipment from direct lightning strokes that would result in equipment outages. Good lightning protection schemes include correctly installed shield wires, shield poles, high quality connections to the shield wire and switchyard ground grid, and an adequate grounding system. The transmission line static wires help to dissipate lightning strikes to the overhead wires by shunting lightning currents to the soil through the tower, or in the case of wood poles through downlead wires. In substations, strikes to the shield wire or pole direct the lightning current away from power equipment and switchyard control wiring to minimize damage to these components. Lightning shield poles may be used to mount lighting fixtures, auxiliary power cabinets, etc in addition to providing shielding protection.

Lightning shielding systems are required for direct stroke protection of overhead buses and equipment in all new substations. Engineering practice 4019-E addresses surge arrester application in Exelon substations.

5.0 Shielding System Design

The optimum location of the shielding system is dependent on strength of the lightning stroke, flashover voltage of the insulation, surge impedance of the bus conductors, and equipment location in the substation. The task of the design engineer is to install a shielding system that protects the equipment, yet leaves enough room for access during maintenance activities. A shielding system may be formed using shield wires, shield poles, or a combination of the two. Because substation areas are so large, it is generally more economical to use shield wires than a system of shield poles. The placement of shield wires within the switchyard may be performed with the aid of the “Rolling Sphere Shielding Model” or by the “Electro Geometric Model” (known as EGM) method. Attachment 9.3 explains the theory behind these two methods and how to create shielding zones of protection using these models. Attachment 9.4 explains the methods for determining shielding zones of protection using shielding masts. Exelon uses IEEE standard 998-1996 as the basis for our design criteria.

5.1 Design Criteria

The shielding system must protect all 69 kV and above outdoor equipment inside the substation from lightning strokes that would exceed the BIL value of the bus insulators. At voltages less than 69 kV the shielding system should protect the equipment from lightning strokes that exceed 300 kV BIL. If possible, masts should be used to adequately cover lower BIL, less than 300 kV, equipment. This value was chosen as the coordinating value because shielding protection of open bus becomes impractical at BIL values below 300 kV, and the risk of flashover is small.

The shielding system design must take into account the height of open disconnect switches and wire sag. Where economically feasible it is desirable to protect the control building, in addition to the power equipment. The shield system shall be designed to prevent bus flashovers by using the Basic Insulation Level (BIL) of the bus support insulators. The zones of protection (critical strike radii) shall be calculated by means of Attachment 9.2 or IEEE Standard 998-1996 Direct Lightning Stroke Protection in Substations.

When expansions are made to existing substations insure that the new areas of the substation are protected according to the design criteria established in this engineering practice.

5.1.1 System Data

The BIL values of bus insulators used at Exelon stations are listed in Table 1.

Table 1

Voltage Level [kV]	4	12	34	69	138	230	345	500	765
BIL [kV]	95	110	200	350	650	1050	1300	1800	1925
* BIL Current [kA]	0.5	0.57	1.0	1.8	3.4	5.5	6.8	9.4	10.2

* Current values based on a conductor surge impedance of 380 Ω

5.1.2 Shield Wire Use

When static wire is used for shielding purposes 7 strand #6 Alumoweld shall be used. Use of 7 strand wire significantly reduces the risk of wire breakage from lightning discharges. Static wire tension and vibration control shall be accommodated by the methods detailed in EP-2130-E Overhead Transmission Design for Aeolian Vibration, Galloping, and Sub-Conductor Oscillation. The static wire shall be solidly bonded by a wire connection at each shield pole. A shield pole is defined as a vertical structure whose primary purpose is to support shield wire used for direct stroke lightning protection.

It is important to locate shield wires so that no more than one transformer, one transmission line, or more than one bus section will be tripped if the shield wire falls to the ground. If necessary, intermediate poles should be used to segregate the shield wires so that the previously mentioned concept applies. The following guidelines will help to minimize exposure to outages should the static wire break.

1. Shield wire spans shall run parallel to bus conductors or transformer leads.

2. Shield wire spans shall not exceed 400 feet in length.

5.1.3 Structures

The use of bus support structures for shielding purposes should be avoided if possible, since there is a possibility of a backflash occurring to the bus. Dead end structures that are considered part of the line are acceptable for shielding use. A shield pole is defined as a vertical structure whose primary purpose is to support shield wire(s) used for direct stroke lightning protection. A shield mast is defined as a vertical structure whose primary purpose is to support a rod(s) used for direct stroke lightning protection.

Shield poles and/or masts shall be located so that they do not obstruct access to equipment for maintenance or removal in the case of replacement. A typical value is 20 feet from power equipment and 10 feet from roadway access. Shield poles and/or masts should be placed 20 to 30 feet from cable trough and control buildings where practical.

The placement of shield poles and shield masts shall be installed inside the substation such that these structures do not cause a full station outage should either of these structures fall to the ground if a physical failure of either the shield pole or the shield mast would occur. Poles and masts shall be located such that should the pole or masts structurally fail that the fallen pole or mast would not cross more than one bus.

5.1.4 Grounding of Poles, Masts, and Dead-End Structures

Where any structure is located within the substation property it must be connected to the substation ground grid. To insure surge current dissipation a 16-20 foot ground rod shall be placed within 2 feet of the pole or dead end foundation. For further details of substation grounding refer to EP-4021-E Substation Grounding System Requirements.

5.2 Typical Lightning Shielding Design Process

Before designing the shielding system several parameters are required. These required parameters are;

- the station physical size and areas to be covered
- the equipment height and BIL level

- placement of the equipment, sub-grade items, and roadway access

The strike radii for the various BIL values are then calculated and compared to the required distances of coverage. The strike radius shall be calculated for the highest bus section being protected. At this stage of the design process the use of shield wires, masts, or both must be decided. The shield poles or masts are preliminarily located, maximum wire tension calculated (if applicable) from which the pole loading is calculated, and the protected coverage is determined. Vertical coverage will be greatly influenced by the wire or mast separation. Refer to Attachment 9.3 (pg 14-20) and Attachment 9.4 (pg 21-26) for further recommendation of wire or mast separation. After the separation distance is calculated shield wire sag and sway must be determined. The resulting values are then used to determine their effect on the protected distances. If coverage, or access, is not adequate the poles must be moved and the coverage must be evaluated for the new pole placements. This procedure continues until the equipment is protected and adequate access clearance is obtained. Section 7 details an example of a shielding system for a typical 345kV substation.

6.0 Shield Poles

6.1 Standards For Shield Poles

ComEd material specification EM-16007 provides technical information for two standard shield poles that have been successfully used for providing shielding in transmission switchyards and generating station switchyards.

PECO Drawing D-233032 provides technical information for four (60, 80, 100, 130 foot high) standard shield poles.

6.2 Shield Pole Loading

A ComEd type “A” pole is designed for a resultant horizontal load at the top of the pole equal to the tension “T” of one shield wire. The designation for the pole is 1.0xT, where T is the shield wire tension. A ComEd type “B” pole is designed for a resultant horizontal load at the top of the pole equal to twice the tension of one shield wire; the designation is 2.0xT.

The allowable loading is found by calculating the resultant horizontal load at the top of the pole, using a tension load of 1.0xT for each shield wire. Next, calculate the resultant horizontal load at the top of the pole again

using a tension load of 1.0xT for each wire assuming any one wire is broken. Using the calculation above, if the resultant horizontal load for both cases is 1.0xT or less, specify a type "A" pole. If the resultant is greater than 1.0xT, but not greater than 2.0xT, specify a type "B" pole. The shielding system design must limit the "T" multiplier to a value of 2.0 or less.

6.3 Shield Pole Height

Two height ranges of shield poles seem to work well at the following substation voltage classes:

- 60 - 86 foot poles in 69, 138, 230, and 345 kV switchyards.
- 100 - 130 foot poles in 500 and 765 kV switchyards.

Required pole height is dependent on the ability of the mast or combination of masts to provide adequate protection to equipment and buswork.

6.4 Dead End Structures

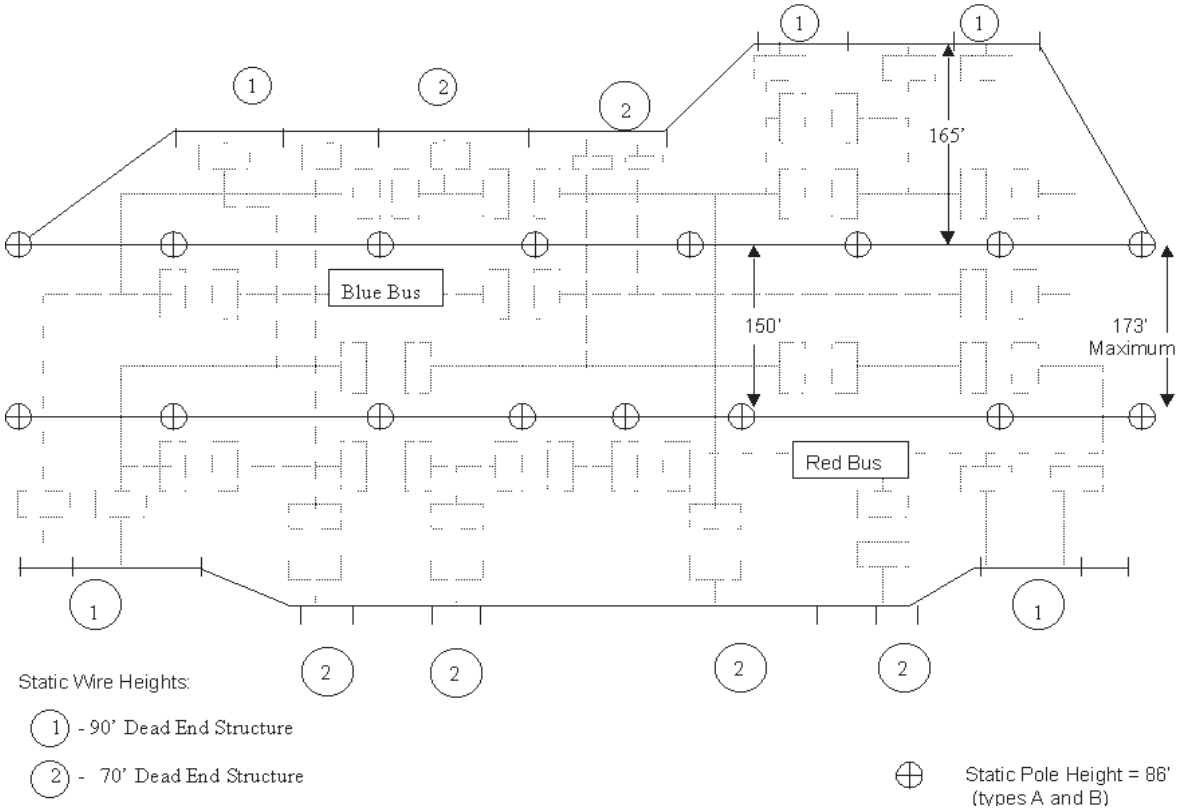
Dead end structures are used as shield wire supports whenever practical. However, their use should not conflict with shielding criteria. Normally, shield wires are installed between the static peaks of dead end structures that are used as shield wire supports.

7.0 Sample Design Of Substation Shielding

7.1 345 kV Switching Type Substation

Figure 7-1 shows the design for lightning shielding of a 345 kV folded ring bus. Six type "A" and ten type "B" shield poles, and 16 dead end structures are used as shield wire supports in the ultimate plan. The 150-foot spacing between the tower center shield wire runs does not violate the 173 foot maximum.

Figure 7.1 Switching type Substation Shielding



8.0 Summary

The use of shield wires and/or masts are essential when substations are being constructed or when new transformers or busses are added to existing switchyards. Careful attention needs to be paid to positioning the bus work in the switchyard so that room is provided for installing the shield poles.

Ground grids in the switchyard must dissipate the lightning energy for direct strikes to the switchyard shield wires. With space permitting, locate the static pole grounds 20 to 30 feet away from the control cable troughs and the control building. This separation will help limit transients entering the control wiring for the switchyard equipment.

9.0 Attachments

9.1 Surge Arrester Energy Capabilities

Substation shielding is designed to protect equipment from direct lightning strokes. Surge voltages on phase conductors in the switchyard can be generated by; lightning strikes to shield wires on the overhead lines that induce surges on phase conductors, lightning strikes to nearby objects, or transmission line shielding failures. The energy from these transmitted surges are well within the energy capability of the arresters connected to the switchyard equipment, however if direct strokes to the equipment occur, they can exceed the short time energy capability of surge arrestors.

Station class surge arrestors are rated at 65kA using impulses of 4μsec rise time and a time to half value of 10μsec. While the rise time value approximates lightning impulse currents, the tail is shorter than a typical negative polarity lightning impulse, which has a median time to half value of 77.5μseconds. Additionally, a typical lightning flash will consist of 3 strokes, which have an inter-stroke interval between 45-35 milliseconds. Statistically the first stroke contains the highest magnitude and slowest rise time. Subsequent strokes contain lower magnitudes but have faster rise times. The median crest value of the initial stroke is 31.1kA and the subsequent stroke crest value is 12.3kA. As will be shown in Attachment 9.4 there is a probability that a stroke will exceed the initial crest of 31.1kA. Thus surge arrestors are in danger of exceeding their design value and that is why shielding systems are required. Optimum protection of the bus and equipment is derived from a combination of surge arresters and the switchyard shielding system. For guidelines on where to place surge arresters consult EP4019-E.

9.2 Determining The Critical Strike Radius

The current resulting from a lightning strike can be thought of as the current in a circuit containing a spark gap. The spark gap is the air between the advancing leader and the protected objects. The normal cloud to ground lightning stroke is best analyzed in two parts. Originating in a charged cloud, the leader stroke advances to the ground with a velocity of about 100-ft per microsecond in discreet steps of 10 to 80 meters, unaffected by any grounded structures. When the dielectric breakdown strength between the advancing leader tip and some ground object has been reached the current from the ground conducts upward to the step leader neutralizing the voltage difference between the step leader and the ground. This current is referred to as the return stroke. This stroke has a current range from 2 to 200 kA, with a median value of 31kA. The time for the leader stroke to complete the circuit from cloud to the stricken object is about 0.01 seconds.

The length of this final leader step is called the strike radius and is approximated by the Equation (B1):

$$R_s = 26.25 \times k \times I^{2/3} ....(ft) \qquad \text{(B1)}$$

Where R_s is the strike radius in feet, k is a strike constant, and I is the stroke current in kAmps. The constant k is equal to1 for strikes to the ground or shield wire and is equal to 1.2 for a strike to a mast. This is consistent with laboratory testing where different breakdown strengths are observed for rod-plane gaps (typical of a downward leader core to the ground) and rod-rod gaps (typical of a downward leader to the tower top). Notice that the strike radius is proportional to the magnitude of the stroke current. For very small currents, the shielding system protects only a very small area around itself. This indicates that switchyard conductors will not be protected from direct stokes for small magnitude lightning currents. The equipment insulation has a significant withstand capability given by the Basic Insulation Level (BIL) voltage. Equation B2 lists the minimum current value that the shield wire must be designed to in order for an object to be inside the strike radius.

$$I_{oc} = \left(2 \times 1.1 \times V_f \right) / Z_{s.....(kAmps)} \qquad \text{(B2)}$$

V_f is the Basic Insulation Level (BIL) of the bus insulators (in kV), Z_s is the overhead bus surge impedance, and the factor 1.1 accounts for a stroke terminating on a conductor instead of the earth. From equation B2 it is evident that the critical stroke current increases with the BIL. Since the critical stroke current is proportional to the BIL the strike distance will also be proportional to

the BIL. Unless extraordinary bus sizes or heights are used the BIL value will have the biggest impact on the strike distance. The design problem is to limit the stroke current to a value that would not cause the piece of equipment having the lowest value BIL to flashover.

Note that some transformers may have lower BIL values than the surrounding equipment (such as on the ComEd system), however they are protected by Surge Arrestors and their BIL value should not be used for determining critical stroke currents.

The standard formula for the surge impedance of a single conductor above ground for a bus can be found using Equation B3:

$$Z_s = 60 \times Ln\left(\frac{2h}{r}\right)....\Omega \qquad \text{(B3)}$$

where **h** is the height above ground in inches and **r** is the outside radius of the bus conductor, refer to EPRI Transmission Line Reference Book, EL-2500 R1, page 554.

Combining equations B1, B2, and B3 the value for critical strike radius, Rsc in feet, can be determined. The critical strike radius is the distance from the bus where lightning current magnitude is sufficient to cause bus insulation failure. The shield system shall be located such that Rs > Rsc. Equations B4 and B5 illustrate this:

$$\mathrm{R_{sc}} = 26.25 \times I_{oc}{}^{2/3}....(ft) \qquad \text{(B4)}$$

$$Rsc = k \times 3.06 \left[\frac{V_f}{\left(Ln\left[\frac{2h}{r}\right]\right)} \right]^{2/3} .....(ft) \qquad \text{(B5)}$$

An example of using the formulas for a 345 kV high bus design is as follows:

V_f = 1300 kV

h = 36 ft, = 432 inches

r = 2.25 inches, for a 4 inch aluminum bus conductor.

$$R_{sc} = 1 \times 3.06 \left[\frac{1300}{\left(Ln \left[\frac{2(432)}{2.25} \right] \right)} \right]^{2/3} = 101.5 \ldots ft$$

The Exelon design value for a critical strike radius at 345kV substations is conservatively set at 100 feet. This lower value will ensure that currents exceeding the BIL of the bus insulation will strike the shield wire and not the phase bus. Smaller magnitude currents may strike the bus, however the surge arresters will absorb the energy of the small magnitude strikes without causing insulation failure. This is an accepted practice at the majority of utilities since designing for stroke currents of less than 2 or 3 kA becomes uneconomical. As mentioned previously surge arrestors are used to provide protection for these smaller magnitude currents. Surge arrestors are impulse tested at values up to 20kA, therefore shielding failure currents are within the energy capability of the arrestor.

In certain situations natural shielding may occur such as, trees close to the substation or buildings located in close proximity. In these situations trees and buildings may be treated as extensions of the ground plane. To explain further consider the ground plane to be elevated by the tree or building height.

9.3 Rolling Sphere and EGM Shielding Techniques – Shield Wires

The lightning Zone of Protection that is determined by the Rolling Sphere method is visualized by imagining a sphere, the radius equal to the critical strike radius of 100 feet (in the aforementioned example), being rolled over the surface of the switchyard. Whatever the sphere touches in its path is susceptible to direct lightning strikes large enough to damage equipment. Objects, such as the switchyard bus, that cannot be touched by the rolling sphere are shielded from damaging lightning strikes. For standard shield wire support structure (known as static poles) the maximum horizontal spacing between the bus conductors and the shield wire spans can be determined. Figures C1 and C2 illustrate this method.

Figure C1 345 kV Switchyard with Rolling Spheres

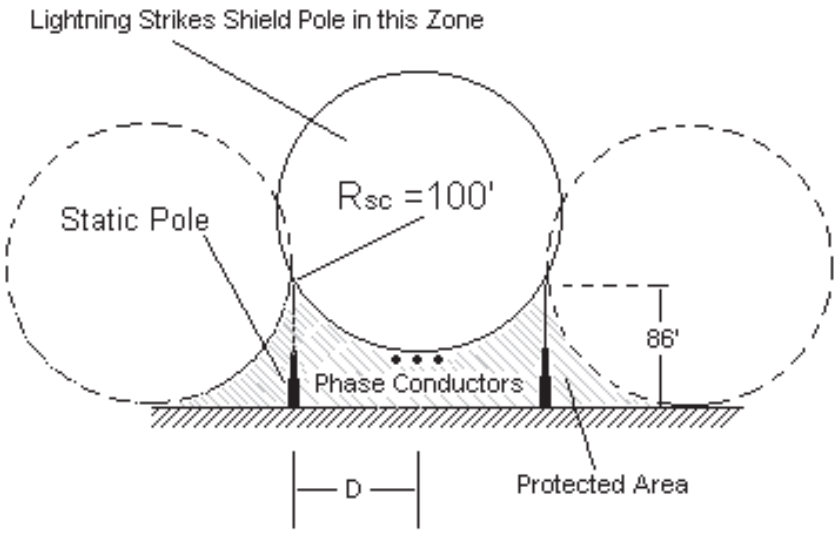
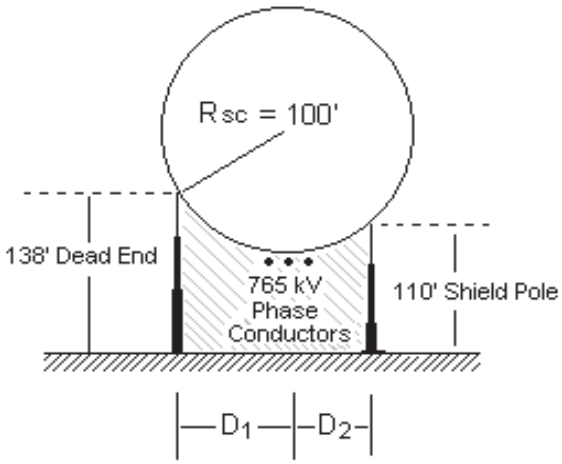


Figure C2 765 kV Switchyards with Critical Radius



Based on common high bus heights, Table 9.3.1 lists the maximum horizontal spacing **between** the shield wire and the buses. Please note that transformers, circuit breakers, and disconnect switches must also fall below the sphere to be protected from direct strokes. Care should be taken to add additional distance to the bus height for open disconnect switches or bushings.

Table 9.3.1 Shield Wire Heights in Switchyards

Voltage Level	Height of shield wire or support structure	Height of 2nd shield wire or support structure	Maximum horizontal spacing
69kV or 138kV High Bus (24 ft)	85’ dead-end	86’ shield pole	126’
230 kV High Bus (29 ft)	85’ dead-end	86’ shield pole	146’ **
345 kV High Bus (36 ft) Note 1	90’ dead-end	90’ dead-end	175’
	86’ shield pole	86’ shield pole	173’
	70’ dead end	70’ dead end	161’
500 kV High Bus (40 ft)	90’ dead-end	110’ shield pole	177’ **
765 kV High Bus (65 ft) Note 2	138’ dead-end	110’ dead-end	180’
	110’ shield pole	110’ shield pole	167’
	105’-8” at mid-span of 200’ span between 110’ poles	105’-8” at mid-span of 200’ span between 110’ poles	161’

Note 1: The high bus configuration is used in shielding calculations.

Note 2: Values calculated at supporting structures are for reference only. Actual spacings must be verified at the lowest point of shield wire span.

** Includes open disconnect switch height (230 kV = 10 ft, 500 kV = 12 ft)

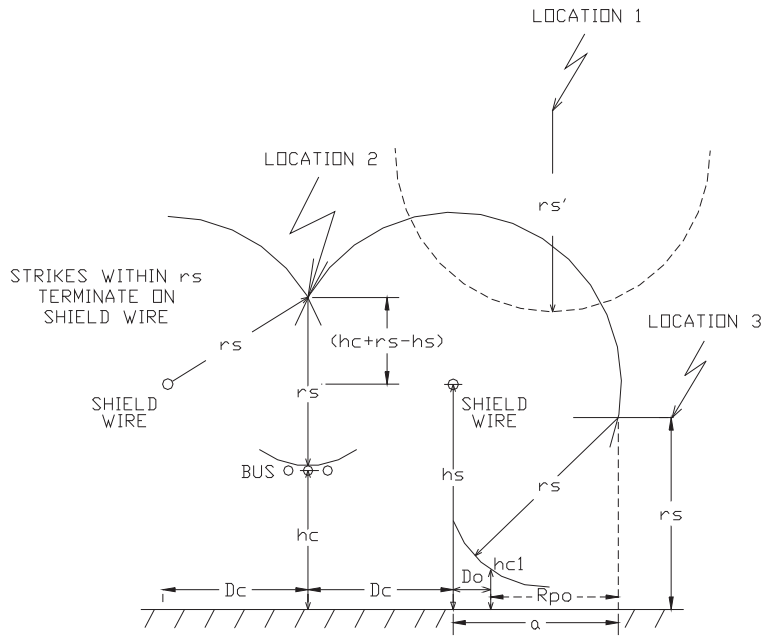
EGM Method

The EGM method uses the shield wire height and protected object height to determine the maximum pole separation. It is important to realize that the shield system also provides some coverage outboard, or opposite the shield wires. In general this coverage is not as great as the inboard coverage.

To visualize the use of the EGM method refer to Figure 9.3.1 below:

Figure 9.3.1

Figure 9.3.1 shows the protected zones using a two wire shielding system.



hs is the shield wire height [ft]

hc is the protected object height [ft]

rs is the striking radius [ft]

Dc is half the shield wire separation distance [ft]

a is the horizontal distance from the shield wire to the max outboard horizontal striking distance [ft]

Do is the protected object distance on the outside of the shield wire. [ft]

In the following discussions a flash is considered to arrive from the vertical direction. This agrees with most observations to date. The strokes considered have a striking radius determined from equation B5, which assumes the stroke current is the critical current from equation B2. Strokes arriving at location 1 will terminate on the shield wires. Those strokes arriving at location 3 will terminate on the ground since they are outside the shield wire sphere of influence. Strokes arriving at location 2 will terminate on the shield wires, but note that the strike radius ends just above the protected object. Thus the distance above the protected object will dictate how far apart the shield wires may be placed. As the shield wires are placed further away from one another the vertical overlapping region distance decreases, refer to figure 9.3.2.

Figure 9.3.2

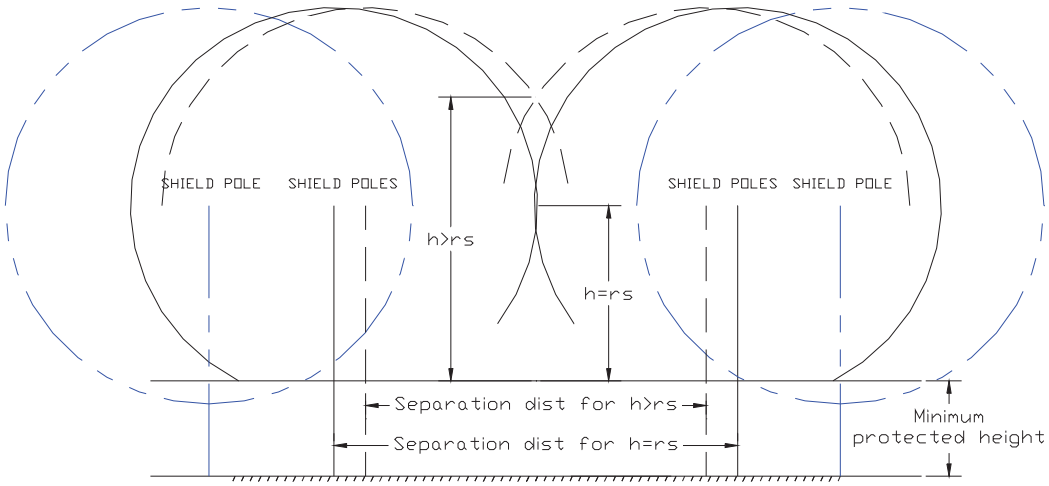


Figure 9.3.2 shows the strike distance (rs) shorter than the pole height. For 69 and 138kV voltages this will be the case provided the pole height is greater than 65 feet. For EHV voltages the opposite is true, the strike radius will be larger than the pole height. In either case the critical fact is the maximum pole separation will be less than twice the stroke distance. Figure C4 illustrates this for voltages at or less than 138kV. For any situation where pole separation is greater than twice the strike radius no overlap occurs and each shield wire acts independently. Where the poles are twice the strike radius strokes will reach below the protected object height. As the pole separation is decreased the shield wires raise the height at which the stroke can reach, until at some point it cannot strike the protected object.

Referring back to figure 9.3.1 note that stroke magnitudes greater than Ioc will terminate on the shield wires. The larger radii correspond to larger currents. This condition is shown at location 1 where a lightning stroke is ready to terminate on the right shield wire.

In shielding design the usual task is to determine the wire separation given the wire height, BIL values, etc. To determine the maximum horizontal distance between the center of the protected object and the shield wire, simple geometric identities are used. By knowing the different heights a right angle triangle may be formed and the horizontal distance calculated. Let the following definitions apply:

hs is the shield wire height [ft]

hc is the protected object height [ft]

rs is the striking radius [ft]

Dc is half the shield wire separation distance [ft]

The only unknown is generally the separation distance between the shield wires (Dc). Equation C7 lists this distance (Dc):

$$Dc = \sqrt{rs^2 - (rs + hc - hs)^2} \;.....(C7)$$

After the minimum separation distance (2Dc) is known it must be modified by the shield wire sway. Thus the actual distance will be 2Dc – 2(shield sway). Similarly the maximum protected horizontal outboard distance can be calculated. The horizontal protected distance at a height h is found by identifying the distance (a) to the strike point from the shield wire and the distance to the

protected object from the shield wire (Rpo), see figure C3. The protected outboard distance (D0) is found by subtracting (Rpo) from (a).

The minimum vertical distance is the striking distance to ground. This height (rs) will extend into the shield system until it intersects the arc of radius rs from the shield wire. This point will define the location where a stroke terminating will end just outside of the protected object. The horizontal distance (Rpo) from the outboard stroke origin to the protected object is then:

$$R_{P0} = \sqrt{rs^2 - (rs - hc)^2} ..[ft]...(C8)$$

The distance from the shield wire to the outboard stroke origin is defined as (a). If the strike radius (rs) is greater than the pole height (hs), the outboard horizontal distance (a) equals the strike distance (rs). Otherwise, the distance (a) is given by equation C9.

$$a = \sqrt{rs^2 - (rs - hs)^2} ..[ft]...(C9)$$

The protected distance between the shield wire and the protected object is D0. D0 is found by equation C10:

D0=a - Rpo ..[ft]…(C10)

An Excel spreadsheet is available from the Transmission and Substation Design Standards Group which can be used for determining maximum shield wire separation based on the EGM method.

9.4 Shielding Using Masts

Shield Pole Locations

As explained in Attachment 9.2 shield wires will usually be the most economical way of shielding a substation. However there may be times when the design engineer wishes to add protection to an individual piece of equipment where masts become a preferred option. Another possibility is that a decision has been reached that static wire should not be used. The number of masts used will depend on the geometry of the protected object and its size. Unlike the interior space between shield wires the zone of protection for a mast system consists of arcs at specified heights, refer to figure D1.

Shield Pole Locations Using Fixed Angles

This methodology is based upon the empirical design approach described in Section 4.0 of the referenced IEEE 998 Guide. A shielding angle of 45 degrees for equipment protected by a single mast or located to the outside of multiple masts, and a shielding angle of 60 degrees for equipment located between adjacent masts. This provides a standard of protection which is better than 0.1% (one shielding failure for every 1000 lightning strokes to the substation). The protection distances afforded by these angles are shown in Table 9.4.1 and Figure 9.4-1.

TABLE 9.4.1

Protection for 45° and 60° Shielding Angles
Equipment Height (e)

e h	15 ft x s	20 ft x s	25 ft x s	30 ft x s	35 ft x s	40 ft x s
130	115 199	110 190	105 182	100 173	95 164	90 156
100	85 147	80 138	75 130	70 121	65 112	60 104
90	75 130	70 121	65 113	60 104	55 95	50 87
80	65 112	60 104	55 95	50 87	45 78	40 69
75	60 104	55 95	50 87	45 78	40 69	35 61
70	55 95	50 87	45 78	40 69	35 61	30 52
65	50 87	45 78	40 69	35 61	30 52	25 43
60	45 78	40 69	35 61	30 52	25 43	20 35
55	40 69	35 61	30 52	25 43	20 35	15 26
50	35 61	30 52	25 43	20 35	15 26	10 17

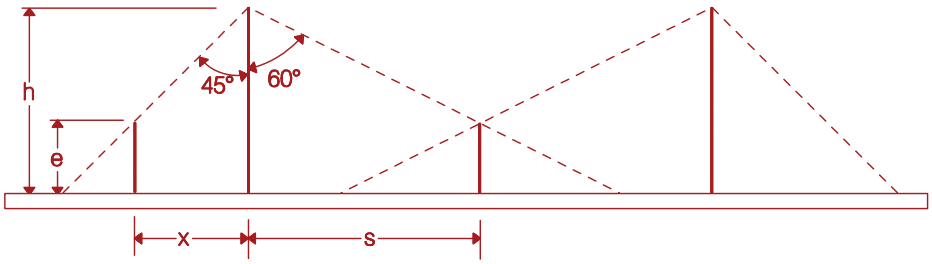


Figure 9.4-1 Elevations associated with Table 9.4.1

The formation of the zones of protection are shown in Figure 9.4-2 (no zone overlap) and Figure 9.4-3 (zone overlap).

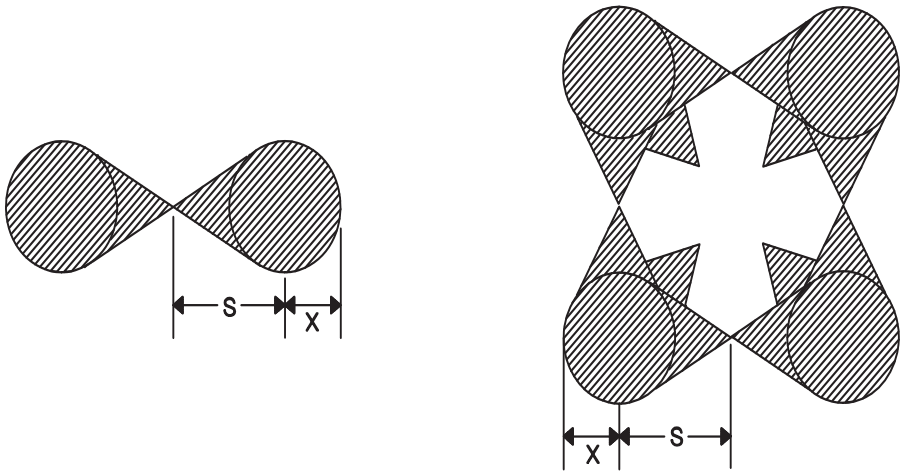


Figure9.4-3 Zones of Protection (no overlap).

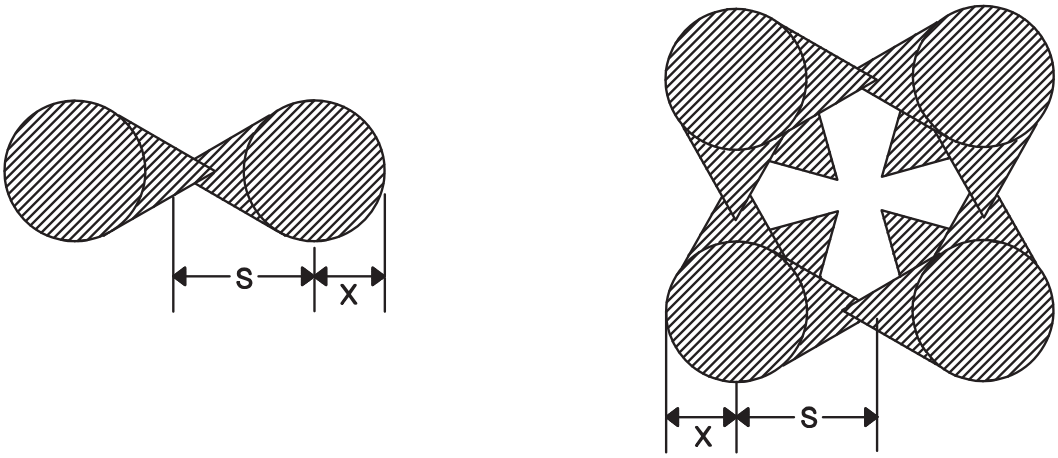


Figure 9.4-2 Zones of Protection (with overlapping zones)

All buswork and equipment 69 kV and above should be within a zone of protection. Special care should be taken to account for the additional height of bus hopovers.

Power transformer protection is of the utmost importance. Therefore, a mast should be placed close to the transformer, so that the transformer is well within the zone of protection and not at the fringe.

Transmission line takeoff towers are considered to provide a zone of protection in accordance with their height. Lightning rod extensions of up to 15 feet may be added atop towers to increase the zone of protection.

Advantage should be taken of the additional coverage achieved between multiple masts.

9.5 Lightning Strike Probabilities

From observations performed over many years statistical data has been gathered on different parameters of lightning strikes. As mentioned in Attachment 9.1 the median value of the crest current during the first stroke is 31kA. The IEEE uses a formula developed by John Anderson that gives the probability of a stroke exceeding this median value. This formula is:

$$P(I) = \frac{1}{1 + (\frac{I}{31})^{2.6}}$$

I is the stroke current in kiloamperes. This equation is valid for negative downward flashes, which occur for object heights of less than approximately 325 feet. To find the probability that a stroke falls within a range, the probability of the higher stroke magnitude is subtracted from the probability of the lower stroke magnitude.

In addition to finding stroke current probabilities we can estimate how many strokes will terminate on the shield wires in the substation. To determine this number use of an equation developed by A. J. Erikkson is employed. Erikkson's equation requires the structure height and ground flash density. The equation is:

$$N(G) = \frac{Ng(28h^{0.6} + Sg)}{10}$$

Where N(G) is the number of strokes per 100km-years, Ng is the ground flash density in flashes/km^2-year, h is the mast height or wire height minus 2/3 of the sag in meters, and Sg is the shield wire separation distance in meters.

Exelon Energy Delivery	ENGINEERING PRACTICE Substation Lightning Protection Requirements	EP-4020-E

10.0 Development history

	Revision 0	Date 12/21/2004
Writers	Carl Schuetz TS&S, Dave Goodwin Major Equip Group	
Reviewer(s)	Mark Fong TS&S, Al Urban TS&S	
Approver(s)	John Garavaglia	
Reason Written	To define the required protection of substation equipment from direct stroke lightning flashes.	

	Revision 1	Date 5/8/2007
Writer	Al Urban	
Reviewer(s)	Al Urban	
Approver(s)	Kathy McHugh	
Reason Written	Clarified numbering of figures in section 9.3. No technical changes.	

	Revision 2	Date 06/30/2014
Writer	Dave Ricotta	
Reviewer(s)	Pat Mintus, Substation Engineering, Mgr Trans & Subst Engineering, Brian Smith, Senior Engineer, Substation Engineering	
Approver(s)	Brian Graham, Substation Engineering, Mgr Substation Engineering	
Reason Written	Remove Transmission Planning as having oversite for when substation arresters are installed.	

	Revision 3	Date 07/02/2014
Writer	Dave Ricotta, Substation Engineering	
Reviewer(s)	Scott Humphreys, Substation Engineering	
Approver(s)	Brian Graham, Manager Substation Engineering	
Reason Written	Revise Section 5.1.3 to add comments from single point of failure review completed for lightning mast structural failures.	