

A Case Study for Substation Lightning Strike Risk Evaluation  
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## **Abstract**

Shielding of substations from direct lightning strokes is a common practice used to protect equipment from damage and reduce the number of system outages caused by lightning. However, when a substation is being upgraded, installation of lightning masts and shielding wires across the substation for full coverage may not be realistic as the necessary outages may not be available.

This paper is a case study for the lightning shielding design of a substation transformer addition and feeder section expansion project. By analyzing the lightning exposure level of the area and risk evaluation of direct lightning strokes to a substation, it is possible to design from a practical perspective of approaching substantial but not complete shielding coverage of the station; hence reduce the outage zone required during construction.

This case study also provides recommendations for future lightning protection design for existing (brownfield) substation.

**Index Terms – Fixed angle method, ground flash density, lightning mast, risk evaluation, rolling sphere method, shield wire, substation.**

## 1.0 Introduction

In early 2012, Amec Foster Wheeler started a capacity addition project. The area of the substation was expanded to accommodate a new 25 kV feeder section and a new 69 kV/25 kV power transformer where the fixed angle method was originally used to protect the substation when it was built in 1964.

The project scope included upgrading the substation lightning protection to use the rolling sphere method, in accordance with IEEE 998 and to conform to the owner's latest engineering standards on lightning protection and enhance the coverage of the expanded new substation area.

Rolling sphere is 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 [1].

Following the calculation method provided in IEEE 998, Annex B, the design for the rolling sphere method would require six lightning masts with shield wire around the perimeter and crisscrossing the switchyard. Figure 1 shows the station fully covered from lightning strikes with masts and shield wires by using rolling sphere method.

The detailed design was progressed using the rolling sphere method. However, it was noted in the constructability review with the client that the outage on transformer T2 might not be available at the time of construction. To avoid the risk of delaying the project and modifying the design greatly, Amec Foster Wheeler performed a detailed study of the possibility of switching to the fixed angle method using the pre-determined locations of lightning masts and surrounding shield wires that were selected based on the rolling sphere method. A risk evaluation between the rolling sphere method and the fixed angle method, as well as the failure rate of each method, were performed and are noted in later sections.

AS DESIGNED LIGHTNING SHIELDING COVERAGE  
(ROLLING SPHERE METHOD (EGM))

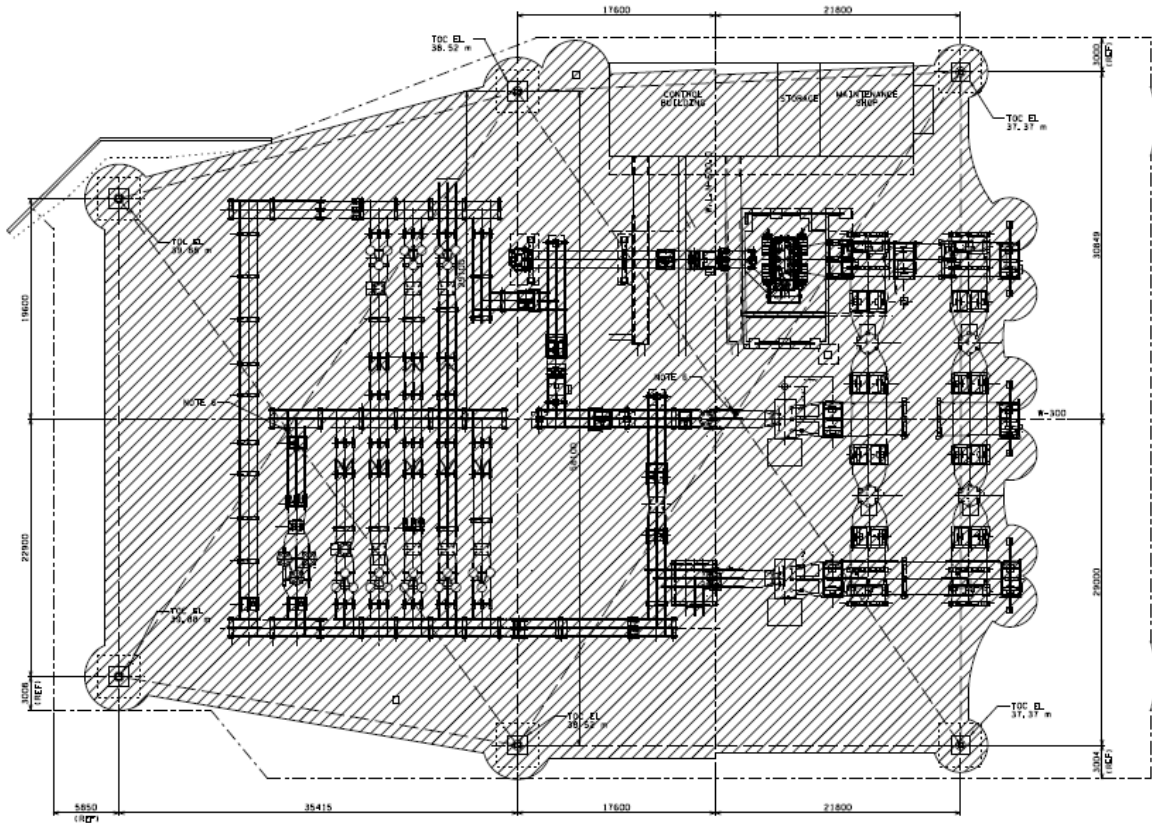
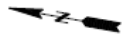


Figure 1: Lightning Protection for the Substation - Rolling Sphere Method

## 2.0 Shielding Coverage with Fixed Angle Method

Fixed angle method is a technique that uses vertical angles to determine the number, position, and height of shielding wires or masts. The protection angle is selected based on the acceptable level of exposure. This fixed angle of protection forms a cone around masts or spires. The protection zone around shield wires forms a triangular prism beneath shield wire.

For the fixed angle method, the value of the angle alpha that is commonly used is 45 degrees. Both 30 degrees and 45 degrees are widely used for angle beta [1]. Horvath [2] suggests a protective angle of 40 degrees to 45 degrees for heights up to 15 m, 30 degrees for heights between 15 and 25 m, and less than 20 degrees for heights to 50 m. With this recommendations, a failure rate of 0.1 to 0.2 shielding failures/100 km/year was assumed.

The protective angle used for this substation is  $\alpha = 45^\circ$ ,  $\beta = 45^\circ$ . Using the lightning mast locations determined by the rolling sphere method, the coverage area in figure 2 indicates that a large portion of the 25 kV switchyard remains exposed. Although the risk evaluation in the later sections shows that this is acceptable for this location, adding an additional mast to improve the coverage was also considered (figure 3).

LIGHTNING SHIELDING COVERAGE AS INSTALLED  
(FIXED ANGLE METHOD - 45°)

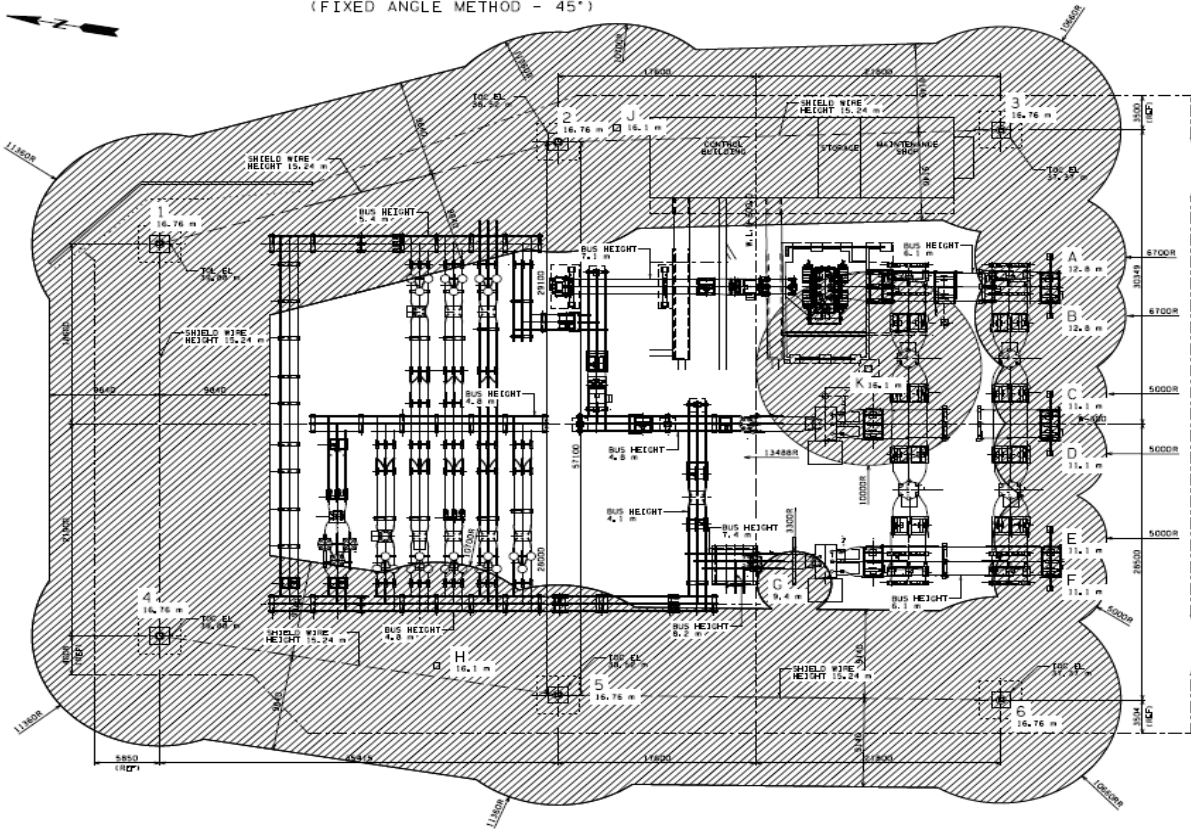


Figure 2: Lightning Shield Coverage Area,  $\alpha = 45^\circ$ ,  $\beta = 45^\circ$

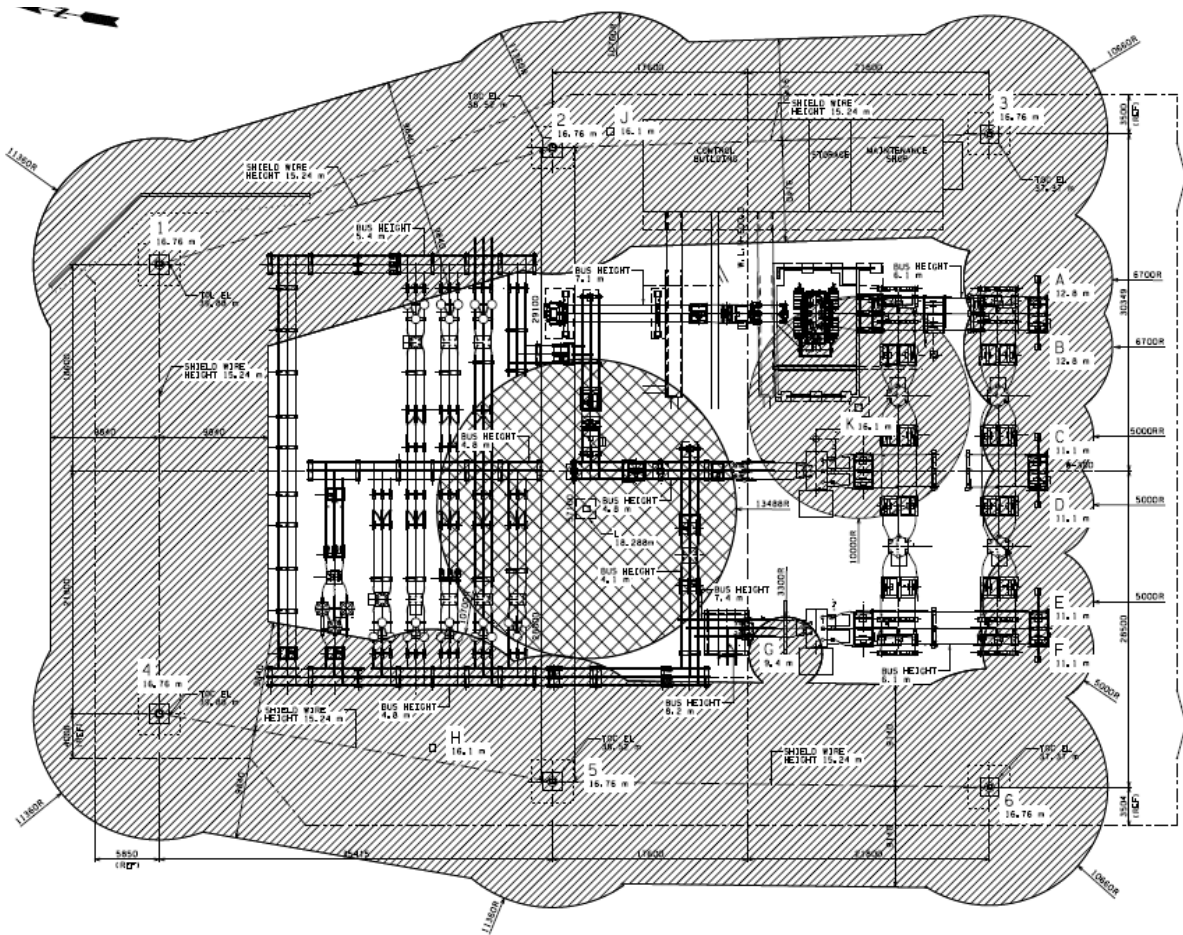


Figure 3: Lightning Shield Coverage Area,  $\alpha = 45^\circ$ ,  $\beta = 45^\circ$ , with a Lightning Mast

Table 1 shows the amount of unshielded area within the substation with two different scenarios.

Options	Coverage Area (m <sup>2</sup> )
Option 1: $\alpha = 45^\circ$ , $\beta = 45^\circ$ , with a lightning mast	1010
Option 2: $\alpha = 45^\circ$ , $\beta = 45^\circ$ , without lightning mast	1581

Table 1: Unshielded Area with Fixed Angle Method

### 3.0 Risk Evaluation

The risk of a direct strike to equipment associated with each lightning protection method is directly related to the lightning activity at the location, exposure rate of the selected scheme, and total equipment area being protected.

#### 3.1 Lightning Activity at the Location

Lightning activity is based on historical data and quantified as the ground flash density (GFD), which is the number of lightning strikes per square km per year. The Canadian Lightning Detection Network has been collecting data between 1999 to 2013. The GFD at the project site is:

$$N_K = 0.04 \text{ flashes/km}^2/\text{year} [3]$$

#### 3.2 Exposure Rate of the Selected Scheme

Without direct stroke lightning protection, the failure rate is determined by the number of flashes predicted to strike within the station area [1].

As shown in figure 4, the equipment area of the substation is 2930 m<sup>2</sup> or 0.002930 km<sup>2</sup> and thus the total expected strikes within the substation is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.002930 \text{ km}^2$$

$$X = 1.172 \times 10^{-4} \text{ flashes/year or } 8,532 \text{ years between flashes}$$

#### 3.3 Tolerable Risk for a Substation

IEC Standard 62305-2 – 2010 [5] identifies the tolerable risk  $R_T$  for a substation, where the risk level is affected by different types of losses. Referring to table 2, the risk level for a substation is defined in L2, loss of service to the public,  $R_T = 10^{-3}$  [4].

Types of loss		$R_T (y^{-1})$
L1	Loss of human life or permanent injuries	$10^{-5}$
L2	Loss of service to the public	$10^{-3}$
L3	Loss of cultural heritage	$10^{-4}$
L4	Loss of economic value	Cost/benefit comparison

*Table 2 – Typical Values of Tolerable Risk  $R_T$*

Based on the risk evaluation and low incidence of strikes in this region, the overall risk with the station unprotected can be kept within acceptable risk levels per IEC 62305-2.

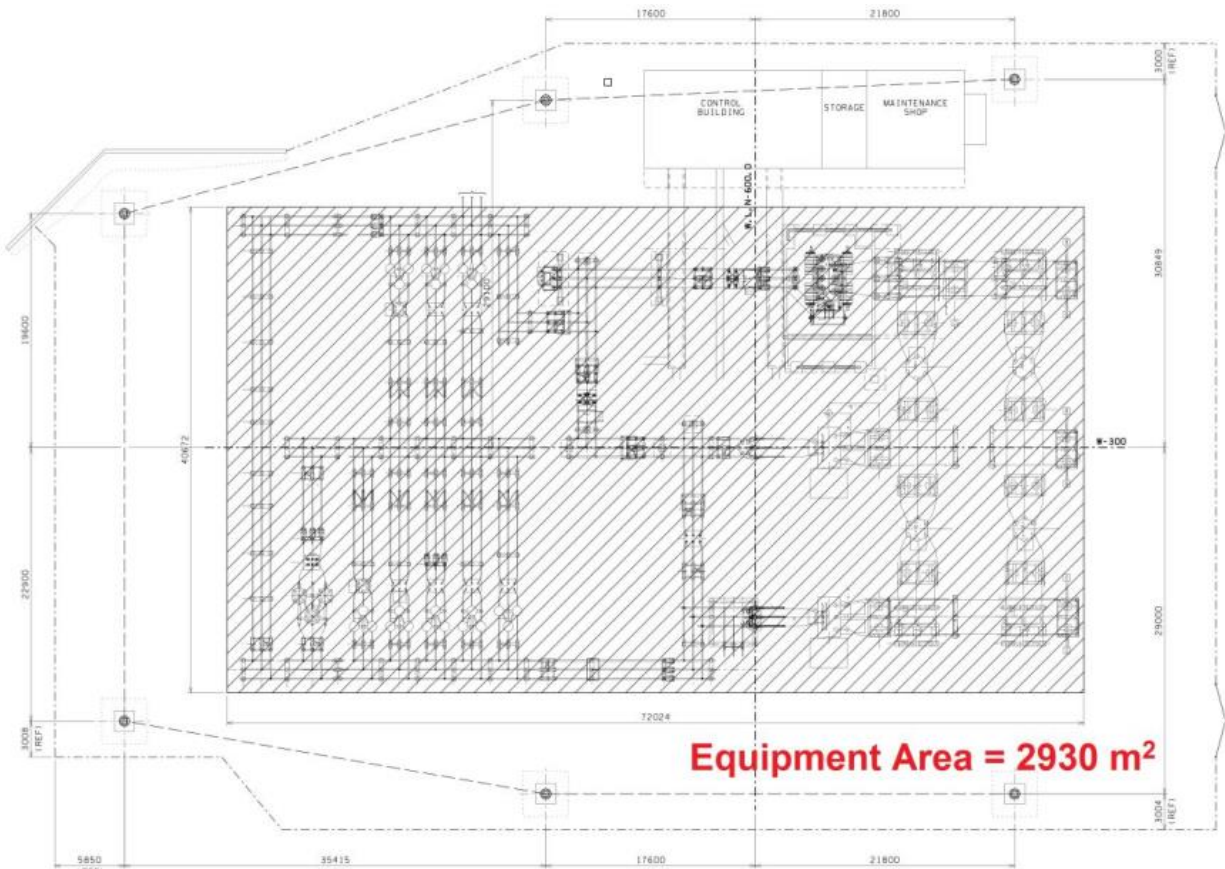


Figure 4: Substation Equipment Area

#### 4.0 Risk Evaluation for Each Method

##### 4.1 Rolling Sphere Method

The rolling sphere method is typically small with a 0.05% failure rate [1]. If masts and shield wires were installed as per the original design, the probability of a strike reaching the equipment or bus is:

$$X = 1.172 \times 10^{-4} \text{ flashes/year} \times 0.0005$$

$$X = 5.86 \times 10^{-8} \text{ flashes/year or } 17,064,846 \text{ years between flashes that strike the equipment or bus}$$

##### 4.2 Fixed Angle Methods

A normally accepted failure rate for  $\alpha$  and  $\beta = 45^\circ$  is approximately 0.2% [1]. Complete coverage using fixed angle with  $\alpha$  and  $\beta = 45^\circ$  results in the probability of a strike reaching the equipment or bus:

$$X = 1.172 \times 10^{-4} \text{ flashes/year} \times 0.002$$

$$X = 2.344 \times 10^{-7} \text{ flashes/year or } 4,266,211 \text{ years between flashes}$$

Since the fixed angle method design is based on the pre-determined location of lightning masts and surrounding shield wires that were selected based on the rolling sphere method, the station will be partially exposed.

#### **4.2.1 Risk Evaluation with an Additional Lightning Spire, Option 1**

Referring to figure 3, the unshielded area within the substation is 1349 m<sup>2</sup> and the shielded area is 1581 m<sup>2</sup>.

The probability of a lightning strike within the unshielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001349 \text{ km}^2$$

$$X = 5.396 \times 10^{-5} \text{ strikes/year}$$

The probability of a strike hitting the shielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001581 \text{ km}^2 \times 0.002$$

$$X = 1.265 \times 10^{-7} \text{ strikes/year}$$

Combining these probabilities, we have:

Total probability of strike =  $5.396 \times 10^{-5} + 1.265 \times 10^{-7} = 5.409 \times 10^{-5}$  strikes/year or 18,489 years between strikes.

#### **4.2.2 Risk Evaluation with Fixed Angle Method of $\alpha = 45^\circ$ , $\beta = 45^\circ$ only, Option 2**

Referring to figure 2, without the lightning spire, the unshielded area within the substation is 1920 m<sup>2</sup> and the shielded area is 1010 m<sup>2</sup>.

The probability of a strike hitting the unshielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001920 \text{ km}^2$$

$$X = 7.68 \times 10^{-5} \text{ strikes/year}$$

The probability of a strike hitting the shielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001010 \text{ km}^2 \times 0.002$$

$$X = 8.1 \times 10^{-8} \text{ strikes/year}$$

Combining these probabilities, we have:

Total probability of strike =  $7.68 \times 10^{-5} + 8.1 \times 10^{-8} = 7.69 \times 10^{-5}$  strikes/year or 13,007 years between strikes.



## 5.0 Comparison between Rolling Sphere Method and Fixed Angle Method

The rolling sphere method provides superior protection from strikes to the substation's equipment, however, the low historical GFD and the small equipment area mean there is a low anticipated frequency of strikes within the equipment area. The comparison proves that fixed angle method with  $\alpha$  and  $\beta = 45^\circ$  reduces the strike probability to a value which is several orders of magnitude below accepted values of  $R_T = 10^{-3} \text{ y}^{-1}$ .

Table 3 shows the comparison of failure rate among each method.

	IEC 62305-2 L3	No Lightning Protection	Lightning Protection - Rolling Sphere Method	Lightning Protection – Fixed Angle Method, Option 1	Lightning Protection – Fixed Angle Method, Option 2
Failure Rate ( $\text{y}^{-1}$ )	$10^{-3}$	$1.2 \times 10^{-4}$	$5.9 \times 10^{-8}$	$5.4 \times 10^{-5}$	$7.7 \times 10^{-5}$

*Table 3: Comparison of Failure Rates for Various Protection Methods*

### 5.1 Comparison between Fixed Angle Method Option 1 and Option 2

Option 1 offers greater lightning shielding coverage. However, the costs and construction risks of installing a 15.2 m tower inside the substation, together with the low incidence of strikes in this region makes option 2 more favorable.

Although option 2 has a higher probability of having lightning strike on the equipment or bus, the likelihood of such an event is still extremely small. Furthermore, one should also consider for the fact that most instances of a strike to equipment or bus would not lead to a full station outage if N-1 redundancy is available. Replacing the damaged equipment is likely the worst case scenario if lightning were to strike it.

Table 4 gives a comparison between these two options.

	Option 1 – New 60 ft. Spire	Option 2 – No Change to Existing Design, only perimeter masts and shield wires and existing internal spires
Pros	<ul style="list-style-type: none"> <li>• Greater station protection.</li> <li>• Lower probability of direct strike to equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Adequate station protection achieved (several magnitudes lower than IEC 62305-2)</li> <li>• Does not need to modify existing design</li> <li>• Have the option of using rolling sphere method should an outage be available during construction</li> <li>• No additional cost if rolling sphere method cannot be implemented during construction</li> </ul>
Cons	<ul style="list-style-type: none"> <li>• Installing the spire would require outages.</li> <li>• Increased congestion in the switchyard due to new spire</li> <li>• Construction costs and risks erecting spire near equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Higher probability of future strikes to equipment compared to option 1</li> </ul>

*Table 4: Comparison between Option 1 and Option 2*

**6.0 Conclusion**

The risk evaluations performed in this case study are useful for future projects. Fixed angle method may be suggested as a mean of lightning protection to the client where their facilities are located in areas with low incidence of lightning strikes.

This case study also serves as a good example of the considerations for upgrading lighting protection schemes within brownfield substations. It highlights the importance of preparing the construction staging plan in the early stages of projects. Being able to identify the availability of required outages allows the design team to ensure their design is constructible. Any modification due to unforeseen circumstances during construction often means the delay of schedule, as well as significant amount of costs.

It is also important to agree upon a minimum acceptable failure rate for substations with the owner and operator based on the substation size and importance of the station to help determine the overall required system protection levels. This allows alternative lightning protection design methods, such as the fixed angle method, to be considered.

## 7.0 References

- [1] “IEEE Guide for Direct Lightning Stroke Shielding of Substations,” IEEE Std. 998-2012, 2012.
- [2] Horvath, T., Computation of Lightning Protection, Taunton, Somerset, England: Research Studies Press, 1991.
- [3] “Lightning Activity in Canadian Cities,” 4 July 2013. [Online]. Available: <https://ec.gc.ca/foudre-lightning/default.asp?lang=En&n=4871AAE6-1>.
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- [5] “IEC International Standard, Protection Against Lightning – Part 2: Risk Management,” IEC 62305-2, Edition 2.0, 2010-12.