Refurbishment & Upgrading Design Options – Lightning Masts versus Overhead Shielding Conductors

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***ABSTRACT* — Failure of overhead shield conductors in substations can result in costly plant damages and lengthy supply outages. From an international perspective, such a rare event has been witnessed within New Zealand resulting in thorough investigations into the cause and mitigation thereof. Configuring substation overhead earthconductors to eliminate busbar crossings or avoiding plant clearance reduction should an overhead shielding conductor fall is highly improbable. Possible mitigation is the replacement of existing overhead earthconductors with lightning masts.**

Risk assessments rely on the probability of lightning strikes. Accurate probability estimates of lightning strikes can be made using site-specific, ground-flash density values that are based upon actual recordings of lightning data. However, results only provide an *indication* of lightning strike return frequency and these results cannot be considered as absolutes. Their most useful function is in determining the relative effects of lightning protection design changes made in the refurbishment of substations.

The change from overhead shielding conductors to lightning masts must effectively utilise the existing steel support structures and gantries. These structures although providing a base for attachments heights, do limit the overall design and layout of masts. Considering this, design options include the "rolling sphere method".

***Index Terms* — lightning discharge current, Lightning masts, overhead shielding conductors, air terminals, laser induction, radioactive induction and grounding system.**

I. INTRODUCTION

Conventional lightning protection systems for ground-based structures provide lightning attachment points. It is anticipated that each of these attachment points will provide a predetermined path for the lightning discharge current to flow from the attachment points into the ground without harm to the plant or equipment that it is intended to protect.

Such protective systems are basically composed of three elements:

- Air terminals at appropriate points on the structure to intercept the lightning,
- Down conductors to carry the lightning current from the air terminals toward the ground.
- Grounding electrodes to pass the lightning current into the earth.

The above three system components must be both electrically & mechanically connected to form an effective lightning protection system.

This paper reviews the first of these components: air terminals. Furthermore it briefly discusses the mechanism of lightning, shielding design methods, shielding design criteria, cost considerations, demographic considerations, maintenance, risks and alternative lightning protection systems.

The electrical system is susceptible to ground faults, lighting and switching surges that may result in high voltage which can constitute a hazard to site personnel and electrical equipment, including protective relaying equipment. The substation will be designed and constructed to have a robust grounding grid which will divert stray surges and faults.

II. Background

A lightning strike begins with a stepped leader, a low-power stroke that progressively propagates downward toward the ground in discrete steps, of about 50 m in length for each step. At this stage the stepped leader traverses a path to ground without regard to local terrestrial features until it reaches within about 10–100 m of the earth or the top of an above ground structure.

At that stage, a more powerful return stroke emanates from ground, meeting the stepped leader. The electrical circuit is then completed, and several repetitive strokes flow along the established path.

Only within 10-100 m of the ground do the geometry and electrical characteristics of the ground and structures affect the lightning's striking point. Because lightning is a high-frequency phenomenon, it is not simple to predict its behavior. An acute change in direction of a ground conductor may create high-frequency impedance that diverts the current to another and less obvious path.

In the absence of a predetermined path, lightning strikes will be attracted to many earth-bound conductors. In substations lightning masts or overhead shielding conductors reduce the probability of strikes to multiple paths such as steelwork and phase conductors. The method of lightning protection does not eliminate the possibility of a strike but it does provide a lower risk of damage path to ground.

Charge dissipation terminals mitigate direct lightning strikes by dissipating the charge of static electricity into the atmosphere through the process of ionization (point discharge principle). This affects the region within the 10 – 100 m as discussed above. The process of dissipation effectively lowers the probability of streamers forming in time to be first to complete the path of the lightning strike, as static electrical charges build between the lower portion of a storm cloud and the opposite charges on earth and structures.

An effective lightning protection design is challenged by the following facts:

- The unpredictable and probabilistic nature of lightning,
- cost of detailed engineering and cost analysis,
- lack of meaningful data due to the low occurrence of direct lightning strikes to substations,
- currently no known system that provides 100% lightning protection.

The choice of design between masts or overhead shield conductors is primarily based on security of supply. Masts are incorrectly perceived to be safer than overhead shield conductors from a failure perspective. *Figure 1: Traditional lightning mast protecting substation from lightning* illustrates a similar lightning mast that suffered mechanical failure in Baltimore Gas and Electricity (BGE) Co. during September 2000.

Figure 1: Traditional lightning mast protecting substation from lightning

III. Shielding Design Methods

Common design methods include, but are not limited to:

- Fixed shielding angle
- Wagner’s 1942 Method
- Lee’s Rolling Sphere Method
- Mousa’s 1976 EGM Method

Geometrical methods assume that the neither the overhead conductor or the mast can intercept all of the lightning strokes arriving over the subject area if the shielding device maintains a certain geometrical relation (separation & differential height) to the protected object.

Electrogeometric methods recognise that the attractive effect of the shielding device is a function of the amplitude of the current of the lightning stroke. Thus, for a given shielding geometry, some of the less intense strokes would not be intercepted by the shielding system & may terminate instead on the live bus or other protected object. The way to accomplish "effective shielding" in this case is by limiting penetration of the shielding system to only those strokes which would not flashover the insulation or would not damage the protected object.

IV. Shielding Design Criteria

From a design perspective, there are different engineering software and calculation tools available to determine the effectiveness of each of the two options. It is advisable that each option for each separate case be investigated. What is not applicable for a particular case may be applicable for other cases. The diversity of various substation designs requires individual studies. This can be illustrated in *Figure 2: Low profile substation (Source: POWERTEAM Electrical Services).*

Figure 2: Low profile substation (Source: POWERTEAM Electrical Services)

Traditional designs are based on heavy gantries or "column and beam" structures as illustrated in *Figure 3: ABB HPL & LTB SF_6 circuit-breaker with integrated disconnector function (Source: POWERTEAM Electrical Services).* These structures provided the necessary mechanical anchorage and electrical clearance for applying overhead shield conductors for lightning protection.

However, what is crucial is the correct anchorage of the conductors. Often conductors were support by means of "D-shackles" without through bonding. This type of termination provides a limited area for electrical contact. Due to circulating currents the contact area erodes the galvanizing coating away. Once this occurs there is an accelerated aging effect and the shackle suffers mechanical failure.

Figure 3: ABB HPL & LTB SF_6 circuit-breaker with integrated disconnector function (Source: POWERTEAM Electrical Services)

V. Cost Considerations

Cost considerations of the two methods do differ. Generally for refurbishment projects, new retrofit designs are constrained in innovation by the existing plant, substation layout and location of steelwork. From a cost advantage point of view, and where possible, existing steelwork and any overhead shielding conductors should be retained during the redesign of the substation.

In comparison, new substation designs offer more opportunities regarding the layout of the substation and the type of equipment specified. In this regard modern electrical plant offers a reduced footprint for the substation layout. Such a reduced space requirement may well necessitate the application of lightning masts.

An example of reducing space requirement is the application of a circuit-breaker with integrated disconnector function as illustrated in *Figure 4: ABB HPL & LTB SF_6 circuit-breaker with integrated disconnector function.*

Figure 4: ABB HPL & LTB SF_6 circuit-breaker with integrated disconnector function

A further development of space reduction is the combination of a circuit breaker, current transformers, disconnectors and earth switches known as the “PASS MO” from ABB – see *Figure 5: PASS MO from ABB.*

Figure 5: PASS MO from ABB

The advantages that compact designs offer have to be weighed against their disadvantages for extendibility during possible future substation upgrading and maintainability.

VI. Demographic Considerations

Although not requiring large areas of land, transmission substations are generally constructed on land that has limited commercial or societal use. These are generally on hilltops or ridgelines. The incidence of the number of lightning strikes is expected to be higher in these higher topography areas. Due consideration must be made in geographical areas with established average annual lightning ground flash densities (e.g. those illustrated in Figure 2.3 & 2.4 of *AS/NZS 1768-2007 Lightning Protection*).

It is the design engineer’s prerogative to factor in the risk of an increase in lightning ground flash density.

VII. Maintenance Considerations

Masts are no more reliable from a lightning protection point of view than overhead shielding conductors and records do reveal that the mechanical failure of masts has occurred. The reliability and performance of overhead shielding conductors are dependent on correct bonding practices as well as appropriate maintenance practices which include routine visual inspections.

Damage to either lightning protection system can be defined as a reduction of its load-bearing capacity. Structures and conductors incur damage from environmental loadings such as wind, snow, and ice. In addition, rain and moisture cause steel structures to corrode. Both overhead shield conductors and masts do require inspection and maintenance. In this regard different condition monitoring techniques are applicable to both masts and overhead shielding conductor installations.

Visual inspections are applicable to both systems. However, each offers their own challenges regarding visual inspections. Unless masts are hinged at the base visual inspections to the top end of masts are difficult when compared to steelwork that can be climbed in the case of overhead shield conductors.

Thermal monitoring is applicable to overhead shield conductors and this form of condition monitoring is effective in detecting damaged conductors. However, this method of condition based monitoring is not applicable to masts.

Masts require special non destructive conditioning monitoring techniques. These include:

- Penetration, methods.
- Magnetic particle analysis.
- Eddy current measurement.
- Ultrasonic measurement.
- Radiographic testing.

Although each with their own merits, they have distinct limitations when testing large lightning masts.

These limitations include the following:

- They have limited depth of penetration.
- The general location of the damage must be identified or otherwise the whole structure requires testing.
- There is no way to easily determine the health of the structure at the boundaries and joints.

To address the limitations of the above, vibration-based condition monitoring techniques have been developed. These techniques use the changes in natural frequencies and/or mode shapes to detect damage and can avoid the above limitations. These require specialist skills making the overhead shield conductor method a more favourable option for maintenance compared to masts.

VIII. RISK

Risk assessments rely on the probability of lightning strikes. Accurate probability estimates of lightning strikes can be made using site-specific, ground-flash density values that are based upon actual recordings of lightning data. However, results only provide an *indication* of lightning strike return frequency and these results cannot be considered as absolutes. Their most useful function is in determining the relative effects of lightning protection design changes made in the refurbishment of substations.

The standard *AS/NZS 1768-2007 Lightning Protection* provides a procedure for risk assessment and the management for lightning protection (see Section 2.6). The current in the lightning discharge is the potential source of damage. In this Section, the following sources of damage, relating to the proximity of the lightning strike, are taken into account (see Table 2.3 of *AS/NZS 1768-2007*):

- S1: direct strike to the structure.
- S2: strike to the ground near the structure.
- S3: direct strike to a conductive electrical service line.
- S4: strike to ground near a conductive electrical service line.

S1 relates to direct strikes to the substation while S3 relate to the direct strikes to the overhead line shielding conductor connected to the substation. In the later case the discharge current propagates along the overhead shield conductor towards the substation.

Where masts are provided for lightning protection, the discharge current is conducted to earth via the terminal gantry. The discharge current is high and depends on the proximity of the strike to the overhead line, the current magnitude and the substation earth grid impedance.

Where overhead shielding conductors are installed, the discharge current distributes itself over the entire substation earthmat thereby reducing the single entry discharge current magnitude.

Although the standard does not specifically compare the application of masts and shielding conductors, it provides a common approach to determine the zones of protection. This is calculated by means of the rolling sphere method. The interception currents are based on IEC documentation.

Some structures are inherently more or less at risk of being struck by lightning. Amongst other factors, the risk for a structure is a function of the size (area) of a structure, the height, and the number of lightning strikes per year per km² for the region.

IX. ALTERNATIVE PROTECTION METHODS

The evolution of the Franklin lightning rod has witnessed the development of modern day devices employing a point discharge phenomenon or early streamer emission. However, their application has been mainly focused on the protection of communication towers and tall structures; and not substations.

The aim of early streamer emission type air terminals is to provide a wider coverage area than traditional Franklin rods. The basic theory utilized is the idea that if an upwards step leader were able to be produced before any would naturally occur on a structure, this early step leader would be able to travel higher and be much more likely to intersect the downward step leader. By initiating a controlled step leader before any naturally occur; early streamer emission systems should be able to direct the main lightning stroke to a small number of lightning rods on a structure. Early streamer emission systems can be regarded as charge transfer systems that claim to eliminate the charge buildup on a structure by transferring it to the surrounding area. The intent is to therefore eliminate the potential for a lightning strike. This method is based on the same concept that prompted Benjamin Franklin to invent the lightning rod. Both masts and shielding conductors are based on this principle.

Numerous documents have been written questioning the effectiveness of early streamer emission systems and that they have never been scientifically proven. Such studies indicate that the zone of protection provided by an early streamer emission lightning protection system is similar to the traditional lightning rod.

In addition to the above radioactive and laser induced systems have been developed. Radioactive protection systems main distinguishing feature from traditional Franklin type systems is the application of radioactive materials in the lightning rods. The theory of this is that the radioactive properties of the rods will ionize the air surrounding the lightning rod sufficiently to increase the probability of that rod being struck, rather than the structure or plant itself. As a result this would increase the zone of protection provided by the lightning rod. However, the effectiveness of radioactive lightning protection is no more effective than that of regular lightning rods. This is because the radioactive materials are only able to ionize air around the lightning rod for a short distance resulting in no increase in the probability of it being struck.

Laser induction of lightning strikes is currently being researched. The main principle of laser induction is that a sufficiently powerful and correctly tuned laser will ionize the air between the clouds and ground level. This ionization will reduce the breakdown voltage of the air and provides a lower resistance path for the lightning. Effectively this acts as a lightning rod tall enough to reach the clouds. So far, scientists have only been able to trigger lightning activity in the clouds and have not been able to induce a cloud-to-ground strike.

In addition to the above methods of lightning protection, lightning masts composed of a combination of polymer and glass fiber reinforcement materials are available. These masts are corrosion-resistant and designed to withstand environmental, chemical, and temperature extremes. Such devices are illustrated in *Figure 6: Glass fibre lightning mast.*

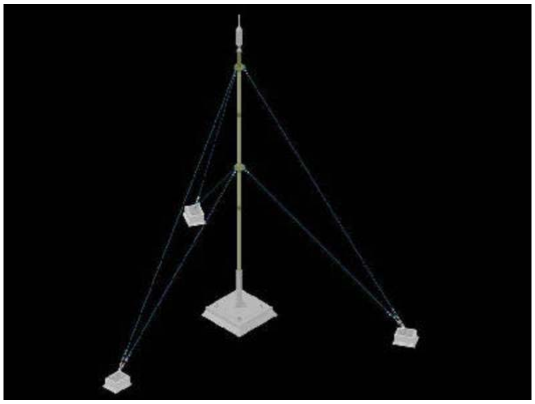

Figure 6: Glass fibre lightning mast.

X. CONCLUSION

Lightning protection must be viewed holistically and although this paper focuses on the installation of shielding devices, other important mitigation measures effecting lightning protection include effective earthing, surge arresters and protection systems. The paper concludes by confirming that overhead shield conductors are effective and reliable lightning protection practices, as well as cost effective and should not be replaced in existing substations with lightning masts. A different approach may be adopted in the design of new substations where the designer is not restrained by an existing substation layout. In this case lightning masts would be considered but not preferred. If the concept of early streamer emission is promoted, then overhead shielding conductors do provide a larger area for such emissions to occur.

Masts are no more reliable from a lightning protection point of view and records do reveal that the mechanical failure of masts has occurred. The reliability and performance of overhead shielding conductors are dependent on correct bonding practices as well as appropriate maintenance practices which include routine visual inspections. From a design perspective, the different engineering software and calculation tools are reviewed to determine the effectiveness of each of the two options.

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