Rationale

The EGM, first introduced by Whitehead in the late 1960’s, links two important parameters of the lightning stroke to an earthed structure, namely the prospective peak stroke current, $I_p$, and the striking distance, $S$. The empirical relationship obtained for $S$ using the downward leader charge and the electric field for air breakdown to link it to the stroke current, is often called the “simple EGM” and is given by

$$ S = 10 I_p^{0.65} $$

(1)

where $S$ is in metres and $I_p$ is in kA. The significance of the striking distance for the attachment process is that if a downward leader tip gets within a distance $S$ from a point on a building, and that point is capable of launching a connecting upward leader, then that point will be the one to which the lightning channel connects. In other words, the striking distance quantifies the range of capture of a strike for a given peak current.

A review of the literature reveals that the commonly used striking distance relation (Eq. 1) appears to rely heavily on only two observational data points from K. Berger’s measurements ($S = 27$ m for $I_p = 16$ kA and $S = 37$ m for $I_p = 27$ kA), and so it mostly relies on a theoretical analysis. More importantly, Eq. (1) is overly simplistic in that it does not consider the varying field enhancement effects of structure height or geometry, or the streamer and leader inception criteria.

Hence, in the 1980’s, Eriksson (1987) proposed, and validated with field data, a striking distance model that also took into account the electric field enhancement effects created by the structure, i.e.,

$$ S = f(I_p, H) $$

(2)

Hence, the “improved EGM” was the next natural step after further research was carried out on the lightning attachment process.

Eriksson considered the approach of a linearly charged downward leader (or downward leader branch) and evaluated the electric field strength developed at the top of the structure and at the ground below the leader. The structure in his original analysis was a 60 m high “research tower”. When the ambient electric field is of sufficient strength, i.e., downward leader sufficiently close to the structure, an upward leader will be initiated from the structure. The distance between the downward leader tip and the upward leader initiated at this instant is defined as the striking distance.

Eriksson found that the attachment of lightning to a structure is not only determined by the striking distance but also the successful interception of the downward leader by the upward leader. Hence, the interception process was found to depend on the structure height, the relative positions of the two leaders and their relative velocities of approach.

Using this physical model, Eriksson defined the capture distance as the “attractive radius”, $R_a$. This concept is illustrated in Fig. 1. Note that the magnitude of the attractive radius is, in general, always less than the magnitude of the striking distance, hence the attractive radius concept provides a more conservative result.

For vertical structures up to 60 m in height, Eriksson defined the attractive radius as

$$ R_a = 0.84 H^{0.6} I_p^{0.74} $$

(3a)

For horizontal conductors and lines up to 60 m in height, the attractive radius is given by

$$ R_a = 0.67 H^{0.6} I_p^{0.74} $$

(3b)
Using the attractive radius, the "collection area" of the structure can be computed. This is useful for applying the concept of "competing features". It is well known that all structures within a facility, such as a substation, are capable of initiating upward leaders and hence intercepting a lightning stroke. Hence, an attractive radius should be computed for each part of the facility in addition to the protective air terminations, lines and masts. As long as the collection areas of the protective elements encompass those of the elements to be protected, the facility is said to be protected at the predetermined level. This is illustrated in Fig. 2.
With regard to protection levels, these are determined from a standard cumulative frequency distribution of lightning stroke currents such as the one shown in Fig. 2.4 of IEEE 998 (1996). Furthermore, following the logic in Section 5.2.2 of IEEE 998, insulator BIL levels can be equated to the minimum stroke currents that will be intercepted. Table 1 presents the relevant information.

Table 1: Examples of protection level correspondence to BIL’s.

<table>
<thead>
<tr>
<th>BIL (kV)</th>
<th>(I_p) (kA)</th>
<th>Protection level</th>
<th>(S) (m)</th>
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</tr>
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<tbody>
<tr>
<td>110</td>
<td>0.81</td>
<td></td>
<td>7.6</td>
<td>25.1</td>
</tr>
<tr>
<td>150</td>
<td>1.10</td>
<td></td>
<td>9.5</td>
<td>30.7</td>
</tr>
<tr>
<td>200</td>
<td>1.47</td>
<td></td>
<td>11.3</td>
<td>37.0</td>
</tr>
<tr>
<td>250</td>
<td>1.83</td>
<td></td>
<td>13.1</td>
<td>42.8</td>
</tr>
<tr>
<td>350</td>
<td>2.57</td>
<td></td>
<td>16.2</td>
<td>53.3</td>
</tr>
<tr>
<td>395</td>
<td>2.90</td>
<td>99%</td>
<td>17.7</td>
<td>57.7</td>
</tr>
<tr>
<td>550</td>
<td>4.03</td>
<td></td>
<td>21.6</td>
<td>71.5</td>
</tr>
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<td>650</td>
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<td>24.4</td>
<td>79.7</td>
</tr>
<tr>
<td>750</td>
<td>5.50</td>
<td>97%</td>
<td>26.5</td>
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</tr>
<tr>
<td>818</td>
<td>6.00</td>
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<td>28.3</td>
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<td>38.1</td>
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<tr>
<td>1364</td>
<td>10.00</td>
<td>91%</td>
<td>39.7</td>
<td>129</td>
</tr>
</tbody>
</table>

As an example, for an insulator BIL of 750 kV, Table 1 implies that 97% of all lightning flashes have a peak stroke current exceeding 5.5 kA and will be intercepted. The remaining 3% of low-energy strikes may bypass the lightning protection system. This is part of the risk management process that is implemented when designing any lightning protection system.

Even though Eriksson’s improved EGM was developed back in the 1980’s, all of the research since that time has supported the fact that the striking distance is not only a function of the prospective stroke current but also the structure height. Readers are referred to the papers of Dellera & Garbagnati (1990), Rizk (1994a,b), Petrov & Waters (1995), Lalande et al (1998), Ait-Amar & Berger (2005), Kumar et al (2005) and Becerra & Cooray (2006) for further detailed information. For example:

- In Dellera & Garbagnati (1990), p.2014, the computed lateral distance for a 30 kA discharge increases from ~ 25 m to ~ 130 m for free-standing structure heights from 10 to 80 m;
- In Rizk (1994a,b), Fig. 1, the computed attractive radius for a 31 kA discharge increases from ~ 60 m to ~ 240 m for mast heights from 10 to 200 m;
- In Petrov & Waters (1995), Table 2 makes a comparison with three other models (Eriksson, Rizk and Dellera & Garbagnati), all of which show an increase in striking distance or attractive radius with structure height;
- In Bondiou-Clergerie et al (1999), Fig. 6, and also in Lalande et al (2002), the critical ambient field needed for stable leader propagation is a function of structure height. For example, for a 100 m structure, continuous leader propagation occurs in an ambient electric field of only ~ 30 kV/m.

Finally, a comment should be made about the revised EGM of Mousa & Srivastava (1989), i.e., to use \(S = 8 k I_p^{0.65}\) as a basis, where \(k = 1\) for the ground plane or wires and \(k = 1.2\) for masts and towers. The use of the coefficient \(k\) is clearly an acknowledgement that the striking distance does in fact vary with the height and/or geometry of the prospective strike point. The values assigned to \(k\) are entirely empirical and may only be valid for certain line and mast heights. In their paper, the authors stated that \(k\) is valid “for moderate height masts” and has a strong effect on the predictions of the EGM. Furthermore, they state the values for \(k\) are based on laboratory data and that “no tests are needed to verify the proposed model”. Consequently, in Mousa & Srivastava (1989), where the concept was proposed for the first time in a refereed publication, it attracted criticism from two leading Italian researchers (Carrara & Dellera) who said they “... agree with the idea, provided .... based on physical aspects ....”. The point is that a fixed value of \(k\) will never provide the opportunity for the optimised designs that are often required when protecting substations.
In summary, the improved EGM takes into account the dependence of striking distance on current amplitude and structure height. In this way, optimised designs can be made, based on the height of the masts and conductors used for the shielding of substations against lightning. Furthermore, whilst traditional methods such as the simple and revised EGM's are based on a “final jump” scenario (strike point is determined, more or less, only by physical distance), the newer models, beginning with the pioneering work of Eriksson in developing the improved EGM, take into account the well-known “leader propagation” characteristics of the lightning attachment process. These concepts are illustrated in Fig. 3.

![Image of a lightning strike](image_url)

**Figure 3:** Illustration of the fundamental difference between the traditional methods such as the simple and revised EGM's and the newer models that are based on more physical criteria.

**References:**


Outline of Proposed Changes

1.1 Scope
Change point (b) to read as follows:

b) The simple, revised and improved electrogeometric models.

5.1.2 Recent improvements in the EGM
Change the title to read "5.1.2 Improvements of the EGM", since the described improvements are hardly "recent" any longer.

5.1.3 Criticism of the EGM
Delete this subsection title and include the following paragraph as the second paragraph of Subsection 5.1.2 above:

Work by Eriksson reported in 1978 [B27] and later work by Anderson and Eriksson reported in 1980 [B5] revealed a number of discrepancies in the simple EGM. Mousa [B67] has addressed some of the discrepancies in his "revised EGM", described in Section 5.2. One of the significant corrections is the use of empirical K factors to make allowance for the differing geometry of lines and masts. Eriksson's "improved EGM", described in Section 5.3, uses a striking distance relation with a more physical basis to account for differences in geometry and height above ground.

5.2 A Revised EGM
Change the title to read "5.2 The Revised EGM".

Renumber sections 5.3, 5.4 and 5.5 to become 5.4, 5.5 and 5.6 respectively.

Insert a new Section 5.3 as follows:

5.3 The Improved EGM

Since the striking distance quantifies the range of capture of a strike, Eq. (5-1A) is overly simplistic in that it does not consider the varying field enhancement effects of structure height or geometry, the streamer-leader inception criteria and, thereafter, the leader propagation effects.

Hence, after extensive research, Eriksson (1987a,b) proposed, and validated with field data, a striking distance model that also took into account the dependence on structure height, namely,

\[ S = f (I_p, H) \]  

(2)

Hence, the "improved EGM" was the next natural step resulting from detailed research carried out on the lightning attachment process.

Eriksson found that the attachment of lightning to a structure is not only determined by the striking distance but also the successful interception of the downward leader by the upward leader. Hence, the interception process was found to depend on the structure height, the relative positions of the two leaders and their relative velocities of approach.

Using this physical model, Eriksson defined the capture distance as the "attractive radius", \( R_a \). This concept is illustrated in Fig. 5-1. Note that the magnitude of the attractive radius is, in general, always less than the magnitude of the striking distance, hence the attractive radius concept provides a more conservative result.

For vertical structures up to 60 m in height, Eriksson defined the attractive radius as

\[ R_a = 0.84 H^{0.6} I_p^{0.74} \]  

(5-5a)

For horizontal conductors and lines up to 60 m in height, the attractive radius is given by

\[ R_a = 0.67 H^{0.6} I_p^{0.74} \]  

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Using the attractive radius, the "collection area" of the structure can be computed. This is useful for applying the concept of "competing features". It is well known that all structures within a facility, such as a substation, are capable of initiating upward leaders and hence intercepting a lightning stroke. Hence, an attractive radius should be computed for each part of the facility in addition to the protective air terminations, lines and masts. As long as the collection areas of the protective elements encompass those of the elements to be protected, the facility is said to be protected at the pre-determined level. This is illustrated in Fig. 5-2.

**Figure 5-1:** Eriksson's improved EGM.

**Figure 5-2:** Example of application of concept of competing features and collections areas to a substation using Eriksson's improved EGM.
With regard to protection levels, these are determined from a standard cumulative frequency distribution of lightning stroke currents such as the one shown in Fig. 2.4. Furthermore, following the logic in Section 5.2.2, insulator BIL levels can be equated to the minimum stroke currents that will be intercepted. Table 5-1 presents the relevant information.

As an example, for an insulator BIL of 750 kV, Table 1 implies that 97% of all lightning flashes have a peak stroke current exceeding 5.5 kA and will be intercepted. The remaining 3% of low-energy strikes may bypass the lightning protection system. This is part of the risk management process that is implemented when designing any lightning protection system.

Even though Eriksson’s improved EGM was developed back in the 1980’s, all of the research since that time has supported the fact that the striking distance is not only a function of the prospective stroke current but also the structure height. Readers are referred to the papers of Dellera & Garbagnati (1990), Rizk (1994a,b), Petrov & Waters (1995), Lalande et al (1998), Ait-Amar & Berger (2005), Kumar et al (2005) and Becerra & Cooray (2006) for further information.

In summary, the improved EGM takes into account the dependence of striking distance on current amplitude and structure height. In this way, optimised designs can be made, based on the height of the masts and conductors used for the shielding of substations against lightning. Furthermore, whilst traditional methods such as the simple and revised EGM’s are based on a “final jump” scenario (strike point is determined, more or less, only by physical distance), the newer models, beginning with the pioneering work of Eriksson in developing the improved EGM, take into account the well-known “leader propagation” characteristics of the lightning attachment process. These concepts are illustrated in Fig. 5-3.

### Table 5-1: Examples of protection level correspondence to BIL’s.

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</table>
Figure 5-3: Illustration of the fundamental difference between the traditional methods such as the simple and revised EGM's and the newer models that are based on more physical criteria.

References for Section 5.3:


Add the above references to the Bibliography (Section 7) and renumber accordingly.
6. Active lightning terminals

1. Change the title of this section to read “6. Improving lightning interception”.
2. Create a Sub-section heading entitled “6.1 Active lightning terminals”.
3. Delete the second last paragraph of the active lightning terminals section, i.e., “Some of the latter devices ....”, since it appears to endorse the devices listed in (c).
4. Add a new Sub-section 6.2, as follows:

6.2. Importance of air terminal geometry

The following comments relate to the use of vertical rod air terminations and slender masts for the shielding of substations against lightning strokes.

Research carried out over the last decade has shown that air terminal geometry is an important factor in the interception of a lightning stroke. As noted in A.4.6.2 of NFPA 780-2004, the field experiments of Moore et al [2000a,b,2003] suggest that the optimum tip radius of curvature of a vertical rod air terminal used for interception of lightning strokes is between 4.8 and 12.7 mm.

The rods used in the above study were mounted at a fixed height of about 6 m above the ground. In a numerical modelling study carried out using the results and concepts described in Moore et al, D'Alessandro [2007] has shown that it is possible to compute the "optimum" tip radius of any lightning rod installed as a free-standing mast or on a structure of any given dimensions. The results of the study show that the optimum tip radius has a significant dependence on the rod length (height above ground) and, if installed on a structure, the dimensions of the structure. In general, the additional electric field intensification created by mounting rods on masts and other structures, particularly when they are positioned near edges and corners of extended structures, means that the tip radii required for optimum effectiveness are larger than their counterparts on the ground surface.

References for Section 6.2:


5. Add the above references to the Bibliography (Section 7) and renumber accordingly.