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Comparison of Striking Distance Formulae and Their Effect on Lightning Shielding Analysis

김 성 삼*
(Sung-Sam Kim)

Abstract - This paper compares the performance of lightning shielding analysis methods using the seven striking distance formulae in substation. For comparison, we evaluate the number of expected strikes and exposed area using WinIGS Software. Seven striking distance formulae are compared using the electrogeometric model analysis and the rolling sphere method. Based on the electrogeometric model analysis, the risk of shielding failure in either the whole substation or parts of it is determined. According to the simulation results, one can justify whether the substation satisfies the criterion of shielding design. In particular, according to the rolling sphere method, the exposed areas in substation determine the location of the additional shielding poles or shield wires. Therefore, the installation of the additional shielding poles and shield wires in substation was accepted by shield design at the phase conductors exposed in the larger area.

Key Words : Lightning, Lightning shielding analysis, ElectroGeometric Model, Striking distance

1. Introduction

Electric power installations are subject to lightning, lightning overvoltages, and the associated risk of damage or disruption. A lightning strike to electric power installations is a crucial problem for electric power transmission [1], [2]. The efficiency and performance of lightning shielding systems, which consist primarily of shielding masts and overhead earthwires, against direct strikes is of primary importance in the design of lightning protection of critical structures. Most of the existing lightning shielding theories are based on an electrogeometric model (EGM) [3], [4]. The EGM estimates the point at which lightning current terminates based on striking distance. The striking distance is defined as the length of the final leg of the stroke current which establishes contact with a ground object. The striking distance is of the form [3]

$$S = A * Ib \tag{1}$$

where A and b are constants that depend on the object; I is the stroke current. Several researchers, notably Wagner et al.,[5] - [7], Young et al.,[8], Armstrong and Whitehead[3], Brown and Whitehead[4], Love[9], and Mousa[10] - [12], have contributed to the EGM of the last step or striking distance of the lightning flash. According to the estimate, they have also provided different values of A and b[4],[9],[13] - [16]. Consequently there are seven striking distance formulae internationally. The model names of the seven striking distance formulae are Brown and Whitehead, IEEE, Erikson, Darveniza, Love, Suzki.et al, and Rizk. Generally, the IEEE standard is used. However, there are no any cases that compare the striking distances formulae using programs or simulations. This paper compares performance of the lightning shielding analysis methods using the seven striking distance formulae in a real substation. For comparison, we estimate the number of expected strikes and exposed area using WinIGS Software [17]. The program WinIGS performs analysis and design of a grounding system or multiple grounding systems that are an integral part of an electric power system. The lightning shielding analysis methods which are used are: the EGM analysis and the rolling sphere method(RSM). The EGM analysis compares the total number of expected strikes at four specific places of the substation using the seven striking distances formulae. The RSM estimates the exposed area and the exposed paths according to the setting value of lightning current in the seven striking distance formulae.

* 정 회 원 : Georgia Institute of Technology 박사후 연구원
E-mail : skim477@gatech.edu
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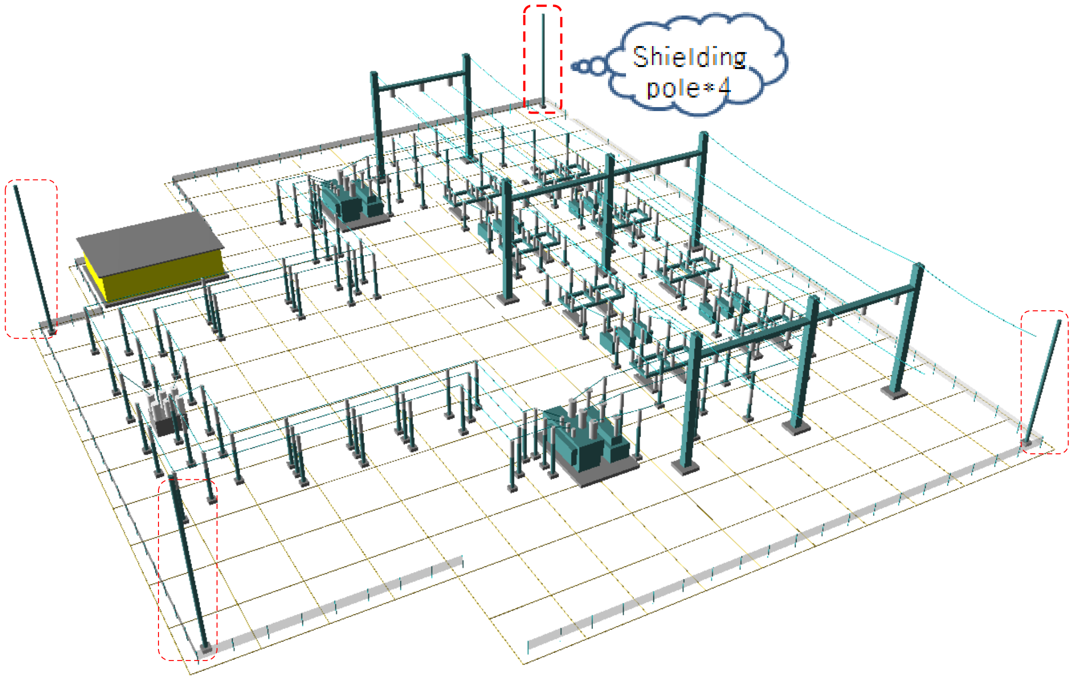


Fig. 1 3-D model of a substation.

Visualization techniques based on animated 3-D graphics are used to demonstrate the results. Therefore, based on the simulations, we consider the result, and estimate the improvement.

2. Description of simulation system

Shielding of direct lightning strikes is an important aspect of power system safety analysis. Theories of lightning behavior and striking distance formulae and their effect on lightning shielding analysis are investigated as are the effects of lightning and the role of specific grounding system designs. The analytical method used in this investigation is based on a 3-D implementation of the EGM of the lightning strike and shielding system configuration together with the structures that need to be protected. Also, several different design methods for the shielding of direct lightning strikes are used worldwide; the RSM is one of the most widely used methods and is suggested by IEEE Std 998-1996[18]. A well known analysis technique used for lightning shielding design is the EGM and its various recent improvements. This model is based on the relationship of the lightning striking distance to the crest value of the lightning current waveform and the height of the structures. This relationship has been derived from empirical data by various researchers. Table 1 lists several of these results expressed in analytical form for the simulations[1], [19].

Table 1 Striking distance formulae.

Model name	Striking distance formula
Darveniza	$S = 2Is + 30(1-e^{-0.147I})$
Love	$S = 10Is^{0.65}$
Whitehead	$S = 9.4Is^{0.67}$
IEEE(1985)	$S = 8Is^{0.65}$
Suzuki	$S = 3.3Is^{0.78}$
Eriksson	$S = 0.67h^{0.6}I^{0.74}$
Rizk	$S = 1.57h^{0.45}I^{0.69}$

S Striking distance in meters
Is First return stroke current in KA

The lightning shielding analysis is demonstrated on the grounding system of a substation modeled based on the real substation in Coolidge, state of Vermont. The 3-D model of the substation is illustrated in Fig. 1. The substation is a 115 KV/12 KV distribution substation with one 115 KV incoming line and one 12 KV outgoing line. It consists of substation (or any electrical installation) ; circuits connected to it (transmission or distribution lines) and possibly lightning protection masts. This substation has been equipped with four shielding poles without shield wire. Specifically, the substation for the simulation includes transformers, switchgear, bus-work, and a control building. Lightning shielding analysis requires accurate 3-D geometric data of electrical equipment and civil structures [8]. The EGM analysis compares the total number of expected strikes at four specific places of the substation using the seven striking distances formulae.

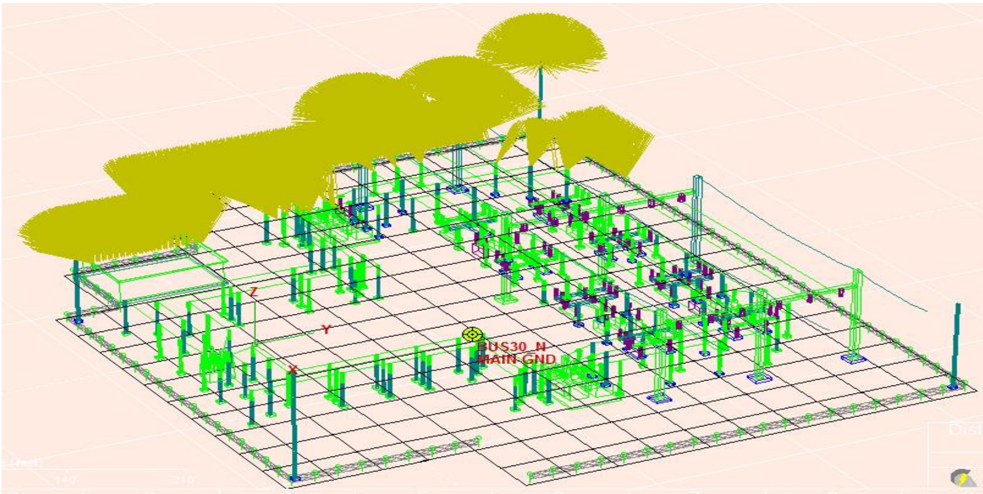


Fig. 2 Graphical illustration of lightning strike by EGM analysis.

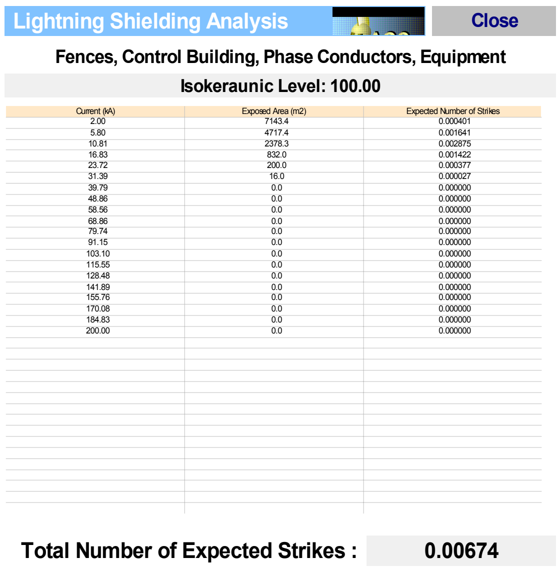
The range of lightning current is from 2 to 200KA in EGM simulation. These four places are the fence, the control building, the phase conductors, and the equipment. The total number of expected strikes means the expected number of lightning failure per year. The RSM estimates the exposed area and the exposed paths according to the setting value of lightning current in the seven striking distance formulae. The exposed area and the exposed paths of four places are compared, for lightning current equal to 10KA.

3. Results

The results of the simulations for seven striking distance formulae are presented below. First the results of the EGM analysis of the substation are displayed in a 3-D perspective view. Next, the results of the EGM analysis of the four places at substation are presented in a tabular report. Finally, the results of the exposed areas and exposed paths of the lightning shielding analysis using the RSM are presented.

3.1 Electro-geometric model analysis

EGM analysis used the IEEE formula at seven striking distance formulae. While EGM analysis is in progress, the lightning strikes considered in the analysis are displayed graphically as illustrated in Fig. 2. The Fig. 2 are a 3-D perspective view of the substation as graphical illustration at the origination and termination of lightning strikes(partial). Once the computations of EGM analysis are completed, a number of statistical reports can be generated. Fig. 3 illustrate the statistical summary of the expected exposed areas and the probability of a direct strike to the fence, control building, phase conductors, and equipment for various values of the lightning crest. The total number of expected strikes is 0.00674 per year.



Lightning Shielding Analysis | Close

Fences, Control Building, Phase Conductors, Equipment

Isokeraunic Level: 100.00

Current (kA)	Exposed Area (m2)	Expected Number of Strikes
2.00	7143.4	0.000401
5.80	4717.4	0.001641
10.81	2378.3	0.002875
16.83	832.0	0.001422
23.72	200.0	0.000377
31.39	16.0	0.000027
39.79	0.0	0.000000
48.86	0.0	0.000000
58.56	0.0	0.000000
68.86	0.0	0.000000
79.74	0.0	0.000000
91.15	0.0	0.000000
103.10	0.0	0.000000
115.55	0.0	0.000000
128.48	0.0	0.000000
141.89	0.0	0.000000
155.76	0.0	0.000000
170.08	0.0	0.000000
184.83	0.0	0.000000
200.00	0.0	0.000000

Total Number of Expected Strikes : 0.00674

Fig. 3 Computed exposed area and probability of direct lightning strikes.

The total number of the expected strikes of the seven striking distance formulae is illustrated in Table 2. The minimum value of overall risk of shielding failure is 0.0002 as estimated by the Erikson and the Rizk method. The maximum value of overall risk of shielding failure is 0.02185 as estimated by the Suzki.et al method. Internationally, there are no standards that dictate the number of lightning outage per year in substations, transmission lines, and electric power installations. However, the number of lightning outage is suggested to be below 0.01 per 100 years as a desirable value. The result of EGM from a formula suggested by IEEE presents that the fault will occur one time during about 148years. Therefore, the substation was well shielded. The simulations results of the six formulae except for the Suzki formula present that the shield design of the substation was satisfying based on the desirable value suggested above.

Table 2 the total number of expected strikes by EGM analysis.

Method	Overall Risk of Shielding Failure	Control Building	Phase Conductors	Equip ment
Brown and Whitehead	0.00451	0.00078	0.00231	0.00001
IEEE	0.00674	0.00117	0.00345	0.00001
Erikson	0.00020	0.00003	0.00017	0.00000
Darveniza	0.00403	0.00066	0.00205	0.00002
Love	0.00319	0.00054	0.00161	0.00000
Suzki.et al	0.02185	0.00386	0.01109	0.00005
Rizk	0.00020	0.00004	0.00016	0.00000

3.2 Rolling Sphere method analysis

This section illustrates the results of the RSM analysis using seven striking distance formulae. The exposed areas of the four places (fence, control building, phase conductors, and equipment) are displayed in meters in the control parameters dialog. Table 3 illustrates the results

Table 3 the exposed areas by the RSM analysis. [m^2]

Method	Fence	Control Building	Phase Conductors	Equip ment
Brown and Whitehead	455	366	1020	0
IEEE	634	503	1396	0
Erikson	–	–	–	–
Darveniza	343	281	739	0
Love	313	247	658	0
Suzki.et al	1925	983	2763	2
Rizk	–	–	–	–

of the exposed areas using the RSM analysis. Fig. 4 illustrate the result (990m^2)of phase conductors of the RSM using the Suzki formula. The blue dots on the substation indicate the strike originating locations, while the red dots indicate the strike terminating points for the selected objects(i.e. the phase conductors). The number of expected strikes can be calculated using the exposed areas of the RSM, ground flash density (GFD), and iso-keraunic level(IKL, T)[18]. The number of expected strikes to the substation area, Ns is computed as:

$$N_s = GFD * A / (1000)^2 \quad (2)$$

Where

GFD is the ground flash density in strokes per square kilometer per year. A is the substation area in square meters. GFD is defined as the average number of

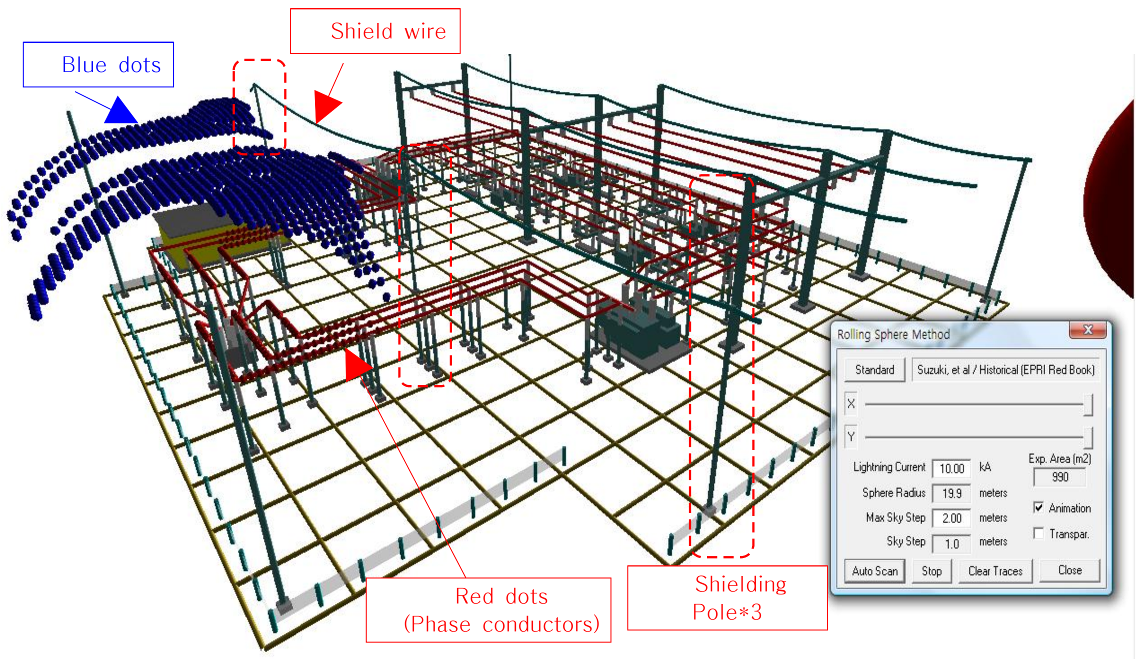


Fig. 4 Rolling sphere analysis results of phase conductors.

strokes per unit area per unit time at a particular location. The GFD is of the form

$$GFD = 0.12T[N/Km^2.Year] \quad (3)$$

For example, according to Suzki formula, when the lightning current is 10KA the expected strikes on the exposed area, 2763 m^2 are 0.03315 per year. Consequently, according to simulation results, the exposed areas in the substation determine the location of the additional shielding poles or shield wires. Therefore, the installation of the additional shielding poles or shield wires in the substation was accepted by shield design at the phase conductors exposed in the larger areas described in Suzki's result. So the total number of expected strikes was reduced from 0.02185(in Table 2) to 0.00609 by EGM analysis. Also the exposed area of phase conductors was reduced from 2763m^2(in Table 3) to 990m^2 by RSM analysis. But, some striking distances depend on the structure height. This means that as the lightning propagates downward, the striking distance changes. The RSM does not support height-dependent striking distance formula. The striking distance computed by the Erikson and Rizk method is a function of striken point height. Therefore, the RSM analysis of the four places of the substation using the Erikson and the Rizk formulae cannot be applied.

4. Conclusion

This paper has compared the performance of the lightning shielding analysis methods using the seven striking distance formulae in a substation. For comparison, we evaluated the number of expected strikes and exposed area using WinIGS Software. The procedure is based on the EGM for the shielding analysis of 3-D models. Seven striking distance formulae are compared using the EGM analysis and the RSM. Based on the electrogeometric model analysis, the risk of shielding failure in either the whole substation or parts of it is determined. According to the simulation results, one can justify whether the substation satisfies the criterion of shielding design. The six formulae except for the Suzki formula in this simulation substation present that the shield design of the substation was satisfying based on the desirable value suggested. In particular according to the RSM analysis, the exposed areas in substation determine the location of the additional shielding poles or shield wires. Therefore, the installation of the additional shielding poles and shield wires in substation was accepted by shield design at the phase conductors exposed in the larger area as described in Suzki formula. However, since the RSM does not support height-dependent striking distance formulae, the exposed areas of the four places of the substation cannot be evaluated using the Erikson and the Rizk formulae when the RSM is used. The simulation results were based on a real substation. In next studies, real models of transmission and distribution lines will be tested and compared by lightning shielding analysis methods.

References

[1] A.P. Sakis Meliopoulos, G.J. Cokkinides, "Substation Lightning Shielding and Risk Assessment", ETEP Vol. 13, No. 6, pp. 407-412, November/December 2003.

[2] Toshio Suzuki. et. al. "Study on experimental simulation of lightning strokes", IEEE Trans. Power App. Syst., Vol. PAS-100, No 4, pp. 1703-1711, 1981.

[3] H. R. Armstrong and E. R. Whitehead, "Field and analytical studies of transmission lines shielding," IEEE Trans. Power App. Syst., vol. PAS-87, no. 1, pp. 270 - 281, Jan. 1968.

[4] G.W. Brown and E. R. Whitehead, "Field and analytical studies of transmission lines shielding: part II," IEEE Trans. Power App. Syst., vol. PAS-88, no. 3, pp. 617 - 626, Mar. 1969.

[5] C. F. Wagner, "A new approach to the calculation of the lightning performance of transmission lines," AIEE Trans. Power App. Syst., vol. 75, pp.1233 - 1256, 1956.

[6] C. F.Wagner and A. R. Hileman, "The lightning stroke-II," AIEE Trans. Power App. Syst., vol. 80, pp. 622 - 642, Oct. 1961.

[7] C. F. Wagner, "The relation between stroke current and the velocity of the return stroke," IEEE Trans. Power App. Syst., vol. PAS-82, no. 10, pp. 609 - 617, Oct. 1963.

[8] F. S.Yong, J. M. Clayton, and A. R. Hileman, "Shielding of transmission lines," AIEE Trans. Power App. Syst., pp. 132 - 154, 1963.

[9] E. R. Love, "Improvements on Lightning Stroke Modeling and Applications to Design of EHV and UHV Transmission Lines," M.Sc. Thesis, Univ. Colorado, Denver, CO, 1973.

[10] A. M. Mousa and K. D. Srivastava, "Effect of shielding by trees on the frequency of lightning strokes to power lines," IEEE Trans. Power Del., vol. 3, no. 2, pp. 724 - 732, Apr. 1988.

[11] -, "The lightning performance of unshielded steel-structure transmission lines," IEEE Trans. Power Del., vol. 4, no. 1, pp. 437 - 445, Jan. 1989.

[12] -, "The distribution of lightning strokes to towers and along the span of shielded and unshielded power lines," Canad. J. Electr. Comput. Eng., vol. 15, pp.

115 - 122, 1990.
[13] D. W. Gilman and E. R. Whitehead, “The mechanism of lightning flashover on high-voltage and extra high-voltage transmission lines,” Electra, no. 27, pp. 65 - 96, 1973.
[14] E. R. Whitehead, “CIGRE survey of the lightning performance of extra high-voltage transmission lines,” Electra, no. 33, pp. 63 - 89, 1974.
[15] R. H. Golde, Lightning Protection. London, U.K.: E. Arnold, 1973.
[16] IEEE Working Group on Estimating the Lightning Performance of Transmission Lines:, “Estimating lightning performance of transmission lines II - updates to analytical models,” 92 SM453-1 PWRD, 1992, IEEE Working Group Rep.
[17] http://www.ap - concepts.com/index.htm, WinIGS Applications Guide.
[18] IEEE Std. 998-1996, “IEEE Guide for Direct Lightning Stroke Shielding of Substations”
[19] J. Eriksson, “An Improved Electro-Geometric Model for Transmission Line Shielding Analysis”, IEEE Trans. Power Delivery, Vol. 2, pp. 871-886, 1987.

저 자 소 개

김 성 삼 (金 聖 三)
2001년 경남대학교 전기공학과 졸업. 2007년 동 대학원 전기공학과 졸업 (공박). 2009년 - 현재 Georgia Institute of Technology 박사후 연구원.