LIGHTNING PROTECTION OF POLE-MOUNTED TRANSFORMERS AND ITS APPLICATIONS

Oleh

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ABSTRACT

Lightning is the single most important cause of failure in medium voltage distribution system. Analysis carried out by world wide utilities has shown that the failure rate of the pole-mounted transformer caused by lightning in medium voltage system goes as high as 4.5-5.0%. This is mainly due to improper installation of lightning arrester and also there is no well established method to access the performance of lightning protection. The objectives of this study are to provide a general bench mark for lightning protection of pole-mounted transformer in medium voltage system and to ensure proper installation of surge arrester to reduce the failure rate of the transformer. Research has found out that the high failure rate of pole-mounted transformer is due to the excessive separation length between the surge arrester and the terminal of the transformer. A method has been proposed that the separation length is determined so that the failure rate of the transformer is below a certain value. With this method, a case study on the lightning protection of pole-mounted transformer of 11kV distribution system in Malaysia is carried out. A program prototype based on this method is also developed with Matlab to deal with the tedious hand calculations of integration and probability. This program is applied to the case study above to further verify the results of hand calculation. In this case study, with parameters of ground flash density (N_g) = 5.8 flashes per m^2 per year, horizontal span of two outmost conductors (b) = 1.07m, conductor height (H) = 7.525m, shielding factor (Sf) = 0.4, transformer lifetime (LF) = 20 years, failure rate (FR) = 5%, maximum surge current (I_0) = 300kA, safety margin (sm) = 20%, residual voltage of arrester (U_p) = 32kV, basic insulation level (BIL) = 75kV, wave front time (t_f) = 5μs, line surge impedance (Z_0) = 450Ω, and arrester length ($lmin$) = 1m, the optimum separation length calculated by the program is 1.3219m. This means that in order to achieve a failure rate of 5% throughout the lifetime of the transformer, surge arrester should be installed 1.3219m from the transformer terminal.

ABSTRAK

Kilat merupakan sebab utama kegagalan dalam sistem pengagihan voltan sederhana. Analisis yang dilakukan oleh saintis mendapati kadar kegagalan bagi pengubah agihan yang tercagak di atas tiang pengagihan kuasa untuk sistem voltage sederhana mencapai 4.5 hingga 5.0%. Ini disebabkan oleh pemasangan penangkap pusuan yang tidak baik dan juga tiada cara yang baik bagi menilai keberkesanan sesuatu perlindungan kilat. Kajian ini berobjektif untuk memberi satu tanda asas bagi perlindungan kilat bagi pengubah agihan yang tercagak di atas tiang pengagihan kuasa dan juga bagi memastikan pemasangan penangkap pusuan yang baik bagi mengurangkan kadar kegagalan pengubah agihan itu. Kajian telah mendapati kadar kegagalan pengubah agihan yang tinggi disebabkan oleh jarak pemisahan antara penangkap pusuan dan pangkalan pengubah agihan yang terlalu besar. Satu kaedah telah mencadangkan bahawa jarak pemisahan itu yang sesuai ditentukan bagi memastikan kadar kegagalan pengubah agihan berada di bawah satu nilai tertentu. Dengan kaedah yang dicadangkan itu, satu kajian kes bagi perlindungan kilat sistem pengagihan kuasa 11kV di Malaysia telah dijalankan. Satu prototaip program berdasarkan kaedah itu juga dibina dengan menggunakan Matlab bagi menyelesaikan pengiraan yang kompleks dengan kamiran dan kebarangkalian. Program ini diaplikasikan pada kajian kes di atas untuk memeriksa keputusan yang diperoleh dengan pengiraan tangan. Dalam kajian kes ini, dengan parameter-parameter seperti kepadatan penyambaran kilat (N_g) = 5.8 penyambaran/m^2/tahun, jarak pemisahan antara dua konduktor terluar (b) = 1.07m, ketinggian konduktor (H) = 7.525m, faktor perlindungan (S_f) = 0.4, hayat pengubah agihan (*LF)* = 20 tahun, kadar kegagalan (*FR*) = 5.0%, arus pusuan tertinggi (I_0) = 300kA, margin keselamatan (*sm*) = 20%, voltan residual bagi penangkap pusuan (U_p) = 32kV, aras penebatan asas (*BIL*) = 75kV, masa bagi depan gelombang (t_f) = 5μs, impedans pusuan (Z_0) = 450Ω dan panjang penangkap pusuan (*lmin*) = 1m, jarak pemisahan antara penangkap pusuan dan pangkalan pengubah agihan yang optimum dikirakan oleh program sebagai 1.3219m. Ini bermaksud bagi mencapai kadar kegagalan 5.0% sepanjang hayat pengubah agihan, penangkap pusuan perlu dipasang pada jarak 1.3219m dari pangkalan pengubah agihan bagi kajian kes di atas.

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CHAPTER 1

INTRODUCTION

1.1 Background

Protection of power system from lightning related damage and faults is crucial to maintain adequate power quality, reliability, and controlling damage costs to the utility system. There are many facets in lightning protection design for cable, transformer, generator etc. Transformer protection plays a vital role in the reliability of a distribution system.

Although less than 20% of lightning strikes cause permanent damage in distribution circuits, lightning records the single most important cause of failure in Medium Voltage (< 72.5kV) lines of distribution systems. When the equipment protection is done poorly, more equipment failure will occur. Lightning strikes directly to or nearby distribution lines constitute most of transformer failures.

Distribution lines cover small geographic areas, so lightning damage and lightning flash over rates show high variability on a circuit. One year a circuit may get nailed with damage coming from many storms; the next year it may have next to nothing. The variability of lightning and the variability of storms are also important for utility planning regarding regulatory incentives for reliability and for performance guarantees for customers. Just a few years of data is usually insufficient to depict the performance of weather-related events for a circuit or even for a whole system. The difficulty in obtaining data for analysis posed a major problem in developing a reliable protection system for distribution system.

Even though high voltage transmission lines are protected by shield wires, in Medium Voltage (MV) lines, however, the insulation strength could not be improved economically to avoid the back flashovers. Direct strikes of lightning onto an overhead phase wire inject an enormous surge that creates a very large voltage. This voltage impulse easily break down most distribution class insulation because of the relatively low insulation levels of the line compare with the voltage. This makes the lightning protection of MV networks difficult.

The analysis done by different utilities world wide shows that the failure rate of transformers goes as high 4.5-5% per year. Most of the failures seem to be due to the excessive separation length between the transformers and the surge arresters. Lacking of proper analysis, improper installation and selection of arrester neglecting also contribute to the high rate of failure.

In addition, there is no well-established way to access the transformer lightning protection system quantitatively. As a result, there are no standards of installation that can provide high protection margin and lengthen the life span of transformer. This is largely due to the unpredictable occurrence of lightning and the very short duration of each strike (100 microseconds – milliseconds). The random and very high value of current carried by lightning not only imposed great hazard to research team but also may damage the measuring equipments. This is because most electrical insulation and electronic IC can not withstand the sudden surge of enormous current.

From all the facts above, we can conclude that with proper analysis of the transient behavior of transformers and their protection equipments, many of the failures could have been avoided.

1.2 Objectives

i. To provide a general bench mark for lightning protection of pole-mounted transformer.
ii. To ensure proper installation of protection equipment.
iii. To reduce the high lightning failure rate of pole-mounted transformer.

1.3 Methodology

Much study on basic theory of lightning, arrester and distribution line need to be carried out prior to the study of lightning protection. The study starts with lightning, which includes lightning characteristics, its formation, statistics and probability of its occurrence and the surge current it carries. The way of how lightning can impose damage to the distribution lines, transformers and also other power equipments connected is also studied. IEEE journals on lightning and protection, handbooks of power system, and research works by world wide utilities are the main source of information. Statistics of lightning occurrence is obtained from the meteorological report through internet and journals.

The journal “Lightning Protection of Pole-Mounted Transformers and Its Applications in Sri Lanka” by Prof J R Lucas and D A J Nanayakkara, April 2001, and its references are main materials in my studies. The methods of improvement in lightning protection of transformer is studied and discussed. Equations in the journal will be then derived and explained in detail. Together with the statistics and data obtained, the suggested method is then applied to the 11kV distribution system in Malaysia as a case study. A program based on the suggested method which calculates and gives the best solution of surge arrester position according to different cases will then be developed. The result of simulation will then be compared with hand calculation for further verification of its effectiveness. A paper on the study will then be written.

1.4 **Report Guideline**

This report consists of 4 main chapters and its sub topics. Chapter 1 is the introduction of the study of this paper which is subdivided into the background of the lightning protection of pole-mounted transformer, the objectives of this study and also the methodology used. Chapter 2 is the fundamental theories which will be used in the case study of this study. Derivation of important equations and also the data and statistics of lightning surges and arrester are also discussed in this chapter. Chapter 3 is a case study on lightning protection of 11kV distribution system in Malaysia. Protection scheme with the present method is analyzed and the drawbacks and weakness are pointed out. An improved method is then suggested and applied for the case of 11kV distribution in Malaysia. An example of the application of a program prototype developed with the Matlab GUI (Graphic User Interface) onto the case study above is also shown. This program prototype calculates the separation length of arrester and transformer terminal based on the improved method and thus eliminates the tedious job of hand calculation. Chapter 4 consists of the conclusion of the study in this paper together with future studies to be carried out to further improve the proposed method. The list of symbols used in this paper is also included after the chapter of conclusion followed by the references. The application file of the program prototype developed based on the improved method is included in the CD attached together at the back cover.

CHAPTER 2

FUNDAMENTAL THEORY

2.1 Lightning surges

A thundercloud is bipolar, often with positive charges at the top and negative at the bottom, usually separated by several kilometers. When the electric field strength exceeds the breakdown value, a lightning discharge is initiated. The first discharge proceeds to the earth in steps (stepped leader stroke). When close to the earth a faster and luminous return stroke travels along the initial channel, and several such leader and return stroke travels along the initial channel, and several such leader and return strokes constitute a flash. The ratio of negative to positive strokes is about 5:1 in temperate regions. The magnitude of return stroke can be as high as 200kA, although an average value is of the order of 20kA.

Following the initial stroke, after a very short interval, a second stroke to earth occurs, usually in the ionized path formed by the original. Again, a return stroke follows. Usually, several such subsequent strokes (known as dart leaders) occur, the average being 3 and 4. The complete sequence is known as a multiple-stroke lightning flash and a representation of the strokes at different time intervals is shown in Figure 2.1. Figure 2.1 is adopted from [3].

Normally, only the heavy current flowing over the first 50μs is of importance and the current-time relationship has been shown to be of the form:

$$i = i_{peak}(e^{-\alpha t} - e^{-\beta t}) \tag{2.1}$$

where i = lightning surge current

i_{peak} = peak surge current

α = constant

β = constant

When a stroke arrives on an overhead conductor, equal current surges of the above waveform propagate in both directions away from the point of impact. The magnitude of each voltage surge set up is therefore:

$$V = \frac{1}{2} \cdot Z_0 \cdot i_{peak} (e^{-\alpha t} - e^{-\beta t}) \quad (2.2)$$

where V = surge voltage set up along the line

Z_0 = the conductor surge impedance.

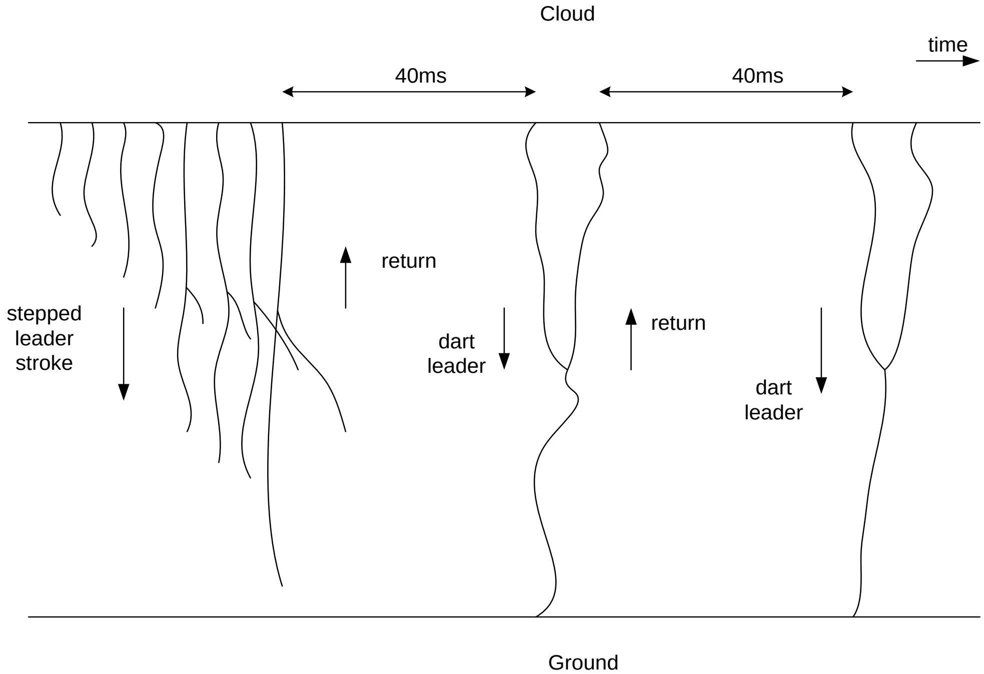

Figure 2.1 *Sequence of strokes in a multiple lightning stroke*

As an example, for a current peak, i_{peak} of 20kA and a surge impedance,Z_0 of 350Ω, the voltage surges will have a peak value of $(\frac{350}{2}) \times 20kV = 3500kV$. When a ground or earth wire exists over the overhead line, a stroke arriving on a tower or on the wire itself sets up surges flowing in both directions along the wire. On reaching neighboring towers they are partially reflected and transmitted further. This process continues over the length of the line as towers are encountered. If the towers are 300m apart the travel time between towers and back to the original tower is $(2 \times 300)/3 \times 10^8 = 20\mu s$, where the speed of propagation is $3 \times 10^8 m/s$. The voltage distribution may be obtained by means of the Bewley lattice diagram [3].

If an indirect stroke strikes the earth near a line, the induced current, which is normally of positive polarity, creates a voltage surge of the same wave shape which has amplitude dependent on the distance from the ground. With a direct stroke, the full lightning current flows into the line producing a surge that travels away from the point of impact in all directions. A direct stroke to a tower can cause a back flashover due to the voltages set up across the tower inductance and footing resistance by the rapidly changing lightning current (typically 10kA/μs); this appears as an over voltage between the top of the tower and the conductors (which are at lower voltage).

2.2 Basic Insulation Level (BIL)

Basic insulation level or basic impulse insulation level is the reference level expressed in impulse crest (peak) voltage with a standard wave not longer than a $1.2 \times 50\mu s$ wave as shown in Figure 2.2 which is reproduced from [3]. Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the BIL. The two standard tests are the power frequency and 1.2/50μs impulse-wave withstands tests. IEEE Std. 4-1995 defines voltage impulse test waves as t_1/t_2 μs, where t_1 is the equivalent time to crest based on the time taken to rise from 30% to 90% of the crest (see Figure 2.3). The time to half value t_2 is the time between the origin of the 30 to 90% virtual front and the point where it drops to half value. The withstand voltage is the level that the equipment will withstand for a given length of time or number of applications without disruptive discharge occurring, i.e. a failure of insulation resulting in a collapse of voltage and passage of current (sometime termed ‘spark over’ or ‘flashover’ when the discharge is on the external surface). Normally, several tests are performed and the number of flashovers noted. The BIL is usually expressed as a per unit of the peak (crest) value of the normal operating voltage to earth; e.g. for a maximum operating voltage of 362kV,

$$1p.u. = \sqrt{2} \times \frac{365}{\sqrt{3}} = 300kV \tag{2.3}$$

Therefore, a BIL of $2.7\,p.u. = 2.7 \times 300 = 810kV$.

According to [3], the shape of lightning and switching surges take the form as shown in Figure 2.2. The former has a rise time of, say 1.2µs and a fall time of half maximum value of 50µs (hence 1.2/50 wave). Meanwhile, the switching surges are much longer, the duration time varying with situation; a typical wave is 175/3000µs. Equation for 1/50 wave is $v = 1.036(e^{-0.0146t} - e^{-2.56t})$.

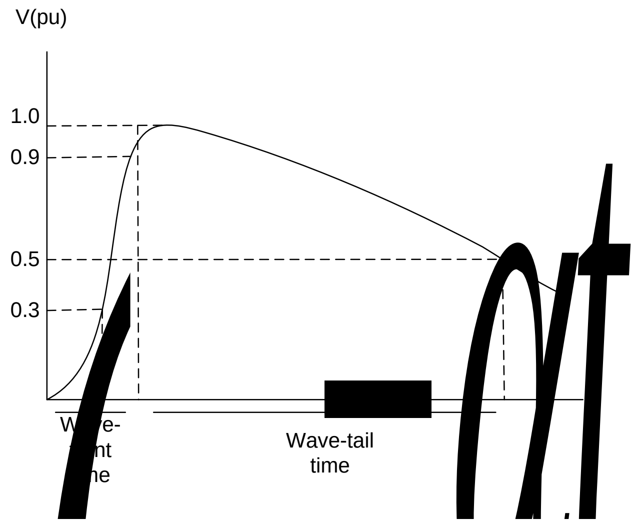

Figure 2.2 *Basic impulse waveforms for lightning and switching surges.*

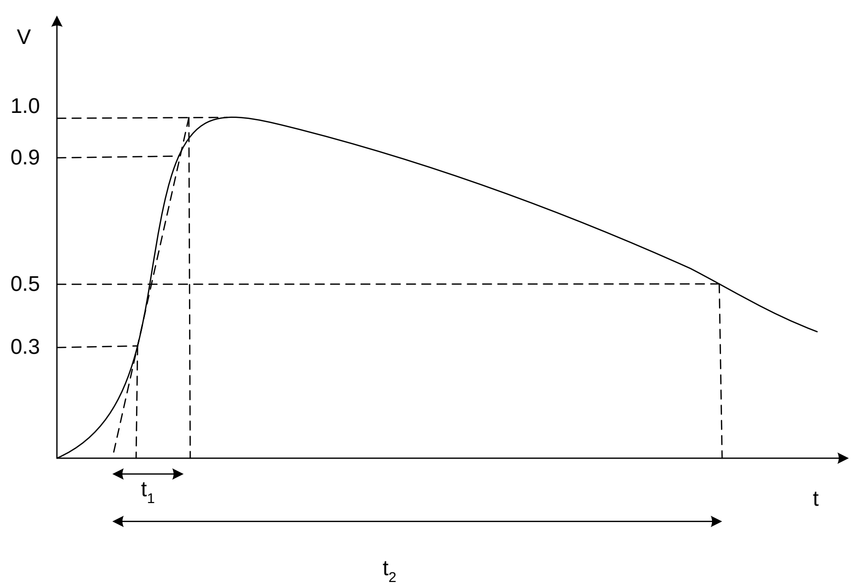

Figure 2.3 *Standard impulse voltage test wave. (Reproduced from IEEE Std. 4-1995. Copyright 1995 IEEE. All rights preserved.)*

The IEEE standard BIL ratings for distribution equipment are 30, 45, 60, 75, 95, 125, 150, 200, 250 and 350kV. The BILs of most equipment are given in Table 2.1 which is reprinted from [7]. With reference to [7], the Indian Standard (IS) has stipulated the power frequency and lightning impulse strength, which are the guaranteed minimum strength of the equipment as shown in Table 2.2.

Table 2.1 *Distribution equipment insulation impulse levels (BIL and CWW)*

Voltage class, kV	BIL, kV	CWW, kV [a]
5	60	69
15	95	110
25	125	145
35	150	175

[a] : For transformers, other equipment may have different CWW.

CWW = chopped wave withstand. A chopped wave test has the same characteristics as the 1.2/50μs wave, but the wave shape is chopped off after 2 or 3μs. Because the voltage stress does not last as long, with most equipment, the chopped wave withstand (CWW) is of larger value compare to BIL.

Table 2.2 *The power frequency and lightning impulse strength are stipulated as per IS: 2165-1977*

Normal voltage of the system, kV	Highest system voltage, kV	Power frequency strength, kV_{rms}	Impulse strength 1.2/50μs as kV peak
0.415	0.450	2.5	5
11	12	28	75
22	24	50	125
33	36	70	170
66	72.5	140	325
132	145	275 230 185	650 550 450

2.3 Surge Impedance

From [3], in more physical terms, when a voltage is injected into a line as shown in Figure 2.4, a corresponding current *i* will flow, and if conditions over a small line length of *dx* are considered, the flux set up between the go and return wires will be:

$$\phi = iLdx \tag{2.4}$$

where Φ = flux set up

i = current injected in to the line

L = inductance per unit length of line

dx = small segment of line length

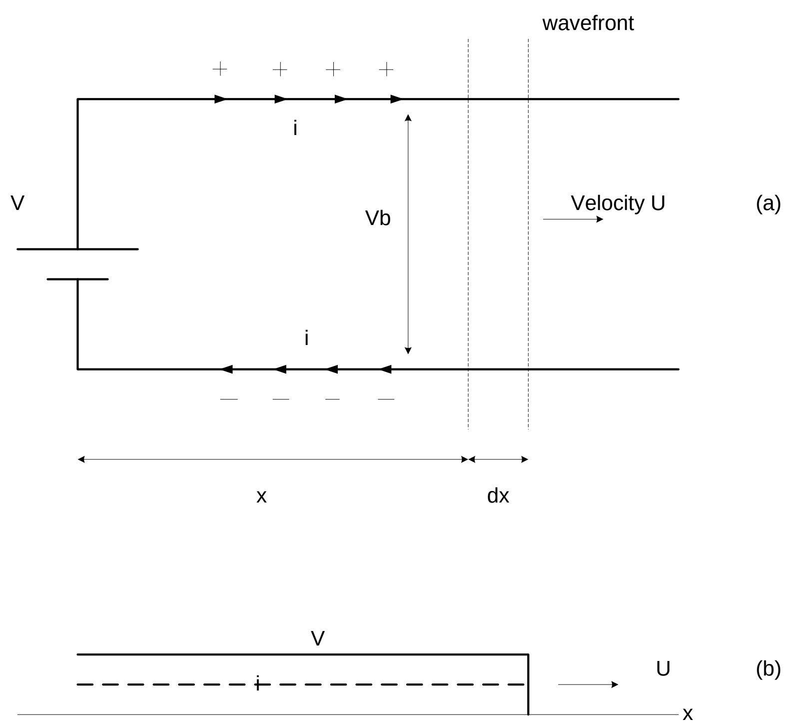

Figure 2.4 *Distribution of charge and current as wave progresses along a previously unenergized line. (a) Physical arrangement (b) Symbolic representation*

This flux will induce a back emf in the line:

$$
\begin{aligned}
v_b &= -\frac{d\phi}{dt} \\
&= -Li\frac{dx}{dt} \\
&= -iLU \qquad (2.5)
\end{aligned}
$$

where v_b = back emf induced in line

U = wave velocity

The applied voltage v must equal iLU. Also, charge is stored in the capacitance over dx as the wave travel along the line:

$$Q = idt = vCdx$$

$$i = vC\frac{dx}{dt} = vCU \qquad (2.6)$$

where Q = charge stored in the line capacitance

C = capacitance per unite length of line

dx/dt = rate of change of line length

v = voltage injected into the line

By replacing $v = iLU$ into Eq. 2.6, the wave velocity will take the form of:

$$U = 1/\sqrt{LC} \qquad (2.7)$$

Replacing Eq. 2.7 into Eq. 2.6, we can have the equation of surge impedance, Z_0 in terms of the line inductance and capacitance as:

$$i = vC\left(\frac{1}{\sqrt{LC}}\right) = v\sqrt{\frac{C}{L}}$$

$$Z_0 = \frac{v}{i} = \sqrt{\frac{L}{C}} \qquad (2.8)$$

where Z_0 is the characteristic or surge impedance

For single-circuit three phase overhead lines (conductors not bundled), the value of surge impedance, Z_0 normally lies in the range of 400-600Ω. For overhead lines, the wave velocity usually will be $U = 3\times10^8 ms^{-1}$ i.e. the speed of light, and for cables, the wave velocity is given by:

$$U = \frac{3\times10^8}{\sqrt{\varepsilon_r \mu_r}} ms^{-1} \tag{2.9}$$

where ε_r is usually from 3 to 3.5, and $\mu_r = 1$.

2.4 Reflection Theory

According to the reflection theory in [3], when an incident traveling wave with voltage of v_i and current of i_i travels along a line, upon arriving at a junction or discontinuity, will produce a reflected voltage v_r and a reflected current i_r which travel back along the line. The incident and reflected components of voltage and current are governed by the surge impedance of the line, Z_0, so that

$$v_i = Z_0 i_i \tag{2.10}$$

where v_i = voltage of the incident traveling wave

i_i = current of the incident traveling wave

$$v_r = -Z_0 i_r \tag{2.11}$$

where v_r = reflected voltage in the line

i_r = reflected current in the line

As shown in Figure 2.5 which is taken from [3], in general case of a line of surge impedance Z_0 terminated in Z the total voltage and current at receiving end impedance Z are:

$$v = v_i + v_r \tag{2.12}$$

where v = total voltage at the receiving end

$$i = i_i + i_r \, . \qquad (2.13)$$

where i = total current at the receiving end

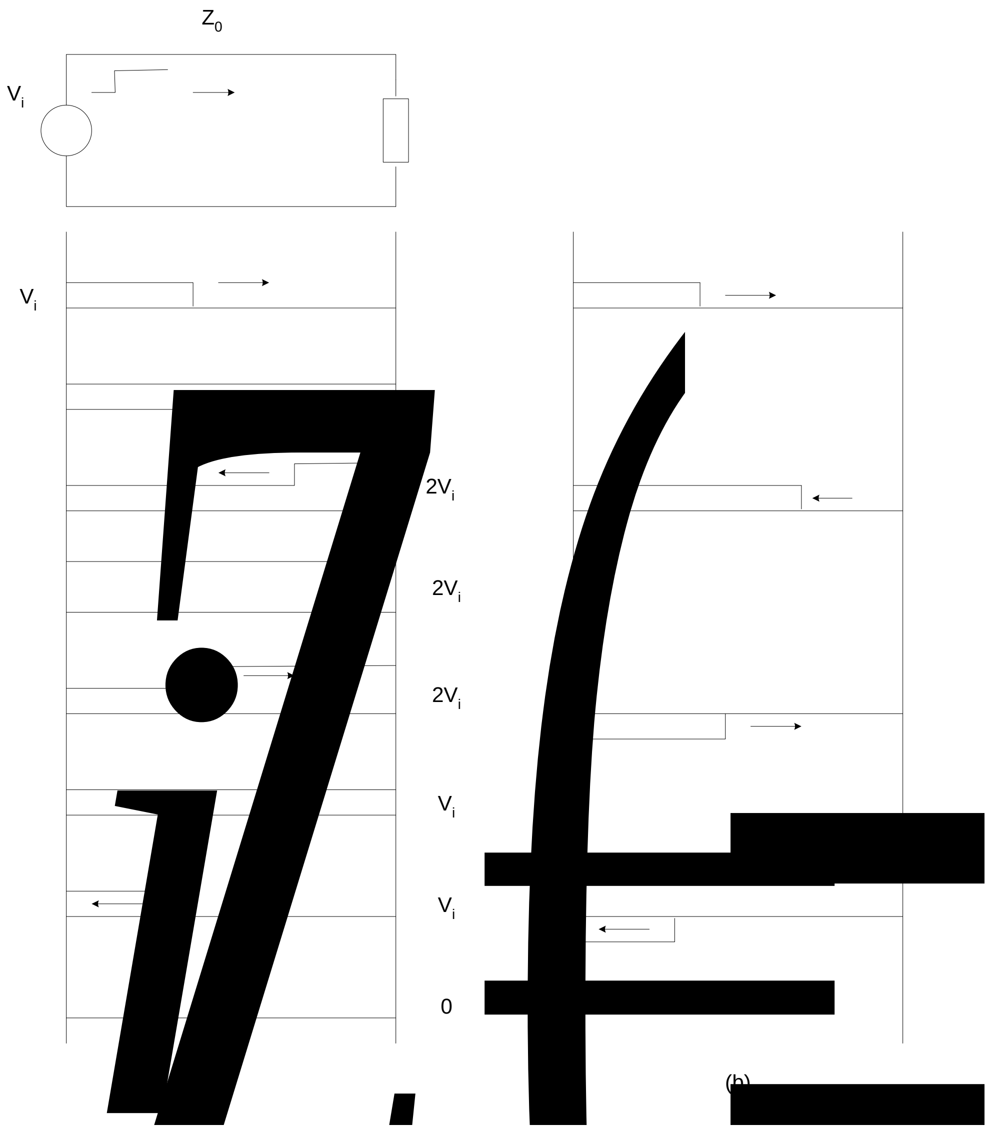

Figure 2.5 *Application of voltage to unenergized loss-free line on open circuit at far end. (a) Distribution of voltage. (b) Distribution of current. Voltage source is an effective short circuit.*

Also, we can express the reflected component of voltage and current in terms of the voltage and current of the incident traveling wave. Considering the total voltage and sending and receiving end, with Eq. 2.12 and Eq. 2.13,

$$v = Zi$$

$$(v_i + v_r) = Z(i_r + i_i)$$

$$Z_0(i_i - i_r) = Z(i_r + i_i)$$

Hence,

$$i_r = (\frac{Z_0 - Z}{Z_0 + Z})i_i \qquad (2.14)$$

where Z_0 = surge impedance of line

Z = impedance at the receiving end

Again,

$$v_i + v_r = Z(i_i + i_r)$$

With $i_i = \frac{v_i}{Z_0}$ and $i_r = -\frac{v_r}{Z_0}$ from Eq. 2.10 and Eq. 2.11, we will have:

$$v_i + v_r = Z(\frac{v_i - v_r}{Z_0})$$

$$v_r = (\frac{Z - Z_0}{Z + Z_0})v_i = \lambda v_i \qquad (2.15)$$

where λ = reflection coefficient equal to $(\frac{Z - Z_0}{Z + Z_0})$

If we look at the Eq. ac and Eq. 2.15, we can make the following conclusions:

If $Z \rightarrow \infty$, $v = 2v_i$ and $i = 0$.

If $Z = Z_0$ (matched line), $\lambda = 0$, i.e. no reflection.

If $Z > Z_0$, v_r is positive and i_r is negative.

If $Z < Z_0$, v_r is negative and i_r is positive.

Hence, the total voltage and current at the receiving end will be

$$v = v_i + v_r \tag{2.16}$$

$$v = (\frac{2Z}{Z + Z_0})v_i \tag{2.17}$$

$$i = (\frac{2Z_0}{Z + Z_0})i_i \tag{2.18}$$

The reflected waves will travel back and forth along the line, setting up, in turn, further reflected waves at the ends, and this process will continue indefinitely unless the waves are attenuated because of resistance and corona. Summarizing, at an open circuit the reflected voltage is equal to the incident voltage and this wave, along with a wave ($-i_i$), travel back along the line; note that at open circuit the total current is zero. Conversely, at a short circuit, the reflected voltage wave is – v_i in magnitude and the current reflected is i_i, giving a total voltage at the short circuit at receiving end of zero and total current of $2i_i$. For other termination arrangements, Thevenin's theorem may be applied to analyze the circuit. The voltage across the termination when it is an open circuit is seen to be $2v_i$ and the equivalent impedance looking in from the open circuited termination is Z_0, the termination is then connected across the terminals of the Thevenin equivalent circuit (Figure 2.6). Figure 2.6 and 2.7 are also taken from [3].

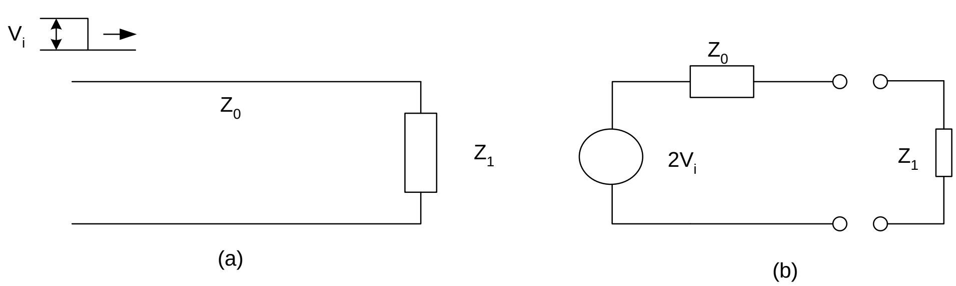

Figure 2.6 *Analysis of traveling waves - use of Thevenin equivalent circuit. (a) System. (b) Equivalent circuit.*

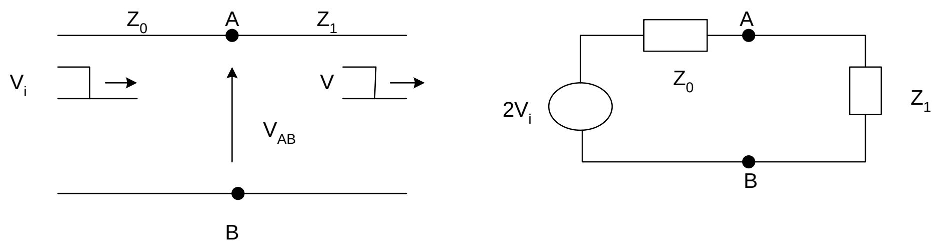

Figure 2.7 *Analysis of conditions at the junction of two lines or cables of different surge impedance.*

Consider two lines of different surge impedance Z_0 and Z_1 connected in series as shown in Figure 2.7; it is required to determine the voltage across the junction between them:

$$v_{AB} = (\frac{2v_i}{Z_0 + Z_i})Z_1$$

$$= (\frac{2Z_1}{Z_0 + Z_i})v_i$$

$$= \gamma v_i \tag{2.19}$$

where v_{AB} = voltage at junction of different surge impedance

γ = refraction coefficient

The refracted current in the series connected line:

$$i = \frac{v_{AB}}{Z_1} = \frac{2v_i}{Z_0 + Z_1} \tag{2.20}$$

2.5 Direct Strikes to Lines

The number of lightning strikes to earth is a function of the lightning activities in a given region. Lightning activity is defined by ground flash density (N_g) or the number of strikes to ground per unit area per year. From year to year, N_g can vary as much as 2 to 1 for a given geographic region.

For many years, weather observers have recorded lightning activity using thunder-days or days on which thunder is heard. Such measurements are compiled into Isokeraunic charts or charts of equal thunder day activity. The world Isokeraunic chart (thunder day level) is shown in Figure 2.8 which is reprinted from [6].

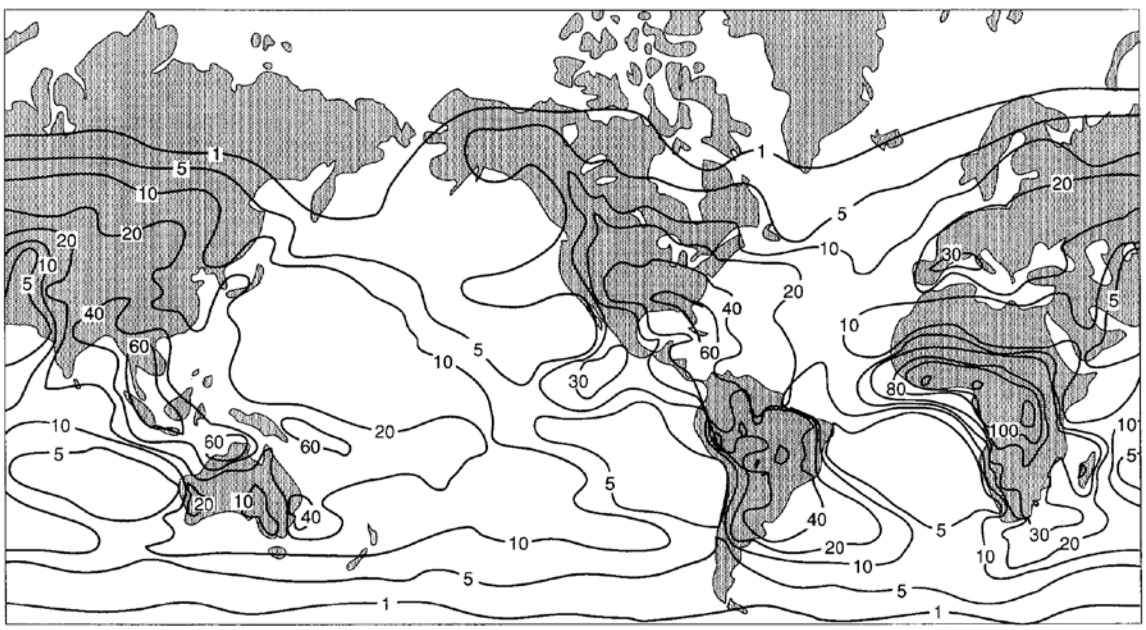

Figure 2.8 *World isokeraunic chart.*

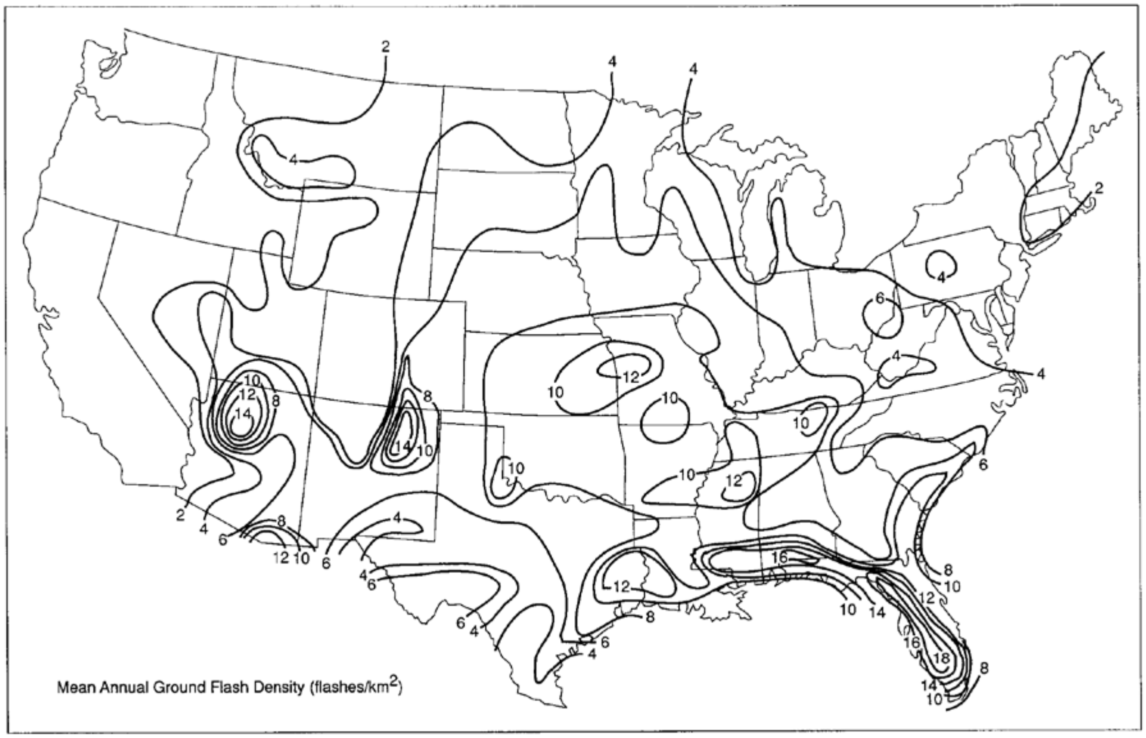

Figure 2.9 *Contour map of mean annual lightning strike density.*

A study of historic weather data was conducted for the Nuclear Regulatory commission to determine the number of thunderstorms by region in the USA from thunder-hour data. Correlations to known lightning ground flash densities for specific regions were used to calculate N_g from the number of thunder storms. With reference to [6], the chart of estimated N_g for the USA is shown in Figure 2.9**.**

According to [6], considerable research has been completed in South Africa on an 11-kV test line built in open country. The results show that, for lines not shielded by nearby tall objects, the number of strikes to the line (N) per year can be calculated from the following expression:

Eriksson Model:

$$N = N_g (b + 28H^{0.6}) \times 10^{-1} \qquad (2.21)$$

where N = number of strokes to the line per year per 100km

N_g = ground flash density

b = horizontal distance between the outside conductors

H = height of the line above ground

2.6 Approximate thunderstorms day to GF density (Eriksson, 1987):

If direct measurements of ground flash density are unavailable, meteorological records of thunderstorms (or keraunic level). Thunderstorm days approximately relate to ground flash density as (Eriksson, 1987):

$$N_g = 0.04 T_d^{1.25} \tag{2.22}$$

where T_d = the number of thunderstorm days per year

If the keraunic level is not available, the relationship between the numbers of thunderstorm hours per year to N_g can be used (MacGroman et al. 1984):

$$N_g = 0.054 T_h^{1.1} \tag{2.23}$$

where T_h = the number of thunderstorm hours per year

Another crude estimate of the lightning level is from NASA's Optical Transient Detector, which measured worldwide lightning activity for 5 years (Chisholm et al., 1999).

Lightning is highly variable. It takes several hundred lightning flash counts to obtain modest accuracy for an estimate of the average flash density. A smaller geographic area requires more measurement time to arrive at a decent estimate. Similarly, a low lightning area requires more measurement time to accurately estimate the lightning. Standard deviations for yearly measurements of lightning activity range from 20 to 50% of the mean (IEEE Std. 1410-1997). Lightning and storms have high variability. Figure 2.10 shows the variability of ground flash density in a high lightning area (MacGorman et al., 1984). Lightning and weather pattern may have cycles that last many years.

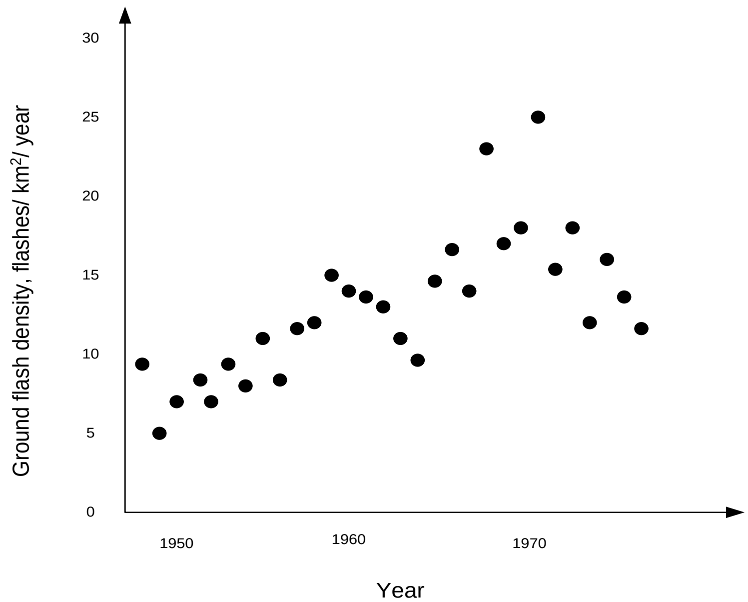

Figure 2.10 *Estimated annual ground flash density for Tampa, Florida based on thunderstorm-hour measurements.*

For pole lengths normally used on distribution lines in the USA (35, 40, 45, and 50 feet), the approximate relationship between N_g and direct strikes to a line unshielded by other structures can be calculated by using Eriksson Model. These calculations are shown in Table 2.3 and Figure 2.11 which are reprinted from [6], and can be used as follows. For an unshielded line of given height, Figure 2.9 is used to determined N_g for region in which line is built and then to determine the number of direct strikes to the line per km or per mile from Figure 2.11.

Table 2.3 *Calculations of strikes to distribution lines.*

Pole length (ft)	Setting depth in soil (ft)	Conductor above pole top 8'' (ft)	Height of line above ground in (ft)	Height of line (H) above ground in meters	$(b+28H^{0.6})*10^{-1}$		Strikes to the line per year per 100km of line, N_g (flashes)					
							With crossarm			Without crossarm		
					With crossarm	Without crossarm	5	10	15	5	10	15
35	6.0	0.66	29.66	9.04	10.721	10.50	53.6	107.2	160.8	52.5	105.0	157.0
40	6.0	0.66	34.66	10.56	11.746	11.52	58.7	117.5	176.2	57.6	115.2	115.2
45	6.5	0.66	39.16	11.94	12.627	12.40	63.1	126.3	189.4	62.0	124.0	124.0
50	7.0	0.66	43.66	13.31	13.462	13.23	67.3	134.6	201.9	66.2	138.3	138.36

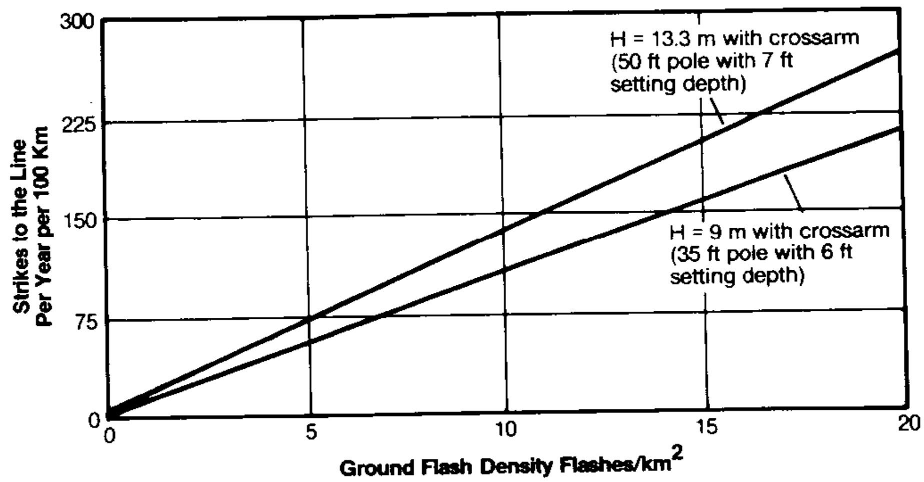

Figure 2.11 *Strike to lines vs Ground flash density.*

2.7 Shielded Line

It is stated in [5] that to determine the strikes to a line shielded by nearby objects, all objects within a distance of four times the height of the line on either side of the line should be considered. As can be seen in Figure 2.12, any object such as a tree or building whose height is equal to or greater than the height of the line will reduce the direct strike incidence to the line. Figure 2.12 is reprinted from [5]. In urban areas, buildings are often taller than the line and effectively shield most of the line. In suburban areas, trees often shield the line from lightning.

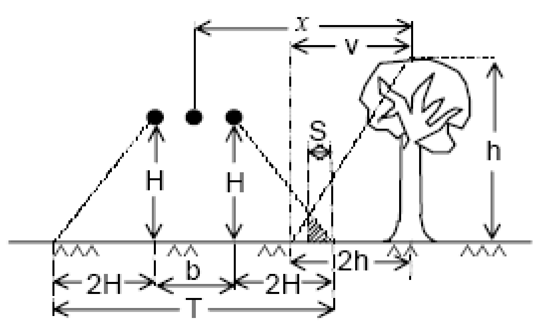

Figure 2.12 *The shielding width S created by a tree near a distribution line.*

For practical line designs, the area where the line is to be built should be surveyed to determine the portion of the line that will be shielded by other structures. Because of the variety in heights and shapes of shielding objects, it is impossible to define accurately the degrees of shielding. In addition, for the time being, a quantitative consensus of the shielding mechanism is not available. The best can be done now is to adopt the simplistic rule that the width (each side of the line) of the protected or shielded area on the earth's surface is approximately the height of the shielding object. In the case of Figure 2.12, the width would be *2h*. By applying this rule for the case where width b in Figure 2.12 is much less than the line height *H*, a set of shielding curves can be constructed as shown in Figure 2.13. Figure 2.13 is reprinted from [6]. The variable shielding factor (S_f) is the per unit portion of the line shielded by a nearby object. The number of strikes to the line is then:

$$N_s = N(1 - S_f) \tag{2.24}$$

where N_s = adjusted number of strikes to the line per 100km per year

N = strikes computed from Eq. 2.21

S_f = shielding factor

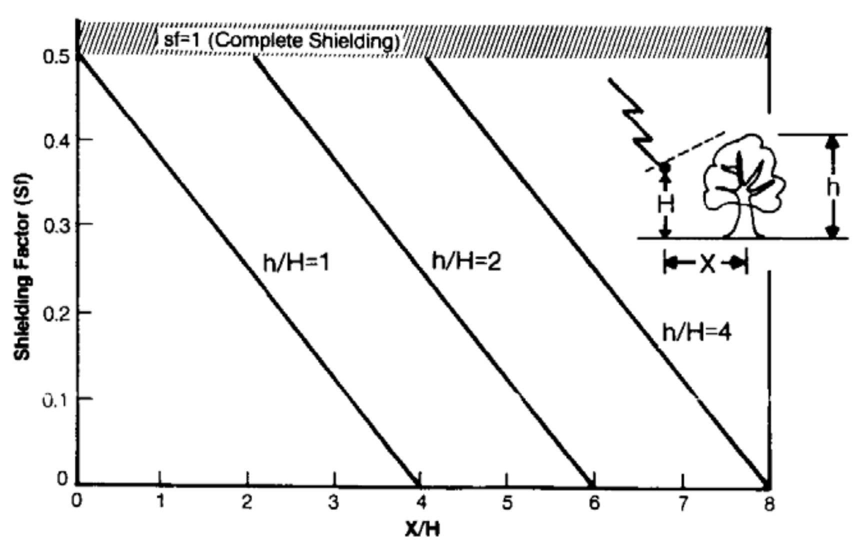

Figure 2.13 *Approximation curves of shielding factor* S_f *vs Line heights and shielding distances.*

As stated in [5], for distribution lines in urban area areas near trees and houses, *Sf* can be as high as 0.3 to 0.5. For lines constructed with overhead shield wires, *Sf* will be approximately 1.0; however, back flash to pole grounds must be taken into consideration. N_g in flashes per km^2 per year can be estimated from the flash density map i.e. the one in Figure 2.9 by interpolating between the contour lines. If local ground flash count data are available for several years, these data are preferable to the data from the flash density map.

2.8 Electrical Characteristics of Lightning to Distribution Circuits

With reference to [6], the most important parameters for the design of distribution lines are the characteristics of the return-stroke current. The entire lightning event is referred to as a flash, and the individual current pulses are referred to as strokes. Approximately 45% of lighting flashes contain a single stroke; however, the mean number of strokes per flash is 3. The characteristics of the lightning return-stroke current are defined by probability distributions associated with the peak current magnitude and the shape of the front of the first and subsequent current waves. These probability distributions are given in Figure 2.14 and 2.15 which are taken from [6]. If the current magnitude or rise time that will result in flashover can be determined, then the distribution can be used to estimate the percentage of lightning return strokes that exceed the critical level of protective methods or equipment that is dependent upon the magnitude or wave shape of lightning currents. The percentage of strokes that cause flashover can be multiplied by the number of strikes to the line to determine the number of lightning flashovers.

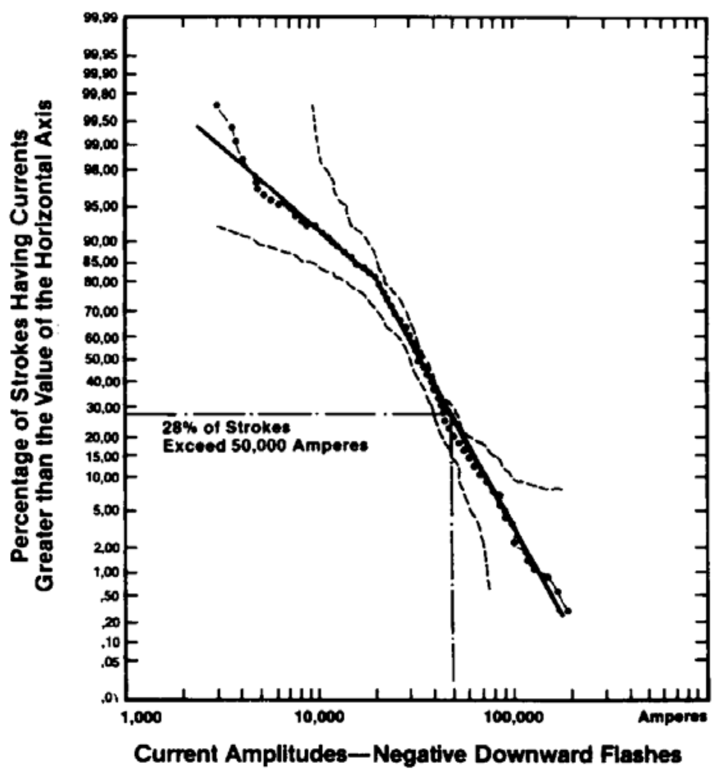

Figure 2.14 *Distribution of peak current amplitude.*

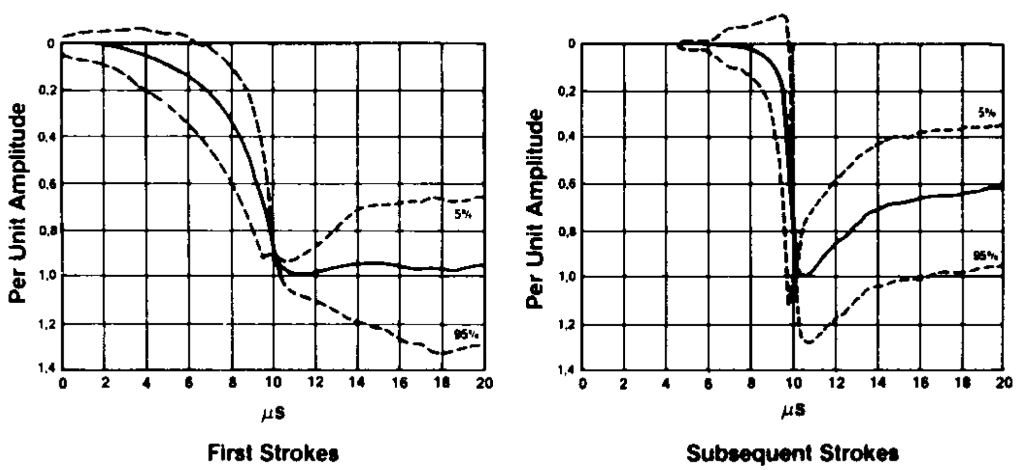

Figure 2.15 *Impulse shape parameters.*