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A SIMPLIFIED METHOD FOR ESTIMATING LIGHTNING PERFORMANCE OF TRANSMISSION LINES

A Report Prepared by the Working Group on
Lightning Performance of Transmission Lines

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SUMMARY

A simplified method for estimating the lightning performance of overhead transmission lines has been evaluated, modified to incorporate newly available information on lightning characteristics, checked against existing line performance, and coded as a simple Fortran computer program by the Working Group. This paper provides the basic characteristics of the method, highlights the changes made from its originally published form, and identifies a few remaining limitations. Comparisons with actual line performance are given, together with some general purpose estimating curves. Ongoing studies directed toward further improvements to the method are reviewed. Future updates to this publication are intended.

INTRODUCTION

On many transmission lines, lightning is the main cause of unscheduled supply interruptions. A number of methods for estimating tripout rates have been developed in the past, together with a very large body of associated publications.

Most predictive methods require several assumptions, and provide answers that vary considerably depending on the particular characteristics assumed. Consequently these methods are usually calibrated against actual line performance. As a result, use of the methods for new designs leads to uncertainties that researchers have tried to address.

Knowledge has improved in recent years in such areas as shielding design, stroke characteristics, and impulse current behaviour of grounds, and international studies now under way will contribute yet more information. An immediate need for the majority of designers, however, is a relatively simple calculation method that includes the benefits of newly available data and that also provides a framework for future improvements.

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The most suitable method found by the Working Group was recently developed from wide experience in lightning performance by John G. Anderson as part of EPRI Project RP68. It uses a number of approximations to provide a relatively condensed calculation suitable for a small computer or calculator[1]. Checking and qualifying procedures by this Working Group have included coding the method in Fortran, comparison of calculated performance with carefully monitored utility lines, and studies of the method and results. A number of minor modifications were made to incorporate newly available information on lightning and related factors, and the method has now been adopted by the Working Group for use as an everyday method of lightning performance estimation.

This paper outlines the essential features of the method, and provides comparisons with the performance of existing lines, plus lookup curves for easy reference. Copies of the Fortran program and supporting documentation can be obtained from the IEEE Publications Center. It is anticipated that future Working Group activity will include updates and improvements to the program as more research results become available.

BASIS OF THE SIMPLIFIED METHOD

By their nature, a large category of real life engineering problems are ill defined. Constants are rarely known precisely and are often not really constant, input stimuli are difficult to describe mathematically except in idealized ways, and outputs may be depictable only in terms of probabilities or average values. Estimating the lightning performance of transmission lines is a good example; lightning flash characteristics vary, flash locations on a transmission line vary, tower footing resistances vary with current and time, the heavy corona created on conductors and on the tower itself by the strokes makes wave propagation effects non-linear, and the transmission tower response is very waveshape sensitive.

As a further complication, lightning incidence can vary widely from year to year and change its characteristics from summer to winter (at least in northern latitudes). Any method of estimating the lightning performance of transmission lines must cope with a variety of these statistical and non-linear effects, and it is pointless, and indeed misleading, to promote a method whose prediction accuracy exceeds the precision of knowledge of the "constants" and stimuli that enter the problem.

The uncertainties of the problem do permit simplification of the solution method, since unless details of a problem are known with precision, there is

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not much point in making precise calculations. Rough estimates are as likely to be as correct as a solution carried out to the sixth decimal place.

This simplified method follows these principles to;

a. linearize the problem so it can be solved without excessive iterative computation

b. provide a method based on classical effects well recognized in the literature

c. provide a solution that recognizes the statistical nature of the problem

d. present the method in the form of a computer algorithm capable of being installed on a large variety of machines

e. be able to adjust this algorithm from year to year as further research permits.

Assumptions About Thunderstorms

Keraunic Level

The method starts with a value of keraunic level, the average number of days per year on which thunder is heard. The keraunic level for a given line is estimated from available isokeraunic maps or from weather bureau records. An isokeraunic map for the world is shown in Figure 1[2].

Estimates of keraunic level may need to be adjusted for mountainous or tropical regions. The accuracy of the final solution is directly proportional to the accuracy of this estimate.

Incidence to Lines

After an estimate for the keraunic level has been made, the number of flashes to earth that are intercepted by the transmission line is approximated. The simplified method [1] assumes that the line throws a sort of electrical shadow on the earth and that any lightning flash which would normally fall within this shadow will contact the line instead (Figure 2). Using this concept, an approximation for the number of flashes to any line is provided by Equation (1):

$$N_L = 0.004T^{1.35} (b + 4h^{1.09}) \tag{1}$$

where

N_L = number of lightning flashes to a line per 100 kilometers per year

T = keraunic level in the vicinity of the line (thunderstorm days/year)

h = average height of the shield wires, meters

b = the horizontal spacing between the shield wires, meters.

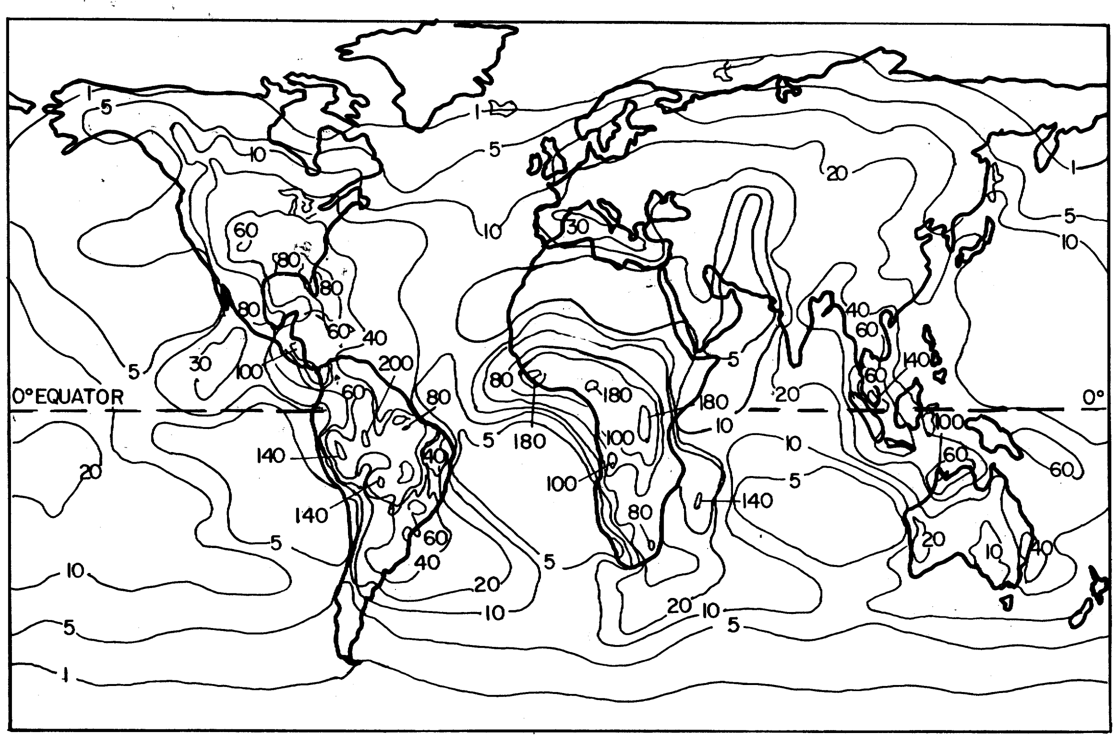
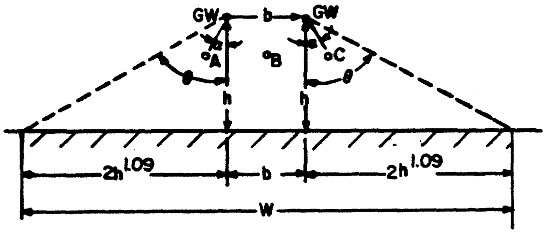


Figure 1. Isokeraunic Map of the World

Figure 2 shows the dimensions h and b in more detail. For the average height of the uppermost conductors, use the height at the towers minus two-thirds of the sag.



θ shadow angle (assumed 63½ degrees)
α shield angle between shield wire and phase conductor
W shadow width on earth's surface
GW shield wire location
A. B. C phase wires

Figure 2. "Electrical Shadow" Created on the Earth's Surface by a Transmission Line

Assumptions About Stroke Characteristics

Number of Strokes

Each lightning flash may contain several strokes. These strokes are the short duration peaks of high current that travel in rapid succession down the flash channel. The entire flash may persist for a second or more, but the high current peaks that can cause flashover will only exist for tens or hundreds of microseconds. About 55% of all flashes will contain more than one stroke [2] and the mean number of strokes per flash is three.

Wave Shapes

Unfortunately, all strokes in a flash, or strokes in different flashes, are not of equal severity. Their amplitudes and waveshapes vary statistically. The simplified method is based on the premise that the first stroke in a flash has a high probability of being the most severe, the reasoning behind this assumption being explored in Reference 1, and the method standardizes on a linearly-rising negative stroke current wave with a 2 microsecond time to crest. Figure 3 compares this assumed waveform with a median waveform developed from measurements of strokes [2]. The crest amplitude varies according to the idealized cumulative probability distribution shown in Figure 4, and this amplitude is assumed to decay linearly to zero current in 100 microseconds. It would be more rigorous to utilize statistical distributions for all the stroke parameters (rise times, tail times, charge, and amplitudes), but the method would no longer be simple, and the increased rigor would not be likely to greatly increase the overall precision of the results, based as they are on rough estimates of lightning incidence to the line.

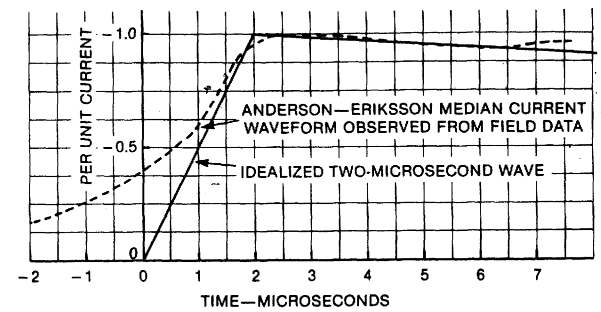


Figure 3. The Idealized Stroke Current Waveshape Used in the Simplified Method

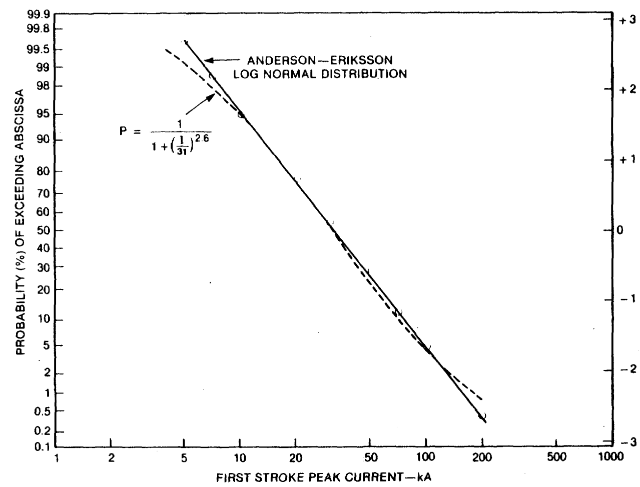


Figure 4. Cumulative Probability Distribution of Stroke Current Magnitude in Negative Lightning Flashes

Magnitudes

The probability distribution of crest current magnitudes is largely based on data provided by R. Anderson and A. Eriksson in South Africa [2] and by Popolansky [3]. The approximating equation is:

$$P_I = \frac{1}{1 + (\frac{I}{31})^{2.6}} \text{ p.u.} \tag{2}$$

where

P_I = probability of exceeding stroke current I

I = stroke current, kA

The simplified method makes insertion of a different probability curve, if preferred, an easy task.

BACKFLASHOVERS

Lightning caused flashovers are subdivided into two groups: backflashovers, where the stroke terminates on a structure or shield wire, changing the potential of the structure sufficiently to cause a flashover to the phase conductor, and shielding failures where the stroke terminates directly on the phase conductor. The following discussions describe effects that are more important to backflashovers.

Bundled Conductors

The simplified method assumes that all subconductors in a bundle are at the same potential, and that any bundle can be replaced by an equivalent single conductor operating at the same potential. The classical theory for doing this is well known [1] and will not be repeated here. This conversion is contained in the computer algorithm.

Corona Effects

At high transient voltages approaching air gap breakdown, corona streamers carry significant quantities of charge away from the conductors and tower members. This effect creates non-linear changes in capacitances to ground and between conductors, and distorts the voltage waveshapes appearing across the insulators. This distortion is large enough to demand at least a crude representation in the simplified method, so it is assumed that corona moving outward from each conductor surface is equivalent to a uniform expansion of the conductor diameter, and that this expansion continues until the gradient at the periphery of the corona envelope drops to some critical extinction gradient E_O. This gradient has been studied by Brown [4] and others, and a value of 1500 kV per meter has been selected. For a conductor suspended horizontally above a conducting earth, Figure 5 provides computed values of the corona diameter of the conductor as a function of the ratio of the conductor voltage V to the critical extinction gradient E_O. For a backflashover calculation the voltage V for shield wire corona in Figure 5 is taken as 1.8 times the lowest critical flashover voltage of the insulators, for a 2 microseconds time to crest.

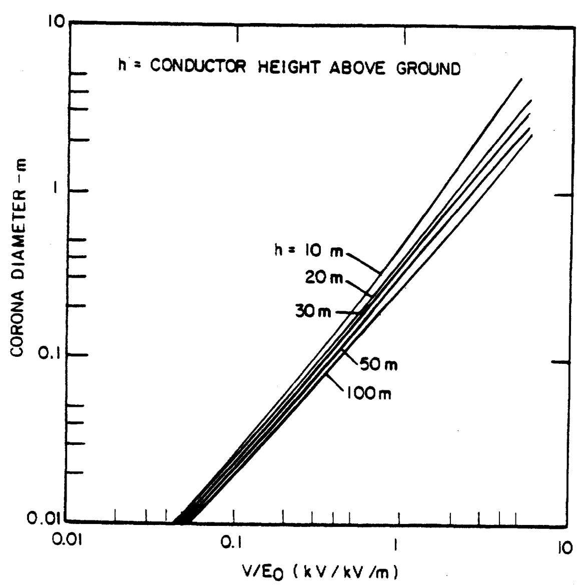


Figure 5. Computed Conductor Corona Diameters as a Function of Conductor Voltage V, Corona Extinction Gradient E_O, and Conductor Height

This 1.8 multiplier is the assumed ratio between tower or shield wire voltages to earth, and the insulator flashover voltage during a backflashover event. The corona envelope is determined by voltage to ground, not insulator flashover voltage. For a shielding failure calculation the conductor voltage to ground and the insulator voltage are about the same at flashover, so no multiplier is used.

The corona envelope is assumed to change the capacitance of a conductor but not its inductance. This increases the no-corona surge impedance of each conductor by a geometric mean relationship:

$$Z_{nn} = 60 \sqrt{\ell n \frac{4h}{d} \cdot \ell n \frac{4h}{D}} \qquad (3)$$

where

Z_{nn} = effective surge impedance of conductor at the moment of flashover (ohms)

h = conductor height at the tower (meters)

d = equivalent conductor diameter without corona (meters)

D = equivalent conductor corona diameter determined from Figure 5 (meters)

Tower Surge Response

The simplified method assumes that a transmission tower can be approximated by a vertical transmission line of constant surge impedance protruding upward from the earth's surface. This transmission line has the same length as the tower height, and the velocity of propagation of current waves up and down it is assumed to be 85% of the velocity of light (the presence of braces and tower crossarms tends to retard wave propagation). Figure 6 provides some relationships which can be used to approximate the tower surge impedance Z_T for various tower shapes. If the user prefers other relationships they can be used.

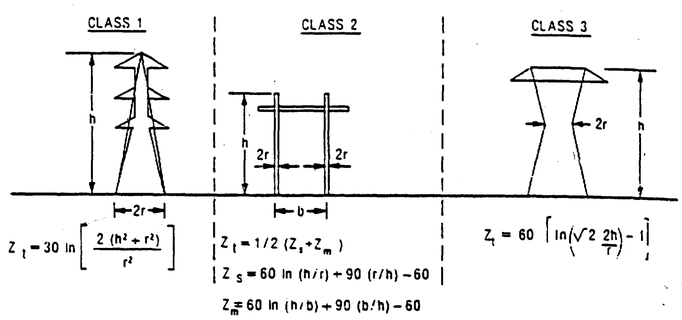


Figure 6. Approximations for Surge Impedance (ohms) for Various Classes of Tower

Footing Resistance

Predictions of lightning flashover performance are very sensitive to the choice of tower footing resistance and, unfortunately, this non-linear quantity is not often well defined. Footing resistance is usually measured with a ground resistance megger [1,5] and is the observed low frequency resistance at low currents. Because of capacitive and ion-conduction effects in the earth, this resistance will change with stroke waveshape and magnitude, and soil moisture content. To avoid having to make all kinds of judgmental corrections for the values of footing resistances to use in a calculation, the simplified method uses the low frequency (meggered) values. This assumption is one that should benefit from present research.

Line footing resistance will vary greatly along a right-of-way, being more than 1000 ohms on rock ledges, and less than an ohm in damp clay. When the footing resistances change widely, the flashover rate should be estimated for several line sections, each with an average footing resistance. The total flashover rate is then given by the relation

$$F = \frac{F_1 L_1 + F_2 L_2 + \ldots + F_n L_n}{L} \tag{4}$$

where

F = total line tripout rate per 100 km per year

F_n = computer flashover rate of section n per 100 km per year

L_n = length in km of section n

L = length in km of the entire line

Computation of Tower Top, Crossarm and Insulator Voltages

When stroke current enters a tower top, it creates a sequence of traveling waves of current that move up and down the tower and along the shield wires. These waves combine to develop a tower top voltage V_T to earth, a voltage V_R across the footing resistance, and a voltage V_C to earth at each crossarm C. In addition, the currents traveling along the shield wires induce a voltage V_p to earth on each phase conductor p (which adds or subtracts from the power frequency voltage present on the phase at the instant the stroke occurs). The insulator voltage for phase p is then the difference between its crossarm voltage V_C and the total phase conductor voltage to earth.

The simplified method computes all these voltage components using a set of traveling wave equations described in Reference 1. The voltages are computed only at 2 microseconds - the assumed crest of every stroke current wave - adjusted slightly for the travel times from tower top to the crossarms. Figure 7 presents an example of the per unit insulator voltages that are created without any power frequency voltages being present. The bottom phase insulator experiences the greatest voltage because it is farthest away from the shield wires and, consequently, has the least coupling from them.

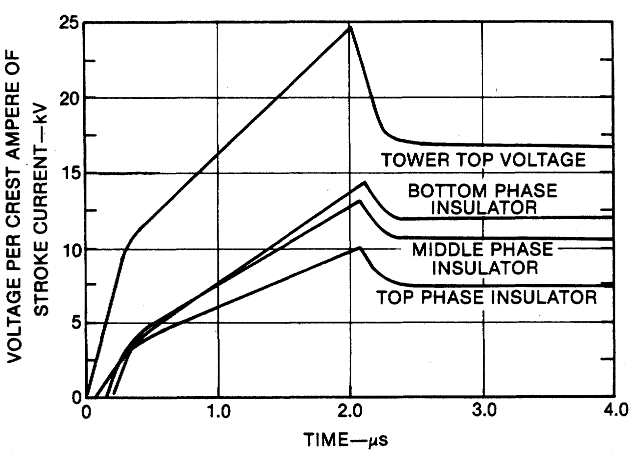


Figure 7. Example of Computed Insulator Voltages for a Lightning Flash to a Tower Top
Stroke Current Time to Crest = 2 microseconds
Magnitude = 1.0 per unit
No Power Frequency Voltage Present

When Does Backflashover Occur?

Figure 8 provides a set of volt-time curves for insulator flashover as suggested by Darveniza, Popolansky and Whitehead [6]. Volt-time curves describe the insulation strength for a 1.2/50 microsecond standard lightning impulse. The crest of the impulse or the maximum voltage attained is plotted as a function of the time-to-breakdown or flashover. In the simplified method, the volt-time curves are used to estimate the insulation strength or flashover voltage for the lightning surge having a 2 microsecond front. Plotted on the figure is an example insulator voltage wave V_S created by a stroke current wave of 2 microseconds time to crest. The simplified method makes the assumption that any insulator volt-time curve that touches or passes through this voltage wave V_S will cause a flashover. In Figure 8, any insulator string less than 3 meters in length will not be able to withstand the voltage wave V_S. This is a very simplistic assumption, but as long as a fixed stroke current waveshape is always used (as it is in the simplified method), the error so created can be adjusted in the final constants of the program.

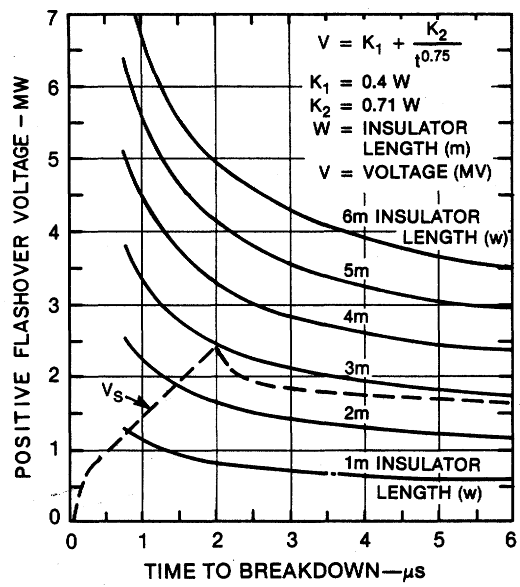


Figure 8. Volt-Time Curves for Line Insulators Plotted with One Insulator Voltage Wave V_S

Effects of Power Frequency Voltage

Although the average power frequency voltage across any line insulator is zero, power frequency voltages do influence the average flashover rate. For example, for three insulators supporting a three-phase circuit, at least one of them will have a power frequency instantaneous voltage that adds to the lightning voltage, forcing a flashover of that phase to take place at a lower stroke current than it otherwise would. The presence of power frequency voltage will generally increase the lightning flashover rate of a transmission line, and this effect must be included. In the simplified method used here, each phase voltage is stepped through 15° increments and the incremented voltage values added to or subtracted from the voltages due to lightning. As a result, flashovers scatter more widely through the insulator array than they would if power frequency voltages were ignored, and the overall flashover rate increases significantly. The details of the calculation are described in Reference 1.

SHIELDING FAILURES

A "shielding failure" is an insulator flashover that occurs when a lightning flash hits a phase conductor directly instead of hitting a tower top or shield wire. It is called a shielding failure because the shield wires have failed to prevent the phase conductors from receiving a direct strike, although the general phenomena are the same if the line is unshielded.

Pioneering research data on shielding failures was developed in the "Pathfinder Project" by Whitehead and associates [7,8]. An electrogeometric theory used to compute shielding failures was first developed by Young, Clayton and Hileman [9] with some modifications by later authors, and provides a useful, although necessarily simplistic, physical model of the shielding failure process. The mechanisms of the final development of a stroke to a line or to earth are presently the focus of considerable research. Typical of this work are publications by Eriksson [16] and Dellera, et al [17], with continuing studies presented at CIGRE WG 33-01, Lightning. A version of the electrogeometric theory is covered in detail in Reference 1, together with a method for calculating shielding angles and shielding failures.

In the present model, as the leader channel of a lightning flash reaches the vicinity of a transmission line, there is assumed to be a "final jump" or "strike" from the tip of the leader to the line. The length of this final jump increases as the charge in the leader channel increases, and this charge is also responsible for the magnitude of the stroke current that occurs (the larger the charge, the greater the stroke current). Thus the length of the final jump expressed as a function of stroke current can be approximated by Whitehead's equation:

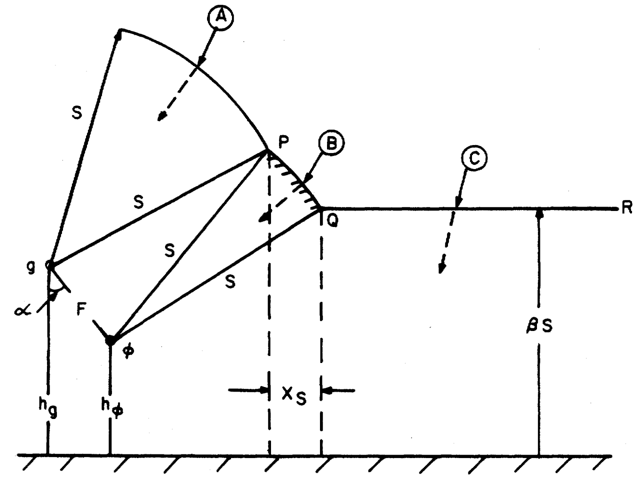
$$S = 8\ I^{0.65} \qquad (5)$$

where

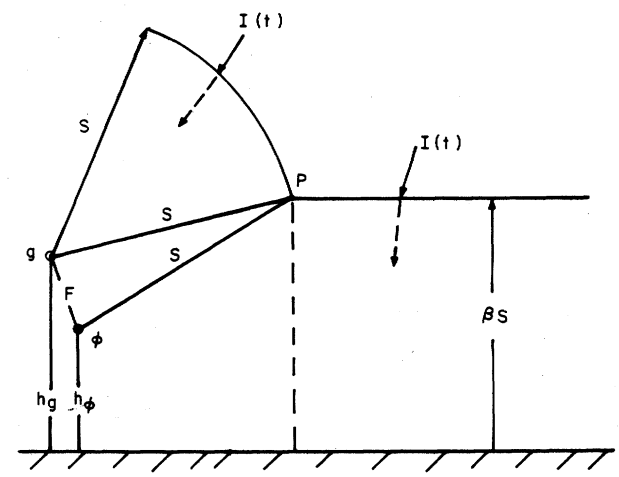
S = length of the final jump, meters

I = expected stroke crest current, kiloamperes (see Figure 4 and Equation (2))

Considering a single shield wire and one phase conductor, the determination of likelihood of shielding failure resolves into a geometric problem, as illustrated by Figure 9. In Figure 9a, the same strike distance S is assumed to exist for both the shield wire and phase conductor. As shown in the figure, if the tip of a descending lightning leader crosses the arc PQ, it is closer to the phase conductor than to the shield wire and, provided it is of sufficient current magnitude to create a jump having strike distance S, a shielding failure will occur. As the length of S increases, a condition is reached (Figure 9b) where the uncovered area shrinks to zero, and "effective shielding" is said to exist. Conversely, if the descending lightning leader crosses the lines QR in Figure 9a, it will jump the distance S to ground before it will jump to the phase conductor. A variable beta is used to account for differences in flashing strength between leader tip and ground plane versus leader tip to conductor. Values of beta used in the simplified method range from 0.64 for UHV lines to 1.0 for low voltage lines.



(A)



(B)

Figure 9. Incomplete Shielding (A) and Effective Shielding (B) According to the Electrogeometric Theory

This model is believed by the Working Group to have some shortcomings; in some instances, estimated shielding failure rates seem low, and design angles for perfect shielding somewhat conservative. The Working Group is actively working on improvements to this component of the program, and recent developments by E. Whitehead appear very promising. In the meantime, the procedure given above is incorporated in the program, since its results provide a guideline and a basis for future development. The computer program automatically solves this geometrical problem, applies the probabilities of the various stroke currents existing and provides the probability of shielding failures occurring.

THE COMPUTER PROGRAM

In the original form, the simplified estimating method utilized a tabular procedure and step-by-step calculations [1]. The length of this procedure, rather than its complexity, made it very desirable to use a computer program. The program FLASH was subsequently prepared by the Working Group, written in FORTRAN. It contains approximately 1100 lines of code and comments. Copies of a Users Guide and the program are available from the IEEE Publications Center.

COMPARISON OF RESULTS WITH LINE PERFORMANCE

Comparison of predicted tripout rate versus actual line performance is often an uncertain task. First, there is only a limited amount of field data available in the literature with adequate experience and data. Second, even if the physical parameters of the transmission lines are adequately defined (and they usually are not), it is never certain how footing resistances were measured, how the surrounding terrain affects lightning performance, and most importantly, what is the ground flash density. Finally, it is very difficult to accurately determine whether an interruption to supply is due to lightning. Many reporting schemes tend to lump unknown tripouts during storms under that heading, and therefore great care has to be taken in comparisons. The Working Group has been developing data on selected line performance for some time.

From this data, some of which is published [15], several lines were selected as having adequately documented tripout rates for comparison. The results of the comparison are shown in Table 1.

TABLE 1
Calculated Vs. Actual Lightning Tripout Rates per 100 km./year

Line Name	Actual Tripout Rate	Predicted Tripout Rate(1)
Johnsonville-Cordova 500-kV	0.30	0.40
Browns Ferry-West Point 500-kV	0.94	1.50
South Jackson-Cordova 161-kV	0.55	0.48
Sequoyah-Charleston 161-kV	3.83	3.90
CIGRE Line #30 (230 kV)	0.24	0.14(2)
CIGRE Line #31 (345 kV)	3.44	2.48(2)

Note: 1. Calculated by dividing line into 4 or 5 component parts by tower type or footing resistance distribution.

2. Data not available for detailed modeling.

From the above tabulation, it can be seen that the simplified estimating method can provide a reasonably accurate estimate of lightning outage rates if the line is accurately modeled. Use of single average values for the physical and electrical factors in the line will often result in inaccurate estimates.

DESIGN CURVES

Previous publications have presented useful generalized design curves for factors such as the number of insulators, conductor arrangement, and tower footing resistance. With the simplified analysis method, solutions for specific line designs can be generated easily, and this procedure, rather than generalized curves, is recommended to ensure the best possible estimates of performance. However, the general curves in Figures 10 and 11 are provided for convenience in initial estimations.

The two basic conductor configurations used for these general curves were single circuit horizontal and double circuit vertical. Dimensions for four voltage (i.e. insulation level) classes were obtained from a survey of lines reported in CIGRE and IEEE literature; and this information is provided in the documentation accompanying the program.

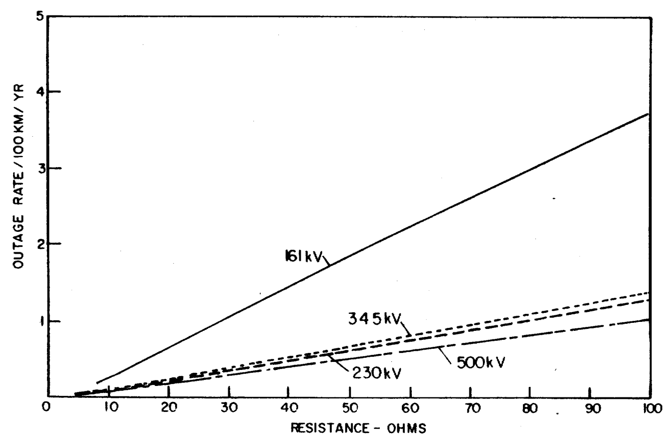


Figure 10. Calculated Lightning Outage Rates for Single Circuit Horizontal Lines Versus Footing Impedance

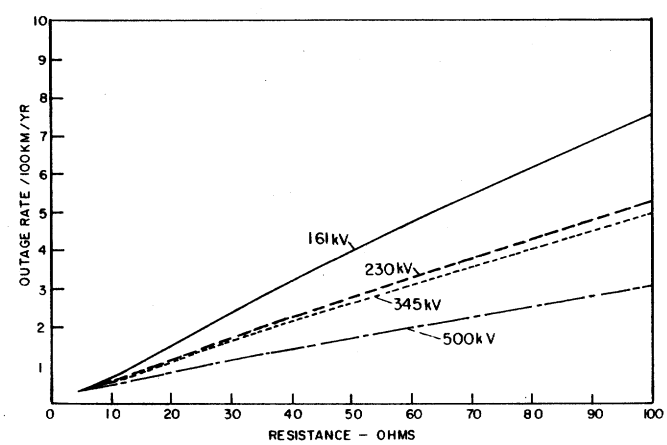


Figure 11. Calculated Lightning Outage Rates for Double Circuit Vertical Lines Versus Footing Impedance

SENSITIVITIES

Table 2 illustrates performance sensitivities to key parameters.

TABLE 2
LIGHTNING BACKFLASHOVER OUTAGE RATE SENSITIVITY FACTORS
(typical, for double circuit 345 kV, 20 ohms footing)
p.u. change in flashover rate/p.u. change in parameter

Insulator CFO	-3.0
Stroke current	2.6
Footing resistance	1.7
Coupling - shield to conductor	-1.1
Keraunic Level	1.0
Travel Time of wave on tower	0.9
Average Conductor Height	0.5
Tower Impedance	0.4
Line Voltage	0.4
Corona on Shield and Conductor	0.2

The effect of changing several parameters at once can be found by converting their sensitivities to percentages and adding them. Multiple changes or large changes can result in accumulated errors, however, so it is generally recommended that a complete calculation be repeated, rather than adjusting results with these factors.

FUTURE IMPROVEMENTS

The simplified method of calculation presented here is based on that developed by J. G. Anderson [1]. While adopting this method, the Working Group agrees with J. G. Anderson that it can be further improved as additional investigations and studies are completed. It is the intention of the Working Group, in cooperation with CIGRE WG 33.01, to continue to study in detail all parameters affecting the lightning performance of transmission lines with the goal of continuing improvements.

Significant research and studies are presently being performed in the areas of lightning flash parameters, shielding performance, and backflash performance. A few of the more important are as follows.

Lightning Flash Parameters

The primary data required for calculations are crest current and waveshape for all strokes in a flash and the number of strokes to a line. The present data base for the current parameters [2] consists of 266 records from which the first stroke current magnitudes are obtained and 140 records from which the waveshape is obtained. This meager data base is being augmented by data from research masts in South Africa and Italy, as well as data from research lines in South Africa and the USA.

The number of strokes to a line is presently estimated from ground flash density, which has been measured in various countries by a ground flash density counter [11] and a lightning location system [12]. This latter system, installed extensively within the USA, also has the capability to provide estimates of crest current and waveshape.

Ongoing stroke current measurements promise a large increase in data and resultant improvements in estimates of current parameters, and in the near future, ground flash density maps of the USA should be available to replace the present keraunic level maps from a lightning location survey (EPRI Project RP2431). This project will also help identify the incidence of severe positive polarity strokes.

Shielding

Present shielding failure analysis is based on a geometric model which in turn is based on a simplified model of the last step of the first stroke of a flash [4,8,9]. This model, combined with field experience, has proved useful, and has been successfully applied in specifying the shield wire location for both lines and stations. As previously noted however, the model presently used is believed to be somewhat unsatisfactory in some respects. Presently, several investigators are attempting to further clarify the phenomena of the last step [13], and it is expected that these studies will result in improvement to the present models.

Backflash

Estimation of the backflash rate is one of the more complex calculations for lightning, and a continual effort is being made by several investigators to improve knowledge of the various parts of the phenomena. Of primary importance are investigations into the only two parameters which are controllable by a line designer: the footing resistance, and the insulation strength. The lightning impulse impedance of either concentrated grounds, e.g. ground rods, or of counterpoise is both a function of current magnitude and time. Test results showing the effect of current for concentrated grounds has recently been analyzed [14] and investigators have suggested procedures for modeling both the concentrated and counterpoise grounds. Similarly, lightning surge voltage across the tower insulation caused by a stroke to the shield wires is of non-standard shape. Methods to estimate the critical flashover of this non-standard surge in terms of that for a standard 1.2/50 microsecond surge are presently being investigated [13].

Other parameters of importance in estimating the backflash performance that are presently being restudied include corona effects on surge impedance; coupling and traveling waves; and surge impedance of towers. In addition, the effect of the charge above the tower on the backflash is also being reconsidered. An additional area of concern is the estimation of the double circuit backflash rate, for which the program MULTIFLASH has recently been developed by J. G. Anderson in EPRI project RP2080.

ACKNOWLEDGEMENTS

In addition to past working group members and the many overseas corresponding members, the authors make special acknowledgement to the contributions of Dr. Karl Berger, recently retired, who contributed so much to our knowledge of lightning for so many years and to the lives of those who know him.

REFERENCES

There are literally hundreds of references that should be acknowledged as background contributions to this paper. This is unfortunately impractical, and these references are therefore limited to the most recent and directly applicable to the topics discussed. Each of the references below obviously lists its own source references, and in addition an excellent source of references for a more wide-ranging review of lightning topics is provided by the two-volume publication "Lightning", Academic Press, 1977, edited by the late R. H. Golde.

1. J. G. Anderson, "Transmission Line Reference Book - 345 kV and Above," Second Edition, 1982, Chapter 12, Electric Power Research Institute, Palo Alto, California.

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Discussion

Edwin R. Whitehead (University of Colorado, Boulder, CO): The report of the Working Group, of which the writer is a member, properly separates the estimation of outages form shielding failure and backflash events. This discussion addresses only the estimation of shielding failure lightning outages.

Shielding failures have been widely studied experimentally, statistically, and analytically, as indicated by the limited, but representative, list the references of the report. I regret only the omission of the pioneering paper by Dr. R. H. Golde [1].

Fig. 1 involves all three approaches. The solid curve permits an estimate of the "worst case" shielding failures for "open country" such as agricultural or grazing land of flat or rolling character. Lines 31, 32 and 39 traversed such terrain in Ohio and Illinois having keraunic levels of 43, 40 and 40 respectively. Lines 31 and 32 were equipped with "Pathfinder" instruments for about six years. Line 39 was designed at the outset of a field research program to have "effective", i.e., "perfect," shielding in accordance with a preliminary design model. The solid black dots of the figure represent independent data from the CIGRE Survey [2] and are for a total exposure of over 53000 km-years. The open-circle points are for recorded shielding failures and serve to define the adjacent solid points as shielding failures. These lines had ground resistances averaging under 5 ohms.

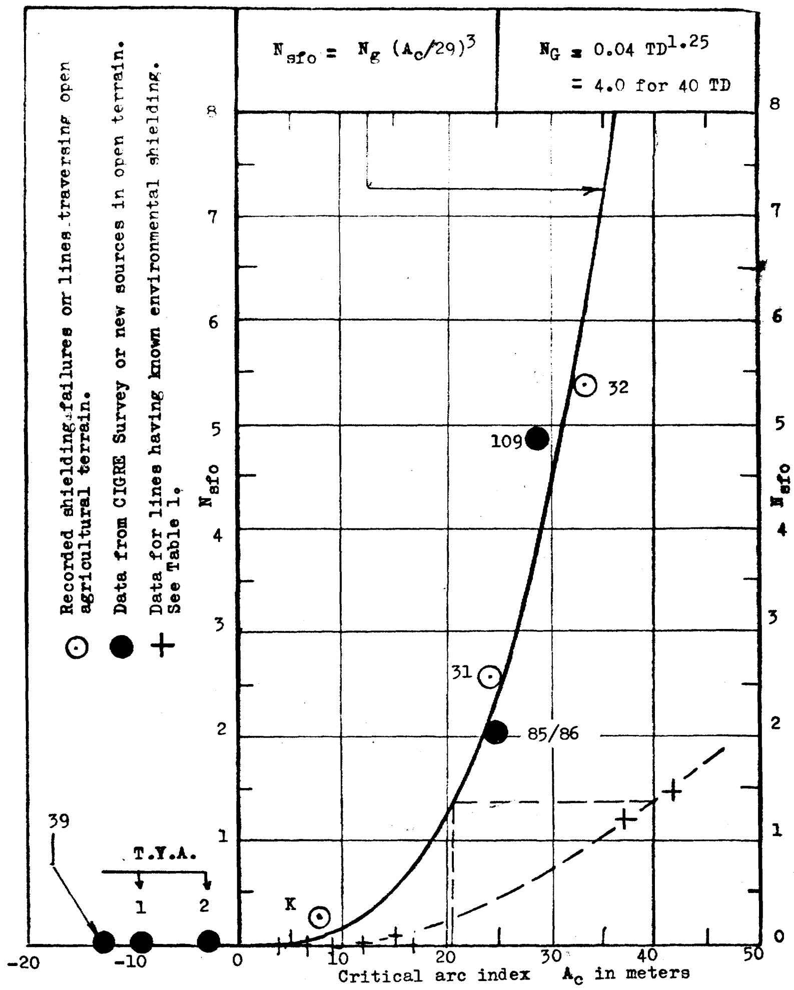

Fig. 1. Estimation of "worst case" shielding failure outages.

The empirical curve fitted to these points is for a ground flash density of 4.0 corresponding to the keraunic level of 40. The shielding failure outage rate for the symmetrical terrain involved varies as the cube of the exposure arc A_C calculated for the critical current to the phase conductor. As in Ref. [2], the critical arc is used simply as an index, but the curve can be used to estimate the "worst case" or "upper bound" shielding failure outage rate. Clearly, lines having a zero or negative critical arc are "effectively" shielded.

Also shown in Fig. 1 are a number of points indicated by a plus + sign having *positive exposure arcs along with shielding failure rates far below those of the solid curve.* It is obvious that some other shielding mechanism is at work in these cases. Such a mechanism has been defined as "environmental shielding." Table 1 lists physical and electrical parameters for lines contributing these points along with the corresponding environmental conditions. Fig. 2 is a plot of the shielding angles versus the mean height/striking distance ratio Y_O/S_C compared to a shielding design curve suggested for consideration of the Working Group. This curve is made possible by John Anderson's ingenious choice of Yo as the mean height of shield and phase conductors together with his earlier work with K. O. Tongen [3]. These figures suggest that

(a) "Worst case" shielding failure estimates *may*, happily, be too high for some existing lines because of environmental shielding, and
(b) Shielding design for *new lines* should be based on *bare earth.*

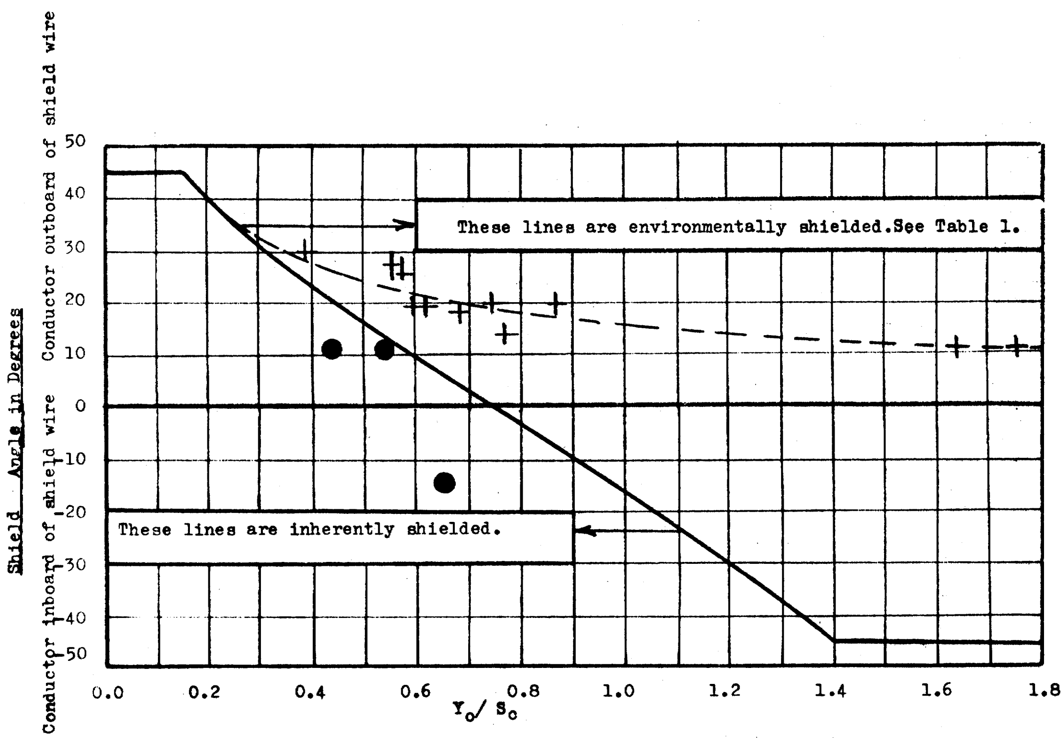

Fig. 2. Illustrating the concepts of inherent and environmental shielding. See Table 1.

Table 1

Line No.	$V_{50}(-)$ kV	Z ohms	I_c kA	S_c m	Y_p/S_c pu	Y_o/S_c pu	β (I) pu	α deg	ϵ deg	θ_p deg	θ_2 deg	A_c m	N_{sfo} *	km-yr	Environment %Open	%Forest
CAN																
88	2160	360	12.0	40	0.46	0.60	0.76	19	8	27	18	6.6	0.00	2570	25	75
89	2160	360	12.0	40	0.46	0.60	0.76	19	8	27	18	6.5	0.00	2345	25	75
SWE																
92	2100	400	10.5	37	0.27	0.38	0.80	30	6	36	32	3.9	0.00	1257	40	60
95	2100	400	10.5	37	0.42	0.57	0.77	26	9	35	21	9.2	0.00	1404	0	100
96	2100	400	10.5	37	0.43	0.55	0.77	27	7	34	20	9.3	0.00	1158	10	90
97	2100	400	10.5	37	0.43	0.55	0.77	27	7	33	20	8.6	0.12	1701	0	100
ZAM																
51	1764	360	9.8	35	0.70	0.87	0.73	20	9	29	2	17.0	0.00	1476	See Note 1	
52	1764	360	9.8	35	0.58	0.74	0.74	20	9	29	9	12.0	0.00	1320	" "	"
JAP																
(105 107)	1464	400	7.3	29	1.37	1.64	0.67	12	16	28	-44	36.7	1.23	10748	28 See Note 2	47**
108	1464	400	7.3	29	1.48	1.75	0.67	12	16	28	-54	41.8	1.49	8037	20	12**

NOTES: (1) These lines are parallel with a separation of 46 meters.
(2) Data are for the center and outermost phase of the double-circuit vertical configuration. Forty four per cent of all outages were on this phase.
* N_{sfo} = shielding failure outages. = 0.85 N_{sf} from the Pathfinder research.
** Additional environmental shielding could be from buildings in industrial areas.

Data below are for an exceptional HV line of the Pathfinder program having tree shielding.

EEI-C
115 kV 950 400 4.75 22 0.77 0.82 0.74 63 2 65 −2 25.7
0.00 2000 30% 70%

line open forested

Trees were often higher than the phase conductors. Sand and gravel soil required the use of a continuous counterpoise. ALL LIGHTNING OUTAGES FOR THE ENTIRE PATHFINDER TEST PERIOD WERE BACKFLASH EVENTS. There were six single-circuit and three double-circuit tripouts. The conductors were in a *horizontal* configuration. Note the very large shielding angle. This is an extreme example of environmental shielding.

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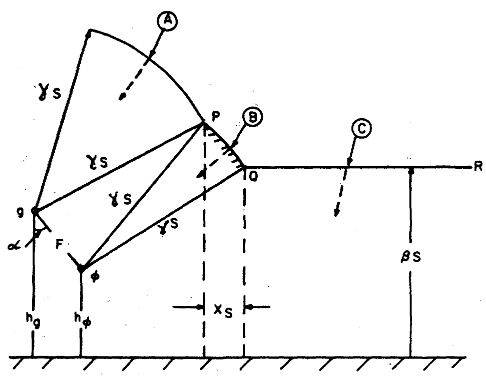
Manuscript received July 27, 1984.

Abdul M. Mousa (BC Hydro, Vancouver, Canada): Producing a simplified standard design method is a huge task where the subject is both complex and controversial, which is the case with lightning. The members of the Working Group deserve our gratitude for their endeavor. The response of the Working Group to the following comments and questions would be appreciated:

1. According to Eq. (5) and Fig. 9(A), and for the same stroke current of 15 kA,
   i. In the vicinity of a 132 kV line ($\beta = 1.0$), the striking distance to ground = 46.5 m.
   ii. In the vicinity of a 1200 kV line ($\beta = 0.64$), the striking distance to ground = 29.8 m.
   The difference between the above two quantities has no justification in physics. This can be rectified by calculating a "reference" striking distance S in terms of the expected stroke crest current I based on the rod-to-plane gap configuration. The striking distances to ground and to conductors would then be obtained from S by applying multipliers β and δ, respectively, as shown in Fig. 9(C). Factor β would be independent of the voltage class and approximately equal to 1.0, while factor δ would be greater than 1.0 and increases with height of conductors above ground. Fig. 9(C) is compatible with the approaches used by F. S. Young et al [9] and by Golde [18]. The opinion of the Working Group regarding the values of factor δ would be appreciated.



$\beta \cong 1.0$ (INDEPENDENT OF VOLTAGE CLASS)
$\gamma > 1.0$ (INCREASES WITH CONDUCTOR HEIGHT)

Fig. 9C. Proposed alternative to Fig. 9A.

2. The striking distances are statistically distributed about their mean value. In earlier works, Whitehead et al (Ref. [19] for example) calculated the shielding failure rate using the "mean" striking distance $\bar{S}$ but designed effective shielding systems based on the "effective" striking distance S. The effective striking distance was given as,

$$\hat{S} = (1 - \sigma)\,\bar{S} \qquad \ldots . (6)$$

with standard deviation $\sigma \cong 10 - 20\%$ [19, 6].

In this paper and in Ref. [1], the differentiation between "effective" and "mean" striking distances has disappeared. It would be appreciated if the members of the Working Group elaborate their opinion about this point.

3. In Ref. [1] and [20], the striking distance is given as:

$$S = 10\, I^{0.65} \qquad \ldots . (7)$$

The value given by Eq. (5) is only 80% of the value given by (7). What is the reason for the difference? Is it related in any way to the earlier usage of the terms "mean" and "effective" striking distances?

4. The width of the line shadow implied in Eq. (1) is as follows:

$$W = b + 4\, h^{1.09} \qquad \ldots . (8)$$

The discusser understands that Eq. (8) was developed by Whitehead using an electrogeometric model in which the striking distances to earth and to shield wires were taken equal to each other. Eq. (1), and hence Eq. (8), is proposed in the paper as applicable to lines of all voltage classes. Shielding failures, on the other hand, are calculated using Fig. 9 which incorporates a modifying factor β. Varying β as a function of the voltage of the line, as suggested in the paper, appears to the discusser to represent an inconsistency with Eq. (1).

5. There is reasonable agreement among researchers that the median value of the amplitude of lightning currents collected by the typical (limited) range of shield wire heights is of the order of 30 kA. On the other hand, there is a controversy regarding the median value of the amplitude of lightning currents to flat ground and the general effect of height on median current. In the method used in the paper, Eq. (2) with a median current of 31 kA represents the frequency distribution of the amplitude of lightning currents to the line, *not to ground.* The discusser suggests that this fact be indicated in the title of Fig. 4, and wishes to emphasize that the Working Group's method does not constitute taking sides in the above controversy.

6. Producing a simple, yet reasonably valid, method for dealing with the complex subject of lightning represents an invaluable service to the industry. As stated by the Working Group, "it is pointless to promote a method whose prediction accuracy exceeds the precision of knowledge of the constants and stimuli that enter the problem." In the paper, Eq. (2) is used to replace the Anderson-Eriksson frequency distribution of lightning current amplitudes. Does this mean that the Working Group does not believe the Anderson-Eriksson distribution to be of high accuracy?

7. Since the Working Group has opted for keeping the list of references very short, it may be rather annoying to the general reader that six out of the seventeen references belong to the "grey literature" class (Refs. [2, 10, 13, 14, 16 and 17]). For example, there is no central location from which the papers of CIGRE Working Group on Lightning can be ordered. Also, the discusser has encountered difficulties in obtaining a copy of Ref. [10]. It may be helpful to mention that the substance of Ref. [2] was re-published as an *Electra* paper (Refs. [21] below) and its summary was published as an official CIGRE paper (Ref. [22]).

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[21] R. B. Anderson and A. J. Eriksson, "Lightning Parameters for Engineering Application," *Electra,* No. 69, pp. 65-102, March 1980.
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Manuscript received July 30, 1984

A. C. Liew (Department of Electrical Engineering, National University of Singapore, Singapore): The working group has produced a useful paper. The group's response to the following points and comments is appreciated.

(a) The simplified method uses the low current meggered value of footing resistance as its input. Does the program automatically surge reduce these values before proceeding with the voltage computations? If not, the voltages calculated at the tower tops and conductors will be higher than they should be and all the corona corrections will be in error. I would have thought that a surge reduced value following a simple curve would have served as a beteter input.

(b) The authors state that the errors created in the simplified method of assuming a fixed stroke current waveshape can be adjusted in the final constants of the program. What are these constants and on what basis are these "adjustments" made?

(c) A very important parameter which is controllable by a line designer and which significantly affects the outage rate of the line is the probability of transition from an impulse flashover to a power follow arc. Double circuit lines of up to 275 kV using wooden crossarms for its proven arc-quenching capabilities have been successfully used in Malaysia with marked improvement in its outage rate as compared to previous all steel structures. This paper does not seem to have discussed this at all.

(d) It is not clear if the method proposed can cater for multiple flashovers for the same lightning stroke incident and if so, how? Consideration of only the first flashover in the assessment of outage rate can lead to serious errors in some cases, e.g., where the first flashover reduces the insulation strength of the remaining phases and thereby trigger more flashovers.

While I commend the working group for the preparation of a simplified method as well as recognize its convenience, I cannot help thinking that in this age of personal computers in every professional's home and super computers in every power utility, access to a medium range computer should ever be a problem. As such, the more comprehensive type computer programs available for double circuit outage rates by backflashover [1] and unshielded line outage rates [2] should not be too difficult to run if they are made available. The argument of not needing to make precise calculations because of uncertainties of the problem can also be carried too far.

I still believe that calibration of results is necessary as a check particularly to ascertain the applicability of the relation between number of strokes to line (N_L) and the thunderday level (T). This is especially so in areas of very high thunderday level, e.g., 180 and above.

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Manuscript received August 10, 1984.

Ian S. Grant: The authors are very grateful for the discussers' comments and their contributions to the paper.

In response to Dr. Whitehead: Dr. Whitehead is, of course, well-known for his work in the Pathfinder project that pioneered much of the shielding design used today, and he continues to be a major contributor in this field. The paper notes that the shielding design method presently used in the simplified method may result in somewhat conservative design in some cases, and this is illustrated in the figures presented by Dr. Whitehead. A priority for improvements to this method by the W.G. will be evaluation of new shielding design metods, for example those based on recent work by A. J. Eriksson on an "attractive radius" concept and by Dr. Whitehead himself.

In response to the several points of Mr. Mousa:

1. The concept of the beta term was developed by both E. Whitehead and J. G. Anderson from an evaluation of field experiences and the stroke mechanism, as somewhat of a catch-all to compensate for a number of effects. Like many other lightning-oriented parameters, it is often considered imperfect, but has been very useful. Without seeking to support this factor in any comparisons to a better model, the beta factor is intended as a representation of the *ratio* of strike distance to ground vs. strike distance to conductor, rather than a representation of the absolute strike distance to ground. The use of a striking distance to ground or earth, rg, and a striking distance to the conductor and shield wire, rc, where rc = γrg offers an improved interpretation as presented by Mr. Mousa and used in Ref. [9]. However, in this case rg perhaps could be defined as the striking distance to level earth terrain. Then this value of rg would require modification, e.g., βrg. tp take into consideration the effects of trees, etc. This composition of striking distances is under active study with the working group.
2. The deterministic relationship between striking distance and crest current must, in theory, be modified to indicate that S is a random variable. However, the form of the probability distribution and the values of its parameters are unknown. The goal in this paper is to provide an equation which when used with the simplified model of the last step of the first stroke of the lightning flash, will provide an acceptable approximation of the shielding failure flashover rate and may also be used for new line designs. The use of a striking distance lower than that given by Eq. (5) to design new lines is another form of a safety factor.

   If alternately, a probability distribution of S and its parameter were known, this total distribution could (and perhaps should) be considered within the shielding failure calculation.
3. As originally proposed, the Eq. $10I^{0.65}$ applied to the striking distance to ground or earth. Subsequent analytical investigations by E. R. Whitehead showed that a striking distance to the phase conductor or shield wire as given by Eq. (5) with S = $8I^{0.65}$ and the use of a $\beta = 0.7$, i.e., the striking distance to ground is $5.6I^{0.65}$, produced a reasonable comparison of the calculated shielding failure flashover rates to field data. As indicated above, the use of a factor γ is presently being actively considered.
4. Eq. 8 of the paper is a refinement from an earlier relationship $S = b + 4h$. As with many lightning parameters it is intended for use as a simple model, developed from limited field data with some analytical background. Any inaccuracies in it are certainly overwhelmed by the inaccuracies in the assumed number of flashes to ground. Until better data are available, further sophistication in this relationship, and added complexity to the simplified method, are not justified. Mr. Mousa correctly identifies the presence of an inconsistency, however. Hopefuly, results from future studies will enable all aspects of lightning calculations to be usefully upgraded.
5. Fig. 4 of the paper is simply a re-presentation of the Anderson-Eriksson stroke magnitude data with all the limitations therein. It is used as a frequency distribution for strokes to a line, although it is mostly obtained from strokes to other objects (only 24% of the records were from lines), as the best information available. Within the bounds of engineering accuracy, it may be equally reasonable to use it for strokes to ground, since there are little data available to support or disprove this, and since virtually all the data were restricted to structures of 60m or less.
6. The Anderson-Eriksson current amplitude distribution is believed by the W.G. to be the best available from the available records. A great deal of effort went into critically reviewing all available stroke records to develop the distribution. However, this distribution is based on 266 records, only 5 of which exceed 100 kA. Experience in using the distribution seems to confirm that its accuracy is sufficient for most design purposes, but obviously designs involving the probability of higher currents will certainly benefit from additional records. Magnitude cannot be regarded as an isolated parameter, of course, as it has limited value unless accompained by waveshape and rise time values.
7. It is unfortunate that many valuable contributions to a subject such as lightning do not justify a full IEEE or other society publication, and are only available through documents of limited circulation, but one function of a W.G. is to seek and promote use of such information for general use as has been done in the paper. Any reference cited can be obtained through the W.G. Conversely, meaningful contributions through active participation in this W. G. are encouraged from industry and utility membership.

In response to A. C. Liew:

a) The simplified method presently compensates for the surge reduction in footing resistance through a relatively crude approach in step 35 of the backflash calculation [1], by reducing the effective number of strokes to the line by 40%. It is agreed that use of a surge reduced value would be preferable, as has been done in more complex calculation methods, and the W.G. is actively considering how best to incorporate this into the method.

b) The accuracy of lightning performance calculations is inevitably justified by comparison to existing lines, and the W.G. has been active in developong high quality line performance data for this purpose. Where predicted performances vary substantially from those actually experienced, 'calibrating' adjustments may be introduced in areas involving assumptions or unknowns. For the simplified method, no particular adjustments were required.
c) The control of lightning tripouts through use of the arc quenching properties of wood have been well publicized, and although relevant to lightning performance design are not specific to a calculation method. Design for wood properties can be easily performed as a simple sequential addition to the simplified method.
d) The simplified method described in limited to calculation of single flashovers. For multiple circuit designs, more complex methods must be used. The point raised that the first flashover may weaken the insulation strength of remaining phases is an interesting one, and seems to be contrary to the expectation that potential over unflashed insulator strings is usually reduced by increased coupling from a flashed over phase. Perhaps Dr. Liew refers to a design incorporating wood insulation?

Estimation of the actual number of strokes to a line, whether as a function of thunderdays, hours, or gound flash density, is perhaps the parameter most urgently needing attention, and the W.G. is in agreement with Dr. Liew's concluding comments on this. Fortunately, a large amount of on-going research is now directed towards this problem, in the U.S., South Africa, and elsewhere.

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