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RS705-4

April 18, 1980

Mr. Sam Duraiswamy, Reactor Eng.
U.S. Nuclear Regulatory Comm.
Advisory Comm. on Reactor Safeguards
Washington, D.C. 20555

Dear Mr. Duraiswamy:

RE: Proposed Regulatory Guide: -
"Lightning Protection for
Nuclear Power Plants"

In supplement to my letter of April 10, 1980, I have the following:

1. Some spelling has been corrected on page 31. The hand printed pages starting with page 33 have been typed.

Accordingly, please substitute the attached typed pages 31-38 (renumbered) for pages 31-40 in my report which was enclosed with my letter of April 10, 1980.

2. On the subject of ground wires and shielding angle which is discussed in Sect. 3 on page 8 of the proposed Regulatory Guide, I have enclosed Att. No. 5 which appeared in CIGRE Paper No. 33-01 of the 1968 Session in Paris This material enlarges upon the required shielding angle as a function of the mean height of the ground wire and of the transmission line operating voltage. See Sect. 5 on Page 11 of Att. No. 5. Shielding angle requirements as well as tower footing resistance and the application of counterpoise wires were covered more recently in Chapter 5 of Ref. 4.

Sincerely yours,

I. Birger Johnson

IBJ/ld
Attachments:

8009100672

THIS DOCUMENT CONTAINS
POOR QUALITY PAGES

It is recognized that a number of investigations have calculated and/or measured estimates of maximum peak currents somewhat greater than the above. Some of these are the following:

1. Ref. 28 Kennedy Space Center depending upon assumptions and calculations the maximum crest currents in the three peaks are given as follows:

   Peak No. 1

   a. 210 kA

   b. 150 kA - 640 kA

   c. 150 kA or more

   Peak No. 2

   a. 200 - 870 kA

   Peak No. 3

   a. 66 - 280 kA

2. Ref. 15 Mount San Salvatore,Lugano, Switzerland. Rare occurrence of a "Type IV Block Buster" current of 180 kA+ with a time to crest of 30 μs.

3. Ref. 29 Lightning current measurements on industrial chimneys in Poland recorded four results above 150 kA, namely: 158, 181.7, 240, and 246 kA.

4. Ref. 30. Lightning current measurements in Czechoslovakia on high objects ranging from 40 to 140 meters yielded a maximum value 186 kA out of a total of 144 records.

5. In Ref. 12 a maximum current of 160 kA+ was indicated on a stack of Anaconda Copper Mining Co. in Montana.

6. In Ref. 31 a maximum crest current of 300 kA+ is shown out of a total of 29,296 first return strokes. The 50, 90, 98 and 99 cent points show magnitudes of about 38, 80, 155, and 190 kA respectively.

Relative to all the various measurements and results obtained thereby is the following excerpt from Ref. 32:

> ### 4.2. Distribution of lightning current magnitudes
>
> *As has already been discussed in Section 2, in considering the effects of any of the lightning overvoltage inducing mechanisms and attempting to predict the probability of line insulation flashover, one requires a knowledge of the probability of occurrence of lightning currents of various magnitudes. To this end the results of various field studies have been incorporated into a number of distributions of lightning current magnitudes, of which probably the most representative is that derived by Popolunsky [8], since it embodies the results of numerous measurements from a variety of sites. A common criticism of all of these measurements is that they are obtained from un-representative situations such as tall structures and mountain-top masts, and Sargent [25] amongst others, has demonstrated that such distributions may well be influenced significantly by the structure height concerned, although a more recent study by Popolansky does not support this observation [26].*
>
> *The additional possibility has also been raised [27] that current magnitude distributions and lightning characteristics generally, may also vary through regions of differing thunderstorm severities. This last point may at least become clarified by comparing the results of established field studies such as Berger's with the results of several field studies currently in progress, as these become available, in Italy, France and South Africa.*
>
> *Liew and Darveniza [15] have shown that variations in the choice of distribution can bring about changes in the results of performance prediction studies in excess of 200 per cent. It is clear therefore that until the situation is better resolved, the assumptions made about this parameter in performance calculation can significantly influence the results obtained.*

In summary, the severity of the maximum peak currents in lightning strokes appears to be a function of latitude and altitude[20,33] terminating structural configuration and height, geological and atmospheric conditions,[31] and other factors. On a more encompassing world wide basis, the foregoing "tolerances" might be increased to ± 25 per cent for the measurements on the maximum peak stroke currents to transmission structures, accounting for measurement accuracy, variations in transmission system configuration and variations in system environmental exposure. Depending upon ones definition thereof, the maximum stroke currents can be considered a relatively infrequent occurrence to transmission lines as a whole and more so to the vicinity of generating stations.

To mitigate, nevertheless, concerns for a maximum stroke current termination on phase conductors or equipment at the generating station and its vicinity, the security and protection of the station and vicinity against direct strokes can be enhanced by one or the other or both of the following schemes:

1. Install diverter rods with low footing resistances parallel to the line for ½ to 1 mile in addition to ground wires and tower masts with low tower footing resistances. See Fig. 3 and Att. No. 3 (Ref. 20).

2. Install a short length of cable - a half mile or so - to interconnect the overhead line and the station.[35] See Att. No. 4 (Ref. 35).

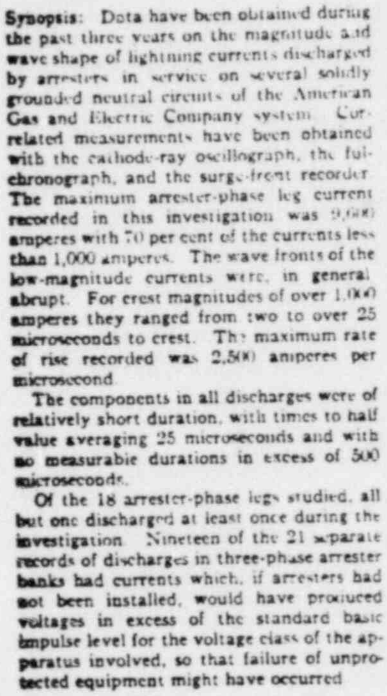
The application of surge arresters in stations postulates that lightning induced surges enter the station as traveling waves over lines or cables. In this manner, the surge impedances of the line and/or cable enter as basic factors in the protection realized during arrester operation. A voltage regulation effect is obtained in addition to the establishment of predictable arrester discharge currents. In turn, this enables predictable arrester discharge voltages to be determined so that the required BIL (Basic Impulse Insulation Level) withstand voltages of the insulation structures can be specified. The specified BIL includes a suitable margin on the arrester protective level. This margin, for example, for transformers is at least 20-25 per cent and recognizes the following:

1. Possible discharge currents in excess of the design value.
2. Separation effects between arrester and protected equipment.
3. Deviations in arrester performance. (already included in the arrester discharge voltages)
4. Single and multishot strength of some equipments.

Accordingly, the standards and procedures documented in ANSI C62.1 and ANSI C62.2 for the design, test and application of surge arresters should still be applicable herein.[4,5,37] This can be augmented and substantiated by some of the field investigations discussed hereafter on arrester discharge currents due to lightning induced surges. In addition, if necessary, modern station arresters based on a zinc oxide material can be readily paralleled without series gaps in the columns. This would enhance the security of arrester discharge currents per column against exceeding those currently in practice in the design, test and application of surge arresters.[8] There does not appear to be a need to use 200,000 amperes per arrester column as the basis for the withstand design of the arrester per se or of arrester protected insulation structures.

In a proposed paper for the IEEE-SPM, co-authored by the writer, the design, development, field tests and service experience of a multi-columned Zn oxide protection device for EHV series capacitors will be presented. The device consists of porcelain columns connected in parallel, each porcelain consisting of several parallel columns of zinc oxide disks in series.

Concurrent with the years of investigation on direct stroke lightning currents, a number were conducted on arrester discharge currents, using the same various array of instrumentation as for direct strokes, From Ref. 24 there is the following:



Synopsis: Data have been obtained during the past three years on the magnitude and wave shape of lightning currents discharged by arresters in service on several solidly grounded neutral circuits of the American Gas and Electric Company system. Correlated measurements have been obtained with the cathode-ray oscillograph, the fulchronograph, and the surge-front recorder. The maximum arrester-phase leg current recorded in this investigation was 9,000 amperes with 70 per cent of the currents less than 1,000 amperes. The wave fronts of the low-magnitude currents were, in general abrupt. For crest magnitudes of over 1,000 amperes they ranged from two to over 25 microseconds to crest. The maximum rate of rise recorded was 2,500 amperes per microsecond.

The components in all discharges were of relatively short duration, with times to half value averaging 25 microseconds and with no measurable durations in excess of 500 microseconds.

Of the 18 arrester-phase legs studied, all but one discharged at least once during the investigation. Nineteen of the 21 separate records of discharges in three-phase arrester banks had currents which, if arresters had not been installed, would have produced voltages in excess of the standard basic impulse level for the voltage class of the apparatus involved, so that failure of unprotected equipment might have occurred.

From Ref. 38 there are the following excerpts:

THE last report on the field investigation of natural lightning on the 132-kv transmission system of the American Gas and Electric Company was presented in a paper by the authors in 1942.[1] Since that time the field research work has been continued, although not as extensively as in the past, the major project being centered around lightning conditions at and close to the stations themselves, with a smaller part of the work being done on the line to determine the relative effectiveness of counterpoises and ground rods.

The objective of this investigation was to determine lightning conditions at major stations where expensive electric equipment is located, the failure of which might have serious effects on equipment, system operation, and electric service. With a better knowledge of the behavior of lightning at stations, it should be possible more adequately to protect important equipment from insulation damage.

The results of the field study from 1942 to, and including part of, 1944 are presented and discussed in this paper. The data have been combined in most cases with that previously obtained, in order to offer a composite picture of all records to date on the particular features studied.

Discussion of Special Records

In studying a large quantity of summarized data such as has been obtained during this investigation, an analysis of a typical case may be of interest. In Figure 8 are shown typical records of a lightning disturbance at the Roanoke 132-kv station. During the servicing period of approximately two weeks, two lightning storms were reported in the general vicinity of the station. From a study of the lightning currents recorded (Figure 8), it appears that there were five lightning strokes to the 132-kv system in the general vicinity of the station. Three of these strokes were on the Claytor circuit: one between the first and fifth towers of 26,000 amperes or more; one between the fifth and seventh towers of possibly 30,000 amperes; and one stroke beyond the seventh tower of 42,000 amperes or higher. Conductor currents measured in the Fieldale circuit indicate a possible stroke beyond tower 8 of this line. The absence of any ground wire records on this line suggests that the stroke may have been several spans past tower 8. One stroke of at least [illegible] amperes was indicated by currents in the ground wire on the Reusens circuit. This stroke occurred between [illegible] and 9,300 feet from the station.

During this disturbance the maximum line current recorded was 2,700 amperes, the maximum rate of voltage change was 440 kv per microsecond; the maximum voltage recorded at the station was [illegible] kv. None of the three three-pole lightning arresters at the station showed measurable currents, although it is possible that the arresters operated but the current was below the measurement range of the instruments.

In view of the records obtained in this one case the following statements seem justified:

1. Where lightning strokes occur some 1,800 feet or more from a station, if the line conductors are shielded, maximum lightning currents in the line wires at the station are in the order of 2,700 amperes or less.

2. Under the same conditions the incoming lightning voltages are not sufficient to cause arrester operation in the station.

3. Rates of voltage change at the station resulting from these nearby surges ranged as high as 440 kv per microsecond, although the nearest stroke was probably 1,800 feet distant. This feature may be significant in indicating that higher rates of voltage change at the station may occur, if the strokes are nearer the station.

" **Summary and Conclusions**

From the results of this investigation the summary data of which have been presented above, the following conclusions are drawn:

1. Lightning disturbances at five stations over a four-year period averaged 5.5 per station per year. Of these, 2.3 per station per year were of sufficient magnitude to cause arrester operation.

2. Lightning currents in conductors at stations showed a median value of 2,000 amperes. Seven per cent were 4,000 amperes or above and the highest was 11,500 amperes. All lines were shielded with overhead ground wires terminating on the station structure.

3. There appears to be no appreciable attenuation of lightning currents in line conductors within the first mile of the station.

4. The highest lightning-arrester current measured was 4,100 amperes, although elsewhere on the 132-kv system one current of 10,000 amperes was recorded.

Based on these results and similar records of arrester current obtained by the authors and others, it appears that the AIEE Standards for distribution and station-type arresters of 65,000- and 100,000-ampere lightning-current discharges are considerably higher than may be expected in practice.

5. The effect of multiple lines emanating from a station in reducing the lightning-voltage and arrester-discharge currents, and consequently the duty on the arresters, is apparent.

6. The maximum rate of voltage change of lightning surges measured at a station was 810 kv per microsecond, the median value being 220 kv per microsecond.

The maximum rate of voltage change due to switching surges was 470 kv per microsecond and the median value was 115 kv per microsecond. When allowances are made for a reasonable factor of safety, the present generally accepted 1,000 kv per microsecond rate of rise for test specifications on apparatus seems reasonable.

7. The rates of voltage change measured within a station varied considerably at different points. Rates of change as high as 470 kv per microsecond were observed at one point in the station, whereas the rate of voltage change at other points was below the range of measurement (ten kilovolts per microsecond). This indicates clearly the necessity of keeping protective devices close to the equipment to be protected.

8. No consistent ratio was observed between lightning currents in conductors and the rates of voltage change at station entrances.

9. The maximum lightning voltage measured at any substation was 525 kv with 50 per cent of the records 165 kv or greater. This maximum voltage value is well below the safe insulation strength of modern 132 kv station equipment and within the range expected from the arrester protection.

10. In this investigation no consistent relationship was found between lightning currents and voltages at a station.

Lightning currents in line conductors of 11,500, 8,500, 8,000, 7,500, and 6,500 amperes were recorded without any arrester operations recorded. These were accompanied by measured maximum rates of voltage rise of 100 to 160 kv per microsecond. The arresters at the station where these high-current records were obtained have a gap breakdown of [illegible] kv. In other " instances arresters discharged where the

With regard to conclusion 4, after some 40 years of industry service experience, the high current short duration test for station valve arresters was reduced from 100 KA to 65 KA recently because 100 KA was considered to be an unreasonably high discharge current. It would appear to be nearly impossible to get a current of 200 KA having any reasonable rate-of-rise to flow through leads of practical length.

Also with regard to conclusion 4, the 16,000 ampere record was the result of a stroke within 400 feet of the station.

From Ref. 4 there is the following excerpt:

> Similarly, for discharge currents in stations, the data are plotted as shown in Fig. 1.20 [45].

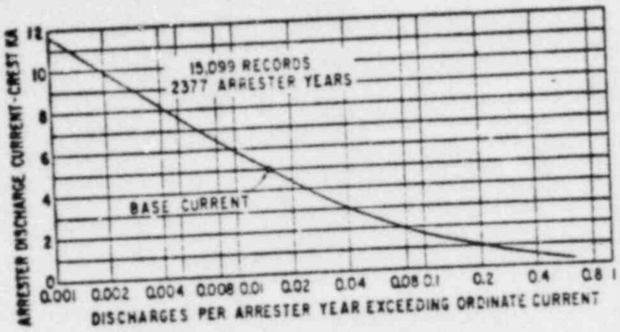


Fig. 1.20. Discharge Currents Measured Through Lightning Arresters in Stations.

> These are lower than open rural lines because the station and overhead line for at least ½ mile from the station are generally protected by overhead ground wires. In this manner the surge will originate as a traveling wave such that the arrester discharge current will be limited by the surge impedance of the line acting in series with the arrester valve element and by the possible multiple paths encountered in the station. It is to be recognized, however, that as transmission voltages increase, the magnitude of the arrester currents in stations or on the line side of circuit breakers may increase due to the higher traveling wave voltages which can be supported by the line insulation and by the lower surge impedance of the line due to conductor bundling.

Accordingly for effectively shielded stations at 362, 550 and 800 KV, arrester discharge currents for the purpose of insulation design and coordination are increasingly greater with higher sytem voltages.[37] These arrester discharge currents are 10,000, 15,000 and 20,000 amperes at line voltages of 362, 550 and 800 KV respectively.

MORE LATER

Paper No.
33-01 CIGRE - - 1968 Paris.

APPENDIX II

THE LIGHTNING PERFORMANCE OF EHV LINES

by
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1. INTRODUCTION

This report is a condensation of a paper of the same title presented and discussed at the 1967 meeting of experts sponsored by CIGRE Committee No. 8. Conclusions are based on a study of 50 papers prior to the meeting, several others brought to the attention of the author at the meeting, and reflect much of the interesting discussion. In the interest of conserving space, only those references directly quoted are listed at the end of the report.

2. FRAMEWORK OF DISCUSSION

As a framework for discussion, it is useful to postulate an electrogeometrical model of the electrical and geometrical situation, defined as existing at t = 0-, wherein the lightning leader [1] is so oriented that a final step to earth [2], the shielding groundwire [3], or the phase conductor [4] is imminent. Such a model enables one to identify clearly the :

2.1 Discharge Paths

P (1, 2) - leader to earth

P (1, 3) - leader to shield wire or tower

P (1, 4) - leader to phase conductor

and to develop solutions for the

2.2 - System response for each discharge path in terms of a quasi-circuit model confined to "near zone" effects.

3. DISCHARGE PATHS AND SYSTEM RESPONSE

The scope of this summary does not permit detailed discussion of the circuit model for each of the three discharge paths. A brief discussion of each, emphasizing its relative importance with respect to the performance of EHV lines, follows.

3.1 Discharge path P (1, 2) to earth - Studies of the lightning performance of distribution and subtransmission lines have resulted in renewed interest in the theory and measurement of lightning voltages on lines arising from lightning strokes to earth near the line. Since such a voltage arises primarily from cancellation of leader charge by the return channel, it will be defined here as the e_a component.

Taken alone, as arising from the P (1, 2) discharge path to earth, it is very generally agreed that this component is not a significant factor in the lightning performance of EHV lines.

3.2 Discharge path P (1, 3) to the shield (protective) wire - This discharge path leads to the most involved response of the transmission line, which obviously accounts for the research effort expended during the past 40 years. Although more detailed discussion will be deferred, it will be useful to define five main voltage components which have been examined as contributing to the voltage across the insulator string for a stroke to the tower or shield (ground) wire.

3.2.1 e_r a resistive component arising from the magnitude of the current.

3.2.2 e_l an inductive component arising from the rate of change of the current.

3.2.3 e_q an electric induction component arising from the integral of the current in the leader charge cancellation process.

3.2.4 e_s the summation of reflections from adjacent towers.

3.2.5 e_p the system frequency voltage to the tower.

In general, it appears possible to design EHV lines for excellent performance for lightning strokes to earth via the P (1, 3) path to the shield wire where low-voltage tower footing resistances, obtained at the tower, lie in the range of 0 - 25 ohms. The meaning of the term "excellent" and other necessary conditions modifying this conclusion will be developed later.

3.3 Discharge path P (1, 4) to the phase conductor - Until recently, this mode of discharge was widely believed to be so unlikely that it could be neglected for lines having a shielding (protective) angle of 30 degrees or less. The relatively poor performance of early postwar EHV lines in the U.S.A. with shielding angles of 25 - 35 degrees and low ground resistances threw serious doubt on this assumption, and an extensive statistical study of the performance of lines in the U.S.S.R. [1] supported the view that shielding failure might account in large measure for the relatively poor performance. Subsequent statistical studies of HV and EHV lines in the U.S.A. [3] and U.S.S.R. [5] as well as that of CIGRE Committee No. 9 [6] have provided additional support for this view. The Edison Electric Institute of the U.S.A. is presently conducting a large-scale five-year study of the "Mechanism of Lightning Strokes to Transmission Lines" consisting of a three-phase program of investigation involving (a) statistical analysis of line performance as related to (b) an analytical model of shielding behaviour, and (c) instrumentation of 433 miles of HV and EHV lines to distinguish shielding failure from backflash sparkovers [4]. These and other earlier studies show that there is a critical relation requiring decreasing shielding angle with mean shield wire height which results in "effective shielding". The term "effective shielding", as used here, refers to a condition achieved within the framework of an analytical model whose mean geometrical and electrical parameters lead to "zero expectation" of shielding failures. Since the relevant parameters must have some dispersion about their means, one cannot refer to "perfect shielding" in this connection.

4. EVALUATION OF LIGHTNING PERFORMANCE LEVELS

Before proceeding with a more detailed discussion of lightning performance as related to the discharge paths and the relative role of the several voltage components, it will be convenient to establish an index number which immediately characterizes the performance level under discussion and serves to clarify the conclusions to follow.

The performance of lines is commonly expressed as the number of lightning tripouts per 100 line length units per year. A logical quick reference index is the power of 10 which describes the order of the performance. Thus one may define

Specific performance = 10^M = tripouts per 100 length units per year.

The tabulation below is expressly applicable to shielded HV and EHV lines, and the qualitative descriptive adjectives are to be regarded as those of the author and not of Committee No. 8.

Table I

Exponent M	Specific Lightning Performance	Qualitative Classification
– 2	0.00 -- 0.05	Exceptional
– 1	0.06 -- 0.59	Excellent
0	0.60 -- 5.99	Common
+ 1	6.00 or more	Poor

Practical results from lightning research can best be achieved if it is always kept in mind that deductions from them must be consistent with the actual behaviour of existing lines.

Moreover, one must be prepared to find a complex of causes for line performance and avoid single preferred solutions which appear theoretically attractive. Table II presents a reasonably large sample of line performance for lines of varying shielding (protective) angle and mean shield wire heights.

Table I

Data for 50 transmission lines, 115 kV to 230 kV, in regions having 35-50 thunderstorm days per year. References [2] and [3] 84,000 km-years, 52,000 mi.-year. Tripouts adjusted to 40 T.D. per year.

Characteristics	Minimum One Line	Average All Lines	Maximum One Line
Tripouts per 100 miles per year	0.00	0.175	0.50
Tripouts per 100 kilometers per year	0.00	0.109	0.31
Mile years	210	1040	6500
Kilometer years	338	1675	10460
Basic insulation level-BIL	950	1300	1625
Mean shield wire height-feet	42	69	110
Mean shield wire height-meters	13	21	34
Mean shielding angle-degrees	– 6	18	39
Mean ground resistance-ohms (35 lines)	2	23	94

Table III has been taken from reference [5] for 500 kV lines in the U.S.S.R. in regions having 20-25 thunderstorm days per year. In order to avoid excessive adjustment, the data presented here have been adjusted to 30 thunderstorm days.

Table III

Lightning tripouts for 500 kV lines in the U.S.S.R. from reference [5] adjusted to 30 thunderstorm days per year. 37780 kilometer years or 23400 mile years

Specific tripouts per 100 kilometers	Specific tripouts per 100 miles	BIL kV	Ground resistance ohms	Ground Wire height meters	Shield angle degrees
0.15	0.24	1800	under 5	under 30	20(*)

(*) In exceptional cases this angle might be as high as 30 deg.

Tables II and III demonstrate conclusively that it is possible to obtain "excellent" lightning performance, of order $M = -1$, over a wide range of basic insulation, geographic location, and thunderstorm exposure. One may reasonably make the necessary assumption that such lines are "effectively shielded" and then compare their height-shielding angle envelope with that deduced from theoretical models for an "expectation" of zero shielding failures. Finally, one should then compare these relations with those for lines which have been found experimentally to have experienced shielding failures.

5. REQUIREMENTS FOR EFFECTIVE SHIELDING

Modern electrogeometrical models relate the strike distance from the tip of the lightning stroke leader to the prospective stroke current to earth and proceed along geometrical lines to determine the critical relation between mean shielding angle and mean ground (shield) wire height. While this approach forms the common background of various recent studies, substantial differences arise in basic assumptions and in the versatility of the analytical models employed. It is not possible to explore these differences here, but one important point should be stressed. "Effective shielding" refers to an expectation of zero shielding failures derived from the electrogeometrical model using a geometry determined by the mean positions of the shield wire, the phase conductor, and the earth surface. Serious errors in shielding design may result if care is not taken to do this. Substantial departures from mean conditions as, for example, in localized mountainous terrain or high river crossings may justify special treatment. In the approach of reference [4], possible departures of electrical parameters from assumed mean values and the effect of trees and other deviations from a smooth earth surface are subsumed in a calibration constant K_{sg} whose value is determined by the envelop of the height- angle data for the lines of Table II.

Tentative height-angle guidelines were presented in the form of curves in the full paper discussed at the Copenhagen meeting. In the interest of space conservation here, only two of the tentative guidelines are given in tabular form in Table IV. In effect, the height-angle relation envelopes for the effectively shielded lines of Table II have been extrapolated to the electrogeometry of EHV lines through the mechanism of an analytical model.

Table IV

Tentative guide for effective shielding of 345 kV and 500 kV lines from reference [4]

Line kV	Basic insulation level - kV	Conductor surge impedance - ohms	Calibration Constant
345	1600	400	0.9
500	1800	360	0.9

Mean shield wire height in meters	20	25	30	35	40	45	50	55	
Mean shield angle in degrees	31	22	14	7	0	– 9	– 15	– 22	(345 kV)
	35	27	21	14	8	2	– 6	– 10	(500 kV)

6. DISCUSSION

The preceding paragraphs have indicated that the discharge path P (1, 2) is innocuous and that the path P (1, 4) is avoidable to a high degree of confidence. If lines are to be designed for reliable performance of order $M = -1$, it will be necessary to continue our study of the response of the line to the discharge path P (1, 3) to the shield (ground) wire. There is, however, a conforting difference in the present situation from that prevailing in the past. The study of effectively shielded lines, even over a reasonably broad range of grounding conditions, should reduce the tripout range to the order of $M = 0$ or $M = -1$ so that comparison of research results and statistical studies should be more meaningful.

In directing attention to this aspect of the problem, those attending the experts meeting found it useful to discuss in some detail the role played by the several voltage components of section 3.2, and other related topics as outlined below :

6.1 - The resistive component e_r bears a relationship to the tower current which may vary from a simple ohmic one at low voltages to non-linear and/or time-variant forms, depending upon the resistivity, permittivity and electric breakdown gradient of the soil as well as the geometry and physical extent of the tower grounding system. The two principal departures from simple ohmic form are illustrated by :

6.1.1 - A non-linear relation, for localized grounding systems, of the form

$$e_r = K\, i^n$$

where n is less than unity when the voltage exceeds the breakdown voltage for the grounding system and breakdown time is neglected.

6.1.2 - A time-varying relation for distributed grounding systems, of the form

$$e_r = I\,[R_\infty + (R_o - R_\infty)\exp(-t/T)]$$

where I is assumed constant and T is a time constant depending upon the resistivity and permittivity of the soil and the geometry of the grounding system. The effect of time-varying current is included through the superposition integral. R_o is the initial surge impedance and R_∞ the final resistance to ground.

Deviations from these characteristic forms occur because of time lag of breakdown in 6.1.1 and because of soil breakdown effects in 6.1.2. The first is an unfavourable deviation, while the second is a favourable one.

Where resistances are moderate, some experts prefer to use low-voltage resistances as linear values in order to obtain conservative estimates of performance. Special cases of the relation 6.1.2 arise when long vertical conductors are used to reach an [illegible] stratum of low resistivity soil through a high resistivity overburden. "Crow-foot" distributed grounding systems in the surface layer have been found effective in improving the [illegible].

6.2 - The inductive component e_l has been the object of recent studies ranging from those based on electromagnetic field theory to those employing spatial and temporal scale models. The existence of current wave fronts with maximum rate of rise at current crest causes the resistive and inductive voltage components to add in unfavourable time relation. It is possible that such a combination may account for rare lightning tripouts in the presence of effective shielding. It should be stressed here that the ratio of e_l to the rate of rise of current is an "equivalent inductance" parameter which should be that derived from electromagnetic theory and the use of the superposition integral or from appropriate tests. The indiscriminate use of handbook formulae is to be discouraged.

6.3 - The leader charge-cancellation component e_q, as discussed here, represents only that part of the "induced" conductor voltage accompanying the retarded release of charge bound on the conductor at $t = 0-$. Because of the relatively slow rate of rise of current, it is believed that the contribution from magnetic effects is generally negligible. While several investigators have calculated induced voltages for the stroke to earth, few have attempted to calculate this component for the stroke to the tower or ground wire. There is substantial difference of opinion as to the magnitude and effect of this component, and it is here that one may suggest further theoretical and experimental studies.

6.4 - It is believed that the summation of reflections, as represented by the component e_s probably plays a marginal role in the performance of EHV lines in view of the insulation levels and ground resistances which are likely to prevail. If this is not the case, then modelling techniques will probably be required for useful study of this component.

6.5 - The instantaneous value of the normal frequency [illegible] easily be included in performance estimates. As operating voltages rise, the marginal role of this component may assume greater significance.

6.6 - Table V shows the results of estimates of the performance of EHV lines based on the following simplifying assumptions :

Effective shielding

Strokes to ground wire --- 62 per 100 kilometers per year

No midspan flashovers

Thunderstorm days -- 30 per year

Current probability curve (Burgsdorf) (1).

Non-linear concentrated grounding, uniformly distributed

Concave current wave front T_f = 4 μ sec. $\alpha = 0.4$

Equivalent tower inductance $L = 20$ microhenrys

Electric induction component e_a = 0.7 MV at 100 kA

Surge impedance coupling 0.25

Table V

Insulator sparkovers per year

R_o ohms	BIL MV	Sparkovers per 100 kilometers	100 miles
20	2.0	0.2	0.3
10	1.8	0.2	0.3
10	1.6	0.4	0.6
5	1.6	0.2	0.3

These estimates are meaningful only to the degree that they suggest the same order of performance as shown in Tables II and III for lines defined as effectively shielded. Much more detailed calculation would be necessary to attempt the minimization of indicated differences.

7. CONCLUSIONS

Based on the foregoing review of more than 50 modern references, as modified by discussion at the Copenhagen meeting of experts, the following conclusions appear to be well founded :

7.1 - The lightning discharge path to earth P (1, 2), critically near the line, does not induce insulator voltages which are a significant factor in the lightning performance of EHV lines.

7.2 - The discharge path to the phase conductor P (1, 4), by shielding failure, constitutes the major threat to the lightning performance of EHV lines. Fortunately, this threat can be effectively overcome by placing the shield (ground) wires with the shielding (protective) angle in proper relation to shield wire height. The mean positions of the shield wire, phase conductor, and earth must be used in establishing effective shielding and the structural design then adjusted accordingly.

7.3 - Although it is clear that effective shielding has been, and therefore can be, obtained, the optimum height-angle relation remains the subject of intensive analytical, statistical, and experimental investigation.