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Honorary Editor: A. W. LINEKER, B.Sc.
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Volume 45 SEPTEMBER 1954 Part 9

PROCEEDINGS AT THE FOUR HUNDRED AND FORTY-EIGHTH GENERAL MEETING

Held at Kelvin House, corner Marshall and Hollard Streets, Johannesburg

Thursday, 23rd September 1954

J. P. ANDERSON (President) was in the Chair and declared the meeting opened at 8.5 p.m.

There were present 55 members and visitors and the Secretary.

MINUTES

The minutes of the monthly general meeting held on the 26th August 1954, were taken as read, and confirmed.

The Secretary announced that in terms of By-Law 5.2.4. the Council had elected the undermentioned candidates to membership of the Institute in the following grades :—

Associate Member : JOHN SMITH CHISHOLM.

Graduates : THOMAS WILLIAM CURRY, NICOLAAS VAN ZYL.

Associates : IB HAGENDORN DANIELSEN, DERMOT CHARLTON SHANKS.

Transfer from Associate Member to Member : GEORGE DOUGLAS GRAEME DAVIDSON.

Transfer from Graduate to Associate Member : CLIFFORD MEY.

AWARDS FOR 1953

THE PRESIDENT said it was his pleasant duty to announce the awards for the year 1953. The Council had decided on the allocation of the awards as follows :—

INSTITUTE PREMIUM

Mr G. ff. Bellairs, A.M.(S.A.)I.E.E. and Mr M. R. Gericke, M.(S.A.)I.E.E. for their joint paper entitled 'A telemetering instrument for the measurement of acceleration and deceleration of mine hoists,' *Transactions, June* 1953.

SOUTH AFRICAN RAILWAYS AND HARBOURS AWARD

Mr. C. F. Boyce (Associate Member), for his report on 'The activities of the Power and Communication Systems Co-ordinating Committee during the period May 1941 to July 1952.' *Transactions*, July 1953.

ESCOM PREMIUMS—PAPERS

(*i*) Mr A. Semmelink (Associate Member), for his paper entitled 'Electro-magnetic testing of winding ropes.' *Transactions*, May 1953.

(*ii*) Mr. W. N. Powell (Member), for his paper entitled 'Colenso/Durban 132-kV overhead line—a description of its design and construction.' *Transactions*, March 1953.

(*iii*) Mr R. S. Arnot (Member), for his paper entitled 'Construction and operation of a 66-kV network in the Copperbelt of Northern Rhodesia.' *Transactions*, October 1953.

ESCOM PREMIUMS—CONTRIBUTIONS TO DISCUSSION

(*i*) Mr. G. R. Gerrard (Associate), for his contribution to the discussion on the paper entitled 'Centralized load control,' by R. G. Hunter. *Transactions*, February 1953.

(*ii*) Mr T. G. Baird (Associate Member), for his contribution to the discussion on the paper entitled 'Colenso/Durban 132-kV overhead line—a description of its design and construction,' by W. N. Powell (Member), *Transactions*, March 1953.

(*iii*) Mr F. J. Hamelberg (Associate Member) for his contribution to the discussion on the joint paper entitled 'A telemetering instrument for the measurement of acceleration and deceleration of mine hoists,' by G. ff. Bellairs, (Associate Member), and M. R. Gericke (Member). *Transactions*, June 1953.

(*iv*) Mr. D. M. Bentley (Member), for his contribution to the discussion on the paper entitled 'Some developments in control of electrically driven hoists with special reference to automatic control,' by D. R. Love, *Transactions*, September 1953.

(*v*) Mr J. M. Magowan (Associate Member), for his contribution to the discussion on the paper entitled 'Construction and operation of a 66-kV network in the Copperbelt of Northern Rhodesia,' by R. S. Arnot (Member). *Transactions*, October 1953.

PAPER AND DISCUSSION

R. B. ANDERSON (Associate Member) then presented Part II 'The lightning performance of transmission lines,' of the paper entitled 'A summary of eight years of lightning investigation in Southern Rhodesia,' by R. D. Jenner (Associate Member) and himself.

The President proposed a vote of thanks to the authors for their excellent paper and contributions to the discussion were made by :— Professor M. J. Meek (University of Liverpool), Dr D. J. Malan (Bernard Price Institute of Geophysical Research) (read by Professor G. R. Bozzoli (Vice President)), R. H. Golde (Electrical Research Association —England) (read by A. W. Lineker (Past President)), F. R. Perry (Metropolitan-Vickers Electrical Co., Ltd.—Manchester) (read by A. S. Leith (Associate Member) and A. G. V. Pearce (Associate Member).

Mr Anderson replied to a number of the points raised by the contributors.

There was no further business and the President declared the meeting closed at 9.55 p.m.

Institute Notes

Cape Western Local Centre

Members of the Institute visiting Cape Town are cordially invited to attend general meetings of the Cape Western Local Centre which are held in the Demonstration Theatre, Electricity House, Strand Street, Cape Town, on the second Thursday of each month.

A general meeting of the Cape Western Local Centre was held in the Demonstration Theatre, Electricity House, Strand Street, Cape Town, on Thursday, 9th September, 1954.

Mr C. G. Downie (Chairman of the Centre) was in the Chair and declared the meeting open at 8.15 p.m. Seventy-four members and visitors were present.

Mr G. Williams (Member) presented his paper entitled 'The main line electrification of the Cape Western System of the South African Railways' (presented at Kelvin House on the 24th June, 1954).

The following contributed to the discussion on the paper: Messrs G. A. Dalton (Past President), G. D. G. Davidson (Member), W. M. de Boor (Associate Member), S. McCracken and H. E. Gillard (Associate Member).

Mr Williams replied to a number of the questions raised by the contributors.

There being no further business the Chairman declared the meeting closed at 11 p.m.

A SUMMARY OF EIGHT YEARS OF LIGHTNING INVESTIGATION IN SOUTHERN RHODESIA

By R. B. ANDERSON, B.Sc.(Eng.) (Associate Member)
and R. D. JENNER, B.Sc.(Eng.) (Associate Member)

Editor's Note: Part I of the paper was published in the July 1954 issue of the 'Transactions'

SUMMARY

This paper is a sequel to that entitled ' Lightning investigation on an 88-kV transmission line in Southern Rhodesia ' which was presented before the Institute in 1948, and now outlines more definite conclusions in respect of the characteristics of lightning, its frequency of occurrence and its severity. The effect of geological formations, heights of towers, span lengths, etc., are discussed, and the performance of an instrument for recording lightning strokes is described. Part II of the paper compares the actual with the estimated performance of the 88-kV line and curves and data are included to indicate the probable performance of typical lines of various voltages up to and including 220-kV. Recommendations for outage levels are made and the earthing conditions to meet them are discussed. Standard impulse insulation levels for transmission lines are suggested, and the factors governing the design of lightning-resistant lines are enumerated.

CONTENTS

PART II

THE LIGHTNING PERFORMANCE OF TRANSMISSION LINES

13. THE PROBABILITY OF LIGHTNING FLASHOVER OF TRANSMISSION LINES

Appendix 2 describes in detail the method used, and the applicable formulae for calculating the probability of insulation flashover for a particular transmission line.

Briefly this consists of calculating the lightning currents which would cause insulation flashover at a tower, for a stroke to a tower, at a tower for a stroke to midspan, and at midspan for a stroke to midspan for various values of tower earth footing resistance, both with and without counterpoise earths.

These lightning currents are calculated for lightning strokes with both positive and negative polarity and the results are then modified in accordance with the ratio of the incidence of negative to positive strokes, which for conditions in Southern Rhodesia has been assumed as 14 : 1.

From a lightning expectancy curve the percentage probability of insulation flashover can then be obtained for each case, and these probabilities can be combined to give an overall probability of flashover for the line, based on the assumption that all strokes within a quarter span of the tower are equivalent to strokes to a tower, and all strokes within a quarter span of midspan can be regarded as strokes to midspan.

Several investigators have produced curves of lightning expectancy which indicate the percentage of strokes which exceed certain values of lightning current. These lightning expectancy curves have been compiled from data obtained on transmission lines, and in all cases it has been assumed that when two or more adjacent towers have carried lightning currents, these currents have emanated from the same stroke, and consequently have have been summated and the resulting current recorded as that of a single lightning stroke. On this basis, lightning currents delivered to ground by main strokes, have been recorded with crest values in excess of 220 kiloamperes.

In order, however, to assess the performance of transmission lines when subjected to lightning, the lightning currents recorded to adjacent towers must be regarded as separate strokes to the towers and the individual tower currents cannot be summated as it is the current in individual towers which determines the voltage impressed across the insulation. For this reason the lightning expectancy curve to be used should relate to the currents in transmission towers converted to the equivalent which would be delivered to zero resistance grounds. Curve A, Fig. 12,* indicates the lightning expectancy curve adopted, and upon which all calculations were based.

Fig. 14 shows the probability of insulation flashover for the 88-kV line calculated from the above curve and based on an average altitude of 3 500 feet, with and without a continuous counterpoise earth.

Fig. 14 shows, for example, that for a tower earth footing resistance of 100 ohms, the line without a counterpoise earth would sustain 73 flashovers per 100 lightning strokes, whereas if a counterpoise is installed this figure would be reduced to 32 flashovers.

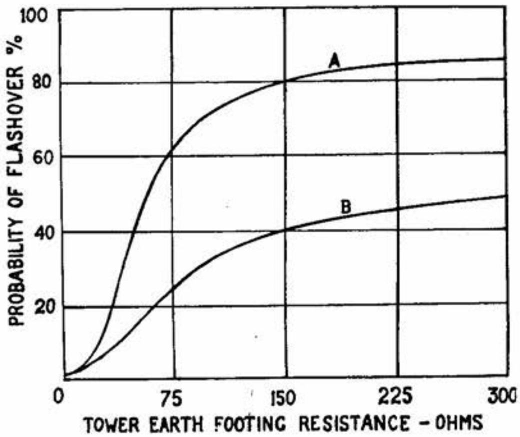

Fig. 14—Curves of probability of flashover on the 88-kV transmission line in S. Rhodesia

A. Line not equipped with counterpoise
B. Line equipped with a continuous counterpoise

14. THE RELATION BETWEEN ACTUAL POWER INTERRUPTIONS AND THE PROBABILITY OF FLASHOVER

From measured values of the tower earth footing resistances of all towers along the route of the line, the average probability of flashover for the line as a whole was calculated for the various lightning seasons.

This average probability of flashover was 21·9 per cent for the 1946/47 and part of the 1947/48 seasons and it was subsequently reduced to 11·6 per cent by the addition of the supplementary earthing indicated on curve C, Fig. 8.* The effect on the probability of flashover for each tower is shown on curve D, Fig. 8.*

From a knowledge of the number of lightning strokes occurring to the line it is therefore possible to estimate the number of flashovers and these can be compared with actual line outages.

Table XV has been prepared to indicate this comparison.

Magnetic links were installed on every tower along the route of the line only during the 1950/51 lightning season and part of the 1949/50 lightning season, while for the remaining periods only portion of the line was equipped. It is possible, however, to obtain an approximate estimate of the number of strikes to the line during each

* *See Part I of paper in July* 1954 *issue of the* Transactions.

TABLE XV

RECORD OF POWER INTERRUPTIONS TO 88-KV SYSTEM COMPARED WITH ESTIMATED PROBABILITY OF OUTAGE

Lightning season	*Route length in commission (miles)*	*Number of interruptions due to lightning*	*Power interruptions per 100 miles per annum*	*Estimated number towers struck per 100 route miles per annum*	*Calculated probability of power interruptions (per cent)*	*Estimated number of power interruptions per 100 miles per annum*	*Deviation from actual number*
Col 1	*Col* 2	*Col* 3	*Col* 4	*Col* 5	*Col* 6	*Col* 7	*Col* 8
1946/47	32*	2	6	75	21·9*	16	+10
1947/48	84	17	20	89	15·7*	14	−6
1948/49	84	0	0	39	11·6	5	+5
1949/50	84	8	10	80	11·6	9	−1
1950/51	84	4	5	79	11·6	9	+4
1951/52	84	1	1	25	11·6	3	+2
1952/53	84	7	8	37	11·6†	4	−4
1953/54	84	8	10	75	11·6†	9	−1
Average 8 years ...	84	6·3*	7·5	62·5	13·4	8·4	+0·9

* Weighted average. † Actual probability of flashover higher in view of theft of counterpoise system

period when the line was not fully equipped by increasing the recorded number of strikes in proportion to the percentage of the line equipped, and these numbers can be further modified to show the estimated number of strikes per 100 miles of transmission line. These estimated figures per 100 miles of line are shown in column 5 of Table XV.

From these it is apparent that over the period of eight years under review the estimated number of lightning strokes per 100 miles of line varied between 89 in 1947/48 and 25 in 1951/52 with an average over the whole period of 62·5.

These figures indicate a reasonably close agreement between actual power interruptions, and estimated power interruptions per 100 miles of line per annum ; namely 7·5 and 8·4, when the numbers are averaged over the whole period under review. The widest seasonal divergences occurred in 1946/47 and 1947/48 and these can be accounted for by the fact that very little severe lightning occurred in 1946/47, and that the lightning was extremely severe in 1947/48.

In addition, only a portion of the line was energized in the early part of the 1946/47 lightning season, and consequently the route length in commission and the calculated probability of outage are weighted averages.

With regard to the 1947/48 lightning season, it must be noted that supplementary earthing was only installed in February 1948, and that prior to this date 15 outages due to lightning had occurred. Consequently the estimated probability of outage for the whole season was again a weighted average, and a divergence between actual and anticipated outages was possible.

During the 1952/53 and 1953/54 lightning seasons considerable quantities of counterpoise earth, and even earthwire down leads connecting earthwires to earthmats, had been stolen, thus increasing the average probability of outage for the line, above the figure of 11·6 per cent, which has been tabulated. This explains the fact that the actual outages which occurred were in excess of the numbers estimated.

When average conditions over a period of time are considered, however, it is apparent that this method of calculating the lightning performance of a transmission line is sufficiently accurate for all practical purposes.

Lewis and Foust[10] draw attention to the possibility that tower footing resistances when subjected to lightning current can be very much lower than the actual measured values. The above comparison, however, does indicate that very close agreement between estimated and actual performance can be obtained neglecting this possibility.

If more data were available relating to the wave shape of lightning surges, and other factors which have to be assumed in compiling the curve of probability of outage used, then the decrease in resistance of tower footings under surge conditions would probably have to be considered.

15. SURGE VOLTAGES ON THE 88-KV TRANSMISSION LINE

15·1 *General*

The maximum voltage appearing across the transmission line insulation, due to a lightning stroke, is given by the following formula :—[15]

$$V = (1 - Cn)\, aR'\, I_o + e \quad \ldots\ldots 7$$

where V = voltage across line insulation

Cn = coupling factor at flashover voltage

a = crest factor

R' = equivalent resistance of earthing system at the point of flashover

I_o = lightning current to zero resistance ground

e = maximum instantaneous phase to ground power frequency voltage.

The following formula can equally be applied if the measured tower current only is known.

$$V = (1 - Cn)\ a\ R\ I + e \quad \ldots\ldots 8$$

TABLE XVI

NUMBER OF RECORDS OF CALCULATED SURGE VOLTAGES IN GIVEN RANGES WITH AVERAGE EARTH FOOTING RESISTANCES AND TOWER LIGHTNING CURRENTS

Calculated surge voltage kV	*Average earth footing resistance (ohms)*	*Average tower lightning current (kA)*	*Number of records*	*Per cent total*	*Percentage which exceed minimum in the range given in Col 1*
Col 1	*Col 2*	*Col 3*	*Col 4*	*Col 5*	*Col 6*
0— 100	7·4	15·2	28	9·2	100·0
100— 200	11·6	21·6	82	26·8	90·8
200— 300	13·9	30·2	62	20·3	64·0
300— 400	21·5	33·3	57	18·7	43·7
400— 500	25·3	39·8	29	9·5	25·0
500— 600	34·7	41·1	14	4·6	15·5
600— 700	26·5	63·0	5	1·6	10·9
700— 800	49·9	48·2	9	3·0	9·3
800— 900	27·3	70·5	6	2·0	6·3
900—1 000	41·0	53·8	1	0·3	4·3
1 000—1 200	53·2	85·6	3	1·0	4·0
Above 1 200	76·4	79·4	9	3·0	3·0
			305	100	

lines would be struck directly, or if they were, it would be impossible to afford any protection against such strokes.

Dr C. L. Fortescue is believed to have been the first to consider the effects of direct strokes on transmission lines and suggested that these strokes, and not induced surges, as was previously thought, were responsible for transmission line flashover.

Subsequent to this, great strides have been made in the design of transmission lines, based on the direct stroke theory, and it has been proved that induced surges have little or no effect on higher voltage lines.

With increased knowledge of local conditions of lightning it is now possible to apply the direct stroke theory with precision to existing transmission lines and to those to be erected in future, and in this paper consideration is given to a number of alternative types of construction for operation up to 220 kV.

Typical designs are considered for 220- and 132-kV operation and for the purpose of comparison details of the 88-kV line and a 66-kV line in use in Southern Rhodesia are included.

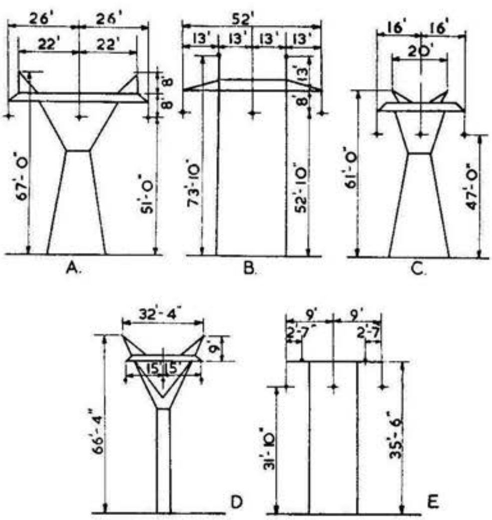

Fig. 15—Types of transmission towers

A 'Waisted' type 220-kV tower
B Portal H type 220-kV tower
C 'Waisted' type 132-kV tower
D Lattice type 88-kV tower
E H-Pole 66 kV

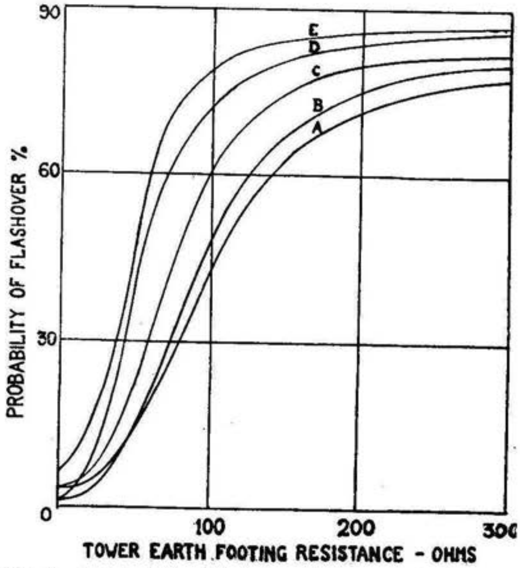

Fig. 16—Probability of flashover of transmission lines of various voltages with NO counterpoise earthing

A Waisted type 220 kV
B Portal H type 220 kV
C Waisted type 132 kV
D Lattice type 88 kV
E H-Pole 66 kV

16·2 *Design details and characteristics of typical transmission lines*

Full details of typical designs of transmission lines are given in Table XIX and are depicted in Fig. 15.

With regard to the 220-kV towers the main differences between the 'portal H' and the 'waisted' types under consideration are the location and clearances of earthwires with respect to conductors and in the overall heights of the towers. The waisted type 132-kV tower is similar to that for 220 kV excepting that the height and conductor and earthwire spacings are reduced. A standard type of 66-kV H-pole tower in use in Southern Rhodesia is included to indicate lower protective limits.

Impulse insulation levels of 1 050, 750, 550 and 450 kV have been assumed for the respective voltages and this is discussed at a later stage. All data have been corrected for an altitude of 3 500 feet for comparison purposes.

16·3 *Probability of flashover curves*

Fig. 16 shows the calculated probability of flashover curves for each of the five transmission lines with no counterpoise earthing, based upon the tower lightning expectancy curve A, Fig. 12.

It is interesting to note the considerable divergence of probability of outage for any one value of earth footing resistance. For instance, with a tower earth footing resistance of 80 ohms, the probability of outage of the 66-kV H-pole line is 75 per cent as compared with 30 per cent for the waisted type 220-kV line.

At the lower values of earth footing resistance, the divergence in probabilities of outage is considerably reduced, and the variation in actual values is due mainly to the probability of flashover at midspan, which is dependent upon the clearance between earthwires and conductors at this point.

The installation of a counterpoise earth has the effect of adding a variable surge impedance in parallel with the earth footing resistance of the tower and reduces the overall effective resistance to a low value in a very short period. This results in a reduction in the probability of flashover particularly at the higher values of tower earth footing resistances.

The counterpoise earth with which the 66- and 88-kV lines are equipped consists essentially of a single continuous conductor buried beneath the line and connected to each tower earth. A more effective method, however, is to install comparatively short lengths of conductor radially from the base of the tower, and this was assumed in the calculations for the higher voltage lines. The resultant probability of flashover is depicted in Fig. 17.

The curves in Fig. 16 and those in Fig. 17 illustrate the marked improvement which would be attained with counterpoise earths for tower earth footing resistances in excess of given values.

A strict comparison of these curves, however, cannot be made in view of the fact that even under the same lightning conditions the number of lightning strokes to each line will vary, depending upon the effective height as discussed in Section 4·5 and shown in Fig. 11.

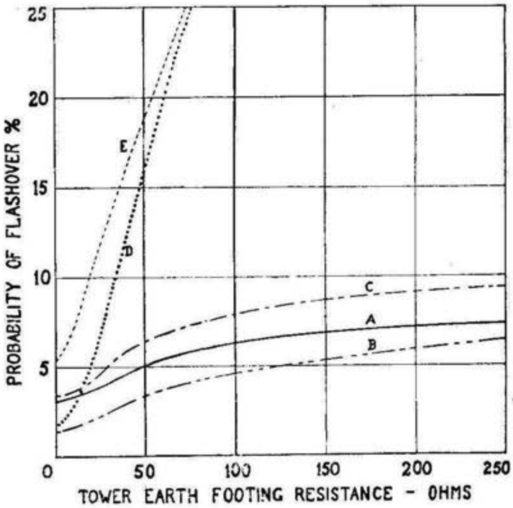

Fig. 17—Probability of flashover of transmission lines equipped with counterpoise earthing

A Waisted type 220 kV
B Portal H type 220 kV
C Waisted type 132 kV
D Lattice type 88 kV
E H-pole type 66 kV

TABLE XX

ESTIMATED NUMBER OF TOWER LIGHTNING STROKES TO TRANSMISSION LINES PER 100 MILES PER 100 THUNDERSTORM DAYS

Index letter	*Type of transmission tower*	*Voltage kV*	*Height of tower ft*	*Average height of line ft*	*Width of lightning area ft*	*No of tower lightning strokes per 100 miles per 100 thunderstorm days*
A	Waisted	220	67·0	49·7	151·0	126
B	Portal H	220	73·8	55·3	136·0	114
C	Waisted	132	61·0	43·0	122·0	102
D	Lattice	88	66·4	47·1	137·7	115
E	H-Pole	66	35·5	31·3	89·6	75

This effective height is defined as the average height of the transmission line, allowing for the sag of the earthwire, less the average height of brush-wood or trees flanking the line and can be obtained from the following formula :—

$$ht = \tfrac{1}{3}(Ht - He) + He \quad \ldots\ldots\ldots\ldots\ldots 9$$

where ht = average height of transmission line

Ht = height of towers above ground

He = height of earthwires at midspan above ground.

In the data which follow, the average height of trees, etc., has been assumed arbitrarily at 10 feet.

16·4 *Estimated number of outages to transmission lines*

The investigation on the 88-kV line indicated that 115 towers will carry lightning currents in excess of 10 kA per 100 route miles per 100 thunderstorm days. On the assumption that lightning strokes are uniformly distributed over a given area, the number of strokes to transmission lines will be proportional to the area which the line covers and which can be calculated from equations 1 and 2, Section 4·5. The results of these calculations are given in Table XX.

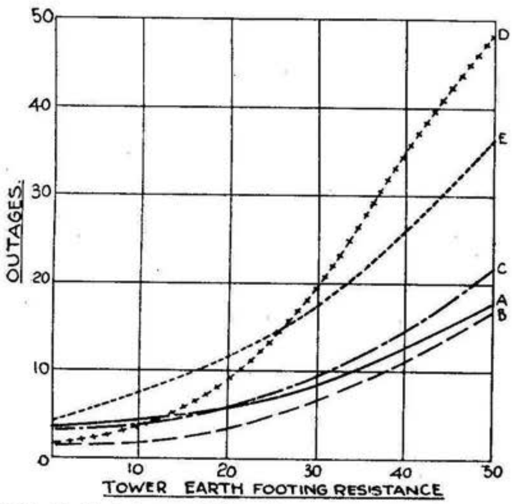

Fig. 18—Outages per 100 miles per 100 thunderstorm days for transmission lines with NO counterpoise earthing

A Waisted type 220 kV
B Portal H type 220 kV
C Waisted type 132 kV
D Lattice type 88 kV
E H-Pole 88 kV

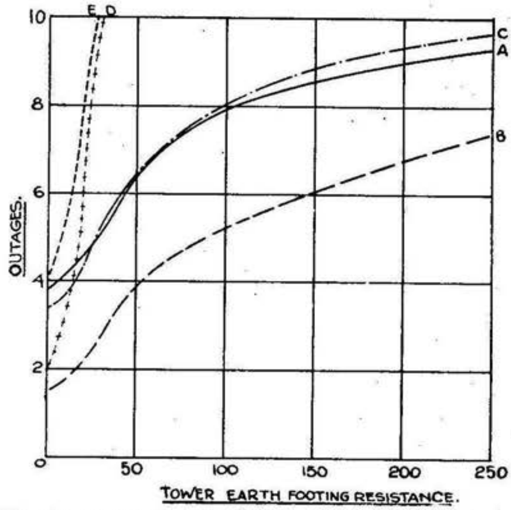

Fig. 19—Outages per 100 miles per 100 thunderstorm days for transmission lines equipped with counterpoise earthing

A Waisted type 220 kV
B Portal H type 220 kV
C Waisted type 132 kV
D Lattice type 88 kV
E H-Pole type 66 kV

Based on the above estimated number of lightning strokes to these transmission lines and the respective curves of probability of flashover, Figs. 16 and 17, the estimated number of flashovers may now be plotted against tower earth footing resistances for each type of construction.

Fig. 18 illustrates the number of outages to be expected when no counterpoise earth is installed whilst Fig. 19 indicates the effect of equipping these transmission lines with counterpoise earthing of the types described.

From a comparison of curves shown in Fig. 18, it is clear that even though the types of construction are generally similar, the performance of the higher voltage lines is superior to that of the lower voltage lines, and this is due to the fact that the margin between basic impulse level and operating voltage is considerably greater in the former cases.

The reduction in the incidence of outages due to the installation of counterpoise earthing is apparent in comparing Fig. 18 with Fig. 19 in which, even for footing resistances up to 250 ohms, the outages on the high voltage lines at any rate are maintained below 10 per 100 miles per 100 thunderstorm days. The effect on the lower voltage lines is similar but not so apparent with the scales used for the curves.

In order to study variations between the respective higher voltage lines more closely Fig. 20 was prepared on a large scale.

The curves shown in Figs. 18, 19 and 20 indicate considerable divergence in the performance of transmission lines of different types. In general where earth footing resistances are low, the relative performance is determined by midspan clearances, and flashovers at midspan would occur more readily than flashovers at towers. Where

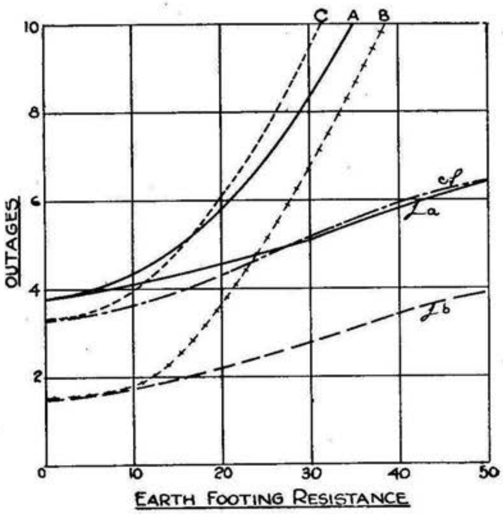

Fig. 20—Outages per 100 miles per 100 thunderstorm days for typical 132- to 220-kV transmission lines

A Waisted type 220 kV with **no** counterpoise
a As above but equipped with counterpoise earthing
B Portal H type 220 kV with **no** counterpoise
b As above but equipped with counterpoise earthing
C Waisted type 132 kV with **no** counterpoise
c As above but equipped with counterpoise earthing

the resistances are high flashover at towers would be more prevalent and the insulation level at these towers and the clearances pertaining, would decide the number of outages occurring. This accounts for the fact that the curves cross at certain values of tower earth footing resistance.

It will be appreciated that tower footing resistances vary considerably in practice, and in order to ascertain the overall lightning performance of a given transmission line, it is necessary to average the outage level for each tower over the complete route. Thus a few towers with higher outage level than required could be permitted provided the average level is maintained.

However, the expected performance of different types of construction may be directly compared from the curves shown.

The outages to be expected on the portal H type 220-kV line are rather lower than those for the 220-kV waisted type. This difference is accounted for by the fact that at these lower values of earth footing resistance the probabilities of flashover at the towers for strokes either to the towers or to midspan are zero, for both types of construction, whereas the probability of flashover at midspan for a stroke to midspan is considerably greater in the case of the waisted type of construction, where the midspan clearance is only 16·49 feet as compared with 24·7 feet for the portal H construction. For the 132-kV construction, a midspan clearance of 15·23 feet has been assumed, and consequently the probability of flashover for strokes to midspan is slightly higher than that of the waisted type 220-kV line, but fewer outages will occur as the effective height is less resulting in fewer lightning strokes.

Thus it is evident that even though very low earth footing resistances are maintained throughout, it is essential to ensure an adequate clearance between earthwires and conductors at midspan, if the number of outages is to be kept to a minimum.

In the 220-kV waisted type of construction the clearance between earthwire and conductor at the tower is less than that of the portal H type, and consequently the coupling factor between the earthwires and the conductors is greater. As the lightning current to cause flashover for a given voltage impulse level is inversely proportional to $(1 - Cn)$ where Cn is the coupling factor, it is apparent that the greater the coupling factor at the tower, the higher will be the lightning current to cause flashover, and the lower will be the probability of outage.

Thus if the number of outages is to be kept to a minimum the coupling factor between earthwires and conductors at a tower should theoretically be high, and the clearances low. This cannot, however, be applied, in practice, because of the necessity of maintaining an adequate clearance between earthwires and conductors at midspan which requires that the earthwires be installed as high as possible above the conductors at the towers also.

From the above it is therefore apparent that the only satisfactory method of ensuring a low probability of flashover at a tower is to ensure a low tower earth footing resistance.

16·5 *Permissible outage levels for transmission lines*

While modern e.h.v. lines are protected by high speed auto-reclosing oil circuit breakers to ensure that any transient outages due to lightning will be of extremely short duration, it is still necessary to limit the number of outages to a level which will be governed by the following factors :—

i whether the transmission line under consideration is a single feeder or is operated in parallel with other lines, which are capable of maintaining supply in the event of failure of any one feeder

ii the transient stability limits of the system, which if critical would necessitate an extremely low outage level

iii the deterioration of generating and transforming plant and switchgear due to repeated faults with consequent reduction in the life of the equipment and increase in maintenance costs

iv the fault capacity available on the system

v the possibility of insulator puncture due to excessive voltages being impressed across the line insulation and the difficulty of locating such damage

vi the costs of lowering earth footing resistances at towers

vii the cost of providing standby equipment in order to maintain continuity of supply during maintenance and in the event of power line failures.

In view of the above it is obvious that no specific outage level could be laid down which would be applicable in every instance, since each case would need to be considered on its merits, but a guide to the trend which should be followed can be obtained from present practice.

Table XXI therefore indicates the lightning performance of some major transmission lines[17] in various countries. Isoceraunic levels and lightning outages per 100 miles per annum are shown and these latter figures have, in addition, been modified for an isoceraunic level of 100 thunderstorm days in order to afford a comparison with the curves drawn on the same basis and included above.

TABLE XXI

LIGHTNING PERFORMANCE OF EXISTING MAJOR TRANSMISSION LINES

Voltage kV	*Power Company*	*Length miles*	*Iso-ceraunic level*	*Actual outages*		*Estimated outages per 100 miles (iso levels of 100)*	*Earth footing resistances*			*Age years*
				Per annum	*Per 100 miles*		*max.*	*min*	*ave*	
230	New England Electric System (U.S.A.)	126·4	30	3·4	2·7	9·0	1500	5	350	18
*220	Pennsylvania Power Co. (U.S.A.)	66·2	35	1·4	2·1	6·0	40	1	5	21
*220	Hydro Electric Power Commission of Ontario	300	25	1·8	0·6	2·4	25	1	6·5	5
*220	Shawnigan Water & Power Co. (U.S.A.)	74·3	40	0	0	0	50	1	—	7
*220	Pennsylvania Water & Power Co. (U.S.A.)	50	35·5	·39	·78	2·2	19	1	10	10
150	Bernese Power Co. (Switzerland)	61·5	20	1·6	2·6	13·0	200	1·6	10	6
†132	Sydsvenska Kraftaktiebolaget (Sweden)	50	10	0·7	1·4	14·0	300	7	80	16
*132	Victoria Falls & Transvaal Power Co. (S.A.)	63·5	114	6·6	10·4	9·1	24	1·5	6·42	9
132	Texas Electric Service Co. (U.S.A.)	162	40	13	8	20·0	250	2	40	19
132	Ohio Public Service Co. (U.S.A.)	45	30	1	2	3·3	250	4	10	20
114	New York State Electric & Gas Corp	26·6	37	1·33	5	13·5	60	5	30	6
110	Hydro Electric Power Commission of Ontario	66	21	10	15	71·5	30	3	15	13
*110	Georgia Power Co. (U.S.A.) ...	61	58	1	1·6	2·8	82	1	10	10
†110	Puget Sound Power & Light Co. (U.S.A.)	130	6·1	0·83	0·64	10·5	Insulated line			15
†110	Virginia Electric Co.	78	40	0·33	0·427	1·1	1210	3	300	7

* These lines equipped with continuous or radial counterpoises where earth footing resistances are high

† Wood pole lines with wood crossarms

The actual number of outages sustained per annum is, however, the criterion of the degree of continuity of supply afforded, irrespective of the length of transmission line or the isoceraunic level pertaining.

From Table XXI it is apparent that with the exception of the New England Electric system 230-kV line, outages per annum have been reduced to a maximum of 1·8, or an average of 0·9, for 220-kV lines. This has been accomplished in all cases, with the above exception, by the installation of either continuous or 2 or 4 wire radial counterpoises where earth footing resistances are high. In one instance the very efficacious earthing has resulted in no outages due to lightning, over a period of seven years in an area with an isoceraunic level of 40 thunderstorm days per annum. In this case the maximum earth footing resistance was of the order of 50 ohms, while the minimum was less than 1 ohm, before the installation of either earthwires or counterpoise. A continuous double wire counterpoise was, however, laid throughout the length of the line, and in addition radial counterpoises were installed at towers where earth footing resistances measured 50 ohms or more.

It is further apparent that larger numbers of outages occurred on the lower voltage lines, the average for 132- or 110-kV lines being approximately 5 per annum.

It would therefore appear that if power supply in Central and Southern Africa is to have equivalent operating characteristics, then the maximum number of outages per annum due to lightning would be limited to something of the following order, if no high-speed reclosing oil-circuit-breakers were employed :—

220-kV transmission lines : 2 outages per annum.

132-kV transmission lines : 3 outages per annum.

88-kV transmission lines : 5 outages per annum.

66-kV transmission lines : 7 outages per annum.

If, on the other hand, high speed reclosing of the circuit after transient faults such as normally occurring with lightning flashover is found to be possible, when stability limits are considered, then the number of outages permitted could be increased.

The general considerations given in the opening paragraphs of this Section would now have to be applied to determine how many more outages could be allowed to occur, but, at least from the point of view of the frequency of maintaining switchgear, it should be possible to double these numbers without serious effect.

In order therefore to assess the likely measures which would have to be taken in earthing the transmission lines illustrated in this paper it is assumed that four outages per annum would be permissible for 220-kV lines and six for the 132-kV line, and that the isoceraunic level would be 100, as appertaining to Northern Rhodesia. For transmission lines of 200 miles in length, therefore, the number of power outages would require to be two and three respectively per 100 miles.

Reference now to Fig. 20 indicates that such low levels could not be attained with the waisted type 220-kV line, nor with the 132-kV line. If, however, the length of the lines did not exceed 100 miles, the 132-kV line would give the requisite performance provided counterpoise earthing was installed where the tower footing resistance exceeded about 20 ohms, and the maximum footing resistance was 40 ohms.

Even with the shorter length assumed for the 220-kV waisted type of construction a performance of 4 outages for the 100 miles may not be within practical attainment.

The advantage of the higher midspan clearance assumed for the portal H type of construction for 220 kV is apparent in that a performance of 4 outages per 200 miles may be achieved provided a counterpoise earth is installed where tower footing resistances exceed about 10 ohms and the maximum resistance does not exceed about 20 ohms.

For the 88-kV line with a length of 84 miles and operating at an isoceraunic level of 54 thunderstorm days per annum, 10 permissible outages per annum would be equivalent to 22 outages per 100 miles per 100 thunderstorm days. This level could be attained if a counterpoise is installed at towers with resistances in excess of about 30 ohms and with a maximum resistance of 60 ohms.

It should perhaps again be emphasized that if a majority of tower footing resistances are less than the above limiting values, a proportion of higher than maximum resistances could be permitted and the desired outage level still maintained. On the other hand, as pointed out in Section 4·6, seasonal variations in thunderstorm activity could account for fifty per cent more outages than the average condition, and to make due allowances for this it would be advantageous to keep within the calculated limits of tower footing resistances.

16·6 *Overhead lightning protection by earthwires*

Whilst the portal H type of 220-kV construction illustrated in Fig. 15, type B, would appear to have the better lightning characteristics of those lines considered, it is to be noted that the earthwires may not afford adequate protection for the outer phase wires, and direct lightning flashes to the conductors may be possible. If this were to happen it is very possible that insulator puncture could occur, in view of the extremely high over voltages which could be induced between the conductor and earth.

It can be shown that if θ is the angle from vertical which the outside conductor makes with the earthwire, i.e. the so-called protective angle of the earthwires, the maximum value permitted for complete protection is given by the following equation :—

$$\theta = \tan^{-1} \frac{(de - dc)}{(He - Hc)} \qquad 10$$

and from equation *1*

$$de \text{ or } dc = (H - ho)\sqrt{\frac{2R}{H - ho} - 1}$$

Where $H = He$ or Hc the height of the earthwire or conductors respectively above ground

$ho =$ average height of trees flanking line

$R =$ critical distance between lightning leader tip and point to be struck

Golde[9] has pointed out that the value of R is dependent upon the total charge deposited by lightning along the leader channel, and for an average stroke of one coulomb the critical distance from which the ultimate point to be struck would be decided, would be approximately 56 feet. For smaller charges, however, this distance is less and consequently it can be shown that the protective angle would require to be correspondingly reduced. On the other hand, the puncture strength of insulators is considerably higher than the impulse level and for a 220-kV string is likely to be of the order of 5 000 kV, and for an average surge impedance of 500 ohms, for the conductor, a lightning stroke of 10-kA magnitude therefore could impress this voltage across the insulators. The corresponding charge in the lightning channel would be of the order of 0·25 coulombs and the critical distance from the point struck at 10 000 V/cm would be approximately 15 feet. For such a small value for R, however, the protective angle θ would require to be zero unless the height of the earthwires above trees flanking the line was less than 30 feet. For the 220-kV portal H type tower considered, however, the height is nearly 74 feet above ground, and this condition is unlikely to be satisfied. It would, therefore, be imperative in this case to mount the earthwires vertically above the conductor if insulator puncture is to be avoided.

17. FACTORS AFFECTING THE DESIGN OF A LIGHTNING RESISTANT TRANSMISSION LINE

17·1 *General*

The design of a lightning resistant transmission line is virtually independent of the system voltage, and the main consideration should be the necessary impulse level to ensure the desired performance under the lightning conditions pertaining along the route of the line.

The following are the basic principles of line design for satisfactory lightning performance, and each factor is separately discussed with particular reference to 220-kV line construction :—

i earthwires should be located so as to shield the line conductors from direct lightning strokes

ii adequate clearance should be maintained between the earthwires and the line conductors along the span length, to ensure as low a probability of midspan flashover as possible

iii the size of the insulators and the number of discs used should be selected to give the desired overall impulse level required

iv tower earth footing resistances should be as low as are economically justified.

17·2 *Size of earthwires*

In the selection of earthwires, the primary consideration perhaps should be the mechanical rather than the electrical properties of the wire. The material should be non-corrosive, be able to withstand the effects of vibration, and the size and quality of the wire should be such that the sag will be less than that of the conductors to ensure a greater clearance between them at midspan than at towers. For these reasons, a factor of safety of 2·0 is recommended for steel stranded earthwire, and vibration dampers should be installed at all towers on major transmission lines.

The above considerations determine the minimum cross section and diameter of the earthwires, and from the point of view of surge protection, only a small increase in the protective capabilities is afforded, by virtue of increased coupling with the conductors, if a larger size of earthwire is used. On the other hand, the earthwires should be able to carry the maximum lightning current discharge without any damage to strands. In this connection, it can be recorded that one case has occurred in Southern Rhodesia of a 7/14 S.W.G. steel wire being burnt completely through by a stroke of lightning.

In view of this and the fact that earthwire failures would have serious consequences with e.h.v. transmission, it is recommended that for these lines earthwires should be of the steel-cored aluminium or copper type in which the mechanical characteristics required are confined to the inner steel core, whilst electrically, the outer conductive strands should be capable of withstanding impulse currents of the order of 160 kA for a minimum of 50 microseconds without serious burning.

17·3 *Location of earthwires*

There has been considerable controversy in the past on the subject of protective angles between earthwires and conductors. Tests with models have indicated that a protective angle of 20 degrees affords 100 per cent shielding, whereas a single earthwire with a protective angle of 45 degrees has been estimated to give about 99·9 per cent protection, and it now appears to be generally accepted that a protective angle of 30 degrees should be adequate. From previous discussions, it would appear that the basis of shielding must be reconsidered with respect to the behaviour of lightning leader strokes of various magnitudes. For e.h.v. transmission lines operating in areas of relatively high isoceraunic levels, it is therefore recommended that earthwires should be vertically above line conductors to afford complete protection from puncture of the insulators due to relatively low current lightning strokes to the conductors.

With regard to the clearance between earthwires and conductors, calculations made during this investigation indicate that for 220-kV lines, a clearance of at least 24 feet should be maintained throughout. Increasing the clearance at midspan, however, would have a beneficial effect on the performance of the line, enabling a lower minimum outage level to be attained.

17·4 *Basic insulation levels for transmission lines*

Standard basic insulation levels for substation equipment have been in use for some time and are based mainly upon the protective level afforded by 80 per cent rated lightning arresters, when used on solidly grounded systems. It has been suggested[18] that, for voltages of 110 kV and above, these levels may be reduced even further because of the greater margin of protection which modern station arresters can maintain below present standard levels, than is possible at lower voltages.

The insulation levels in general use for transmission lines vary, however, but since the surge voltages on them cannot be economically limited by means of valve type protective equipment, it is usual to insulate for somewhat higher values for transmission lines than for substation equipment; in fact, an insulation level of one step in excess of standard basic substation levels roughly conforms to average modern practice. The basic insulation levels which are, therefore, at present in general use are indicated on Table XXII and the number of insulator discs which would be required to meet these levels, together with their impulse flashover characteristics, are shown.

Whilst there would appear to be legitimate reasons why the insulation levels for substation equipment can be reduced below standard for voltages of 110-kV and above, the same reasons would not be tenable for

TABLE XXII

PRESENT DAY BASIC INSULATION LEVELS FOR SUBSTATIONS AND TRANSMISSION LINES

System voltage kV	*Substations*		*Transmission lines*							
	Standard basic insulation level	*Proposed reduced level*	*Transmission line insulation level*	*Number of insulator discs*		*Size of insulator discs*	*1·5/40 μs impulse flashover voltages*			
							3 500 ft altitude		*5 000 ft altitude*	
				3 500 ft altitude	*5 000 ft altitude*		*Positive stroke*	*Negative stroke*	*Positive stroke*	*Negative stroke*
220	1 050	900	1 300	16	17	5¾in × 10in	1 275	1 350	1 272	1 351
132	650	550	750	10	10	5¾in × 10in	842	860	796	812
110	550	500	650	8	9	5¾in × 10in	679	662	725	738
88	450	450	550	7	7	5½in × 10in	604	591	571	569
66	350	350	450	6	6	5½in × 10in	529	512	500	483

transmission lines. Nevertheless, the question was investigated as to whether or not it might be possible to lower the insulation level of a 220-kV line from 1 300 kV to 1 050 kV because of the adequate performance of lines designed to this latter level indicated by the curves produced in Fig. 20.

On the basis of the insulation level of 220-kV transmission lines being 1 300 kV, namely one step higher than the standard basic level for substation equipment, it will be noted from Table XXII that it is necessary to have 16, 5¾-in by 10-in insulator discs per string for an altitude of 3 500 feet, whilst as previously stated, only 13 discs are required for a level of 1 050 kV.

The probability of flashover was calculated for 16, 15, 14 and 13 insulator discs for the waisted type of 220-kV line, and resultant curves are shown on Fig. 21.

It will be noted from Fig. 21 that the probability of flashover for tower earth footing resistances of between 0 and 20 ohms is virtually unaffected by the removal of 3 insulator discs. At higher earth footing resistances, however, the probability of flashover increases rapidly and at 80 ohms earth footing resistance, there is an increase of 80 per cent in the probability of flashover.

Curve B, Fig. 21, illustrates that the effect of the installation of counterpoise earthing exceeds by a very considerable margin the installation of three insulator discs. Whilst the cost of a four wire counterpoise would be slightly more than that of three extra discs per phase, its installation would therefore be more than justified by the reduction in probability of flashover which can be effected.

As pointed out in Section 16·5, the outage level of the waisted type 220-kV line under discussion would not meet requirements when insulated for a level of 1 050 kV. From Fig. 21, it is also clearly apparent that since it is the performance at low values of tower footing resistance which is critical, no improvement can be effected by increasing the level to 1 300 kV.

Exactly similar considerations could be applied in the case of the portal H type of

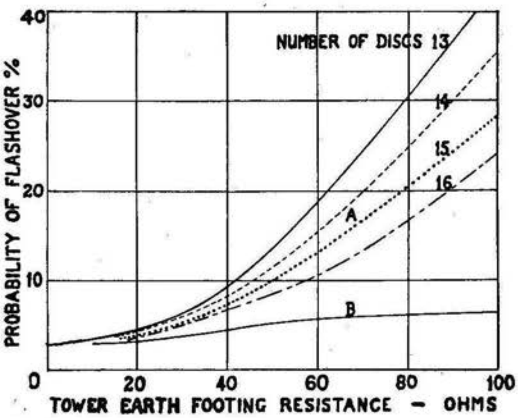

Fig. 21—Curves of probability of flashover for a waisted type 220-kV line for insulation levels of 1 050 to 1 300 kV

A—Curves for 13 to 16 insulator discs, no counterpoise earth
B—Thirteen insulator discs and transmission line equipped with counterpoise earthing

220-kV line, or the 132-kV line considered, and therefore it can be concluded that provided tower footing resistances are low, and the outage level required necessitates such values, the insulation level of transmission lines may likewise be reduced as for substations. Accordingly, new basic insulation levels, one step higher than proposed levels for substations, could be considered. These levels are shown in Table XXIII.

TABLE XXIII
PROPOSED BASIC INSULATION LEVELS FOR SUBSTATIONS AND TRANSMISSION LINES

System voltage kV	*Substation insulation level kV*	*Transmission line insulation level kV*
220	900	1 050
132	550	650
110	500	600
88	450	550
66	350	450

17·5 *Methods of lowering earth footing resistance*

There are several methods of lowering tower earth footing resistances, and the type of soil, the geological formation, the presence or otherwise of rock in the vicinity and the specific resistance of the soil should all be taken into consideration in selecting the most economic method.

On the 88-kV line in Southern Rhodesia, a 6 feet diameter copper earthmat buried under the concrete plinths forming the foundations of the towers proved particularly effective. Footing resistances as low as two or three ohms were obtained in good ground. On the other hand, there was a number of cases where even with earthmats of this type, resistances of the order required for e.h.v. lines could not be achieved owing to the high inherent resistivity of the soil. Provided tower bases are in concrete and the steelwork therefore not exposed, it might be possible to ensure a low earthmat resistance by chemical treatment.

If the depth of soil is sufficiently great, probably the most efficacious and the cheapest method of lowering tower footing resistances would be by means of the driven earth rod. Curves are available[19] for estimating the number of earth rods necessary for reducing a tower footing resistance to a particular value when the soil specific resistance is known.

Either one long rod, or several short rods can be used, and this, of course, will be a function of the depth of the soil.

An earth rod driving machine has recently been constructed based upon a proprietary design, and preliminary tests indicate that it provides a very efficient means of deep driving. This machine incorporates a petrol driven hammer which slides in a framework and operates directly on the top of the earth rod which is secured in sliding guides located in the framework, thus preventing the rod from whipping. The earth rods are threaded top and bottom and couplings join the sections together. With a similar machine, it was found possible to attain a depth of approximately 160 feet, when tests were carried out in America.

The equipment is permanently mounted on the back of a truck, and can be lowered and clamped in position during transportation.

This driving equipment is shown in Fig. 22.

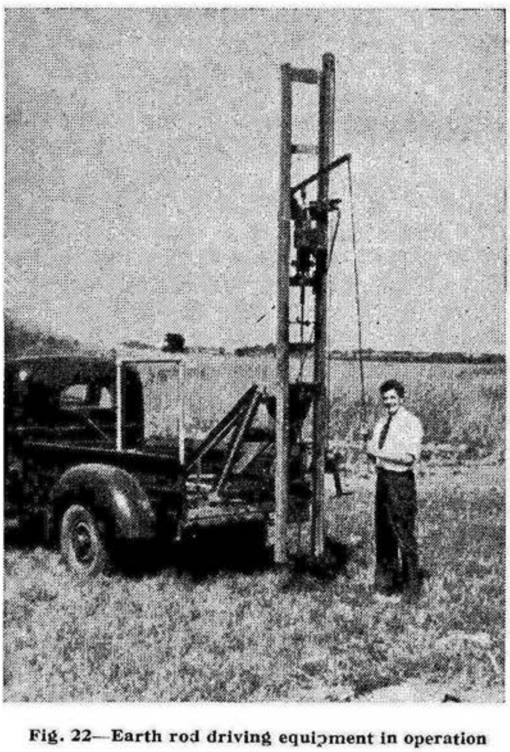

Fig. 22—Earth rod driving equipment in operation

Where there is little depth of soil and the tower earth footing resistance is high, the counterpoise earth is probably the only other effective means of ensuring a low probability of flashover. As indicated in Section 16·5, however, the tower footing resistance itself should not exceed a definite maximum to maintain a given outage level and if this is not possible, it would be necessary to raise the earthwires further above the conductors to decrease the probability of flashover at midspan, and so permit a higher maximum tower earth footing resistance.

It is more effective to employ a radial counterpoise consisting of a minimum of four wires each 200–300 feet in length, rather than a long continuous counterpoise. The depth at which the wire is laid is not important as it does not materially affect the resistance of the counterpoise, and therefore it is only necessary to bury it deep enough to prevent theft. A plough has been used effectively when in suitable ground.

18. SUMMARY AND RECOMMENDATIONS

18·1 *The characteristics of lightning*

Over the period of eight years, 305 records of transmission tower lightning currents were obtained; the maximum single tower current was 132 kA, the lower measurable limit being 10 kA. Over 50 per cent of lightning strokes affected single towers only and the remainder affected two or more up to a maximum of six, approximately five towers being affected by every three lightning strokes. Reasons are given, however, why only four towers can be definitely assumed to have been involved in a single lightning stroke, and on this basis the maximum lightning current recorded was 155 kA.

The number of individual towers carrying currents in excess of 10 kA amounted to 115 per 100 route miles per 100 thunderstorm days and the number of lightning strokes occurring was 63—on the same basis. It was shown that whilst different span lengths would result in different tower current characteristics, the lightning frequency curve for tower currents could be used with confidence for calculations of the probability of flashover for transmission lines of any span length. On the other hand, the heights of towers and that of trees flanking the line had an important bearing upon the number of lightning strokes that can be expected to fall on transmission lines, and expressions were derived from which these variations could be calculated. These expressions are based upon the theory[9] that the tip of a leader lightning stroke would not be 'attracted' to a transmission line until it had progressed to within a short distance (56 feet for an average stroke) of the tower top or earthwires.

The same expressions were used to calculate the proportion of lightning strokes which would hit towers as compared with midspan, and there was very good agreement with actual observations. Further, the number of lightning strokes occurring to ground per square mile per thunderstorm day could be estimated. The figure obtained, namely 0·35, was low in comparison with 0·5 derived by R. H. Golde.[11]

The performance of a 'ceraunometer,' described in detail in Appendix 1, (see Part I), for recording the number of lightning strokes occurring to ground and between clouds is discussed. On the assumption made regarding average lightning characteristics, the results obtained indicated that 0·28 lightning flashes occurred to ground per square mile and the ratio of cloud to cloud flashes, to those to ground, was about 5 : 1.

The figure for ground flashes, although also perhaps on the low side, is sufficiently close to that obtained for strokes to the transmission line, so as to warrant continued investigation. The instrument, when carefully standardized and controlled, is recommended for recording the comparative lightning frequency of different areas as opposed to recording thunderstorm days.

The polarity of lightning currents in transmission towers was in the ratio of fourteen negative to one positive, whilst for lightning strokes to the line, the ratio was slightly greater.

Frequency distribution curves have been prepared for lightning currents in towers and in strokes, and considering the lower limit of currents measured are in fair agreement with other investigators, any variations being probably due to differences in local lightning characteristics.

Although it had been previously suggested[1] that geological formations upon which towers were erected might have some bearing upon the frequency or severity with which lightning struck those towers, no such relationship was found, but reasons are given why this does not necessarily invalidate the fundamental theory upon which the suggestion was originally based.

Just under half of the towers which were equipped did not carry measurable lightning currents, even though the number of equipped tower-years was little less than those for towers which were struck. This was partly, but by no means completely explained by the fact that currents below 10 kA were not measured, and it was therefore suggested that major topographical or geological features in the vicinity of the transmission line did in fact 'attract' lightning long before the leader tip had progressed to within a hundred feet or so of the ground.

The frequency or the severity of lightning strokes to ground was found to be apparently unaffected by the altitude of the base of cumulo-nimbus clouds, but the average height of cloud charges was estimated to be about one kilometre, and this was used for calculating the performance of the ceraunometer.

18·2 *The lightning performance of transmission lines*

Formulae are included for the calculation of the lightning performance of transmission lines, details being given in Appendix 2, and the expectancy curve for lightning currents to transmission towers, obtained from the data collected during the investigation, was used to calculate the probability of flashover for the 88-kV line in Southern Rhodesia.

Comparisons were then drawn between the calculated and actual performance of the line from which it was apparent that the number of line outages, and the number of cases where surge voltages exceeded the impulse strength of the line insulation, were in close agreement with calculated values.

The calculations were then extended to typical transmission lines up to 220 kV, and the number of outages per 100 miles per 100 thunderstorm days was determined, due allowances being made for the different heights and dimensions of the respective transmission lines. Curves were drawn relating outages with the resistance of tower footings, and the effect of the installation of counterpoise earthing is included.

These curves illustrate that it is the clearance between earthwires and conductors which determines the optimum lightning performance of a transmission line and that the addition of a counterpoise earth reduces the number of outages which would otherwise occur particularly at high values of tower earth footing resistances.

Recommendations for the outage levels of transmission lines are of the order of two and three per annum for 220 and 132 kV respectively, up to 7 per annum for a 66-kV line, depending, however, upon individual circumstances which are enumerated. It is suggested that if high speed auto-reclosing switchgear is utilized, these numbers may, under certain conditions, be increased.

On the assumption that the outage levels could be twice those enumerated above, the earthing conditions which would be required to achieve these levels was examined. One of the 220-kV lines, 200 miles in length and operating in an area with an isoceraunic level of 100, would meet the required performance but another design would not, the main reason being the smaller clearances assumed between earthwires and conductors. Tower earth footing resistances, even with counterpoise earthing, had to be low, the maximum for the 220-kV line considered being 10 ohms.

It was shown that for complete protection of the conductor, an earthwire should be located vertically above it, and it is suggested that current theories on the protective angle of an earthwire should be reconsidered in the light of the behaviour of the tip of a lightning leader stroke.

Recommendations are made regarding the major factors to be taken into account for the design of lightning resistant power lines, with particular reference to 220-kV systems. It is suggested that earthwires should be designed for a factor of safety of 2·0 and should consist of a composite conductor with a steel core and should be capable of discharging lightning currents without damage.

Impulse insulation levels are compared with standard basic levels for substation equipment and it is recommended that standard levels, one voltage class higher than for substations, can be adopted for transmission lines. The suggestion[18] that substation levels may be reduced below standard for system voltages of 110 kV and above may also be applied to transmission lines and supporting data for this statement are given.

Various methods for reducing the tower footing resistance of transmission lines are discussed, and details are given of earth rod driving equipment recently tested out.

19. ACKNOWLEDGMENT

The authors wish to acknowledge their indebtedness to the Electricity Supply Commission of Southern Rhodesia for permission to present this paper and to Mr R. A. Jubb and his colleagues on the staff of the Meteorological Department, Salisbury, for the loan of two ceraunometers and for much helpful data compiled in connection with cloud heights. Our thanks are due also to many members of the staff of the Electricity Supply Commission for co-operation during the investigation.

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APPENDIX 2

THE PROBABILITY OF FLASHOVER—RESUMÉ OF CALCULATIONS

1. *Theory and calculation of lightning currents from measured tower currents*

The electrical circuit of a tower struck by lightning may be represented by Fig. 23 (a) and (b).

I_o = current which lightning could deliver to a zero resistance ground

i = current in tower

Z_o = surge impedance of lightning stroke

Z_n = surge impedance of earthwires in parallel

R = tower earth footing resistance

E = surge voltage on earthwires

Z_c = surge impedance of counterpoise earth

Referring to Fig. 23 : $E = I_oR'$ *19*
where R' = equivalent resistance of the

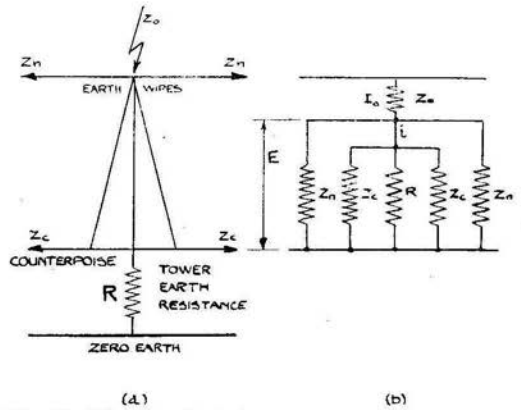

Fig. 23—The electrical circuit of a tower fitted with continuous earthwires and counterpoise when struck by lightning

circuit as represented by the surge impedance of the lightning stroke, earthwires, counterpoise earth and footing resistance all in parallel.

Hence the equivalent resistance

$$R' = \frac{1}{\frac{1}{Z_o} + \frac{2}{Z_n} + \frac{n}{Z_c} + \frac{1}{R}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 20$$

where n = number of counterpoise wires

But the tower current $i = \dfrac{E}{R_c}$.............. *21*

where R_c is the impedance of the counterpoise and tower earth resistance in parallel.

$$\text{So } R_c = \frac{1}{\frac{n}{Z_c} + \frac{1}{R}} \quad \ldots\ldots\ldots\ldots\ldots\ 22$$

$$\text{Hence } i = \frac{I_oR'}{R_c} \text{ or } I_o = \frac{R_ci}{R'} \quad \ldots\ldots\ldots\ 23$$

Hence we are able to calculate from tower current i what the lightning current I_o would be if striking a zero resistance ground. This method suffers from the defect that the surge impedance of lightning has to be assumed, and that the resistance of grounds and counterpoise earths are known to be variable especially under impulse-current conditions.

However, lightning currents calculated in this manner are sufficiently accurate for comparative purposes, and provided the same parameters are used for calculations of the probability of flashover, the resultant values will be accurate and will give results which conform to actual conditions.

Calculated values of the surge impedance of lightning depend upon a number of assumptions such as the assumed values of the diameter of the lightning channel and of the electro-static and electro-magnetic fields associated with the current in the stroke.

Values of between 150 and 500 ohms have been calculated, but in view of the lack of data on the actual dimensions involved, an average value of 400 ohms could be assumed for the surge impedance of a lightning stroke.

The initial surge impedance of a counterpoise earth has been estimated at between 150 and 200 ohms, which decays exponentially to the final leakage resistance in a time in microseconds equal to approximately six times the length of the counterpoise in thousands of feet.

A value of 150 ohms can be assumed, for the surge impedance of a single counterpoise, as little reduction in surge impedance is likely to occur within two microseconds of the lightning wave front.

Where a counterpoise is installed, the coupling effect has been taken as 5 per cent.

2. *Calculation of coupling factors*

The calculated coupling factors between earthwires and conductors are modified by corona, and it is necessary to ascertain the applicable corona radii before coupling factors are calculated.

The general formula for corona voltage is :—

$$E'\,(\text{kV}) = 76 \log_e \frac{2H}{R} \times \phi \qquad \ldots\ldots 24$$

where H = height of the conductor above ground

R = corona radius

ϕ = correction factor for altitude and humidity

A curve of corona voltage versus assumed values of corona radius can then be drawn.

To ascertain the applicable corona radius the surge voltages to cause flashover can then be calculated from the following formulae, using various assumed values of corona radius

$$E' = \frac{V}{(1 - C_n)} \qquad \ldots\ldots 25$$

where V = voltage to cause insulator or midspan flashover for positive or negative strokes

C_n = applicable coupling factor

The coupling factor is defined as :—

$$C_n = \frac{\text{voltage induced on an adjacent wire}}{\text{voltage of the main surge}} = \frac{Z''}{Z_n} \qquad \ldots\ldots 26$$

where in this instance Z'' = the average of the mutual impedances of each earthwire with the conductor

Z_n = the surge impedance of the earthwires in parallel

and $Z_n = \dfrac{Z + Z'}{2}$ for two earthwires ……27

where Z = the self surge impedance of each earthwire

and Z' = the mutual surge impedance between earthwires

The self surge impedance of a single wire can be calculated from the formula

$$Z = 60 \sqrt{\log_e \frac{2H}{R} \times \log_e \frac{2h}{r}} \qquad \ldots\ldots 28$$

where H = height of wire above ground

$2h$ = distance of wire from its current image in the ground

and $h = H + 40$ can be assumed

R = corona radius

r = radius of wire

The mutual surge impedance between one wire and another is obtained from

$$Z' = 60 \sqrt{\log_e \frac{a}{b} \times \log_e \frac{A}{b}} \qquad \ldots\ldots 29$$

where a = distance between the one wire and the current image in the ground of the other wire

A = distance between the one wire and the voltage image in the ground of the other wire

b = distance between the two wires

Two curves, relating corona radius with voltage one for positive and one for negative strokes can then be drawn, and the intersection of these curves, with that obtained from equation *24* above, gives appropriate corona radii for both positive and negative lightning strokes, and from which the applicable coupling factors may then be deduced.

3. *Lightning currents to cause insulation flashover*

The lightning current to cause insulator flashover at a tower, for a stroke to a tower is given below :—

$$I_o = \frac{(V - e)}{(1 - C_n)\ a\ R'} \qquad 30$$

where V = voltage across insulators

C_n = coupling factor

a = crest factor (taken as unity for long spans)

R' = equivalent resistance at the stricken point

I_o = lightning current which the stroke can deliver to zero resistance ground

e = average positive voltage of line conductor above earth potential

For horizontally arranged conductors with two symmetrically placed overhead earthwires, the coupling between any one conductor and the two earthwires in parallel is approximately equal, and hence also the induced voltage on all three conductors. The average potential, therefore, of any conductor above earth due to power frequency can be taken as $0{\cdot}676 \times$ rms line voltage of system.

The crest factor can be assumed as unity, if the average electrical span lengths of the lines under consideration are in excess of 1 microsecond and a reflected wave from a neighbouring tower will not return to the stricken tower, to reduce the voltage there, till at least 2 microseconds after the start of the stroke.

This assumption is justifiable in that 45 per cent of lightning strokes are estimated to have wave fronts of less than 2 microseconds. In addition, lightning strokes with wave fronts in excess of 2 microseconds would be less severe in their effect on the line insulation than strokes with shorter wave fronts.

To calculate the currents necessary to cause insulator flashover at a tower for a stroke to midspan it is necessary to take into account the effect of reflection of the surges at the tower, and the flashover formula must be modified accordingly as follows :—

$$I_o = \frac{(V - e)}{b\ R'_s\ (1 - C_n)} \qquad 31$$

where I_o = lightning current to zero ground

V = insulator flashover voltage

R'_s = equivalent resistance at midspan

C_n = coupling factor at tower

b = refraction coefficient

$$= \frac{2R}{Z_{nt} + 2R} \qquad 32$$

where Z_{nt} = self surge impedance of the earthwires at the tower

R = tower earth footing resistance

$$R'_s = \frac{1}{\frac{1}{Z_o} + \frac{2}{Z_{ns}}} \qquad 33$$

where Z_o = surge impedance of the lightning stroke

Z_{ns} = self surge impedance of a single earthwire at midspan

In calculating the lightning current to cause flashover at midspan for a stroke to midspan, it is necessary to take into consideration the reduction in voltage at midspan due to reflected waves returning from the tower and the flashover formula has to be modified accordingly to :—

$$I_o = \frac{(V - e)}{(1 - C_n)\ R'_m} \times \frac{2}{(x + by)} \qquad 34$$

where I_o = lightning current to zero ground

C_n = coupling factor at midspan

R'_m = equivalent resistance at midspan

$$= \frac{1}{\frac{1}{Z_o} + \frac{2}{Z_{ns}}} \qquad 35$$

where Z_o = surge impedance of the lightning stroke

Z_{ns} = self surge impedance of a single earthwire at midspan

x = electrical span length in microseconds

y = assumed wave front of the lightning stroke minus the electrical span length in microseconds

b = refraction coefficient as equation *32*

4. *The probability of flashover*

On the assumption that any stroke within a quarter of a span of a tower can be considered as equivalent to a stroke to the tower itself, and any stroke within a quarter of a span of midspan can be assumed as a stroke to midspan, the lightning currents to cause flashover for various values of earth footing resistance can then be calculated for :

i flashover at a tower for a stroke to a tower

ii flashover at a tower for a stroke to midspan

iii flashover at midspan for a stroke to midspan.

The lightning expectancy curve A, Fig. 12, can then be utilized to ascertain the probabilities of insulation flashover in per cent, for each of the three cases given above, and these can be combined on the following basis to give the overall probability of flashover for various values of tower earth footing resistance :—

Let P_1 = probability of flashover at a tower for a stroke to a tower

P_2 = probability of flashover at a tower for a stroke to midspan

P_3 = probability of flashover at midspan for a stroke to midspan

$$\text{Then } P = \frac{P_1 + (\text{the greater of } P_2 \text{ or } P_3)}{2} \quad \ldots 36$$

DISCUSSION

PROFESSOR J. M. MEEK : I am exceedingly glad to have had the opportunity of hearing the paper to-night. It is only within the last two weeks or so that I heard about this paper, and have since had great interest in reading it.

The particular part of the paper that interests me most is actually the first part. I hope I shall be forgiven for referring to some of that rather than to the second part of the paper.

The reason is that the calculations carried out by Mr Golde were based on a theoretical prediction which I put forward some fifteen years ago, in which I calculated the probability of streamers going up from the ground to meet the descending negative feeder strokes. I made some calculations at that time which showed lightning would have to approach within about 100 feet or so of the ground before the upward streamers would develop.

At that time, I did not carry the calculations forward any further, because I felt there were so many variables that it was not worth while doing anything more about it other than to put forward a sort of qualitative picture of the process.

Since then, Mr Golde has developed these ideas and, as shown by Mr Anderson to-night, they give very good agreement with practice. I would not like to say the agreement is fortuitous, but I am rather surprised at the way in which the theory and experiment do agree, because there are many assumptions made which I do not think are fully justified.

For instance, I do not know that it can be assumed, as Mr Golde has assumed, that the lightning strokes in which the highest currents are attained are those in which the leader stroke lowers the largest charge towards ground. I think that still has to be proved ; there are certain justifications for it, but I do not think the assumption is anything like fully justified.

Then, the assumption is made that the leader stroke develops as a single filament ; that is, it goes down a single sort of filamentary line towards the ground. Well, as we know, lightning is invariably branched, that is, during the leader stroke many branches occur, so that a sort of forked lightning effect occurs when the lightning discharge goes towards ground.

If one takes forked lightning into consideration it makes a very different figure from the 56 feet that has been put forward here to-night. I think the 56 feet is quite unjustified, it could well be 40 feet, 60 feet or 80 feet. Very close assumptions in the calculations would have to be made and to calculate the final figure as 56 I do not think is justified.

Another thing that has been completely neglected in this theory by Mr Golde is the influence of space charges, which I think will be quite considerable about the transmission line—in other words, the presence of a transmission line is going to alter the space charge distribution in the atmosphere below the cloud.

Again, the assumption is made, I think, that trees are as equally likely to be struck as transmission towers. I do not know whether that is true or not. It can be an assumption, but I should be surprised if there was the same probability for a tree being struck as a transmission tower. In his theory all that is taken into account is the height of the object and its resistance has not been considered.

The other assumption, which I think is a very doubtful one, is whether one should take 10 000 volts per centimetre as the voltage of the ground at which the upward going streamer will develop. It could well be 5 000 volts per centimetre or 3 000 volts per centimetre. All these make a very big difference to the calculation of the 56 feet, which, as I say, could well be 40 feet or 60 feet.

Hence the slight disagreement of 0·9, which I think the author gets between his experiment and theory, could well be made to be exact if one altered the assumptions slightly.

I would like the authors' comments on what I have said and, also, I would be interested to know whether they feel that the tower footing resistance, which I think is taken with A.C., is strictly applicable to the case of lightning, which is an impulse condition. I think the impulse footing resistances are thought to be different from the a.c. footing resistances, possibly higher. One ought to take into consideration the inductance of the tower, for example, in considering the possibility of flash-over.

Dr D. J. Malan: I have studied Messrs Anderson and Jenner's paper on their lightning investigation with great interest and consider it a very valuable contribution to the knowledge of what happens when the lower end of a lightning stroke approaches the earth and also to the design of power-line protection.

I would like to make the following relevant remarks as regards the geophysical significance of their paper.

Experimenters from different countries often try to explain discrepancies between observations as being due to differences between thunderstorms in different geographic latitudes whereas the disagreement can mostly be explained by faulty interpretation of their results. As it is my firm conviction that the mechanisms of thunderstorms and lightning do not vary essentially from locality to locality, it is pleasing to see that the distribution of lightning currents found by Messrs Anderson and Jenner in Rhodesia agrees remarkably closely with the results of other investigators in different parts of the world.

Even their maximum current of 210 kA is practically the same as the maximum of 218 kA recently published by Harder and Clayton of the Westinghouse Electric Corporation.[1]

However, as the authors suggest, this high total current spread over six towers may be due to separate flashes or to what they call forked lightning and what we called root branching.[2] In these cases the initial component strokes strike one point and later strokes following after an abnormally long interval of more than 100 msec strike another point several hundred yards distant. From our observations, root branching occurs in less than 1 per cent of flashes and not as frequently as the authors suggest. It thus seems that this eventuality hardly needs consideration since the probability that the second point of impact is also on the line is remote.

As the authors themselves indicate, their assumptions in calculating zero ground lightning currents is open to criticism owing to the uncertainty of the surge impedance of the lightning channel which they have assumed to be 400 ohms. Harder and Clayton calculate this as 5 000 ohms and consequently conclude that footing resistance and ground wire impedance have a negligible effect on the lightning current. Under different conditions either assumption may be right.

The occurrence of positive currents in 7 per cent of the strikes is very intriguing. In my own observations involving several thousand field changes of flashes to ground I have found only two which involved positive currents from the cloud, and even these may have been mistakenly associated with ground flashes.

It thus seems as if the high incidence of positive currents is due to an inductive effect from the earth wires as Golde suggested, or to an oscillatory effect in the base of the lightning channel itself. It would therefore be of great value if the wave form of successive surges of these positive currents could be experimentally determined.

It is very interesting to me to note that the geological formation was found to have no bearing on the frequency or severity of lightning strikes.

A thunderstorm may be considered as an electrical generator in motion at a great height above the ground. Its activity is governed by meteorological factors in the cloud, and the storm path is determined by the prevailing wind direction. Its activity will also be affected by geographic features. Even low hills, by deflecting air currents in an upward direction, may accelerate the upward motion of positive point discharge ions from the ground to the cloud base and thus cause a more frequent triggering of the discharge to ground. This is probably the reason why it appears to the authors that hills attract lightning.

I have always held the view, which is now substantiated by their findings, that the relaxation discharges which are initiated in the cloud itself are governed by the rate of generation of electricity and take place intermittently at haphazard intervals no matter what the geological features of the ground below may be.

It is not surprising that the height of the cloud base has no relation to thunderstorm severity, as the negative region of charge is well above the cloud base and usually extends upwards from the −4°C level whereas the cloud base itself is at the 100 per cent humidity level.

Unfortunately I do not agree with the calculations in Appendix 2 relating to the ceraunometer.

It is assumed that a stroke to ground removes 1 coulomb from a height of 1 km. Actually, several authors have estimated that the average charge drained by the rapid return stroke is 5 coloumbs. The average height of the charge drained by the first stroke has been found by us to be 3·5 km (later strokes may reach heights up to 8·5 km).

Substituting these values in equation *11*, the ceraunometer will count ground flashes up to 25 km and not 10 km.

As the negative charge is situated between 3·5 and 8·5 km and the upper positive charge above 8·5 km and as the discharge in the cloud takes place slowly, it is futile to attempt a calculation for cloud flashes.

My personal observations show that cloud flashes only show negative field changes at distances greater than 15 km, although overhead flashes may show minor negative-going pulses.

We calibrated our own ceraunometers by direct observation of lightning flashes and thus determined their overall response practically and not theoretically.

In view of these facts, the agreement between the figures of flashes per square mile as found by the ceraunometer and as calculated from transmission line data must be fortuitous.

As this only relates to a minor point in the paper, it does not detract from its value.

As the authors suggest, a dependable lightning counter will be of great value. We have been testing a ceraunometer which only counts ground flashes but this instrument is still in the experimental stage.

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R. H. Golde (*communicated*); I am honoured by your Council's invitation to contribute to the discussion of this valuable and informative paper. I merely regret that, owing to the short time available for its perusal, my contribution, at this stage, can hardly do justice to the wealth of information presented. As I understand that to-day's discussion is confined to Part II of the paper I shall concentrate my remarks on one or two of the larger problems raised there although, occasionally, I may revert to Part I in which the authors' basic observational data are presented.

I am particularly interested in the authors' method of calculating the probable lightning performance of transmission lines. A method[1] developed by E.R.A. (Electrical Research Association) is, in principle, similar to that described by the authors although it avoids such a doubtful parameter as the surge impedance of the lightning channel. However, apart from being applicable to lines with and without earth wires, the E.R.A. method also takes more detailed account of such factors as the ratio of flashes to towers and midspan, the variation of the attractive effect of a transmission line with the intensity of the lightning discharge, and the wave shape of the potential impressed on the line insulation.

With respect to the relative frequency of direct lightning flashes to earth wires in midspan and to transmission towers, the authors deduce from their observations (sections 4·3 and 4·5) that this ratio is less than unity, whereas application of the simple equation *3* developed in the authors' reference 9 would suggest that this ratio is nearer 3·5. This discrepancy is of considerable importance, since the risk of a back flashover due to a stroke to midspan is considerably smaller than due to a stroke to a tower. Now, as a lightning flash to a tower discharges through it a current of roughly twice the amplitude as does an equivalent lightning flash to an earth wire in midspan it follows that, for a given lower sensitivity of magnetic links, more tower currents due to flashes to midspan remain undetected than direct flashes to towers. This, incidentally, is one of the reasons why the E.R.A. method is based on the amplitudes of lightning currents and not on tower currents, the amplitudes of which vary not only with tower footing resistance but also with span length and number of earth wires.

The problem of the attractive effect exerted on a leader stroke by a transmission line is rather complex and the authors' reference 9 should merely be regarded as a first attempt to remove this problem from the realm of fancy and reduce it to physically acceptable conceptions. It appears, as clearly indicated by the authors, that a lightning leader stroke is not attracted by an earthed object until it has progressed to a comparatively low height above ground[2] (see fig. 1 of ref. 2). In addition, it is also shown in the authors' reference 9 that a transmission tower is liable to exert a greater attractive effect than the earth's surface, a conception which has been overlooked in section 4·5 and which invalidates the authors' conclusion that the number of lightning flashes to transmission lines exceeding a clear height of 56 feet above surrounding growth would be constant. In fact, application of expression *3* in reference 9 would suggest that the width of the 'area of attraction' increases from about 100 feet at an effective tower height of 27 feet to about 300 feet at a tower height of 100 feet.

The third factor which has to be considered when assessing the risk of back flashover is the wave shape of the potential across the tower insulation produced by a direct stroke to a tower or to an adjacent span. In the calculation described in Appendix 2 the authors tacitly assume that back flashover always occurs at the minimum flashover value of the insulation. Even if that was so, it would not be strictly correct to adopt the 1·5/40 microsecond flashover value, since the potential impressed on the top of the tower struck appears to have a much shorter wave tail, particularly for higher values of tower footing resistance (see figs. 15 and 16 of the authors' reference 4).

There is a further factor which may have to be considered when determining the amplitude and wave shape of the potential across the tower insulation. This is the electrostatically induced surge on each phase conductor which is of opposite polarity to the coupled surge considered in equation *7* and which is by no means of negligible amplitude.[1] The wave shape of the potential impressed on a conductor struck also affects the risk of midspan flashover to which the authors make repeated reference. As mentioned by the authors, the crest value of the earth wire potential as a result of a stroke to midspan occurs, for a 1 200 feet span, after 1·2 microsecond, after which the potential is rapidly reduced. For such a wave shape it is again extremely pessimistic to base the risk of back flashover on the minimum flashover value between earth wire and nearest phase conductor.

From what has been said some of the complications will be obvious which arise in a more detailed estimate of the probable lightning performance of transmission lines. Although the authors' simplified method appears to provide good agreement with observational results it might be advisable to exercise caution in drawing too definite conclusions for other types of line construction in which some of the above factors may assume predominant importance. This comment appears to be particularly pertinent in connection with section 17 which, it is true, is confined to lines with two earth wires. Incidentally, it would be interesting to have the authors' views on a comparable wood-pole line without earth wire protection apart from the last mile or so in front of substations. A wood-pole line either with wooden crossarms or with unearthed metal crossarms would, in effect, be appreciably lower in height than an equivalent steel-tower line with overhead earth wires and, because of the absence of earthed points, is liable to attract considerably fewer lightning flashes to itself, a rough estimate giving a ratio of 2·6 : 1 for the numbers of direct flashes attracted to the two types of line considered. Such a line would, of course, be subjected to a certain number of inter-phase faults due to direct strokes to phase conductors but these need not cause any troublesome supply interruptions if the system is provided with fast-acting auto-reclose breakers. There may be objections to the use of wood in Africa but operationally and economically such a line should compare favourably with the type of line construction discussed in the paper.

I am also very interested in the authors' contribution to the problem of the frequency of occurrence of lightning flashes to earth. First of all, I should emphasize that the tentative figure of one flash for two square miles per thunderstorm day quoted by the authors (authors' reference 9 and ref 3 below) was derived by me from data obtained in England and the U.S.A. and was never suggested to apply to tropical or sub-tropical regions. From Schonland's pioneering investigations in South Africa the height of the seat of the negative (or lower) thunderstorm charge is known to be about 12 000 feet above ground level as against about 8 000 feet in Britain and this difference should, at least partly, account for the difference in the ratio of cloud-cloud to cloud-earth flashes, which was found to be 5 : 1 by the authors as against about 2 : 1 in England.[4] For these reasons alone the density of flashes to earth in tropical regions might be expected to be lower than in temperate regions.

The value of the number of lightning flashes to earth per square mile deduced from the authors' magnetic link measurements depends on the width of the area over which lightning may be expected to be attracted to the test line and on the number of observed lightning flashes to the line. The first parameter has already been mentioned and my own estimate agrees sufficiently closely with the authors' value of about 138 feet for the average width of the 'area of attraction.' As to the authors' estimate of the number of lightning flashes to the line, this could be affected to an unknown degree by the fact that the line was patrolled, on an average, no more than twice during each lightning season. According to the authors' results the ratio of negative to positive lightning flashes to the line was about 14 : 1, so that the chance of detecting a case of repeated flashes involving adjacent towers by means of the 'reversal' method is remote. Repeated flashes of like polarity, on the other hand, cannot be detected by magnetic links, since the residual magnetization of a link is exclusively determined by the highest magnetizing field to which it was subjected. The number of lightning flashes to transmission lines and to earth in different parts of the world are two of the basic parameters on which information is at present being sought. In the interest of technical progress I should therefore like to appeal to the authors not only to continue their important investigations but also to try to keep all towers equipped with magnetic links and to spare no effort to inspect these as often as possible.

Another problem which cannot be regarded as solved is the effect of topographical and geological features on the frequency of occurrence of lightning flashes to earth.[4] Although it is difficult to visualize how these can affect the early development of a leader stroke they may conceivably influence the development of the mature stage of a cumulonimbus cloud, thus increasing the probability of lightning discharges (between clouds and to earth) over certain regions. Applying Poisson's distribution, the 228 lightning discharges during eight years' observation should have produced the following number of flashes to the 382 towers assuming the distribution of flashes being random :—

Number of times struck	*Towers struck the indicated number of times*
0	210
1	126
2	37
3	8
4	1

If the observed distribution differs significantly from the random distribution it might help to provide interesting information on the above problem. It also shows that the probability of a single tower being subjected to more than one lightning flash between two line patrols is by no means negligible, particularly if it is realized that any single storm may cross only a limited section of the entire line under observation.

I support the authors' view that more work is required on the protective effect of an earth wire although, for practical operational purposes, a shielding angle of about 30° can, in general, be taken to reduce the number of direct strokes to the 'protected' phase conductors to a tolerable level. Unless a single earth wire is positioned vertically above a phase conductor it would be misleading to assume that complete protection is given by any definite shielding angle. The shielding effect should instead be regarded as subject to statistical variation being affected by such features as the intensity of the lightning current, the geometry of the electrostatic field around earth wires and phase conductors, and the availability of the charge required to produce an upward streamer by which a downcoming leader stroke could be attracted.

It is regretted that within a reasonable scope of this contribution no mention can be made of several other interesting aspects raised in the authors' paper. However, I would not like to conclude these remarks without expressing to the authors my sincere congratulations on an excellent investigation carried out with perseverance in difficult circumstances and a high degree of ingenuity in interpreting the results obtained.

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F. R. PERRY (*communicated*) ; I feel very honoured by the action of your Council in inviting me to contribute to the discussion on the paper by Messrs Anderson and Jenner. My predominent reaction, however, to this request is that the paper is so full of information and so detailed in its analysis that it needs to be studied for a longer time than I have been able to devote to it and therefore my comments may do the paper less than justice.

The authors are to be encouraged for the careful and systematic way in which they have amassed information on lightning statistics in their region and for the way in which they have used this material to try to predict the lightning performance of overhead lines. I hope they will be encouraged to pursue this work further as, although a period of eight years may seem to be a long time for an investigation of this kind, it is one of the marked characteristics of this type of work that results can vary widely from season to season. When I was studying lightning phenomena in Johannesburg, many years ago, I was permitted to examine the lightning records of what was then the Victoria Falls and Transvaal Power Co and these records showed frequent examples of cases where flashovers occurred, each lightning season, for two or three consecutive years on certain masts or sections of a line. However, in the next two or three seasons such masts or sections showed no recorded flashovers but instead other masts or sections were struck. This kind of variation makes it very difficult, for example, to decide how far the geological formation, as discussed in section 9 of the authors' paper, has any influence on flashes to ground or to transmission line towers, and in fact suggests that other factors, such as variation in storm tracks from year to year may have a comparable or a greater effect in determining which towers are struck in any one season.

Superimposed on the first kind of variation was a wide variation in total flashovers on the system from season to season which was undoubtedly largely due to variation in storm intensisty and activity during these periods. This overall variation increases the difficulty, for example, of deciding the value of any new protective measures which may be introduced, such as a counterpoise earth or the provision of a second overhead earth wire, at least until several seasons have elapsed, so enabling the innovations to be judged by a comparison of 'average' conditions before and after the change.

Hence it is to be hoped that the authors will not feel that they have reached finality with the paper presented this evening but will continue along the same lines so that in say a further eight years they will be in a position to review the additional data obtained and so confirm, or correct, their present calculations and conclusions.

I was particularly interested in Section 3 of the paper dealing with the interpretation of the magnetic link data and for the sake of brevity my comments are presented in a series of statements without quoting the particular remarks in the paper to which these comments apply :—

a It is most desirable, in order to obtain a clear picture of what has happened and when, that any magnetic links installed should be inspected as soon as possible after a storm has occurred, otherwise it becomes impossible to associate any particular record either with a given storm or with any recorded outage. Further it is known that many strikes can occur to transmission lines without involving an outage of the line. It should be added that the more complete the installation of links, the more important it is that this ideal should be attained but the more difficult it is to attain it.

b It is possible for currents flowing in the four legs of a mast to vary by as much as 2 to 1.

(See Table 2 of Perry, Webster & Baguley, *J.I.E.E.* Vol. 89, Part II (June 1942), pp. 185-203).

c Crossmembers may carry currents up to about half the magnitude of currents in the legs. (See previous reference). This, however, applies to a mast structure of much larger base area than that described by the authors.

d When a lightning discharge strikes a mast or tower on a line where all masts are interconnected by an overhead earth wire, then, in theory, all the masts will carry some lightning current to earth as they are all in parallel. In practice, however, the current carried by masts removed more than a few spans away from the stricken mast will be so small that they will not be measurable by normal means. A typical example, however, of current measurements on a 33-kV line, carried on steel poles (i.e. only one current path to earth at each point) is taken from Table I of the above reference.

Pole number	37	38	39	40	41
Current (crest amperes)	1 500	3 200	5 500	9 100	1 600

Here the lightning discharge either took place to pole 40 or to the earth wire at a point nearer to pole 40 than to pole 39. It is clear that the comparative insensitivity of the magnetic links used by the authors is liable to give a misleading picture of the way lightning currents are distributed between the neighbouring masts as, in the example given, magnetic links as used by the authors might have detected the current in pole 40, but would not have indicated any of the currents in adjacent poles. However, if the total lightning discharge current had been, say, three times the value, then the authors' links would probably have shown currents in poles 38, 39 and 40, whereas more sensitive links would probably have detected measurable currents beyond poles 37 and 41. (I have not been able to find a record of the span length but it would be less than, perhaps only half, that given in the authors' case).

On the other hand, from the point of view of calculating probable flashovers, the currents in adjacent masts would probably be too low to modify the authors' analysis although a current of, say, 5 500 amperes might give rise to flashover if the footing resistance were 100 ohms. In the case of a discharge to the midspan of the earth wire, the expectation would be that the two masts on either side of the stricken point would carry roughly equal currents, depending upon their relative footing resistances, and masts still further removed would carry currents of diminishing magnitude and importance.

I am interested in the authors' suggestion, in section 4.3, that separate 'branches' of the lightning discharge might strike the line one or two spans apart and so account for the fact that three or more towers show measurable lightning currents but on the arguments I have discussed above it seems to me unlikely that this mechanism need be invoked to explain all such cases. In fact, if the criterion suggested by Golde is correct, and which the authors accept, for example in section 4.5, that the final point of strike may not be 'selected' until during the last 100 feet or so of travel, then the chances of two separate branches both striking a line (rather than one striking the line and the other striking open country or a tree in the neighbourhood) seem to me to be small. There is, however, another possibility, though again the probability does not seem to be high, which is as follows :—in a multiple-stroke flash it is usual for all strokes succeeding the first to follow exactly the trail blazed out by the first leader though if this is branched, the branches are rarely traversed by the subsequent strokes. However, cases are known where, if the interval between one stroke and the next is unduly prolonged, then the leader of the later stroke may blaze a trail which departs at some point from the original track, and reaches the ground at some distance away from the original point of strike. However these cases are comparatively rare, and hence this mechanism does not seem to be the likeliest explanation of why several adjacent towers should show measurable lightning currents.

The authors' use of the ceraunometer, and the estimates from the records of this instrument (section 5.2) and from the analysis in section 5.1 of the number of ground strokes per thunderstorm day per square mile are extremely interesting, as figures of this kind still require supplementing by whatever additional data can be obtained. It is also valuable to have the authors' estimate (near the end of section 5.2) of the relative frequency of cloud-to-cloud and cloud-to-ground discharges. This is a problem which gives rise to frequent argument, and has some bearing on the view, widely held, that the ratio of cloud-to-cloud activity to cloud-to-ground activity in sub-tropical and tropical areas is much higher than for storms in temperate zones. The evidence for this view is mainly of an indirect nature but one of the arguments advanced is that in spite of the known high intensity of storms in tropical zones, compared with that in temperate zones, the trouble on transmission lines due to lightning in tropical zones does not seem to be high as would be expected by comparison, say, of figures for thunderstorm days per annum in the two cases. It is believed that this is due to the fact that in temperate zones the proportion of ground strokes is relatively much higher thus offsetting the overall reduced activity. Unfortunately I know of no figures for temperate zones to compare with the authors' 5 to 1 ratio but it is of interest to note that the Electrical Research Association is hoping to obtain, by a purely photographic method, information of this kind. If successful, the data should be even more reliable than that given by the ceraunometer where certain ambiguities of interpretation cannot be avoided.

Although I would like to comment on many other points in the paper, to do so would make this contribution far too long. I found Part II of the paper, dealing with calculations designed to establish the lightning performance of transmission lines, to be of great interest though confirming my previous opinion that such calculations, at the best, are of necessity always based on inadequate data and hence can only form a rough guide which may well be belied by events. Support for this view is given by an examination of the authors' Table XV, where the estimated number of power interruptions per 100 miles per annum differs markedly, in 6 out of the 8 years considered, from the actual number of power interruptions experienced, even though the 8-year average figures in the two cases are in quite good agreement. In connection with Table XVIII it would be of interest to enquire whether the authors were able to detect signs of flashover at those towers where the calculated voltage exceeded the impulse level. Detection of such flashovers is often very difficult from ground level, as unless the insulator string is visibly damaged, the only clue to the flashover may be burn marks on the conductor which can only be seen from the tower itself.

One final point, though it may be considered outside the scope of the present paper, is whether the authors have collected any figures for values of the lightning current flowing through arresters (see Fig. 7) and whether the lightning stroke counters have given any information on the frequency of operation of the arresters. Both these points are of high interest in view of present discussions taking place in the International Electrotechnical Commission on the subject of an agreed specification for the testing of lightning arresters.

A. G. V. Pearce (Associate Member) : The authors are to be congratulated on their thorough investigations into a problem which is of such primary importance in the design of high-voltage transmission lines.

The Copper Belt of Northern Rhodesia is subjected to severe lightning storms during the summer months, and outages due to atmospheric disturbances in the early stages of operation of the 66-kV interconnection scheme soon focussed attention on this problem.

High footing resistances were encountered, presumably due to the micanaceous nature of the ground and after a series of exhaustive tests fully covered in Mr Arnot's paper it was decided in May 1953 to increase line insulation 20 per cent and install continuous counterpoises.

Work was commenced in October 1953 and completed early in December on the 40-mile connection between the switching station and Nchanga, two other circuits being completed by the end of January 1954.

Although much of the storm season had passed by the time these measures could be expected to have had effect, results so far have been encouraging, the number of storm faults during the period November to April for 1952/1953 and 1953/1954 being decreased from 40 to 27.

The following statistics for the three major 66-kV circuits in service during the whole of 1953 may be of interest :—

STORM FAULTS 1953

Circuit	No. of Faults	Faults per 100 miles per year
C.S.S./Nchanga ...	11	29
C.S.S./Roan ...	17	57
C.S.S./Mufulira ...	10	43

As many as 7 storm faults in 24 hours have been recorded, and in order to reduce outage time and lighten the load on control during such periods steps have been taken to install reclosing relays on all non-generating line oil circuit breakers. It is proposed initially to adopt a cycle of 3 reclosures at 4 to 5 second intervals followed by a lock out.

It is hoped that the above measures—which are largely in accord with the authors' findings—together with the duplicate feed provided to all consumers will in the future result in maximum continuity of supply.

The authors' treatment of flashover probabilities for 220-kV designs is of particular interest in view of the 220-kV connection between the U.M.H.K. network in the Belgian Congo and the Copper Belt which is now under construction.

This line, the design of which was effected in collaboration with the Belgian consultants, is similar to the ' waist ' type dealt with in the paper, and is illustrated in Fig. A.

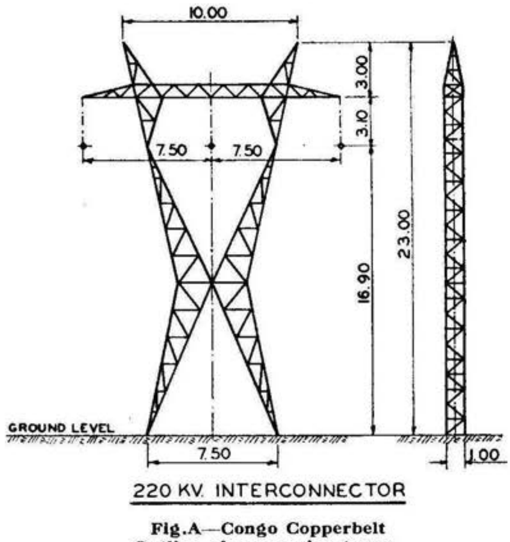

Fig.A—Congo Copperbelt Outline of suspension tower

Other details briefly are as follows :—

Average span length—300 metres

Number of earthwires—2 at 10 metres

Vertical height of earthwire above phase at towers 6·1 metres

Vertical height of earthwire above phase at midspan 8·05 metres

Counterpoises—2 × 4 mm diameter

Suspension insulation—16 toughened glass discs 5·75 inches by 10 inches

Flashover voltages line:
- System frequency dry 800 kV
- 1/50 microsec positive wave 1 300 kV
- 1/50 microsec negative wave 1 480 kV

Flashover voltages (terminal apparatus) 1/50 microsecond positive wave 1 050 kV (S.L.)

Average altitude 4—4 500 feet

High-speed single-phase reclosing is provided with a line dead period adjustable between 0·25 and 1·0 seconds.

The improvement in lightning performance secured by continuous counterpoise in the paper is further borne out by experience in the Congo on 110-kV and 50-kV lines.

In the former case lightning faults were reduced from 10 per year per 100 km of line to about 1 per year when individual pole earths were replaced by a single counterpoise of 4 mm diameter.

For the Belgian 50-kV system using counterpoise, the average annual number of faults is 3·5 per 100 km with a maximum in any year of 7·5.

In conclusion, the question of line insulation flashover and increased levels has been very fully covered—could the authors provide any details of terminal apparatus bushing flashovers and lightning arrester performance ?

R. B. ANDERSON (*in reply*) ; It is very pleasing to me to note contributions to the discussion from overseas and from members of the Institute. Since the detail of these contributions is rather voluminous, I must ask for further time in which to make a more considered reply ; I have, however, noted a few points which I would like to mention.

I am very thankful to Professor Meek for his remarks in the first contribution this evening.

Regarding one point about tower footing resistances which he raised, it was appreciated that these resistances under impulse conditions were, generally speaking, lower than the measured a.c. tower footing resistance, but so little information is available that corrections could not be applied. In any case, the disparity would appear to be much greater when the a.c. footing resistances are of the order of 200 to 300 ohms rather than of the low values, which were found to be necessary and which are apparently not quite so affected by the breakdown of the soil under impulse current conditions.

Regarding Dr Malan's remarks concerning the ceraunometer, I would stress that the main claim in the paper is that the instrument, as it stands, gives a very much better comparative measure of thunderstorm activity than any other known method, particularly that of recording thunderstorm days. I would be very interested in his development of an instrument to record ground flashes only as distinct from cloud flashes because, after all, that is the one condition of lightning with which engineers are mainly concerned.

As regards fundamental data which could be derived from the readings of the ceraunometer, the parameters used were given in good faith and with some measure of justification and there appeared a very striking correlation between the number of lightning strokes to ground thereby calculated, as compared with the number to transmission lines and this gave rise to the statement that further investigation would be justified.

In reply to one quotation by Mr Scholes, the accepted international standard for a thunderstorm day is a day on which thunder is heard and, as can be appreciated, this would constitute a very rough guide only of thunderstorm activity ; engineers throughout the world, I think, would agree that a more definite basis is required whereby the operation of transmission lines in various parts of the world could be accurately compared.

Mr R. H. Golde, raises the question of wood-pole lines and Professor Meek has made the point that it is not at all certain that trees would be struck as often or as easily as transmission towers ; it did seem to the authors, however, from observation of the number of wood-poles and trees which are destroyed by lightning in Southern Rhodesia, that the effect of trees was very important ; a large proportion of the 11-kV lines constructed in Rhodesia is of the all-insulated type, on wood poles, and the number of wood poles which are shattered by lightning is quite large and is confined to open country. Where these wood pole lines traverse areas where the tree height is roughly the same as that of the line, however, no poles have been destroyed by lightning to date. There appears to be some basis, therefore, for assuming that trees have a very marked effect on the number of flashes which would occur to a line.

Regarding Mr Perry's remarks about the frequency of observation, there would appear to be something to be said for the fact that, although the number of line patrols was small, admittedly so, it was still evident from the results that towers were struck by lightning relatively infrequently ; some, although being in operation with link equipment for the whole of the eight-year period, were not struck at all ; others were struck a maximum of four times and, as an average, it was calculated that a tower would be struck at least once in 11 years. Under those conditions, there is some support for the contention that the magnetic link installation could be left unattended and unobserved for a while without expecting that tower or even the one next to it to be struck.

The suggestion that forked lightning explained more than two towers being struck, was based mainly on the fact that the lightning currents to single towers in which the tower on either side received no measurable current was almost as high as the records where lightning struck up to four towers. The inference was that if lightning could strike one tower and produce a very high current, and also strike four towers and produce the sum total of the current much the same, an explanation was required, and this theory of forked lightning or a strike from branch leaders was put forward to explain such a case.

It is appreciated that the first paper on this subject presented by the authors did refer to lightning arresters. During the remainder of the observations it was found that at intermediate substations, in the first place, no lightning counter operations were recorded and secondly, the currents carried by ligntning arresters at terminals were relatively small, much smaller than the usual design characteristics of these arresters. That part of the investigation was, therefore, discontinued, with the exception of having recorders at the terminals.

I was very interested in Mr Pearce's remarks and in particular in the details he gave of the 220-kV system between the Copper Belt and the Belgian Congo and I would very much like further to study those particulars.

I must express thanks, Mr President, on behalf of Mr Jenner and myself, for the very great honour it has been to have had the opportunity to present this paper and to have had the comments which have been made this evening. I am sure that the contributions to the discussion will make a difference to the pattern which the investigation should take in the future.

R. W. Ferguson* and A. R. Hileman* (*communicated*) ; The authors have made an important contribution in their field investigation of lightning strokes to transmission lines. Because the isoceraunic level is approximately four times the isoceraunic level in the United States, there is indeed the opportunity to obtain valuable data on characteristics of lightning in a relatively short period of time. We agree with the authors that more information is needed on the wave shapes of stroke currents.

It might be informative at this time to compare the methods used by the authors to calculate line performance with the method used in the AIEE Committee Report[1] entitled 'A Method of estimating lightning performance of transmission lines' which is based on a previous technical paper.[2]

One of the fundamental differences is the treatment of lightning stroke current. The AIEE Committee Report treats the lightning stroke current as a constant fixed current rather than as a constant voltage back of a stroke impedance as assumed by the authors. This constant stroke current concept introduced by G. D. McCann and C. F. Wagner[3,4] assumes the stroke current to be independent of the terminating impedance and that travelling waves on transmission lines are not affected by the stroke channel. The velocity of the return stroke up the stroke channel is approximately one-tenth that of light. Thus the stroke channel behaves as a constant current source rather than a surge impedance.

The authors neglect the tower surge impedance in their calculations of lightning performance. However, the AIEE estimating method assumes that the tower is an inductance of approximately 20 microhenries or about 0·2 microhenries per foot. More recent high-voltage tests[5] on an 86-foot single circuit, flat configuration, steel tower showed that this tower could be represented by an inductance of approximately 10 microhenries or approximately 0·12 microhenries per foot which shows that the value of 0·2 microhenries per foot assumed is slightly conservative.

A 4/40 microsecond stroke current wave shape was used in the AIEE Committee report. The four microsecond front was selected since it is the average of fronts which have been measured for strokes above 30 000 amperes. The average of strokes over 30 000 amperes was selected because strokes below this value generally will not cause flashovers on shielded lines. The authors

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used a 2 microsecond front which we believe is conservative and too severe.

The estimating curves given in the AIEE Committee report were obtained by setting up a typical transmission line on the electrical analog computer[6] to determine the tower-top and mid-span potentials for strokes entering these points respectively. Stroke currents were applied at the tower and at the midspan and the potentials at the mid-span and at the tower were measured in terms of volts per ampere of stroke current.

The permissible stroke current which will cause flashover of the line insulation can be expressed by the equation

$$I = \frac{V_K}{P\,(1\text{-}C)} \qquad \mathit{1}$$

where I = permissible stroke current

P = volts per ampere of stroke current at the midspan or at the tower depending on which flashover path is being analyzed

C = coupling factor

V_K = insulation strength of line insulation to the particular voltage wave shape appearing across the line insulation.

As the voltage on the ground wire increases, a similar voltage appears on the phase conductors, induced by both electromagnetic and electrostatic coupling to the ground wire. It is assumed that the wave shape of induced voltage on the phase conductors is the same as induced voltage on the ground wire, although results from recent high-voltage tests[5] indicate that this is not strictly true. The coupling factor is the ratio of the induced voltage on the phase conductor to the inducing voltage appearing on the ground wire, and can be calculated from conventional formulae. The coupling factor used in the AIEE Committee report was increased due to the increased effective radii of the ground wire.[7] However the same recent high-voltage tests on transmission lines[5] show relatively small increases in coupling even at high voltage four times the critical corona voltage. For the significant quantity (1—coupling factor) the maximum change amounts to only about 4 per cent. It appears therefore that this change is so small as to be negligible on high-voltage lines with large clearances. This knowledge was used in calculations of lightning performance presented in a recent technical paper.[8]

The insulation strength of line insulation is known for the standard test 1·5/40 microsecond wave shape. However the typical wave shapes of tower top or midspan potentials deviate widely from this standard test voltage. Therefore methods have been devised to emulate the effect of non-standard wave shapes. The method used in the AIEE Committee Report to convert the non-standard wave shapes to an equivalent standard wave was based on visual examination of the complex waves. As an example the general type of wave shape obtained at the tower for a stroke terminating at the tower rose to maximum value in 4 microseconds and then dropped abruptly. This abrupt drop was due mainly to the loss of the inductive voltage rise caused by the tower inductance but is also influenced by the negative reflections returning from adjacent towers. This abrupt drop at 4 microseconds indicates this wave to be equivalent to a 1·5/40 microsecond wave having the same magnitude as the non-standard wave but chopped at 4 microseconds. Therefore the insulation strength V_K would be the basic insulation level of the line insulation increased to the 4 microsecond time lag point.

Another recent method for evaluating non-standard wave shapes is the integration method.[9] This method used in a more recent paper on lightning performance of distribution lines[8] gives essentially the same results as the visual observance method used in the AIEE Committee report.

Knowing the permissible stroke current as defined by equation *1* it is now possible to obtain the flashover probability by use of a stroke current probability curve.

The results of this analog computer study presented in the AIEE Committee report should not be taken as rigorous but rather be used for considering preliminary designs on a comparative basis. The chief value of the general lightning performance estimating curves derived from the analogue computer data lies in the facility provided for considering alternate designs on a comparative basis; however, a check of the curves against a large amount of actual line experience does indicate good agreement.

Because the figures of this paper were not available to the reviewers, it was impossible to compare the lightning performance estimating curves as given by the authors with curves calculated from the AIEE Committee report. However with the information given in this discussion and in the references to this discussion, this comparison can be made.

The author's contribution to the knowledge of both natural lightning phenomena and lightning performance estimating methods is a welcome contribution. The paper is an excellent example of a complete, thorough investigation where all assumptions and conclusions are well stated.

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ERRATA—PART I.

Institute's *Transactions* Vol. 45 Part 7 July 1954.

Page 237. Section 12. The first paragraph of this section to read :—

"The heights of tne base of cumulo-nimbus clouds varied in accordance with a well-defined distribution curve depicted in Fig. 13."

Page 239. Equation *14* to read :—

$$\text{“}C = \frac{33{\cdot}8L}{2\left[\log_e\left(\frac{48L}{d}\right)-1\right]-\log_e\left[\frac{^3/_2\,L+H}{\frac{1}{2}\,L+H}\right]}\ \text{picofarads ...... } \mathit{14}\text{”}$$