The Transactions of the South African Institute of Electrical Engineers

FOUNDED—JUNE 1909 INCORPORATED—DECEMBER 1909

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Volume 45 JULY 1954 Part 7

PROCEEDINGS AT THE FOUR HUNDRED AND FORTY-SIXTH GENERAL MEETING

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

Thursday, 22nd July 1954

PROFESSOR G. R. BOZZOLI (Vice-President) was in the Chair and declared the meeting opened at 8.5 p.m.

There were present 75 members and visitors and the Secretary.

OBITUARY

Before opening the meeting, the Chairman said he regretted to have to refer to the death of Dr J. H. Dobson who joined the Institute in 1910 and died on the 29th June 1954. He was President of the Institute in 1918, and was also a Past President of the South African Institution of Mechanical Engineers, the Chemical, Metallurgical and Mining Society of South Africa and the Associated Scientific and Technical Societies of South Africa.

As a mark of respect to the memory of the deceased and in sympathy with the bereaved, all present stood in silence for a few moments.

MINUTES

The minutes of the monthly general meeting held on the 24th June 1954, were taken as read and were confirmed.

MEMBERSHIP

The Chairman 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 : GERHARD PAUL GERBER

Associates : QUINTIN VISSER DAVIS, FREDERICK JACOBUS DU TOIT, JOHN ARTHUR NEILSON, FREDERICK ANGUS UTTERTON.

Transfer from Associate Member to Member : STANLEY THOMPSON SMITH.

Transfer from Graduate to Associate Member : ROY YOUNG.

Transfer from Student to Graduate : LEWIS BALFOUR BALLENDEN, PETER ROBERT MAX, DAVID SYMES THOMAS.

PAPER AND DISCUSSION

THE CHAIRMAN : This Institute is proud to be the venue for the presentation and discussion of another paper dealing with lightning and power transmission. To-night's paper will be presented by Mr R. B. Anderson who has come from Southern Rhodesia in order to read it in person.

The authors will be known to members as the authors of the 1948 paper on an 88-kV transmission line in Southern Rhodesia. They describe their present work as a sequel to their earlier paper which they refer to as a preliminary report. With the six years of lightning data which they have accumulated in the interim, to-night's paper promises well and we are all, I am sure, very eager to hear the outcome of the long and detailed study which has been made.

Owing to the length of the paper, it has been considered wise to divide it into two parts. The first part, dealing with the lightning aspect, will be presented to-night and the second part at the September meeting.

R. B. Anderson (Associate Member) then presented Part I 'The characteristics of lightning' of the joint paper entitled 'A summary of eight years of lightning investigation in Southern Rhodesia,' by R. D. Jenner (Associate Member) and himself.

The Chairman proposed a vote of thanks to the authors for their interesting paper and E. H. Scholes (Associate Member) and F. W. Stutterheim (Associate Member) contributed to the discussion. Mr Anderson replied to the remarks made by Mr Stutterheim.

AUGUST MEETING

Before closing the meeting, the Chairman announced that the Institute's August meeting would be the Annual Joint Meeting with the University of the Witwatersrand and the Fourth Bernard Price Memorial Lecture would be delivered by Professor Meek, Professor of Electrical Engineering at the University of Liverpool. He would be visiting this country for a period of three months as a guest of the University and had kindly agreed to deliver that lecture. Professor Meek was very well known in the field of the spark discharge and general high-voltage laboratory research. That would be the general subject on which he would deliver his lecture.

There was no further business and the Chairman 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, 8th July, 1954.

Mr C. N. Larkin (Vice-Chairman of the Centre) was in the Chair and declared the meeting open at 8 p.m. Thirty-five members and visitors were present.

Mr F. D. Opperman (Member) presented an address on 'The contractor and the consulting engineer,' and pointed out that his address was more in the nature of a discourse and he treated his subject with an incisive directness, supported by his long experience.

The subject matter of the address invoked a lively and largely spontaneous discussion of a very high order, those who contributed to the discussion were :—Mr E. G. Ivey (Associate Member), Dr H. D. Einhorn (Member), Messrs G. D. G. Davidson (Associate Member), J. M. Georgala (Associate), C. W. Tebbit (Associate), Col G. H. Webster (Associate Member), Messrs J. D. MacHutchon, P. Gilmour (Member) and K. Lewis (Associate Member).

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

Considering the inclement weather the attendance at this meeting was gratifying ; it is recorded that one of the worst winter blizzards experienced in Cape Town occurred that evening.

There being no further business the Chairman declared the meeting closed t 10.25 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)

This paper was received on the 3rd June 1954

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 I—THE CHARACTERISTICS OF LIGHTNING

1. INTRODUCTION

In the six years which have elapsed since a preliminary report[1] was first made on lightning investigation on an 88-kV transmission line in Southern Rhodesia, events have moved rapidly. A Central African Federation has been brought into being and one of the first subjects discussed was the provision of adequate electrical power for the Federation. Hydro-electric generation at Kafue and Kariba Gorges has become of paramount concern and it is generally agreed that if the power requirements of the Federation are to be met, bulk electricity must be available from these sources by about 1960 or even sooner.

The inauguration of either of the above schemes will necessitate 220-kV transmission for 200 to 250 miles in each direction north and south from the Zambesi River, and in the first stage single transmission lines would probably be erected. Even though these transmission lines would be controlled by high-speed auto-reclosing circuit-breakers, it would be necessary to limit the number of operations to the smallest possible, consistent with the duty which would be imposed upon the switchgear and associated electrical plant, and with due regard to the transient stability limits available on the system.

Lightning will most assuredly be the major cause of power interruption, as records on existing transmission lines both in Northern[2] and Southern Rhodesia indicate. That the area is subjected to lightning conditions which are as severe, if not more so than anywhere in the world, is evident from Table I.

TABLE I

Isoceraunic levels
Thunderstorm-days per annum

Copperbelt[2]	115
Lusaka	79
Ndola	101
Chirundu	79
Salisbury	65
Bulawayo	53
Gwelo	46
Johannesburg	114
United Kingdom	21
Florida, U.S.A.	90

Therefore, the provision of adequate insulation levels, and protective equipment for transmission lines in these areas becomes of prime consideration, if damage due to lightning is to be prevented or minimized and thus preserve the 100-per cent continuity of supply which is the ideal for all power transmission, and is essential for a major system now proposed for the Federation.

On the other hand, due regard having been paid to the lack of information on local lightning conditions, it would be possible to design equipment for a margin well in excess of normally accepted standards for insulation levels, but such a policy is likely to prove extremely expensive and is, therefore, to be avoided where possible.

The object of the lightning investigation undertaken and reported upon in this paper was, therefore, to endeavour to rationalize the subject, in terms of local conditions, in order that the margins of safety adopted might bear as true a relation to actual operating conditions as possible.

At the same time, the paper, and indeed the purpose of the investigation, would not be complete if it did not contribute to the state of knowledge of lightning and its effect upon transmission lines in general as far as it is possible and, furthermore, unless all data is presented in a form in which it may be readily adapted for other conditions of lightning frequency and severity and for any assumed design of transmission line.

2. INSTALLATION CONDITIONS AND PROCEDURE

2·1 *Terrain*

Fig. 1 indicates the general disposition of transmission lines in Southern Rhodesia and the investigation was confined to that portion of the 88-kV system connecting Gatooma in the North, and Gwelo in the South, with the Umniati River Power Station. The line traverses more or less plateau-like country, but there are sections of it which are undulating and studded with rocky outcrops two or three hundred feet high. The Northern end is 3 500 ft above sea level, whilst the Southern end rises to 5 000 ft altitude, and the profile of the route is indicated on curve F, Fig. 8.

2·2 *Type of construction*

The line is constructed of 66-ft high steel-lattice towers set in concrete, the dimensions of which are given in Fig. 2. Two overhead earthwires of 7/14 S.W.G. galvanized steel wire spaced 32 feet apart were used, bonded together at one-third of the span on either side of all towers. The insulation consists of seven 10-inch by $5\frac{3}{4}$-inch porcelain discs fitted with double arcing horns set to a 36-inch gap and having an impulse level of about 550 kV at 5 000 feet altitude. Steel-cored copper conductors of 0·2 and 0·1 sq. in. equivalent copper section were used over spans of 1 200 feet and arranged horizontally with a spacing of 15 feet, and these conductors were, therefore, shielded by the earthwires in the normal sense.

Substation equipment is protected by station-type lightning arresters and the insulator gap settings are reduced to 33 inches for one span on either side. A view of the Gatooma Substation is shown in the photograph Fig. 3 which also illustrates the type of tension tower employed throughout the transmission line.

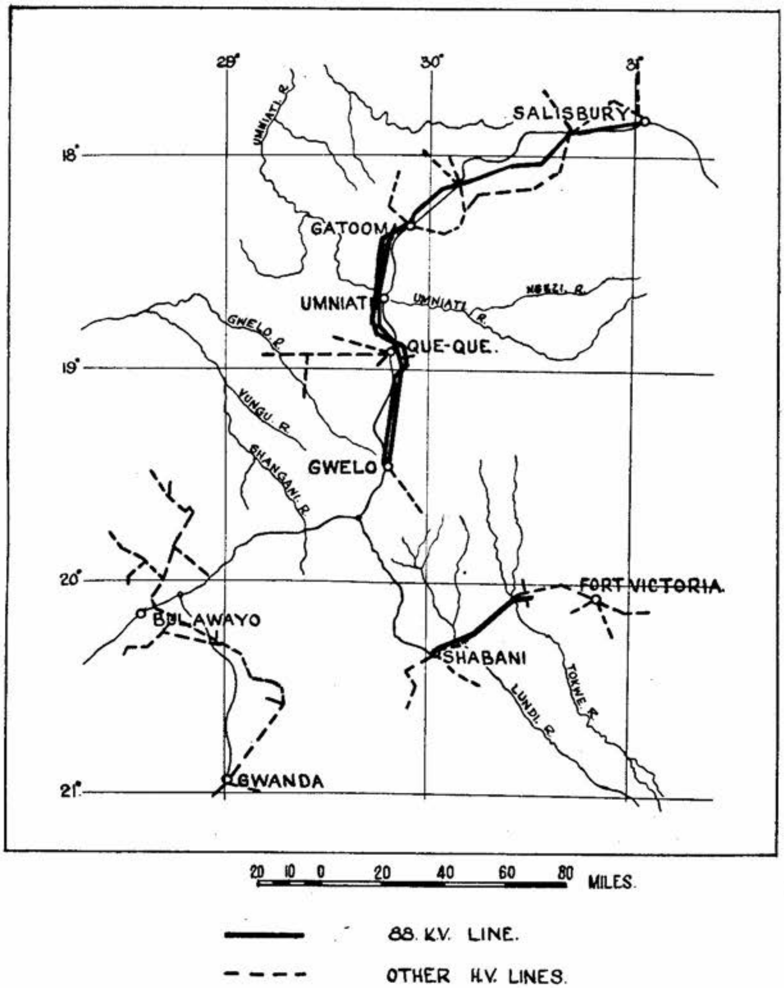

Fig. 1—Map showing h.v. transmission lines in S. Rhodesia

Two of the four legs of tension towers were earthed to earthmats, buried alongside or under their concrete plinths whilst the remaining two legs were not directly earthed. Suspension towers, illustrated in the photograph Fig. 4, were all earthed to earthmats, and the original resistances to ground are shown graphically on curve E, Fig. 8.

A 22-mile length of counterpoise earthing and a number of radial counterpoises were installed towards the end of the 1947/48 lightning season to improve the lightning performance of the line, details of the location of this supplementary earthing being shown on curve C, Fig. 8.

2·3 *Lightning measuring equipment*

The full complement of lightning measuring equipment used throughout the investigation consisted of a ceraunometer, magnetic links of proprietary manufacture, a surge crest ammeter calibrated by manufacturers to read the peak current for a given value of the residual magnetism, and an a.c. demagnetizing coil for use with the links.

Fig. 5 is a photograph of the links, the ammeter and the demagnetizing coil.

The surge crest ammeter was maintained in good order by constant checking and cleaning, and in order to facilitate the

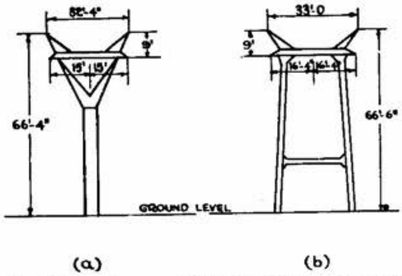

Fig. 2—Dimensions of 88-kV steel-lattice towers
(a) Suspension tower
(b) Tension tower

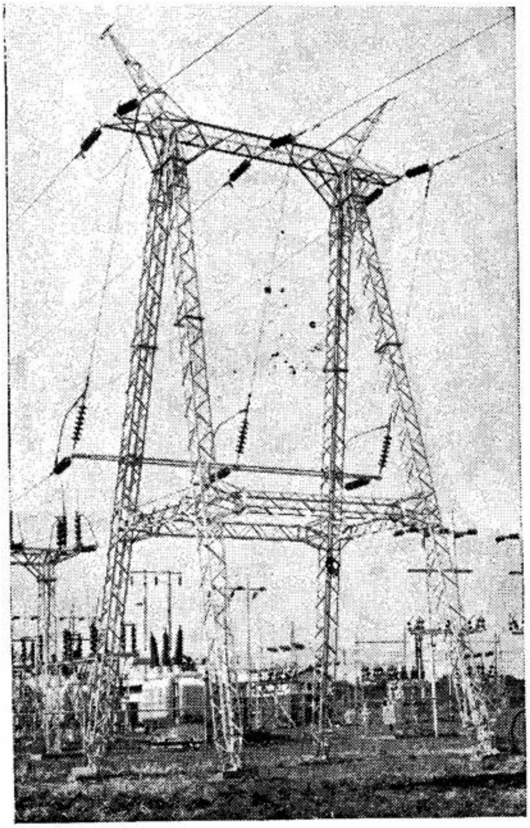

Fig. 3—Photograph of Gatooma 88-kV substation showing tension tower in foreground

calibration of the instrument, three pairs of pre-magnetized magnetic links were purchased from the manufacturers in early 1950. These were transported by air, each being protected by an aluminium shield and in addition being wrapped in cotton wool.

These links were subsequently returned to the manufacturers with a view to ascertaining whether the air journey had caused loss of magnetism, and after two trips, the loss was found to be only 1 per cent and 3½ per cent respectively on the two most highly magnetized links.

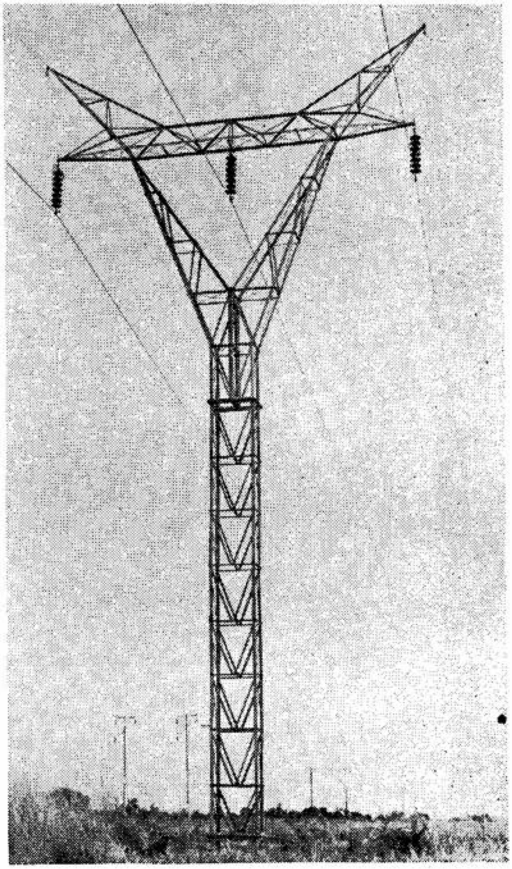

Fig. 4—Photograph of 88-kV suspension tower

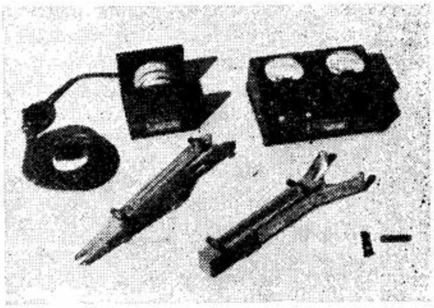

Fig. 5—Lightning measurement equipment

The surge crest ammeter when properly adjusted, and the calibration checked by the above method, proved to be entirely satisfactory.

The magnetic links had a standard maximum deviation from average residual magnetization characteristics which would result in current readings correct to plus or minus 10 per cent. The peak values of currents measured with two links could, therefore, be considered to be accurate to within less than 10 per cent. The magnitude of polarity reversals of current could also be estimated from curves supplied by the manufacturers of the links, but the accuracy

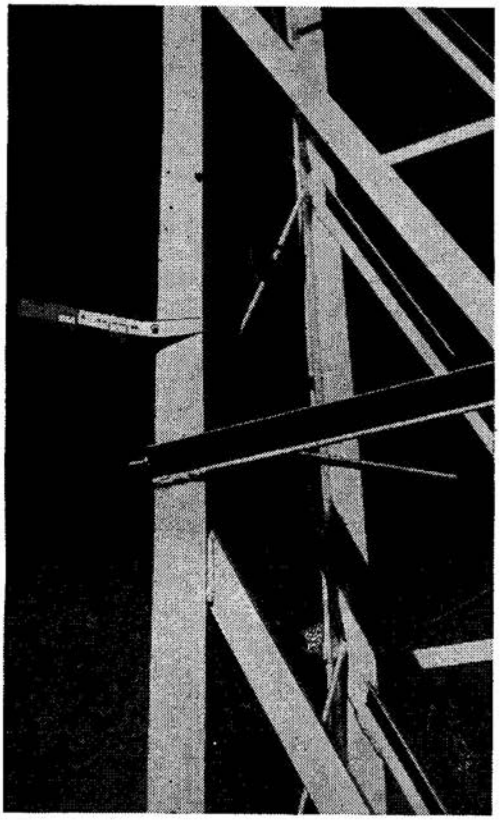

Fig. 6—Installation of angle bracket on suspension tower

of these readings would be more dependent on the varying characteristics of the link material. If polarity reversal does take place, however, the measured current would be less than the current which actually flowed, and therefore it was necessary to apply these corrections to obtain a closer approximation to the true value.

Since lightning currents vary over a very large range, the actual value of a particular measurement is perhaps not so important as the value of the probability that such current

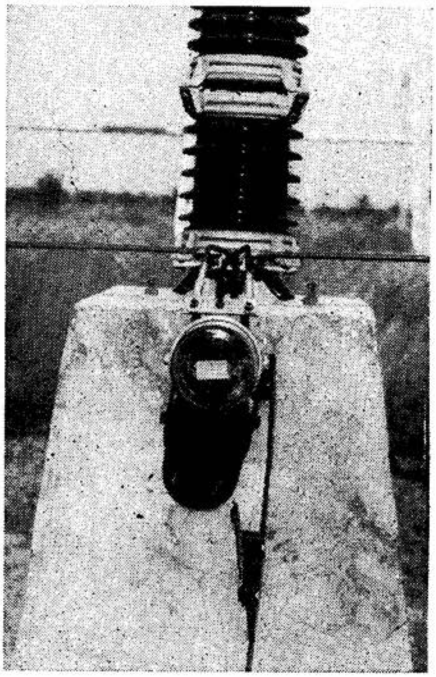

Fig. 7—Installation of line bracket below lightning stroke counter in lightning arrester earth lead

will be exceeded, and provided that the error involved over a large number of readings is small, the data obtained could be regarded as accurate. Since the errors involved in the investigation tended to compensate each other when taken over a sufficiently large number of cases, the results obtained may be considered accurate for all practical purposes.

Pairs of magnetic links were installed by means of brackets fitted to the suspension towers as illustrated in Fig. 6.

During the earlier part of the investigation, smaller brackets were attached to the earth leads on tension towers, as indicated in Fig. 7.

Termites were responsible for damaging considerable numbers of these 'line' brackets, and they were all subsequently replaced by 'angle' brackets as illustrated in Fig. 6.

A further instrument developed by the Bernard Price Institute[3] in Johannesburg has been used. This instrument, called a ceraunometer, counts the number of field changes above a predetermined level due to lightning, and is described in greater detail in Appendix 1.

It consists of an aerial coupled to two electronic circuits, one of which records the number of large positive pulses induced in the aerial by near lightning strokes, whilst the other circuit is sensitive to small negative pulses induced by more distant strokes. The instrument was installed at Gatooma during the 1953/54 lightning season and the interpretation of the results obtained is discussed further below.

2·4 *Procedure*

During the 1946/47 lightning season, magnetic links were installed on alternate towers throughout the route of the line excepting for main substations where links were installed on approximately sixteen adjacent towers on one or both sides of the substations, depending on whether the substation was a terminal, or was at an intermediate position in the line.

During 1947/48, the links were concentrated on every tower on the section between Gatooma and Que Que, but the following year, namely 1948/49, the arrangement of equipping alternate towers was reverted to. This was continued until February 1950, when sufficient magnetic links were obtained to equip every tower on the complete route. Since that time, this manner of equipping the line was maintained except for losses due to pilfering which amounted to 73 by the end of the 1953/54 season.

The line was patrolled as frequently as conditions would permit, a jeep being used and found to be ideal for the purpose. Sixteen patrols were carried out over the eight lightning seasons, and a total of 305 records of tower currents obtained. In this connection, it might be mentioned that although more frequent patrolling is obviously ideal, this is often impossible due to rain and mud, and the consequences of relatively few patrols are discussed below.

3. INTERPRETATION OF MAGNETIC LINK DATA

3·1 *Magnetic links installed on tension towers*

During most of the period of the investigation, magnetic links were installed on both earthed legs of the four-legged tension towers and the resultant currents were added algebraically. This method has been criticized,[4] but in view of the small number of cases where tension towers were struck by lightning, the effect of such errors on probability curves for lightning currents would,

TABLE II

DIVERSITY OF RATIO OF INNER TO OUTER LINK MAGNETIZATION NEGLECTING RESULTS WHERE OUTER LINK READING WAS LESS THAN 5

Range of magnetization ratios	2 inch/8 inch link installations		1 inch/2¼ inch link installations	
	No. of records	Per cent total	No. of records	Per cent total
Greater than 4·00	nil	0	nil	0
3·51 to 4·00	3	1·2	nil	0
3·01 to 3·50	5	2·0	nil	0
2·51 to 3·00	25	9·9	1	3·7
2·01 to 2·50	111	43·6	6	22·2
1·51 to 2·00	99	39·0	17	63·0
1·01 to 1·50	11	4·3	3	11·1
Less than 1·00	nil	0	nil	0
	254	100·0	27	100·0

in this instance, be negligible. In fewer cases still, during the first year of the investigation, tension towers were equipped with only one pair of links, and the respective tower-leg currents were assumed to be inversely proportional to the tower footing resistances of the two earthed legs.

3·2 *Magnetic links installed on suspension towers*

Reference to the photograph Fig. 6 might suggest that considerable error could be introduced in the interpretation of the magnetic link registration due to unequal flow of current down the four main angles making up the tower section, or due to cross currents flowing in cross members and bracing.[4] It was suggested[5] in a previous paper that the currents would divide equally between the four main vertical angles, and the equivalent current distance from the links could be calculated. Support for this theory, at least for a narrow structure such as depicted, can be deduced from the results of readings obtained.

If it were to be assumed, for instance, that the total current flowed down the centre of gravity of the one vertical angle nearest the link installation, it can be shown that the ratio of the inner to outer link magnetization, assuming no reversals in current polarity, should be 2·85, and if all the current flowed down any of the other more remote legs, the ratio should be little greater than unity.

On the other hand, the link magnetization ratio assuming equally divided currents would be 2·235 for the same link arrangement where the links are 2 inches and 8 inches respectively from the vertex of the angle.

Table II indicates the actual diversity of link magnetization ratios on readings obtained during the investigation, neglecting all those cases in which the outer link reading was less than 5, as being unreliable, owing to the inaccuracy of reading the surge crest ammeter at the lower end of the scale.

It is clear from the analysis shown on this table that over 85 per cent of the link magnetization ratios were less than 2·50 and approximately 4 per cent were less than 1·50, whence it can be inferred that tower currents did not at any rate favour the path in the legs remote from the link installation; also, few, if any, cases occurred which could be attributed to all current flowing in the leg upon which the links were mounted. Values of ratios less than the theoretical maximum can be accounted for if reversals in current polarity at the tail end of the current wave occurred, and values greater than the maximum are probably due to inaccuracies of reading especially when the outer link reading is small.

It can, therefore, be concluded that the theoretical assumption of equal tower-leg currents is substantially supported by results, and this distribution is furthermore what would be expected under electrostatic considerations. Currents would be more likely to flow in positions as far removed from the centre line of the tower as possible, and for this reason, currents in cross members or bracing would be negligible.

3·3 *Minimum measurable values of tower current*

The scale on the surge crest ammeter is such that it is virtually impossible to obtain an accurate reading on the 0–10 and 80–100 portions of the scale.

Thus, using the angle brackets depicted in Fig. 6, the minimum tower current which can be accurately measured is 7 kA, which would result from a lightning current to zero resistance ground of approximately 10 kA.

The line brackets, however, which are indicated in Fig. 7, ensure that the magnetic links are in close proximity to the tower current path, and with a full-scale reading on the surge crest ammeter, the maximum tower current which can be measured is only 6 kA. As was explained earlier, the majority of the line brackets were replaced by angle brackets, very early in the investigation, and consequently, there are relatively few records available from magnetic links installed in these brackets.

In view of the above, the records are almost all of tower currents in excess of 7 kA, it being impossible, without fully equipping the line with line brackets in addition, to measure lower values of current accurately.

3·4 *Calculation of equivalent tower lightning currents*

The currents measured in all cases were those flowing in the towers only, and did not include currents flowing in earthwires, but it is possible to assess the total current and, also to express the values in terms of the current that should flow had lightning struck zero-resistance ground. Details of these calculations are given in Appendix 2, which describes how tower currents can be expressed in terms of lightning currents. These are slightly greater depending upon the values of the parameters of the circuit which include the surge impedance of earthwires, counterpoise systems and that of the lightning channel, and the tower-footing resistance.

In these calculations, the surge impedance of earthwires may be calculated from their configuration and height above ground, and that of counterpoises can be assumed to equal the initial surge impedance of 150 ohms.[6] The surge impedance of lightning has been severally estimated at from 200 to 600 ohms, and a value of 400 ohms has been taken for the purpose of this investigation.

The above assumptions are admittedly open to criticism as regards evaluating actual lightning currents, and could account for some of the anomalies which appear to exist between data collected and published by various investigators. However, in the absence of more accurate information, the results obtained may be taken to indicate a fairly close order of magnitude of lightning currents to transmission lines.

It can be shown, however, that, provided the same assumptions are maintained consistently throughout, in evaluating the probability of flashover of transmission lines, and the calculation of lightning currents, the probability will be accurate. Therefore, any inaccuracy in the above assumptions in no way invalidates the practical application of the data to the lightning performance of transmission lines.

3·5 *The evaluation of the total current in a single lightning stroke*

After each line patrol in which magnetic link data were collected, it was apparent that there was a number of cases on sections of line in which every tower was equipped, where two or more adjacent towers had all carried currents of various magnitudes. On the other hand, there was also a large number of cases where individual towers had carried current, but those on either side had not, although also equipped with magnetic links. If the total current in a single stroke was therefore to be ascertained, it would also be necessary to determine whether, where two or more adjacent towers carried current, those cases were involved in one single lightning stroke.

In view of the lower limit of 7 kA as measured by magnetic links, it is to be expected that a number of lightning strokes up to 10 kA would go undetected.

Strokes to three towers, for instance, could aggregate 30 kA, but if the currents were evenly divided, no measurable registration would occur on the magnetic link installation. Hence, it is clear that the total number of lightning strokes recorded should on an average include only strokes with currents in excess of say 15 kA.

The extent of these cases is given in Table IV, from which it is evident that out of 140, just over 50 per cent involved single towers only and the remainder apparently involved two or more, there being one case in which six towers were apparently involved in one stroke. Owing to the time elapsing between patrols, it is quite conceivable, and very probably correct, to say that a proportion of the cases apparently involving more than one tower were due to more than one stroke. On the other hand, one case did occur in which four adjacent towers carried currents which were of positive polarity, and since currents of this polarity occurred in no less a ratio than once to every fourteen negative strokes, it is highly probable that this was a single stroke, and therefore it can be accepted that up to four towers were actually involved together in one stroke of lightning. Furthermore, it is evident that a lightning stroke to midspan must of necessity draw current from the two towers at either side unless proof can be found that the earthwires would be capable of accommodating sufficient charge to satisfy the requirements of cloud-to-earth lightning discharges.

It has also been pointed out[7] that considerable inaccuracy could occur in the value of total lightning current obtained by summating the currents in individual towers algebraically, owing to the relative phase displacement between them.

In view of the above, it can be stated that the values of total lightning stroke currents abstracted by adding together the values obtained from towers apparently involved together, must inevitably be on the high

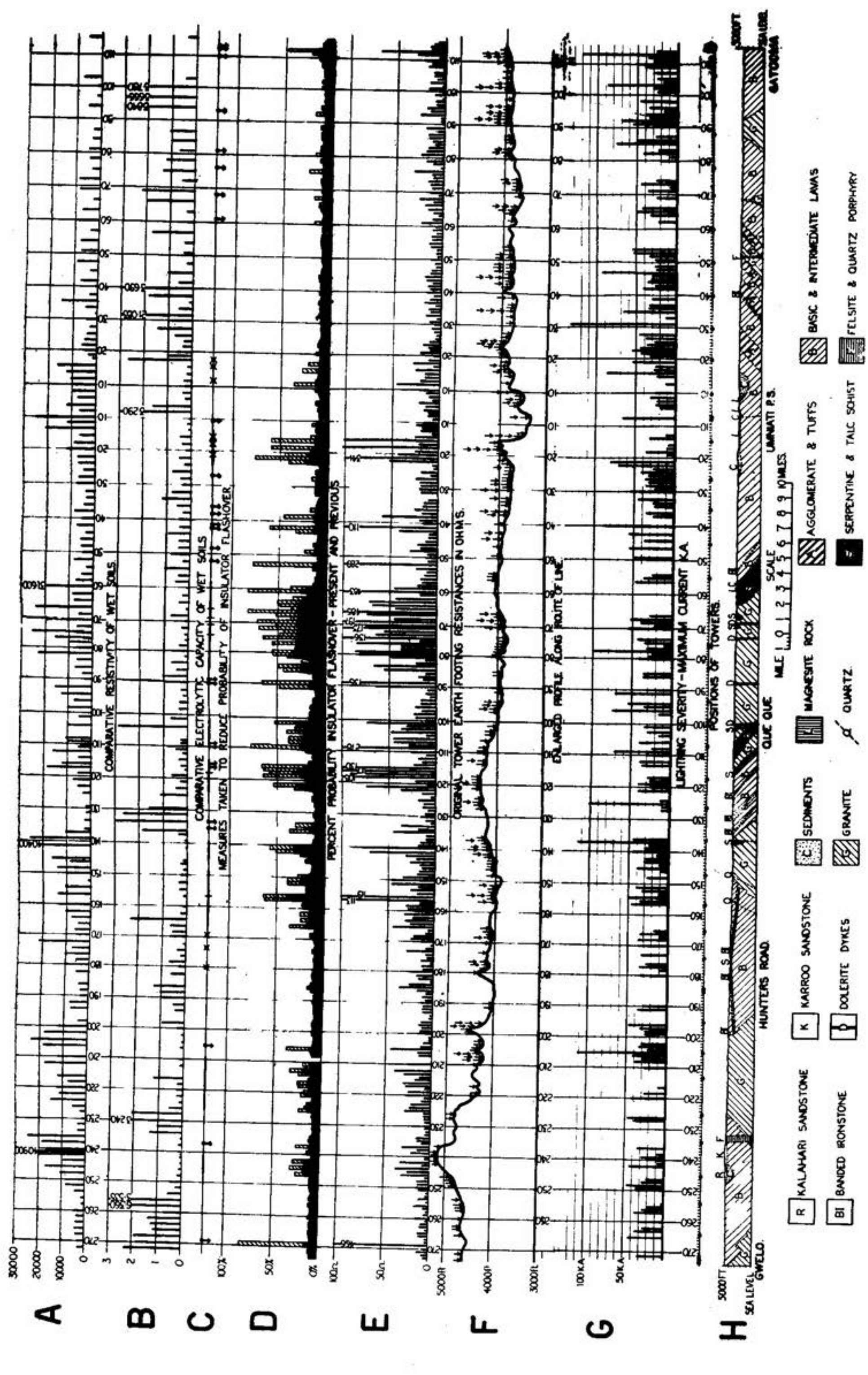

Fig. 8.—Comparative data on an 88-kV line in S. Rhodesia

A—Comparative resistivity of wet soils
B—Comparative electrolytic capacity of wet soils
C—Measures taken to reduce probability of insulator flashover
D—Percentage probability insulator flashover
E—Original tower earth footing resistances
F—Enlarged profile along route of line
G—Lightning severity
H—Geological formations

side, and conversely, the number of strokes thus calculated must be less than those actually occurring. Nevertheless, the information presented, has the value of indicating the probable magnitudes of lightning current in strokes. It should be mentioned, however, that the probability curve for total stroke currents is not used for estimating transmission line performance since it is necessary to base such calculations on the probability of currents in individual towers, these being the currents which determine the potentials appearing across the line insulation.

4. THE FREQUENCY OF OCCURRENCE OF LIGHTNING STROKES TO TRANSMISSION LINES

4·1 *General*

The eight years' investigation realized 2 286 equipped tower-years of operation during which 305 towers carried lightning currents which varied from 10·0 to 132·0 kA, values below 10 kA not being recorded. The number and distribution of the towers struck by lightning is illustrated on curve F, and the maximum lightning currents sustained by individual towers on curve G, Fig. 8. Other information pertinent to the transmission line is also given.

4·2 *The number of towers struck by lightning*

Table III is a record of the frequency with which towers may be struck by lightning under the conditions of basic data shown, the significance of which is discussed further.

It is evident that, under these conditions, the investigation was equivalent to approximately six years of operation with all 382 towers equipped and during this period 45·6 per cent of the towers were not struck by lightning at all and the remainder were struck at least once. The number of lightning strokes to towers per 100 equipped per annum was remarkably constant considering the variations of lightning storm-days from year to year, and averages 13·3.

As an average over the whole period of the investigation, 9·3 different towers were struck each year per 100 equipped, suggesting that all towers could be expected to be struck at least once over a period of about eleven years, but it is possible that some towers were shielded by surrounding kopjes and may be struck very rarely indeed, if at all. The data, of course, is applicable only to areas where lightning frequency is not more or less severe than for this particular line, and also it will be shown that lines either with shorter spans or with taller towers should indicate greater proportions of towers struck over the same period.

4·3 *The number of towers involved in one lightning stroke*

As discussed in Section 3·5 above, the evaluation of data in connection with

TABLE III

NUMBER OF CASES OF INDIVIDUAL TOWERS STRUCK BY LIGHTNING

Period equipped	Towers equipped	Tower-years	Number and percentage of cases where individual towers were struck by lightning										Total no. of lightning strokes to towers	No. of towers struck per annum per 100 equipped	Lightning strokes to towers per annum per 100 equipped
			Nil		Once		Twice		3 times		4 times				
Years	No.		No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent			
8	39	312·0	13	33·4	12	30·8	7	17·8	4	10·3	3	7·7	50	8·3	15·2
7·01	103	722·5	39	37·8	38	36·9	19	18·5	5	4·9	2	1·9	99	8·9	13·7
6·3	78	491·4	35	45·0	27	34·5	10	12·8	5	6·4	1	1·3	66	8·8	13·4
6	31	186·0	14	45·2	13	41·9	4	12·9	—	—	—	—	21	9·1	11·3
5·27	59	311·2	33	55·9	22	37·3	4	6·8	—	—	—	—	30	8·4	9·7
4·27	44	188·0	21	47·7	18	40·9	4	9·1	1	2·3	—	—	27	12·2	14·4
2·69	28	75·1	19	67·8	8	28·6	1	3·6	—	—	—	—	10	11·9	13·3
5·98	382	2 286·2	174	45·6	138	36·1	49	12·8	15	3·9	6	1·6	305	9·3	13·3

Basic Data: Lightning frequency ... 62 tower strikes per 100 miles per annum
Tower height ... ... 66 ft 6 inches
Span ... ... 1 200 ft
Thunderstorm-days ... 54

TABLE IV

NUMBER OF CASES OF LIGHTNING STROKES APPARENTLY INVOLVING ONE OR MORE ADJACENT TOWERS IN SECTIONS FULLY EQUIPPED WITH MAGNETIC LINKS

Period	1946/47	1947/48	1948/49	1949/50 to 9.2.50	1949/50 after 9.2.50	1950/51	1951/52	1952/53	1953/54	Total	
Percentage route fully equipped	23·7	54·7	9·7	5·8	100	100	92·7	92·7	77·0	Average 61·5	
Estimated number of towers struck by lightning ...	63	75	33	45	22	66	21	31	63	419	
Number of cases	No.	No.	No.	No.	No.	No.	No.	No.	No.	No.	Per cent
Isolated towers ...	3	25	2	–	3	7	12	9	14	75	53·6
Two adjacent towers	1	8	–	1	2	11	4	7	11	45	32·1
Three adjacent towers	1	–	–	–	2	5	–	2	3	13	9·3
Four adjacent towers	–	–	–	–	1	4	–	–	–	5	3·6
Five adjacent towers	–	–	–	–	1	–	–	–	–	1	0·7
Six adjacent towers	–	–	–	–	–	1	–	–	–	1	0·7
	5	33	2	1	9	28	16	18	28	140	100·0

lightning striking more than one tower at one stroke, is beset with difficulties; nevertheless, the information provided in Table IV is capable of an interpretation which leads to a number of interesting conclusions.

Firstly, the data had to be confined to that collected from sections of the transmission line in which every tower was equipped with links. Fortunately, this covers 235 towers struck by lightning out of the 305 strikes recorded for the complete investigation and can therefore be accepted as fairly representative. If it is assumed that where two or more adjacent towers were found to have carried current, this would be due to a single stroke of lightning, there were then 140 strokes of lightning involving 235 towers or roughly five towers for every three strokes.

Over 50 per cent of the cases were definitely strokes to single towers, and the remainder were strokes either to the earthwires at midspan, which involved two towers, or were the result of three or more towers being coupled together, it is suggested, by separate branch channels feeding the main lightning channel some height above the transmission line. The phenomenon of so-called 'forked' lightning in which at least two points on the ground, sometimes a few miles apart are struck almost simultaneously during a single lightning stroke, is a common enough occurrence, and is illustrated in Schonland's[8] mechanism of a lightning discharge.

TABLE V

LIGHTNING CURRENTS IN TOWERS APPARENTLY INVOLVED IN A SINGLE LIGHTNING STROKE

Tower numbers (inclusive)	Line section	Polarity of stroke	Zero ground lightning currents in individual towers apparently involved together in a single lightning stroke—kA						Apparent total stroke kA current
31	Umniati—Gatooma	Negative	132·0	—	—	—	—	—	132·0*
112—113	Umniati—Gatooma	Negative	35·5	119·0	—	—	—	—	154·5*
36— 37	Umniati—Que Que	Negative	21·6	24·6	—	—	—	—	46·2
247—249	Hunters Road—Gwelo	Negative	26·4	46·9	15·0	—	—	—	88·3
124—127	Que Que—Hunters Road	Positive	11·2	87·2	17·6	10·1	—	—	126·1*
45— 49	Umniati—Gatooma	Negative	22·4	29·2	92·0	12·4	25·4	—	181·4*
25— 30	Umniati—Que Que	Negative	32·2	35·7	32·0	34·0	22·6	53·8	210·3*

* Highest recorded stroke currents for these combinations.

Representative values of tower lightning currents (adjusted for zero ground) for cases of up to six towers apparently involved in one stroke, are shown in Table V.

A stroke to a single tower gave rise to a maximum of 132 kA whilst there are numerous cases of strokes to two or more towers which do not aggregate to this maximum, indicating that the number of towers involved is not necessarily dependent upon the severity of the stroke.

Under 50 per cent of cases of strokes to two towers indicated approximately equal currents in each tower, but in the remainder, one of the towers carried more current than the other.

The case shown on Table V for three towers is typical but there were a few cases where two out of the three towers carried more current than the third.

There were five cases in which four towers were apparently involved in one stroke, and that case in which the currents were of positive polarity indicated on Table V is considered to be genuine because of the probability involved. The two cases of five and six towers respectively would, however, be seriously open to question on account of the period between line patrols which was February, March and September in the first, and October to January inclusive in the second case. Six towers would furthermore span over a mile, and two lightning strikes could conceivably occur in this distance during even a single thunderstorm.

4·4 *The effect of shorter spans*

If it were assumed that the number of towers per route mile were doubled, for instance, from the considerations put forward in Section 4·3 above, it would be expected that many more towers would be affected for the same lightning frequency, up to eight being involved in a single stroke of lightning. Whilst the number of towers carrying current would be greater, the currents would be proportionately less and therefore the probability of flashover no different since this depends both upon the frequency with which tower lightning currents exceed given values and upon the total number of towers so affected. A curve of the probability of lightning currents to towers 1 200 feet apart therefore could be used with confidence for calculations of the probability of flashover of transmission lines with different spans, other things being equal.

4·5 *The effect of different heights of towers*

Regarding the probable effects of different heights of transmission lines, and of the height of earthwires, the following considerations are pertinent.

If it is assumed that lightning will strike the nearest object when the tip of the leader channel reaches a distance R from it, as illustrated in Fig. 9, the area covered by a

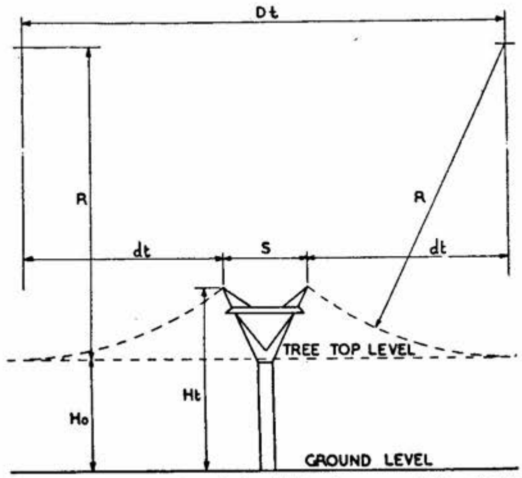

Fig. 9—Diagram showing width of area within which lightning strokes will fall on transmission lines

transmission line within which all lightning strokes will hit the transmission line can be calculated from the following formulae :—

$$dt = (Ht - Ho)\sqrt{\frac{2R}{Ht - Ho} - 1} \quad \ldots\ldots\ldots 1$$

and $Dt = 2dt + S$ 2

Where R = distance of leader tip from object to be struck

Ht = height of tower above ground

Ho = general height of tree tops flanking line

S = spacing between earthwires

dt = horizontal distance from earthwires to nearest lightning stroke to tree tops

Dt = total distance over which lightning will strike the transmission tower.

Golde[9] has pointed out that the leader tip of a lightning stroke could descend to a level even as low as a tower top above ground before finally selecting the point to be ultimately struck. If it is assumed that a potential gradient of 10 000 volts per centimetre is required at a point just above ground, before lightning will be likely to strike this point, he shows that the lightning tip must progress to within about 17 metres (56 feet) of the point for a lightning charge of 1 coulomb and about 107 feet for a charge of twice the intensity. The average peak

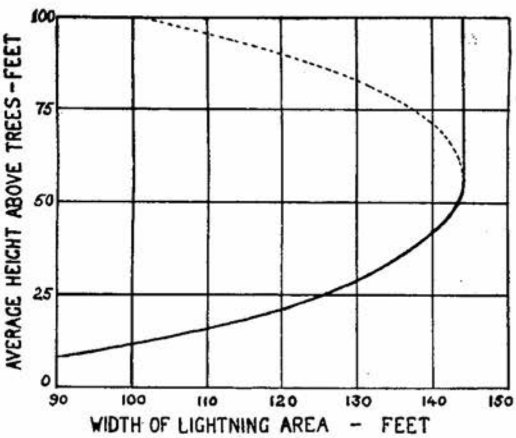

Fig. 10—Diagram showing width of area within which lightning will strike transmission lines, versus effective height of line

lightning current measured during the investigation was 40 kA, and one coulomb would be discharged if a duration of 50 microseconds were assumed and this is of the correct order of magnitude. Hence it would be reasonable to adopt 56 feet for the value of R in equation *1*.

Substituting this value therefore, the width of the strip within which average lightning strokes could be expected to strike transmission lines of various heights can be calculated, and the results are shown in Fig. 10 for transmission lines with an earthwire spacing of 32 feet. Since for given thunderstorm conditions, the number of lightning strokes to ground per unit area would be expected to be reasonably constant, Fig. 10 is also representative of the number of strokes to transmission lines of various heights. Transmission lines, therefore, with a clear height above surrounding trees and kopjes of 56 feet or more would sustain the same number of lightning strokes, unless it can be shown as is likely, that the height of a transmission tower would have a definite effect upon the progression of the leader stroke, and can attract it from a greater distance than at present assumed.

It is furthermore possible to deduce from equations *1* and *2* the likely ratio of strokes to midspan and towers if it is assumed that strokes to the earthwires for a quarter of a span on either side of a tower would cause current to flow in this tower only, whilst strokes to the remaining half span would affect the two towers on either side. The average height of the earthwires in each case is given by the parabolic relations which follow, if Ht is the height of a tower, and He the height of the earthwires above ground at midspan.

$ht = 7/12\ (Ht - He) + He$ for tower strokes *3*

$he = 1/12\ (Ht - He) + He$ for midspan strokes *4*

The calculated ratio of midspan-to-tower strokes is 0·856 which is equivalent to 52·3 per cent of all strokes affecting single towers and this compares favourably with the 53·6 per cent recorded in Table IV if all strokes to two or more towers can be regarded as equivalent to midspan strokes.

4·6 *The number of lightning strokes to transmission lines and towers*

On the assumption that several towers were involved together in one stroke of lightning in sections of line which were fully equipped with magnetic links, the total number of lightning strokes recorded to the line could be ascertained and these figures could be adjusted to cover the complete route by proportional increases depending upon the number of towers equipped as compared with the total. The results of this treatment are shown in Table VI, from which it is evident that over the eight-year period, an average of 34 strokes in excess of 15 kA occurred per 100 route miles per annum. It has already been indicated in Section 3·5 that this is likely to be on the low side, but since this information is not used directly in calculations of transmission line performance, the inaccuracy is of no practical importance.

The numbers of towers struck by lightning, however, does not suffer the same

TABLE VI

NUMBER OF LIGHTNING STROKES TO TRANSMISSION LINES BASED ON SECTIONS FULLY EQUIPPED, 235-TOWER RECORDS 140 APPARENT STROKES

Lightning season	Total No. of towers	No. of towers equipped with links	Number of observations apparently single lightning strokes	Estimated number of lightning strokes to complete 84 mile route of line	Estimated number of lightning strokes per 100 miles per annum
1946/47	383	88	5	22	26
1947/48	383	209	33	60	71
1948/49	383	36	2	21	25
1949/50 Part	383	22	1	17 } 26	31
1949/50 Part	383	382	9	9 }	
1950/51	383	382	28	28	33
1951/52	383	354	16	17	20
1952/53	383	354	18	19	23
1953/54	383	294	28	36	43
			140	29 per annum	34

Basic Data Height of tower, 66·5 ft.; Span, 1 200 ft.; Thunderstorm-days, 54.

TABLE VII

NUMBER OF LIGHTNING STROKES TO TRANSMISSION TOWERS

Year	Total number towers	Number of towers equipped	Details	Observed number of towers struck by lightning	Estimated total number of towers struck on 84 mile route	Estimated number of towers struck per 100 route miles per annum	Per cent seasonal variation
1946/47	383	231	Alternate towers equipped plus 16 consecutive towers on either side of substations	38	63	75	+20
1947/48	383	209	Every tower equipped on Que Que —Gatooma section	41	75	90	+43
1948/49	383	195	Approximately every alternate tower equipped	17	33	40	−36
1949/50 (Part)	383	178	ditto	21	45 } 67	80	+28
1949/50 (Part)	383	382	Every tower along route equipped	22	22 }		
1950/51	383	382	ditto	66	66	79	+26
1951/52	383	360	ditto except for 22 towers	20	21	25	−59
1952/53	383	359	ditto except for 23 towers	29	31	37	−41
1953/54	383	309	ditto except for 73 towers	51	63	75	+20
				305	52 per annum	62 per annum	Plus 43 Minus 59

Basic Data: Height of tower 66·5 ft. Span 1 200 ft Thunderstorm-days 54 defect of observation and it has been shown that even though this information will vary considerably in data taken from lines of different span lengths, it can be used directly together with the probability curve for lightning currents to the same towers for calculations of the performance of any transmission line.

The data recorded during the investigation was extrapolated in a similar manner to that for lightning strokes and Table VII summarizes the results. Shown also on this table is the seasonal variation above and below the average of 62 towers struck per 100 miles per annum. Although the full extent of this variation of roughly plus or minus 50 per cent might be applicable only to Southern Rhodesia, it is nevertheless a variation to be taken into account in assessing the calculated number of power-line interruptions due to lightning if based on average conditions.

The above data was taken from a transmission line of particular dimensions in an area averaging 54 thunderstorm days per annum, and in order to make the data applicable to any other conditions under which a transmission line might be required to operate, recourse could be made to a comparison based upon the number of lightning strokes per 100 route miles per 100 thunderstorm-days. Table VIII indicates that on this basis 115 towers would be struck with 63 lightning strokes per annum.

The average height above ground for the transmission line is 47 feet from equations *3*

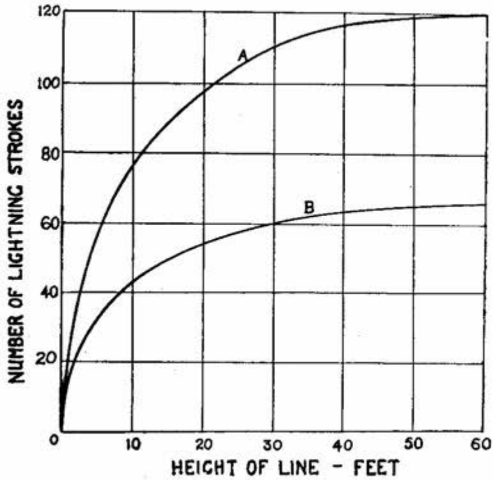

Fig. 11—**Strokes per 100 route miles per 100 thunderstorm days, based upon tower currents in excess of 10 kA and lightning currents in excess of 15 kA**
A—Strokes to towers
B—Strokes to lines

TABLE VIII

LIGHTNING STROKES TO TOWERS AND TO TRANSMISSION LINES PER THUNDERSTORM-DAY

Lightning season years	Thunderstorm-days				Lightning strokes per 100 miles			
	Gwelo ¼ route	Que Que ½ route	Gatooma ¼ route	Weighted average	To individual towers	Per thunder-storm-day	To trans-mission lines	Per thunder-storm-day
1946/47	25	—	—	25	75	3·00	26	1·04
1947/48	58	—	—	58	89	1·53	71	1·22
1948/49	40	—	—	40	40	1·00	25	0·63
1949/50	36	—	35	36	80	2·22	31	0·86
1950/51	39	—	63	51	79	1·55	33	0·65
1951/52	43	69	83	66	25	0·38	20	0·30
1952/53	62	89	89	82	37	0·45	23	0·28
1953/54	63	73	73	71	75	1·06	43	0·61
Average	46	77	69	54	62	1·15	34	0·63

Basic Data : Height of tower 66·5 ft Span 1 200 ft and *4*, and if it is assumed that the average height of trees, scrub or kopjes throughout the length of the line was 10 feet, the width of the area in which lightning strokes could be expected to fall on the transmission line of 37 feet effective height is 138 feet. Taking this distance as the standard, it is therefore possible to convert the data shown in Fig. 10 to curves indicating the number of lightning strokes per 100 route miles per 100 thunderstorm days for different effective heights of transmission lines. This data is now plotted in Fig. 11 and indicates, for example, that doubling the effective height of a transmission line from 30 feet would increase the number of strokes to towers, and therefore the number of power interruptions by 10 per cent, whereas a 20-per cent increase could be expected when doubling the height from 20 feet.

5. AN ESTIMATE OF THE NUMBER OF LIGHTNING STROKES TO GROUND

5·1 *Calculated from lightning strokes to transmission lines*

In Section 4·5, formulae were given relating the height of transmission lines with the probable width of the strip within which all lightning strokes could be expected to fall on the transmission line. As indicated above, for the transmission line under discussion, this width is of the order of 138 feet and is equivalent to an area of 2·6 square miles for each 100 miles of route. Since it is estimated that 63 lightning strokes in excess of 15 kA should occur to this area per 100 thunderstorm-days, the number of lightning strokes to ground per thunderstorm-day is of the order of 0·24 per square mile. The total number of lightning strokes per square mile will, of course, be greater. Lewis and Foust[10] found that about 32 per cent of their total records of lightning strokes were less than 15 kA and if this figure of 0·24 is adjusted accordingly, 0·35 strokes to ground per square mile should occur per thunderstorm-day, and even this may be on the low side because of the difficulty in counting the strokes that occurred to the line. The above figure, however, is a good deal less than the 0·5 which can be derived from data calculated by Golde[11] also based upon the performance of transmission lines. It is unlikely that an adequate basis could be established to reduce the effective width of the area covered by the transmission line and so increase the number of strokes per unit area, and therefore it must be concluded that lightning strokes to ground vary considerably with different thunderstorms and in other parts of the world.

5·2 *Lightning strokes to ground calculated from the readings of a ceraunometer*

The need for a precision instrument which will give more adequate data on lightning conditions than the present method of counting thunderstorm-days has been frequently demonstrated, and is obviously essential to compare information obtained by scientific observers and investigators in different parts of the world. The nearest approach to such a device is, so far as the authors are aware, the 'ceraunometer,' a circuit for which was developed by the Bernard Price Institute,[3] and this instrument is described in greater detail in Appendix 1. Basically the instrument works on the principle that all near lightning flashes, cloud-to-cloud or cloud-to-ground, produce large positive electrostatic field changes, whilst more distant cloud-to-cloud flashes produce small negative and cloud-to-cloud flashes small positive field changes at a given point. The circuit is designed therefore in two parts, the first responding to and counting large positive field changes in excess of a given amount, and the second portion of the circuit counting negative changes in excess of a relatively small value. If, therefore, the radii could be determined for each circuit for conditions of average lightning discharges, it is at least theoretically possible to determine the number of cloud-to-cloud and the number of cloud-to-ground lightning flashes per unit area.

Two instruments were installed at the Gwelo and Gatooma terminals of the transmission line but the former unfortunately developed an electrical fault which could not be immediately rectified. The instrument at Gatooma, however, was in continuous operation from October 1953, to February 1954, and was set to respond to positive signals in excess of 600 mV and negative signals in excess of 100 mV. The ratio of input circuit capacitances was such as to permit minimum aerial responses of 18 volts and 3 volts respectively, and since the effective height of the aerial was about a metre, field changes in excess of 18 volts per metre positive and 3 volts per metre negative would be counted on the respective 'near' and 'far' counters.

The data indicated so far can be accurately calculated, and the instrument calibrated and checked, and even if it were not possible to derive any further fundamental data, the information obtained from such standardized and controlled instruments would, in the opinion of the authors, go a long way to providing strictly comparable measures of thunderstorm activity throughout the world.

storms, but considered over a month and longer, more definite relations appear.

If it is assumed that an average lightning discharge of 1 coulomb occurs from a height of 1 km, the average height of the base of cumulo-nimbus clouds at Gatooma during this period, it can be calculated that the positive counter should record all cloud-to-cloud flashes up to 2 km and all cloud-to-ground flashes up to 10 km and the negative counter would record all cloud-to-cloud flashes from 2 km up to 18 km radius from the station based on electrostatic field changes

TABLE IX

PERFORMANCE OF CERAUNOMETER AT GATOOMA AND CALCULATED NUMBER OF LIGHTNING FLASHES

Month 1953/54	Indicated thunder-storm-days	Counter recordings		Ratio N_2/N_1 negative to positive	Number lightning flashes per square mile		Ratio flashes cloud to cloud over cloud to ground	Cloud to ground flashes per thunder-storm-day per sq. mile
		Positive N_1 $>18V/_m$	Negative N_2 $>3V/_m$		Cloud to cloud	Cloud to ground		
October ...	5	186	768	4·13	1·5	1·4	1·1	0·29
November	16	1 274	12 911	10·1	30·1	8·9	2·7	0·56
December	14	563	9 309	16·5	22·6	3·6	6·4	0·26
January ...	18	788	11 720	14·9	28·5	5·1	5·6	0·29
February ...	14	110	10 470	9·5	2·4	0·8	3·1	0·06
Total ...	67	2 921	45 178	15·5	110	18·8	5·4	0·28
Estimated March ...	5	186	768	4·13	—	—	—	—
Total for season	72	3 107	45 946	14·75	111	20·2	5·5	0·28

The counts obtained from the instrument at Gatooma are shown in Table IX, and observations of the 'near' counter daily readings clearly indicated thunderstorm-days with activity varying from one positive count to a maximum of 328, depending mainly on how near a particular thunderstorm was to the instrument aerial. The negative counter, apart from recording approximately three to five counts for electrical supply switching surges per day, recorded a maximum of 4 417 counts during an overhead storm. The day-to-day readings are of no particular fundamental importance in view of the haphazard paths taken by thunder-

alone. It has been assumed furthermore that the negative counter will also count the electro-magnetic field changes due to cloud-to-ground flashes up to a radius of 10 km. Naturally, for more or less severe lightning discharges, these radii would be considered modified, but it is thought that the average condition might give a reasonable approximation to the likely order of magnitude of the frequency of lightning occurrence.

If N_1 = positive counter operations

N_2 = negative counter operations

and $R = \dfrac{N_2}{N_1}$

Then the number of cloud-to-cloud flashes per

$$\text{square mile} = \frac{2{\cdot}6N_1\,(R-1)}{1\,000} \quad \ldots\ldots\ldots\ldots\ldots 5$$

And number of cloud-to-ground flashes per

$$\text{square mile} = \frac{N_1\,(80-R)}{10\,000} \quad \ldots\ldots\ldots\ldots\ldots\ldots 6$$

The numbers of lightning flashes thus calculated are shown also in Table IX, together with other pertinent information drawn up for comparison purposes.

Firstly, the figure of 0·28 ground flashes per square mile per thunderstorm-day over the complete season agrees well with that of 0·35 calculated from transmission line data in Section 5·1, and it is also noticed that the variation in different months was from 0·06 to 0·56, which further confirms that thunderstorms are extremely variable in their characteristics. It is of interest to note that the frequency of electrical activity in the upper atmosphere appears to be about five times that occurring between clouds and ground, and although the authors cannot find any reference to previous estimates of this ratio, it is known that cloud-to-cloud flashes certainly predominate.

It is therefore apparent that the data obtained from the ceraunometer recordings is not greatly at variance with present concepts.

6. THE SEVERITY OF LIGHTNING DISCHARGES TO TRANSMISSION LINES

6·1 *Lightning currents in transmission towers*

A total of 305 records of peak lightning currents in transmission towers was obtained and these were corrected for apparent reversals in polarity and expressed as the equivalent lightning currents to zero ground as explained in Section 3·4. The range of values obtained is shown in columns 2 and 3 in Table X, in which it should be noted that because of the lower limit of magnetic link measurements of about 10 kA, a number of readings in the first range would be omitted.

This data can be represented in the form of a lightning expectancy curve which indicates the probability that lightning currents in towers will exceed given values as shown in curve A of Fig. 12. The maximum lightning current recorded to single towers was 132 kA and the majority of currents were within the range of 20 to 30 kA. Fifty per cent of the recorded readings exceeded 28 kA, but owing to the absence of data below about 10 kA, the actual average tower current would be somewhat lower. On the

TABLE X

LIGHTNING CURRENTS IN TRANSMISSION TOWERS AND IN LIGHTNING STROKES

Range of lightning currents	*Equivalent lightning currents in towers*		*Lightning stroke currents*	
	No. of records	*Per cent*	*No. of records*	*Per cent*
Column 1	*Column 2*	*Column 3*	*Column 4*	*Column 5*
0– 10 kA	39	12·8	6	4·3
11– 20 ,,	33	10·8	6	4·3
21– 30 ,,	95	31·1	31	22·1
31– 40 ,,	71	23·3	19	13·6
41– 50 ,,	32	10·5	26	18·5
51– 60 ,,	14	4·6	12	8·6
61– 70 ,,	4	1·3	9	6·4
71– 80 ,,	5	1·7	6	4·3
81– 90 ,,	5	1·7	6	4·3
91–100 ,,	2	0·6	2	1·4
101–110 ,,	1	0·3	5	3·6
111–120 ,,	3	1·0	4	2·9
121–130 ,,	—	—	1	0·7
131–140 ,,	1	0·3	1	0·7
141–150 ,,	—	—	—	—
151–160 ,,	—	—	4	2·9
>160 ,,	—	—	2	1·4
	305	100·0	140	100·0

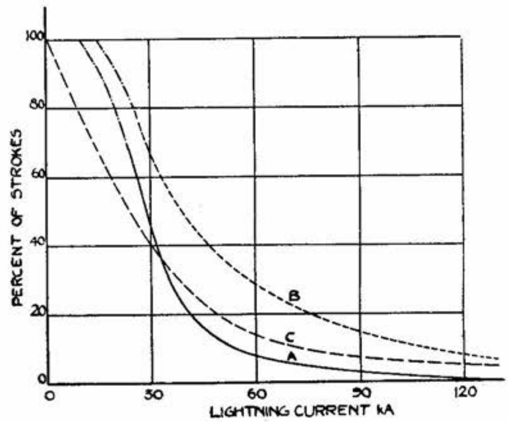

Fig. 12—Lightning expectancy curves. Per cent of number of cases of currents which exceed values given by abscissae

A. Lightning currents above 10 kA to towers (305 records)
B. Lightning stroke currents above 15 kA (140 strokes)
C. Lightning strokes. Lewis & Foust[10] (2 721 records)

other hand, since the number of towers struck per 100 miles also excludes those carrying current below 10 kA, the application of curve A, Fig. 12, to calculating the number of power-line outages will be strictly accurate.

6·2 *Lightning stroke currents*

Considering the minimum current of 10 kA measured by the magnetic links used in the investigation, it is conceivable that if up to three towers were involved in one lightning stroke, a few strokes delivering a total of about 30 kA might go undetected, and a proportionately greater number up to about 20 kA if two towers were involved. The above considerations, therefore, should be borne in mind when examining the data representing lightning stroke currents presented in columns 4 and 5 of Table X. Furthermore, the total current in a lightning stroke has been obtained by adding together algebraically, the tower currents in towers apparently involved in one stroke, in those sections of line which were fully equipped with magnetic links. The maximum stroke current obtained in this manner was 210 kA which compares with the maximum of 218 kA measured by Lewis and Foust.[10] This stroke occurred in the one case where six adjacent towers were found to have carried currents, the details of which were shown in Table V, and this case has been considered suspect (refer Section 4·3). Neglecting also the case of five towers reported on Table V, the next highest maximum recorded current was 155 kA which occurred to two towers, one of which carried 119 kA and the other 36 kA, and it is to be noted that this value is only 17 per cent in excess of the maximum current recorded to a single tower.

With similar reservations regarding the minimum currents recorded, the total lightning stroke current expectancy curve is indicated on curve B, Fig. 12.

Curve C has been added to Fig. 12 to indicate the comparative currents compiled by Lewis and Foust[10] covering 2 721 records from transmission lines of 66 kV up to 220 kV. These records apparently included about 32 per cent of all lightning currents which were below 15 kA, and if the equivalent percentage were to be added to the 140 records, the expectancy curve thereby obtained would approximate more closely to that of curve C.

Fifty per cent of the recorded lightning stroke currents exceeded 40 kA, but in view of the minimum limit imposed by the magnetic link current range used, the actual average stroke current would be somewhat less.

The average value of one coulomb discharge per lightning stroke may still, however, be regarded as approximately representative in view of lack of precise knowledge of the wave shape and duration of the discharge.

7. THE POLARITY OF LIGHTNING STROKES

The observed ratio of negative to positive lightning discharges has been quoted from about 4·5 : 1[10] to 17 : 1[12] and must obviously be related to the type of thunderstorm which occurs. In this investigation, 285 tower currents were negative as against 20 which were positive giving a ratio of 14 : 1. Since in assessing the probability of flashover, the tower current polarity is significant, this figure has been used in compiling the combined probability of flashover for positive and negative strokes.

With regard to the polarity of lightning strokes, of the 140 records obtained, 131 were negative to 9 positive, and the ratio was therefore slightly greater than 14 : 1.

There was no noticeable difference in the currents delivered in positive strokes as compared with negative, and although one case occurred of four towers being affected by one positive stroke, the remaining eight cases were confined to single towers.

It is furthermore evident that the number of cases of positive ground flashes is small enough to justify neglecting them as far as the performance of the ceraunometer is concerned. It is also possible that the ratio of positive to negative strokes is equally small for cloud-to-cloud flashes.

8. POLARITY REVERSALS IN TOWER LIGHTNING CURRENTS

A uni-directional single lightning stroke would produce an effect on a pair of magnetic links such that the ratio of the inner to outer link remanent magnetism is constant for whatever value of current flowed. This constant, as explained in Section 3·2 would be 2·235 for the 2-inch and 8-inch bracket installation depicted in Fig. 6. If now a second stroke of reversed polarity were to occur, the ratio of remanent magnetism of the two links would alter and would be less than 2·235. Manufacturers of the magnetic links supply calibration curves from which the ratio of the second current to that of the first of opposite polarity can be readily obtained and this is expressed as a 'percentage reversal.' The extent of these apparent polarity reversals of tower currents measured during the investigation is given in Table XI (neglecting all records in which the outer link reading was less than 5 as being inaccurate).

TABLE XI

EXTENT OF APPARENT REVERSALS OF POLARITY IN TOWER CURRENTS

Description	*No. of cases*	*Per cent of total cases*
Magnetic link ratios greater than maximum		
(*a*) High current readings	53	19·3
(*b*) Low current readings	9	3·3
Reversals in range		
0— 5 per cent ...	61	22·3
6—10 ,, ...	15	5·5
11—20 ,, ...	36	13·1
21—30 ,, ...	34	12·4
31—40 ,, ...	34	12·4
41—50 ,, ...	32	11·7
Total	274	100·0

It will be apparent that the greater proportion of tower current measurements indicated this phenomenon. It cannot be assumed that there were in effect two separate lightning strokes of opposite polarity in each case, because there would then be no reasonable explanation as to why in the majority of cases the first and largest stroke should have been negative. Golde[13] has suggested that the apparent current reversals are due to electro-magnetic induction from currents flowing in the earthwires on one or other side of the tower depending upon which side a lightning stroke occurred.

It is doubtful, however, if this theory could account for reversals of the order of 40 to 50 per cent in these very narrow towers. On the other hand, there were approximately 23 per cent of cases in which the link ratios were greater than maximum, and whilst some may have been due to successive strokes occurring of lesser magnitude but of the same polarity as the first, this would certainly not explain all the results.

It would appear therefore that this matter requires further investigation, and measurements of the waveform of lightning currents in transmission towers appear to be essential for this purpose. Such information would also prove of value in assessing the true performance of transmission lines, since the impulse characteristics of insulation are so dependent upon the waveform and duration of the surges applied.

9. THE EFFECT OF GEOLOGICAL FORMATION

Curve H, Fig. 8, indicates the basic geological formations upon which the transmission line is erected and it was found[1] that the electrical properties of various soils differed very widely even if they did not entirely conform to the geological categories assigned to them. It has, however, often been suggested that lightning will strike given points more frequently than others and various possibilities have been published by different investigators. The application of Golde's[9] theory would suggest that the point to be ultimately struck will only be determined during the last 100 or so feet of the progression of the lightning leader stroke towards the ground, and hence if the objects struck happen to be trees or transmission towers, there is unlikely to be any relation found from data collected from these sources.

On the other hand, the possibility of the general electrical permittivity of the ground having an effect upon the level of potential gradients to be expected under the influence of a charged cloud has been postulated[14] and it has been suggested that this factor would influence the frequency and the total quantity of charge in lightning strokes to ground.

In order therefore to investigate this point, and to include as large a number of records as possible, the frequency with which lightning affected towers situated in various geological formations was compared on the basis of equipped tower-years of operation, and a frequency index was calculated for each formation assuming the frequency of strokes to basic and intermediate lavas as unity. This information is given in Table XII, from which it will be apparent that if the number of tower-years of the first four cases can be considered to be an adequate

TABLE XII

LIGHTNING STROKES TO TOWERS SITUATED ON VARIOUS BASIC GEOLOGICAL FORMATIONS

Basic geological formation	Type letter	No. of towers in section	No. of equipped tower years	No. of tower lightning strokes	No. of strokes per 100 tower-years	Frequency index	Average tower lightning current
Basic and intermediate lavas ...	B	188	1 144·1	157	13·70	1·00	32·2
Granite	G	87	488·4	65	13·31	0·972	34·7
Sedimentary rocks	C	22	145·9	21	14·40	1·05	32·5
Serpentine and talc schists	S	25	147·9	17	11·50	0·84	35·7
Agglomerate and tuffs	A	15	100·1	18	18·00	1·314	25·4
Banded ironstone	bi	11	59·8	3	5·03	0·367	27·1
Magnesite rocks	L	11	76·5	7	9·15	0·668	19·6
Kalahari sandstone	R	8	43·5	5	11·50	0·84	29·0
Karroo sandstone	K	7	33·2	4	12·05	0·88	19·1
Dolerite dykes	D	3	20·6	3	14·57	1·062	31·9
Felsite and quartz porphyry ...	F	3	13·6	2	14·70	1·072	26·8
Quartz	Q	2	12·6	3	23·80	1·738	26·9
		382	2 286·2	305	13·34	0·974	31·9

TABLE XIII

COMPARISON OF PERFORMANCE OF TOWERS STRUCK BY LIGHTNING WITH THOSE WHICH WERE NOT

Basic geological formation	Type letter	Towers struck by lightning				Towers not struck by lightning		
		No. of towers	Equipped tower-years	No. of strokes	No. of strokes per 100 tower-years	No. of towers	Equipped tower-years	Anticipated no. of strokes
Basic and intermediate lavas	B	105	656·0	157	23·9	83	488·1	117
Granite	G	49	287·5	65	22·6	38	200·9	45
Sedimentary rocks	C	13	82·4	21	24·3	9	63·5	15
Serpentine and talc schists ...	S	13	79·5	17	21·4	12	68·4	15
Miscellaneous formations ...	—	29	185·3	45	24·2	31	174·6	43
Total	—	209	1 290·7	305	23·6	173	995·5	235

record, the frequency of incidence of lightning to towers situated in serpentine and talc schists would be less than for basic lavas, granite and sedimentary rocks, but the average tower currents were about equal. On the other hand, if the towers which were not struck are not included, on the assumption that there may be some other cause for this, the incidence of lightning strokes is approximately equal for all four types of formation, as indicated in Table XIII.

It should be emphasized, however, that these results do not necessarily invalidate the general hypothesis given above for the reasons that, firstly, a more correct comparison could be carried out on the basis of lightning strokes to completely equipped sections for the applicable tower-years, but if this information were to be extracted in this instance, both the number of records and the aggregate of tower-years would be considerably reduced and the results would, therefore, be probably misleading. Secondly, it has been assumed that the electrical characteristics of basic geological formations of the same origin are uniform, and yet, as indicated from curves A and B, Fig. 8, some measured properties of soils were found to vary considerably even though from identical formations.

10. LIGHTNING-FREE SECTIONS OF THE TRANSMISSION LINE

Reference to curve F, Fig. 8, indicates a number of gaps in the route of the transmission line in which apparently no towers were struck by lightning. These cases were further analysed in Table XIII, which indicates a comparison between them and the remainder of the towers which did sustain lightning strokes, showing also the main basic geological formations. Regarding the towers which were struck, the table clearly shows a remarkable constancy of lightning strokes per 100 equipped tower-years as between different geological formations, and on the assumption that the remaining towers should have sustained a proportionate number of strokes, a total of 235 more strokes should have been recorded. Since the aggregate period of operation in both cases was equivalent to approximately six years, it is therefore to be concluded that either the majority of the towers in question did sustain lightning currents less than 10 kA but this could not be measured on the magnetic link range used, or there is some other reason for this phenomenon.

Considering the first possibility, Lewis and Foust[10] record approximately 40 per cent of total records of tower currents below 10 kA. If this figure could be accepted for this investigation, then approximately 500 total tower strokes should have been recorded of which 200 would have been less than 10 kA, and these would have been distributed over the whole route of the line, and this would account for about 90 of the 235 anticipated strokes to the apparently lightning-free sections, still leaving about 60 per cent unexplained.

It is unlikely that there was a prevalence of well defined storm-free areas, since none of the sections of line concerned was sheltered by mountainous ridges or major plateaux. As mentioned in Section 9, the serpentine and talc schist belts indicated almost equal lightning frequency to towers situated on the remaining major formations when the lightning-free cases were excluded, and it is perhaps significant that these belts coincide with broken hilly country in which the schists form long ridges of hills up to 200 feet in height. It is therefore very likely that the reason for some towers not being struck by lightning is to be found in the characteristics of the surrounding terrain. It would therefore appear that the possibility still exists that prominent hills and ridges ‘ attract ’ lightning and the progress of the leader strokes is not entirely so haphazardly downward as has been assumed.

11. LIGHTNING STRIKING THE HIGHEST POINT

Thirty-three high points and 32 low points were selected for the analysis which appears in Table XIV.

TABLE XIV
STROKES TO HIGH AND LOW POINTS ON LINE

	High points	*Low points*
Number of towers	33	32
Number not struck by lightning	14	11
Number of recorded tower-strokes	27	33
Number of equipped tower-years	196	179
Strokes per 100 tower-years ...	13·73	18·40

From this table, it is apparent that, if anything, lightning favours striking those towers which are situated in valleys. In this respect, however, it is perhaps significant that valleys may be generally open grassland, whilst where the transmission line traverses the high points, the country is broken and studded with hills and the route selected through such country invariably takes the gaps and rarely (though sometimes) traverses the highest point.

12. THE EFFECT OF THE ALTITUDE OF THE BASE OF CLOUDS UPON THE SEVERITY OF LIGHTNING

The heights of the cloud bases, however, do clouds varied in accordance with a well defined distribution curve depicted in Fig. 13.

Since it had been suggested[1] that a relation might exist between these heights, which represent the probable length of lightning strokes, and the currents delivered in a stroke, the cloud heights were ascertained to within half an hour of the recorded time of interruption of the power line, due to lightning strokes during the 1953/54 season. For the eight power interruptions sustained, the cloud heights varied from about 700 feet to 5 500 feet, and since the heaviest lightning strokes could be expected to have occurred to cause the interruptions, it must be assumed that there is no relation whatever between these factors.

The heights of the cloud bases, however, do indicate the order of magnitude of the minimum probable heights of the cloud charge centres, which in this instance, averages about 3 150 feet or approximately 1 km—hence the average height assumed for the cloud charge for calculations of the field changes due to strokes to ground in assessing the probable ranges of the ceraunometer described in Section 5·2.

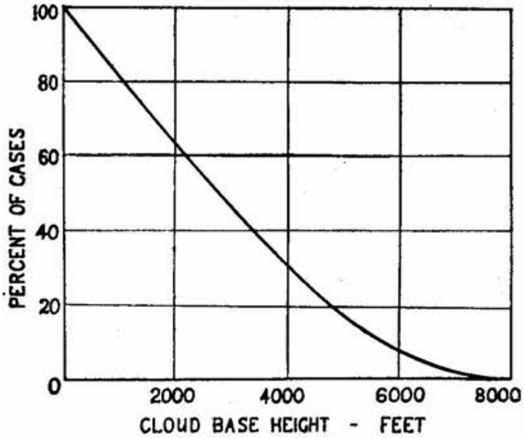

Fig. 13—The altitude of the base of cumulo-nimbus clouds
Per cent of cases which exceed altitudes shown on abscissa

12*a*. REFERENCES

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6. Edison Electric Institute, N.Y. Publication No. F.6.

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8. Schonland, B. F. J. *Roy. Soc. Proc.* A. Vol. 164 (1938), p. 132.

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10. Lewis, W. W., and Foust, C. M. 'Lightning investigation on transmission lines, VIII.' *Trans. A.I.E.E.* (1945).

11. As reference (9), but p. 8.

12. Surge Phenomena. *E.R.A. Technical Report*, S/T35, p. 25.

13. As reference (4).

14. As reference (1), Appendix II, p. 243.

APPENDIX 1

THE CERAUNOMETER, ITS FUNCTIONS AND APPLICATION

1. *General*

A full description of the ceraunometer circuit is given elsewhere[3] but, briefly, it consisted of two circuits one of which will accept negative pulses only of the order of 100 mV, amplified to the desired requirements for the operation of a post office type relay counter. The other circuit which is in parallel and coupled to the same aerial system will respond to positive pulses of about six times the magnitude of the negative pulse circuit. Adjustable grid bias on the second stage is provided for calibration, and a 'flip flop' circuit is used in the output stages.

2. *Alterations to the circuit*

The original circuit provided for an electrical interlock which prevented the negative circuit from operating whilst a positive count was in operation, but this was found to be an unnecessary complication since the results of the counts could in any case be adjusted. Furthermore, a change to a Class B output stage also produced a more definite counter operation. Variations in the supply voltage were found to affect the calibration and voltage-regulating tubes were therefore introduced.

A special instrument was developed for calibrating the ceraunometers, which consisted of a non-inductive potentiometer and milliammeter, together with a post office key. The selected signal, either positive or negative, could then be applied to the aerial terminal on the ceraunometer, and bias varied until the respective counter only just failed to operate on three successive applications of the signal.

Lastly, the spark gap in the aerial was found to discharge prior to a 'near' stroke of lightning, causing excessive counter operations. When this gap was removed and inductive earthing introduced into the input circuit, the aerial operated satisfactorily.

3. *Theory*

The operation of the instrument is based upon the assumption that the majority of ground and cloud lightning flashes originate from a negative charge centre situated in the base of the storm cloud. Electro-magnetic field changes produced by a lightning discharge are oscillatory in character but small as compared with the electrostatic component up to a given radius from the point of discharge. Hence only the negative circuit of the ceraunometer may count such field changes up to a limiting radius from the station, this depending upon the severity of the discharge. Regarding the electrostatic component of the field change, cloud and ground flashes close to the instrument would produce positive field changes of large magnitude up to given radii, and these flashes would be counted by the positive or 'near' counter. Beyond the limits of these radii cloud flashes would produce small negative field changes and be counted on the negative or so-called 'far' counter, whereas ground flashes would produce small positive field changes which would not therefore be counted at all.

The electrostatic field changes produced by lightning flashes are given by the following expressions :—

i For ground flashes

$$Eg = \frac{M}{(H^2 + D^2)^{3/2}} \times 9 \times 10^3 \text{ V/m} \quad \ldots\ldots\ldots \textit{11}$$

Where M = dipole moment = 2 QH coulomb-kilometres

Q = charge in lightning stroke coulombs

H = height of negative charge centre above ground Km

D = horizontal distance from point struck on ground to point at which field change Eg occurs-kilometres

ii For cloud flashes

$$Ec = \left[\frac{M_1}{(H_1^2 + D^2)^{3/2}} - \frac{M_2}{(H_2^2 + D^2)^{3/2}} \right] \times 9 \times 10^3 \text{ V/m} \quad \ldots\ldots\ldots\ldots\ldots \textit{12}$$

Where M_1 = dipole moment which the negative cloud charge Q_1 makes with its image at a height of H_1 above ground = 2 Q_1H_1

M_2 = dipole moment which the positive cloud charge Q_2 makes with its image at a height of H_2 above ground = 2 Q_2H_2

If it is assumed that the positive charge Q_2 is vertically above the negative charge Q_1 and is twice the height above ground and that the two charges Q_1 and Q_2 are equal, equation *12* reduces to

$$Ec = \left[\frac{M}{(H^2 + D^2)^{3/2}} - \frac{2M}{(4H^2 + D^2)^{3/2}} \right] \times 9 \times 10^3 \text{ V/cm} \ldots\ldots\ldots\ldots\ldots \textit{13}$$

Where the values of M, H and D are identical to those for ground flashes in equation *11*.

Now for an average lightning discharge of one coulomb from a height of one kilometre $M = 2$ and $H = 1$ and curves may then be drawn of the electrostatic field change variation with the distance from the discharge, for ground and cloud flashes.

Regarding the input circuit of the ceraunometer, the aerial consisting of a rod approximately eight feet in length is connected to a coaxial cable, the capacitance of which is approximately 600 picofarads. The capacitance to ground of a vertical rod L feet in length and d inches in diameter erected with its base H feet above ground is given by the following expression :—

$$C = 2\left[\log_e\left(\frac{(48L)}{d}\right) - 1\right] - \log_e\left[\frac{{}^{3}/_{2}\,L + H}{\frac{1}{2}\,L + H}\right] \ldots 14$$

For the installation at Gatooma, the capacitance of the aerial to ground was 20 picofarads approximately, and if the charge built up on the aerial is assumed to be discharged into the coaxial cable during a lightning flash, 1/30 of the voltage induced in the aerial will be available at the aerial terminal of the ceraunometer. Since the aerial has an effective height of about one metre, a field change of one V/m will therefore produce 1/30 volt at the instrument.

If the ceraunometer circuits, therefore, are calibrated to count positive signals in excess of 600 mV and negative signals in excess of 100 mV, the corresponding minimum field changes to produce counts will be 18 V/m positive and 3 V/m negative.

From the curves produced from equations *11* and *13*, it will be apparent that for average lightning discharges, the positive circuit will count all cloud flashes up to 2 km radius and all ground flashes up to 10 km, and the negative circuit will count all cloud flashes from 2 up to 18 km and it is assumed this circuit will also count ground flashes up to 10 km due to the electro-magnetic component of field change.

If G = the number of ground flashes per sq. km.

and C = the number of cloud flashes per sq. km.

And if N_1 = number of positive counts

and N_2 = number of negative counts

and $\frac{N_2}{N_1} = R$

then from the above radii

$$N_1 = 4\pi C + 100\pi G \ldots\ldots\ldots\ldots (15)$$

$$\text{and } N_2 = 320\pi C + 100\pi G \ldots\ldots\ldots\ldots (16)$$

Whence $C =$

$$\frac{N_1(R-1)}{316\pi} \text{ cloud flashes per sq. km. } (17)$$

and $G =$

$$\frac{N_1(80-R)}{7\,900\pi} \text{ ground flashes per sq. km. } (18)$$

It will be appreciated that the above data are strictly applicable only to average lightning discharges, and the response limits of the ceraunometer will vary if the magnitudes or dimensions of the discharges are either more or less than the assumed values. It is considered, however, that the assumption of the average condition will give results which will approach the correct order of magnitude of the numbers of flashes to ground and cloud as has been demonstrated in the operation of a ceraunometer at Gatooma, described in Section 5·2.

It is considered that if the parameters of the ceraunometer circuit were to be the subject of international standards, the instrument should provide data on lightning conditions in different areas of the world which would be strictly comparable, whether or not more fundamental information can be obtained from the readings.

END OF PART I

DISCUSSION

THE CHAIRMAN: It is fitting that the two important papers on this topic prepared in our neighbouring country should be presented in this Institute. They have had worthy forerunners in the papers by Rendell and Gaff in 1933, Schonland in 1933 and 1934 and Perry and Jobling in 1936, and you will agree that a most significant contribution to our knowledge has been made to-night.

It is a striking fact that an investigation as far reaching as this, has required the use of such very simple apparatus. Only two instruments would appear to have been used, namely, the surge crest ammeter with the magnetic links and the B.P.I. ceraunometer. In fact, of course, the authors have used one of the most powerful of modern tools by analyzing statistically the great mass of data collected over a long period, and theirs is the credit for the good agreement achieved between the estimated and measured strokes to ground; to mention but one result from their paper. It seems that the design of transmission lines to within a given degree of immunity of disturbance from lightning strokes is feasible and this aspect is treated more fully in the second part of the paper, which is to be presented at our September meeting.

Owing to the fact that the many intending contributors to the discussion prefer to discuss the paper as a whole, the main discussion will take place at the September meeting. However, there may be members present who wish to offer some remarks this evening, and their opportunity will arise in a few moments.

E. H. SCHOLES (Associate Member): The authors have used the magnetic-link method to make a thorough investigation of the characteristics of lightning as it affects a typical high-voltage transmission system. Their data, gathered from some 383 towers over periods ranging up to eight years, provides a fruitful source for study of both the predictable and unpredictable features of lightning strokes. From this data the authors make certain deductions regarding the behaviour of lightning and have been able to produce a curve showing the probability of lightning currents reaching certain values. They have also obtained an average frequency for lightning strokes to towers of 62 per 100 miles of route per annum, for towers of a certain average height and spacing and for an isoceraunic level of 54 thunderstorm-days per year. From this basic data it is shown that the probability of insulator flashover due to lightning for any particular transmission line may be calculated, and the line designed with an adequate insulation level.

In order that data of this nature obtained from one system can be used for judging the performance of existing systems elsewhere or applied to the design of overhead transmission lines, certain comparative information is necessary, and appears to fall under the following headings:—

a Isoceraunic level

b Spacing, height and construction of towers and arrangement of conductors and earth wires

c Tower earthing

d Topographical and geological features of the routes.

In connection with isoceraunic level, the authors use the term 'thunderstorm-days.' Could they define what constitutes a thunderstorm-day and from what source the records of the number of such days per annum are drawn? Is, for example, a thunderstorm-day recorded when there is cumulo-nimbus cloud about, or when thunder is heard or when there is thunder plus rain? At how many points on the system is such data recorded and if at more than one point is there reasonable agreement between the records? It seems that this term places some reliance on the human factor and needs to be clearly defined. Furthermore, some relationship needs to be established between isoceraunic level, that is, the number of thunderstorm-days and the number of strokes to ground. Audible thunder may be the result of cloud-to-cloud strokes which have no effect on the transmission line.

The use of the ceraunometer is particularly interesting as it is an attempt to eliminate the human factor, and at the same time differentiate between types of lightning stroke.

The big variation shown in Table IX of the number of cloud-to-ground flashes per square mile, ranging from 0·06 to 0·56 for different months is an indication of considerable variation in intensity of electric storms, and it seems that again one must be cautious in defining isoceraunic level, since a thunderstorm-day in February obviously means something quite different from a thunderstorm-day in November. It would also appear that a doubling of the number of thunderstorm-days will not necessarily mean a doubling of the frequency of lightning strikes per 100 miles of line.

A difficulty in the use of the instrument appears to arise from the knowledge required of the height of the base of the cloud above the ground. In the paper an average figure of 1 kilometre or 3 150 feet is used, though it is stated that cloud heights varied from 700 to 5 500 feet. The instrument appears to have a limited and variable radius of action and records all surges whether produced by lightning or other causes. It would also be appreciated if the authors would explain how the instrument differentiates between cloud-to-cloud and cloud-to-ground strokes.

The authors calculate (Fig. 11) that there is a slight increase in the probable number of strokes to towers as transmission-line height above ground is increased (10 per cent increase in frequency for an increase in height from 30 to 60 feet). There seems to be some difference of opinion amongst investigators regarding this point.[1] Experiments in the United States on models indicate that the effect of increasing tower height should be greater than analysis of field results show to be the case, possibly due to the topographical conditions of the route.

It is also stated that if the number of towers per route mile were doubled, i.e. the span length reduced from 1 200 feet to 600 feet, more towers, up to eight, would be involved in the same stroke of lightning. There does not seem sufficient evidence to justify this statement. The authors do not place much weight on their own data of strikes involving more than four towers, and the latter could be satisfactorily explained by assuming a midspan stroke, some of the effect of which has 'spilled over' from the two immediately adjacent towers to the next towers on either side, which might happen if the footing resistances were high. If lightning strokes spread over more towers as the span length is reduced one would expect to find lines of short span lengths more free from outages than lines of long span lengths, which I do not believe is the case. Possibly the authors could clarify this point.

It is observed that, with the greater volume of data now at their disposal than at the time of their previous paper on this subject, the authors are rather more cautious regarding the possible effect of different geological formations on the incidence and magnitude of lightning strokes. From the authors' Table XIII there seems to be no definite evidence that geological formations affect the frequency of lightning strokes. This, it should be noted, is quite distinct from the proven fact that different geological formations cause difference in footing resistances and as a result the probability of line outage is increased for the same isoceraunic level.

The authors are to be congratulated on the thoroughness of their investigations and on their attempt to base overhead line design in Southern Rhodesia on fundamental data obtained by painstaking research of local conditions.

REFERENCE

(A) *Westinghouse Transmission and Distribution Reference Book*, page 312.

F. W. Stutterheim (Associate Member): I would like to ask Mr Anderson with what frequency or at what intervals these links were checked? In other words, was there a possibility of any particular tower being struck on more than one occasion during these intervals?

R. B. Anderson (*in reply*): As regards the frequency with which the tests were carried out, they were not as frequent as we would have liked. They were generally during the period December to April, and there was a possibility that, during the intervening time, more than one tower was struck more than once. That is why we do not place so great a reliance on the calculation of lightning currents as on measured currents, but this does not affect the calculations in regard to individual tower currents; those are the calculations which are used to calculate the probability of towers being struck. They are more reliable and can be accepted.

In passing, may I say I would like to reply to Mr Scholes at a later date.

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(*Terms expire January*, 1956)

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