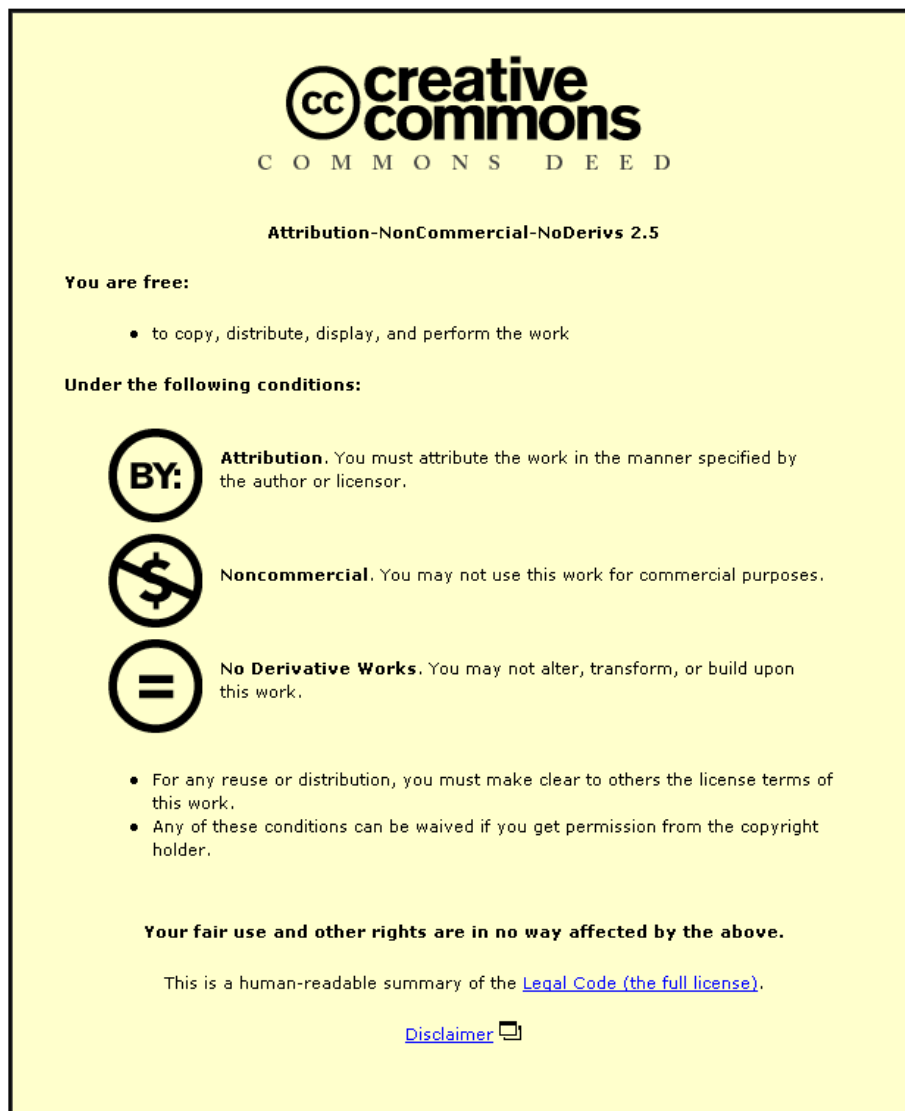


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SURGE PROPAGATION IN HIGH VOLTAGE, RURAL DISTRIBUTION
NETWORKS FROM INDIRECT LIGHTNING EXCITATION

by

FREDERIC SAVILLE, M.Sc.

A Doctoral Thesis

Submitted in partial fulfilment of the requirements
for the award of

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February 1980.

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SUMMARY

A survey is made of past work associated with the indirect lightning stroke in relation to the 11 kV rural electricity supply network in this country. Facts are established which are considered relevant to this specific type of system with pulse excitation. A² complimentary field study, based on extensive lightning fault records of a particularly affected area, provides sufficient evidence to establish a characteristic pattern of behaviour to be expected from the network. Each faulted circuit is assumed to be made up of several basic topologies, which are considered as lossless elements, on which single conductor surge analysis is performed by means of a graphical method devised by Bergeron. This is regarded as an efficient first stage assessment of the propagation response, and may be directly compared with the pattern of responses in the field study to explain those fault processes due to simple travelling waves alone. The preparation and analysis of a three-conductor circuit is also given some attention. To account for the frequent appearance of anomalous faults, some consideration is given to the influence of local topography associated with the fault, and to a further source of excitation in the form of the prestrike charge which has hitherto been neglected. The study ends with suggestions for the continuation of the work.

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This work is dedicated to

Paul Bernard Kenneth Saville

1944-1960

and to

Kenneth John Ridgewell, R.A.F.V.R.

1920-1940

c

SURGE PROPAGATION IN HIGH VOLTAGE, RURAL DISTRIBUTION
NETWORKS FROM INDIRECT LIGHTNING EXCITATION

BY

F. SAVILLE M.Sc.

Quilibet in arte sua credendum est

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List of symbols

V	voltage	E	travelling wave voltage
h	height	Z	surge impedance
\mathcal{E}	field strength	Q, q	charge
M	dipole moment	i	current
r	distance from dipole	x	distance
c	Velocity of light	t	time
v	velocity of propagation	λ	wavelength

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PART I

Introduction, objective and survey of past work related to the present study.

1.1 Introduction: Lightning discharges and their effects upon the overhead line system.

In high voltage rural power distribution systems the overhead line conductors cover very large areas of the countryside to form the principal supply links. Consequently, an inherent and unavoidable hazard to system reliability is presented by these circuit elements and their associated equipment simply by being exposed to the atmosphere. This is clearly shown by the annual fault records of the Area Boards in the United Kingdom. Supply interruptions are seen to be caused by wildlife, high winds and cold weather conditions, occasional accidents, but principally by the effects of electric storms.

Although a low isoceraunic level is to be found in these latitudes, evidently a large number of incidents of lightning origin do take place. An earlier study of five years of lightning fault records^{*} by this investigator revealed, amongst other things, that the overall effect of the thunderstorm was one which subscribed to very nearly one half of the total outages during that period.

The loss of continuity and hence the earning potential which inevitably follows in the wake of every electric storm is to a large extent, only currently made acceptable by the widespread use of the automatic circuit recloser. The distribution network in general owes much to the efficacy of this piece of apparatus for its present state of reliability. However, it is clearly evident that a high level of faults of lightning origin continues to be maintained each year. Any further improvement in system reliability from this cause alone may well depend, therefore, upon

^{*} Fault data supplied by Eastern Electricity for 1963-1967.

the strategic deployment of other suitable protective devices. To some extent this practice is already carried out by means of rod-gaps on transformer bushings, and elsewhere, and the modest use of non-linear resistors. Nevertheless, the need for "a priori" knowledge of specific sections of a distribution network to lightning excitation seems to be essential before some rules for improved protection can be envisaged. Hence an understanding of the behaviour of travelling waves generated in common circuits appears desirable when the system is disturbed in this manner.

Golde and Jones¹ have shown the preponderance of lightning incidents in any one year of operational service of a typical Area Board. Golde² separately, has concluded from a national survey of high voltage distribution supply systems, that the rate of lightning incidents increases more rapidly than in proportion to the number of thunderstorm days. One single lightning discharge may indeed be responsible for several lightning incidents.

The effect of cloud-to-cloud lightning discharges on overhead wires was extensively examined by Bewley³, Norinder⁴ and Rudenberg⁵ et al, but it was Wagner and McCann⁶ who first showed that the voltages induced in overhead line conductors are not of any great significance on their own account, at least when primarily concerned with overhead transmission lines. The hazard of the electric storm is, however, chiefly presented by the cloud to ground polarization of the lightning discharge according to the earth terminal effect, i.e. the transfer of a substantial amount of cloud charge to a point or points on the overhead line system, or to ground or earthed objects outside the system. The former then defines the direct lightning stroke and the latter the indirect lightning stroke.

In this country an average stroke current² has been found to be between 5kA and 20kA so that a direct stroke to mid-span of a single distribution line conductor, whose self-surge impedance can be taken to be about 500 ohms, could thus establish a momentary line-to-earth potential of

1.25 MV for the minimum stroke current of 5kA. This magnitude of voltage is not only far in excess of the BIL of any high voltage distribution circuit but since the voltage appears within one or two microseconds of stroke contact, it provides an almost instantaneous rate of rise literally dealing all local insulation a hammer blow. A further simple calculation reveals that the momentary power transfer likewise cannot be contained, although the energy level is relatively small. Since no protection is available at the present time against the effects of direct strokes, permanent damage to line equipment is unavoidable.

When the charge transfer of the thundercloud is outside the conducting system, as in the case of a ground stroke in proximity to the overhead line, the effect on the system is the result of changes experienced by the associated electrostatic and electromagnetic fields in which the former predominates. Lower orders of voltage than those due to the direct stroke, are to be found in the nearby line conductors resulting from the induced effects. The actual magnitudes of these voltages have been shown to be approximately proportional to the product of the lightning stroke current and the height of the conductor above ground, and inversely proportional to the distance from the stroke. In addition, it is observed that the positively rising wave front is characteristically less steep than the similar part of the voltage waveform from a direct stroke.

The fault records⁷ associated with this study show that there are many more "transient faults" than "persistent faults" due to lightning causes. The former are defined here as circuit interruptions resulting from h.v. fuse blowing or autorecloser "lock-outs", and the latter as circuit interruptions due to permanent damage to line equipment. This suggests that the surge voltage levels are considerably lower in the case of transient faults than in the case of persistent faults. Since there are about four times as many transient faults as there are persistent faults, by these definitions, it would follow that there are far more indirect

* Basic Impulse Level.

lightning strokes affecting the line system than there are direct strokes to the actual overhead conductors or associated equipment. A conclusion which does not seem unreasonable from an analysis of the number of discharges from cloud to ground during the life of a thunderstorm.

A lightning discharge to an earthed structure, such as a terminal pole, momentarily raises the potential at this point to a very high value above earth to exceed the impulse flashover level of the line insulation and so cause back flashover. Some assistance maybe provided by the conductor service voltages so that the ultimate discharge involves one or more conductors. This process can be considered as the result of an indirect lightning stroke.

In all instances where the cloud charge is conveyed to the conducting system, to the ground or to earthed objects in the vicinity, travelling waves are initiated in local overhead line circuits and propagated primarily in the TEM mode. When studying the effects of indirect strokes field measurements and observations reveal a wide range of charge dissipation and point sources of excitation may vary considerably, although the same pattern of behaviour is recognisable.⁸ Nevertheless, little seems to be known of the propagating effects generated from this source of pulse excitation into the multibranch, and multiloaded single and polyphase high-voltage circuits to explain the behaviour with any degree of certainty.

1.2 Objective of study.

(i) To summarise and relate the present state of knowledge of the generation of induced voltages in overhead conductors, due to thunderstorms, to the 11kV rural distribution network in the United Kingdom. Hence, to establish the principal parametric effects which produce the characteristic forcing functions, and to examine the factors influencing the propagation of travelling waves in the high voltage distribution circuits.

(ii) To present the results of a field study of a sample 11kV rural

distribution system to lightning excitation, utilising the fault records attributed to thunderstorms, and to examine a number of selected examples in detail.

(iii) To investigate the propagation response to indirect lightning strokes in circuits having frequent discontinuities, by means of explicit travelling wave solutions of common circuit topologies related to the field study.

(iv) To compare the results of the surge analysis with the predictable responses found in practice, and to account for certain anomalous effects.

1.3 The generation of indirect surges.

1.3.1 The distribution of electricity in thunderclouds.

In fine weather the average electric-field gradient at ground level is found to be about 100 Volts/metre and the direction of the electric field indicates that the upper layers of the atmosphere carry a positive charge and the earth a negative charge. Potential measurements made on horizontal insulated wires suspended at different heights above a flat earth plane clear of trees and buildings confirm this, according to the equation

$$dV = V_h - dh = V_h = - E \cdot dh$$

The wires must be ionised by some means as, for example by heat, or by being exposed to the atmosphere for several weeks before measurements are attempted. It is clear, therefore, that an overhead distribution line is a natural detector of the electric field gradient.

The ground gradient undergoes a great increase in the presence of thunderstorms. Schonland⁹ gives a maximum figure of 50kV/metre but comments that 10kV to 20kV/metre appear to be usual. Recent work on ground gradients in the vicinity of a lightning stroke to earth have been carried out by Beck¹⁰ et al, in U.S.A., and records have been obtained within 45-60 metres of known stroke locations. The highest gradient claimed was

230kV/metre at a distance of about 55 metres from the stroke. As could be expected, the ground gradient is continually changing during electric storm activity as a result of lightning discharges and the neutralization processes of local charge centres within the thunderclouds and their subsequent replenishment. An active thunderstorm is reckoned to produce one flash about every twenty seconds and the following regeneration of the electric field within the cloud is known to be only a matter of a few seconds.⁹

The electrification of thunderclouds has been studied continuously over the past half century by meteorologists, physicists and engineers and the subject still remains one of considerable complexity. It has been established that the distribution of electricity within a charged area of cloud generally follows the pattern of an upper positive charge several kilometres above a lower negative charge. A further small positive charge often exists in the base of the cell.

11

Simpson and Scrase first made measurements of the electric field within thunderclouds, using electrograph equipment attached to balloons. Confirmation of the cellular configuration of the electric charges is provided by Workman, Holzer and Pilzer¹² from measurements of ground gradients. From their experiments a number of positive and negative discharge centres were identified extending upward to approximately 11000 metres (\approx 36100 ft.) and having a width of about 8000 metres (\approx 26250 ft.). The U.S. Thunderstorm Project pursued independently by Byers and Braham¹³ in 1949 utilised aircraft to measure the electric fields within the thunderclouds whilst simultaneous measurements were made from ground stations. Electric field gradients within the charged clouds have also been investigated by Gunn¹⁴ using electric fluxmeters attached to both sides of a wing of an aircraft in order to eliminate the "autogenous" field produced by the charge on the aircraft. Confirmation of the existence of the general positive-negative dipole system within thunderclouds has come from Gish and Wait¹⁵ using similar equipment in flights above the tops of these clouds.

The mechanism of the build up and decay of the cells, the characteristic of which decide the intensity and duration of a thunderstorm, is shown to be a continuous process. They exist as an essential component of the atmospheric system between the earth's surface and the ionosphere. Since most of the discharges to earth during thunderstorms evolve from the middle regions of thunderclouds it is of interest to note the following altitude distribution of the three charges typical in these latitudes. The data is supplied by Schonland⁹, together with the corresponding related temperatures.

<u>Polarity</u>	<u>Altitude</u>	<u>Temperature</u>
+ (upper)	7.0km (23000 ft.)	- 27°C.
- (lower)	2.5km (8200 ft.)	- 4°C.
+ (lower)	1.5km (4900 ft.)	+ 2°C.

A frequent altitude for cell discharges in the middle region usually lies between 3-5km.

The presence of a thundercloud above the line has been shown to greatly increase the electric field gradient at ground level. Although the overhead line is normally part of a circuit carrying current, nevertheless, it remains a detector of the ground gradient registering any change in the form of a travelling voltage wave or surge.

1.3.2 Induced effects due to cloud-to-cloud discharges.

Earlier investigators of lightning phenomena associated with transmission lines are principally concerned with the effects of the direct lightning stroke, and their studies of the induced effects in the line conductors are solely related to the cloud-to-cloud lightning discharge. For this to take place, it was assumed that the breakdown of air in the vicinity of thunderclouds was necessarily 3000kV/metre i.e. the same value as that usually assigned to ground flashover experiments, and the subsequent flashover formula is based on this value. Schonland⁹ has shown that the field strength within charged clouds required for

breakdown need be only about one tenth of the normal laboratory figure to start the process of discharge.

The sudden change in the electric field gradient initially established by the thundercloud above the line is then brought about by the cloud-to-cloud discharge. It is evident prior to this taking place that the electrostatic effect of the charge establishes the so-called bound charge of opposite sign on the overhead line which very slowly decays by leakage across the insulators contained within the charge distance. In general, a negatively charged thundercloud establishes a positive bound charge on the line. i.e. a reversal of ground gradient is normally therefore a characteristic of the thunderstorm condition. The effective length of the thundercloud, parallel to the ground, is utilized for the purpose of calculation. Any fluctuation in the bound charge is neglected and it is assumed that it is held in this steady state prior to the collapse of the cloud charge. A sudden reduction therefore redistributes the bound charge. In this way, travelling waves are generated in the line conductors. The waveshapes of the voltages induced being some function of the bound charge release. Hence, the change in the ground gradient conditions as a result of the lightning discharge can be expressed in terms of the product of the voltage and the law of the cloud discharge.

Using D'Alambert's solution to the wave equation and $F(t)$ as the law of the cloud discharge,

$$F \propto \int_0^t f(x \pm ct) \cdot \frac{dF(t)}{dt} \cdot dt$$

and since $F(t) = \frac{1}{Q} \int_0^t i \cdot dt$, this becomes

$$F(t) = \frac{1}{Q} \int_0^t e^{-at} \cdot dt$$

if the discharge current is given its usual form.

1.3.3 Estimations of the cloud-induced voltages.

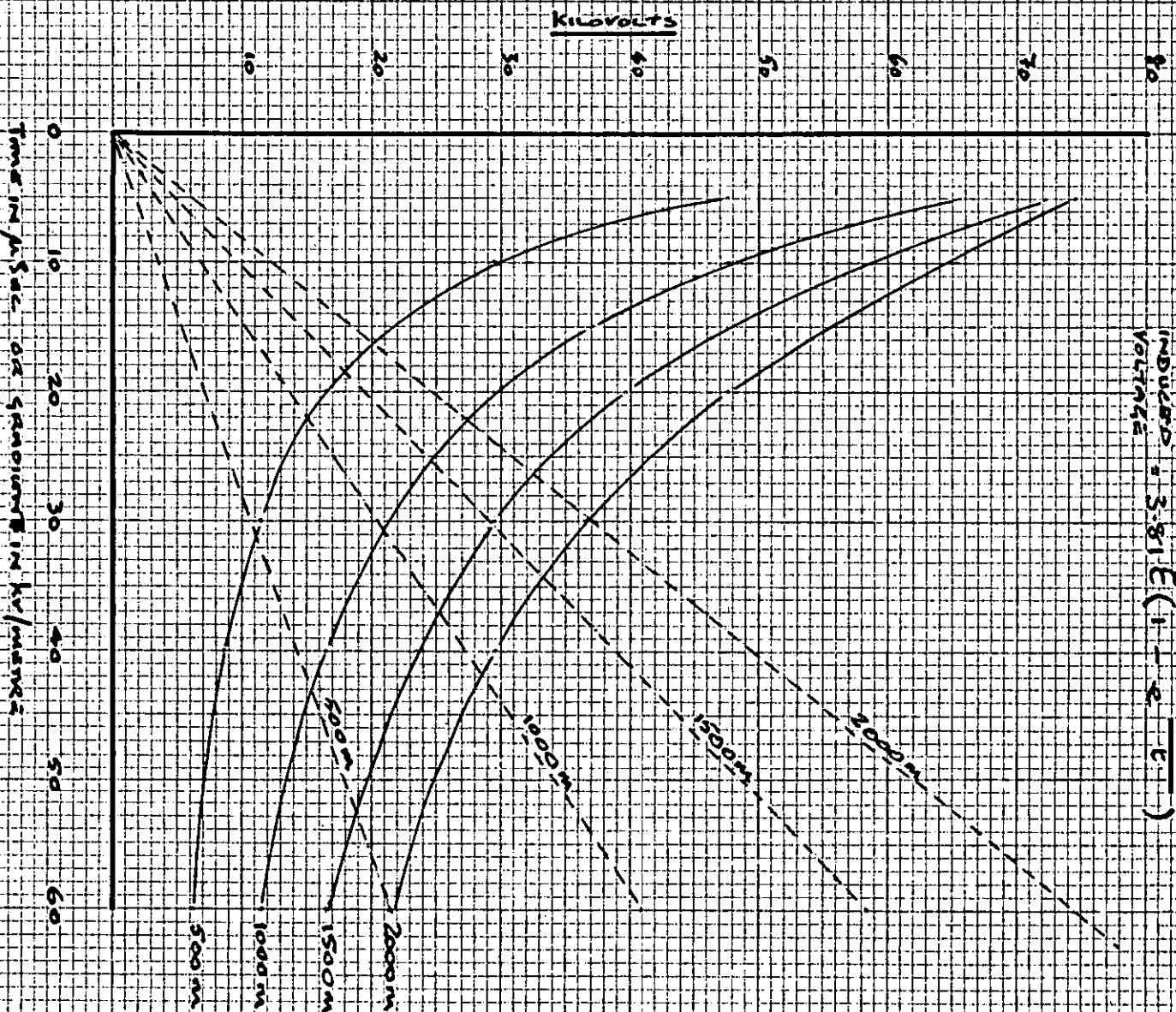
The amplitudes of the voltages induced in overhead line conductors following the process of cloud-to-cloud discharges are derived by Bewley³, Rudenberg⁵ et al using a simple exponential law for the cloud discharge. Equations are given by Bewley which can be identified for use with this present study of the distribution system. These equations enable the induced voltages to be estimated assuming the collapse of at least 95% of the cloud charge in the first instance. For specified dimensions given to the bound charge it is shown that as the time of the discharge reduces so the voltage induced in the conductors increases. However, values give to the ground gradients by Bewley appear to be unrealistic, e.g. 328kV/metre (100kV ft.), and are more in keeping with the actual field gradients found later within the thunderclouds by Gurn¹³. Consequently, the induced voltages presented by Bewley appear excessively high even though they are calculated for transmission conductors. Using a distribution line height of 25 ft (7.62 metres) and a ground gradient specified by Schonland⁹ previous, a more modest result can be obtained. In figure 1, the first set of characteristics are calculated from a ground gradient of 20kV/metre and show the effect on the magnitude of the induced voltage for various discharge times and several lengths of bound charge. The lower orders of time of discharge can be ruled out since the reduction in the cloud charge is dependent upon the cloud-to-cloud stroke which needs a relatively substantial time (possibly 100 msec. or more) to take effect. The second set of characteristics show the effect of increasing ground gradients together with several lengths of bound charge which determine the slope. Again, the higher induced voltages can be disregarded since they depend upon excessively high sustained ground gradients.

This evaluation of an induced voltage from a charged cloud assumes the charge to be uniformly distributed so that the overhead line has a rectangular bound charge. Such a model enables the simplest orthogonal

INDUCED VOLTAGE AS A FUNCTION OF CLOUD

DISCHARGE TIME AND GROUND GRADIENT.

$$\text{INDUCED VOLTAGE} = 3.81 E \left(1 - e^{-\frac{9.836x}{t}} \right)$$



Legend

Time
Gradient

Figure 1

field pattern to be conceived assuming the ground to be a perfectly flat conducting plane and that conductor sag is absent. It soon becomes apparent that the law of the cloud discharge has a much greater influence on the shape of the induced voltage wave than the shape or length of the bound charge.

Wagner and McCann⁶ assert that the cloud-to-cloud discharge is of little importance when the finite time of discharge is taken into account. This observation is based on the Bewley calculations and has a direct reference to transmission lines. It is seen however, from the evidence in figure 1, that the magnitude of the induced voltages from this source is unlikely to exceed about 20kV in distribution lines, and higher potentials are only possible with very short waves. These are improbable from the induced effect.

Field measurements of lightning discharges are based on the three terms of the well known radiation equation,

$$E = \frac{M}{r^3} + \frac{1}{cr^2} \frac{dM}{dt} + \frac{1}{c^2r} \frac{d^2M}{dt^2}$$

The first term, representing the electrostatic field, is the most important component for calculating the induced effect since this is much larger than the other two terms up to a distance of about 10 kilometres.⁹ Norinder¹⁶ has used both open and closed antennae systems for the study of lightning discharge phenomena. The open aerial arrangement, being the most suitable for detecting the vertical component of the electric field, in one form consists simply of a horizontally suspended insulated wire of suitable length. Clearly, an overhead distribution conductor is identical and must record the field change in exactly the same way. Difficulties occur in precisely measuring the vertical component due to the fact that the lightning discharge is made up of separate stages. Each of these stages is complicated and of such short duration as to impose a limited time for observation. Consequently, there is not enough information about the time variation of the field strength, especially when

discharges are very near to the aerial wire. Much of Norinder's studies with antennae systems, is concerned with the measurement of the electric field strength at ground level, the magnetic component of the radiation equation and the current and charge distributions in the lightning stroke at some distance from the discharge. The calculated potential, for example, induced in an overhead line of moderate height at a distance of about 6 kilometres from the discharge, was found to be 1.75kV but only 300V at a distance of 11 kilometres. There appear to be no corresponding calculated values for discharges much closer to the line.

1.3.4 The mechanism of the lightning discharge to ground.

A large amount of knowledge has now been amassed concerning the mechanism of the lightning stroke. Much of the research has been stimulated by the need to assess the operation stability of transmission lines in thunderstorm conditions. The basic difference here, between these lines and distribution lines, is clearly one of insulation level, and it has been shown earlier that the latter are quite unable to survive a direct lightning stroke without some permanent damage. So it is necessary to account for the large number of fuse operations in which surge voltages of lightning origin are initially responsible. The cause per se appears to be due primarily to the induced effects from lightning discharges to ground or earthed objects relatively near the line.

Much of the present knowledge of the lightning discharge comes from the classic researches of Schonland, Malan and their associates¹⁷, in which the Boys camera has undoubtedly made an important contribution. At least 90% of the lightning discharges are negative. That is, a negative charge is conveyed from the charge centre in the cloud to the ground via the leader stroke. Unlike the direct stroke to a line conductor, the indirect stroke induces a voltage of opposite polarity into the conductor and consequently most induced voltage surges are positive. There are exceptions and these are the result of positive charge transfer which,

though infrequent, appear at the end of a thunderstorm and often with great intensity. Apart from differences in the initial leader formation, the process of discharge has apparently the same characteristic as for the negative charge.⁹

Since the electrostatic field is the predominating component of the "electromagnetic effects" from a nearby lightning stroke to ground, it is as well to examine the process by which this component undergoes changes over the whole time of discharge. The following account however is a somewhat necessarily simplified description of behaviour. There are three clear stages, the first of which is established by the stepped leader. This, in early development, progresses to earth at the slow velocity of about $0.001c$. For this reason alone, the field change is regarded as unlikely to seriously affect the ground gradient. The progress to earth takes the form of a series of faintly luminous discontinuous steps. As the stroke approaches the earth, the ground gradient immediately below increases very rapidly to liberate an upward streamer which meets the descending negative leader charge. This is the end of the second stage.

The length of this streamer appears to be subject to considerable variation depending upon several parameters. Schonland gives between 15 to 50 metres. Wagner and Hileman¹⁸ estimate orders of between 25 to 100 feet (7.62 to 30.5 metres) from towers etc. but only a few feet from open level ground. The final stage is the return stroke commencing at the point of contact between leader and streamer, and ending at the charge centre in the cloud. Maximum velocity of propagation, about $0.3c$, of the return stroke current, occurs at the commencement of this stage but falls off rapidly as the current travels upward into the charge centre. Clearly, the final stage is the one in which maximum voltages will be induced in the line conductors. The first two stages may take as long as 10 millisenohds but the completion of the final stage only about 40 microseconds. These figures have been quoted from a Boys camera example given by Schonland.⁹

Since a lightning flash may consist of a single stroke or a series of strokes, the elapsed time between successive discharges is likely to be between 40 to 100 milliseconds, though it can be up to half of one second. The total duration of the flash, therefore, is dependent upon the number of component strokes which, in these latitudes, average from two to three strokes, and about half of the lightning discharges consist of multiple strokes. This means that the induced excitation in the conductors could be extended from about 200 milliseconds to possibly one second or more. The second leader stroke (the dart leader) travels continuously to earth, unlike the stepped leader, within a time of approximately 1 millisecond and the return process then takes place in precisely the same manner, and in the same time, as the previous stroke. Some useful comparative data on this aspect can be found in a paper by Bruce and Golde.¹⁹

1.3.5 Estimations of the induced voltage.

As will now be seen, differences exist between various investigators in resolving the magnitudes of the voltages induced in the overhead conductors and in assessing the corresponding wave form.

Golde^{20,21} utilises the neutralisation of the leader charge as the source of the induced voltages by the release of the bound charge on the conductors. To evaluate these voltages, it is assumed that both the charge density distribution in the leader channel and the velocity of the return stroke have an exponential variation and each then decreases with height above the ground. It is also assumed that the rate of neutralisation takes a finite time and likewise follows an exponential law. The basis of these assumptions follow from an earlier study in collaboration with C.E.R. Bruce¹⁹, in which an attempt is made to correlate the data and experimental work of various investigators of lightning phenomena at that time. The step-by-step calculations by Golde, include the evaluation of the ground gradients due to the downward coming leader stroke and the return stroke, and the attenuation of the surge with distance travelled. It is to be noted that the

"transition stage" is taken to be some distance above the ground plane. Minimum stroke distances are calculated based on the relative attractive distances of earth and the line structures to the lightning channel. These are found to be proportional to the stroke current.

Simpler assumptions are made by Wagner and McCann⁶ in that the distribution of charge and the velocity of the return streamer are taken to be constant along the lightning channel. The induced voltage is then derived from the electromagnetic effects by representing the return streamer as a vertical propagating conductor moving with uniform velocity. As this progresses so it neutralises the uniformly distributed charge on the leader. Any change in the velocity has a significant effect on the magnitude of the induced voltage. The calculations are based on model studies and the application of field theory and Maxwell's equations. They involve the physical dimensions of the stroke channel which must depend to some extent on speculation. Golde²⁰ observed that the results "seem reasonable" for distances of several hundred to a few thousand feet between the stroke to ground and the overhead line but do not appear realistic for near strokes.

Lundholm²² develops a solution, using the same methods of analysis as Wagner and McCann, and the same simplified assumptions, but avoids the use of the lightning channel dimensions. An inducing voltage function is employed for the solution of the induced voltage. In addition, one important contribution is an equation relating the stroke current and its velocity of propagation. The results, from the application of the derived equations, show good agreement with those obtained from the field studies of Schonland, Malan and their associates¹⁷. Earlier calculations by Schonland utilised a uniform charge distribution in the leader channel allowing for variation to take place in the velocity of propagation of the return stroke current. The former, of course, is an assumption giving some simplification to the problem.

1.3.6 The "prestrike" effects.

A study of the leader head dynamics has led to the "prestrike theory" of Griscom²³ to explain certain ground gradient effects and anomalous flashovers immediately prior to the actual return stroke. This theory takes into account the critical air gradients that may be presented by the projection of objects above the ground plane. The so-called "corona burst" is a description given to the sudden discharge from the leader head and the corona envelope of grounded objects in an intense electric field which is related to the dynamics of the downward-travelling leader head. Griscom has calculated the corona currents emitted by grounded objects when influenced by an electric field of 0.01 of the critical gradient. These include the current for a blade of grass, taken as 5cm height, and metal poles of different heights. It is to be noted that the sum total of the corona currents from foliage or other natural ground irregularities (trees for example), to a heavily charged cloud above is likely to be considerable and must influence the upward streamer. Griscom is principally concerned with the effect of steel transmission towers, but obviously the natural landscape must exert some influence in the case of wood-pole lines associated with the distribution circuit. Ground gradients are calculated only in relative terms from estimations of the cloud capacitance and the leader charge, so that the characteristic shapes of ground gradients are shown but without any quantitative results.

1.3.7 The waveforms of induced voltages.

The shape of the induced voltage wave determined by Rudenberg⁵, Golde²¹, Wagner and McCann⁶ et al, is essentially aperiodic and can be loosely described in mathematical terms as the difference of two exponential functions. Some investigators may favour an approximately linear wave front with exponential tail, whilst others a sinusoidal front and an exponential tail. In general, however, the double exponential statement seems to serve as the accepted shape.

In the last decade or so, renewed interest has been shown in the indirect lightning stroke and its inducing effects. This has led to a re-examination of earlier field studies and experimental work notably that of Perry, Webster and Baguley^{24,25}, and early American papers²⁶. From these and subsequent experimental and theoretical studies, it is now established that the bipolar waveform assigned to the induced voltage is represented as an alternative to the usual aperiodic shape.

This waveform consists of an induced negative loop attached to and preceding the otherwise normally-induced positive voltage pulse. This means that a negative charge conveyed to the ground appears, initially, to induce a negative voltage in the line conductors followed by a sudden reversal of polarity. Golde^{*} has recently suggested that the origin of the bipolar effect could be the consequence of coupling between conductors on a polyphase line. Although this is a well-known response to distance travelled by induced surges in systems with several conductors, and analysed as long ago as 1935 by Bewley²⁷ using his multivelocity components, that explanation does not account for the fact that the phenomenon is not always present. It is necessary to distinguish between the reversed loop effect with distance travelled by induced surges on multiconductor lines and the initiating surges from nearby lightning strokes which sometimes result in the appearance of the bipolar characteristic. Clearly, the two features can be confused.

Chowdhuri and Gross²⁸ are among the first to attempt a theoretical study of the stroke mechanism to justify a bipolar shape to the induced voltage wave. Only the electrostatic and the electromagnetic components generated by the return stroke current are considered. Their method of approach is similar to Lundholm²² in that an inducing voltage function is found. The solution is based on the assumption that the inducing field prior to the return stroke is zero, and that the total field which exists

* Discussion on "Lightning" reported in Electronics and Power, Journal I.E.E., Sept. 1977.

during the return stroke stage appears suddenly with the commencement of the return stroke.

Singarajah²⁹ disagrees with this premise. He maintains that the upward streamer plays an important part. He determines the electrostatic and electromagnetic field components separately and then combines them to obtain the induced voltage, taking into account the length of the upward streamer. His conclusions indicate that the bipolar characteristic given to the induced voltage is shown to be due primarily to the upward streamer. He shows clearly that this characteristic is only present when ground strokes are within a specified distance from the overhead line, although this distance is also related to the intensity of the stroke. This explanation seems to be the best account offered so far as to the phenomenon.

A number of bipolar waveforms have been recorded by the Electricity Council³⁰ in their investigation of the induced effect due to lightning strokes. Their earlier studies are based on the work of Chowdhuri and Gross²⁸ and, more recently, on the researches of Singarajah²⁹, since it is found that the electromagnetic effect alone as represented by the Chowdhuri and Gross equations is inadequate and the inducing voltage is not the complete driving function but only part of it. Singarajah maintains that "the loop characteristic" of the waveform gives indirect evidence of the existence of upward streamers of substantial heights. His analysis has shown also, that the discharge characteristics just before the return stroke have an important bearing both on the magnitude and the waveshape of the indirect surge. This suggests that serious consideration should be given to that stage of the stroke mechanism, and indeed, emphasises the relative importance of Griscom's prestrike theory. Meanwhile, field evidence in this area is still inconclusive and more research is evidently required.

Very recent work by Gary and Fieux^{*} for Electricité de France was designed to initiate lightning discharges by means of rockets fired when the ground gradient exceeded 10kV/metre. Seventy or more discharges

* reference on previous page.

are claimed to have been initiated by this method, and the data obtained, from a nearby line, suggests that it includes current magnitudes and waveshapes.

1.3.8 The rod-plane gap.

According to evidence obtained with the Boys camera by Allibone and Meek³¹, the laboratory discharge differs from the natural discharge in that the ground streamer is much longer in proportion to the total length of the discharge. Hence the model assembly, not having the same scale as the natural discharge, cannot have quite the same behaviour. Nevertheless, the study of long electrical discharges in the laboratory can be related to the lightning stroke but it is considered necessary to exercise some degree of caution before making any direct interpretation. The results of model tests simulating the ground conditions is an example.

Norinder¹⁶ relates one such experiment in an investigation into the behaviour of multiple strokes, using an impulse generator and a flat surface of dry sand. Photographs are shown of the stepped leader, the completion of the stroke and subsequent multiple strokes. The development of the leader was found to depend upon the polarity of the discharge and, to some extent, the composition of the earth plane. It was discovered that when the discharges were positive, the appearance of upward streamers depended entirely upon the composition of the earth terminal. If this was a good conducting surface then no streamer appeared, but if the surface was a poor conductor, (dry sand for example), a short, rather complicated path was traced by the streamer. In the case of negative discharges, the result was quite different. The conductivity of the ground was of no importance and an upward streamer appeared for every initial negative discharge. Norinder then concludes that there should always be an upward streamer from the ground with lightning discharges from negatively-charged clouds (the majority), whereas upward streamers may be expected only from poorly conducting ground surfaces if the cloud discharges are positive. A creeping effect

to these streamers in the latter case have frequently been observed in the natural discharge, whilst McEarchron in U.S.A., Malan in S. Africa, and others elsewhere have photographed and confirmed the existence of upward streamers to many lightning discharges from negative aerial charges.

Naturally, speculation arises as to the extent that the geology of the ground may affect lightning strokes to ground, and, to this end, Norinder has extended the experiment by burying a thin conducting path in the sand. Again, marked differences in the behaviour of positive and negative discharges were observed. The former showing a preference for seeking out the better conducting path in the sand, whereas the negative discharges appeared indifferent to any such selection. From this investigation, Norinder concludes that negative discharges are the more dangerous since they do not attempt to select the best ground conductor but are just as likely to terminate on ground of poor conductivity.

Obviously much can be learned from the simulated model tests but, of course, these cannot replace the actual field study of lightning discharges. Since more than 90% of the cloud discharges are of negative polarity it should, however, then follow that most lightning discharges will initiate ground streamers. Similarly the division frequently observed in lightning streamers close to the ground may be a characteristic of some positive discharges.

1.4 The propagation of indirect surges.

1.4.1 Differences between transmission and distribution lines.

It is to be concluded from the previous discussion that the shape of the waveforms of induced voltages representing the forcing functions can be either aperiodic or bipolar. It is noted that this evidence, in the main, has been assessed from measurements of the vertical field component in association with transmission lines. It is tacitly assumed here that the same evidence would be found from similar measurements made on overhead

distribution lines of 11kV and below. With the exception of surges tests conducted by Ouyang³² in 1961, on an existing section of 11kV, three-conductor line with spurs, all other investigators of the induced effects in overhead lines are involved directly with systems of 33kV and above. The Electricity Council's lightning measurements, for instance, are taken from a 33kV single-circuit line system chosen, for the stated reason that longer lengths of unearthed section are available at this service voltage. Singarajah's field studies relate to a 132kV transmission line, and the 500kV Wallingpau³³ transmission line serves as a model for the Chowdhuri and Gross calculations.

There remain fundamental differences between transmission and distribution lines apart from the simple variations in height of conductors above ground, length of span and insulation level. These differences are most important when considering the propagation effects of pulse excitation. The widespread use of wood poles for the line supports is a salient feature of the high voltage distribution network. Comparatively short runs, seldom more than a few miles, are also characteristic with frequent tee-offs or spurs of line or cable sections. The conductor configuration, commonly to BS1320, employs the horizontal, three-wire construction with no earth wire, and the practice is not to use transposition. In consequence, electrical symmetry does not exist leading to complications in the analysis of surges for the polyphase case. This is eliminated, of course, where older line construction use an equilateral triangular cross-arm system.

Lines to BS1320 are primarily of unearthed construction so that the line has a high insulation resistance. Only certain points are earthed as, in the case of transformer terminations. The electrical strength of wet wood can be taken to be at least 50kV/ft. (164kV/metre). With the steel cross-arm bolted directly to the pole, leakage from the conductor through the pin insulator and 17 feet or 25 feet of wood to ground must be minimal. Little comparison can be made, correspondingly, with a steel transmission

tower, and this has not an inconsiderable bearing on the propagation effects. Ouyang's study³² of the Avebury-Marlborough section of the 11kV distribution circuit showed clearly that surges propagated on these lines attenuate very slowly. In fact, the peak voltages of test waves after 6.5 miles were found to be as high as 81% of the original value, and estimated about 4% higher after the first mile if spur lines were discounted, but thereafter, little different at distant point.

1.4.2 Summary of field observations.

The first oscillographic records of the waveforms of lightning currents appeared in U.S.A. about 50 years ago. The early part of the fronts of these waveforms often seem poorly defined which can probably be attributed to the stage of development of the recording apparatus. Records of induced lightning voltages are absent although experimental studies on multiconductor transmission lines were carried out by McEachron, Helmstreet, Rudge, Seeley, Brune and Eaton^{26,40} et al, as part of a sponsored programme of lightning research about 1930. The investigation remains unfinished. Induced effects are examined, only on the basis of conductor coupling, with the aid of an impulse generator. This appears to be the first instance of the recording of the reversed loop effect of induced voltages with distance travelled. Subsequently, the phenomenon was analysed mathematically by Bewley, as previously mentioned.

A relevant study of transmission lines in disturbed weather fields was made by Perry²⁴ on a 40kV circuit in S. Africa and later, on a 33kV system in Nigeria. Measurements of both voltage and current during electric storm conditions were obtained. Currents were measured by magnetic link equipment. Oscillograms of induced voltages show aperiodic and bipolar waveforms. The oscillograms also show multiple peaks and depressions. Some of these effects are considered by Perry to be due to pulses in the lightning channel which, as suggested by Malan and Collins¹⁷, is the result of irregularities in the stroke current.

A later paper by Perry, Webster and Baguley²⁵ concerns the results of a further investigation on the same section of 33kV transmission line in Nigeria, with increased measuring equipment. The effects of both direct and indirect lightning strokes were studied again and it is noted, for example, that oscillograms of the induced voltage differ for each phase in sample recordings, which is of some significance. Singarajah's²⁹ measurements on an unenergised 132kV transmission line of 75km in length was also carried out in Nigeria. Records of the waveforms of induced voltages over a period of two months showed that some had the bipolar characteristic with an initial loop of negative polarity in the majority of those cases. It was found, in addition, that most of the surges recorded appeared to be due to indirect lightning strokes.

The Electricity Council's investigation³⁰ of the induced effect utilised three sections of 33kV line of the N.W. Electricity Board, and in one season's operation, obtained 26 recordings from three measuring stations. The conclusion reached is that induced voltages of lightning origin are generally bipolar with the negative peak preceeding the positive peak and having a higher magnitude. There is little doubt that Singarajah would dispute the concluded dominance of the bipolar waveform.

Operation experiences of 3.3kV and 6.6kV distribution systems under thunderstorm conditions in Japan, are related by Uchara and Ohwa³⁴. A special emphasis is made of the effects of indirect surges on system reliability due to nearby lightning strokes to ground. They claim that between 85 to 95 per cent of the total faults of lightning origin are the result of induced surges. This is interpreted to signify that the majority of surges are due to this cause alone. This may well be the case if it is accepted that at the lower operating h.v. distribution networks are indeed more sensitive to overvoltage conditions. A re-examination is called for of the problem of dangerous voltages appearing when a lightning stroke is very near an overhead line.

The evidence available from surge tests on service lines show that a high level of voltage is maintained for significant times in parts of the system. It has been suggested that this period of time is sufficiently long enough to cause simultaneous flashover on rod gaps of widely spaced transformers, and this leads to the subsequent, characteristic widespread simultaneous h.v. fuse operations. Miller³⁴ has established that the latter effect is due to the follow-through power frequency fault current. Uchara and Ohwa endorse this conclusion from the flashover of rod gaps since these, in effect, provide momentary short-circuit points. They maintain, however, that the problem is not one solely due to the effects of travelling waves (e.g. voltage doubling at transformer terminations), but requires, in addition, consideration of the nearness of the intense electric field due to the descending leader head, and the resulting point-discharge effect of ground objects. This can be interpreted clearly as a reference to the prestrike principles of Griscom.

Obviously, some of the effects revealed in the oscillograms of the induced voltages in transmission lines are of no consequence when considered in relation to the distribution lines and the present study, on account of the short distances represented by these circuits and the frequency of discontinuities.

1.4.3 Surge tests of service lines.

Circuit homogeneity is disturbed if cables or single-phase overhead lines are taken from the feeder resulting in the wide differences of the surge impedances of these circuit elements. The surge tests by Ouyang³² on a section of 11kV distribution line were initiated for the explicit purpose of assessing the attenuation and distortion of indirect lightning surges below the corona level. The feeder consists of a three-phase, three-conductor, horizontal configuration, wood-pole line to BS1320 specification. The length of the tests section was 6.5 miles on which there were eleven spur lines. These spurs were disconnected during the

tests at the first poles (isolator poles), so the average length of the remaining spur lines was about 250 feet. Six of these were single-phase lines normally dispersed between the feeder conductors to provide an approximate balance of load.

The impulse generator supplied an aperiodic wave whose maximum value was reached in 4.9 microseconds and the time to half value was 20.7 microseconds. This excitation was first applied to all of the section feeder conductors connected in parallel, and then to either the middle conductor or to one outer conductor, the remaining conductors being isolated in each case.

The results of the first test show that the duration of the front of the wave increases approximately at the rate of 0.9 microseconds per mile. Subsequent theoretical analysis indicates that this rate would be less if the spur lines were not present. When the test waves were applied to either the middle or an outer conductor, the lengthening of the wavefront was found to have decreased to approximately 0.8 microseconds per mile. Again, this rate should be less in the absence of spur lines.

Oscillograms obtained from the second group of tests show that the coupled waves (isolated conductors) develop a reversed loop while travelling along the line, and this effect was beginning to become apparent after the waves had travelled only 1.04 miles to the first recording station. The rate of increase of amplitude and duration of the reversed loop with distance travelled was shown to be faster for the induced wave on a remote conductor than on an adjacent conductor. The rate of attenuation of the coupled waves was found to be faster than the rate of attenuation of the inducing voltage surge. All this, of course, is easily identified with the response to similar tests on transmission lines with shorter waves (Bewley et al). However, the fact that the reversed loop characteristic appears so early in the propagation of induced waves along the distribution feeder is of some importance.

Insulator flashover occurred at the open end of the test section and the reflected wave was therefore chopped. An estimated 112kV, with a time delay of about 9 microseconds, showed that the flashover took place on the front of the wave. The estimated reflected voltage would have been about 56kV. The reflected voltage at a point 2.92 miles back from the end of the section was found to be 37.4kV. This showed an attenuation of about one third in that short distance. Clearly, the rate of attenuation was therefore much faster than for the initiating full wave (reference, Section 1.4.1 previous). The voltage doubling effect at the end of the line is seen to impose a voltage equal to or greater than the incoming incident voltage and the voltage may be propagated back over a considerable distance. With a flashover at the termination, the reflective wave, with a steep voltage swing, then momentarily dominates the line system.

From this response, it is concluded that the surge voltage may be more severe on spur transformers than the initial surge voltage on a terminal transformer connected to the feeder. It is suggested that this offers an explanation of the simultaneous fuse operation over widely separated points referred to in Section 1.4.1.

The tests show that the presence of spur lines on a feeder delays the wavefront of the incidence surge, but this delay is not necessarily distributed equally in all three lines. Further, the presence of a single-phase spur line may actually contribute to increasing the magnitude of the voltage transmitted in one of the lines beyond the point of discontinuity.

The surge tests are continued later³⁶, on a section of 11.9 miles of 33kV wood-pole line with the horizontal conductor arrangements, but without spurs. The main purpose here was to extend the scope of the tests by studying the effects of surge propagation above the corona threshold. The relevant part of these tests concern the application of test waves to all three conductors, to simulate the indirect lightning surge.

Approximate figures are derived for the attenuation of the peak value of a travelling wave, and given in a form which can easily be used for practical work. The amplitudes of waves can thus be estimated when propagated over some distance. Various aperiodic pulses are utilised, and those representative of an induced wave are given as $6/19$ microseconds and $8/31$ microseconds.

The corona observations are of some interest also since it is possible to exceed the corona limit on the overhead line of the 11kV system under certain conditions. As the surge voltage rises above the corona threshold, the wave front shows the well-known characteristic of shearing due to the corona losses. It is observed that this effect is likely to disappear before the peak of the wave is reached. In which case, the corona has no direct effect on the attenuation of the maximum voltage of the surge. This phenomenon was only found in the tests with waves having long fronts, whereas in the past, other investigators have used only short-fronted waves when the shearing effect has extended close to the crest of the wave. The effect of corona cannot therefore be considered as independent of the waveform as assumed by the present theory. Again, it is usually accepted that corona is a function of the voltage alone, but these tests clearly indicate that this is only true at the commencement of propagation. Due to the presence of the reversed-loop effect, and other distortions of the travelling waves in multiconductor lines, the response to corona is seen to be a dynamic process rather than a static phenomenon, as regarded hitherto.

It is noted that the excitation voltages used by Ouyang for all these tests, are of the usual form derived from the output of a normal Marx-type impulse generator. The response of a section of distribution circuit to the other type of pulse is, of course not known.

1.4.4 Transfer of surges.

The coupling between lines of a multiconductor system is shown to be responsible for the complex response to inducing surges. Similarly,

the transfer of surges through coupled windings gives rise to a response of some complexity. Since the transformer is utilised extensively within the distribution network, its behaviour to lightning surges requires some consideration, for surges that are realised in the circuits which are exposed to the lightning hazard, are transferred to the circuits which, not unexpectedly, have a much lower BIL designation. This particularly applies to obsolescent equipment which inevitably present increasing opposition to system reliability.

The surge transferred to the secondary winding is made up of four components, one of which is derived from the capacitive coupling between windings and to earth. Another results from the turns ratio, the leakage reactance and the surge impedances of the connected secondary circuits. Superimposed on these, in differing amounts, are the free oscillations in the windings.

An early paper by Palueff and Hagenguth³⁷ examines the relative importance of these components, and shows that very powerful secondary surges can be transmitted by the direct electromagnetic transformation alone from lightning surges. The electrostatic component, although of short duration and independent of the turns ratio, clearly becomes more dangerous as the service voltage and the corresponding insulation level is reduced. Palueff and Hagenguth are largely concerned with the response due to the electromagnetic component on the grounds that the parameters used i.e. the leakage reactance and the turns ratio, are generally known and therefore very definite and specific conclusions can be arrived at. One of these conclusions is that an incoming surge of at least 20 microseconds duration can produce a secondary voltage of between 3.4 to 6 times the normal secondary service voltage. However, a contribution from the other components must also be added and, in particular that due to the capacitive coupling. This component has a great rate of rise and a magnitude which can, in some circumstances, at least equal the electromagnetic component. It was found from experiment

that the wave front of the surge is always lengthened in passing through the transformer, but large units show this effect least when connected to circuits of high surge impedances. The test case of equal surges entering the primary of a delta-star transformer is shown to produce no transmitted surges in secondary circuits.

The response to connected secondary terminations made up of various arrangements of circuit elements likely to be found in practice, is studied by Belaschi.³⁸ A single-phase network is employed throughout and the standard impulse voltage (U.S.A.) provides the forcing function. Conversion factors are then introduced to establish the corresponding response of three-phase transformers. Significantly, simplified equations for the calculations of the components are presented which deal sufficiently with the various connected circuits, thus avoiding the long and rigorous analysis usually demanded of each particular case. Hileman³⁹ extends the single-phase impulse tests to three-phase transformers with two and three windings and different connections. The purpose of the investigation is to show the validity of equivalent transformer circuits in assessing the surge voltage transferred by electromagnetic coupling. It is noted here that the electrostatic component can be suppressed by the introduction of additional capacitance in the secondary circuit, or by an inherent low surge impedance secondary load. The latter condition is unlikely to exist in the distribution network since, with the exception of the cable conduits, all connected apparatus have high surge impedances.

1.4.5 Cable insertions.

The effects of lengths of cable connected to the overhead line before termination, and other arrangements, are studied by McEachron⁴⁰ et al. Tests show that little protection is available at a terminal point (substation, for example) against overvoltage surges when the waveform has a long duration near the crest value. Waves with long fronts and extended tails, whose duration corresponds to several times the electrical length

of the cable run are only reduced in magnitude by a few per cent at the first discontinuity. This response is easily verified by subsequent surge analysis where it is clear that the attenuation of the voltage wave passing into the cable is constrained by successive reflections from the discontinuities at the ends of the cable.

If the effective duration of the pulse is about the same as the propagation time of the cable, the peak value of the incoming voltage surge is then substantially reduced, according to the relative self-surge impedance of the line and cable, since $E_t = 2E_i \cdot (Z_c/Z_L - Z_c)$, and $Z_L \gg Z_c$. This is the effect usually taken for granted when a cable is inserted in a system.

The test waves utilised fronts varying from 8 microseconds to 27 microseconds and tails to 50% of the maximum value from 15 microseconds to 50 microseconds. The wave fronts of all these waves were extended in the presence of cables indicating that the cable is a predominantly capacitive element. This fact is shown as one of the methods for calculating the surge impedance of the cable. It was found that a wave front of 8 microseconds was expanded to 12 microseconds over a 500 ft. of cable, and to 24 microseconds, if the cable was increased to twice that length. Assuming the propagation velocity of the voltage wave passing along the cable is $\frac{c}{2}$, these two lengths of cable have propagation times of about one and two microseconds respectively. There is, therefore, little reduction in the magnitude of the test surges since their effective duration times comfortably exceed these times. However, considerably longer lengths of cable would have the desired result, and long lengths of cable run are not uncommon to find connected to overhead distribution lines.

1.5 Assessment of survey.

A horizontal wire, insulated from earth, is a natural detector of the change in the electric field gradient close to the ground. Thus, an overhead distribution line fulfils the same function.

In the majority of cases, the presence of the thundercloud produces a reversal of polarity in the ground gradient, i.e. it is now positive with respect to the cloud above.

Changes in the ground gradient are subject to changes in the corresponding electric charges within the clouds above a line. Hence, a thundercloud, although imposing a bound charge on the distribution line, is also subject to fluctuations in its influence because of the changing structure of the generating cells within it. The sudden release of this bound charge can only come about by a cloud-to-cloud lightning discharge and, subsequently, the law of the cloud discharge is the most important parameter.

Since the process leading to flashover between two charge centres within a thundercloud takes a relatively long time, the magnitude of the voltage induced in the line conductors is seen as unlikely to exceed about 20kV in distribution lines 25 feet in height, and even less in lines of 17 feet in height, above the ground at the pole. At transformer terminations, therefore, the surge voltage is unlikely to approach the basic impulse level of the system insulation. It is considered then, that this source of induced voltage can be discounted for the present study.

A direct lightning stroke to the overhead line is shown to result in permanent damage to line equipment at one or more points in the locality. In the majority of cases, lightning faults consist of h.v. fuse operation and/or autorecloser lockout. These faults are considered, by this investigator, to be the most probable response to indirect lightning strokes near to the overhead line system. They are referred to as transient faults to distinguish them from persistent faults which represent supply interruptions resulting from permanent damage.

The description of the principle sequence of events making up the lightning discharge indicates that maximum velocity of propagation of the current occurs at the commencement of the third stage. This is then also, the period of maximum electrostatic (and electromagnetic) field change.

The upward streamer together with the proximity of the lightning discharge to the overhead lines are seen to play a very important part in establishing the waveshape of the voltage induced in the line conductors. This waveshape may have an aperiodic or a bipolar characteristic.

The ground streamer follows from the sequence of events described as the prestrike effects, in which the intensity of the charge in the head of the descending leader, and the configuration of grounded objects immediately below, greatly distort the ground gradient. Corona envelopes are developed around grounded objects which may then be the cause of anomalous flashovers, and are certainly responsible for the liberation of the ground streamer.

Since at least 50% of ground strokes are found to be made up of multiple discharges, usually two or three in number, the induced excitation may extend beyond that of a simple pulse.

Surge tests on service lines show the slow attenuation of surge voltages on wood-pole lines of the type associated with this study. In addition, the effect of spur lines, and in particular single-phase spurs, indicate that a high level of excitation, however asymmetrical, is maintained in a multi-conductor feeder over a considerable distance from the feeder termination. This could affect spur transformers in particular and at the same time operate h.v. fuses at widely spread points on the feeder.

The propagation of an aperiodic pulse in a single conductor on a multiconductor line is shown to induce bipolar characteristics in the free conductors. This effect is observed after about one mile of travel of the initial impulse. The effect of corona is modified by the reversed loop waveform of the induced voltage showing that corona is not simply a function of the voltage alone, but is also influenced by the shape of the voltage waves in adjacent conductors due to coupling.

Lightning surges transferred to secondary circuits through transformer windings have their wavefronts extended in time and may reach voltage

magnitudes which are in excess of the basic impulse level of those secondary circuits.

Laboratory impulse voltage tests on the rod-plane gap assembly give results which are certainly applicable to the behaviour of natural discharges but with some reservations. Distinct differences in behaviour are seen to occur between positive and negative discharges to the ground plane. This leads to speculation as to the effect that the geology of the study area could influence the discharge from positively charged clouds to earth.

Interconnecting cable links such as road crossings and terminal connections need to be carefully assessed in respect of their propagation times. Their presence may reduce the amplitude of the surge voltage considerably, or have virtually no effect, according to the relation between the length of the cable and the duration of the voltage surge. In all cases, however, the presence of a cable lengthens the wavefront as with a capacitive termination.

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PART II

The field study: Fault definitions; presentation of data; selection of case studies; analysis and observations.

2.1 Definition of the lightning fault.

The Area Board's definition of a transient fault includes that of a fault cleared by an automatic circuit recloser (autorecloser). Similarly, a persistent fault is defined as one in which a circuit is interrupted and ceases to supply energy. Hence a blown fuse and the lock-out of a recloser therefore come within this category.

These identities are not able to be used for this study since records of the lightning faults as kept by the Electricity Authority are logged simply as

- (i) the date and time of the report of circuit interruption together with the clearance time,
- (ii) the location of the fault,
- (iii) the apparent cause of the outage,

and no record of autorecloser clearances is accountable during the life of the thunderstorm. The log entry for the cause of outage is taken from one of the following references.

- (a) single, two or three fuse operation.
- (b) autorecloser lockout.
- (c) equipment damage e.g. transformer failure, shattered insulator etc.

It is necessary to find an alternative interpretation of the classification of the lightning faults as taken from these records before attempting to analyse the responses associated with indirect surges. Using the entry information a, b, and c above, faults are selected which are assumed to be related to surges generated by indirect lightning strokes. For this study the following definitions have been adopted.

- (i) a transient fault is that recorded as a blown fuse(s) or autorecloser

lock-out, since either of these effects could be considered as the response to overvoltage/current of moderate surge level. This then suggests that these surges are initiated by indirect excitation which is the natural response to indirect lightning strokes.

(ii) a persistent fault is that recorded as equipment damage. The result of direct lightning strokes to the overhead line circuits results in the total failure of apparatus at some point. This was discussed in section 1.1.

Nevertheless, failure of equipment takes place from time to time when there is evidence that the origin of the surge is generated from a lightning stroke close to the line. Similarly, where severe damage follows from a direct stroke, a limited number of fuse operations can be expected. These effects were found by this investigator in a previous study and are taken to be representative of faults from lightning excitation in general. It is assumed that for a first approximation, the indirect stroke is responsible for a and b previous, and the direct stroke largely responsible for c. Additional information is now required to associate the failure of equipment in the first case with the transient fault, and vice versa. This information is presented if the topographical features of the terrain and the electric network information are readily available. It is then found that this data is sufficient to satisfy the cases under review.

2.2 The field study.

2.2.1 The study area.

All references to lightning faults in this study relate to the rural areas of Buckinghamshire and Hertfordshire designated by the Electricity Authority as the Aylesbury and Hemel Hempstead Districts. These two distribution networks are adjoining and have the present advantage, since reorganisation, of coming under the surveyance of one principal engineer. A fact which enables a wider area of varying topographical features to be included in the study. At the same time it is located within The Wash - Peterborough - Bedford - Oxford extension having one of the highest

isoceraunic figures for the United Kingdom.

The records of the lightning faults are extracted from the total faults on the relevant 11kV circuits of these two "Districts," and extend over a period of ten years from 1968 until 1977. The first five years, however, relate only to the Aylesbury District since a division is necessary to cope with the rationalisation that has taken place within the Authority since 1969.

The area of study is mostly covered by the 1:63360 scale Ordnance Survey map number 159* on which the enclosure is approximated by most of the ground north of the grid references 760930 to 030930. The lower portion of map number 146 references 630180 to 970180 is also required together with a small portion of map number 160 covering the Hemel Hempstead area.

The associated 11kV network distribution diagrams consists of 24 sheets issued by the Electricity Authority and dated October 1977. These are numbered as shown in the following grid.

	Aston	Aston			
	Abbots	Clinton	Ashridge		North
H 1	H 2	H 3	H 4	H 5	H 6
Waddesdon	Aylesbury		Tring	Hemel	
				Hempstead	
Long	Aylesbury	Halton		Bourne	Leverstock
Crendon		Wiggington	End		Green
H 7	H 8	H 9	H 10	H 11	H 12
Cuddington			Chartridge	Bovingdon	
	Stone	Stoke	Buckland		
		Mandeville	Common		
H 13	H 14	H 15	H 16	H 17	H 18
Haddenham		Wendover	Chesham		Bedmond
Thame	Ilmer	Hampdens			
H 19	H 20	H 21	H 22	H 23	H 24
	Saunderton			Amersham	Kings
Chinnor					Langley

These references are used in the subsequent studies where they are employed solely as locations in the electrical circuit. The electrical diagrams have no direct relation to the Ordnance maps representing the study area.

* Now superseded by the latest series of Ordnance maps to 1:50000 scale.

2.2.2 Analysis of lightning fault data.

Selected periods of greatest thunderstorm activity are taken from each year of the fault records. These are shown in table 1 together with the corresponding division of transient and persistent faults as defined in section 2.1

TABLE 1

Year	Period	No. of Days	Fault Days	Transient Faults	Persistent Faults	Percentage Trans. Faults
1968	Apr/Aug	131	7	12	4	75 .
1969	May/Aug	98	9	26	13	66.67
1970	May/Sep	129	11	69	18	79.3
1971	Jul/Sep	87	7	37	5	88.1
1972	Apr/Aug	92	10	24	9	72.7
1973	Apr/Sep	146	15	69	21	76.7
1974	Jun/Nov	162	15	148	17	89.7
1975	Mar/Aug	177	14	30	11	73.2
1976	Jun/Sep	134	16	68	21	76.4
1977	March only	31	1	8	2	80

*

✱

Notes:

* This column does not represent the isoceraunic reference but actual days on which lightning faults were recorded.

✱ This column represents the percentage transient faults of total lightning faults.

General Note: Aylesbury district only 1968-1972 inclusive.

It is found that fuse operations and autorecloser lock-outs amount to 80.2% of the total lightning faults corresponding to 105 fault days. This proportion is in agreement with earlier work completed by the writer in 1973 following a survey of the lightning faults over the previous five full years of the Aylesbury District alone. The relation between the transient and persistent faults for the selected period of each year is

shown in figure 2, and clearly indicates the difficulties in making a prediction of system reliability based on past fault data, as for example, an increase in the number of transient faults does not necessarily presuppose an increase in the number of persistent faults. In fact, there appears to be no direct relation between the two types of fault as revealed by an inspection of the two characteristics in figure 2. In 1970, a sudden increase in the number of transient faults did not produce a very great increase in equipment failure. 1974 shows a sudden rise in the number of transient faults but, quite unpredictably, a fall in persistent faults over the previous year. This independent behaviour is clearly shown in the shapes of the two graphs and it is apparent that the number of persistent faults can be accounted for much more easily in terms of the subsequent classification of the equipment failure which is displayed in table 2, and corresponds to the respective fault days of those selected periods.

Table 2

Year	Fault Days	Trans ^{R.}	Cable	Cond ^{R.}	Switch ^R	Insul.	Divertor	
1968	7	2	-	1	1	-	-	
1969	9	3	4	2	3	1	-	
1970	11	7	3	4	1	3	-	
1971	7	1	1	-	2	1	-	
1972	10	3	1	3	2	-	-	
1973	15	4	7	7	2	1	-	
1974	15	10	2	2	-	3	-	
1975	14	6	2	-	2	-	1	
1976	16	5	8	4	2	2	-	
1977	1	2	-	-	-	-	-	
Totals	105	43	28	23	15	11	1	= 121

Regular and frequent casualties are the transformers, the majority of which are pole-mounted. In fact, these losses amount to nearly 36% of the total persistent faults, whilst cable and conductor failures approximate to 23% and 19% respectively. Again, these figures verify the

earlier work by this investigator. In that study, transformer failures accounted for 32% of the persistent faults, and the combined cable and conductor failures were found to be 38.5%, for the full five years of records.

It is noted that six of the faults listed under cable failure are attributed to pole-boxes. These are examined later when discussing weak-link structures.

Transient faults are classified in the following manner:

- (i) Automatic circuit recloser operation in the lock-out position.
- (ii) h.v. fuse operation
 - (a) one fuse only
 - (b) two fuses
 - (c) three fuses.

The year by year selected distribution of the above is shown in the following table:-

Table 3

Year	Fault Days	1 fuse	2 fuses	3 fuses	AR	% AR	% AR _T
1968	7	9	3	-	-	-	-
1969	9	12	5	-	9	34.6	23.1
1970	11	28	25	1	15	21.7	17.2
1971	7	13	18	1	5	13.5	11.9
1972	10	15	6	1	2	8.3	6.1
1973	15	35	17	7	10	14.5	11.1
1974	15	89	18	5	36	24.3	21.8
1975	14	14	10	2	4	13.3	9.8
1976	16	32	20	5	11	16.2	12.4
1977	1	6	2	-	-	-	-
Totals	105	253	124	22	92	*	≠

= 491

Notes: *This column represents the percentage autorecloser lock-out of the total transient faults.

†This column represents the percentage autorecloser lock-out of the total lightning faults.

In some instances, the fault records include the phase identity of single and double fuse operations. In addition, the rating of the faulted fuse(s) is also given. Regrettably, these two features are somewhat infrequent as such details have been found to provide useful data.

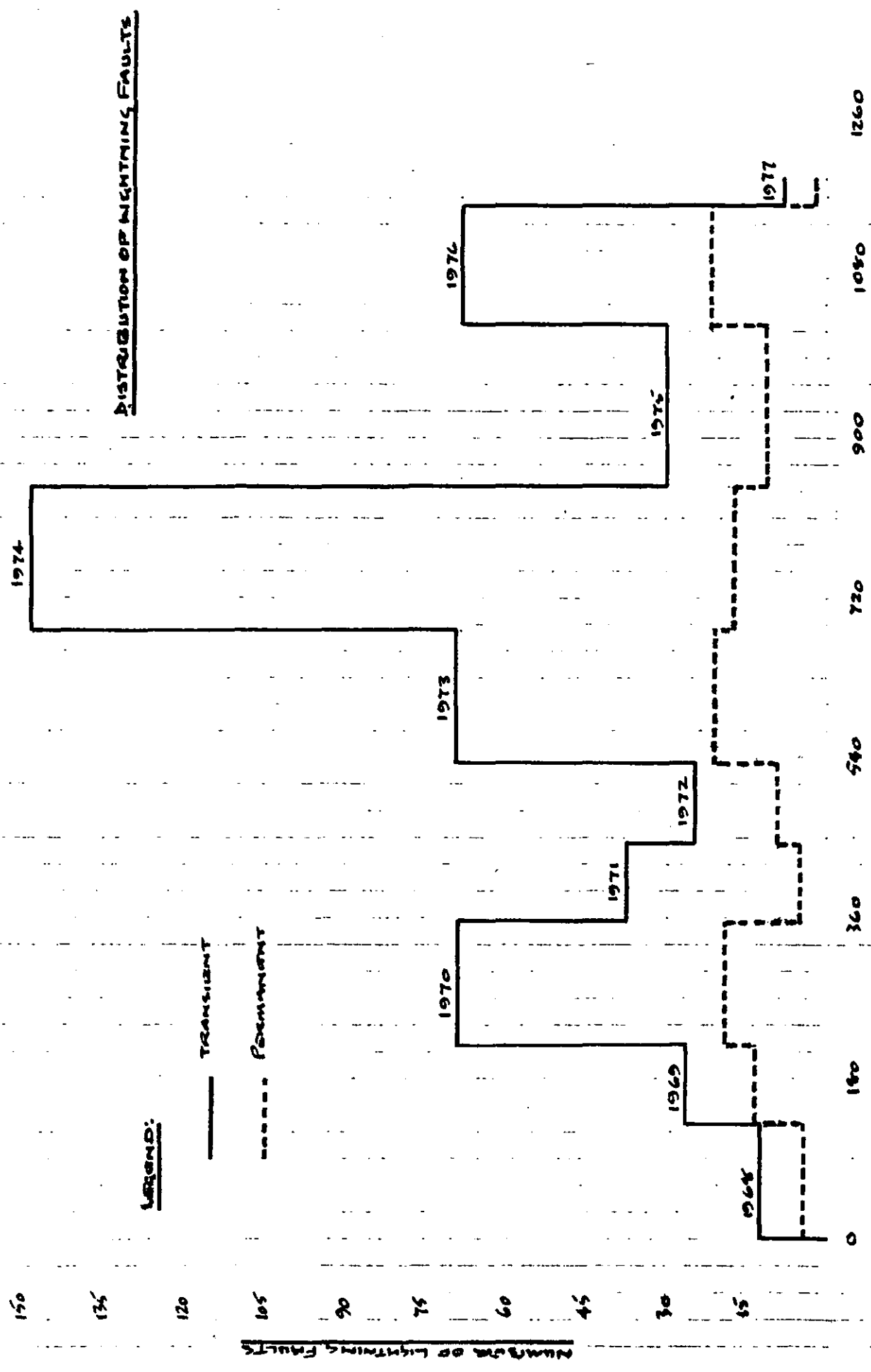
Since the number of transient faults has been shown to be just over four times the number of persistent faults, there is a clear indication that a major contributor to this state is the preponderance of single fuse operations. This alone contributes to more than one half of the transient faults and to about 41% of the total faults. A fact which is noted and referred to at a later stage. The comparative rarity of the operation of a three-fuse assembly where installed, again confirms similar results from the previous study. This type of fault, incidentally, is generally attributed to the secondary effects of direct stroke excitation.

2.3 Case studies.

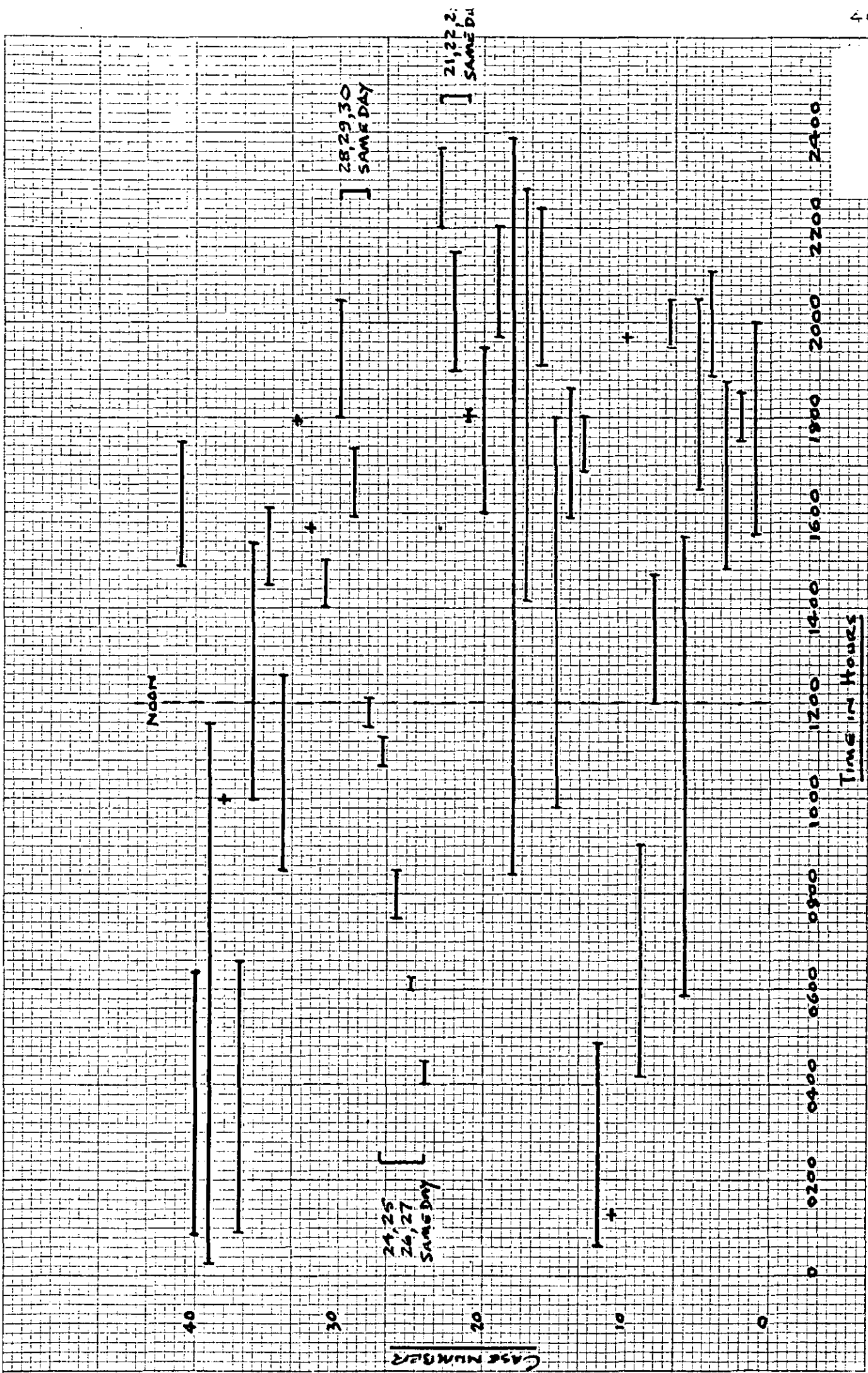
2.3.1 Presentation of studies.

A set of 41 examples are presented which are made up of selected cases taken from those periods of most thunderstorm activity in each year. The basis for selection is made in the following manner:

- (i) The same day faults are subdivided into the apparent simultaneous groups according to the logged times.
- (ii) The persistent faults are eliminated when recognised.
- (iii) The electrical network diagrams H1-H24 are used in association with the Ordnance Survey maps to determine the relation between simultaneous operations by grouping



NUMBER OF DAYS CORRESPONDING TO EACH YEAR



DIURNAL DISTRIBUTION OF SAME-DAY LIGHTNING FAULTS (1)
FAULT EXTENSION TIMES.

FIGURE 3

- as
- (a) one single electrical circuit
 - (b) several related electrical circuits
 - (c) unrelated electrical circuits linked by topographical features.

The examples selected provide a good representation of the year by year variation in lightning performance of the transient fault response.

A chart showing the time distribution of these case studies indicates that more circuit interruptions occurred during the second twelve hours of the day. Electric storms arising in the early hours of the morning are seen to be less frequent but appear to give rise to an extended series of faults. (examples 9, 11, 25, 39, 40). The chart is shown in figure 3

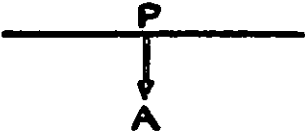
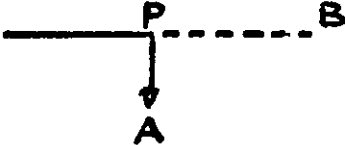
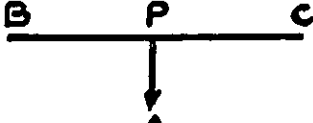





An inspection of the construction of the distribution network in general, shows that the various circuits are built up from several elementary topologies. Using this conceptual analysis, it is easy therefore to associate a fault with any one particular elemental circuit arrangement and catalogue accordingly, and this has been done in the following case studies. In this way a comparison and probable explanation of the field response from the surge analysis of these basic configurations is then made possible.

It is necessary to distinguish between a spur and a tee-off in the circuits, as they should not be considered as identical in this study. A spur is recognised as having zero propagation time on the high voltage side, except for that given for the primary winding of the spur transformer if required, and is that connection between the 11kV feeder and the transformer. Thereafter, the overhead line or cable spur is a low voltage system. A tee-off, however, has a specific transit time (of say $1\mu\text{sec}$ to $10\mu\text{sec}$) according to the length and nature of the conduit, and is, in effect, a secondary h.v. feeder to which spurs are connected, as defined above.

Terminations and cable insertions in overhead lines are simple series circuits in which the circuit elements are cascaded without need for explanation.

The case studies are made up from a selection of same-day log entries pertaining to lightning faults and rearranged to read in chronological

Elementary circuit topologies (11kV only)

<u>Code</u>	<u>Circuit</u>	<u>Comment</u>
a		Point P is the point of location of the spur transformer. PA is the l.v circuit.
b		PA and PB can be interchanged in b.
c		Point P is the line tap for the tee-off. Thus, BPC is the 11kV feeder.
d		PA and PC can be interchanged in d.
e		PA and PB can be interchanged in e.
f		Cable insert as for road crossings, etc.
g		Termination with cable insertion
h		Ditto, but with line and cable transposed.

Case 1.Date. 17.8.68.Report data.

1	Marsh Farm, Winchendon	1534	1F	H7	1650	c
2	Spa Farm, Dorton	1625	1F	H1	1945	a
3	Whaddon Hill Farm, Hartwell	1634	2F	H7	1800	a
4	Cowley Farm, Dinton	1945	1F	H13	2045	a
5	Boswells Farm, Wendover	2000	1F	H15	2020	c
6	Leylands Farm, St. Leonards	2000	2F	H9	0025*	c

* signifies time on following day.

All are fuse faults to farms which are located in every case, on high ground in exposed positions. There are clearly two distinct periods of storm attention.

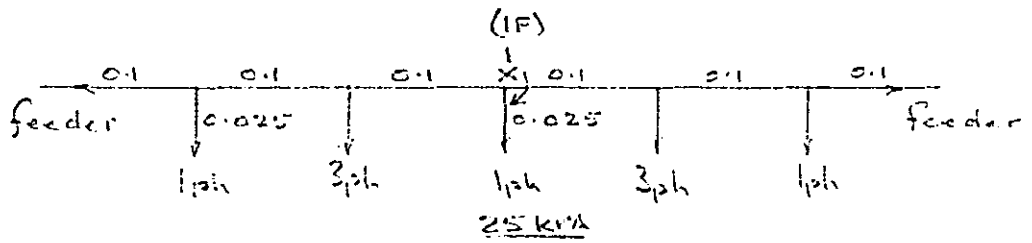
(i) 1534-1634 hrs. 1, 2 and 3 lie in a straight line over a distance of about 7 miles with Marsh Farm about midway. None of the electrical circuits are related hence only a probable topographical link exists.

(ii) 1945-2000 hrs. 5 and 6 are connected to the same feeder and about 2 miles apart although they are separated by five spurs. 4 is unrelated and is about 8 miles to the N.W.

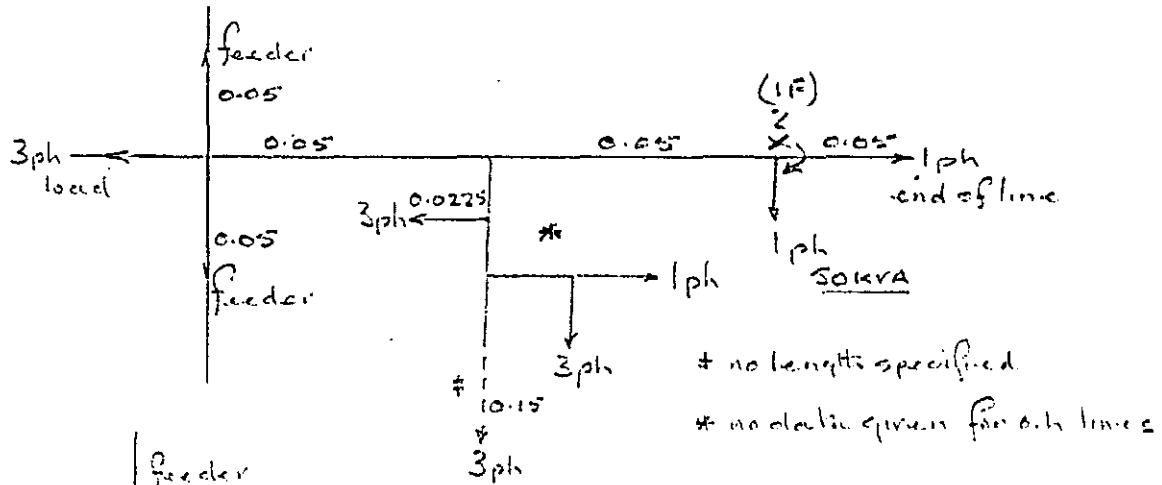
It is possible that 5 and 6 are the responses to a single incident surge since they are relatively close together (about 10 μ sec transit time) and the circuit may exhibit special propagation properties as demonstrated by Ouyang^{*}. The remaining faults have no common circuit connections but can be considered the result of separate isolated induced overvoltages of ground stroke origin.

* Ref. 32. Part I.

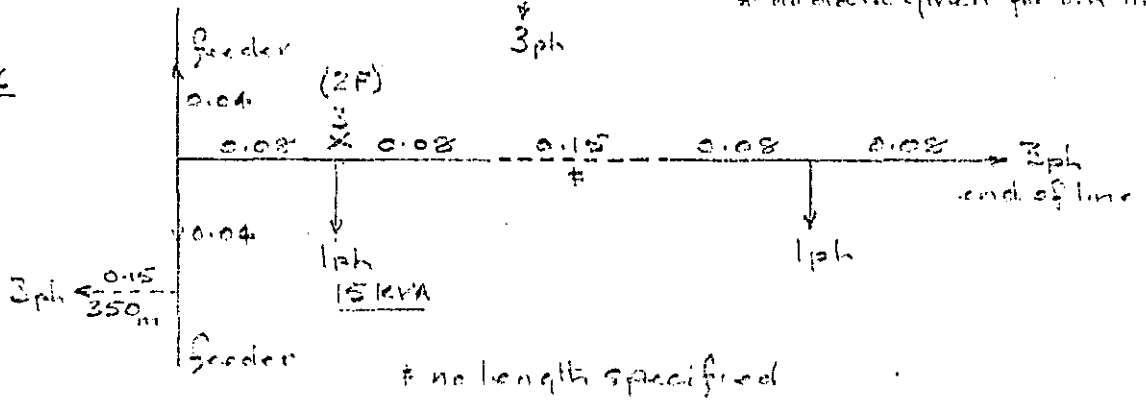
Part 1



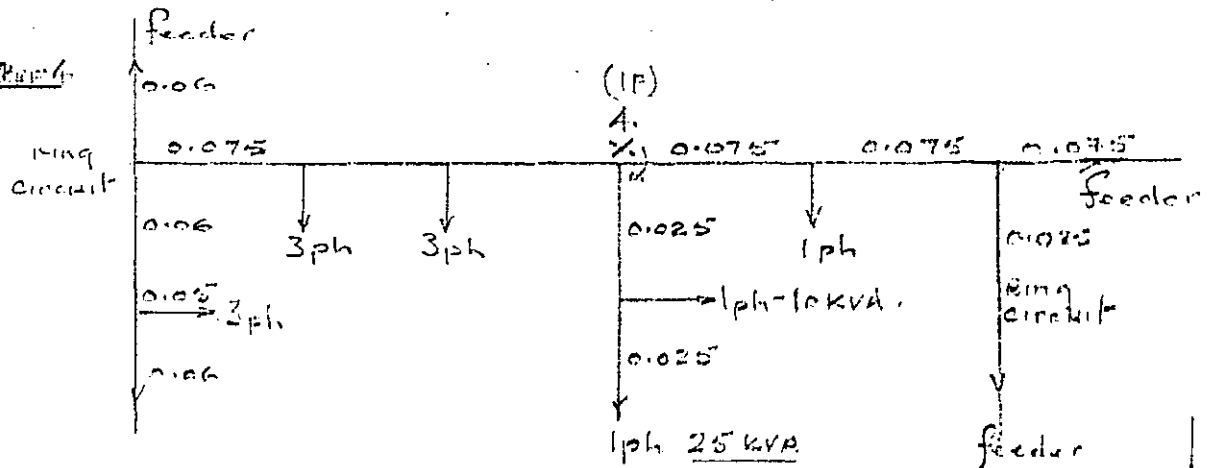
Part 2



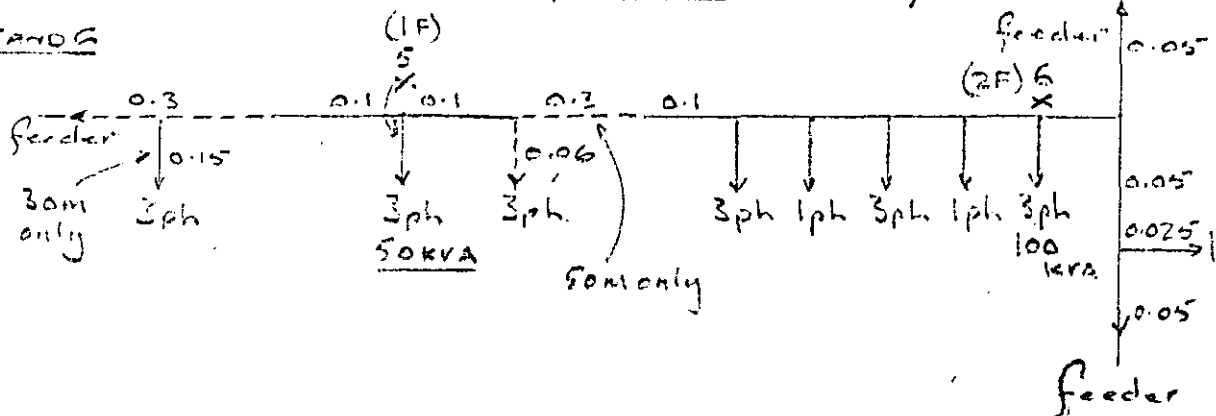
Part 3



Part 4



Part 5 and 6



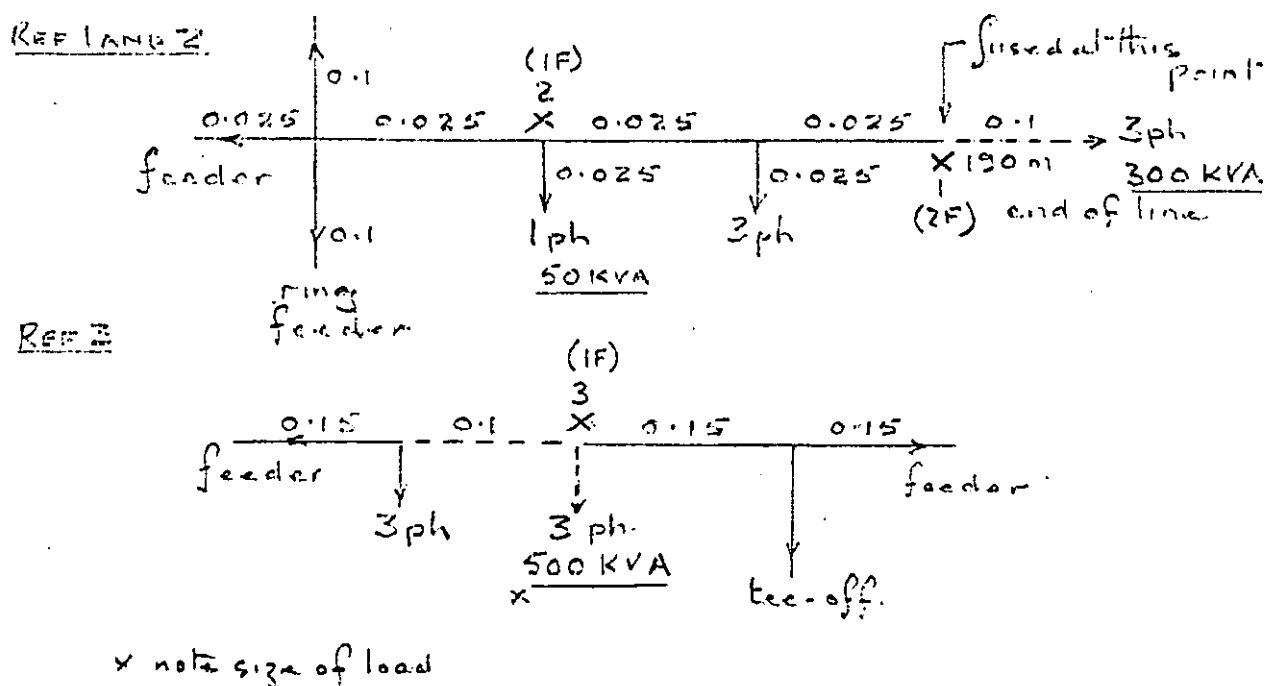
Case 2.Date. 27.8.68.Report data.

1	Shardloes spur	1730	2F	H23	0930*	g
2	Child Farm, Woodrow	1830	1F	H23	0930	c
3	Winchmore Hill, Amersham	1830	1F	H23	2030	e

* signifies time on following day.

These faulted points are located on contours 450-550 ft. in partly wooded but generally open country typical of Chiltern farmland. 1 and 2 are connected to a common spur but 3 is more remote as the fourth spur on the ring feeder from the junction. The fault time seems to preclude a travelling wave link between 1 and 2 unless these times are not exact, since it is noted that the clearance times are identical on the following day.

It is assumed that 1 and 2 are related by propagation effects and 3 by topography, since 1 is about 1.5 miles and 2 less than 1 mile N of 3. Therefore, these three outages appear to be the result of one single discharge.



Case 3.Date. 16.5.69.Report data.

1	Upper Pollicott	1450	1F	H7	1845	a
2	Chinnor Hill spur	^x 1515	1F	H20	1620	c
3	Doddeshall	1750	CAB	H1	-	
4	Collett Farm, Woodham	1752	AR	H1	1915	
5	Quainton Food Store	1752	TR	H1	-	
6	Oving Road, Whitchurch	1752	CON	H2	2210	
7	Hardwick tee-off	*1800	1F	H2	2324	c
8	Aylesbury Road, Bierton	1815	1F	H2	2300	c
9	Grendon Hill Farm tee-off	1825	1F	H2	2230	a
10	Luton s/s	1845	CB	-	-	
11	Tring Primary	1846	CB	H4	-	

* fault at take-off point.

^x Repeat fault location or circuit.

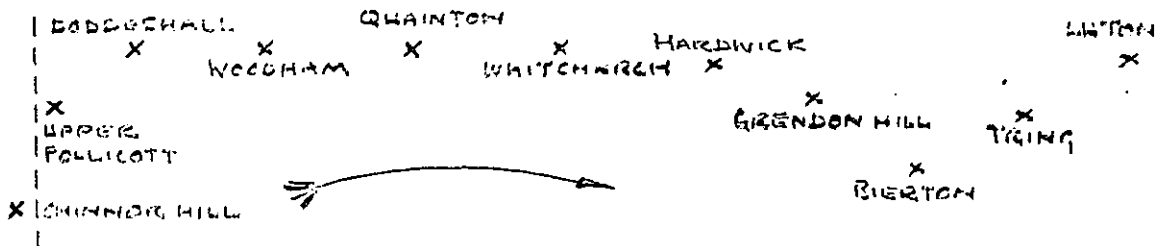
3 and 5 are adjacent spurs on a ring feeder to which 4 is also connected, though somewhat remotely, being separated by six spur lines and a cable run of 210 metres. Since the faults 3 and 5 are permanent faults, the autorecloser lockout at 4 is presumed to be due to perturbations resulting from a probable direct stroke.

1 is isolated at 450 ft. on the Plain of Aylesbury, and reference 2 is 10 miles south at a point 600 ft. in the Chiltern Hills. They are unlikely to be associated in anyway to a single indirect stroke to ground.

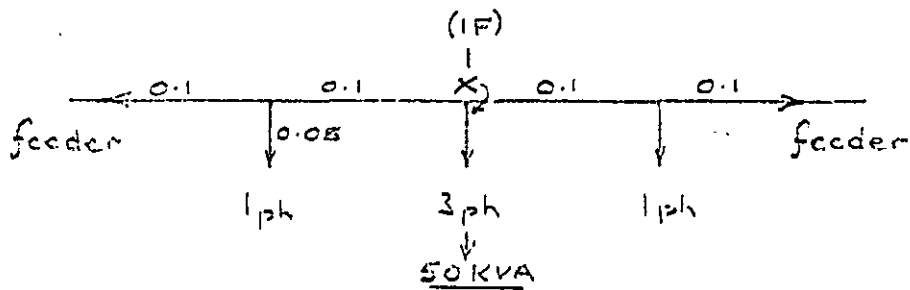
6, 7, 8 and 9 are connected to a ring circuit but only 8 and 9 are close spurs. The total distance covered is about 4 miles, and excluding 6, about 2.7 miles but the feeder has several tee-offs so that only 8 and 9 can be considered as related by the effects of propagation. It is noted that there are several long cable runs in this area. e.g. 1200 metres

directly in series with 700 metres and 1950 metres to substation.

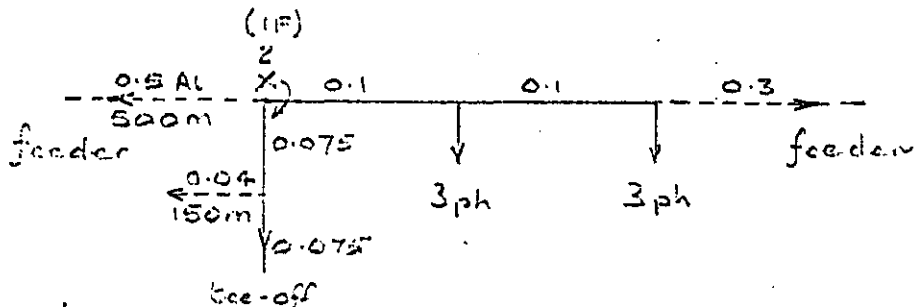
The outages are spread over a wide area, some of which are 12 miles apart, and it is clear that these are the responses to an electric storm moving round the northern boundary of the study area. Between 1400/1500 hrs. the storm centre is to the west of the region and only its tip is evident. But from 1750 hrs. it is moving clockwise as shown below. Five faults are considered representative of an induced response.



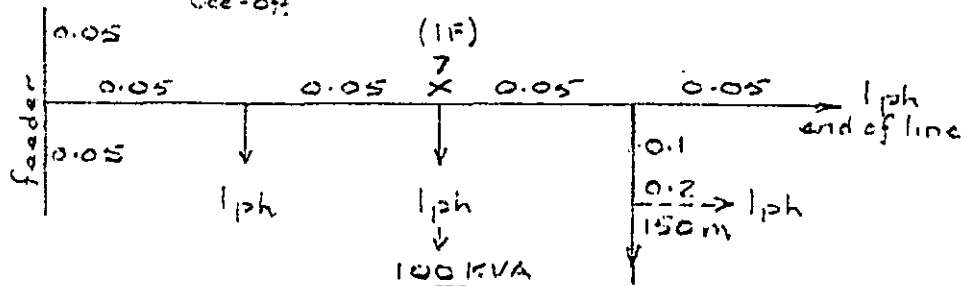
REF 1



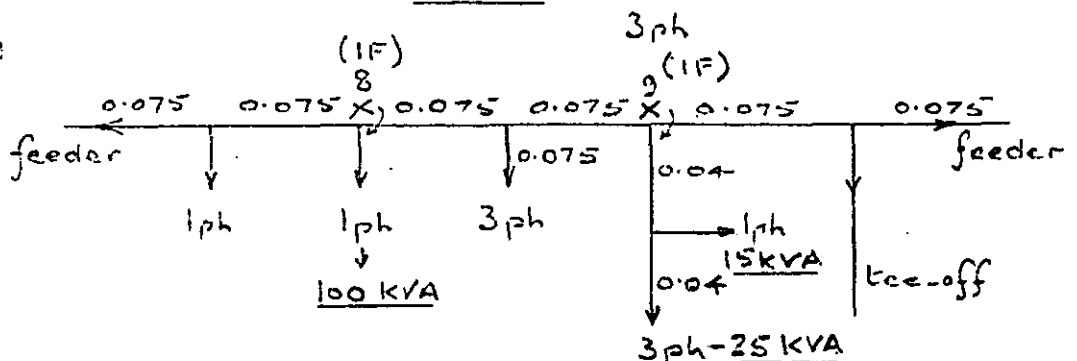
REF 2



REF 7



REF 8 AND 9



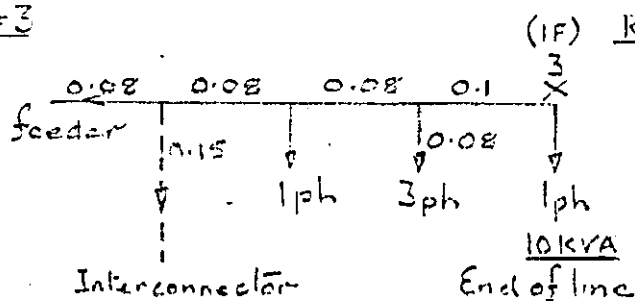
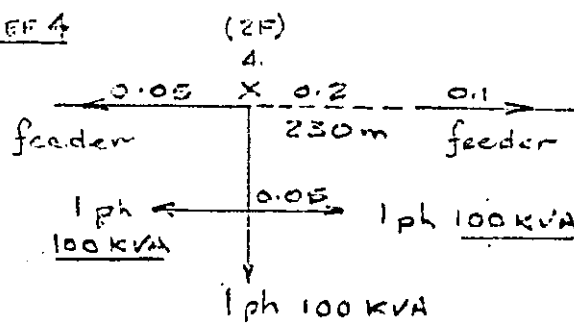
Case 4.Date. 18.5.69.Report data.

1	Saunderton Primary - Bledlow	1855	CB	H20	2020	
2	Mollins, Saunderton	1915	AR	H21	2015	
3	Kingswood Lane, Lacey Green	1922	1F	H22	2250	c
4	Routs Green, Bledlow Ridge	1930	2F	H21	2255	a
5	Saunderton Primary - Lacey Green	2108	CB	H22	2149	

3 and 4 are about two miles apart and at altitudes of 500 ft. and 700 ft. respectively. Both locations are well into the Chiltern Hills and well exposed but are connected to separate electrical circuits. Both are single phase faults. Item 3 is the last load at the end of a single phase spur.

The disturbance, represented by the total log, comes in the "transient" category. With the exception of 5, which is not accountable, the responses are assumed the outcome of one single lightning discharge in the vicinity. The circuit of item 4 is of special interest. One load is taken directly from the feeder (junction of line and cable) but the fault has taken place at the end of a line at the transformer whilst the second tee line remains unaffected. This response could be explained by

- (i) A travelling wave phenomenon, in terms of the relative electrical lengths of the tee-offs,
- (ii) An example of a prestrike component voltage addition, nearer to one line than the other,
- (iii) Combination of both (i) and (ii).

REF 3REF 4

Case 5.Date 15.6.69.Report data.

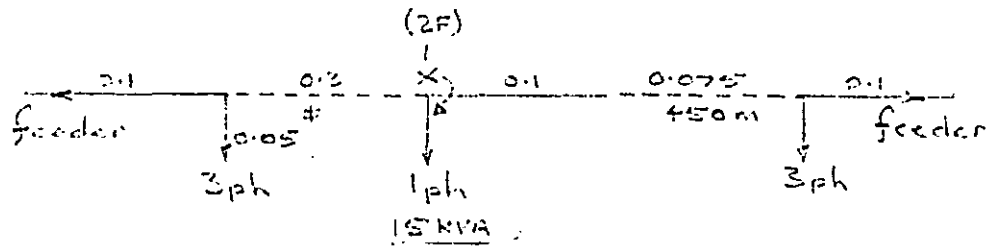
1	Flint Cottage spur, Chinnor Hill	1630	2F	H20	1830	b
2	Waddesdon - Cuddington feeder	1638	AR	H7	1741	
3	Waddesdon - Chilton Feeder	1638	AR	H7	1738	
4	Westcott Wireless Station, Brill	^x 1746	1F	H1	1910	a
5	Northlea Feeder, Mandeville Road	1805	AR	H14	2000	
6	Grendon Prison Housing	1900	TR	H1	-	
7	St. John's Hospital, Stone	1900	CAB	H7		
8	Kingssy Spur	1900	1F	H13	2335	c
9	Longwick Mill	1910	1F	H20	2025	b
10	Kingswood Spur	2030	2F	H1	0830 [*]	b

* Signifies next day clearance time. ^x Repeat fault location or circuit.

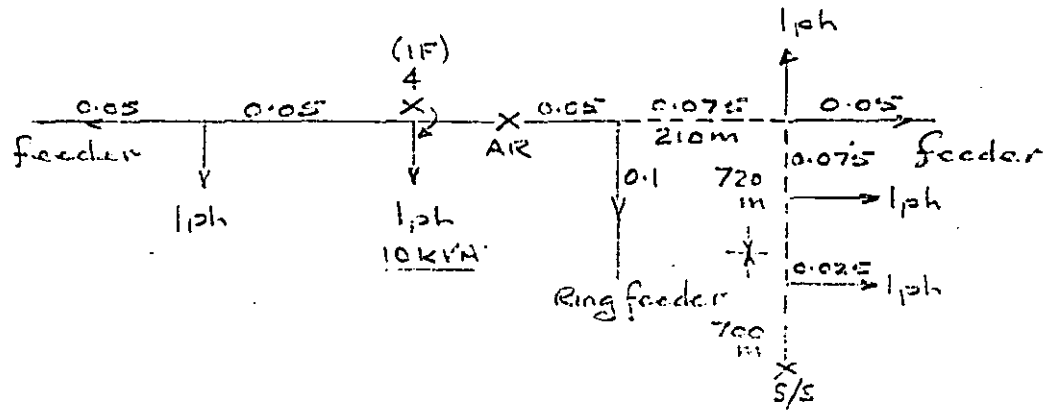
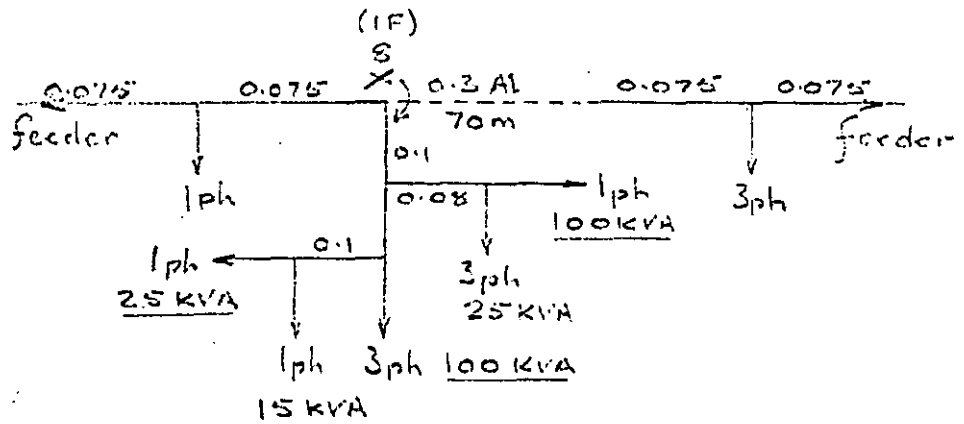
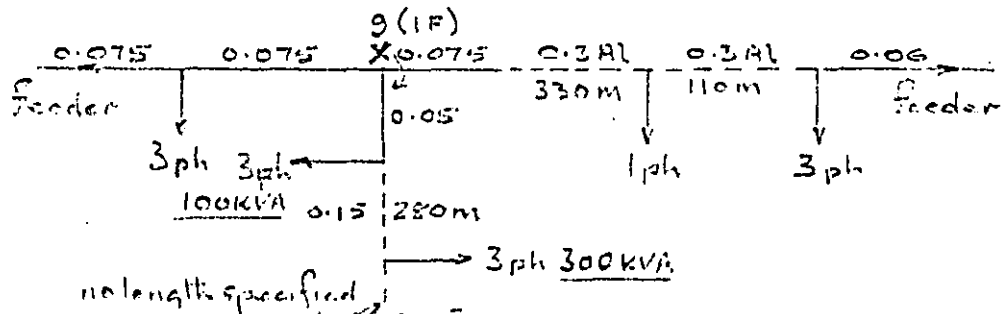
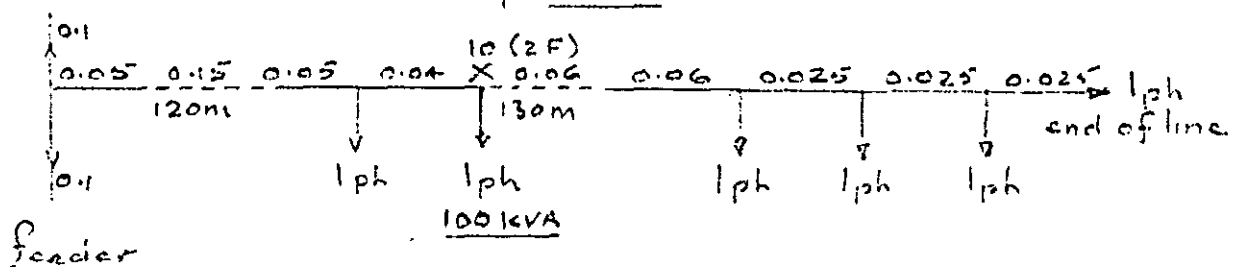
2 and 3 probably refer to the same fault since there is a common feeder to the bifurcation point leading to Cuddington and to Chilton, and the only recloser evident is located at Waddesdon. (Electrical diagram H1).

The faults are presented over a wide area and there is little evidence of common electrical connection according to the logged times. With the exception of 8, all other fuse faults are single phase only.

It is clear that there are two storm periods. The first is in the west of the region from the edge of the Chiltern Hills up to the northern boundary. The second period, a little later, shows the affected area to be further east but remaining on the lower ground around Aylesbury. A good indication of the local nature of this type of thunderstorm. It is assumed that the disturbed weather moved away north of the area as no other records appear for this day. All transient faults take place in independent electrical circuits and whose initiation appears the result of separate ground strokes.

REF 1

* cable length is not given.

REF 4REF 2REF 3REF 10

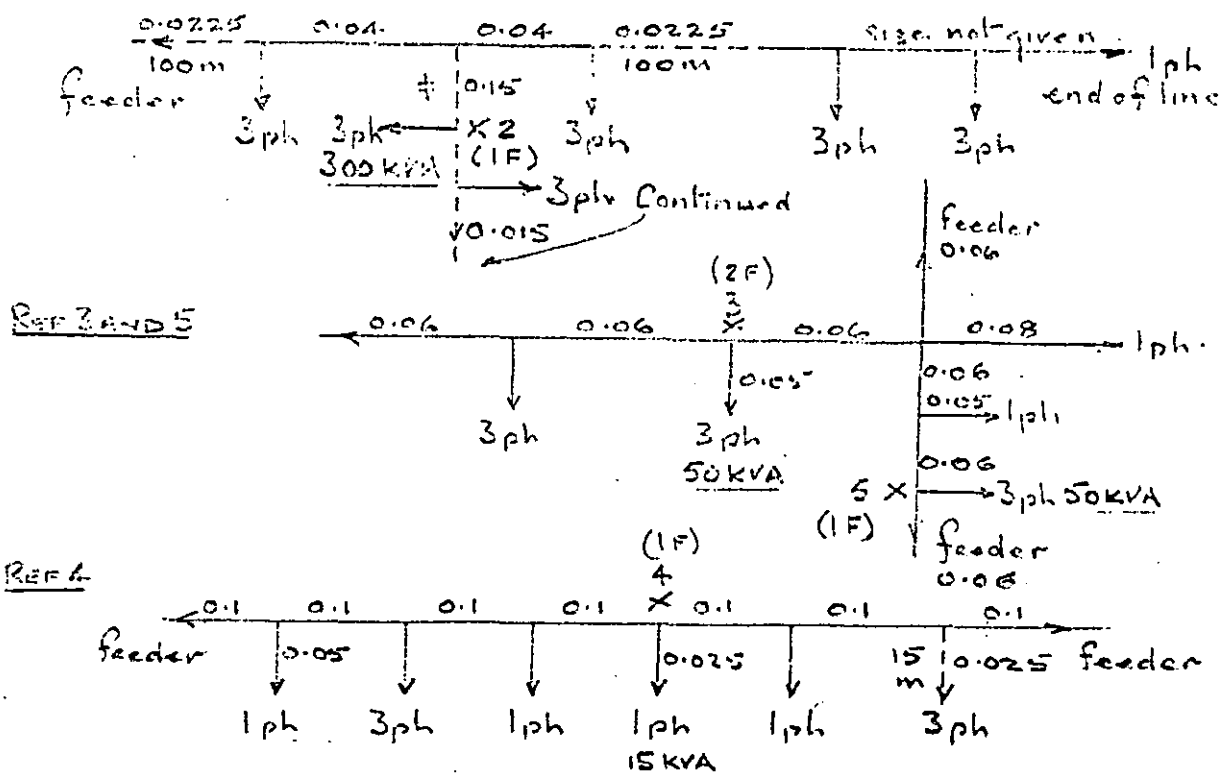
Case 6.Date 10.5C.70.Report data.

1	Wigginton, Hastoe, Aldbury	0550	AR	H10	0855	
2	Aldbury	* 0550	1F	H4	1010	a
3	Haddenham Low	0814	2F	H13	0910	a
4	Field Farm Cottages, Westcott	0900	1F	H7	1157	c
5	Budnall Farm, Haddenham	1530	1F	H13	1050	c

* Repeat fault.

These transient faults are well separated except for references 3 and 5. The locations cover a distance of 16 miles which are again (as with the previous case) in the northern part of the study area. Two of the locations are on high ground (600 ft. and 400 ft.) and the rest are in open country to the west of Aylesbury. The electrical circuits are isolated.

Since the locations are so widely spaced and the logged fault times mostly dissimilar, the response is the same as case 5, except that the storm direction appears to be from East to West, i.e. the response to independent ground strokes near enough to the overhead lines to be significant.

Ref 2

Case 7.Date 11.6.70.Report data.

1	North Camp, Aston Clinton	1930	2F	H9	2247	c
2	Hall Farm, Westcott	1930	1F	H1	0012*	a
3	Puttenham	1944	INS	H3	-	
4	Aston Abbotts feeder, Tring	1944	AR	H4	2132	
5	Ellesborough Road, Wendover	1950	2F	H15	2200	c
6	Wellwick Lodge, Ellesborough	1950	1F	H15	2355	a
7	Quainton-Waddesdon feeder	e 1954	AR	H1	2020	
8	Waldridge feeder from Ilmer	x 1954	AR	H14	2103	
9	Bucombe Lane, Wendover	1955	1F	H21	2255	c
10	Terrick, Stoke Mandeville	** 2000	AR	H14	2110	
11	Bishopstone spur - the Chapel	2000	1F	H13	2210	a
12	Bishopstone Crossroads s/s	2000	1F	H13	2210	c
13	Woodham Brickworks	2000	2F	H1	1025*	c
14	Binwell Lane Farm	2005	2F	H1	1005*	c
15	Chilborough Hill Farm	2010	1F	H13	0930*	c
16	Risborough Road, Stoke Mandeville	2010	2F	H15	2225	f
17	Marsh Lane, Stoke Mandeville	2010	1F	H15	2325	d
18	Needles Farm, Quainton	2030	2F	H1	0915*	c
19	Apsley Farm	2030	1F	H15	1730*	a

* Signifies time record next day.

A substantial number of faults on one day all of which are transient faults, with the exception of the insulator failure (reference 3), and mainly located in the northern part of the region. Since these particular records (1968-72) are associated with the Aylesbury District only, the faults are largely in the Plain of Aylesbury. Consequently high ground is not a significant characteristic. The range is about 12 miles

and the time variation in the records is exactly 1 hour. A close examination of the responses therefore of both location and time is required to correctly identify these faults. Additional information is added to this case study as to the sizes of load lost to outages of this nature. The samples taken are marked accordingly, viz:

Ø 450 consumers, 600 KW load, Maximum Demand 1270 KW.

e 600 Consumers, 800 KW load. Maximum Demand 1700 KW.

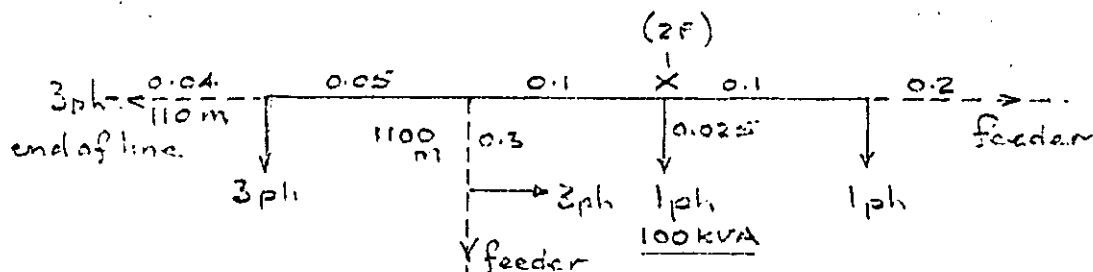
x 900 Consumers, 1227 load. Maximum Demand 3 MW.

** 130 Consumers, 195 KW load. Maximum Demand 500 KW.

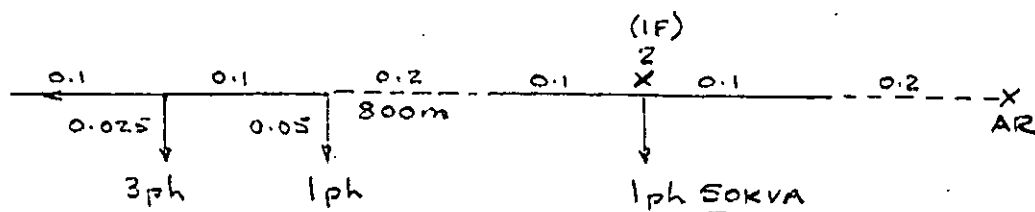
Although the fault times are identical for references 1 and 2 there is no link between them since they are 10 - 12 miles apart, and a topographical link is not feasible from a single lightning discharge.

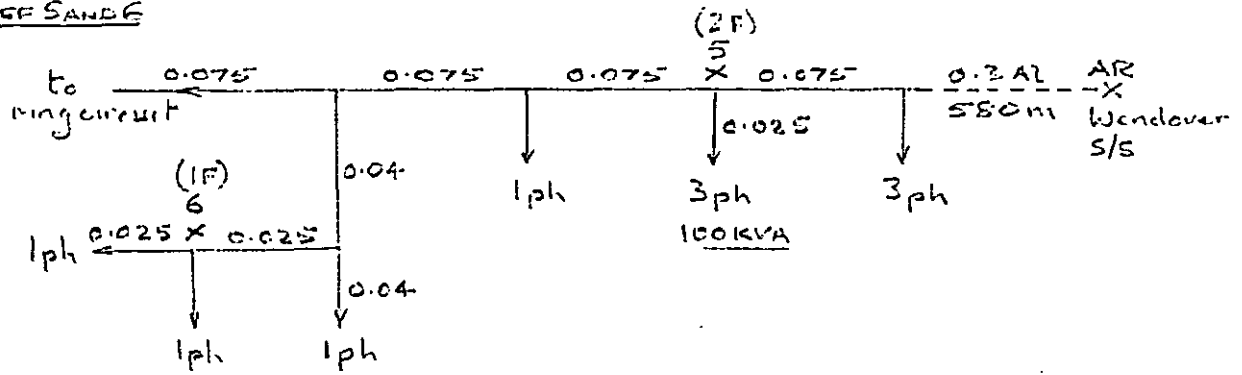
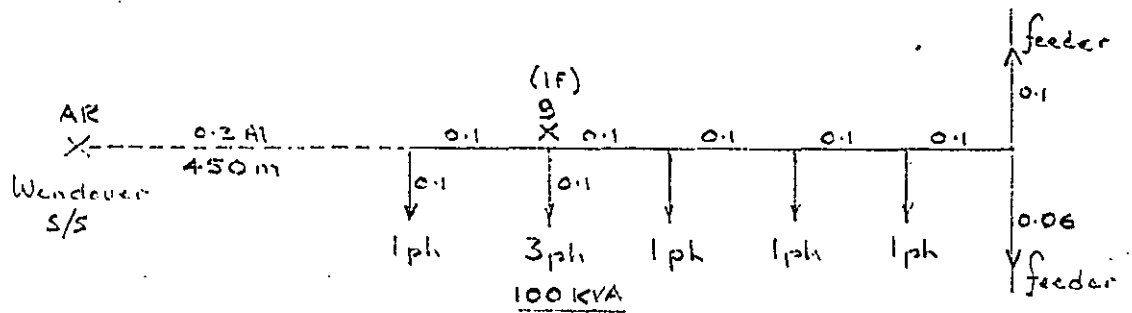
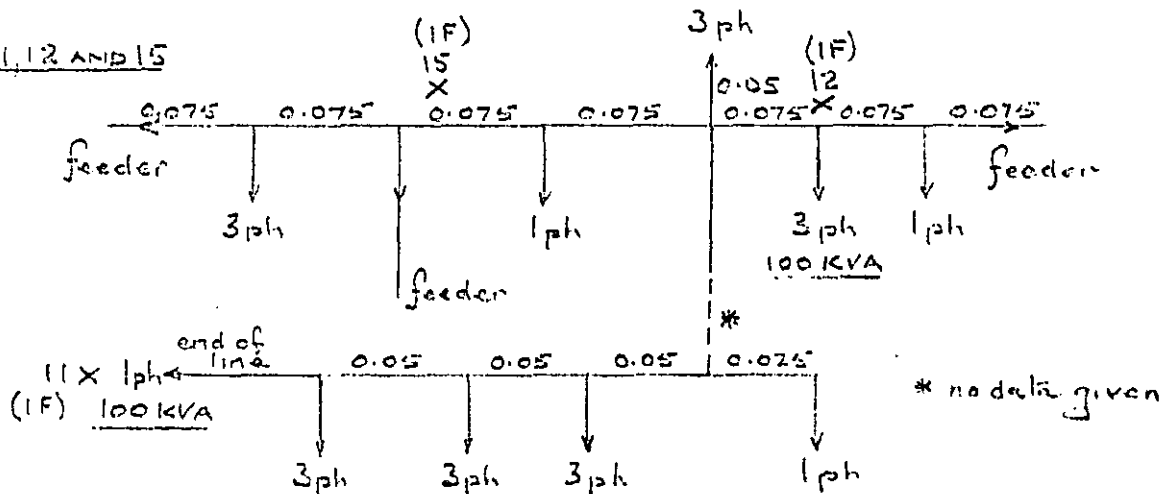
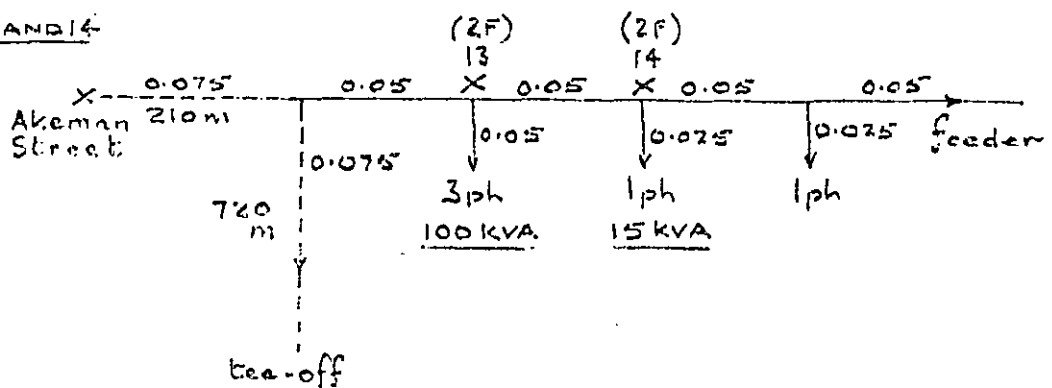
The separation of the outages according to their locations can be offset by seeking a topographical link. In this particular case study, clearly the faults are able to be grouped apart from those with common circuit connections. An example is shown by 3 and 4 which are closely associated without any direct circuit attachment. Thus, 9, 10, 11, 12, 15, 16 and 17 could well be the response to one single ground stroke since the extreme distances are not more than 4 miles. 13 and 14 are about 8 miles to the N.W. of this group and although logged within the same period of time, are most unlikely to have been influenced by the same ground stroke.

REF 1

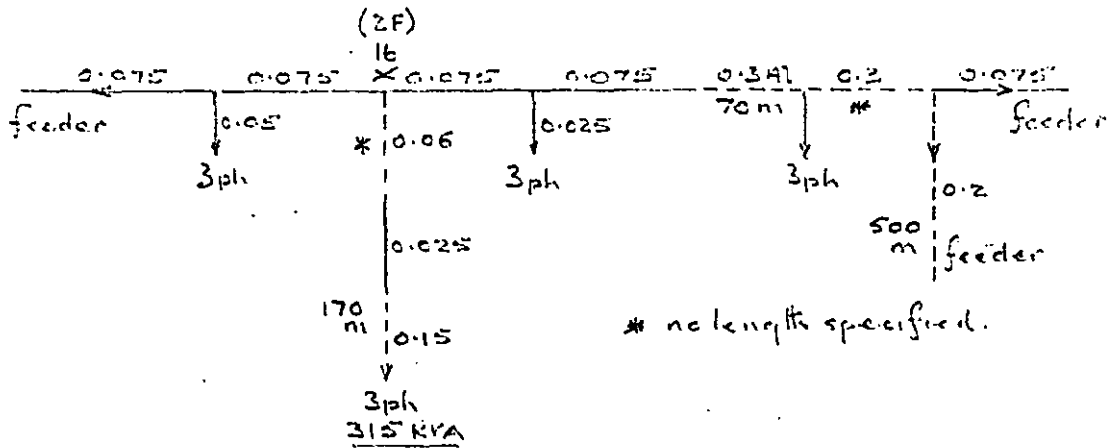


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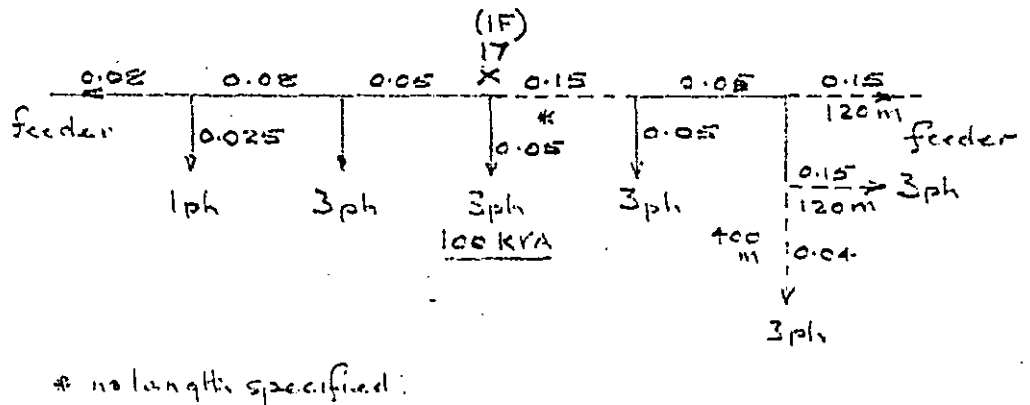


REF SANDGREF 9REF 11, 12 AND 15REF 13 AND 14

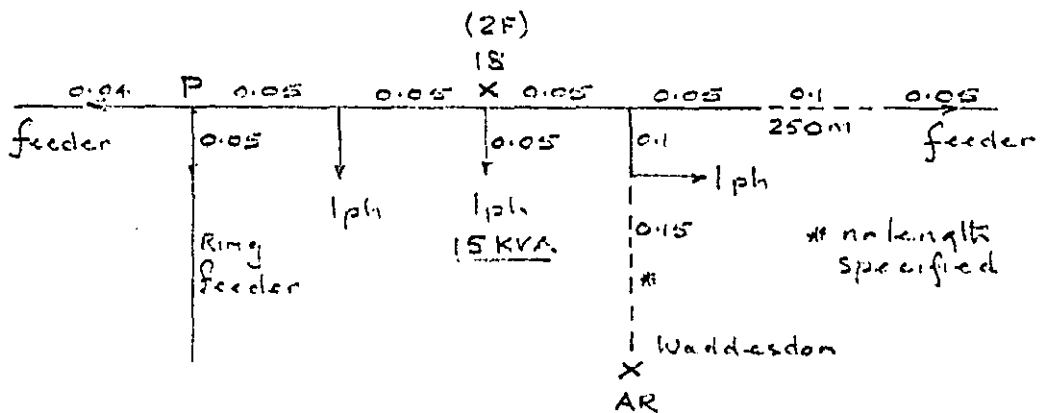
REF 16



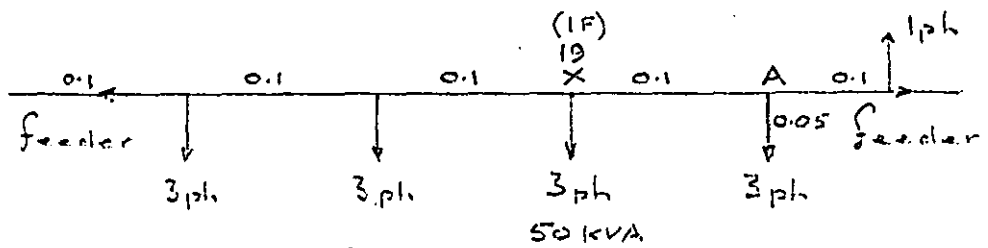
REF 17



REF 18



Point P is the tee-off connected to references 13 and 14.



REF 19

all spur lines on feeder except for point A

Case 8.Date 27.6.70.Report data.

1	Whitehouse Farm	e 1200	2F	-	1710	
2	Newground Pumping Station	1225	AR	H10	1709	
3	Tring Track feeder station	1230	1F	H4	1720	f
4	Redwing Farm	1230	1F	H10	1800	b
5	Kiln Farm	1230	1F	H10	0130	c
6	Lodge Farm, Wiggington	1240	TR	H3	2245	
7	Longwood Cottages	1240	CON	H21	2040	
8	Aldbury Village	x 1400	2F	H4	1916	a
9	Whitchurch School and Mill House	1440	CAB	H2	1715	

e Not found

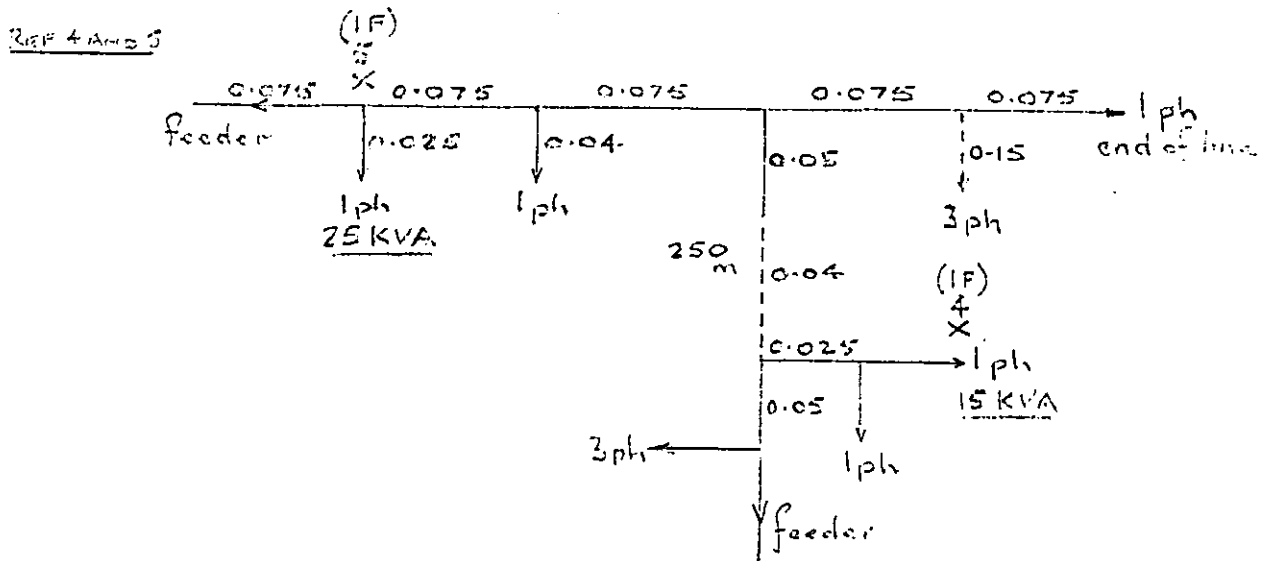
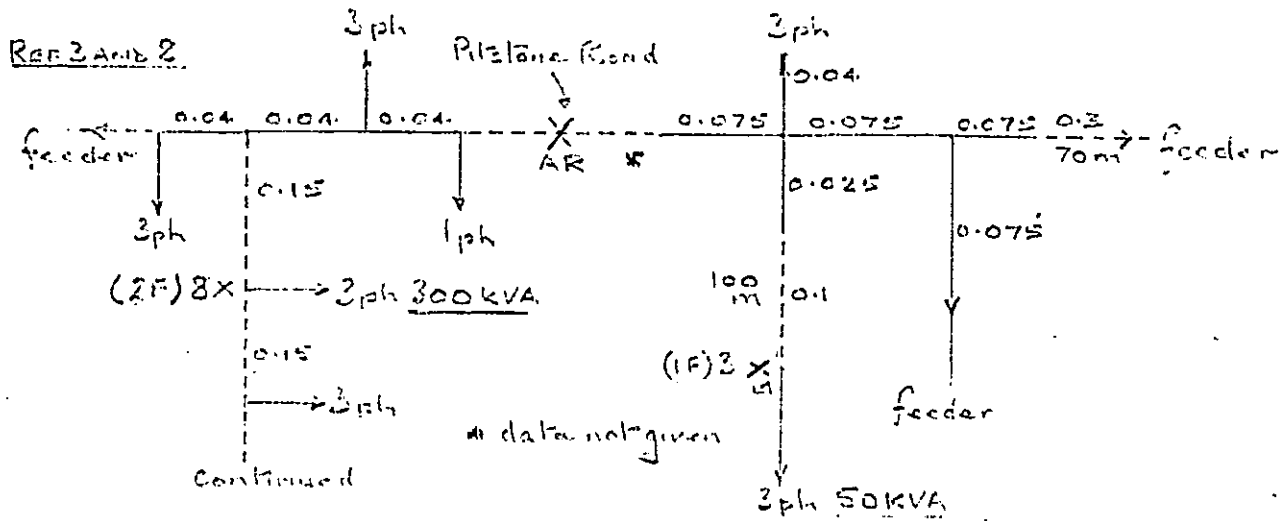
x Signifies time record next day.

Equipment damage recorded here would appear to be due to separate single direct strokes. It is noted that Aldbury Village circuit is the same as that in Case 6. The faults are restricted to a relatively small area in the N.E. of the region and most of these are on the high ground on the edge of the Chiltern Hills. The recloser lockout and the single fuse operation of references 2 and 3 are not related by direct connection although they are not far apart.

It is recorded that following this storm, a pole-mounted transformer failed next day at Cuddington. This is about 10 miles to the west of the affected area recorded above. No other storm records exist for that area.

There seems to be no particular evidence of simultaneous faults from a single stroke. References 4 and 5 could be however the response to

one ground stroke. The overall pattern would appear to be due to a local storm with the characteristic behaviour to several lightning discharges.



Case 9.Date 8.7.70.Depart data.

1	Ilmer Grid s/s.	0410	CON	H20	2019	
2	Wendover tee-off, Weston Turville	0415	INS	H3	0725	
3	Chinnor-Saunderton No. 2 s/s	0418	CB	H19	0800	
4	Tring No. 2 s/s	0420	CON	H4	1530	
5	Saunderton s/s.	0430	TR	H20	0720	
6	Waddesdon No. 2 s/s.	"	CON	H1	1907	
7	Aston Abbotts	"	AR	H2	0823	
8	Cuddington feeder	"	AR	H7	0823	
9	Winchendon Hill	"	2F	H7	1700	e
10	Holbourne Hill Farm, Oving	"	1F	H2	1225	c
11	Whitchurch - Creslow tee-off	"	2F	H2	1055	c
12	Odly Lane, Saunderton	"	1F	H20	1540	c
13	Sheepcot Hill, Waddesdon	"	1F	H7	1030	c
14	Littleton Manor Farm	"	1F	H1	1300	a
15	Hardwick	"	1D	H1	1300	c
16	Folly Farm, Haddenham	"	2F	H13	1730	c
17	Hewden Farm, Haddenham	* "	1F	H13	1745	c
18	Little Marsh Farm	"	1F	-	1800	-
19	Drayton Beauchamp	"	2F	H3	1615	a
20	Drayton Holloway	"	2F	H3	1650	c
21	Chesham Road, Wiggington	"	2F	H16	1500	c
22	Griffin Lane, Aylesbury	"	2F	H2	1715	-
23	Meadle	"	1F	H14	1610	b
24	Little Lane Looseley Row	"	2F	H21	1610	c
25	Burcott Lane, Bierton	"	2F	H3	1400	a
26	Church Farm, Aldbury	"	1F	-	1615	-
27	Dunsham Farm	"	1F	H2	1630	a

28	Wilstone Canal	0430	1F	H4	1645	c
29	Bledlow School	"	2F	H20	0750	c
30	Bishopstone	*	"	2F	H13	1140 a
31	Kingsey	"	1F	H13	1130	c
32	Norduck Farm, Aston Abbots	"	2F	H2	1155	c
33	Horsenden	"	1F	H20	1545	a
34	Manor Farm, Ilmer	"	2F	H20	1030	b
35	Bumper Farm, Horsendon tee-off	"	CON	H20	1030	
36	The Hale, St. Leonards	"	CAB	H15	1215	
37	Aylesbury No. 3 s/s.	0431	CB	H8	0538	
38	Ilmer s/s.	0442	CB	H20	0940	
39	Long Marston, Wingrave	0445	TR	H3	1000	
40	Westcott W.T. Station	*	0500	TR	H1	1145
41	Richmond Road, Aston Clinton	0510	AR	H9	0920	
42	Weedon Hill (Kiosk) s/s.	*	0615	1F	H2	1000 -
43	Dancers End s/s.	0630	AR	H9	0940	
44	Longwick Mill	"	CON	H20	1600	
45	Tring s/s. Primary	0632	AR	H4	0649	
46	Auriole Records, Aston Clinton	0900	CAB	H3	1428	

* Fault repetition.

Clearly a very intensive storm covering a wide area of the Aylesbury District, from Chinnor in the west on the edge of the Chiltern Hills, north to Waddesdon and Whitchurch, but mainly in the centre and east of the region. 22% of the faults can be classified as persistent so that the overall division of outages is typical of lightning response, i.e. a ratio of 4 transient faults to every supply interruption due to permanent damage of equipment. It is noted that with the exception of reference 42, all the fuse faults are logged at the same time, namely 0430 hrs. These number 26, in which single and double fuse operations are, by coincidence, equally

divided. With two exceptions, the persistent faults occur outside this time. The circuit for reference 42 is made up of cables only. There is one overhead line tee-off which could have accepted the induced overvoltage. This reference also pertains to case 1.

Only two pairs of fuse faults indicate common circuit connection. However, 34 and 35 are plainly related although the latter comes in the other category of fault definition. In this case, there appears good reason to include 35 in with the transient fault as it is a terminal point and both faults are the likely response to the same incident wave. (The distribution of the electrical lengths may be a contributing factor). A similar case may exist for 33 and 44 even though the logging of the fault times is not the same. In general, however, 21 separate circuits represent 23 fuse faults for the common entry time of 0430 hrs. A curious situation but which should be made clearer from a topographical investigation.

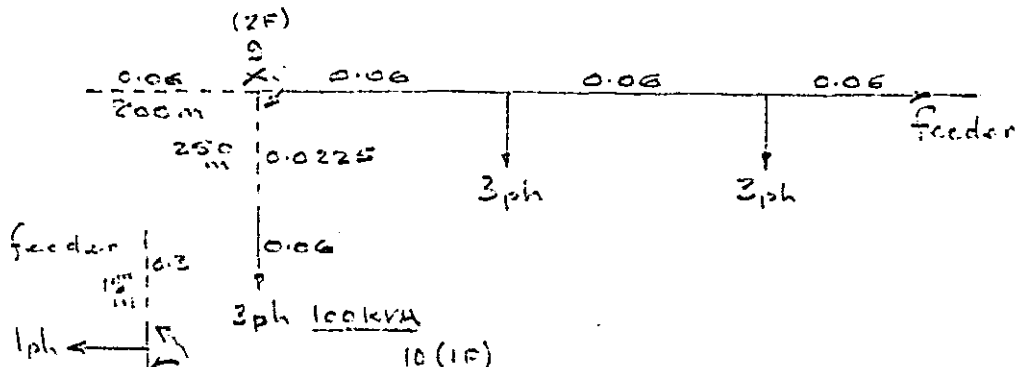
The distribution of these fuse faults is displayed in figure 4 showing that the west of the region is completely unaffected. This is also true if the persistent faults are included. Without attempting to correlate all 23 fuse faults because of their common logged time, but grouping according to area, the distribution now becomes,

- (i) 12, 16, 17, 18, 23, 24, 29, 30, 33, 34
- (ii) 11, 13, 14, 15, 22, 25, 27, 32
- (iii) 19, 20, 21, 26, 38

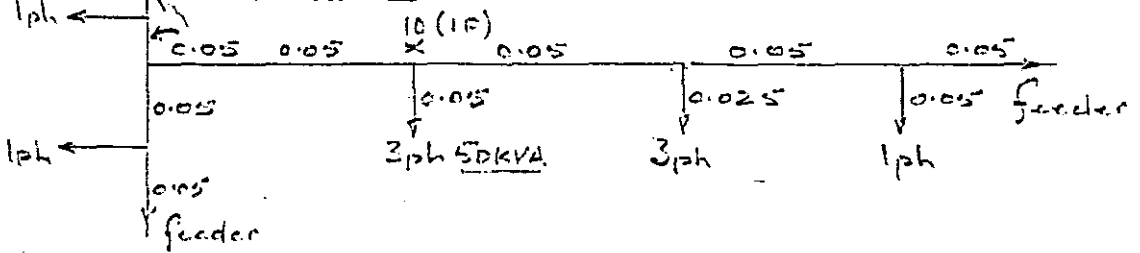
Simultaneity can be given those faults within each group in the same manner as that given to case 10 that follows. Therefore a single indirect lightning stroke links the fuse faults in each group, but probably not between the groups.

The duration of the storm is likely to be less than one hour in spite of the log entry of faults. This is based on the high number of faults (46) which generally indicates an electric storm of high intensity and these are characterised by a relatively short duration.

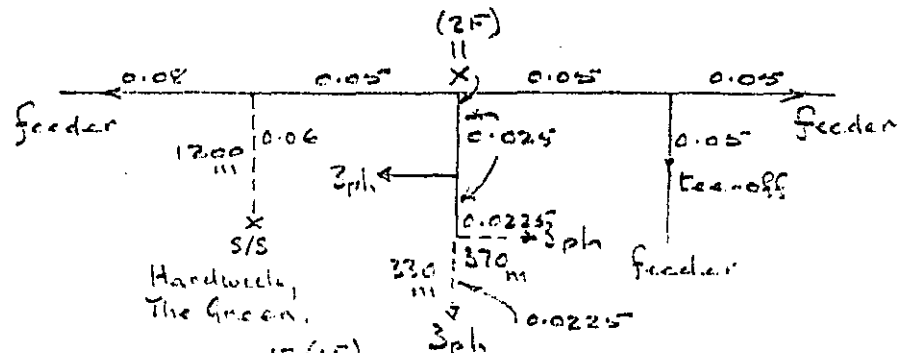
REF 9



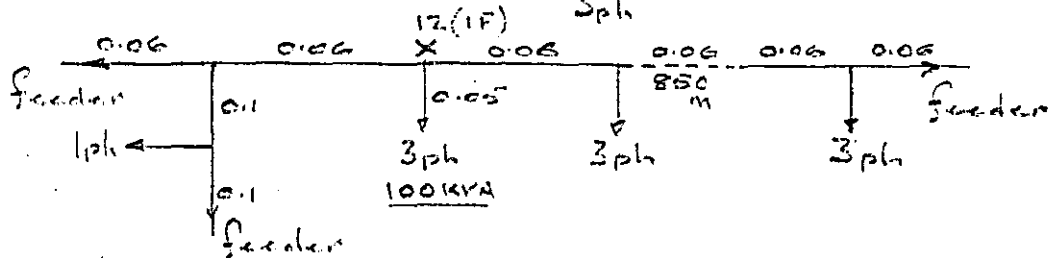
REF 10



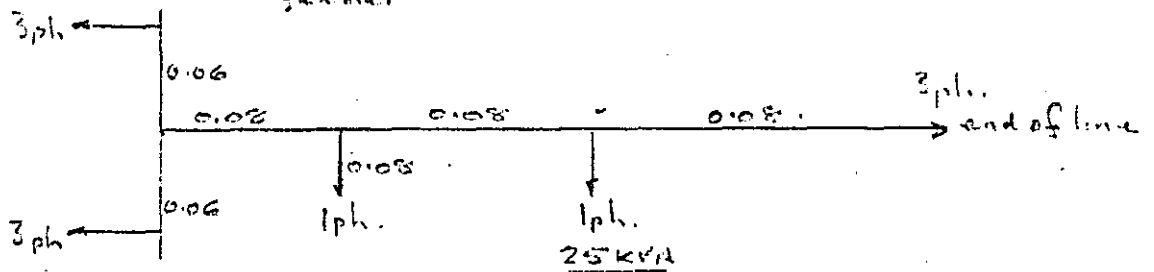
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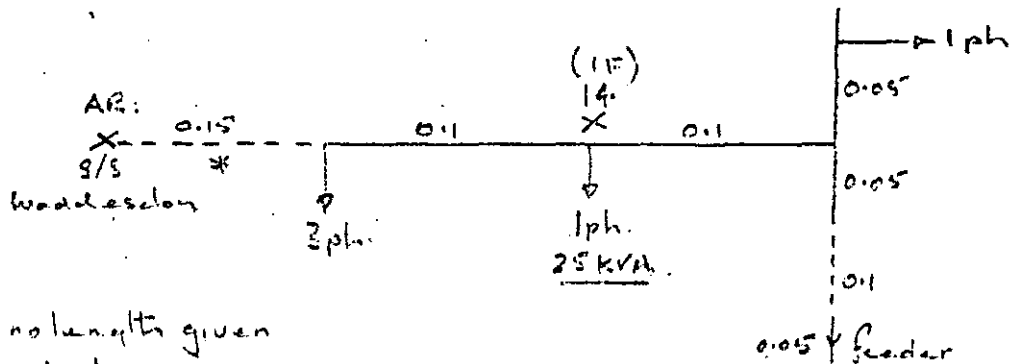
REF 12



REF 13

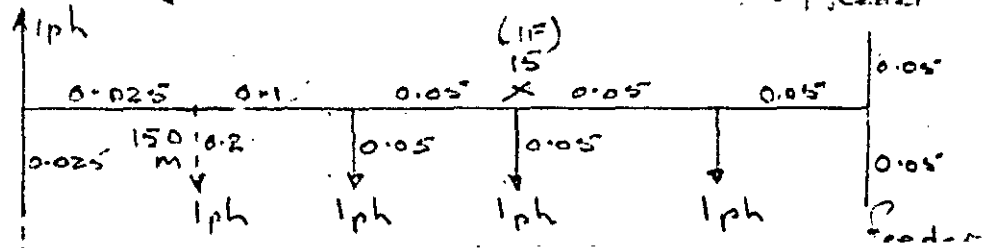


REF 14

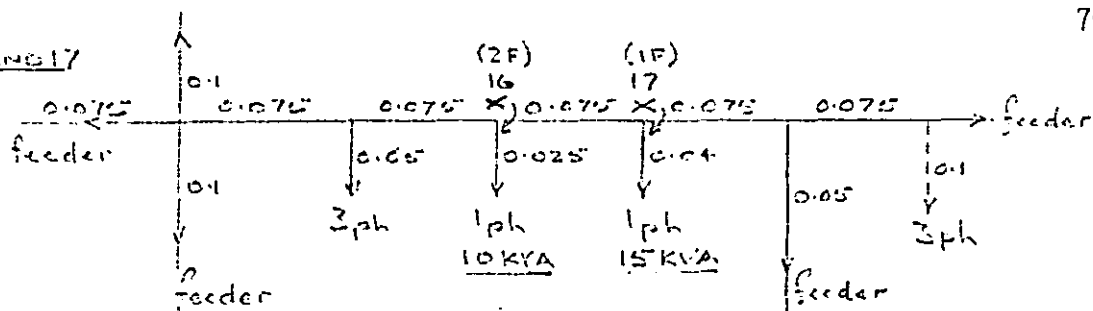


* no length given

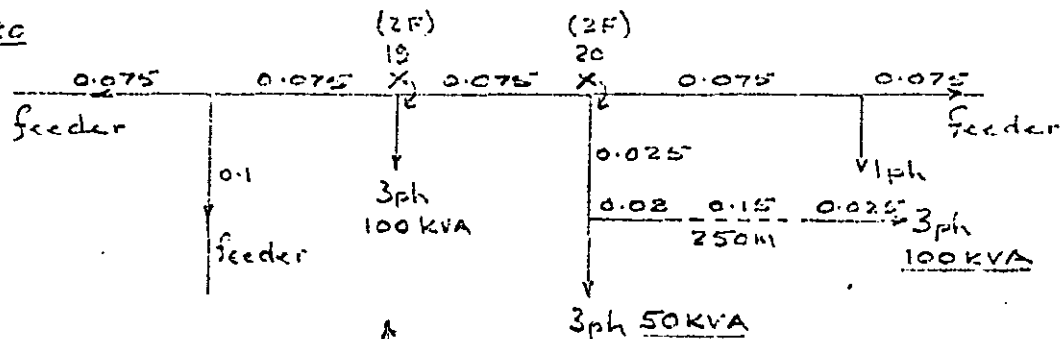
REF 15



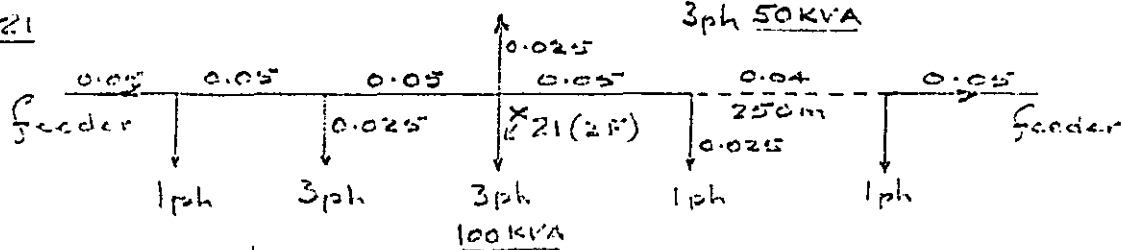
REF 16 AND 17



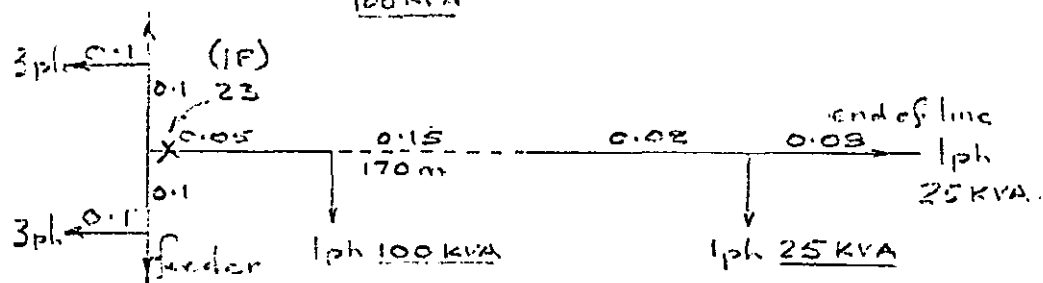
REF 19 AND 20



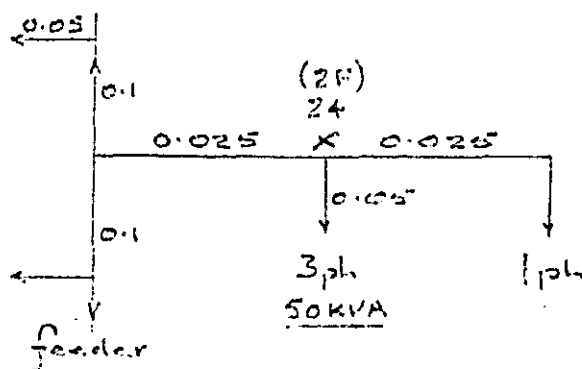
Ref 21



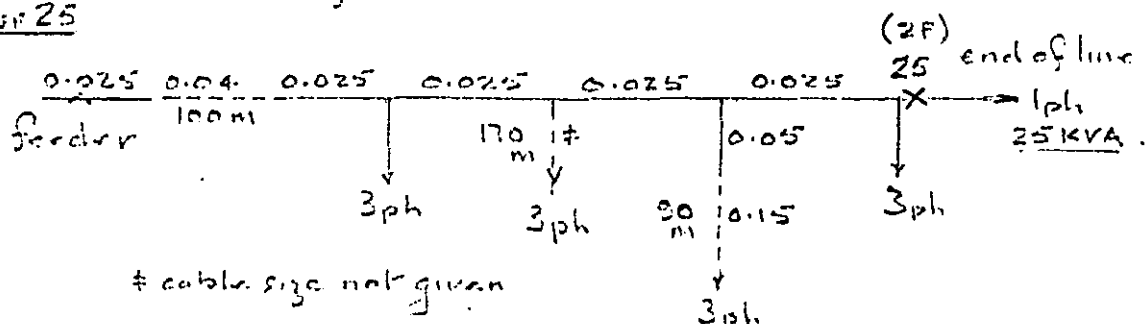
Ref 22



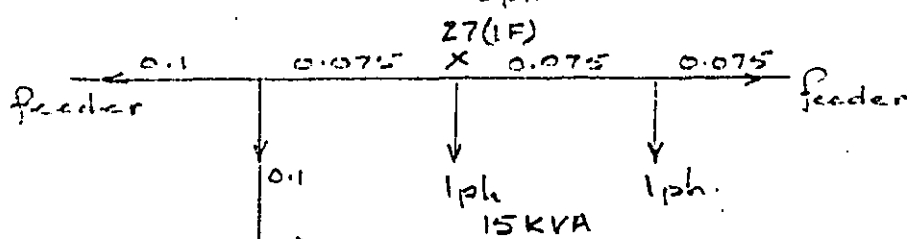
Ref 24



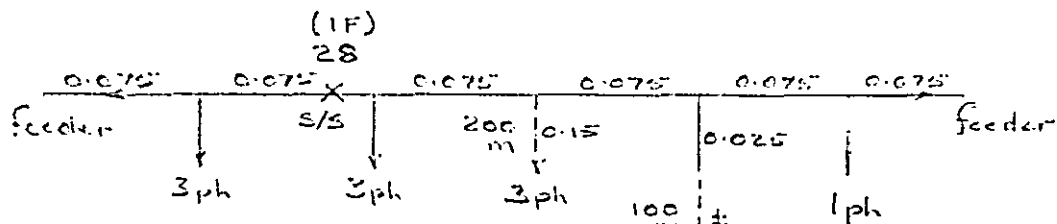
Ref 25



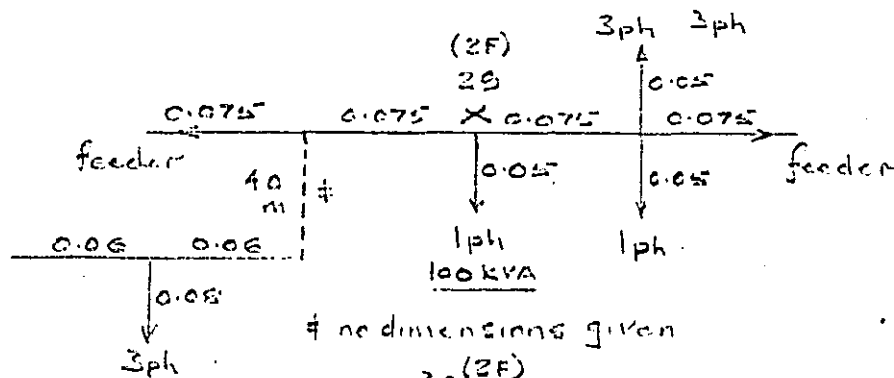
Ref 27



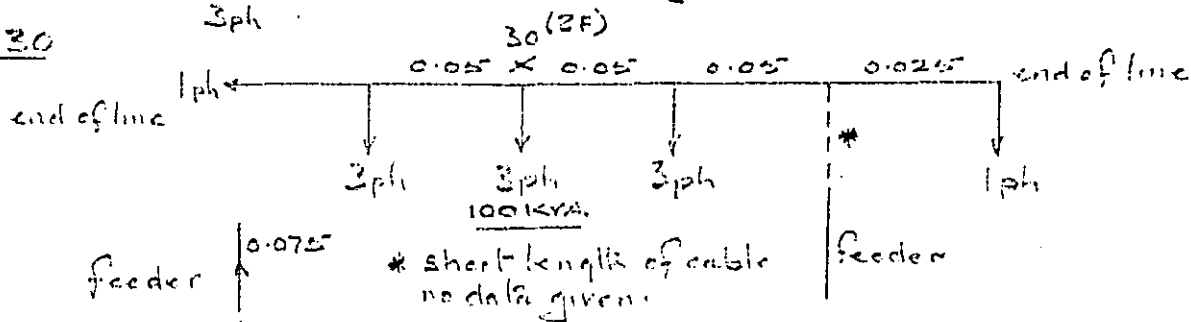
REF 28



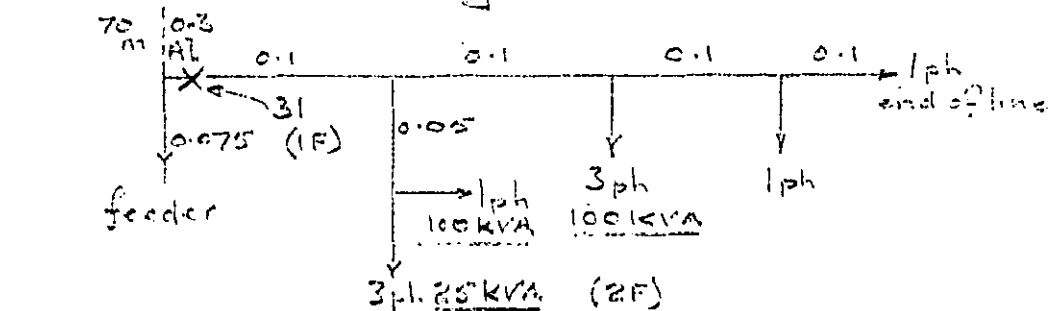
REF 29



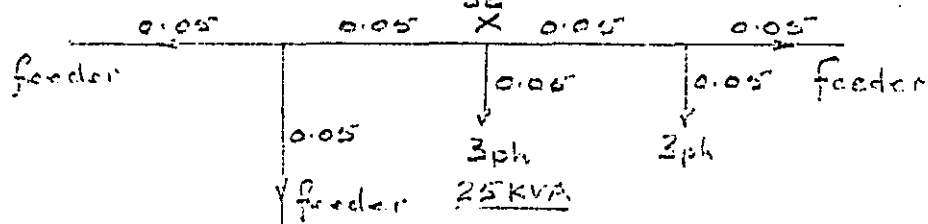
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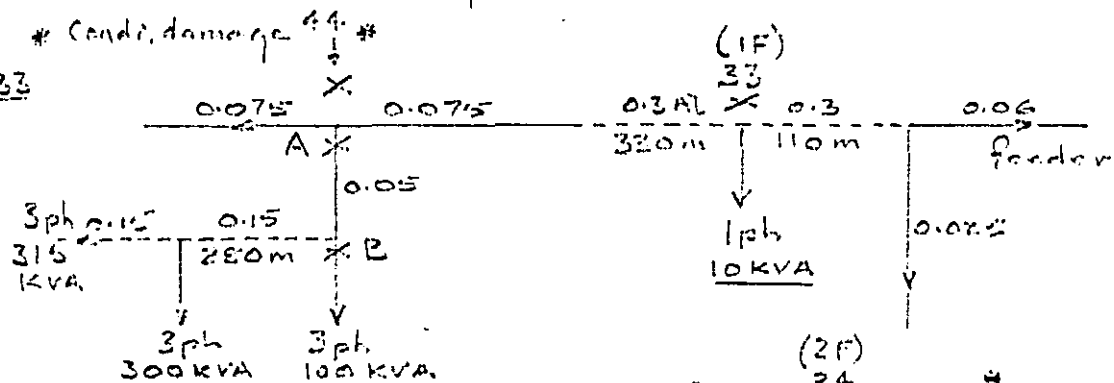
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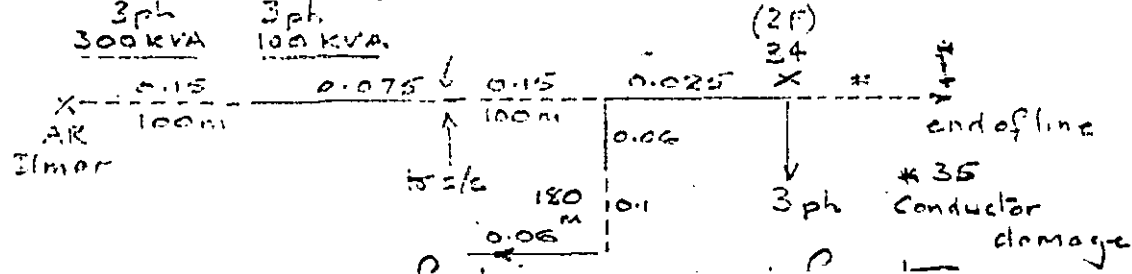
REF 32



REF 33



REF 34



Case 10.Date 4.7.71.Report data.

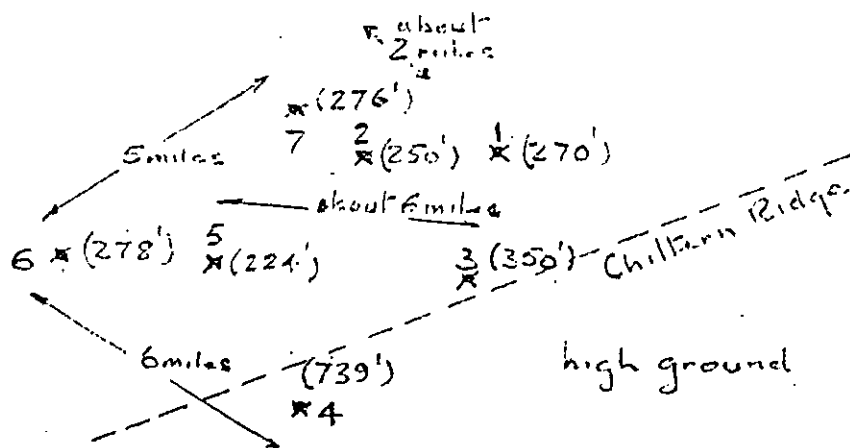
1	Marsh Farm - Sidney Farm	1940	2F	H14	2340	f
2	Aston Mullins	"	2F	"	2245	c
3	Brookside Farm, Kimble	"	1F	"	2300	a
4	Harpers Farm spur, Bledlow Ridge	"	2F	H21	2300	a
5	Park Grange Farm, Thame	"	1F	H19	2150	a
6	Moreton	"	2F	H13	2110	c
7	Hewden Farm, Haddenham spur	*	"	1F	"	1407 c
8	Buckingham Road, Waddesdon	1943	INS	H1/2	2212	

* Repeat fault.

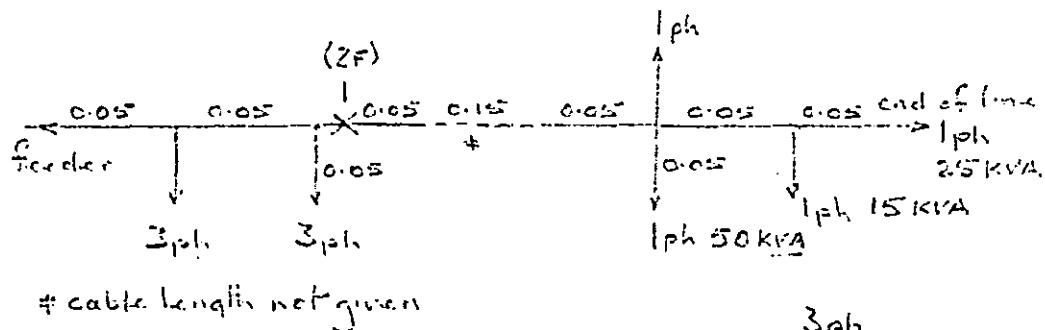
References 1 to 7 are located in the S.W. of the study area and connected to isolated electrical circuits. The outages are able to be linked by their geographical position such that, for simultaneous fuse operation in, all cases appears to be due to a single lightning discharge initiating travelling waves leading to the subsequent flashover of rod-gaps.

Reference 8 is discounted since it is too far away to be included in the response. The disposition and altitude of faults 1 to 7 is shown below.

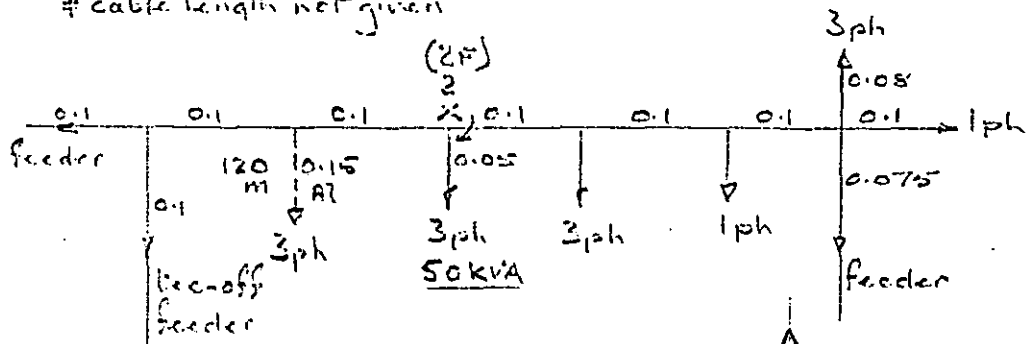
A good example of simultaneous transient faults associated with an indirect lightning stroke. Also of interest is that only two of the basic circuit topologies are involved.



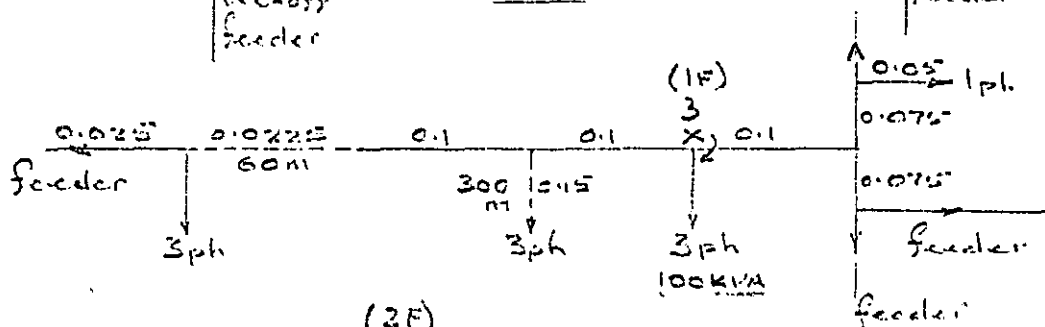
REF 1



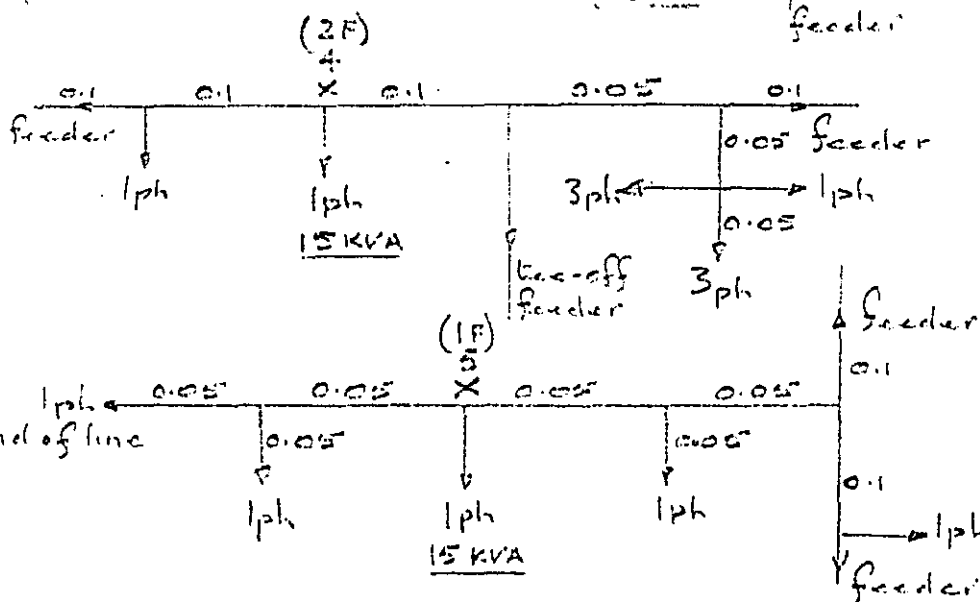
REF 2



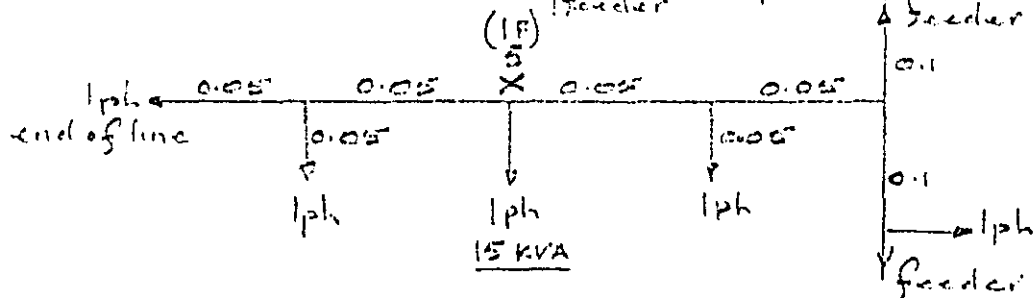
REF 3



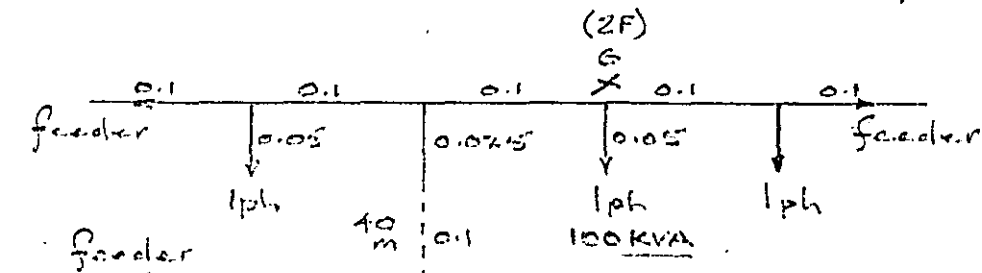
REF 4



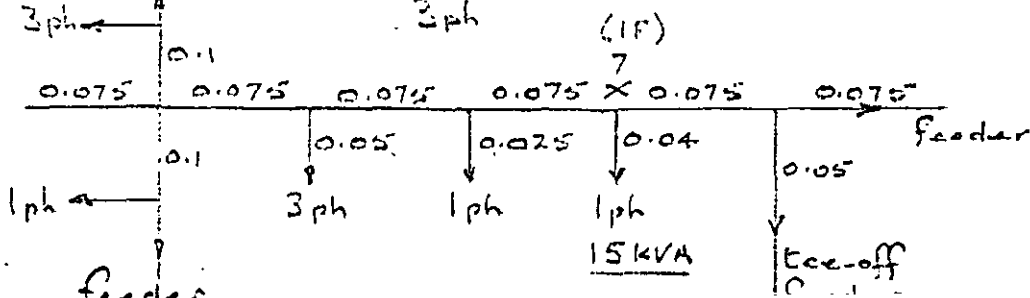
REF 5



REF 6



REF 7



Case 11.Date 31.7.71.Report data.

1	Cromwell Hill	x	0115	1F	-	0340	-
2	Chilborough Hill Cottages	*	"	2F	H13	0530	a
3	Sedrup, Stone		"	2F	H14	0507	a
4	Hinton		"	2F	H20	1500	a
5	Bottle and Glass, Dinton		"	1F	H13	0846	c
6	Whirlbush Farm, Kingsey		"	1F	H13	0853	a
7	Bumper Farm, Ilmer	*	"	2F	H20	0918	c/g
8	Bledlow Crossroads feeder		"	2F	H20	0940	c
9	Penn Farm, Towersey		"	1F	H19	1030	c
10	Upper Westcott - Brill Village feeder		0130	AR	H1	0555	
11	Twitchett Farm, Ham Green, Waddesdon		"	2F	H1	-	c
12	Grubbins Lane spur		"	2F	H22	1550	a
13	Risborough Road, Stoke Mandeville	*	"	1F	H15	0830	f
14	Weston Mead, Aylesbury		"	1F	H3	1710	d
15	Buckland Common, Cholesbury		"	CAB	H15	0430	
16	Dancers End Pumping Station	e	"	SW	H9	-	
17	Longcroft spur		"	1F	H9	2000	a
18	New Road, Aylesbury	*	"	2F	H3	1730	b
19	Long Marston		"	2F	H3	1230	f
20	Richmond Road, Aston Clinton	*	"	AR	H9	0430	

* Repeat fault location or circuit

x Not found

e Classed as switch fault but actually a C.T. failure.

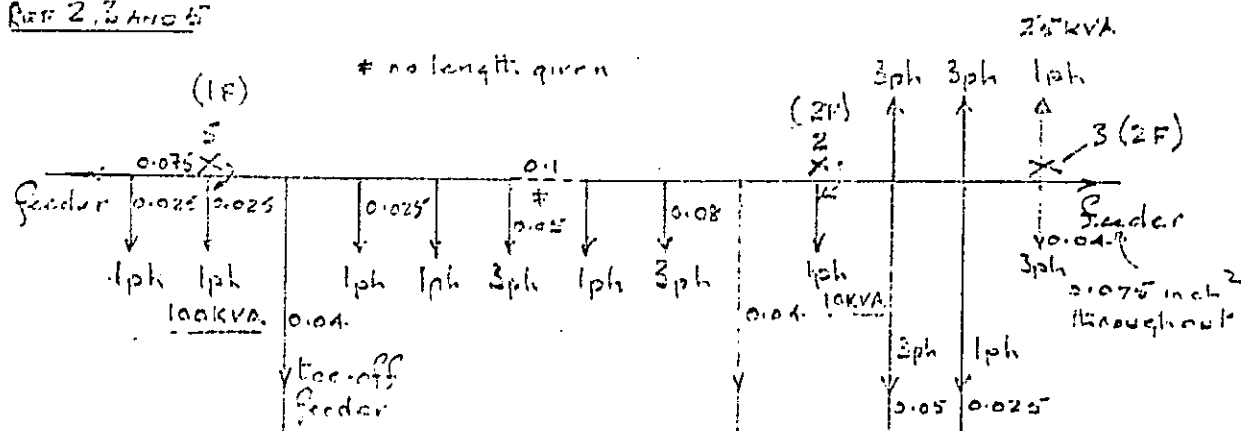
Two sets of records separated in time by 15 minutes. In this case, the two periods are also separated by location. The first set at 0115 hrs. are all fuse faults and are distributed in the west of the region

and have some common circuit connections. This covers an area of about 5 miles by 3 miles on a N.E. axis, in what is principally flat country. For the second set at 0130 hrs. this storm has shifted to the east by only a few miles, the axis now turning in a N.W. direction.

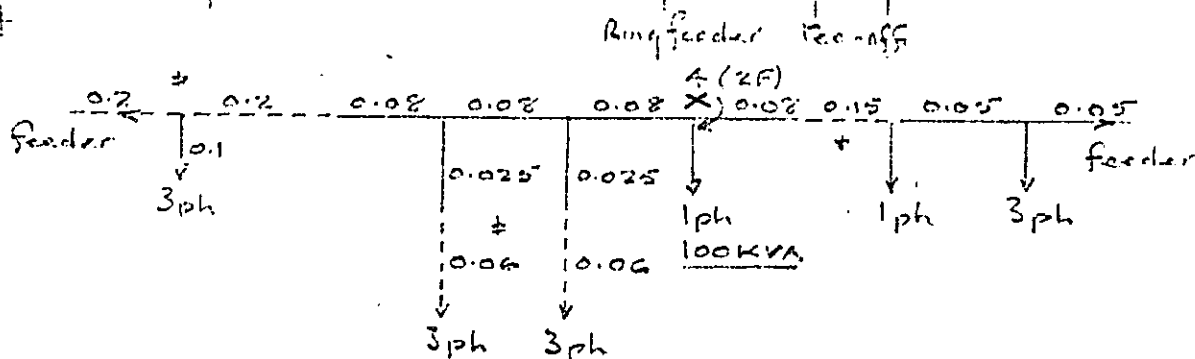
It is noted that the same feeder was influenced on 15.6.69 when the next spur load (Westcott W.T. station) to the present fault was affected. This was also a fuse fault. Again, the second group of faults are in the Plain of Aylesbury (with the exception of the Cholesbury outage) and consistent with single excitation as with the first group, the faulted area being about the same. However, the second group contains two persistent faults but both are consistent with overvoltages of a moderate level which could be magnified by propagation effects and by a prestrike component. Both of these faults are on separate circuits and quite independent of the transient faults in this group.

It is assumed that because both sets of faults are able to be grouped for topographical as well as time reasons, they are the results of single indirect stroke excitations.

Ref 2, 3 and 4

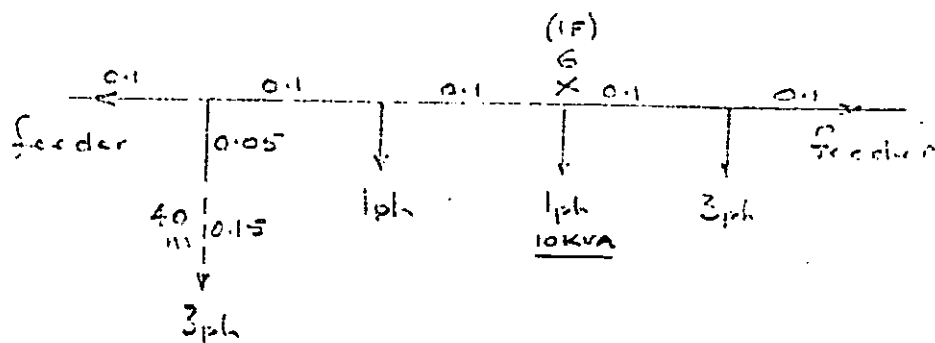


Ref 4

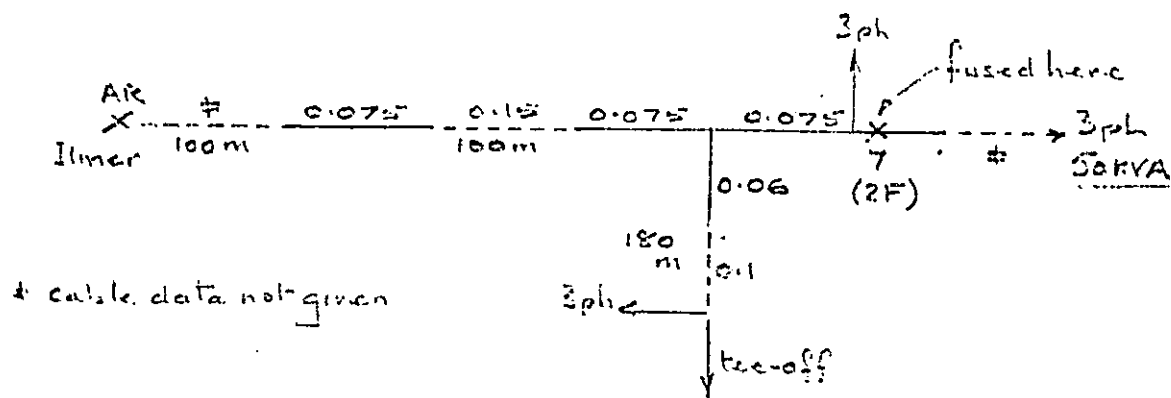


no lengths given to any of the cable sections.

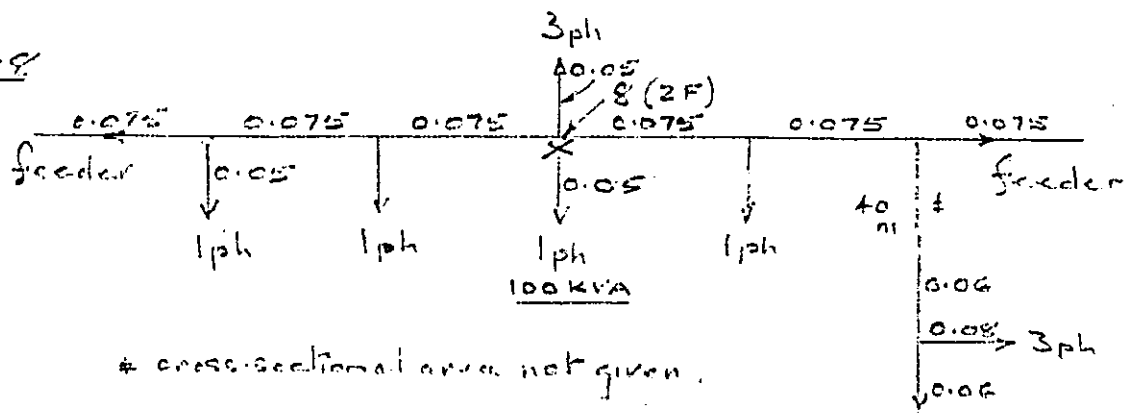
REF 6



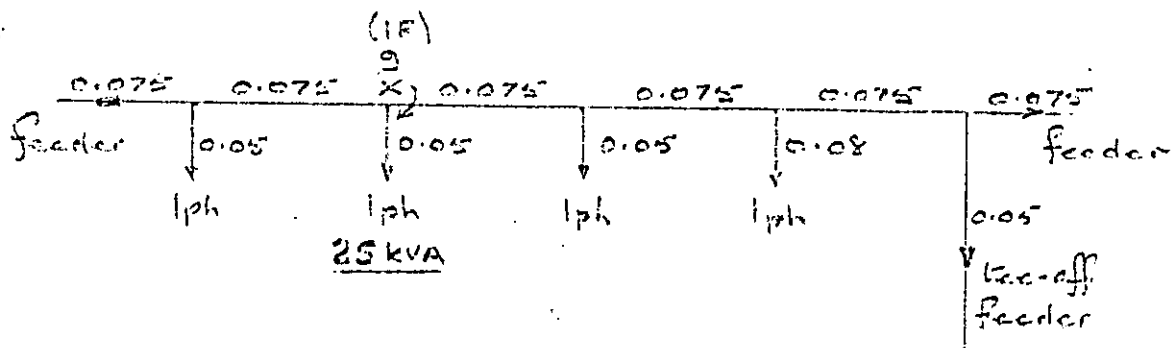
REF 7



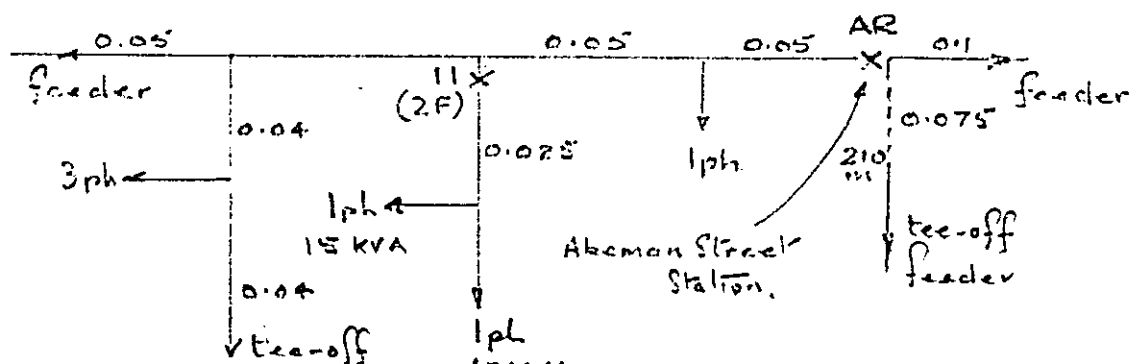
REF 8



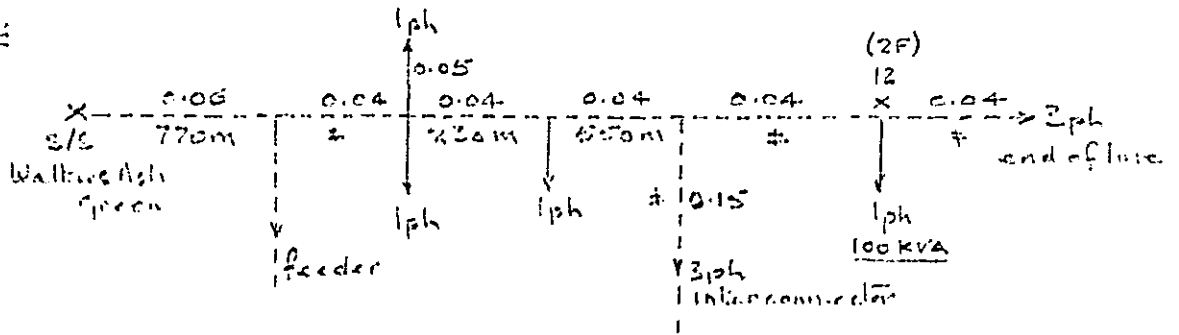
REF 9



REF 11

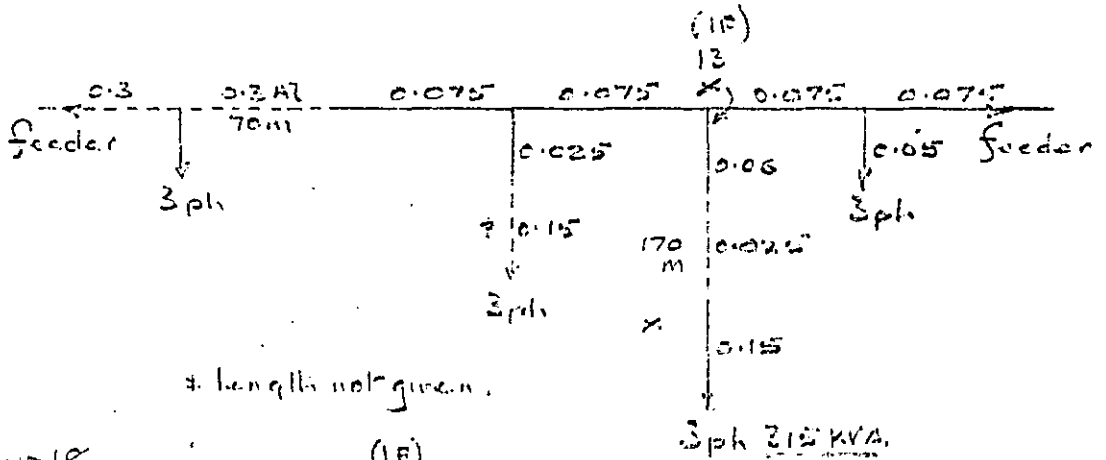


REF 12



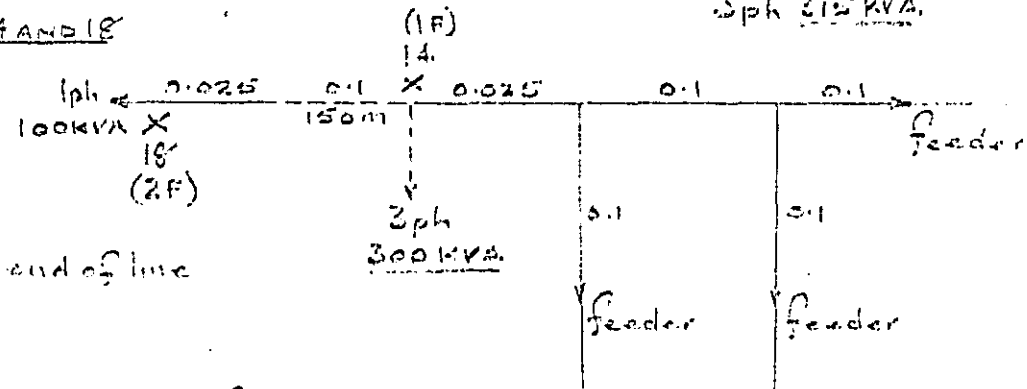
* distance not given.

REF 13

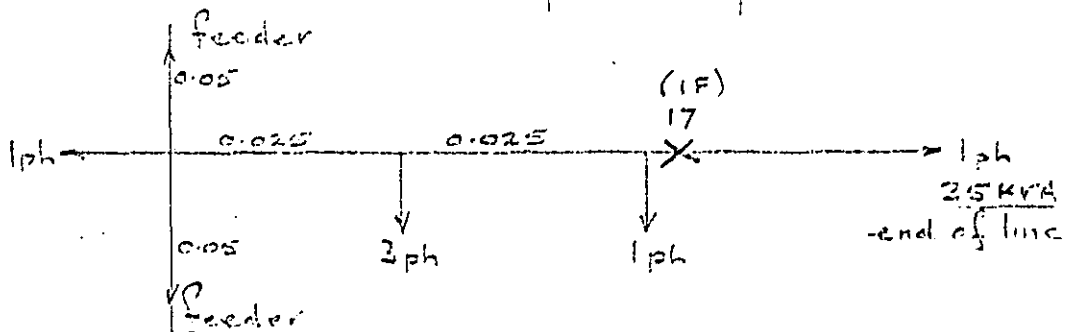


* length not given.

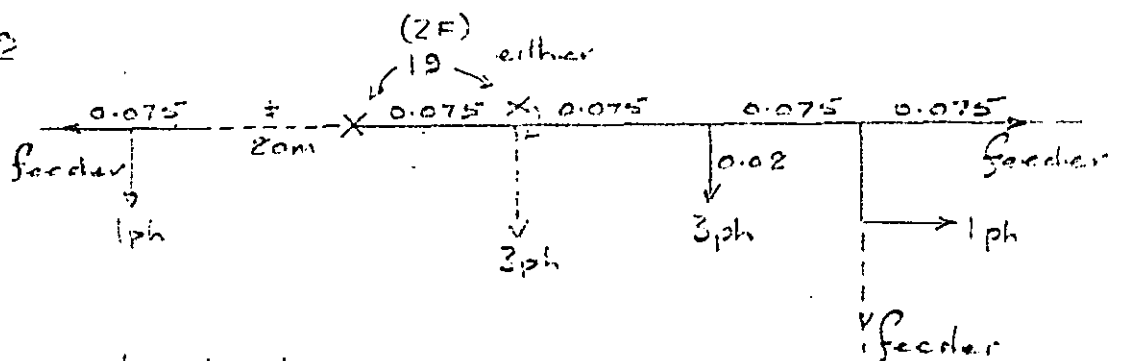
REF 14 AND 18



REF 17



REF 12



* length not given.

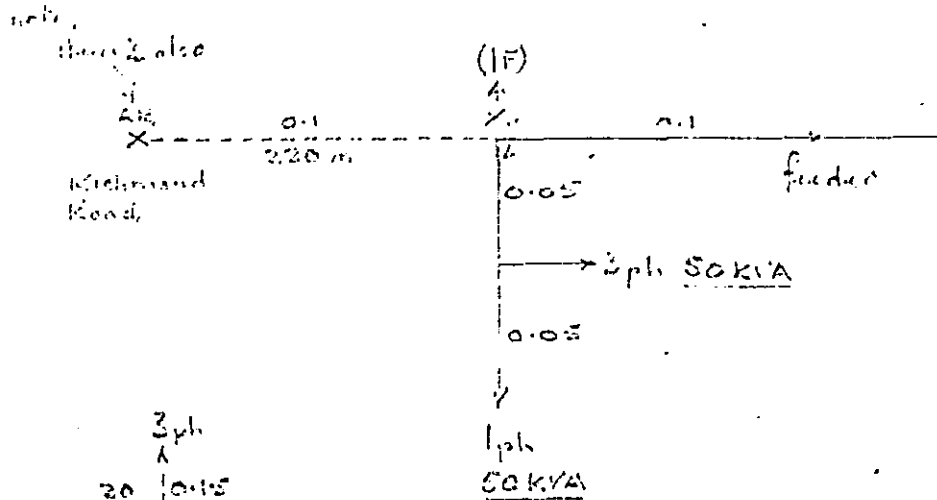
Case 12.Date 19.8.71.Report data.

1	Quainton s/s. Waddesdon	*	0037	AR	H1	0345	
2	Looseley Row		0100	SW	H21	0334	
3	Richmond Road, Aston Clinton	*	0110	AR	H9	0158	
4	Broughton Village spur		0110	1F	H9	1058	c
5	"Lord Nelson", Winchmore Hill		0230	1F	H23	1030	b
6	Chinnor Hill spur	*	0310	2F	H20	0615	
7	Quainton Road spur		0350	2F	H20	0615	c
8	North Weston spur		0410	2F	H13	0830	c
9	Buckingham Road, Waddesdon	*	0452	AR	H1	0624	

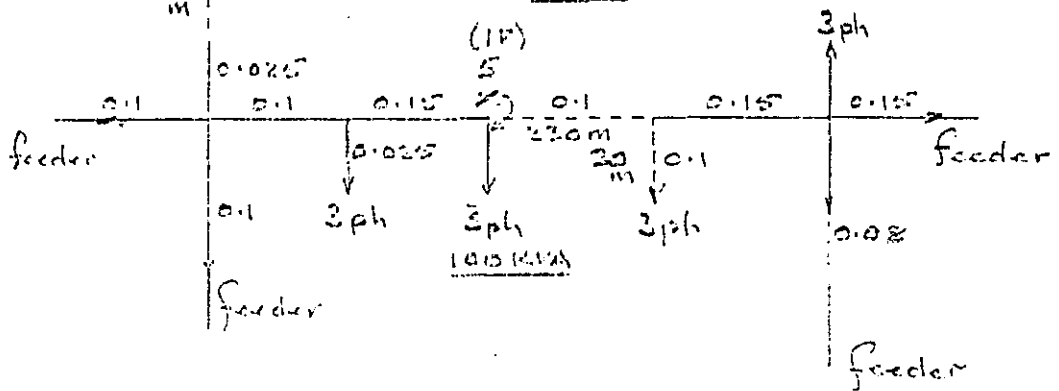
* Repeat fault location or circuit.

There is little evidence of a topographical link between faults with the wide variation in the fault entry times and the scattered locations. However, it is likely that the repeat areas have some such connection. References 3 and 4 are connected to the same feeder and presumably, since they are recorded at the same time, have succumbed to a nearby ground stroke. All other outages therefore appear as the direct action to separate ground strokes over the storm period. It is noted that a 3-fuse fault is shown (in isolation) but there is no entry for related permanent damage around the same time on this day. The storm intensity is seen to be moderate since only one persistent fault is recorded, and as this refers to switchgear, the actual damage here could be quite slight.

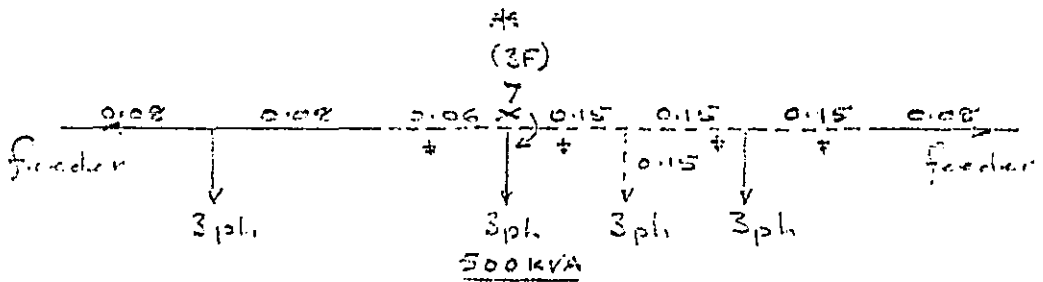
REF 4.



REF 5



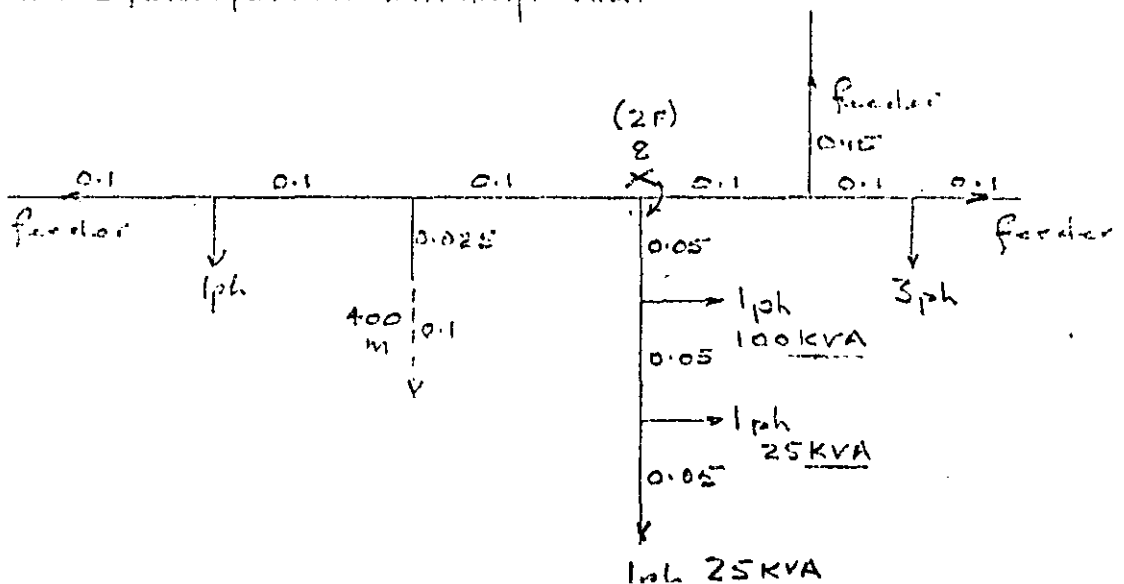
REF 7



† no lengths given to the cable sections.

* note 3 feeders operational and large loads.

REF 8



Case 13.Date 11.4.72.Report data.

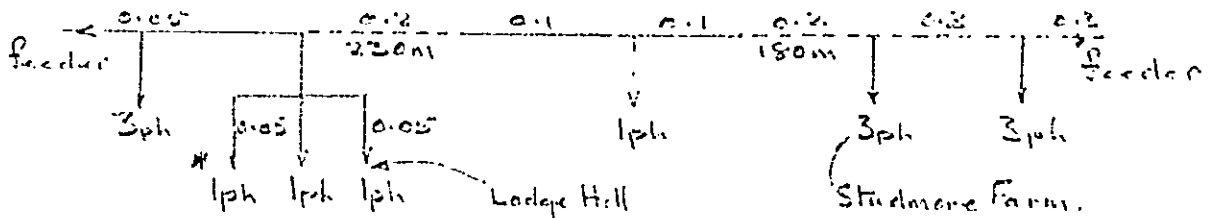
1	Tring Flour Mill	*	1655	1F	H4	1725	d
2	Tring Sewage Works	"		1F	H4	1738	c
3	Bulbourne, Tring	"		2F	H4	1806	g
4	Kings Ash		1700	1F	H10	2025	b
5	Highwood Bottom - Kingswood Farm		1800	1F	H22	1950	c
6	Lodge Hill, Molins	"		CON	H21	2136	
7	Studmore Farm, Bledlow Ridge	"		TR	H21	-	
8	Lodge Farm	"		CON	H21	-	
9	Rose and Crown spur, Sunderton	"		1F	H21	2250	c
10	Saunderton Lee spur	"		1F	H21	2308	c
11	Dormers	"		2F	H18	-	c

* Repeat fault location or circuit.

A survey of the list of faults shows that this storm is different in several respects to the previous case. 25% of the faults are classified as persistent. Due to the limited number of outages occurring in the time, it is easy to correlate most of them with specific areas according to their logged times. Thus, topographically, 1, 2 and 3 are related, and similarly 5 to 10 occurring simultaneously (as recorded) are all in the same area within 2 or 3 miles of each other on the higher ground of the Chiltern Hills.

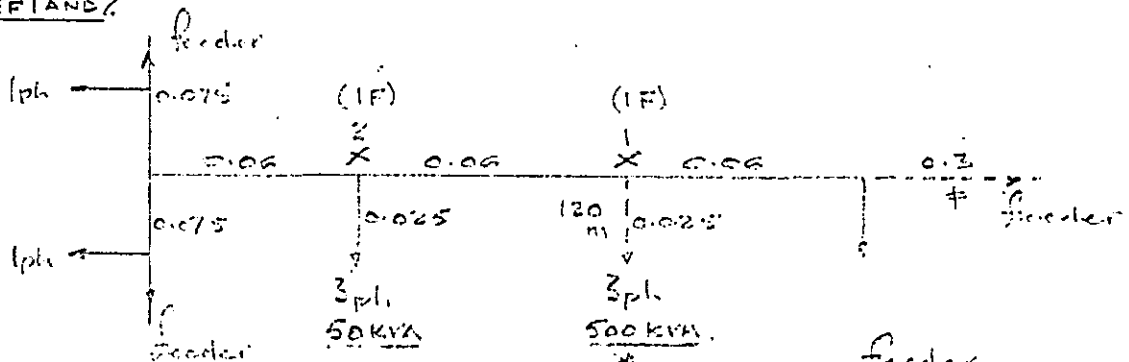
The storm is observed to move from N.E. to S.W. over a distance of about 12 miles in the recorded time of 65 minutes. The path taken is an approximate straight line following the edge of the Chiltern Hills. Probably 1, 2 and 3 are accounted for by a single ground stroke. The persistent faults 6, 7 and 8 could also be the result of the same indirect stroke as 9 and 10 because of their position. Examining the local circuit it is

likely that 6 and 8 refer to the same fault as diagram H21 does not show Lodge Farm, only Lodge Hill. The circuit including Studmore Farm is shown to be



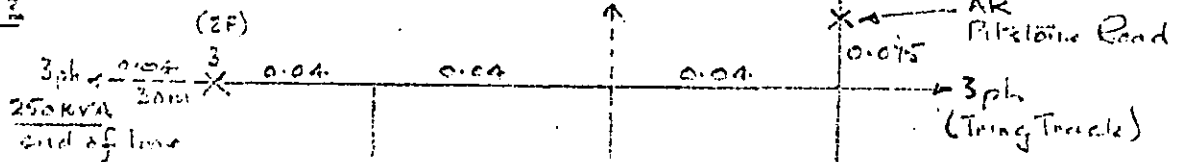
Case 4 shows a section of this circuit for reference 4. In this example, a double fuse fault occurred at the point marked *. Propagation effects may therefore have some bearing on the appearance of faults in this particular circuit. 11 is totally unrelated to the present area. It is considered that possibly a single ground stroke (indirect) could be responsible for the faults 6 to 10.

KEFLAND?

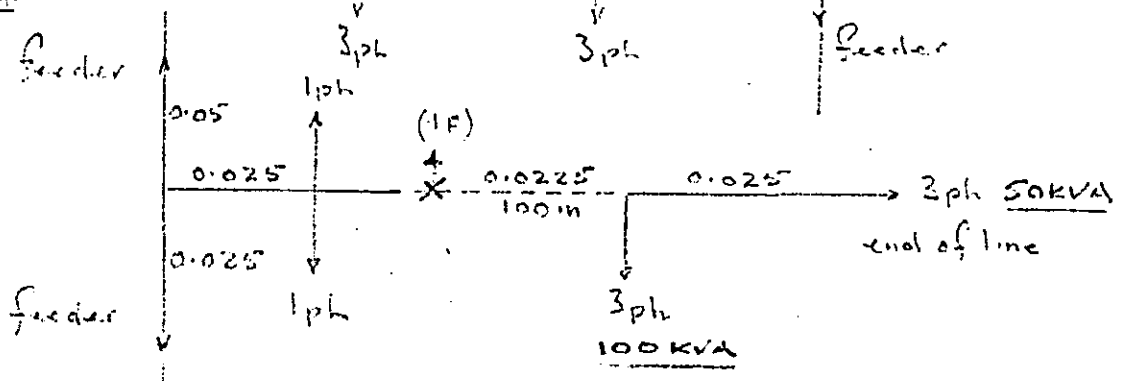


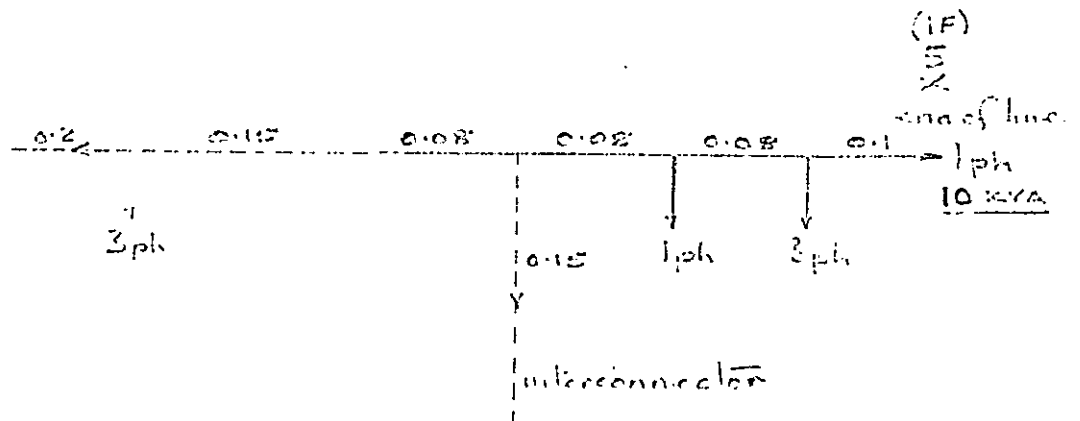
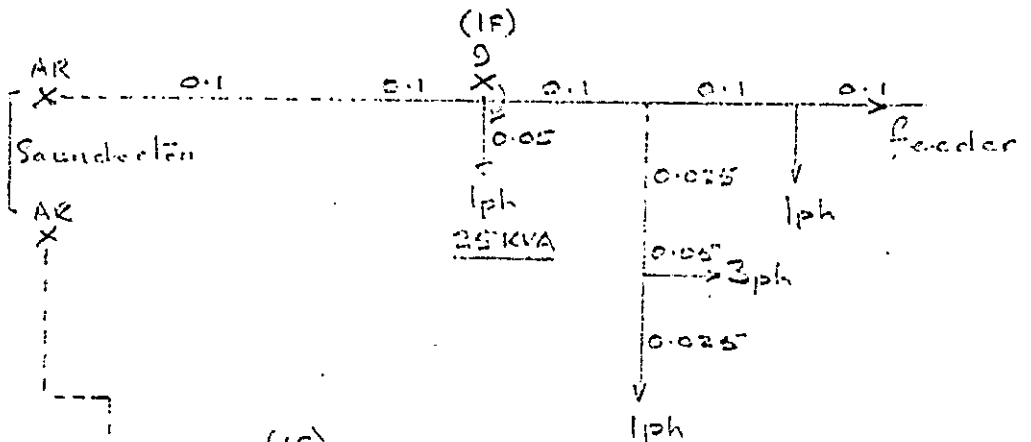
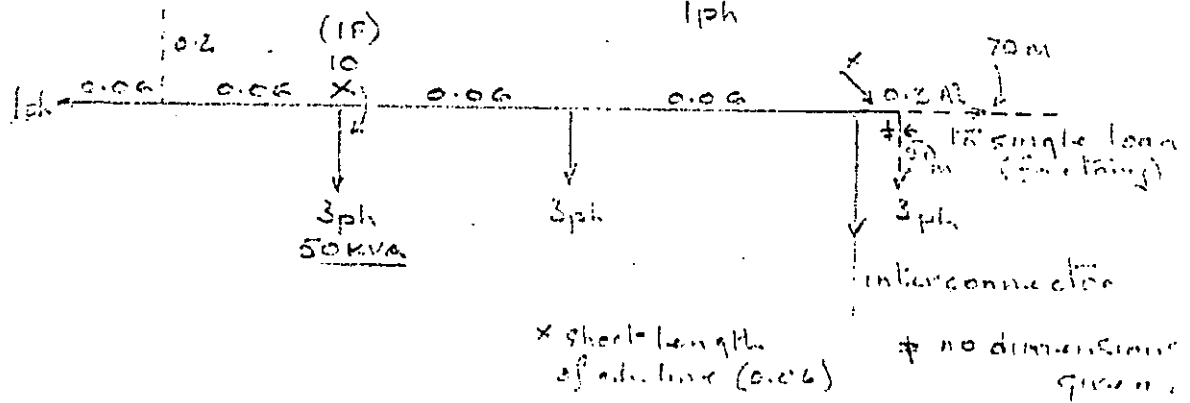
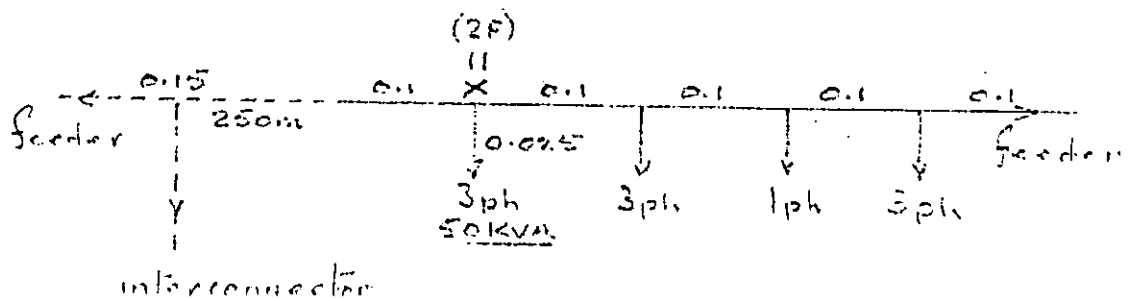
* note size of land.

REF 2



REF 4



Ref 8Ref 9Ref 10Ref 11

Case 14.Date 1.8.72.Report data.

1	Ilmer- Walldridge feeder	1557	1F	H14	1800	d
2	Lower Walldridge Farm	e "	3F	H14	-	c
3	Chinnor-Emmington spur	1603	1F	H19	1850	c
4	Wendover Primary - Ilmer	1708	AR	H15	1800	
5	North Mill, Bledlow	* 1725	1F	H20.	1905	c
6	Kingswood Farm, Spur Bottom	* 1837	1F	H22	2330	c

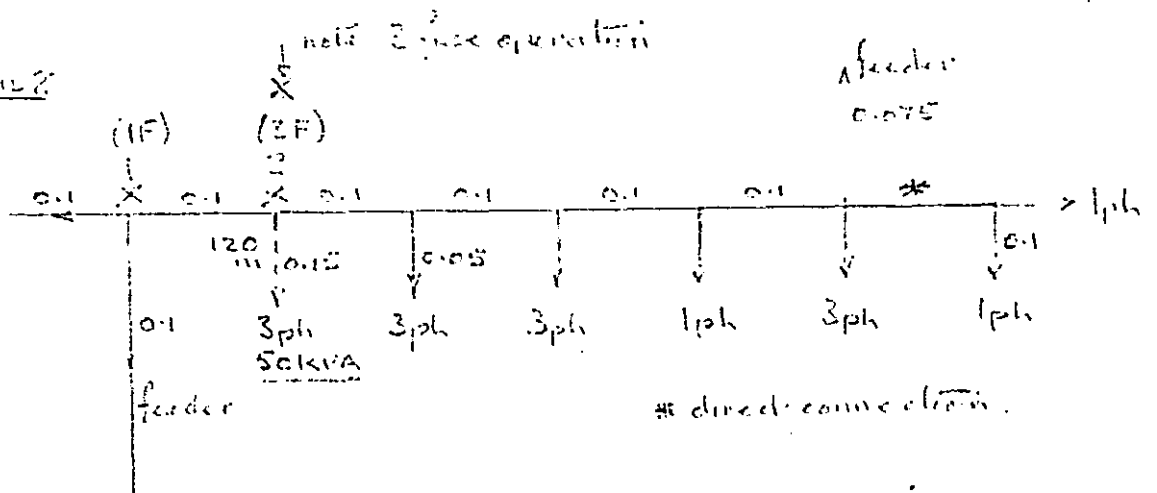
* Repeat fault location or circuit.

e Direct stroke to farmhouse reported.

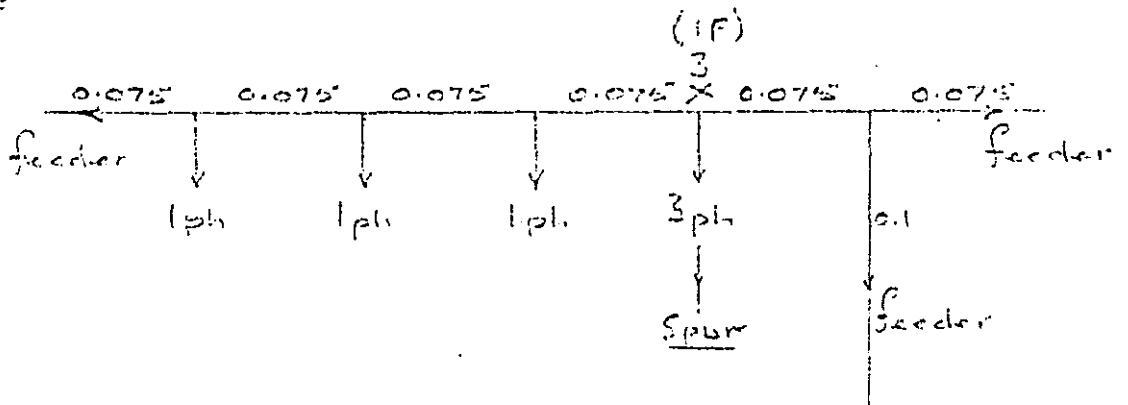
An infrequent 3 fuse fault has appeared once more (previously, case 12) but again there is no follow through reference to permanent damage. This group entry with 2 hrs. 40 minutes maximum difference of records are all transient class faults signifying that they are the likely response to moderate ground strokes. From the locations it is evident that this is a very local storm for none of the entries are separated by more than 4 miles and, in fact, 1, 2, 4 and 5 are within a circle of about one mile radius. The general fault area is the S.W. corner of the region but actually in flat country except for 6 which is just on the high ground south.

Differing times appear to suggest separate ground stroke excitation and this should be the conclusion for this case, but for the exception of 1 and 2 which are shown to be connected by entry time, location and also circuit. It is noted that the fault is an exact repetition of 5 in the previous case.

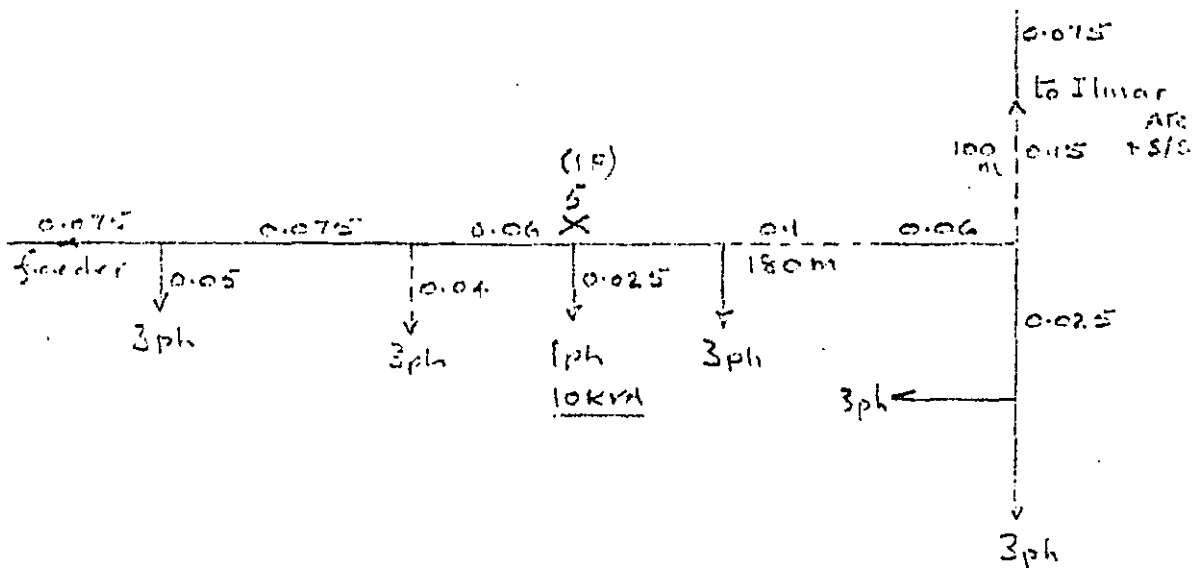
REF 1 AND 2



REF 3



REF 5



REF 6

Circuiting for Case 13, ref. 5

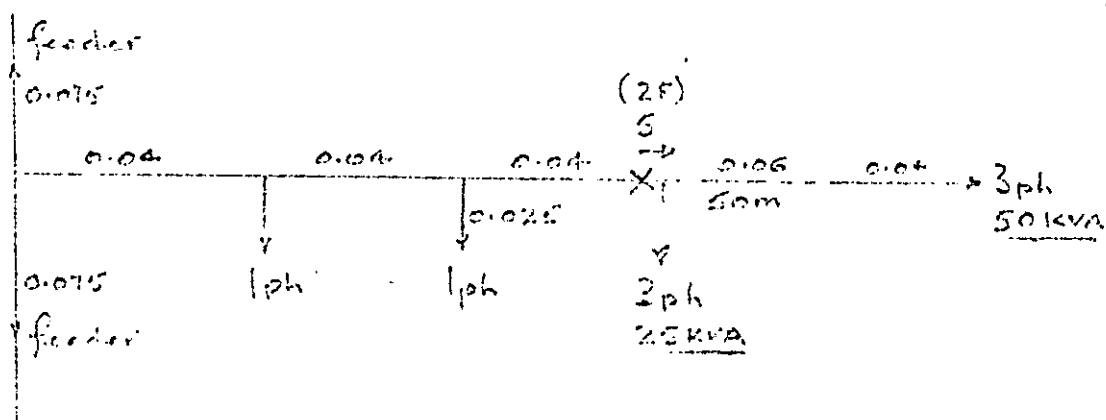
Case 15.Date 26.6.73.Report data.

1	Eastbrook Hay	0946	CAB	H6	1157
2	Pendley Manor spur	1634	CON	H4	1855
3	Cross Farm, Gadeview	1730	AR	H18	1914
4	Ashendon Feeder - Waddesdon	1736	INS	H1	0043
5	Drayton Lodge spur	* 1800	2F	H9	2335 h/d

* Repeat fault location or circuit.

The first of a series of faults involving both "Districts", i.e. Aylesbury and Hemel Hempstead, although this present case is largely concerned with the former area. The faults have a spacing of about 12 miles along a straight line, passing from high ground just into the Chiltern country through Aylesbury and beyond, where the ground is of relatively flat contour. There is seen to be no electrical connections between any of the faults, and the double fuse fault is the only one of interest.

A local electrical storm and the wide fault times extend this to about 8 hrs. but in effect is probably only about $1\frac{1}{2}$ hrs. No emphasis is put on a topographical link because of the 60% permanent damage basis.

Fig 5

Case 16.Date 27.6.73.Report Data.

1	Luckings Farm, Herts.House	1907	CON	H23	0253	
2	Meadhams Farm	1914	1F	H17	0920	a
3	Kiln Cottages	"	1F	H11	0425	c
4	Weedon Hill Spur	*	"	1F	H16	0650 c
5	Wood Lane	"	1F	H16	0301	c
6	Two Dells Cottage	"	1F	H11	0500	d
7	Commonwood	"	TR	H24	1546	
8	Keepers Lane	"	1F	H16	0920	a
9	Finch Lane	"	CAB	H24	0715	
10	Darlington	* 1915	1F	H17	0940	c
11	Bourne End	1917	AR	H11	2145	
12	Nettleden Lodge	"	1F	H5	2300	a
13	Palmers s/s	"	1F	H6	2335	
14	Pedley Hill Farm	"	1F	H5	0220	a
15	Road Farm, Gt.Missenden	1926	AR	H16	2131	
16	Hyde Lane, Gt.Missenden	"	CAB	H16	0205	
17	Shardloes	1930	1F	H23	0950	h
18	Gaddesden	"	1F	H5	0955	a
19	Barnwood	"	1F	H10	1030	c
20	Strawberry Hill	"	1F	H10	1130	a
21	Tylers	"	1F	H4	1205	g
22	Marshalls	e "	1F	-	1230	
23	Champneys	"	TR	H10	1715	
24	Bottom Farm, Lt. Hampden	"	1F	H22	1540	a
25	White End Park Farm	"	1F	H17	1735	b
26	Tring No. 1 s/s	1942	AR	H4	1955	

27	Tring - Aldbury Feeder	1942	FB	H4	2019	
28	Northchurch Tunnel	* 2000	1F	H4	0116	b
29	Grossmiths Poultry	"	1F	H5	0220	a
30	Haresfoot Lane	2030	CON	H11	1325	
31	Theobalds Spur	"	1F	H4	0600	c
32	Sedges Farm	"	1F	H16	1000	c
33	Frithsder Spur	"	1F	H5	1152	a
34	Game Farm - Lye Green feeder	2223	CAB	H18	0513	

e Not found

* Repeat fault location or circuit.

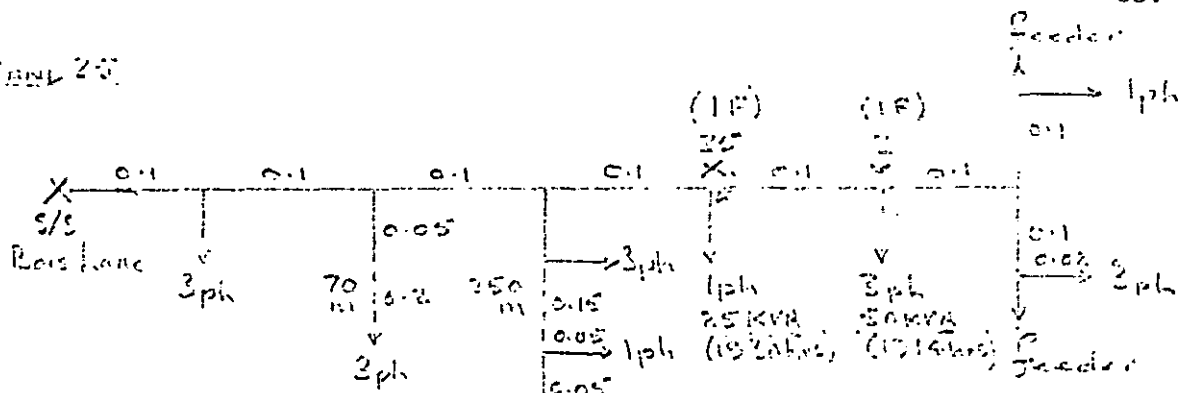
A substantial number of fuse actions (nearly 68% of total faults) all of which, surprisingly, are single fuse faults. This suggests the widespread operation of rod-gaps. There are only three references to recloser lockout but this could well be due to the absence of autoreclosers in the specific faulted circuits. The eight persistent faults show evidence of a little above average performance in giving 23.5% of the total outages.

Some fuse faults are evidently grouped with common circuits, notably those references 12, 18, 21, 31 and 33, but are not necessarily simultaneous in action as inspection of the fault entry times reveals.

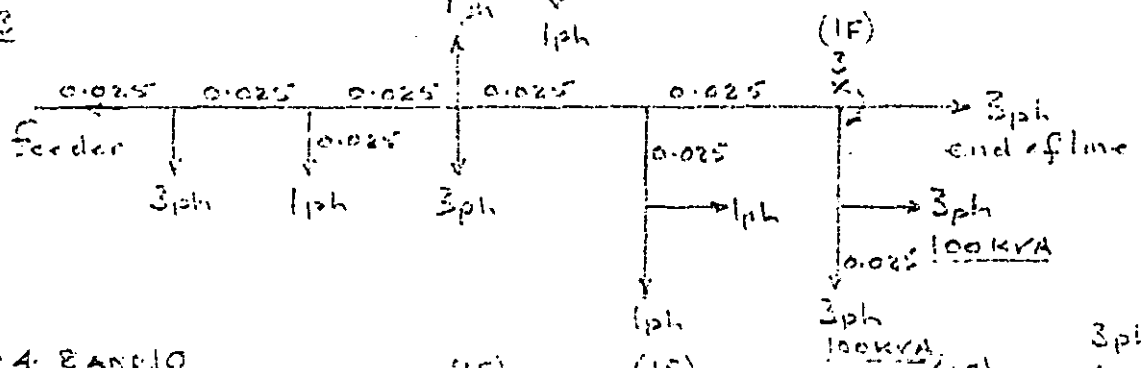
The storm period, which is logged over $3\frac{1}{2}$ hrs. is largely concentrated into $1\frac{1}{4}$ hrs. during which most of the interruptions to the supply take place. The groups of simultaneous faults occur at various times during this period and an analysis of existing topographical connections appear necessary.

It is noted that the fault locations extend on a N.E. axis of approximately 8 miles and a width of about 5 miles. The distribution of the fuse faults is shown (over) indicating the scattered nature of these actions relative to their logged times.

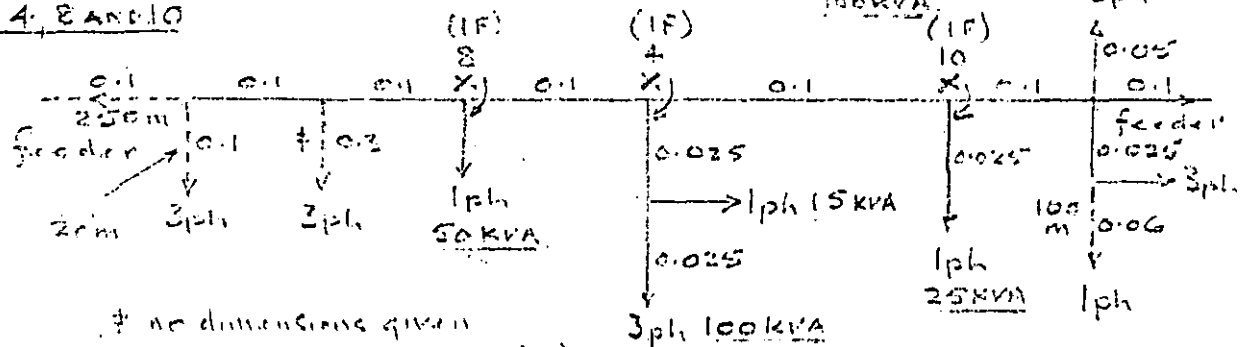
Page 2 of 2



Page 3

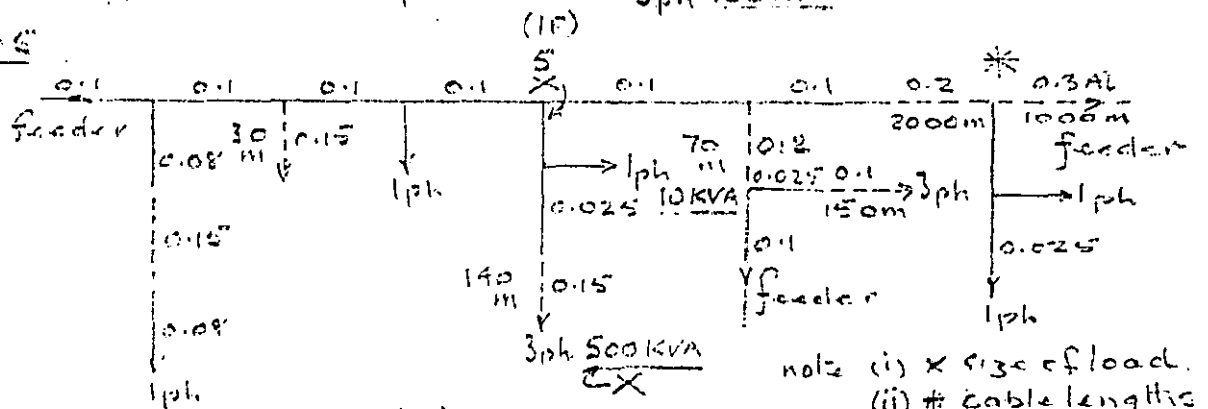


Ref 4. E And 10



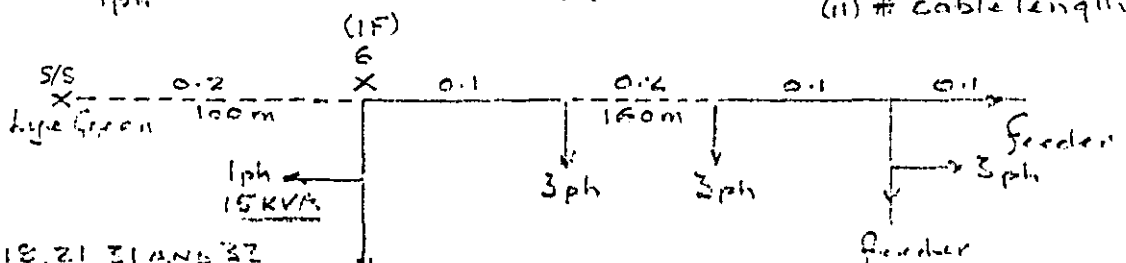
* no dimensions given

Ref 6:

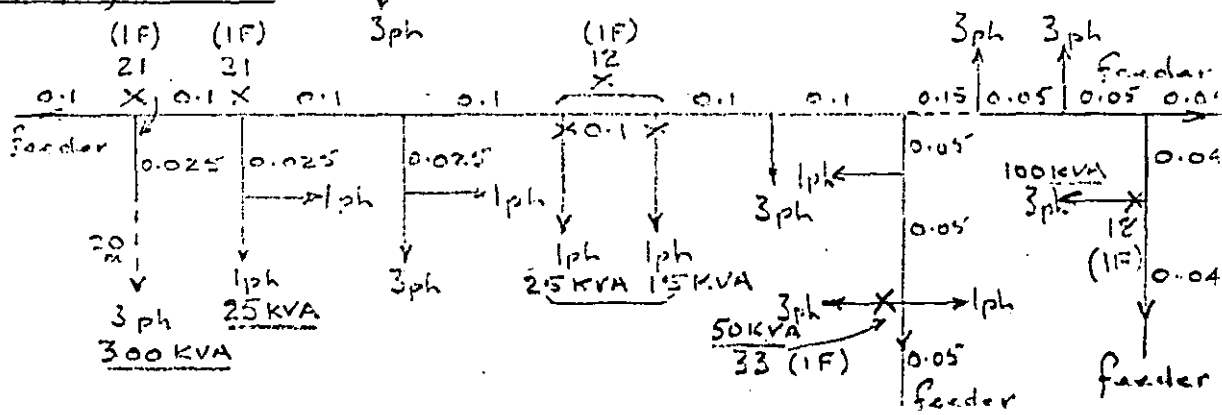


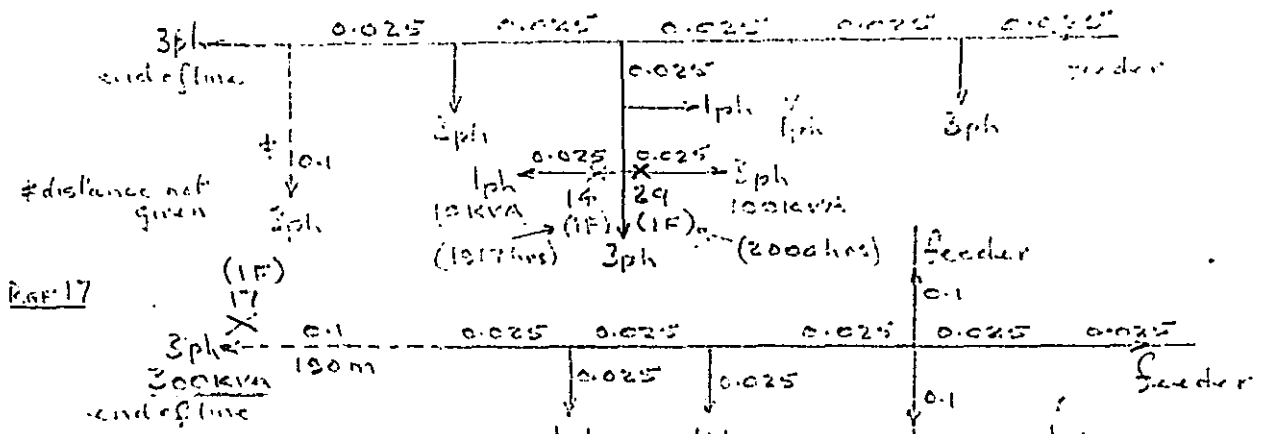
note (i) \propto size of load.
(ii) cable lengths

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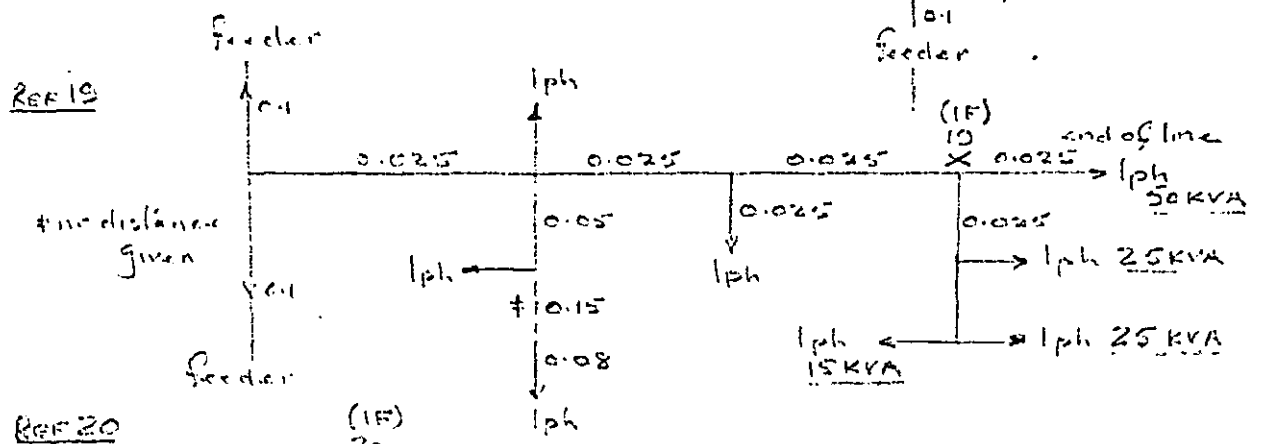


REF 12.18.21.31 AND 32

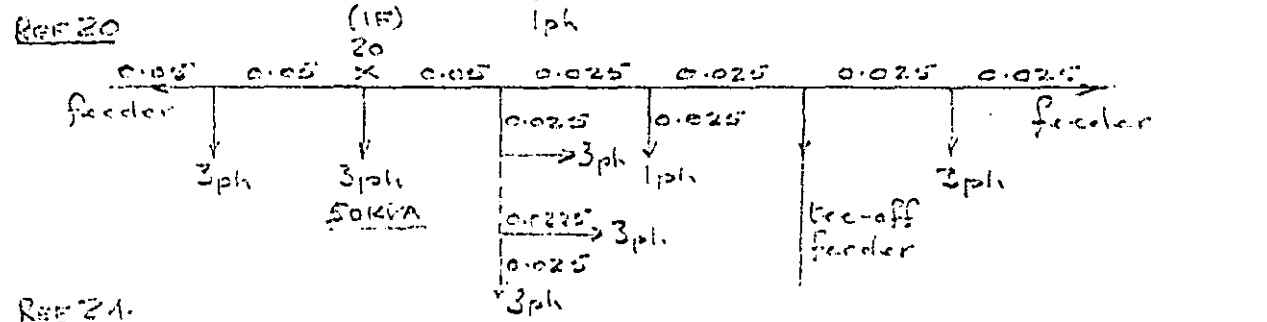




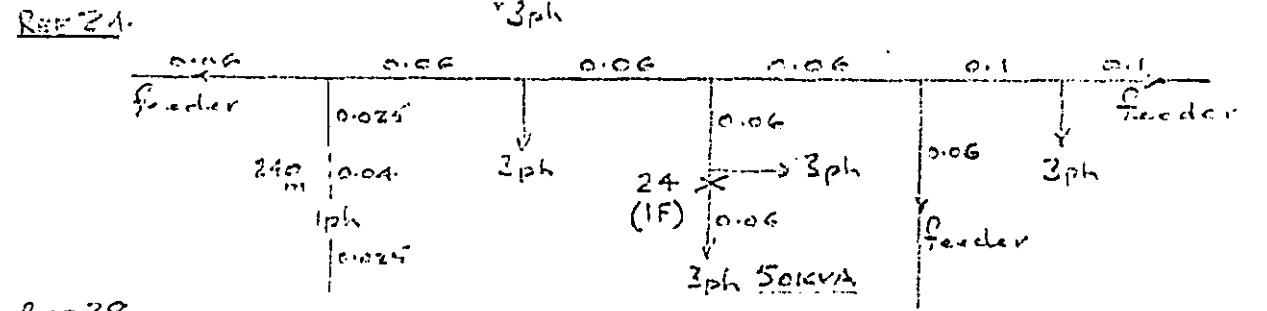
Ref-17



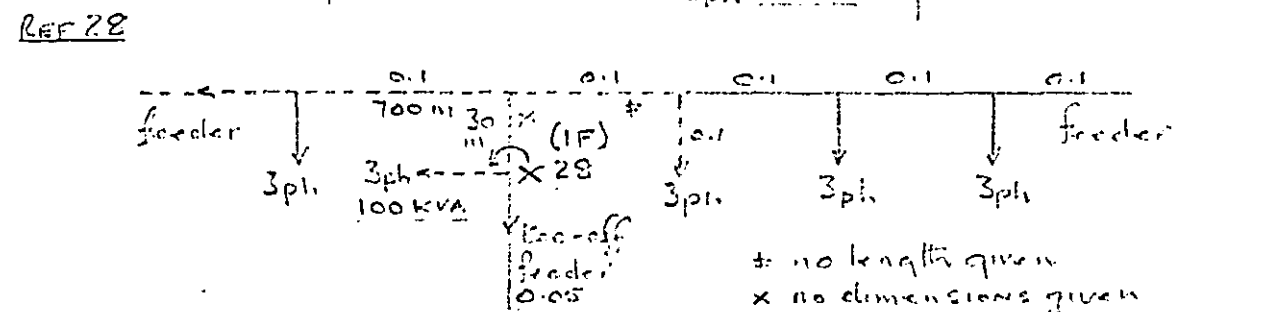
REF 19



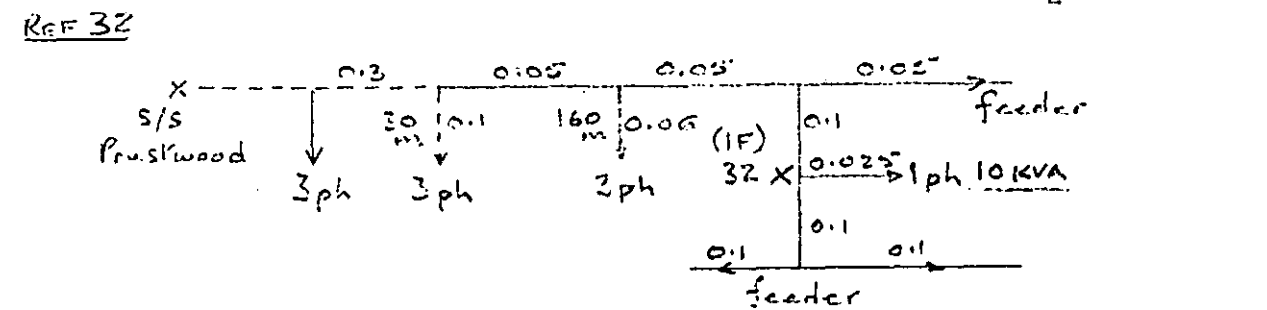
Ref 20



Ref 24.



REF 22



REF 32

Case 17.Date 6.7.73.Report Data.

1	Field Farm, Worminghall	1410	CON	H7	1522	
2	Grass Products, Worminghall	1410	CON	H7	1852	
3	Bumpers Farm, Ilmer	* 1557	2F	H20	c/g	
4	Verney Close, Tring	1948	2F	H4	1731	a
5	Tring No. 1 Aylesbury East	1648	CON	H2	1652	
6	Park Road, Tring	Ø 1650	AR	-	1820	
7	Estate Farm, Gt. Westwood	1700	1F	H24	1849	g
8	Cholesbury Common	1714	1F	H15	1957	a
9	Drummond End, Bovington	1727	2F	H12	2110	c
10	Promised Lane Farm, Looseley Row	1729	2F	H21	1914	c
11	Northchurch Tunnel	* 1733	2F	H4	1922	b
12	Great Greenstreet Farm	1800	1F	H24	1945	c
13	Grovehill Farm, Towersey	2248	1F	H19	2306	c

* Repeat fault or circuit.

Ø Not found.

From 1 to 13 a spread of faults over approximately 8 hrs. The three conductor faults are not explained further so they may be simply burnt jumpers, but can be discounted as they are strictly not transient faults. Their cause, however, may be the result of moderate propagation effects. 3 and 4 are widely separated. None of the affected fused circuits are related and it appears that there is no topographical link either.

The fuse faults are clearly the response to separate excitations provided by ground strokes and there are no electrical or topographical connections apparent. It is noted that 10 is the same circuit as fault 9, Case 13, where the latter is the adjacent spur.

Tracing

A/c

0.2

0.2

0.2

0.2

0.2

0.2

0.2

0.075

0.075

3ph

2ph

2ph

3ph

500 KVA

3ph

0.1

3ph

feeder

[* note size of load
! cable lengths not given

The diagram illustrates a power distribution system. A vertical dashed line represents a feeder, with a '3ph' load to its left and a 'Feeder' label at its base. A horizontal dashed line represents a bus, with a '3ph' load below it. A vertical dashed line labeled 'S/S' (Substation) is at the left end of the bus. A horizontal dashed line labeled '(1F)' (1st Feeder) is at the right end of the bus. The bus has a length of '0.06' and a '60m' distance to the 'S/S'. The (1F) line has a length of '0.05' and a '150m' distance to the 'S/S'. The bus is labeled '15kVA' and the (1F) line is labeled '50kVA'. The bus is also labeled 'end of line'.

Diagram illustrating a power distribution system with a main busbar and various feeders and loads.

The main busbar is divided into segments labeled 0.05, 0.05, 0.05, 0.05, and 0.05.

Key components and connections:

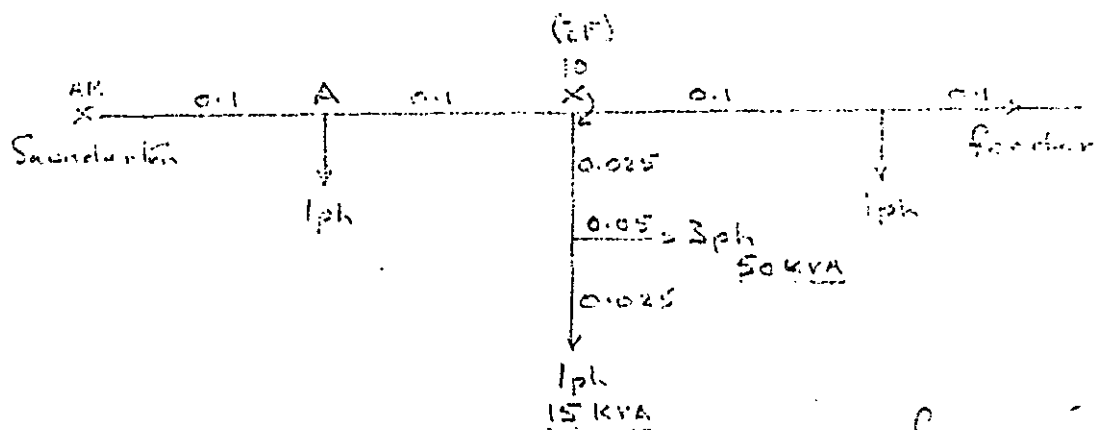
- Feeder 1:** Connected to the first 0.05 segment, labeled "feeder" and "3 ph".
- Load 1:** Connected to the busbar between the first and second 0.05 segments, labeled "100 m" and "1 ph".
- Load 2:** Connected to the busbar between the second and third 0.05 segments, labeled "25 kVA" and "3 ph 100 kVA".
- Load 3:** Connected to the busbar between the third and fourth 0.05 segments, labeled "200 m" and "1 ph".
- Feeder 2:** Connected to the last 0.05 segment, labeled "feeder" and "0.05".

The diagram is signed "S/S Bushfield" at the bottom right.

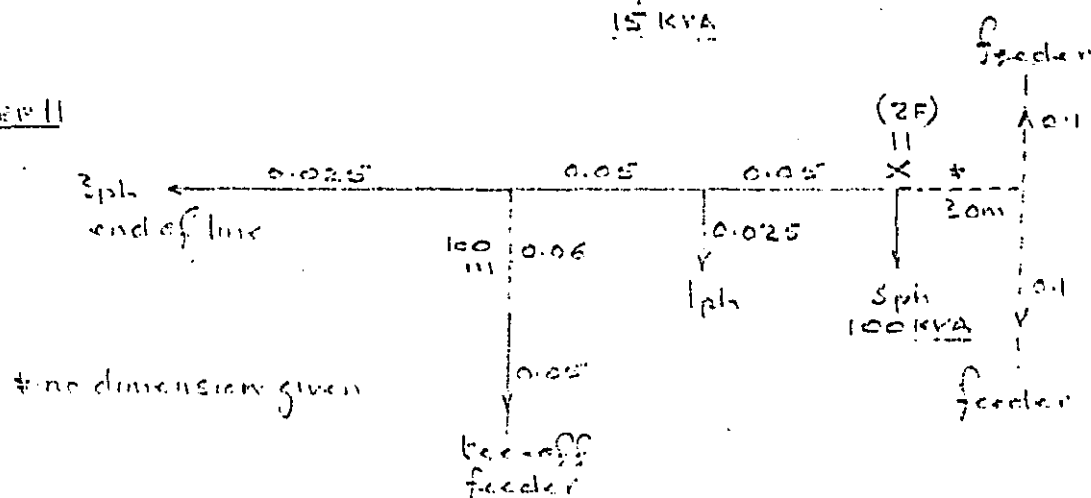
Diagram illustrating a power distribution system:

- A horizontal line represents a 3-phase 50kVA line from the "end of line" to a junction.
- The line has two segments: 0.05 and 0.06.
- At the junction, a 3-phase 50kVA load is connected.
- The line continues to a transformer (X) labeled "9 (2F)".
- From the transformer, a vertical dashed line represents a feeder to "S/S Bushfield Road".
- The feeder has three segments: 0.15, 0.15, and 0.15.
- A 3-phase 240m line is also connected to the feeder.
- The total length of the feeder is 0.45.

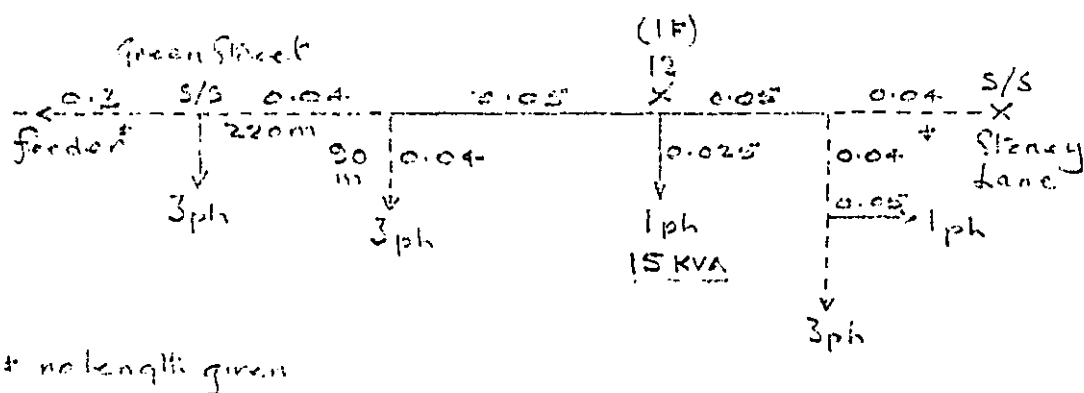
Ref 10



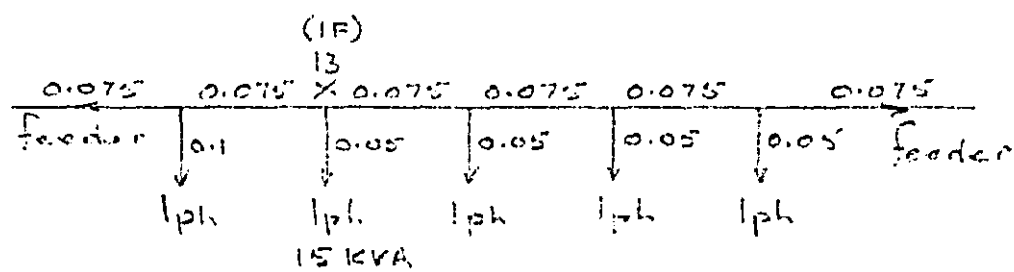
Ref 11



Ref 12



Ref 13



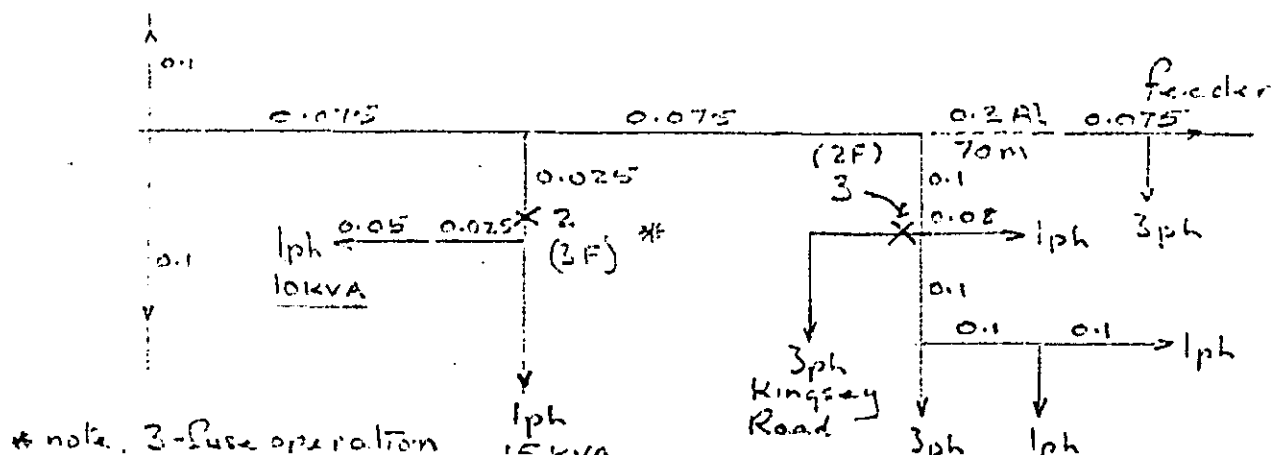
Case 18.Date 27.8.73.Report Data.

1	Weir Sewage Works	0824	PB	H7	1115	
2	Tythrop Farm, Kingsey	1921	3F	H13	2220	a
3	Kingsey Road, Thame	1921	2F	H13	2318	a
4	Weedon Hill, Copperkins Lane	* 2042	SW	H17	0155	
5	Shendish House	2045	CAB	H18	1740	
6	Smokey Row	2330	TR	H14	1605	
7	Copperkins Lane	2351	SW	H17	0250	
8	Ilmer - Walldridge feeder	2353	AR	H14	0056	

* Repeat fault location or circuit.

The lightning faults largely consist of widely scattered equipment damage. Certainly, 8 can be grouped with 7 due to resulting perturbations, and 2 and 3 are closely connected by the electrical circuit as well as being located within 1 mile of each other. They also show identical log entry times.

Since 2 and 3 show all the necessary evidence for excitation by a single indirect ground stroke it is again unusual to find a 3-fuse failure which can be listed as a transient fault on its own. As there is no connection with any of the permanent faults, it is taken as a special case in which travelling waves and the prestrike effect possibly combine.

REF 2 AND 3

Case 19.Date 15.9.73.Report Data.

1	Pix Farm	1942	1F	H12	2345	b
2	Bottom Farm	1949	2F	H11	2200	c
3	Fields End. Bosted	1949	1F	H5	2315	c
4	Bulbourne	2049	2F	H4	1745	g
5	Bourne End Church	* 2100	2F	H11'	0815	c
6	Old Saxe Farm	2100	2F	H10	0255	g
7	Chesham Vale	2200	2F	H11	0100	c
8	West Dean Lane	2200	1F	H10	0920	a

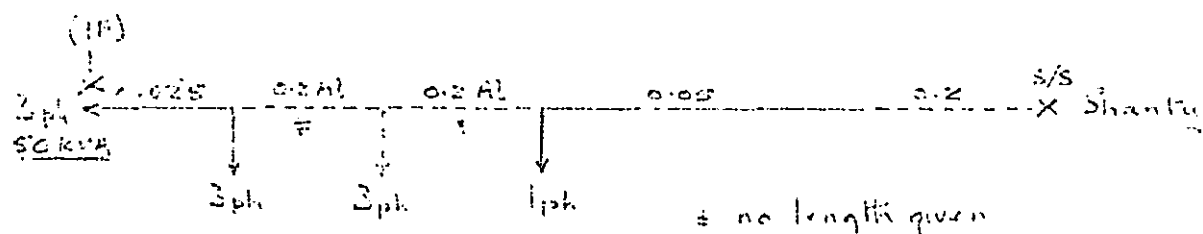
* Repeat fault location or circuit.

All are fuse faults with a predominance of double fuse operations distributed over a small area. 6 and 8 are adjacent spurs, 2 and 5 are spurs on adjacent feeders and close together geographically. Other examples are isolated faults but, all have a general location in the S.E. corner of the wider study area where the terrain is made up of hills and valleys.

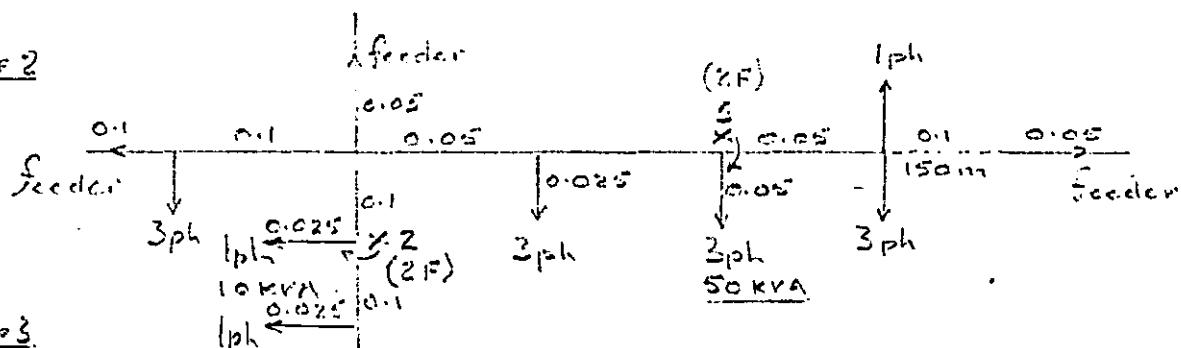
Because of the differences in logged times for those items showing common circuit connection some latitude would appear to be necessary for their interpretation as, for example, with 6 and 8 as adjacent faults. Effect of the landscape is seen to be characteristic for hill country according to storm direction.

A distance of about 5 miles accounts for most of these transient fault locations during a period of two hours so it may be concluded that the major part of the storm was outside the study area.

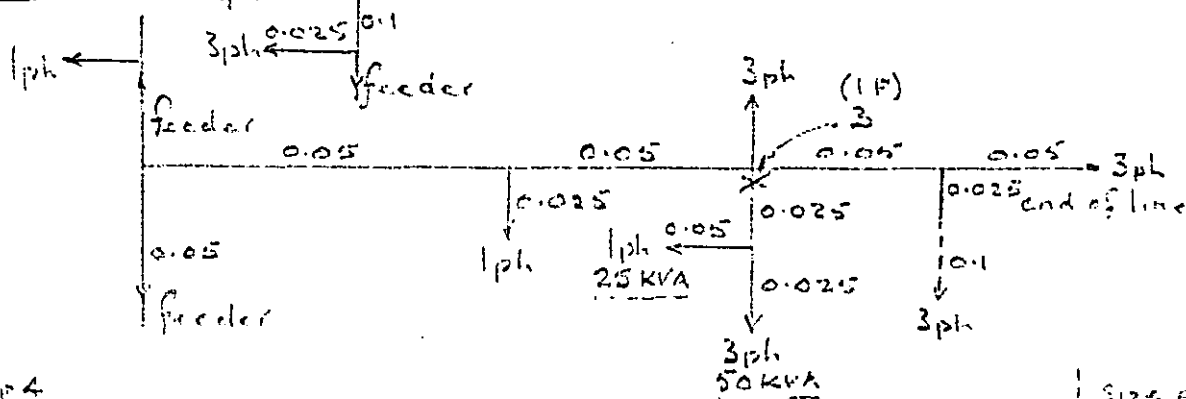
REF 1



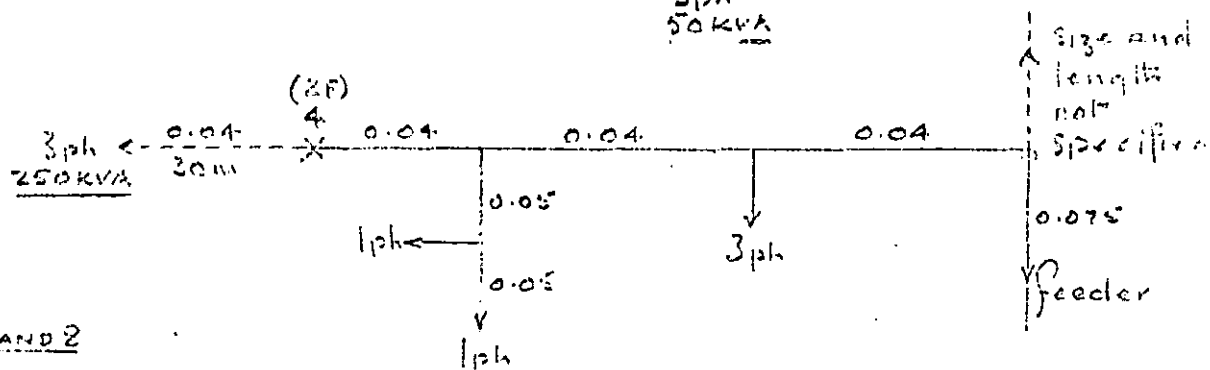
REF 2



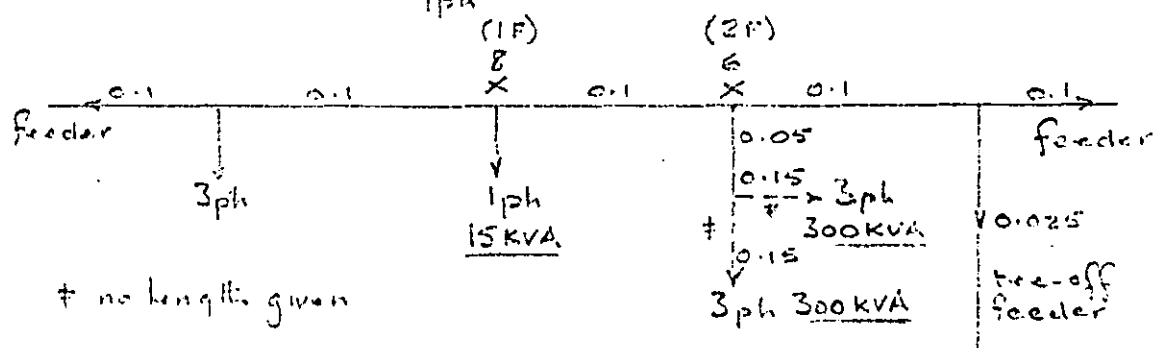
REF 3



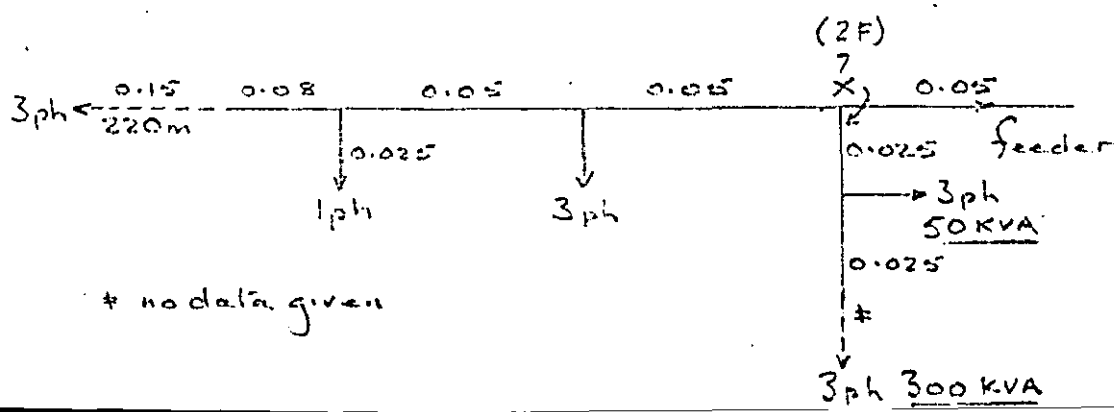
REF 4



REF 5 AND 2



REF 7



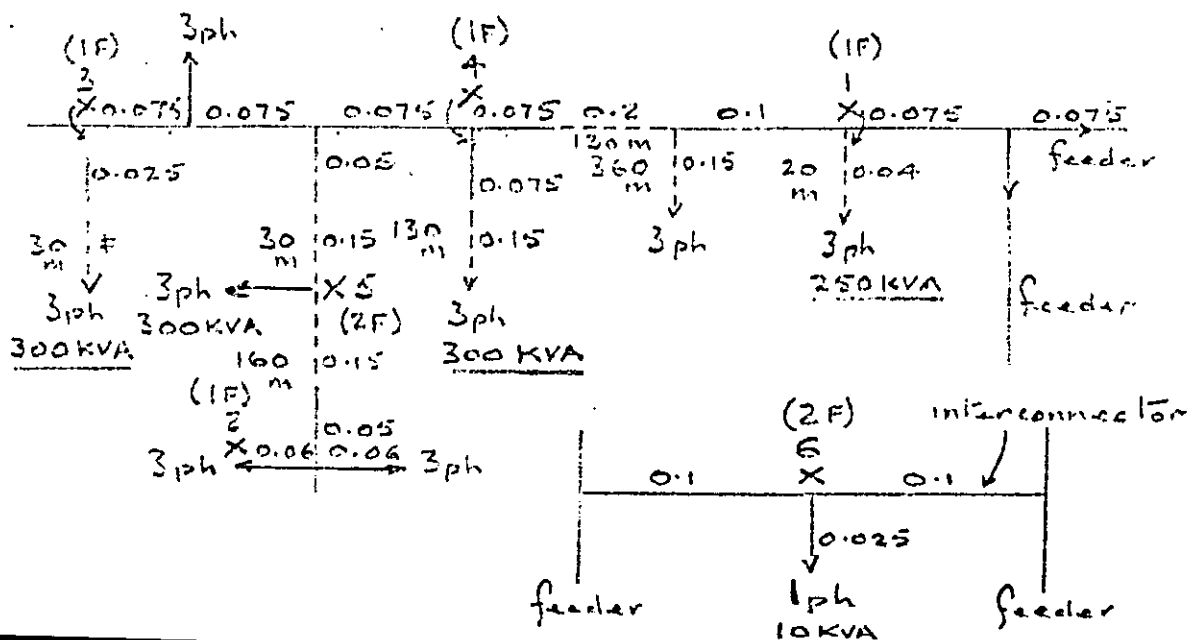
Case 20.Date 6.6.74.Report Data.

1	Bucklands s/s	1600	1F	H3	1740	d	
2	Brooke Street	"	1F	"	1730	c	
3	Bucks Joinery s/s	"	1F	"	1706	g	
4	New Road s/s	*	"	1F	"	1934	a
5	Green End Street, Aston Clinton	"	2F	"	1934	a	
6	Sedges Farm	1928	2F	H16	2034	c	

* Repeat Fault location or circuit.

A similar example to Case 19 although single fuse action predominates here in that the outages are all fuse faults. With a single exception, all occur at the same time and so would appear to be related to a single initial excitation. Certainly, the electrical circuits associated with 1-5 bear this out very well. 6 is quite a separate fault away from the Aylesbury area. The location of faults 1-5 are along a ridge of high ground.

Again an example where the nature of the terrain appears to be an influencing factor. Clearly, propagation effects are outstanding to account for the five simultaneous fuse faults and any special effect of prestrike is likely to be of less significance.



Case 21.Date 16.6.74.Report Data.

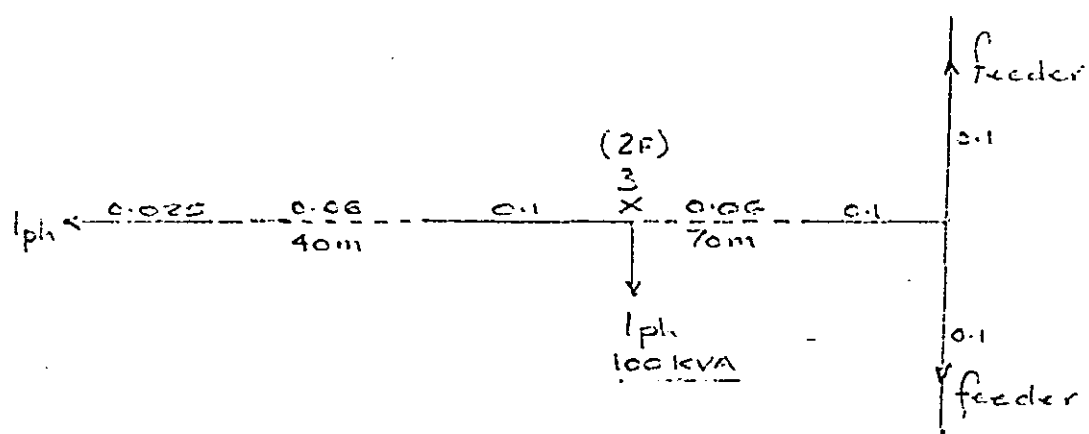
1	Greenlands feeder, Saunderton	1755	AR	H21	1850	
2	Garners Farm feeder	1755	AR	H21	1850	
3	Wendover Dean	1800	2F	H16	1955	b
4	Hewden Farm, Haddenham	* 1800	1F	H13	1020	c
5	Bacombe Lane, Wendover	1800	3F	H21	1320	c
6	Castle Park, Wendover	1810	AR	H9	1008	

* Repeat fault location or circuit.

Since all faults are in the transient classification it would appear, from the recorded times, that they are the result of a single stroke. Firstly, all of the circuits associated with the faults are isolated so the only possible link is that through their locations. With the exception of 4 the faults are on high ground (450-550 ft.) grouped together on the Chiltern Hills. The exceptional case is in the Aylesbury Plain at (270 ft.). This is a location which has been faulted previously (Case 9) and near by (Haddenham low) Case 6. It would suggest that the disposition of this line is such that it is more exposed, although in this case it is some 5-6 miles N.W. of the group. It is noted that a 3 fuse operation again occurs so that a prestrike component could be considered.

High altitude is common to most of the fault locations and all the electrical circuits are unrelated, thus a single ground stroke could be responsible or possibly two separate strokes could be envisaged. In the latter case 1, 2 and 4 with 3, 5 and 6 could be the grouping according to the topography. Either conclusion will suffice to establish indirect stroke excitation as the cause of the outages.

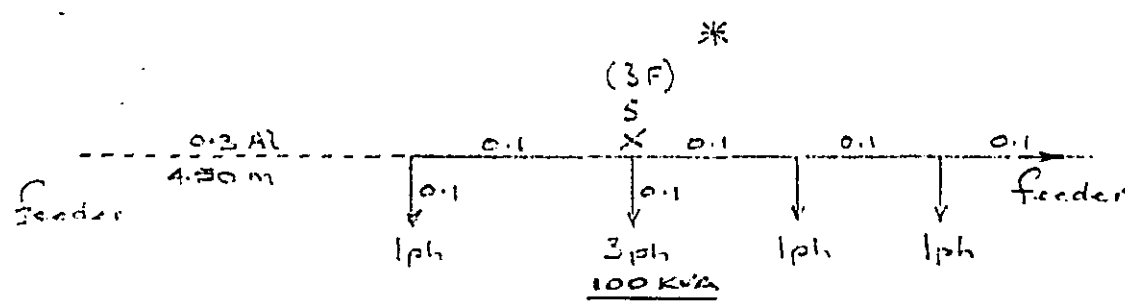
Ref 3



Ref 4

As case 9, reference 17

Ref 5



* note, 3-phase operation.

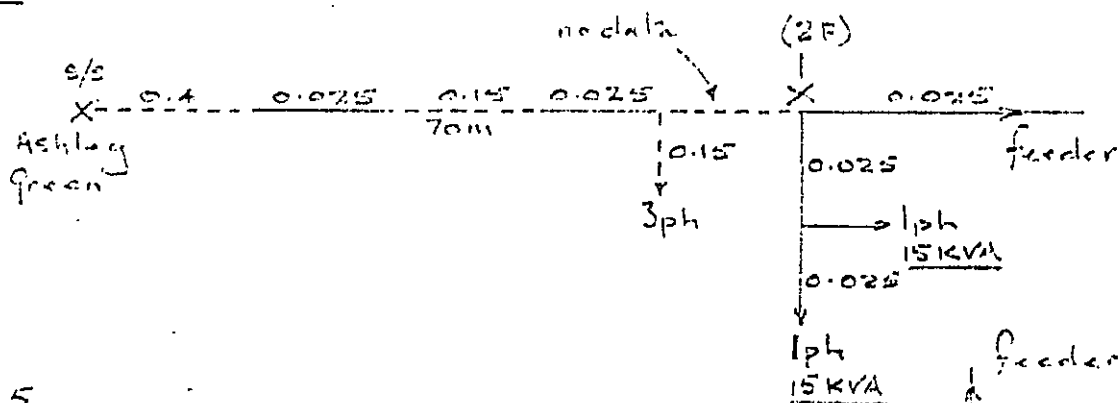
Case 22.Date 16.6.74.Report Data.

1	Johns Lane Farm, Pancake Wood Spur	1900	2F	H11	1000	d
2	Garners Farm feeder	* 1954	AR	H21	2045	
3	Greenlands feeder, Saunderton	* 1954	AR	H21	2045	
4	Longwick and Walldridge	* 1959	AR	H14	2222	
5	Twelve Acres	2000	1F	H2	0922	c
6	West Field, Princes Risborough	"	TR	H20	1600	
7	Dancers End	* "	1F	H9	1005	a
8	Odley Lane, Saunderton	* "	1F	H20	1205	c
9	Heath End Farm, Lye Green	"	1F	H16	1205	c
10	Wooton House	"	1F	H1	1750	a
11	Field Farm Cottages, Westcott	* "	1F	H7	1818	c
12	Chesham Vale Spur	* 2005	2F	H11	2020	c
13	Thorne Barton Farm	2005	1F	H11	2020	a
14	Grange Farm, Towersey	2010	TR	H19	1800	
15	Aston Sandford	2010	1F	H13	0615	c
16	Weedon Hill Farm	* 2015	2F	H17	1555	c
17	Buckingham Road, Waddesson	* 2020	AR	H2	2036	
18	Red Barn, Stone	2028	AR	H14	2323	
19	Buckingham Road, Waddesdon (No. 1)	* 2028	AR	H1/2	2036	
20	North Lee, Mandeville Road, Aylesbury	2028	AR	-	1032	
21	Marsh Farm, Winchendon	* 2030	1F	H7	1715	c
22	Elm Farm feeder, Stoke Mandeville	2033	CON	H14	2159	
23	North Drive	2033	AR	H14	2130	
24	Lower South Farm, Doddeshall	2100	1F	H1	1215	c
25	Potash - Puttenham	2100	1F	H3	1250	a
26	Brill	2130	AR	H1	0855	

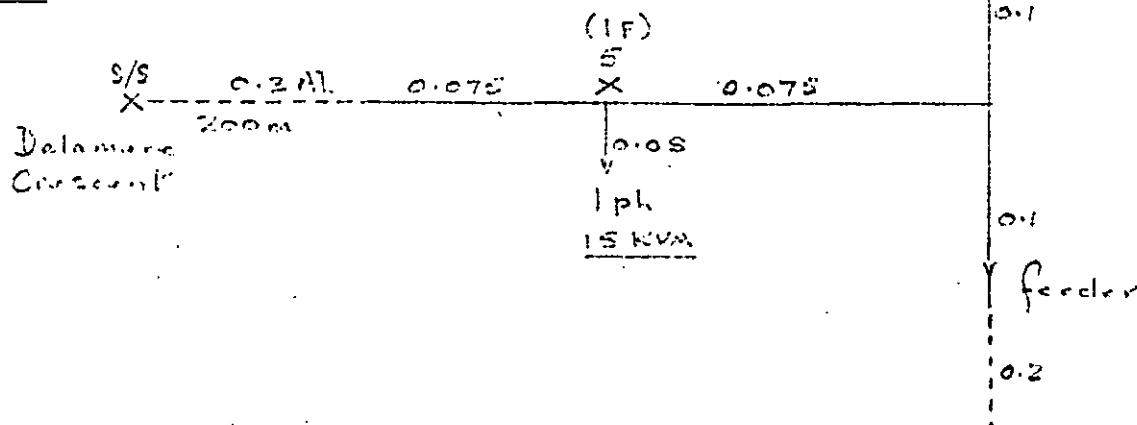
* Repeat fault location or circuit

Clearly, a second thunderstorm period following on from the previous case 21, with the affected area now considerably extended showing a 35% autorecloser function and only 12% persistent faults. Two of these are transformers. It is well, perhaps, to study the circuit connections first as the area covered is now so much wider. It is assumed that 2 and 3 are actually new entries since there is 2 hrs. between them and those corresponding in the previous case. The example is particularly outstanding for the number of repeat fault locations and case 15 shows that this feeder appears to suffer from much attention at a nearby spur (H.Farm). Apart from these location identities, none of the fuse fault circuits in the list of faults are directly connected electrically but can be brought together in groups according to their topographical identities and recorded times. Leaving aside the last three entries of later time, one group is confined to the Chiltern Hills area (Saunderton, Princes Risborough) whilst another around Aylesbury and Waddesdon. Although there is no evidence of circuit connection, it is possible because of the grouping, that the listed locations are the response to only a few ground strokes.

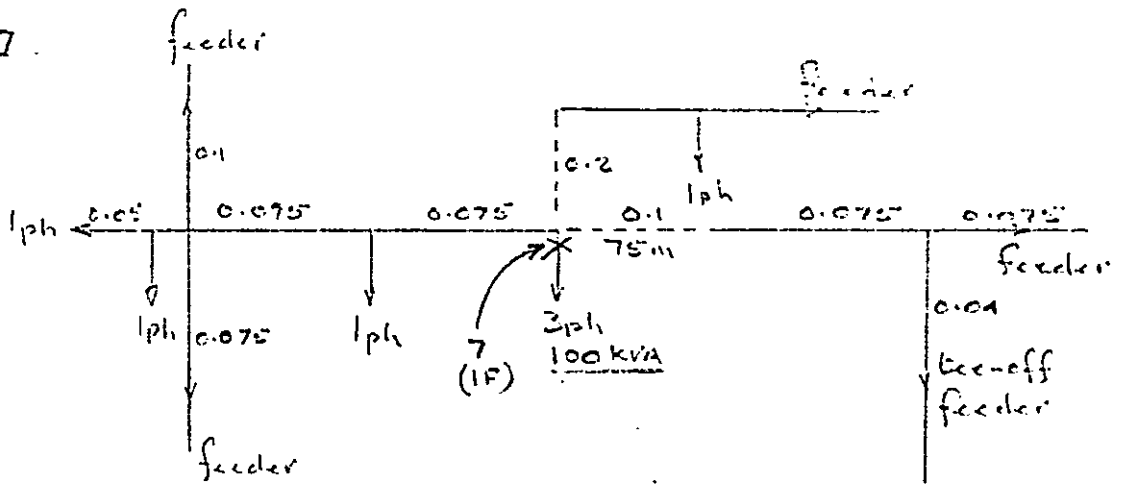
Ref 1



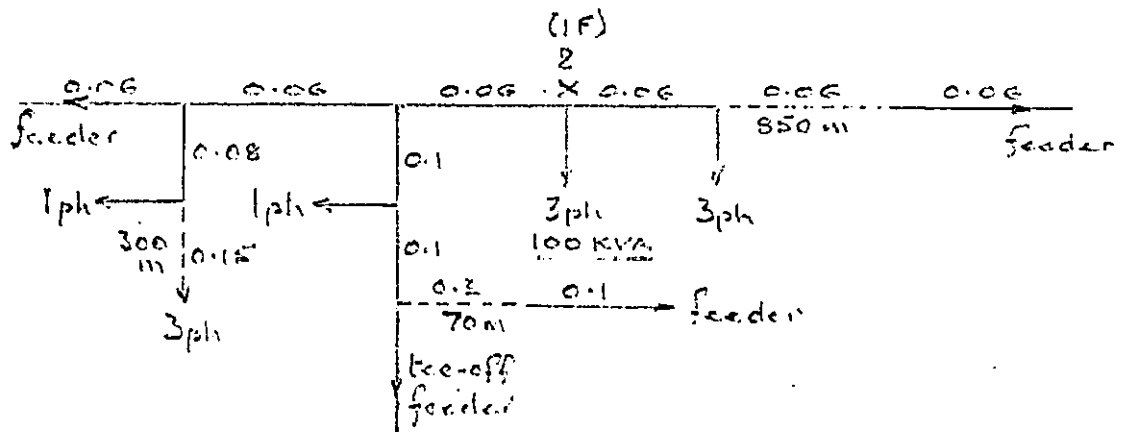
Ref 5



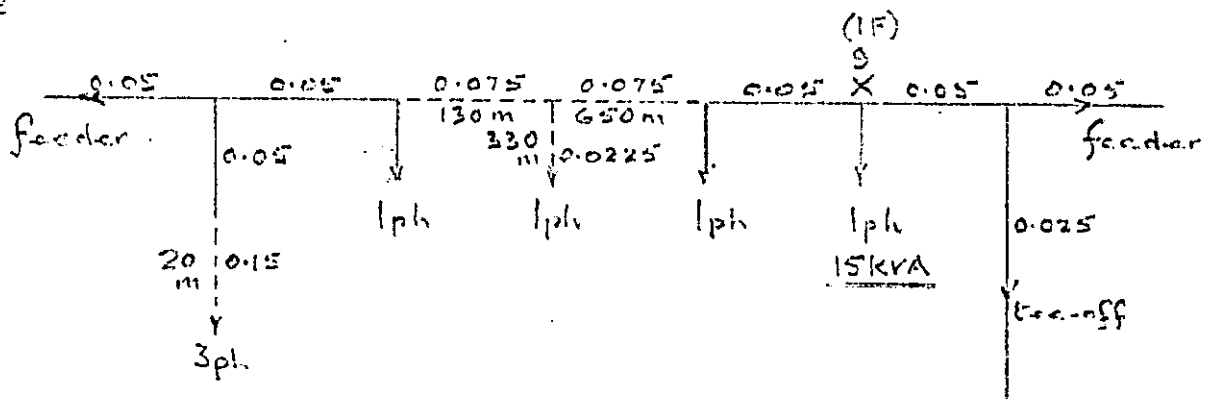
REF 7



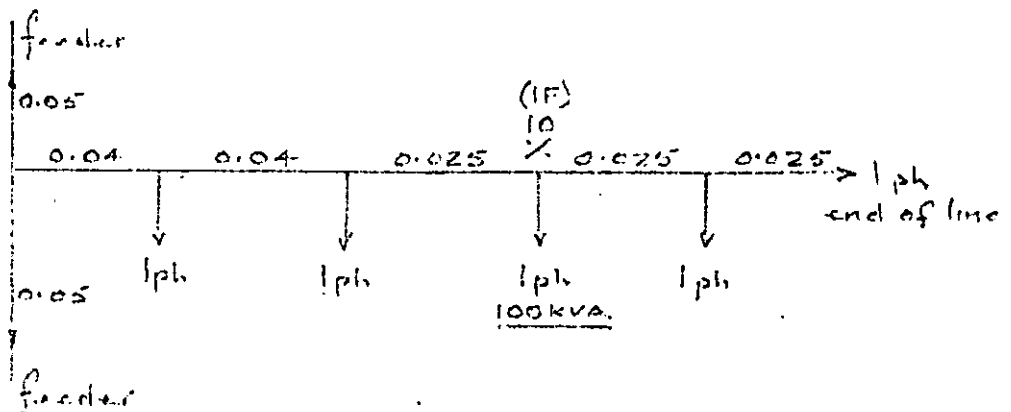
REF 8



REF 9



REF 10



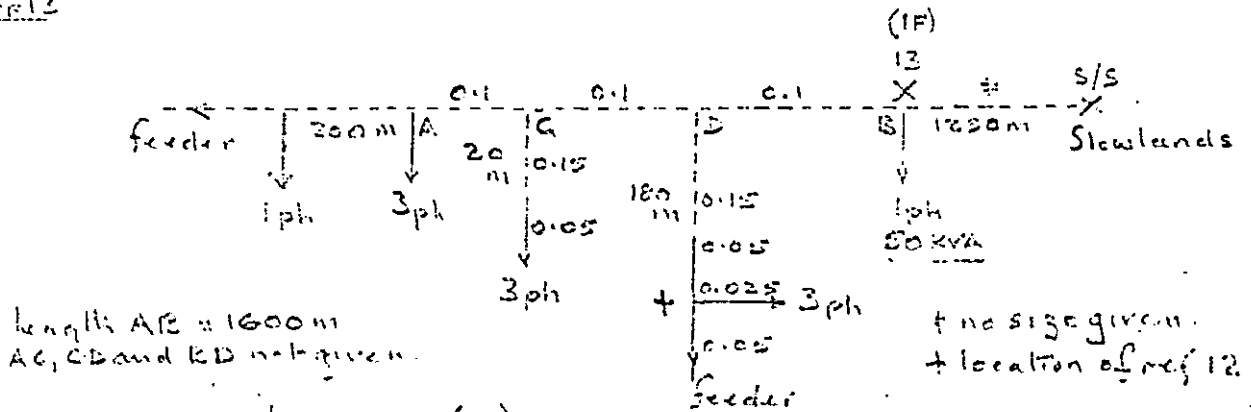
REF 11

As Case G, mfg 4

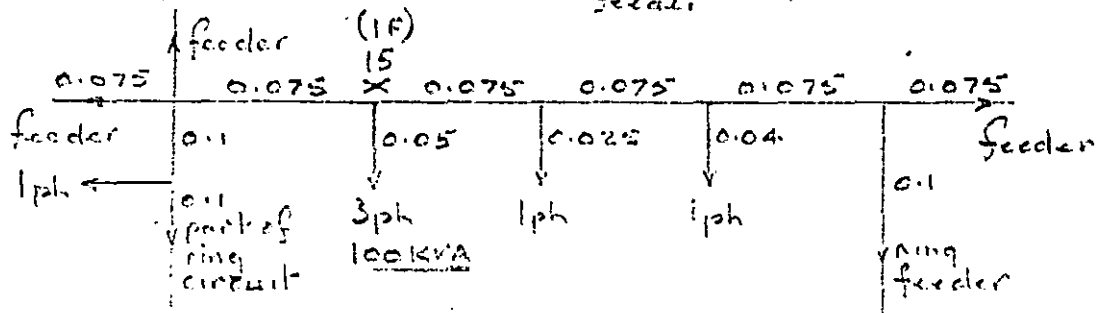
REF 12

as Case 19, ref 7

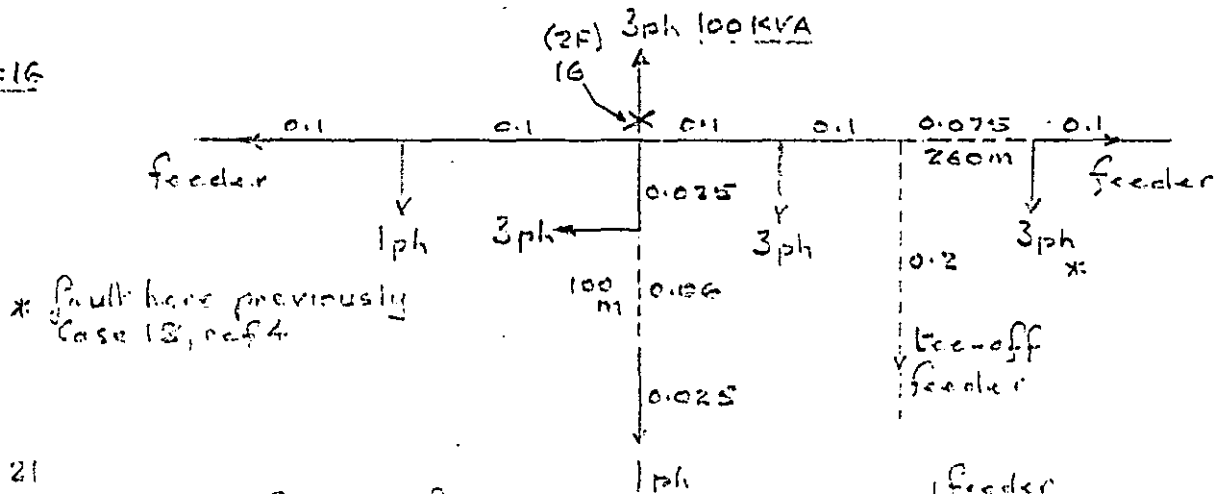
REF 13



REF 15



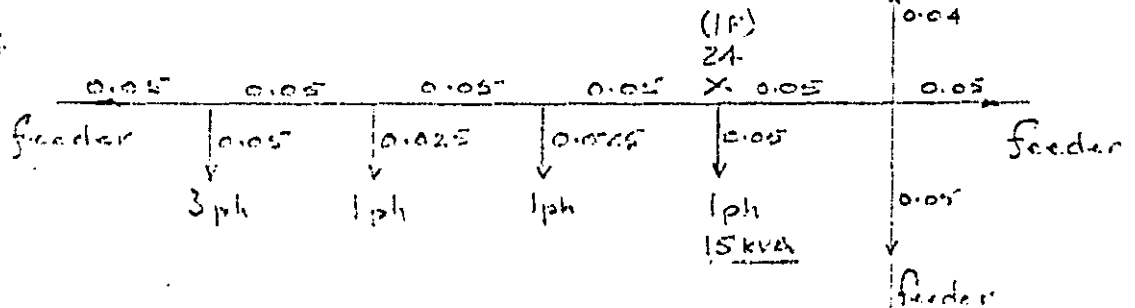
REF 16



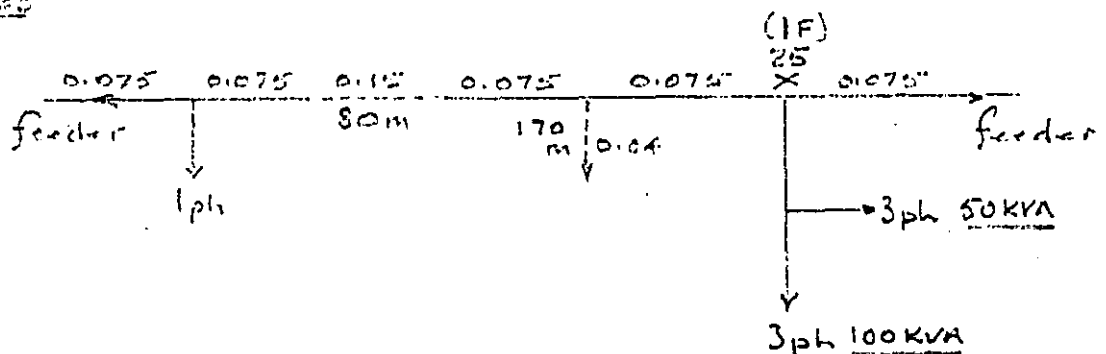
REF 21

as Case 1, ref 1

REF 24



REF 25



Case 23.Date 16.6.74.Report Data.

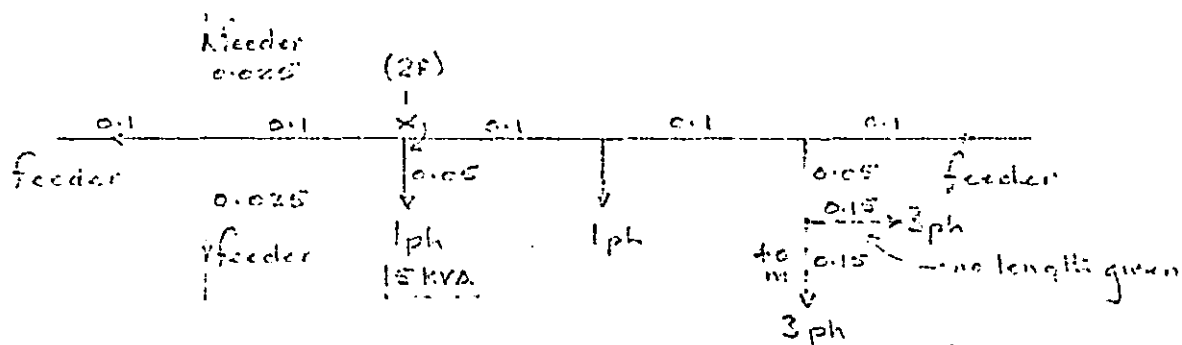
1	Restomel	2200	2F	H10	1305	c
2	Drakes Farm, Long Crendon	"	1F	H13	1206	c
3	Needles Farm, Quainton	*	"	1F	H1	1450 c
4	Hampden Sawmills, Saunderton	"	1F	H21	1910	a
5	Doddeshall - Waddesdon s/s	2204	AR	H1	0020	
6	Kings Langley - Apsley s/s	*	2228	AR	H24	2312
7	Greenlands, Saunderton	2326	SR	H21	2357	
8	Meadhams Farm, Ley Hill	2335	1F	H17	1010	a
9	Henton Sewage Works	2340	1F	H20	1322	a
10	Dunsham Farm, Buckingham Road	2341	AR	H2	0152	
11	Aston Abbotts	*	2341	AR	H2	0410

* Repeat fault location or circuit.

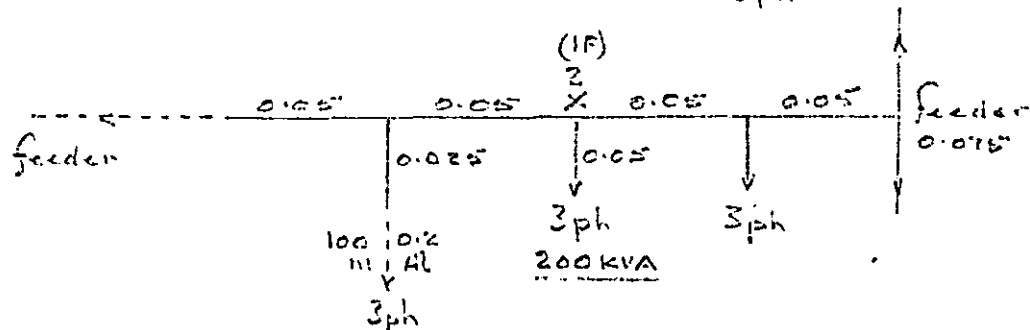
There are no persistent faults although 1 hr. and 41 minutes separates the first and last log entries. However, allowing for time variations and location, it is not easy to group the faults so that simultaneous operation is apparent. For example Quainton (3) is a long way from Saunderton (4). In fact about 12 miles N-S, although Long Crendon is about 7 miles from Saunderton and from Quainton - still a considerable distance for the response to a single indirect stroke. With the large number of AR operations (45% of total faults) it is fairly evident that a single stroke is unlikely to be the cause of many of these faults. A storm drift or passage is difficult to follow from the fault entry times and corresponding locations.

It is assumed that the fuse faults are due to separate indirect ground strokes acting on widely separated circuits. This is a continuation of case 22 but as with this case, the area affected is more expansive.

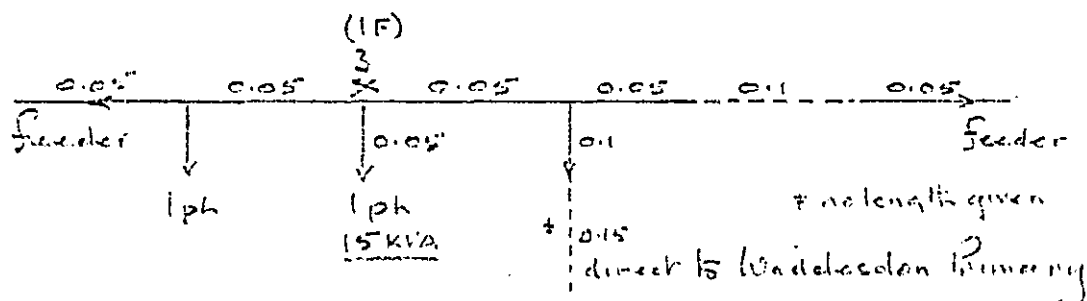
REF 1



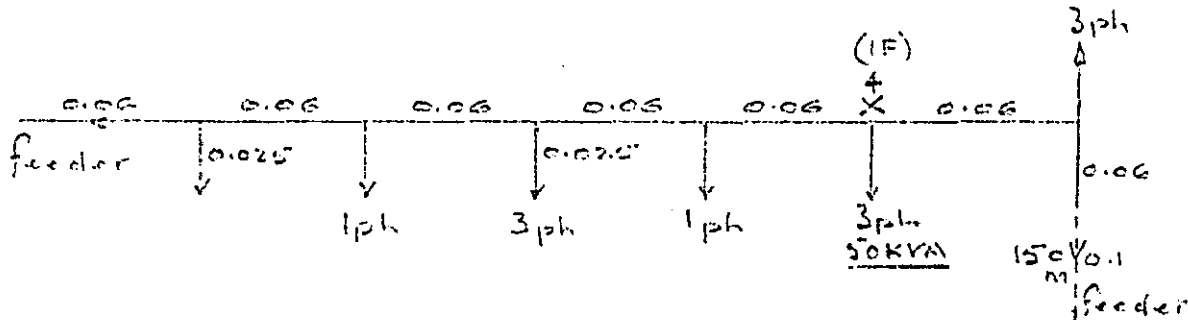
REF 2



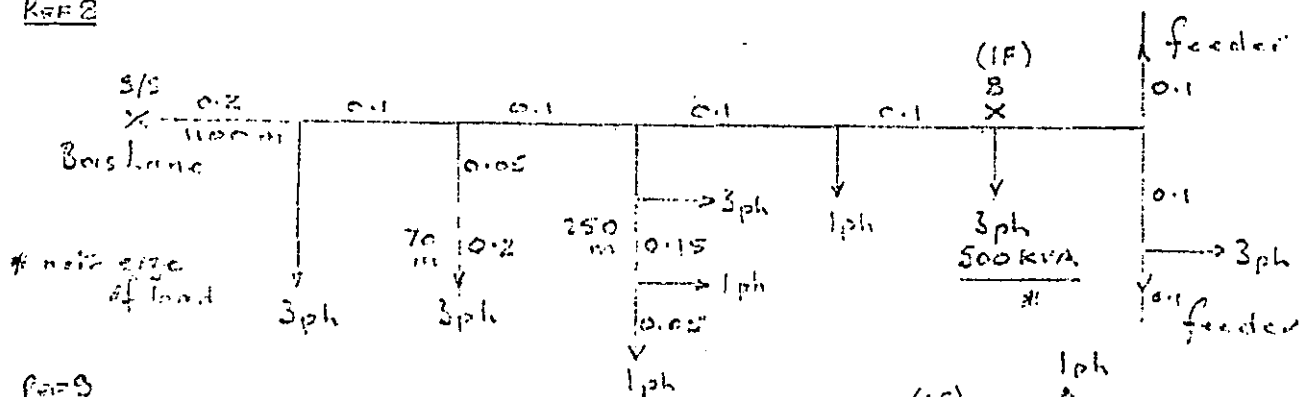
REF 3



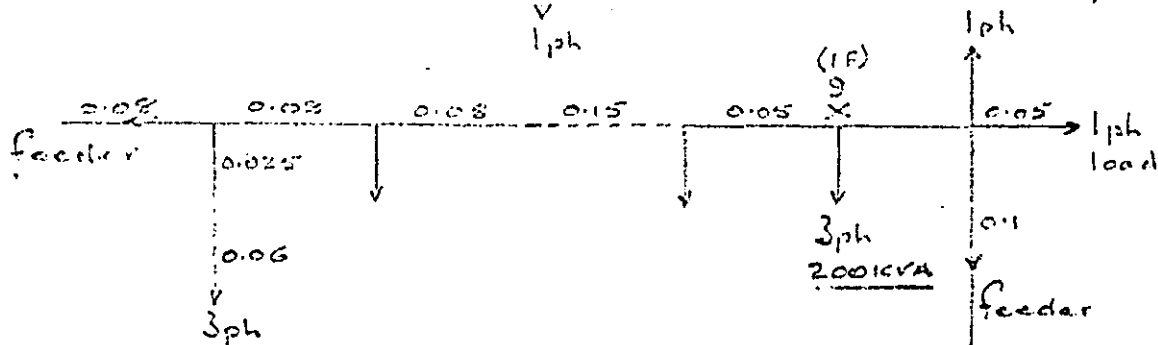
REF 4



REF 2



REF 3



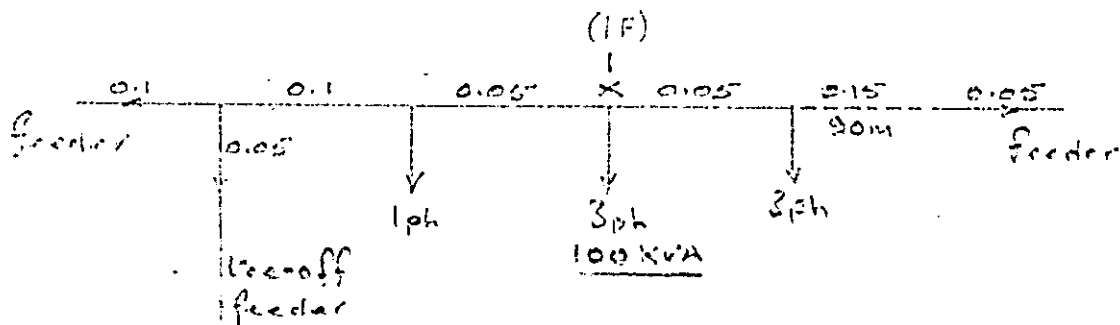
Case 24.Date 17.6.74.Report Data.

*	Quarrendon Farm	0400	1F	H23	0708	c
2	Chartridge End	0400	*	H10	0745	c
3	Whitesfield Farm, Quainton	0415	"	H2	0755	c
4	Moreton Tee-off	0420	"	H13	0654	c
5	Chilborough Hill Cottages	* 0430	"	H13	0520	a
6	Bishopstone Road	* 0430	"	H13	0530	a

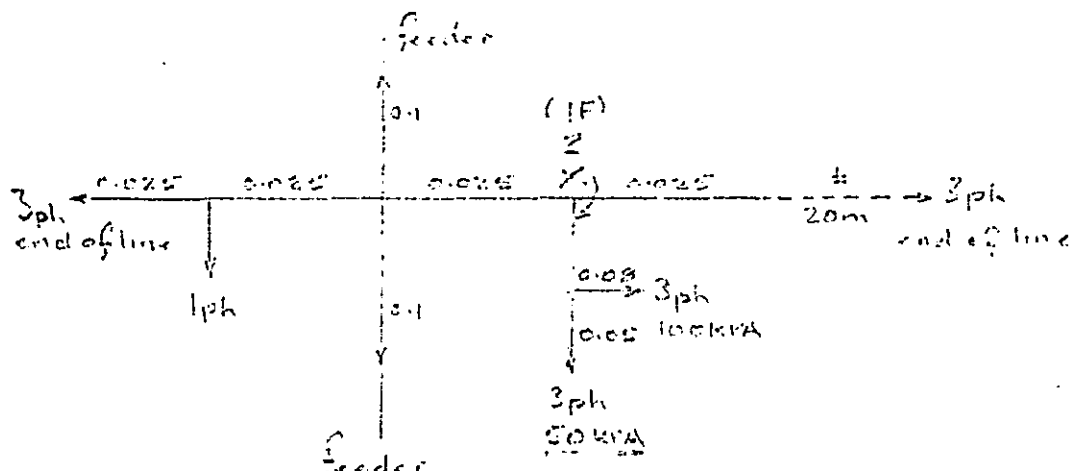
* Repeat fault location or circuit.

All single fuse faults presented over a half hour period. 1 and 2 can be related to a single stroke. They are about 5 miles apart at altitudes 425 ft. and 575 ft. well into the Chiltern Hills. 3 is at least 12 miles to the N.W. of 2 and cannot be linked with any other fault. Similarly 4, west of Thame is also an isolated fault. 5 and 6 can be associated by a common circuit and are less than 2 miles apart.

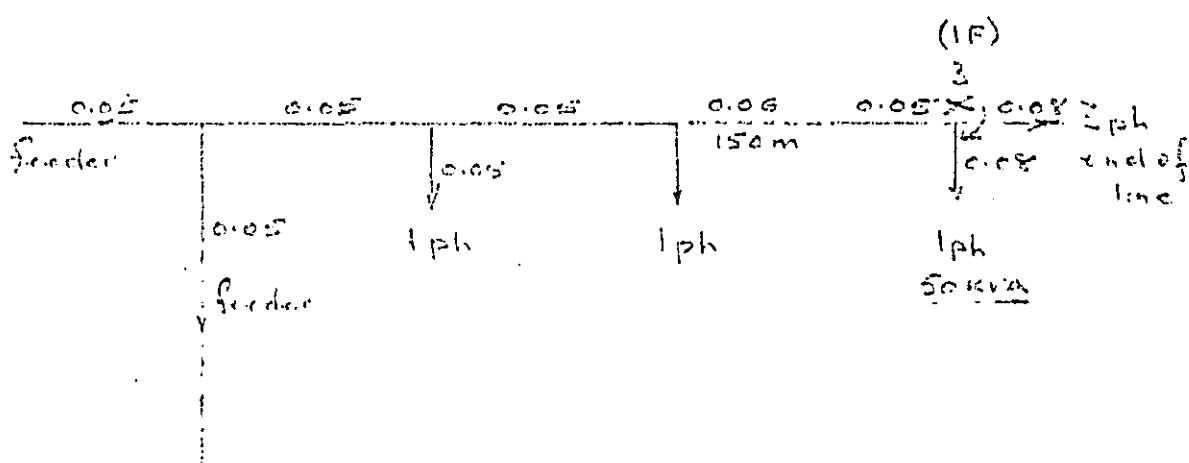
Separate ground strokes responsible for single fuse faults. Possible single stroke for 1 and 2. Certainly a single stroke for 5 and 6 since the simple circuit connection is evident. It is noted that this particular circuit appears to receive repeated attention, viz., case 11, Ref. 2 and 3; case 9, Ref. 30; case 7 Ref. 11 and 12. Also, the fault distribution extends over both hill and flat country.

REF 1

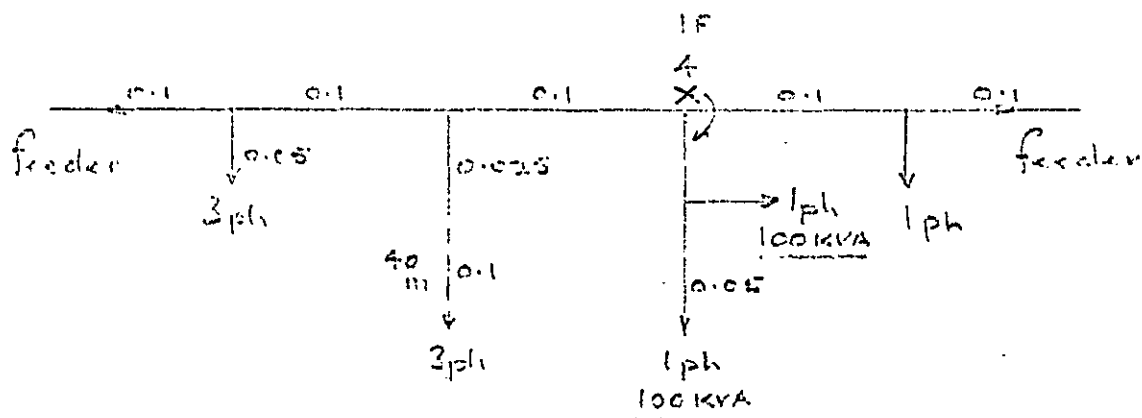
Per 2.



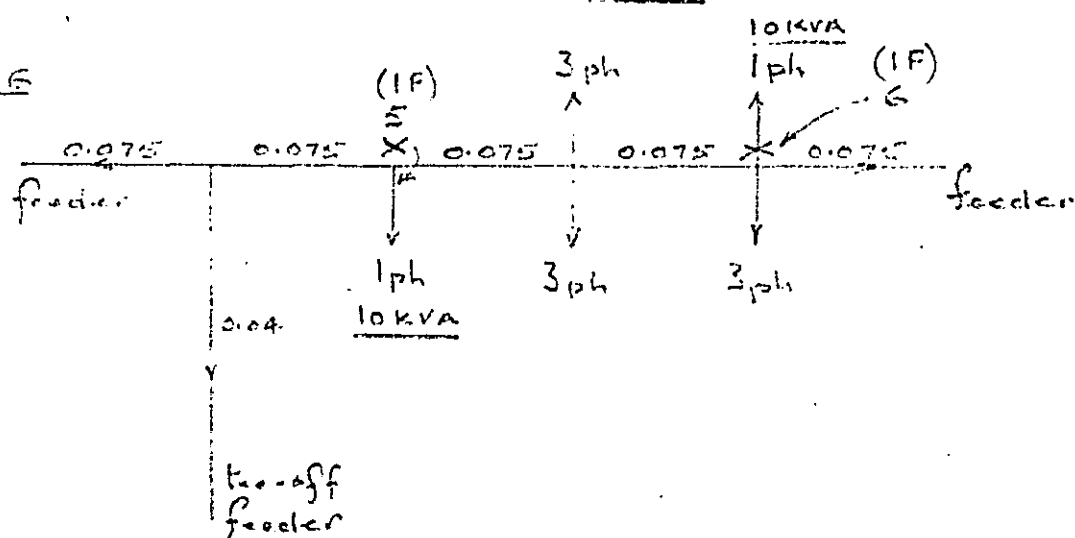
Ref 3



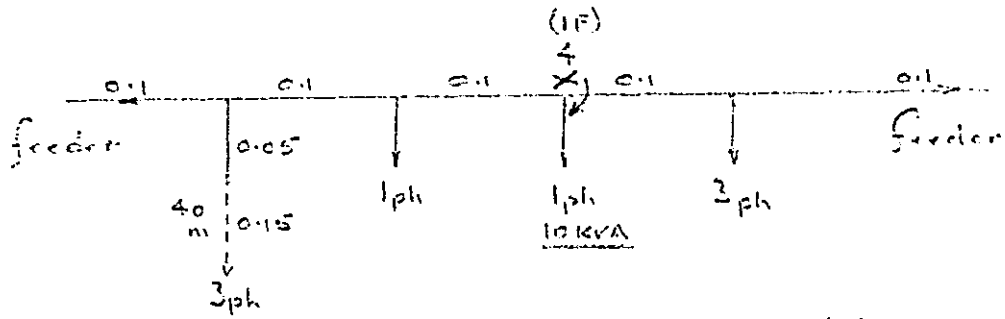
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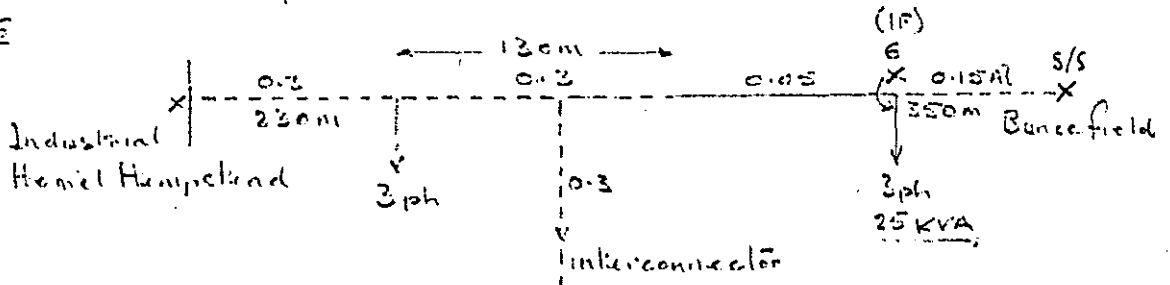
REF 5 and 6



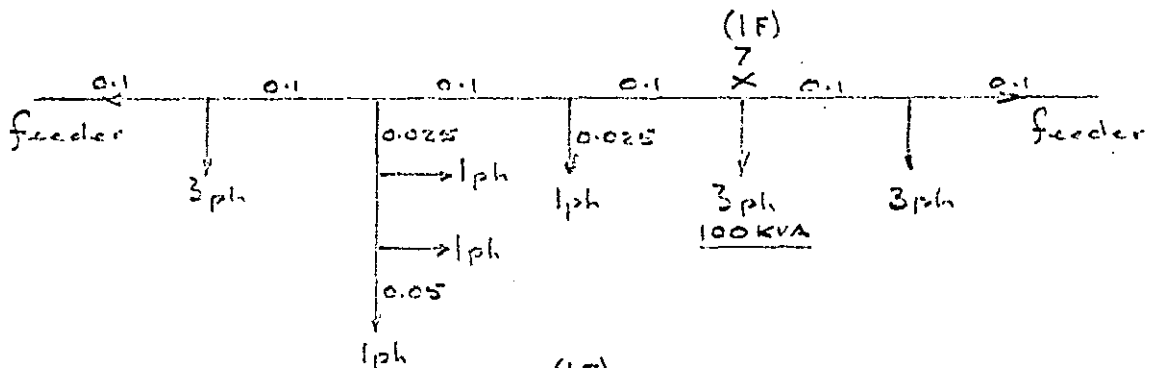
Page 4-



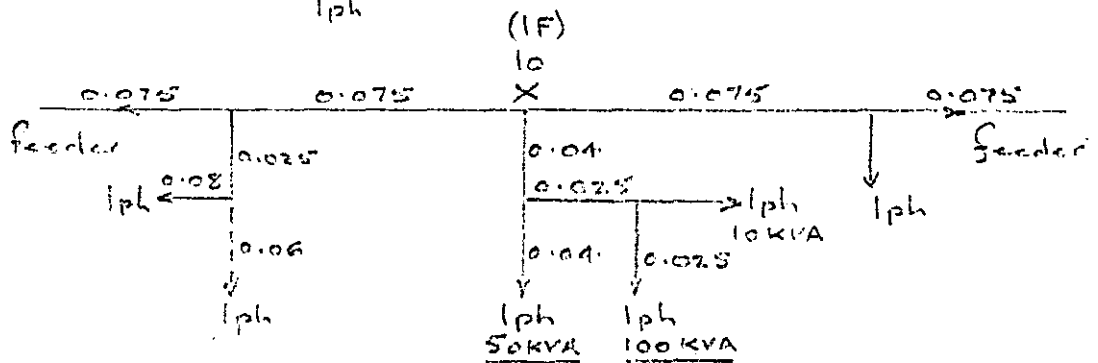
Ref 6



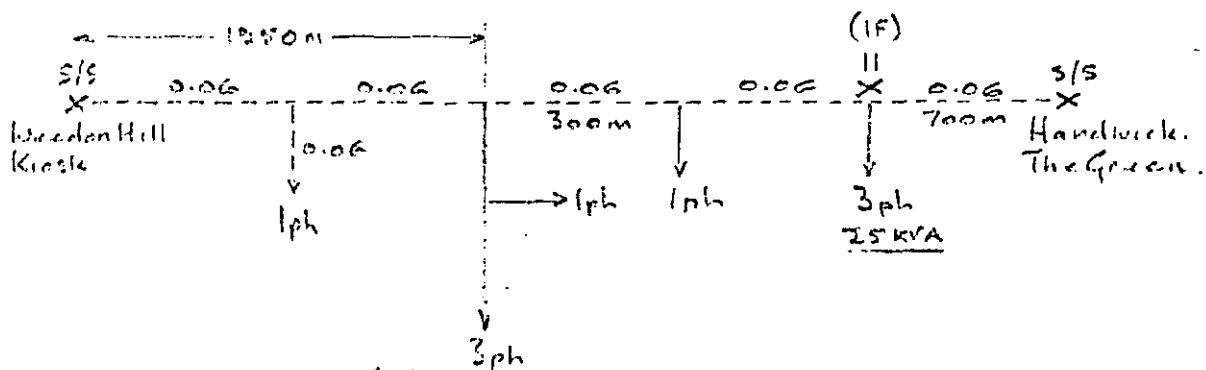
Page 7



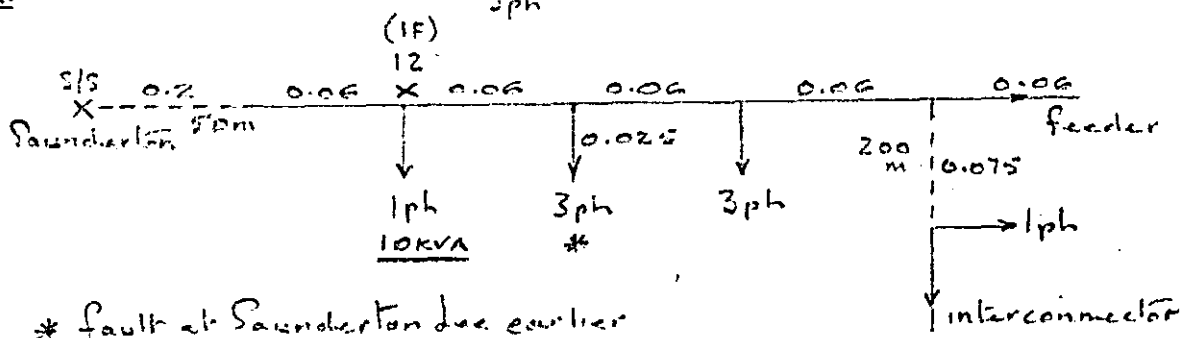
2.5.10



P. 11



Page 12



* fault at Sanderton loc. earlier

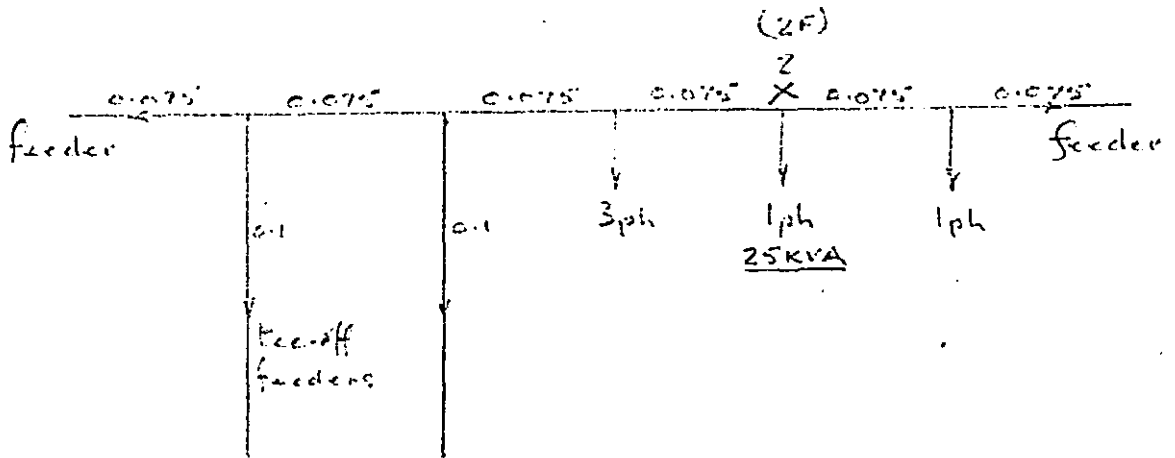
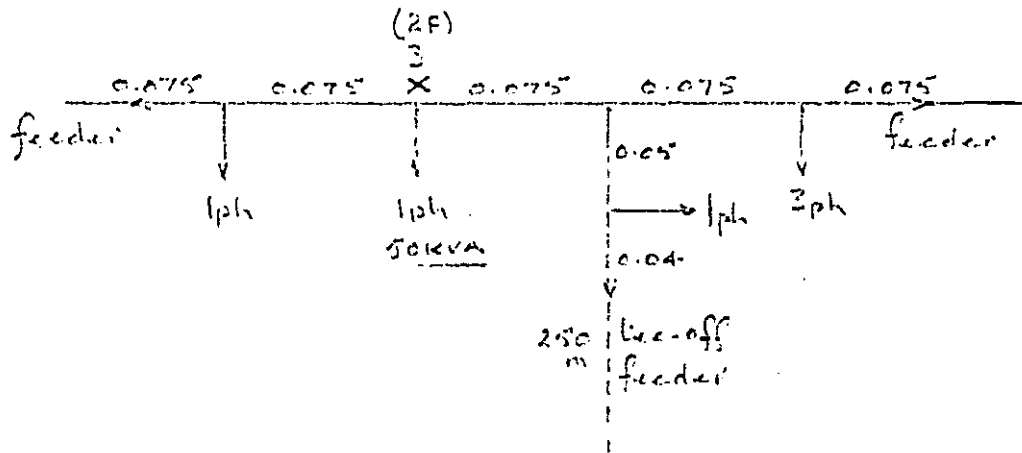
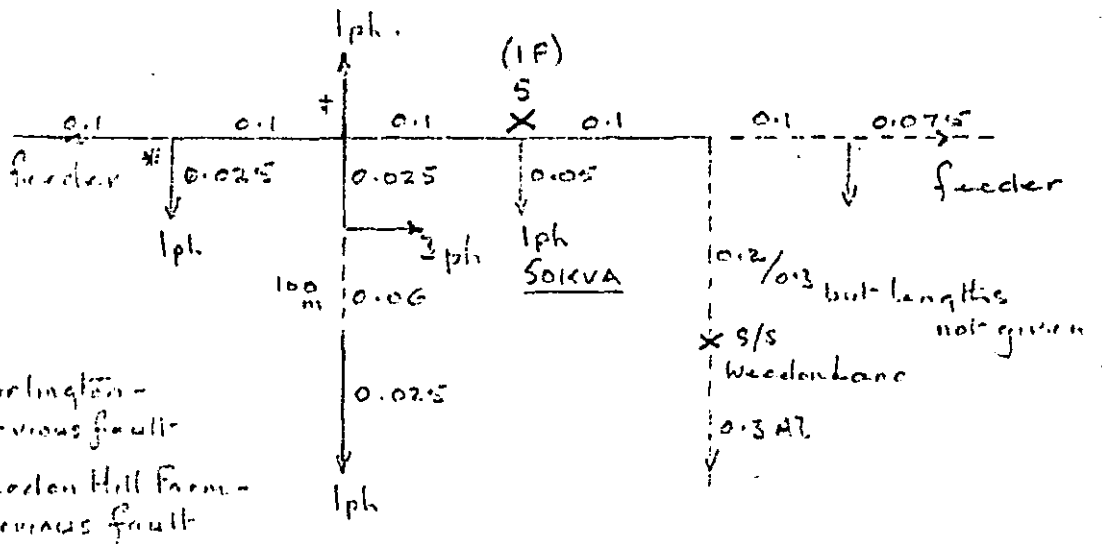
Case 26.Date 17.6.74.Report Data.

1	Brill - Policott	0730	AR	H7	0931	
2	Hastoe Cross	0730	2F	H9	1023	a
3	Wick Farm, Wiggington	0730	2F	H10	0932	c
4	Greenlands, Saunderton	0735	AR	H21	0900	
5	Mayhall Farm spur	* 0830	1F	H17	1108	c

* Report fault location or circuit.

This group of transient faults appears to correspond to a single discharge with the exception of item 5. All the affected circuits are unconnected, which appears to be a characteristic of this day of continuous thunderstorm activity and are only linked by the terrain.

The simultaniety however requires investigation because the separation distances between the faults are seen to be considerable. Between 3 and 4, for example, there is about 10 miles and about the same distance between 1 and 4, whereas 2 and 3 are less than two miles apart. The single discharge conclusion is therefore erroneous, and probably only 2 and 3 are linked by a single stroke to earth.

Ref 2Ref 3Ref 5

* Darlington -
previous fault

† Weeden Hill Farm -
previous fault

Case 27.Date 17.6.74.Report Data.

1	Brick Kiln Farm Cottages	1040	2F	H4	1330	d
2	Doddeshall - Frederick Street Spur	*	1100	CAB	H1	1845
3	Shrublands Farm	1100	TR	-	1500	
4	Nash Lee Road, Terrick	1100	1F	H15	1658	a
5	Coppice House, Speen	*	1100	1F	H21	0920 c
6	Chenies Rectory, Flaunden	1108	TR.	H24	1840	
7	Kingswood Farm, Speen Bottom	1115	TR	H22	2215	

* Repeat fault location or circuit.

This final storm of the day again shows evidence of group response but unlike the outages on the previous three occasions, it presents a high proportion of permanent damage in the form of three transformer failures and a cable fault. Also, again the simultaneous effect is present and all the affected circuits are in isolation. It seems unlikely that direct stroke action is the principal cause because of the simultaneous entry times representing widely scattered locations some of which occur on high ground and the rest in flat country.

Case 28.Date 4.8.74.Report Data.

1	Cathodic Protection, Haddenham	1130	2F	H13	1145	a
2	Place Farm feeder	1141	AR	H20	1156	
3	Wendover Primary	1158	AR	H15	1245	
4	Longwick School	* 1200	1F	H20	1345	g
5	Pasture Farm, Ilmer	"	1F	H14	1435	a
6	Hampden Saw Mills, Saunderton	"	1F	H21	1555	a
7	Nether, Winchendon	x "	1F	-	1600	
8	Garners Farm, Coppice House spur	* "	1F	H21	1645	c
9	Buntings, Owlswick	"	1F	H14	1730	a
10	Three Crowns, Askett	"	1F	H20	1435	c
11	Ashendon Tee-off	"	1F	H1	2040	c
12	Green Hailey	"	1F	H21	1528	c
13	Alscott, Ilmer	"	1F	H20	2110	a
14	Hewdon Farm, Haddenham	* "	1F	H13	1635	c
15	Buckingham Road, Waddesdon	* 1206	AR	H1	1237	
16	Aylesbury East	"	AR	H2	1251	

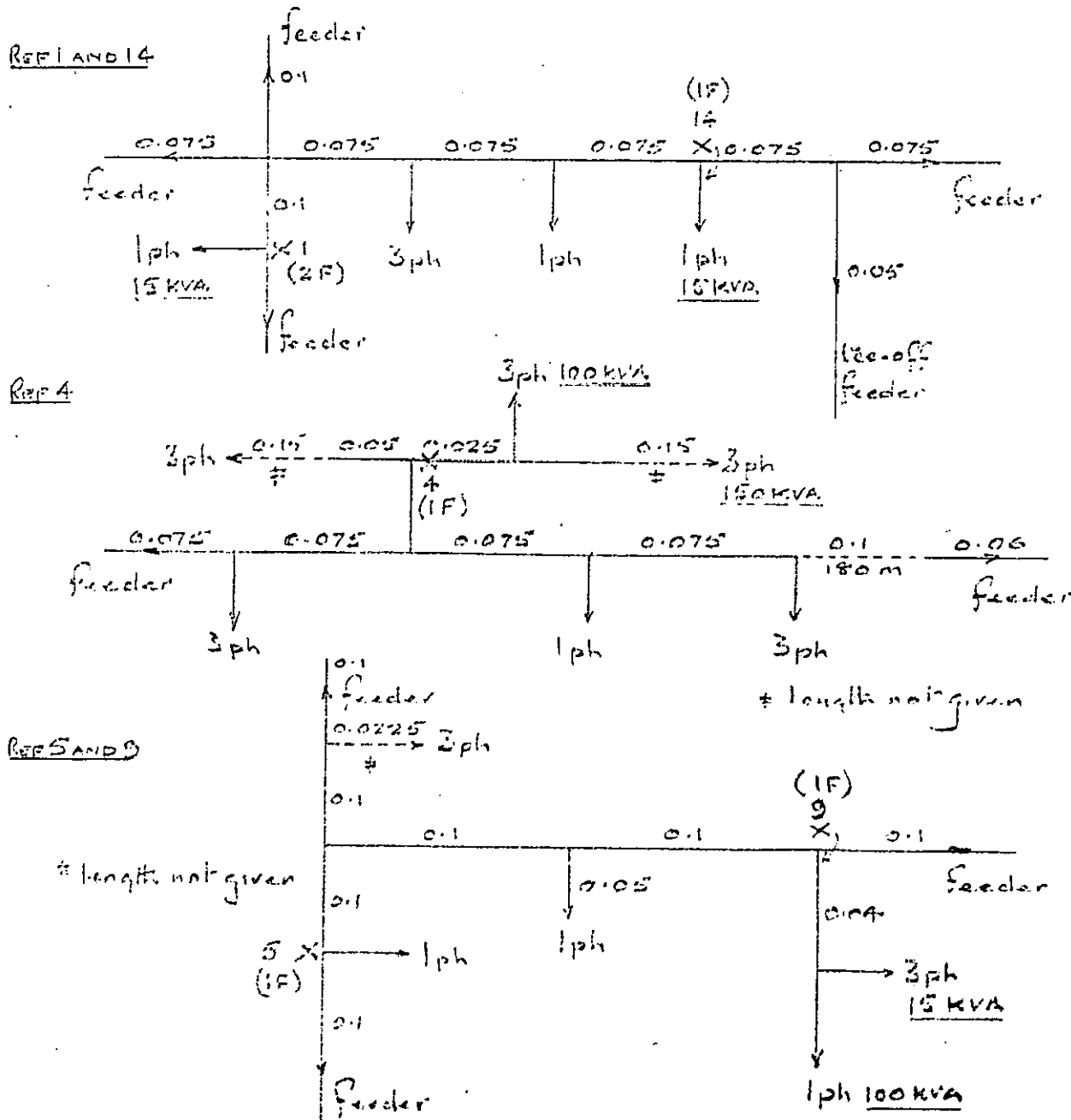
* Repeat fault location or circuit. x Not found.

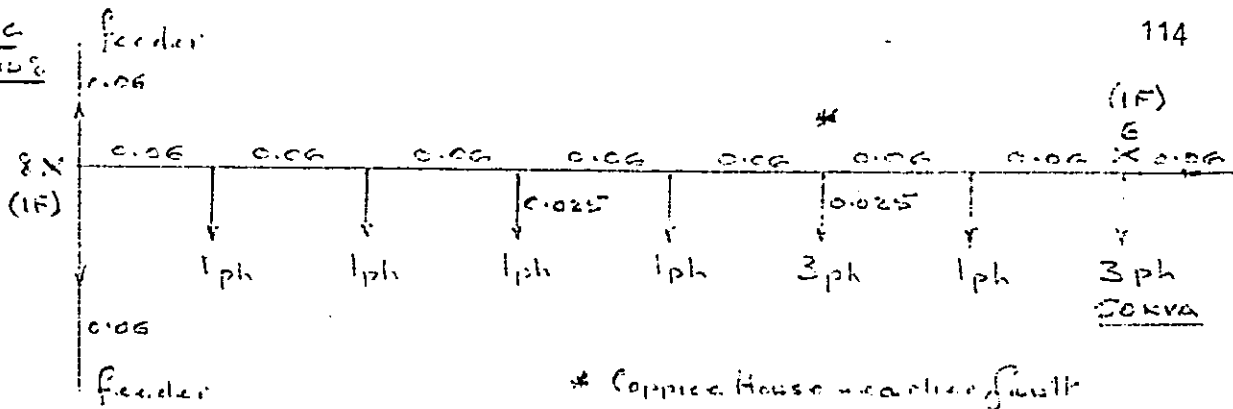
The following three cases provide a storm pattern similar to the previous four cases in that the thunderstorms extend over a considerable period of the day. In this case from 1130 hours to 2026 hours, and the fault pattern is very similar. Two of the cases contain virtually transient faults only, with mostly simultaneous operation, whilst the last storm records one third persistent faults made up of transformer failures and a conductor fault.

This particular case shows a probable totally simultaneous

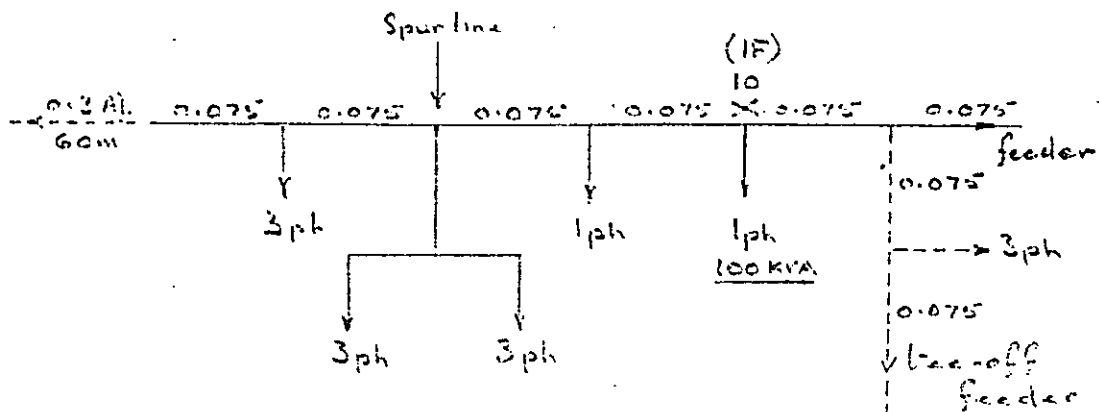
action in spite of a log entry diversity of 36 minutes. Half of the fuse faults can be linked to three circuits and the other half to single circuits. The circuit involving ref. 1 and 14 is shown to be clearly disposed to lightning attention from the previous references to lightning incidents. This also applies to that part of the network in which faults 6 and 8 are located.

Most of the fuse faults are to be found in the Plain of Aylesbury but items 6 and 8 are located a little way into the Chiltern Hills. The maximum separation distance is about 10 miles which raises doubts that a single ground stroke is solely responsible for all the entries in case 28. However, the effect of a multiple stroke discharge could provide an explanation.

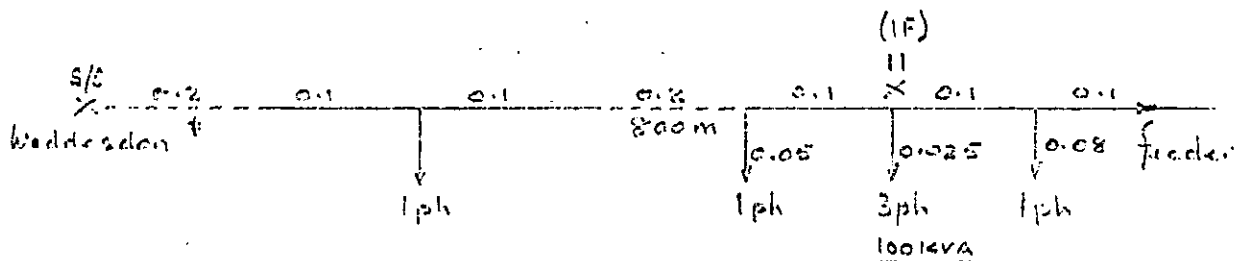




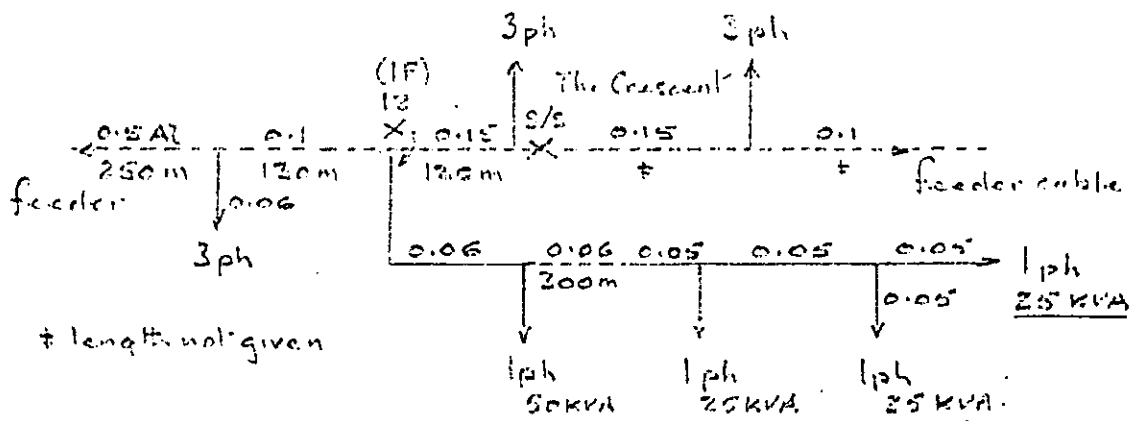
Ref 10



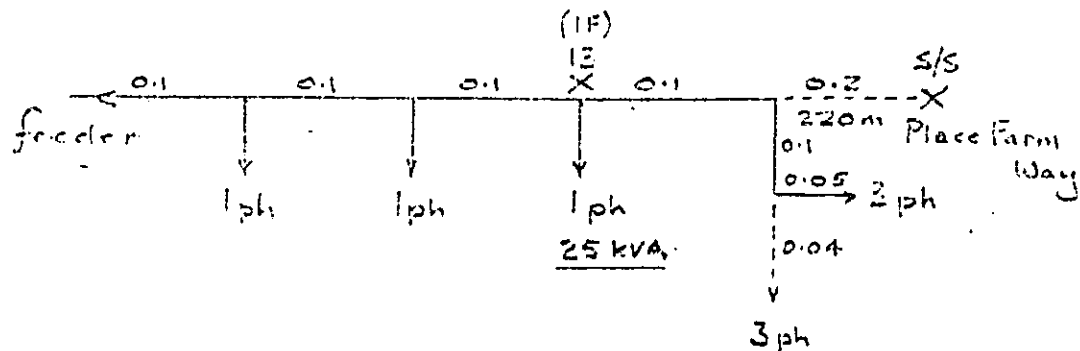
Ref 11



Ref 12



Ref 13



Case 29.Date 4.8.74.Report Data.

1	Potter Row	1556	AR	H10	2002	
2	Temple Croft, Upton	1610	1F	H13	1855	c
3	Rosemead, Halton	"	1F	H9	2000	c
4	Small Holdings, Kings Langley	x 1615	1F	H24	1745	
5	Birch Lane, Flaunden	1615	1F	H18	1920	c
6	Thame Park	1620	1F	H19	2230	d
7	Black Farm, Latimer	1630	1F	H18	2125	a
8	Chivery	∅ "	TR	H9	1440	
9	Mill Farm, Chenies	"	1F	H24	2000	c
10	Rusheynead	"	1F	H23	1940	d
11	Spencers Farm	"	1F	H11	1940	a
12	Game Farm, Hye Green	"	1F	H18	1830	a
13	Poleshill	"	1F	H18	1830	c
14	St. John's Lane, Ashley Green	"	1F	H11	1830	a
15	Hogg Lane	"	1F	H11	1830	c
16	Eastbrook Hay, Lovetts Farm	"	1F	H6	2300	c
17	Jenkins Lane, St. Leonards	"	1F	H9	-	c
18	Tylers, Little Gaddesden	"	1F	H4	2350	g
19	Lombardy Drive, Bourne End	1655	AR	H5	1804	
20	Chartridge Spur	* 1659	2F	H10	2235	c
21	Old Saxe Lane	* 1719	1F	H10	2300	c

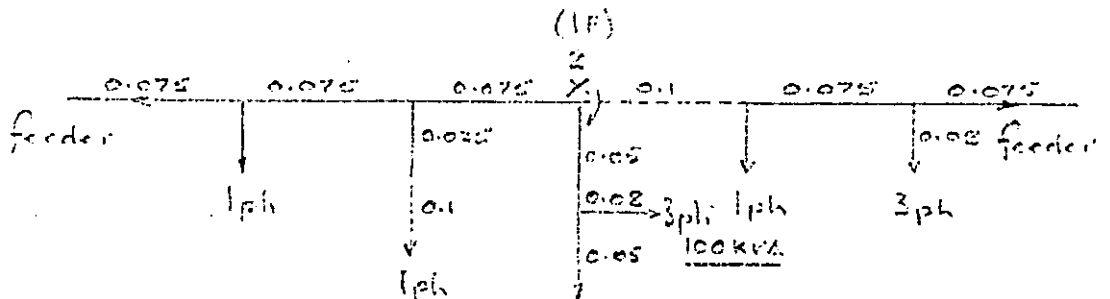
* Repeated fault location or circuit. ∅ Next day. x Not found.

The storm has now shifted to the S.E. and broadened a little to the extent that it fully covers a portion of the Chiltern Hills. Again, all the faults are in the transient classification with the single

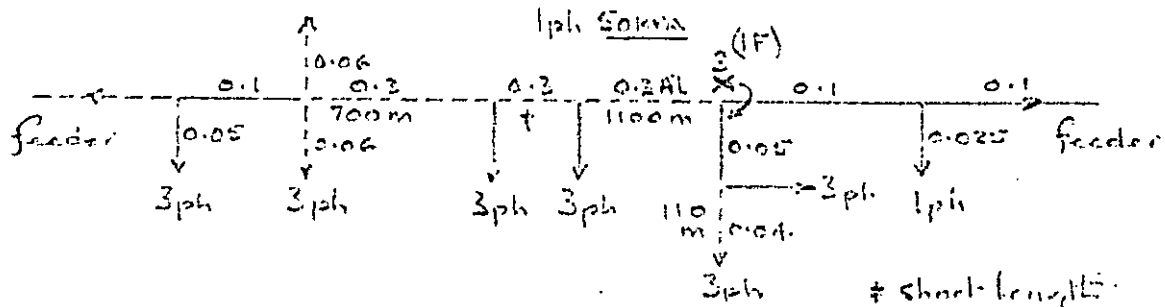
exception of ref. 8. It is likely that this fault, a transformer failure, is linked with 17 as it shows the same log entry time, and is on the same circuit.

Simultaneous fuse operation is to be seen in the majority of the entries but the wide disposition of the outages rather precludes a single stroke source and again the effect of a multiple stroke discharge suggests one explanation. However it is clear that the total entry is unlikely to be the response to a multiple stroke because the distances covered are too great, for example, 4 is probably 20 miles in a direct line from 6, and this is indeed a large distance to attribute to an indirect discharge resulting in a fuse operation in both places. On this basis, it is better to group the faults according to their location. This leaves only a few points in isolation, namely 1, 6 and 21. The majority therefore are associated with a log entry time varying by only 50 minutes. It is concluded that a single stroke is probably responsible for at least 70% of these single fuse actions through the functioning of rod-gaps.

Ref 2



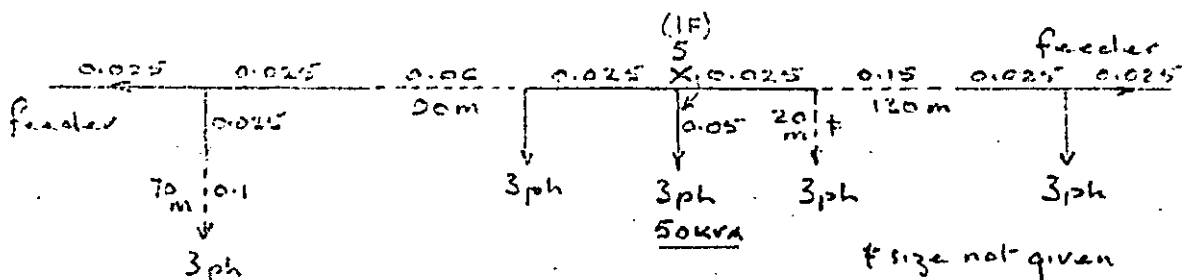
Ref 3



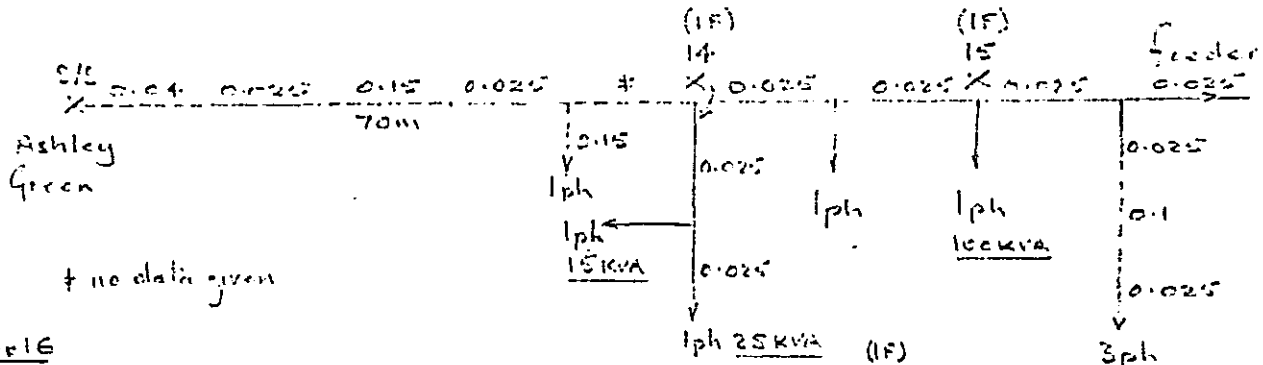
Ref 4

short cable run from nearby substation.

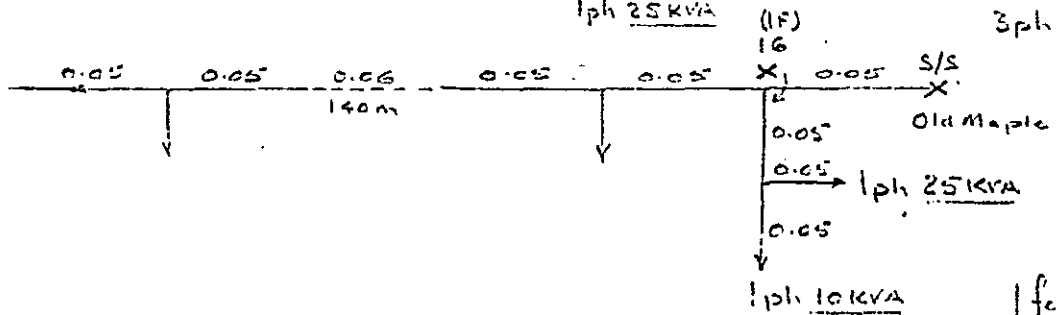
Ref 5



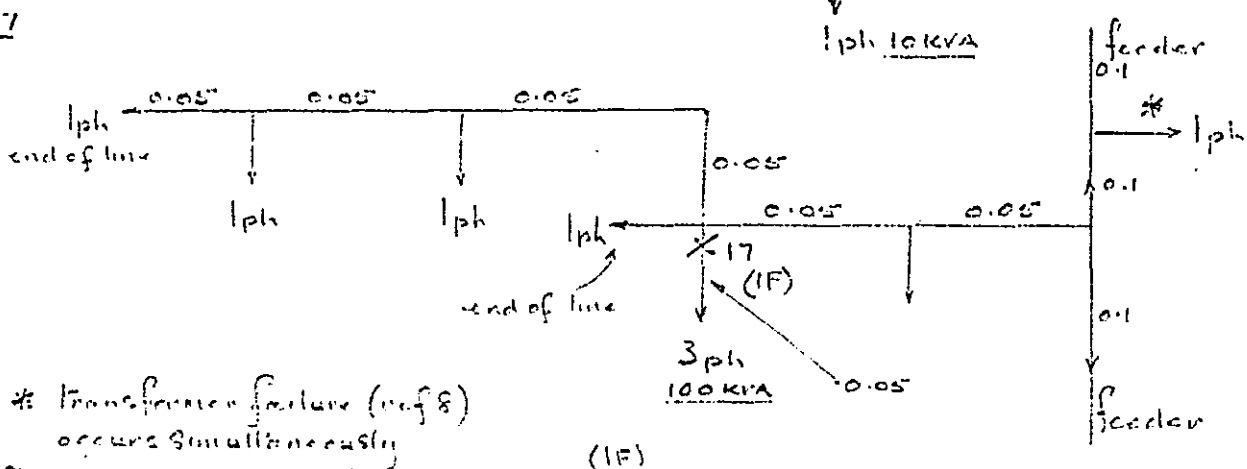
Ref 14 and 15



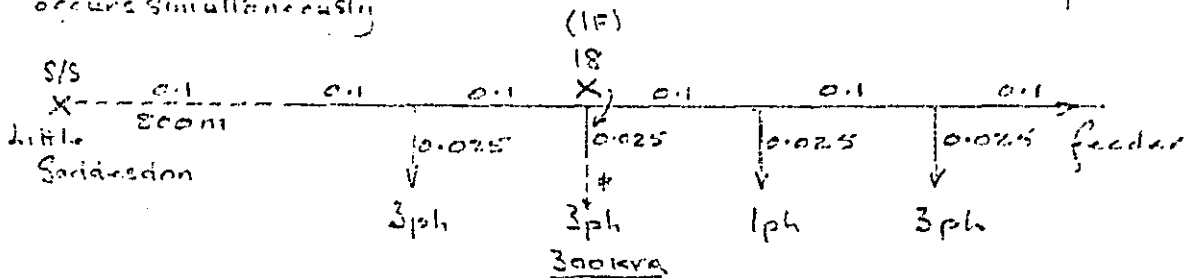
Ref 16



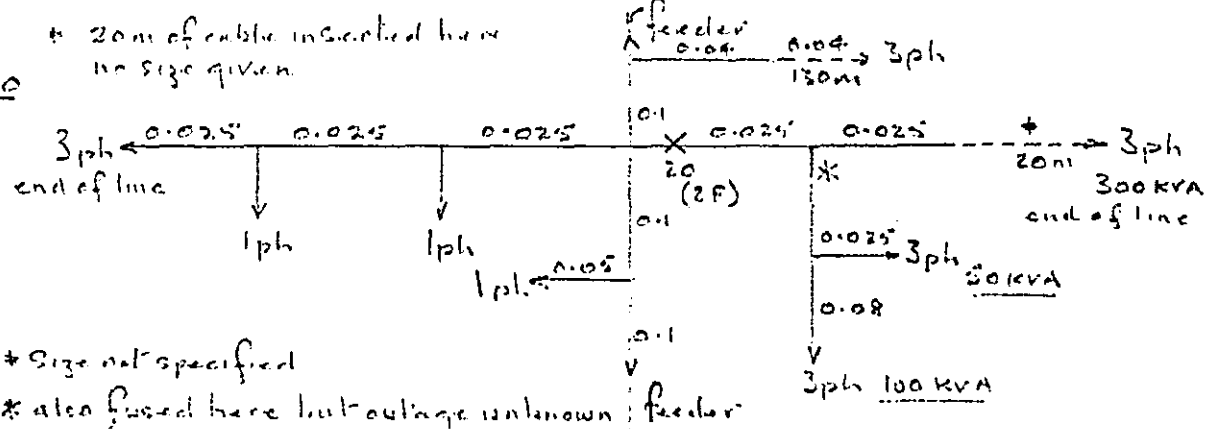
Ref 17



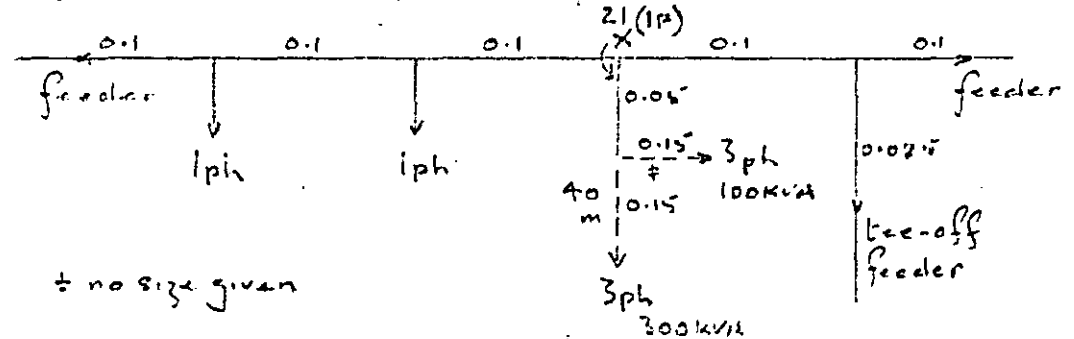
Ref 18



Ref 20



Ref 21



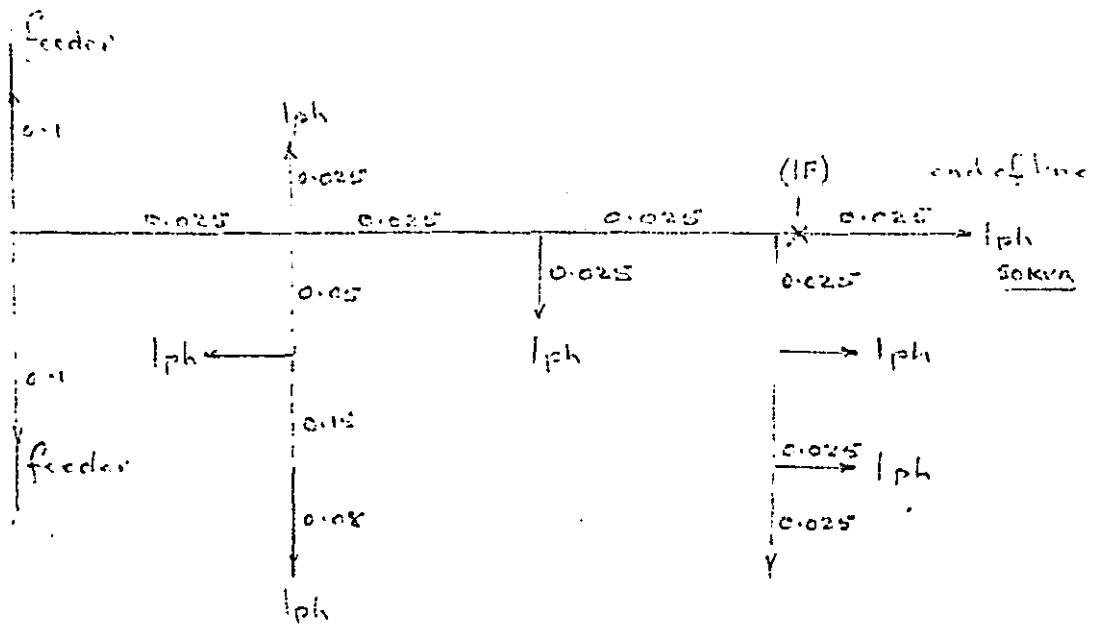
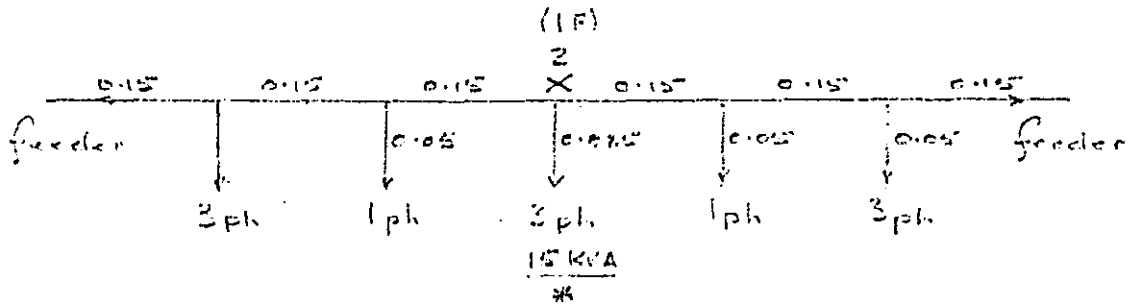
Case 30.Date 4.8.74.Report Data.

1	Hundridge Manor, Bellinger	1759	1F	H10	2315	c
2	Shabbington Sewage, Thame	1800	1F	H13	1118	c
3	North Mill spur, Longwick	"	CON	H20	2115	
4	Orchard Leigh	"	2F	H11	0021	d
5	West Leith	"	AR	H9	1850	
6	Great Gaddeston	1815	AR	H5	1844	
7	North Camp, Willstead	* 1820	TR	H9	0115	
8	Doddeshall - Frederick Street, Aylesbury	1851	AR	H1	1937	
9	Bellingdon spur	* 2026	TR	H11	1220	

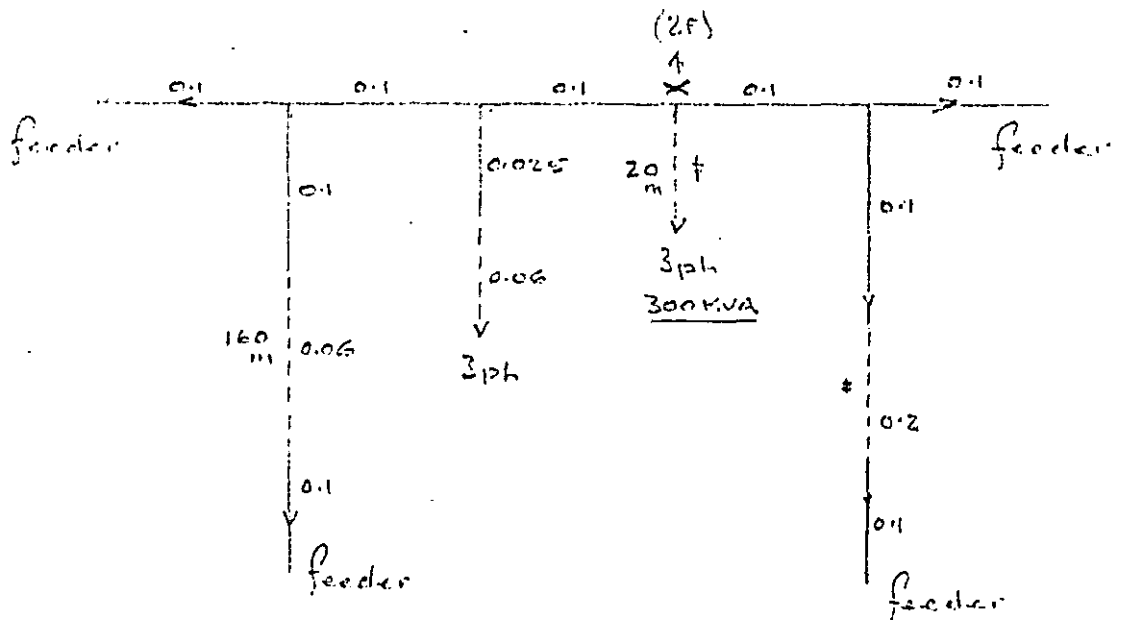
* Next day.

In this example, transformer failure is evident as with case 27 and the previous case. If, as suggested, the flashover of rod gaps is the primary cause of most of the fuse outages, the occasional failure of transformers can also be anticipated (subject to age and frequency of h.v. surging) from the same cause.

The log entries to this case cover a wide area and although identical times appear for four of the items, it is unlikely that there is any close connection between them. Only 2 and 3 are within reasonable proximity to each other in flat country. About twenty five miles separates 2 and 6 and about seventeen miles lie between 2 and 9 and whereas 2 is in the west of the region in flat country, the other items 1, 4, 5, 6 and 9 are all on high ground well to the East. Thus, apart from 2 and 3 which may be the result of a single ground stroke the remaining faults appear as isolated incidents and certainly, the fuse faults, 1, 2 and 4 are separated.

Ref 1Ref 2

* low 3 ph load.

Ref 4

* no size given

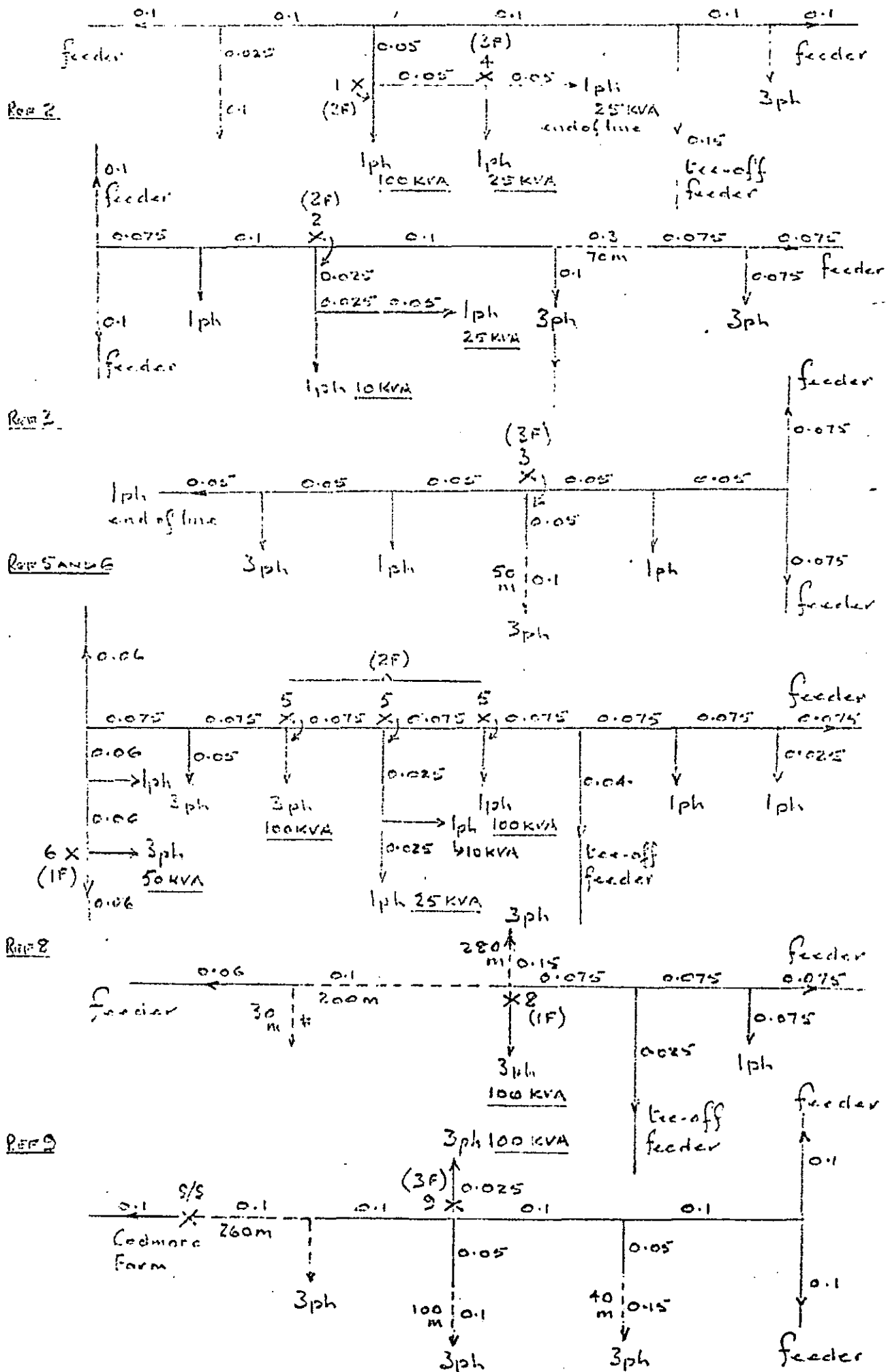
Case 31.Date 1.9.74.Report Data.

1	North Weston spur - Thame Park	1400	2F	H13	1740	a
2	Tythrop House spur, Ilmer	* 1401	2F	H13	1605	a
3	Emmington cross roads spur	"	3F	H19	1940	g
4	Manor Farm, Long Crendon	"	3F	H13	1900	c
5	Waldridge Farm, "Bottle & Glass"	1404	2F	H13	1940	
	Cowley Farm, Low Farm, Dinton	"	2F	H14	"	c
6	Budnall Farm, Pasture Farm, Ilmer	* 1415	1F	H13	0936	a
7	Waddesdon - Cuddington Bridge	1426	AR	H7	1523	
8	Cuddington Baptist Chapel spur	"	1F	H7	1830	a
9	"Hen & Chicken", Lye Green spur	1500	3F	H11	1740	c

* Repeat fault location or circuit.

This is an unusual log entry since there are three references to 3-fuse action. Although all the entries are classified as transient, it can be assumed that the storm period of 1 hour is fairly active to produce such a high proportion of multi-fuse faults, many of which occur virtually simultaneously. All faults are located in the same area to the west of the region and to the N. of the Chiltern Hills. Two circuits provide for pairs of faults, but in general the related circuits are isolated.

It is suggested that with the increased storm activity shown here, the presence of a prestrike component should be included to account for increase in the multi-fuse action especially for those references marked for 3-fuse faults. The circuit diagrams for those particular references (3, 4 and 9) show no special features of basic topology which could suggest direct travelling wave reasons for the response, and it is concluded that special consideration is justified for each of these entries.

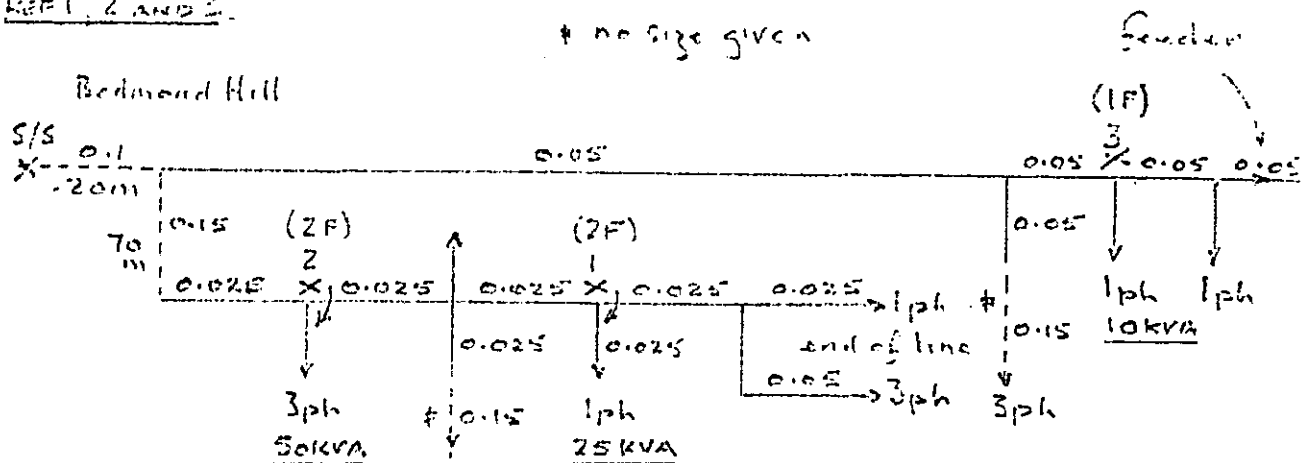
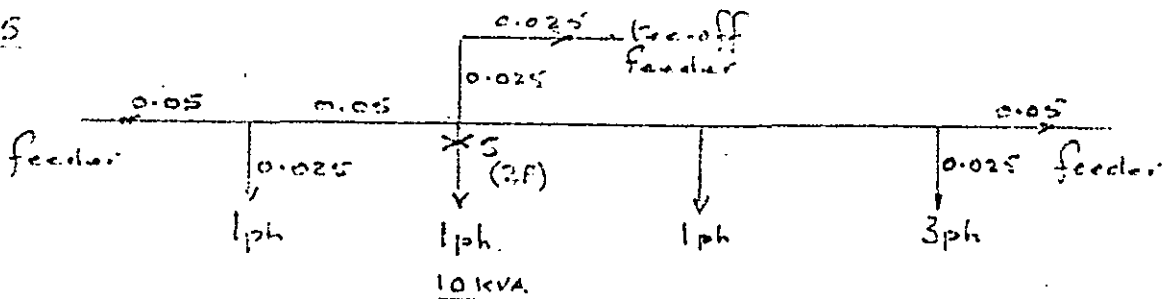


Case 32.Date 7.3.75.Report Data.

1	Hyde Lane Farm, Bedmond Hill	1542	2F	H18	2100	c
2	Harthall Farm, Bedmond Hill	"	2F	"	-	c
3	Highwood Hall Farm	"	1F	"	1753	a
4	Kings Langley	*	"	AR	H24	1735
5	Dropshort, Jockey End spur	"	2F	H5	1830	a

* Repeat fault location or circuit.

These faults are physically very close together and, with simultaneous action, a clear example of the response to a nearby lightning discharge. The ground stroke appears to indicate a directional property since only two circuits are affected. One of these produced three outages so that travelling waves are probably responsible. The induced surge level is seen to be quite moderate.

REF 1, 2 AND 3.REF 5

Case 33.Date 30.4.75.Report Data.

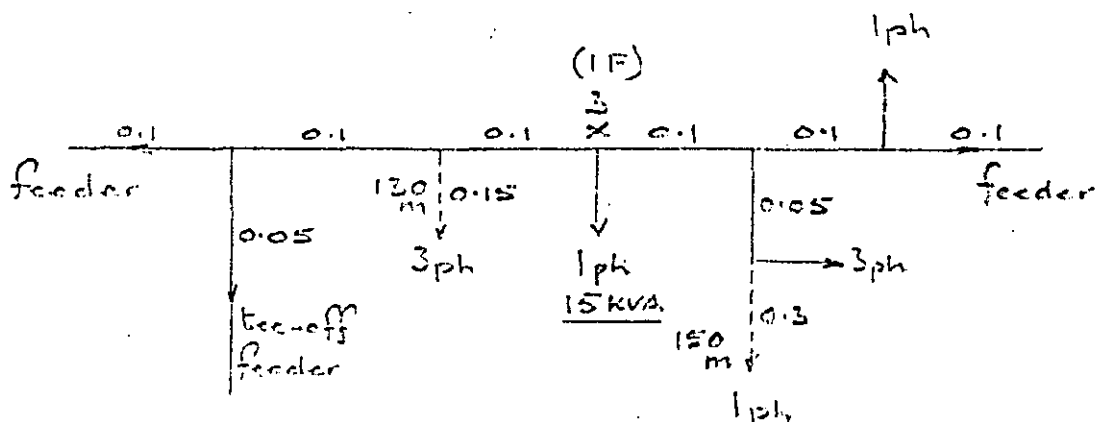
1	Chartridge spur	*	1750	2F	H10	2240	c
2	Kings Ash, Wendover		"	TR	H10	2158	
3	Dutchlands Farm	*	1800	1F	H16	2300	a

* Repeat fault location or circuit.

Item 2, although fed by the same feeder, is rather remote to be connected by surge propagation to 1 but these two faults are separated only by a distance of about 2 miles. It is therefore assumed that a single ground stroke accounts for them and they are linked topographically. Both are on high points in the Chiltern Hills.

Ref 1

as Case 22, ref 20

Ref 3

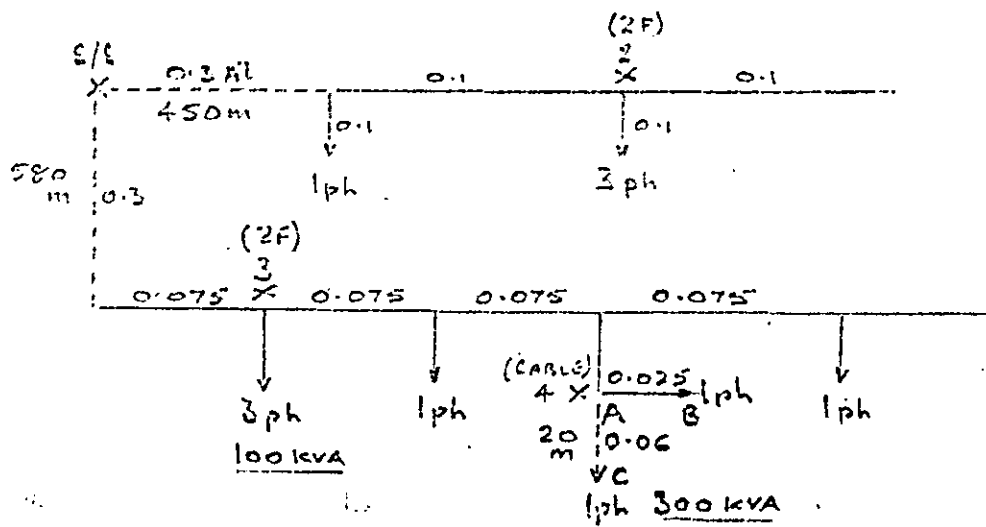
Case 34.Date 17.6.75.Report Data.

1	Westcott Works	x	0830	1F	-	0930
2	Bacombe Road, Wendover		1236	2F	H21	1455 c
3	Ellesborough Road, Tee-off		"	2F	H14	1536 c
4	The Gables, Terrick Cross roads	+	"	CAB	H15	1840

x Not found. + Complete cable replacement between terminal pole and cross roads.

The Gables is actually at the end of the o.h. line AB in the diagram shown. However the fault record states "cable fault" and this must obviously refer to the load at the end of AC which is Terrick Cross Roads. This has the unusual load of 300KVA 1 ph as marked on the electrical diagram H15.

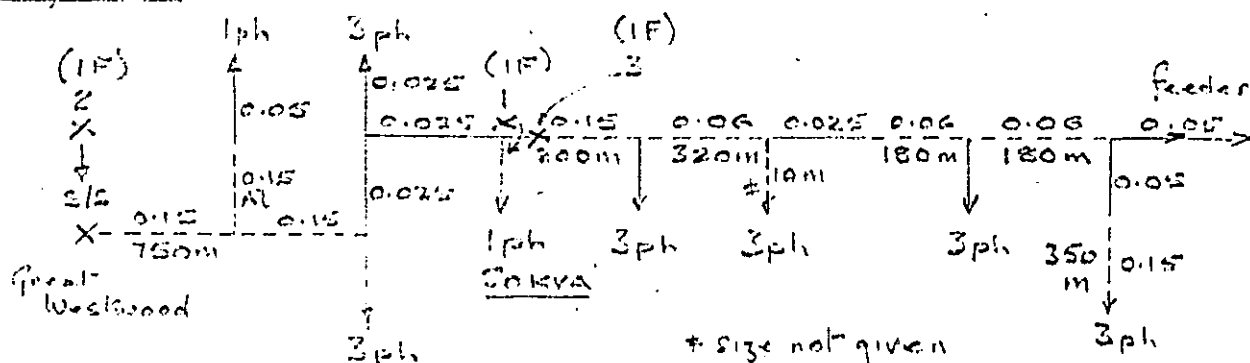
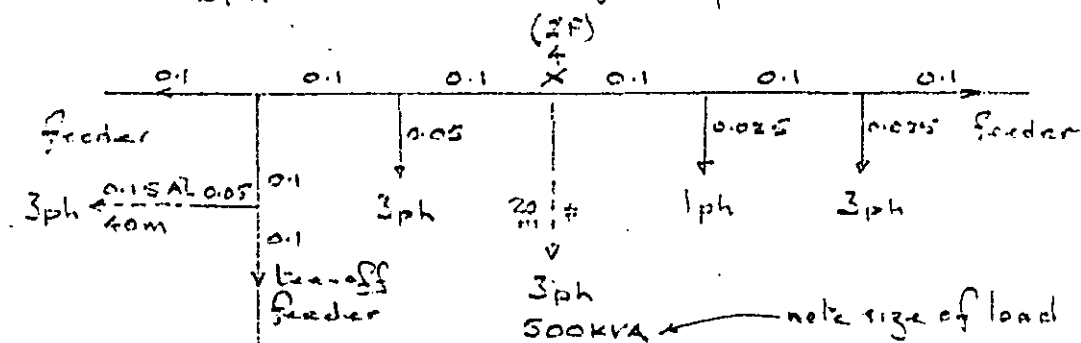
Clearly 2, 3 and 4 are related having identical log entry times; are associated with a common electrical circuit and are situated within 1 to 1½ miles of each other. A single stroke is therefore likely to be responsible. The ground stroke could be fairly close to the point where the cable fault occurred, leading to the two double fuse actions. A direct stroke is unlikely as the damage should then be more extensive.

REF 2 AND 3

Case 35.Date 18.7.75.Report Data.

1	Deadmans Ash Lane, Gt. Westwood	1430	1F	H24	1540	a
2	Chipperfield - Gt. Westwood s/s feeder	"	1F	H24	1528	
3	Deadmans Ash	"	1F	H24	1535	a
4	Jasons Hill	1605	2F	H11	1753	g

Again, a very local group of transient faults the first three of which can be easily linked by location and accounted for by a single ground stroke. The last entry is some 4 miles to the N.W. more than $1\frac{1}{2}$ hours later. It is difficult to know with any certainty whether this is the result of an extension of the storm or simply a late recording of that particular fault. Since there are no further log entries it would appear unlikely that the storm had moved only about 4 miles in that time. It is most likely that the storm left the study area by the S. or S.E. and therefore item 4 is the response to a separate discharge at some time nearer to 1430 hours. All of these outages occur on the high ground of the Chiltern Hills.

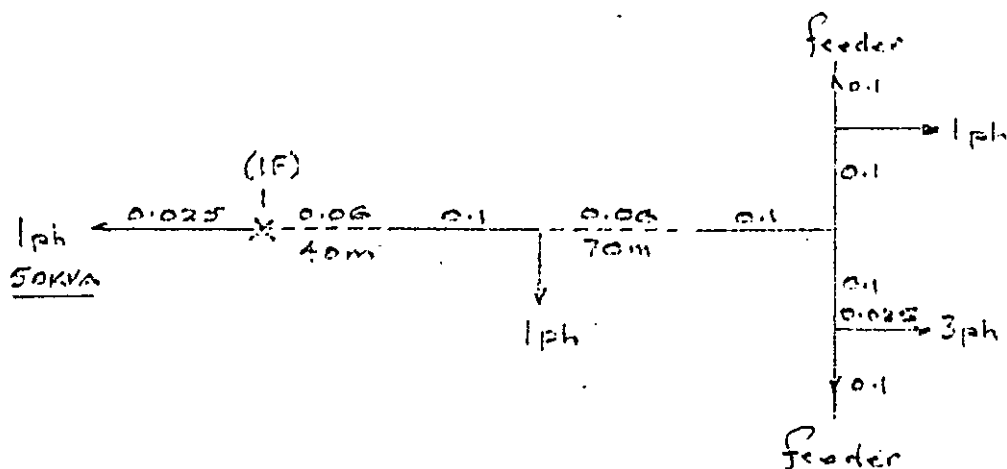
REF 1, 2 AND 3.REF 4.

Case 36.Date 5.8.75.Report Data.

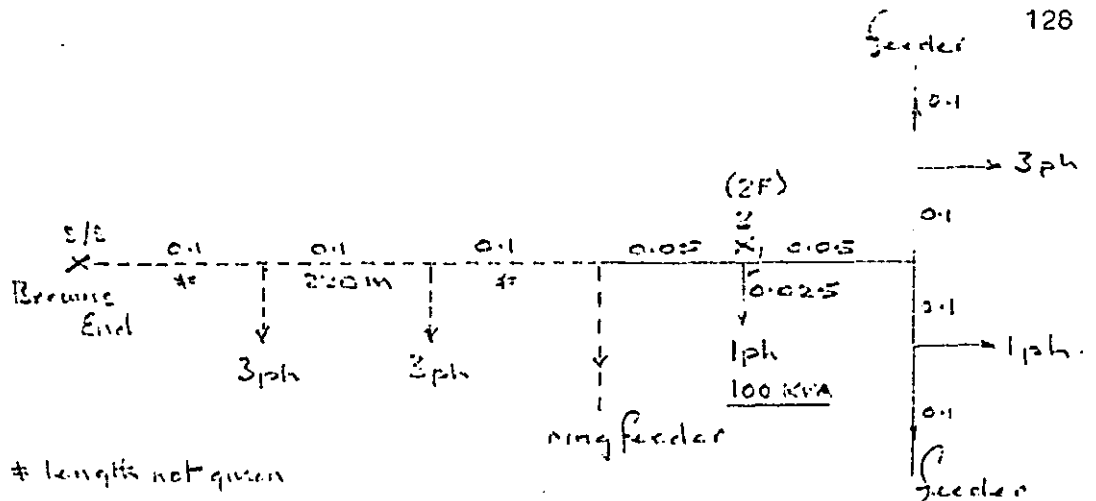
1	Rocketeer, Wendover Dean	1000	1F	H16	1215	h
2	Beamond End	1008	2F	H22	1228	c
3	Ballinger Grove	1011	1F	H10	1137	c
4	Frith Hill, Gt. Missenden	"	AR	H16	1034	
5	Rignall	1020	1F	H16	1230	g
6	Loweever Benston spur	1022	2F	H2	1612	c
7	White End Park Farm	1100	1F	H17	1635	b
8	New Zealand spur	1150	TR	H3	1714	
9	Park Hill Farm spur, Tring Station, Wiggington	1517	TR	H4	2038	
10	Highwood Hall Farm	* 1520	1F	-	1635	

* Repeat fault location or circuit. x Not found.

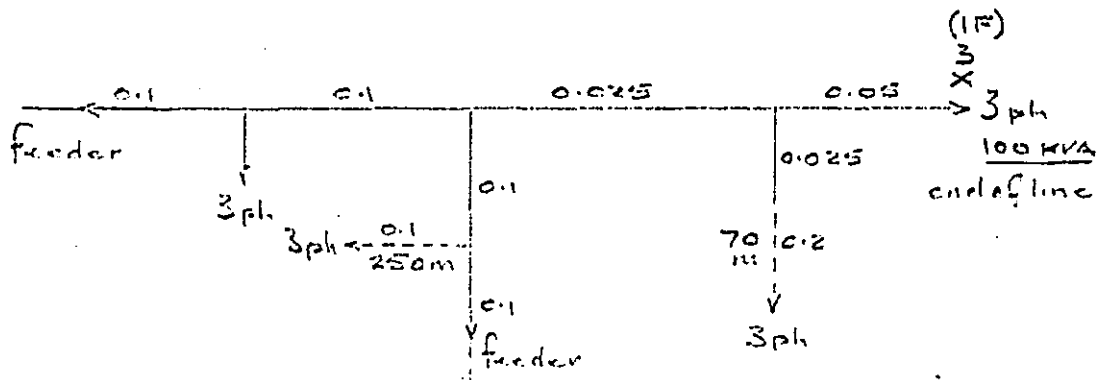
Most of these faults are confined to the Chiltern country on the S.E. side of the study area, but 6, in particular, is to the N. above Aylesbury and well away from the Chiltern Hills. The diagrams show the isolation of these fuse faults and the entry times suggest that perhaps only two of these can be linked to a single excitation and generally the response is to separate ground strokes.

Fig 1

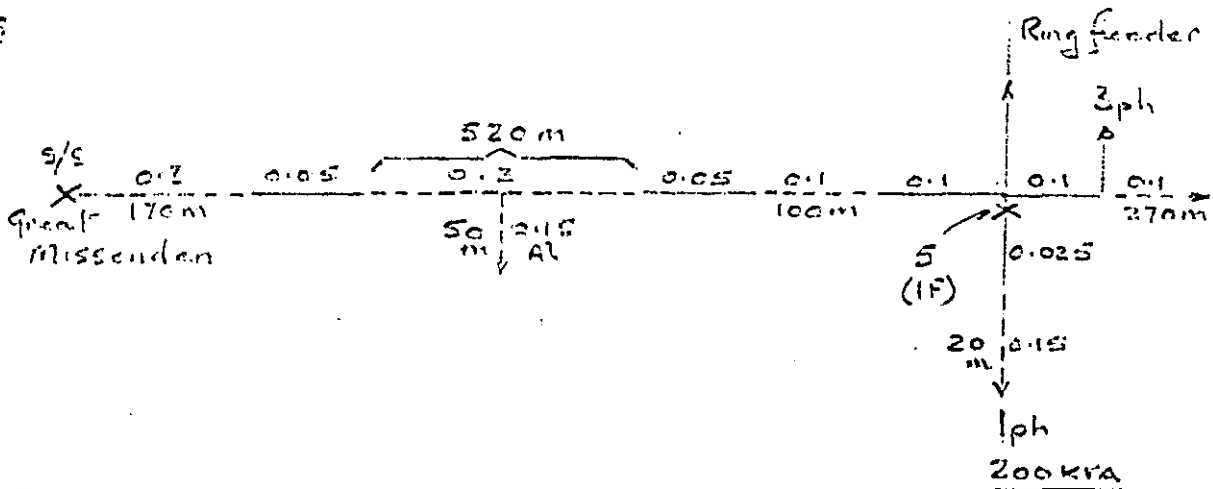
REF 2



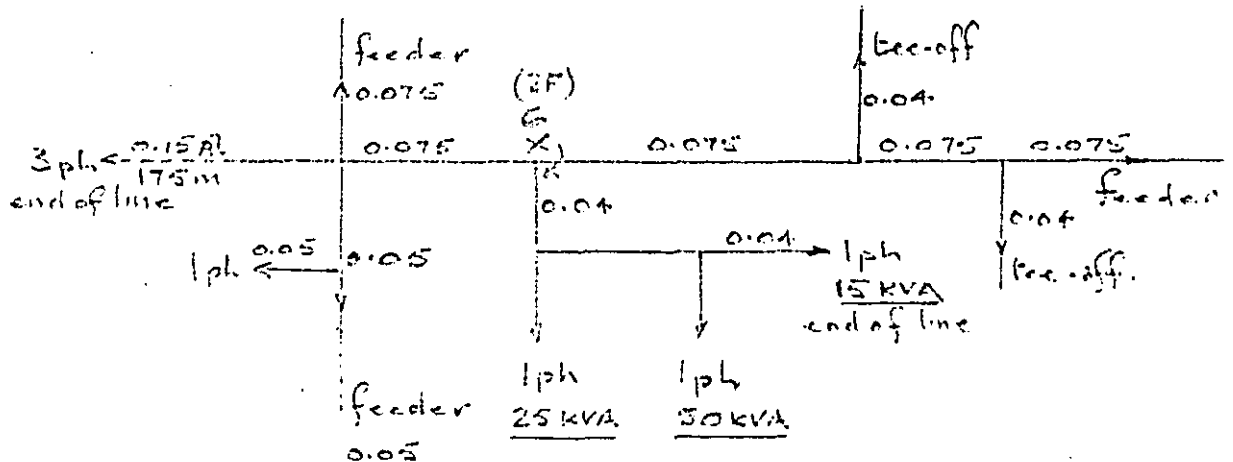
REF 3



REF 5



REF 6



REF 7

as case 16, Reference 25

Case 37.Date 9.8.75.Report Data.

1	Cumberland Close spur	*	0054	3F	H23	0210
2	Cromwell Hill spur, Chinnor Hill	x	0412	TR	H20	1030
3	Cromwell Hill s/s	x	"	TR	"	1030
4	Ilmer No. 1 to Aylesbury East		0635	DIV	"	1320
5	Buckingham Road, Waddesdon	*	"	AR	H2	0700

* Repeat fault location or circuit. x Although reported separately this
is probably the same fault.

Only two faults can be classified as transient. The fuse fault is a completely isolated incident and is shown to be a three-fuse operation at the substation. Item 2/3 could possibly be represented as direct stroke damage since there is no reference to local fuse faults. Reference 4 may refer to the 33 kV side at the primary s/s. as a diverter is involved. The cause of the 3-fuse fault is not seen to include a prestrike component since there are no other instances of fuse action around this time, and indeed, the fault, although attributed to lightning in the records, may not necessarily have this origin.

Ref. 1.

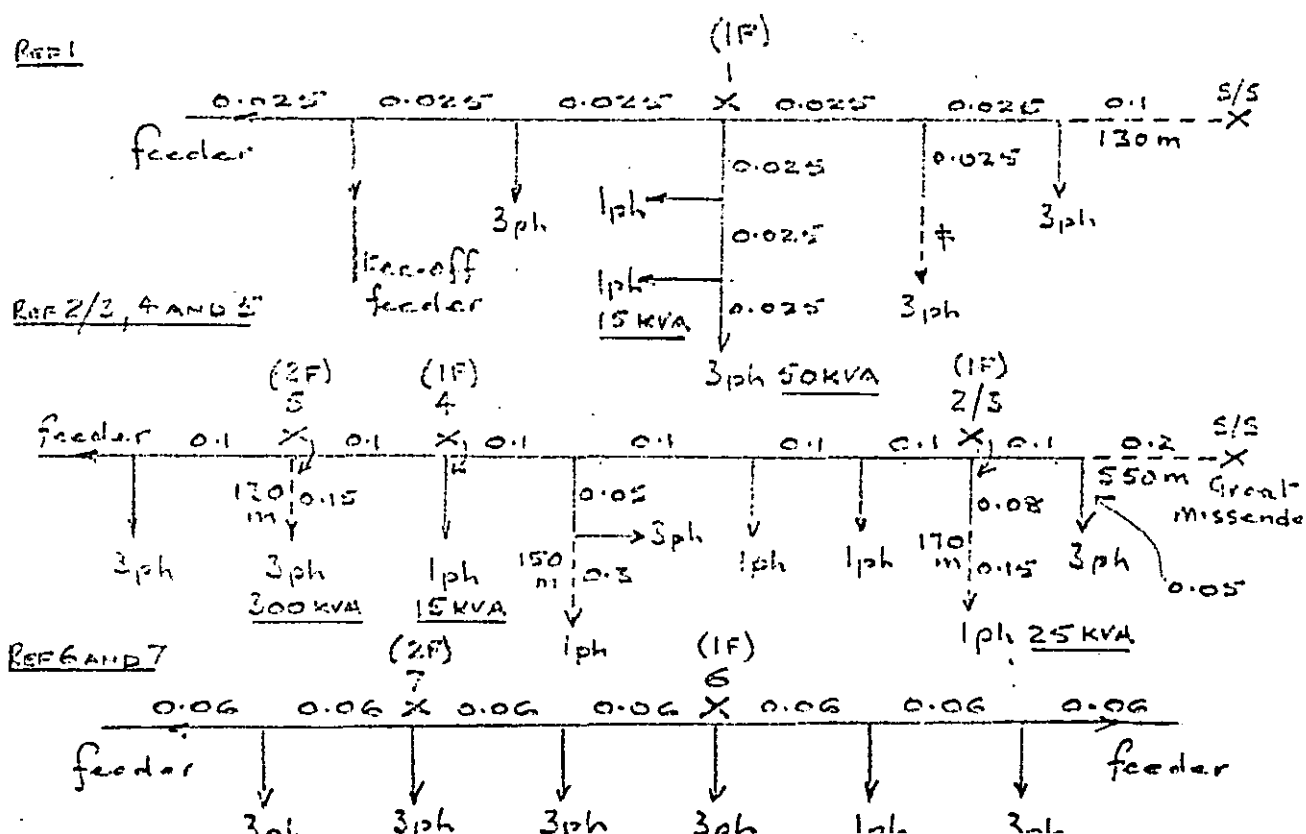
fault at substation - no diagram necessary here.

Case 38.Date 29.5.76.Report Data.

1	Field End Cottage	0958	1F	H10	1445	c
2	Hammonds Hill Farm	"	"	H16	1523	
3	Hammonds Hill Farm Tee-off	"	"	"	1523	c
4	Dutchlands Farm Tee-off	*	"	"	1200	a
5	Wendover Dean Pumping Station	"	2F	"	1125	d
6	Coppice House	*	"	1F	H21	c
7	Parsloe Hillock	"	2F	"	2300	c

* Repeat fault location or circuit.

The location of most of these faults is on high ground within the Chiltern Hills. The greatest separation distance is about 3 miles and since the log entry times are identical, clearly a single ground stroke would account for the group fuse response. It is likely that 2 and 3 refer to the same fault. Four circuits accommodate all the faults and it is noted that two of these have been previously faulted.

Part 1

Case 39.Date 16.7.76.Report Data.

1	Waddesdon	0016	AR	H1	0230	
2	Woodham Brickworks	0030	2F	*	0947	c
3	Frith Hill feeder	0049	PB	H16	1200	
4	Hog Lane Farm	0110	3F	H11	0312	c
5	Manor Farm Spur	* 0130	1F	H13	0949	
6	Keepers Lane, Hyde Heath	"	"	H16	1009	a
7	Weedon Hill	* "	"	H16	1053	a
8	Darlington	* "	"	H17	1100	c
9	Chinnor Hill	* * 0140	2F	H20	1240	c
10	Ballinger Grove	0200	1F	H10	1058	c
11	Kings Langley	* 0223	AR	H24	1119	
12	Great Missenden	0230	AR	H16	0354	
13	Ballinger Bottom	"	CON	H10	1559	
14	Chiltern Road, Ballinger	"	PB	"	1200	
15	Ballinger	"	1F	"	1118	g
16	Ballinger Grove	* "	CON	"	1009	
17	Mount Pleasant s/s.	"	2F	"	1135	a
18	Gaybird Farm	"	CAB	H16	1730	
19	Lodge Farm spur	0240	2F	"	1007	a
20	Northchurch Farm	* 0300	1F	H4	1600	c
21	Greyholme Egg Farm	0713	"	H22	0908	a
22	Stephens Close	"	CAB	"	1700	
23	Peterlea	"	CAB	"	0755	
24	Chartridge End	* 1134	TR	H10	-	
25	Ashendon	-	2F	H1	-	c

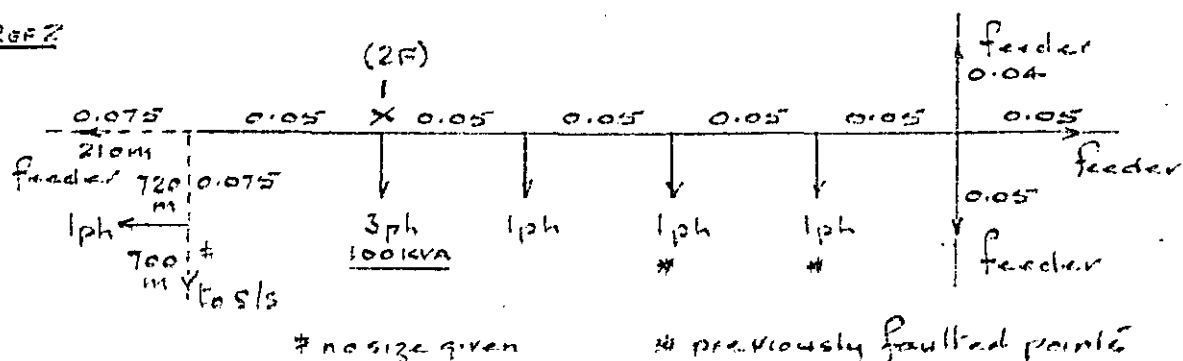
* Repeat fault location or circuit.

Autorecloser operation has only moderate success here with 12% of the total outages, but this could be due to their absence from the affected circuits. Nearly one third of the faults are classified as persistent which is well above the usual proportion, and if the pole-box fault is grouped with the cable fault, this means that 20% of the persistent faults are associated with cables. In which case, faults of this nature can be accounted for solely by the effects of travelling waves. With the high percentage of persistent faults it is assumed that the storm intensity is greater than usual which then also accounts for a number of multi-fuse actions.

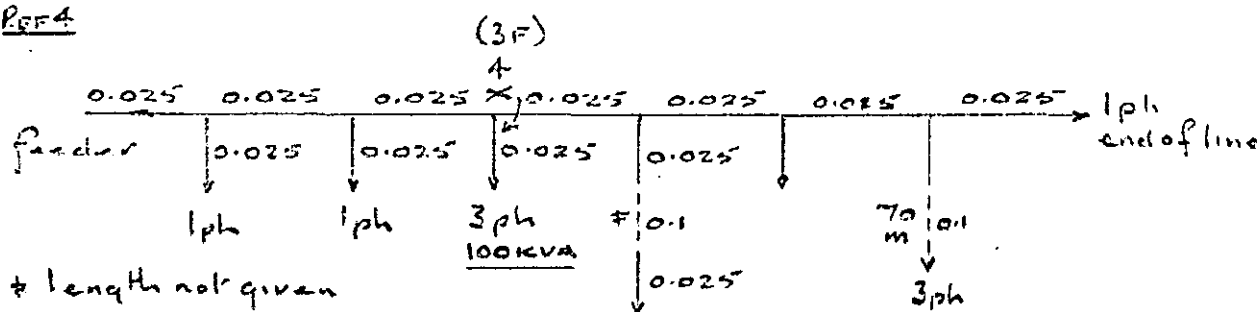
The group of simultaneous single fuse faults (5/8) all take place within a small area of countryside in the Chiltern Hills. A single ground stroke can be assumed to be responsible.

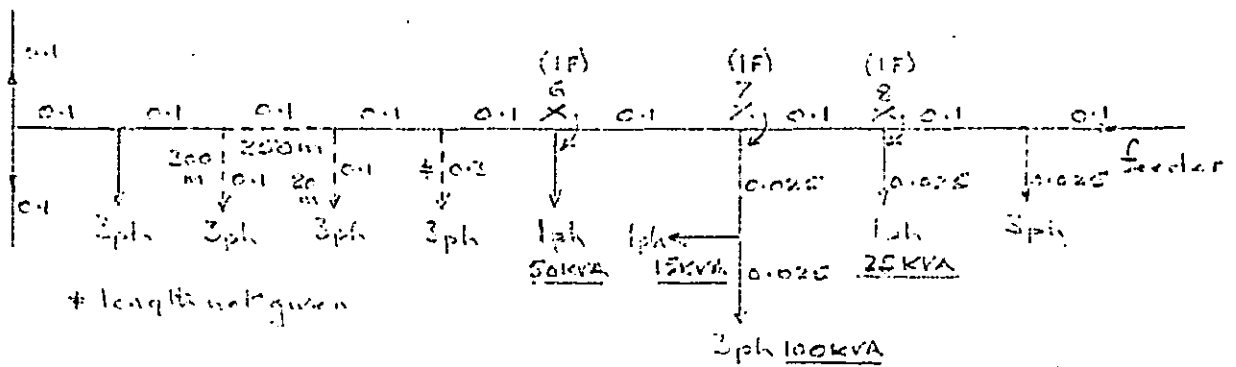
The second and third groups of simultaneous faults (12-18 and 21-23) respectively also take place in the same characteristic countryside but two or three miles further to the north. The nature of these faults suggest that some may be the results of direct stroke attention. Certain remaining items could well be included within these groupings for reasons of topographical connection although their time of entry in the log is a little different. The presence of a prestrike component may be considered in relation to some fuse faults, particularly that of reference 4.

REF 2



REF 4

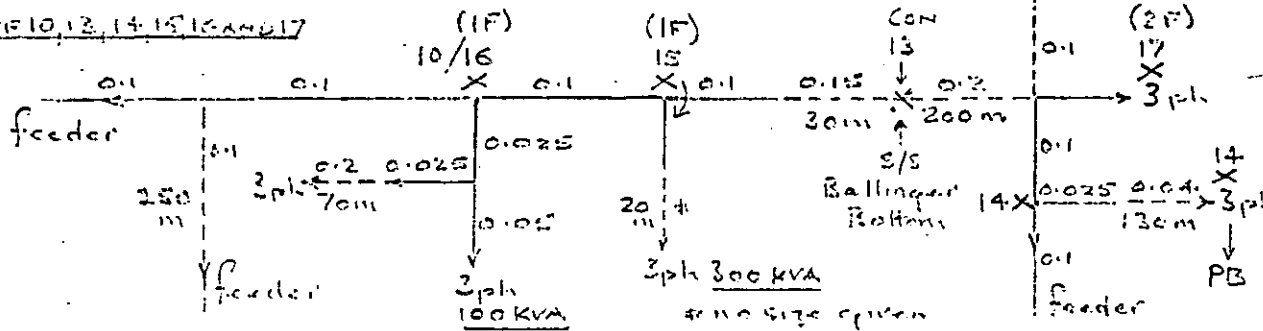




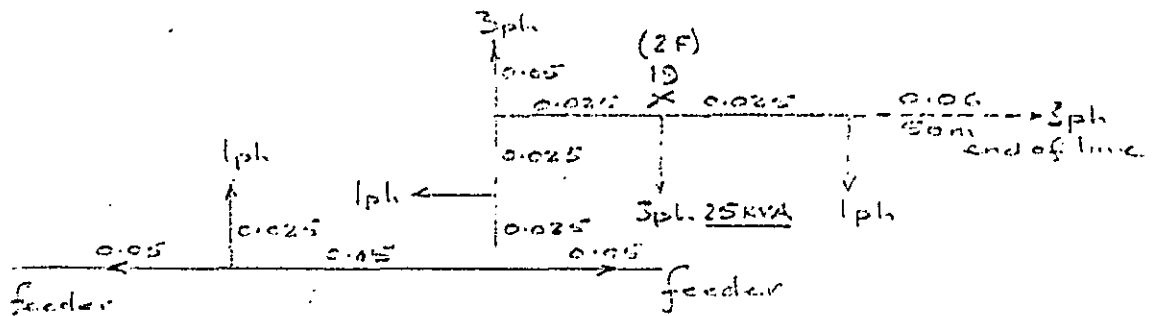
Part C

as case 12, ref 5, and case 2, ref 2.

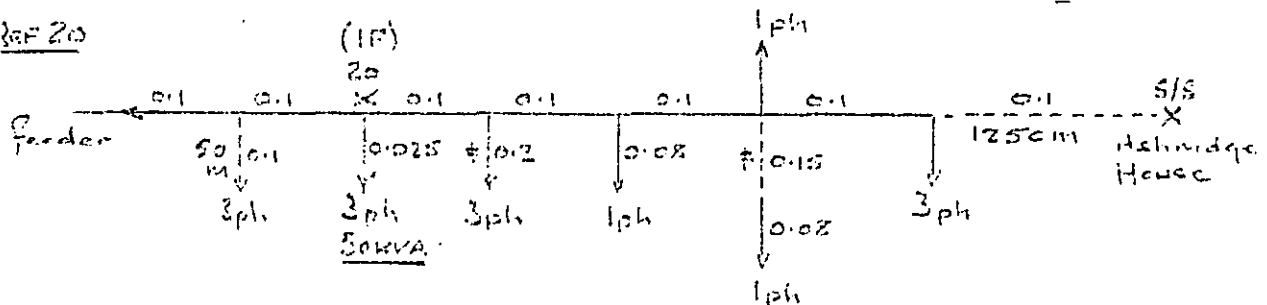
REF 10, 12, 14, 15, 16 AND 17



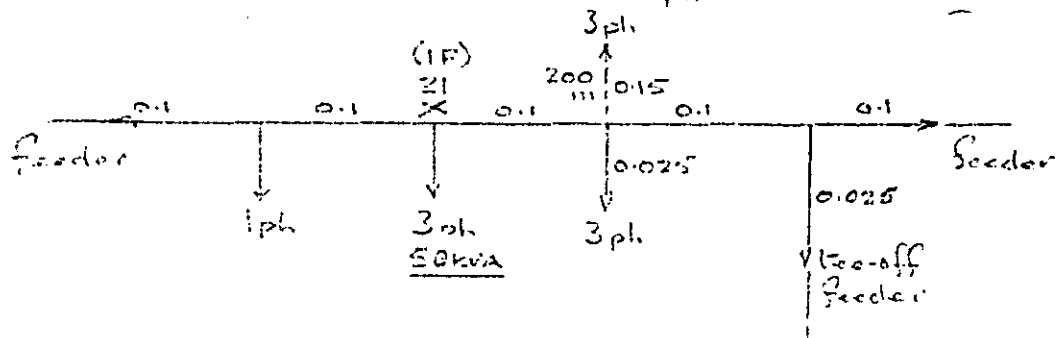
Ref: 13



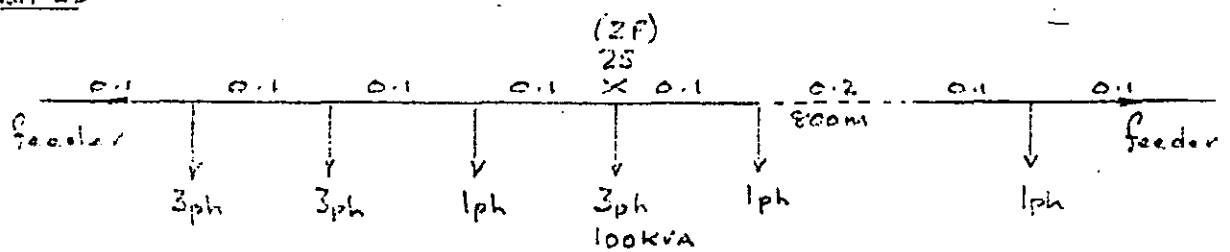
Ref 20



Ref 21



REF 25



Case 40.Date 25.9.76.Report Data.

1	Quainton Sewage	*	0852	TRAN	H1	1030	
2	Hall Farm, Westcott		0052	1F	"	0633	a
3	Glebe Farm, Waddesdon		0052	3F	"	0708	a
4	Upper Cranwell Farm spur		0052	2F	H7	0752	a
5	Manor Farm, Dadbrook		0052	AR	"	0456	
6	Lower South Farm		0052	1F	H1	0925	a
7	Cuddington Mill		0200	1F	H7	1515	c
8	Lower Farm, Westcott		0200	1F	H1	1245	a
9	Spurlands End Farm, Gt. Missenden	∅	0200	2F	-	1245	
10	Crows Nest, Tring	*	0200	1F	H3	1515	c
11	Aylesbury Road, Aston Clinton		0200	2F	"	1408	a
12	Spriggs Alley spur, Saunderton		0226	1F	H20	0955	a
13	Loxborough House, Saunderton spur		0226	1F	H21	1050	a
14	Stoney Lane s/s. Amersham		0241	2F	H24	0810	a
15	Latimer Village, Bois Lane		0241	3F	"	1004	c
16	Bourne End Sewage Works		0250	2F	H5	0854	c
17	Bourne End Church		0250	2F	H11	0823	c
18	Boxted spur, Berkhamsted		0500	2F	H5	0724	c
19	Crows Nest, Tring		0610	2F	H3	1135	a
20	Drayton Beauchamp		0610	1F	"	0950	a

* Repeat fault location or circuit. ∅ Not found.

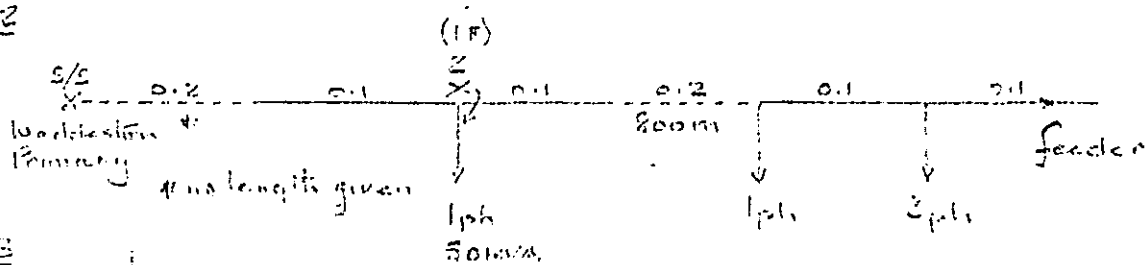
With the exception of the first item, the log is made up entirely of fuse faults and, significantly, there is no record of recloser operation. This could, of course, be due to their absence in the particular circuits.

It is likely that the transformer failure is part of the indirect excitation pattern rather than the result of a direct stroke since no other equipment damage is recorded, and this item is one of the six responses resulting from a probable single ground stroke. Prestrike influence may be considered here in connection with this group which are found to be relatively close together in the N.W. corner of the study area. The greatest separation distance between these faults is about 4 miles, hence all are within the influence of a single discharge.

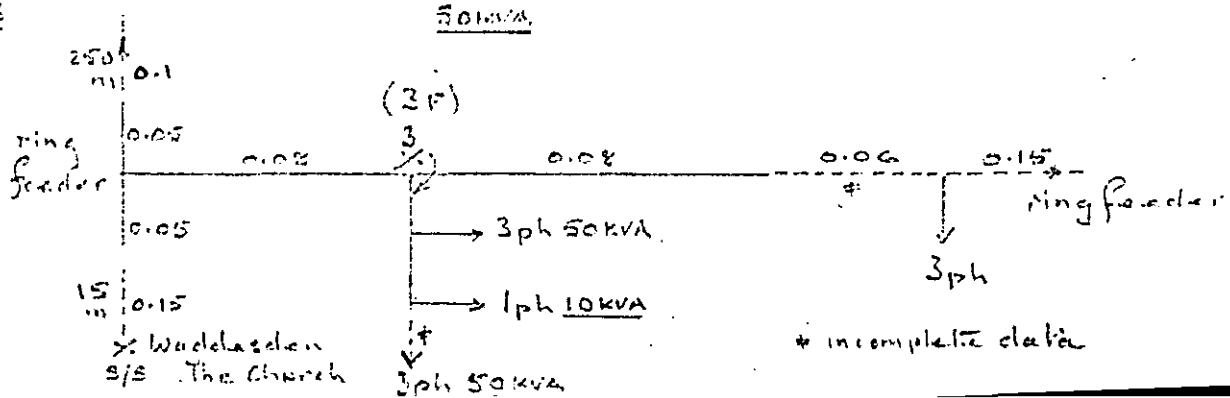
References 7, 8, 10 and 11, are more widespread where 7 and 8 are close to the previous location of references 1-6, whereas 10 and 11 are eight miles to the east. Consequently, although showing the same report time, these two pairs are likely to be responses from separate sources of excitation. There are four subsequent pairs of simultaneous fuse faults all at different times and each pair is clearly the result of single ground strokes, as witnessed by their locations, and to some extent, by common circuits.

The movement of this storm is seen to be slow and its coverage fairly extensive. The drift appears to be to the S.E. from the N.W. over a distance of about 24 miles. It is quite a different storm to the previous case as indeed the log entry shows noting that in the previous case most of the faults are related to the higher ground in the Chilterns whereas in this case many of the faults occur in the Aylesbury Plain.

REF 2

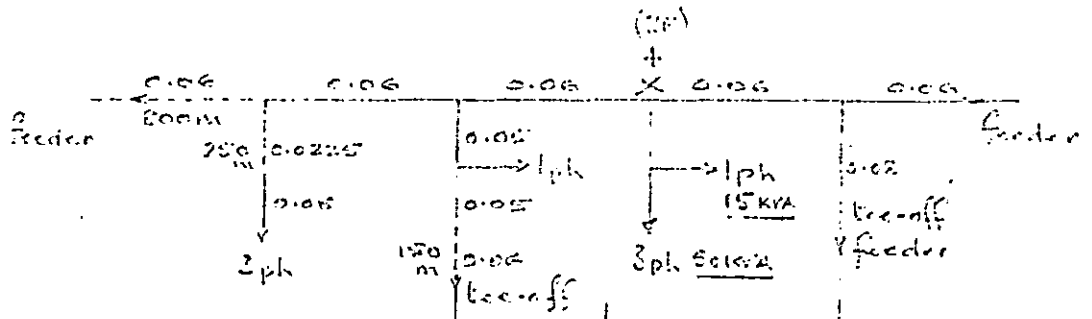


REF 3

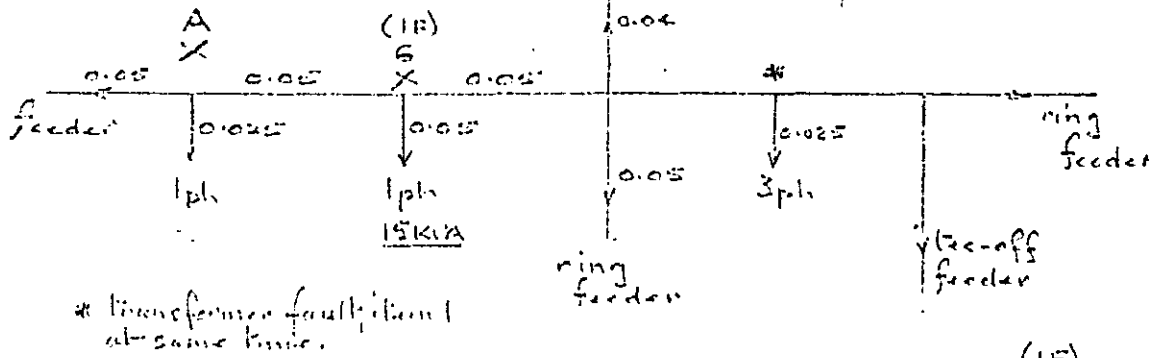


* incomplete data

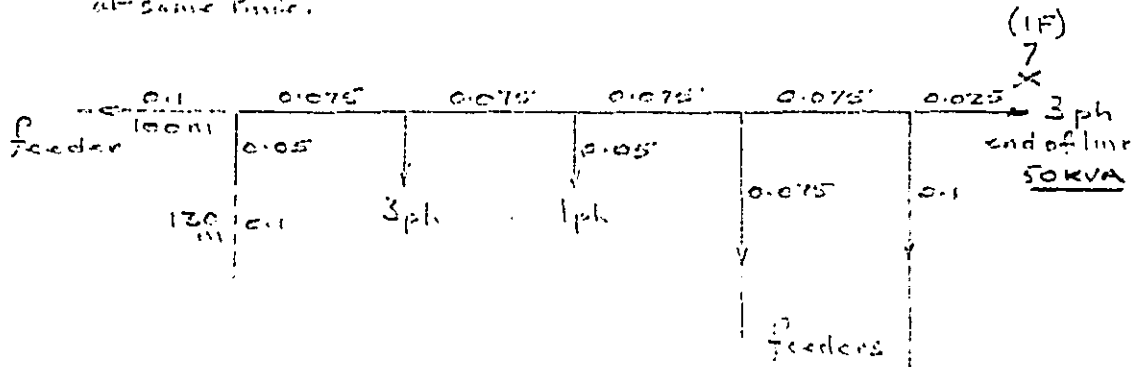
Ref 4



Ref 6



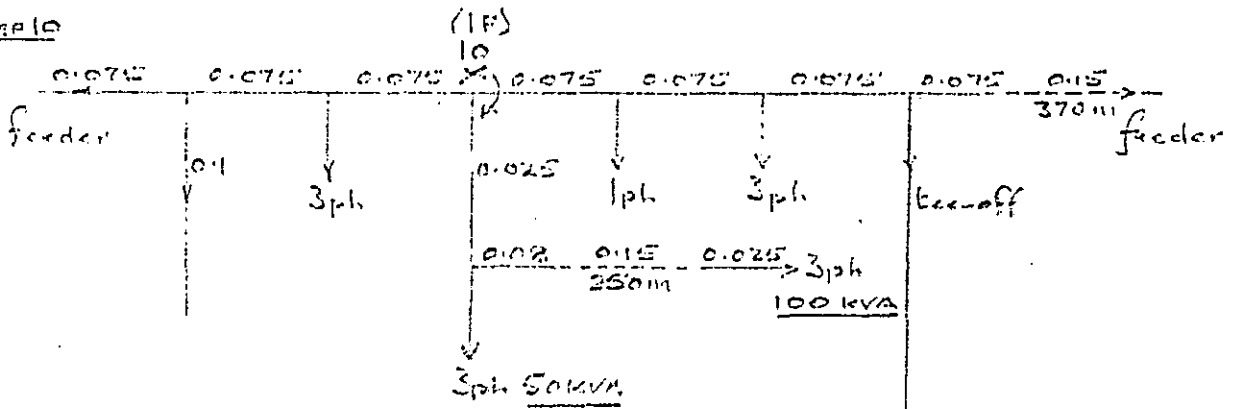
Ref 7



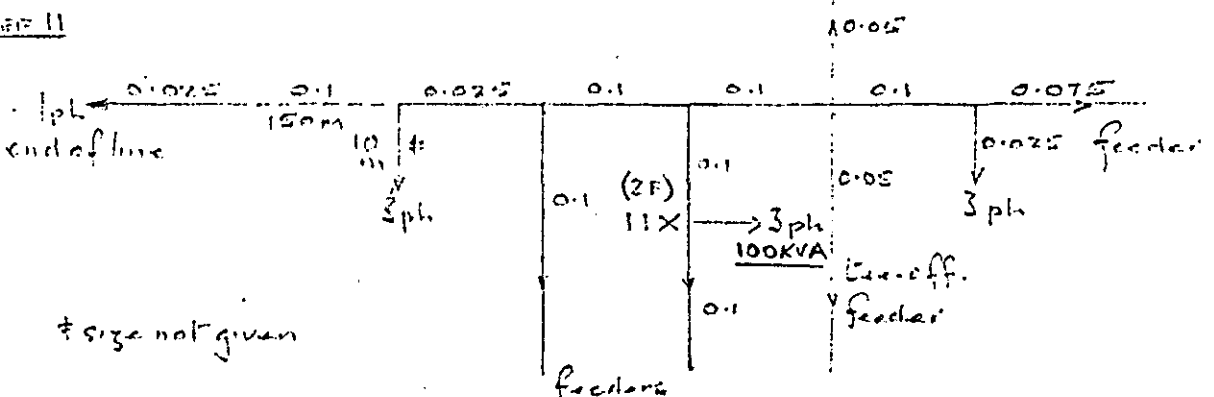
Ref 8

as diagram for reference 6, tree-off A, 1hr, 8mm. after fault G, and recorded as 1ph, 25 kVA, IF.

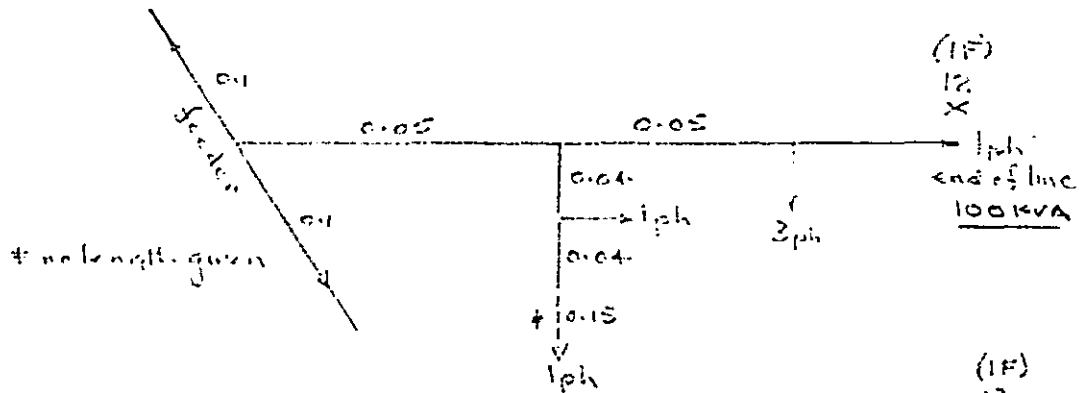
Ref 10



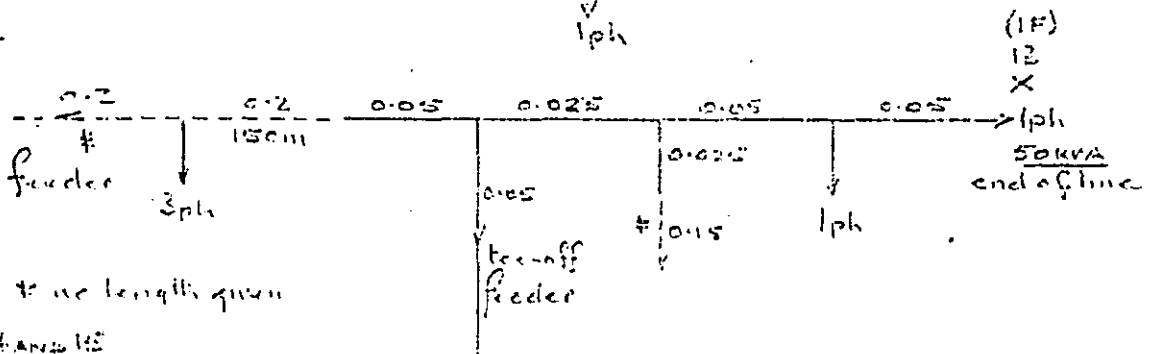
Ref 11



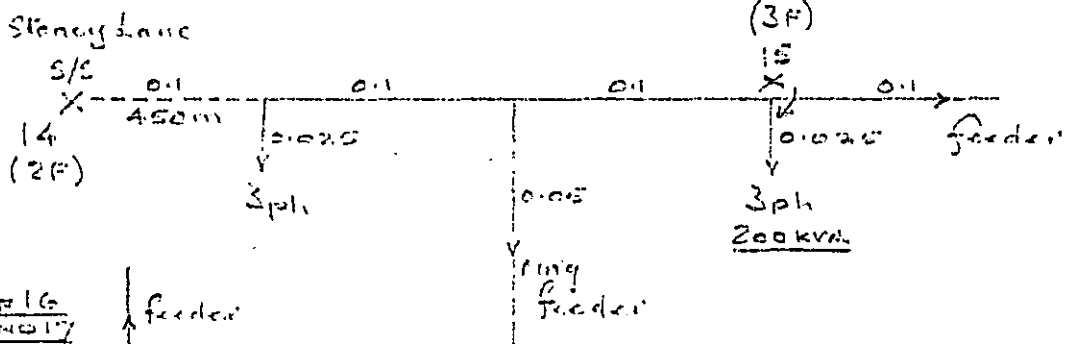
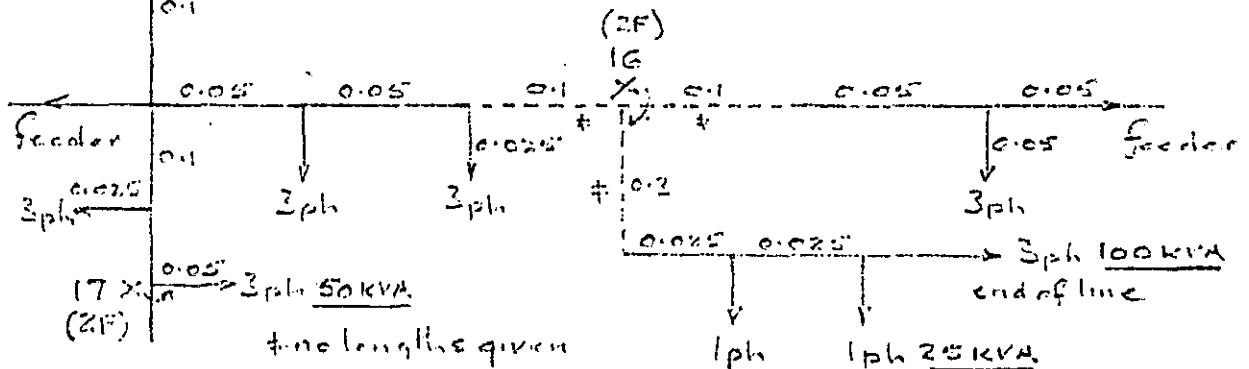
Ref 12



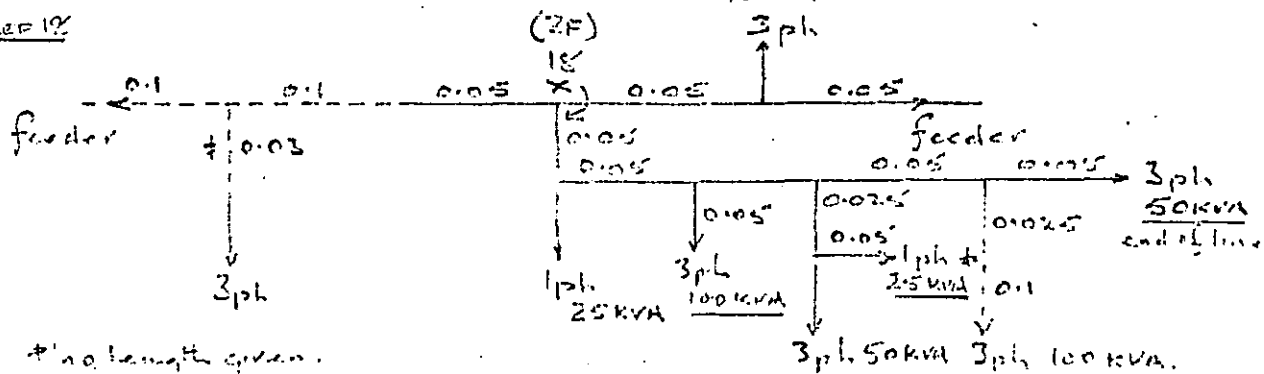
Ref 12



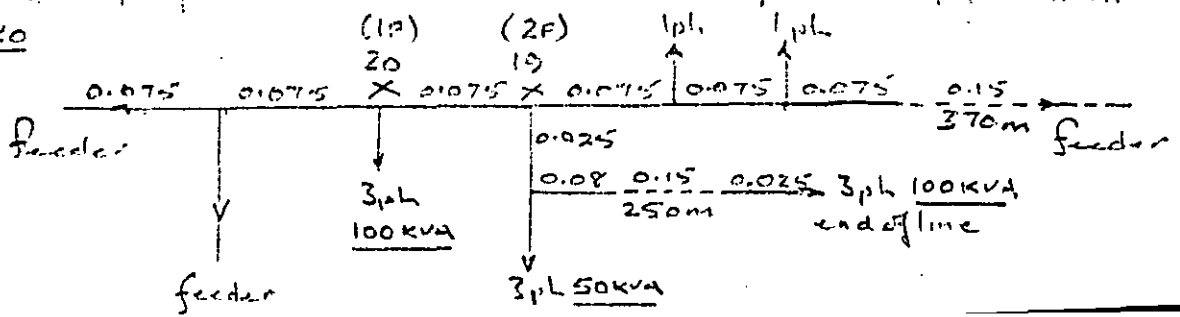
Ref 14 and 15

Ref 16
AND 17

Ref 18

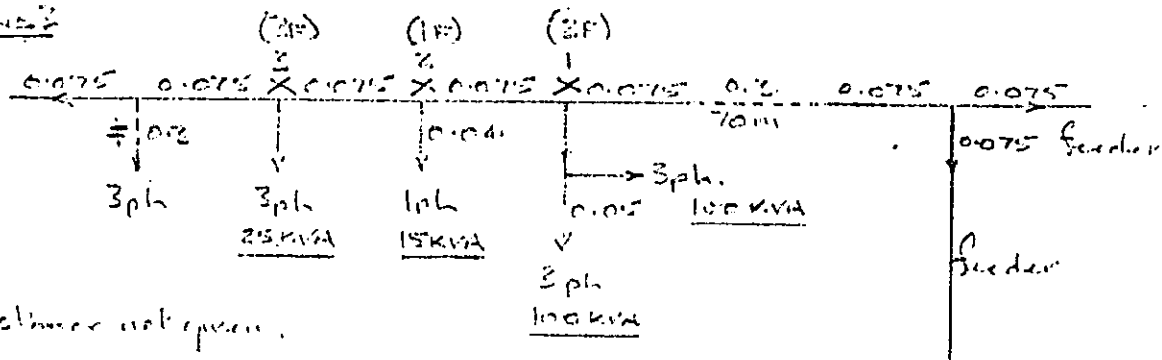


Ref 20

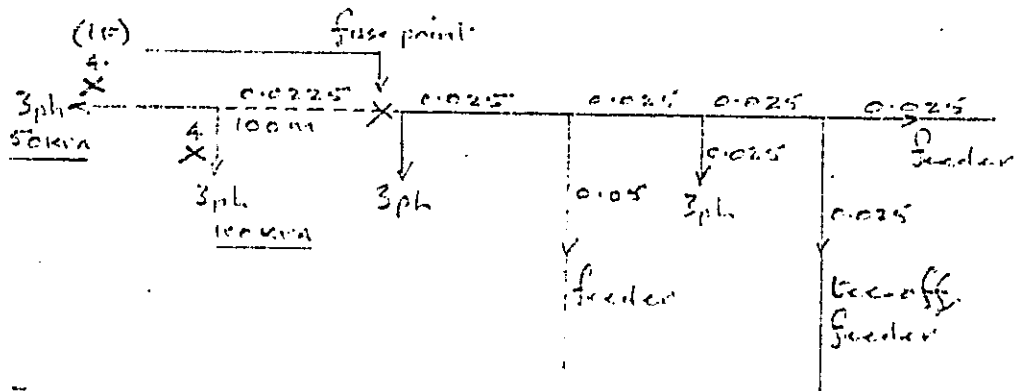


The groups 1, 2 and 3, as well as 6 and 7, are clearly the results of two single ground strokes, but all the fuse references are linked since they lie in the path of the storm on high ground. In this instance, valleys are transverse to this path which establishes the well know characteristic that only hill tops are affected by lightning strokes.

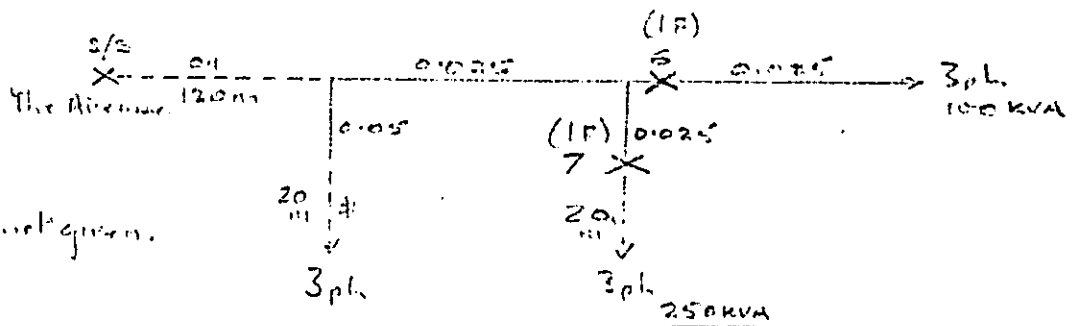
Ref 1, 2 AND 3



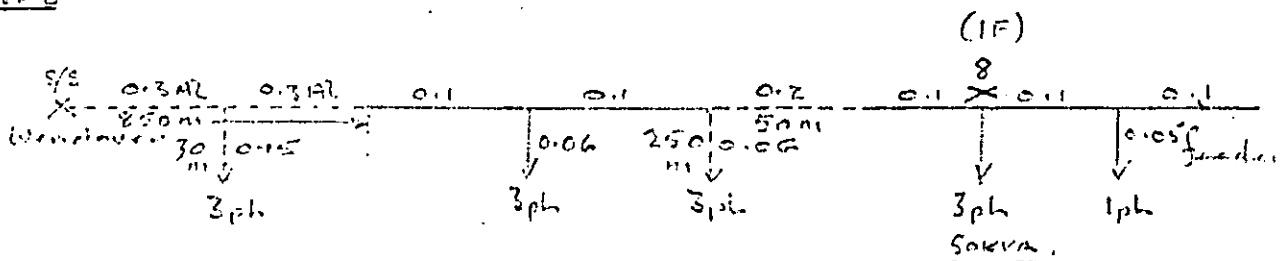
Ref 4.



Ref 6 AND 7



Ref 8



2.3.3 The classification of the case studies.

The 41 examples of same-day faults are represented by 34 fault days. To cover those selected days in 1974, it was found expedient to subdivide the entries on the three days 16th June, 4th August (3 cases each), and 17th June (4 cases). *

These studies can be arranged into three principal groups, viz: those having

- (i) transient faults only, made up of switch and fuse operations
- (ii) transient faults consisting of fuse faults only
- (iii) transient faults with some persistent faults

It is seen that there are 9 cases in the first category, 8 in the second, and 24 in the last group. Hence, there are 17 studies in which no permanent damage to the line equipment is recorded. Further, it is noted that there are 7 studies in group (iii) having only a single persistent fault, and three of these (7, 29 and 40) each contain an average of 20 items and therefore nearly qualify for either groups (i) or (ii). On this basis, it can be concluded that about one half of the examples have no equipment damage and they represent mostly fuse faults.

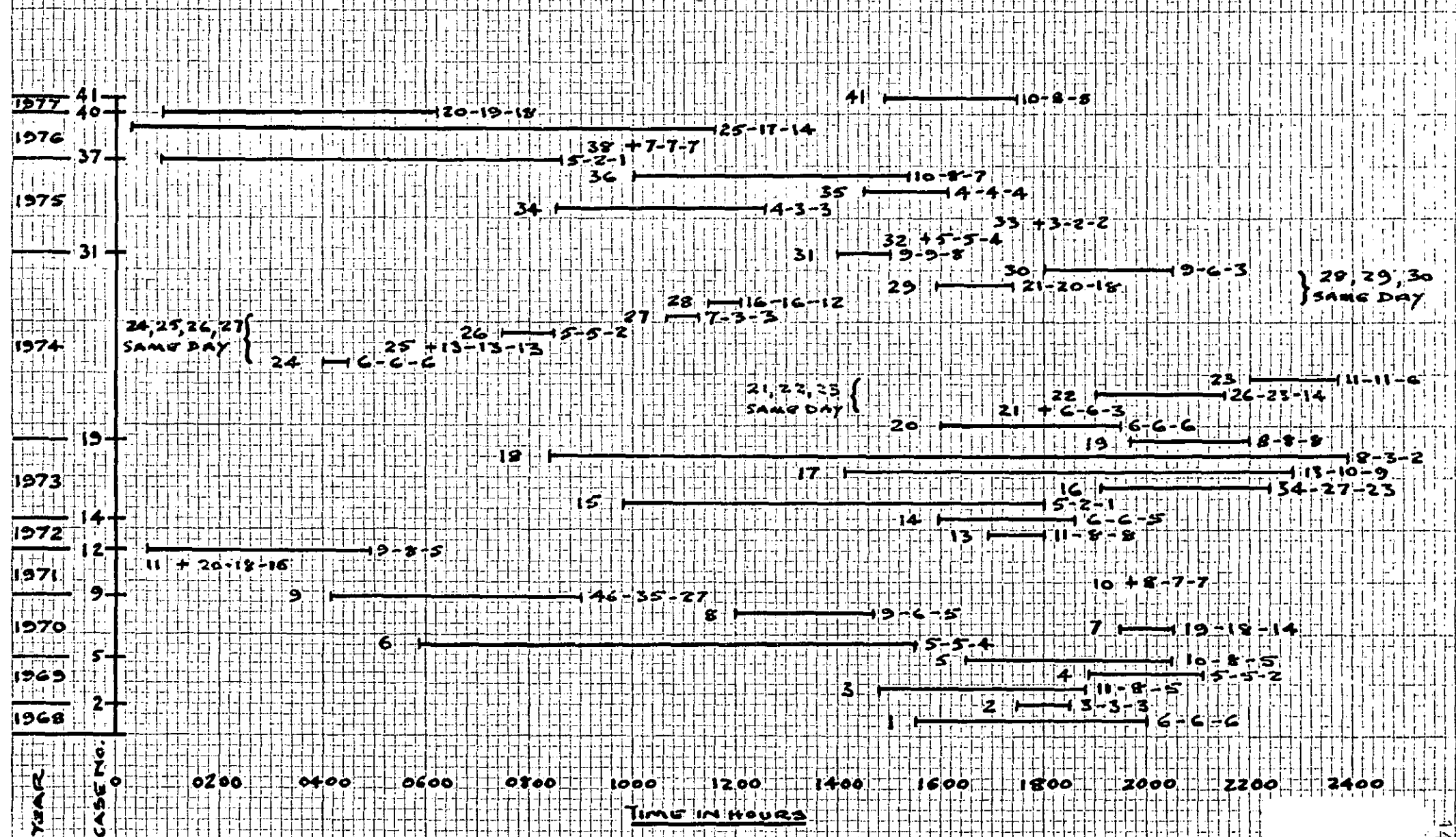
The remaining cases, in the third classification, possess two or more persistent faults but these need to be examined not only in relation to the total number of recorded outages in each case, but also on the fault pattern presented by the outages. The appearance, for instance, of simultaneous groups of faults is found to be a common occurrence, and in fact this is a characteristic which appears in all three groups.

In addition, the time span of the case references is no indication of the contents. For example study 9 possesses the largest number of entries (46) with a logged time of nearly 5 hours, but 32 of these faults

* The selection is based upon the relative isolation of the groups of faults during each of the fault days.

are recorded for the same time (0430 hours), and several others are close to this time. The duration of the log entry may give some indication of a description of the disturbed weather, but not necessarily the duration of the storm, and is not related to similarities in performance when comparing cases. Figure 5 which is an extension of figure 3 on page 46 supplies information on the entry duration in relation to the classification of the faults. The figures on the right of each example are respectively, the total lightning faults, the number of transient faults and those defined as fuse operations only. Some of the case studies are seen to have contents spanning substantial periods of time but when closely examined clearly contain only a few incidents. Case 18, for example, has the longest duration and yet has only 8 faults. At least ten of these cases have records exceeding 4 hours, and it is evident that several have little content. e.g. cases 6 and 15 show only five entries for corresponding times in excess of eight hours. In contrast, six studies are completed by virtually instantaneous fault times. One example is case 11 presenting 20 outages entered over a period of 15 minutes. Since no other fault is recorded in each of the six cases, it is concluded that only part of the storm was within the study area on these occasions. In this investigation, it is assumed that instantaneous fault times are the responses to single lightning discharges to ground. Thus, as most of the studies show some evidence of this response, it can be concluded that such actions can be expected from the majority of lightning storms irrespective of their duration.

Though some reservations are necessary when making an assessment of auto-recloser performance, the efficacy of their presence (inclusive of circuit breaker tripping) is perhaps demonstrated in certain cases where there is a high outage rate. A good example is case 22 showing 34.6% of the total outages (26) over a period of $2\frac{1}{2}$ hours. Cases 7 and 9 are lesser examples giving 21% for a total of 19 faults, and 17.3% for a total of 45 faults.



DIURNAL DISTRIBUTION OF SAME DAY LIGHTNING FAULTS (II) - FAULT IDENTITIES

FIGURE 5

The corresponding times are 1 hour and $2\frac{1}{2}$ hours (if item 46 is discounted). Higher percentages of autoswitch operation are achieved (as in cases 21 and 26), where the total number of faults is few, but these examples really have less significance and it is difficult to make comparisons. Again, in the "middle range", assessment remains uncertain as illustrated by cases 23 and 25. In the former, the total number of outages is eleven and five of these are due to autorecloser operations. The rest are fuse faults. In the latter, there are thirteen outages all of which are fuse faults.

Electrical circuits having association with more than one fuse fault are shown to be present in quite a number of the cases. In fact, they exist in about 63% of the examples, but in terms of the number of fuse faults so connected, it reduces to about 33% of the total fuse faults. This means that about one third of these outages are linked conductively in some way. These faults however may not occur at the same time although actually this is found to be so in the large number of the examples. Summarising the common circuit identity, the following table displayed below also relates these faults with the number of circuits involved, together with the total number of faults.

Table 4.

Case No.	1	2	3	6	7	8	9	11	13	14	16	18	19
* No. of linked faults	2	3	2	2	7	4	6	5	2	2	12	2	4
* No. of total faults	6	3	5	4	14	4	23	15	8	5	21	2	8
No. of linked circuits	1	1	1	1	3	1	2	2	1	1	4	1	2

Case No.	20	24	25	28	29	31	32	34	35	38	39	40	41
* No. of linked faults	5	2	3	6	4	4	3	2	3	3	9	4	5
* No. of total faults	6	6	9	11	17	8	4	2	3	6	13	17	8
No. of linked circuits	1	1	1	3	2	2	1	1	1	1	2	2	2

* fuse faults only.

Hence, just over one half of the 41 examples show one or two common faulted

circuits, and in a few cases (8, 18, 34 and 35), all the fuse faults are associated with one respective circuit.

Simultaneous fuse operations are not confined to linked circuits but also are seen to take place in circuits in isolation. A further classification can therefore be considered concerning (a) the repetition of faulted circuits, and (b) the simultaneity of fuse faults. Thus, the response to one single indirect stroke is seen to result in

- (i) some fuse faults with common circuit connections in which the action is simultaneous.
- (ii) some fuse faults in isolated circuits in which the action is simultaneous.

There remain those responses to separate indirect strokes on the same day resulting in

- (iii) some fuse faults with common circuit connections which then occur at different times.
- (iv) some fuse faults in isolated circuits taking place at different times,

and finally, on separate fault days, there are

- (v) some fuse faults which may be identified with previous faulted circuits or load points.

The cases identified with the above classification are presented in the following table.

Classification	Table 5.	Percentage of total cases.
(i) 1, 3, 7, 8, 9, 11, 13, 14, 16, 18, 20, 24, 25, 28, 29, 31, 32, 34, 35, 38, 39, 40, 41		56.1
(ii) 2, 7, 9, 10, 11, 13, 16, 17, 19, 21, 22, 23, 24, 25, 27, 28, 29, 30, 31, 32, 35, 38, 39, 46		58.5
(iii) 2, 3, 6, 8, 9, 16, 19, 28, 31, 39		24.4
(iv) All cases except 10, 11, 18, 20, 25, 28, 32, 38		80.5
(v) All cases except 2, 4, 5, 18, 19, 20, 26, 28, 30, 34, 35		73.2

From this table it can be shown that four of the studies (9, 16, 31 and 39) are connected with all groups (i) to (v) and whereas three of these have a large number of fuse faults, case 31 has only eight. Four studies (4, 5, 20 and 26) can only be identified with one group. None of these exceed six fuse faults and a low number of faults might well be anticipated in this instance. In general, about two thirds of the case studies can be identified with three or more of the groups. It can be concluded from these observations that a substantial number of fault days can be expected to have the characteristics of simultaneous fuse faults, faults in isolated circuits, and faults in circuits which have had previous lightning attention.

2.3.4 The influence of topography.

The fact that a substantial number of the case studies contain outage points which have appeared as earlier faults is not seen to be fortuitous. Moreover, this occurrence is also extended to some electrical circuits. They give every indication of attracting lightning attention. A similar experience has been met with before in the earlier study by the writer, although not emphasised then in any great detail. In considering the reason for this phenomenon, there can be little doubt, based upon those observations made when compiling the case studies, that the nature of the terrain in association with the prevailing wind at the time of the electric storm have some bearing on the lightning performance of these overhead line distribution systems. The influence of landscape upon the pattern of lightning discharges has been discussed elsewhere,^{*} and a few examples taken from the previous studies will serve to demonstrate the validity of the influencing factors.

Over level ground to the north of the Chiltern Hills, the characteristic lightning response associated with indirect strokes is likely to be either (i) where high points only are selected. The first four items in case 1 are a good example here and the fact that they all refer

* R.H. Golde.

to farms need not be considered unusual. Or (ii) where an exposed level surface of land is presented to the thunderclouds and then attention is more likely to be paid to objects which seriously disturb the uniformity of the equipotential distribution. The cases which include areas of country around Aston Clinton to the South of Aylesbury, and Waddesdon to the north west demonstrate these effects.

The storm pattern in the "hill country" is again of two types. The last example, case 41, is a demonstration where the prevailing wind drives the thunderstorm across the valleys. In the Chilterns, a series of valleys run approximately N.W. to S.E.. The lightning faults are most likely to take place on the high ground between each valley and this is seen to be so in case 41. Whereas, in case 8 the records show a different pattern in a landscape of a similar character where, from the records, the storm appears to be passing along the valleys. Thus, in this example, the lightning faults take place on the lower ground.

Reference has already been made in the appropriate studies where the topographical influence is apparent and clearly affects the fault pattern. However, a topographical component has been evaluated for every reference as a contribution to the fault classification mentioned on page 145.

It is to be noted that those studies with a large number of log entries frequently include both types of terrain. This, for instance, is shown in cases 9, 22, 29, 39 and 40, but not in cases 7 and 16 where the former is associated with the Plain of Aylesbury whilst the latter is confined to the Chiltern country. There is some diversity of total log entry time between all these cases as indicated in figure 5, but it can be largely discounted since all contain groups of simultaneous faults (case 9 is probably the best example) which could well be the subject of topographical interest. It does not follow from this, however, that either hill and valley country or level ground is a prerequisite for

simultaneity in fuse action although cases 7, 13, 25, 29 and 38 for example would yield this information. On the other hand cases 21, 24, 28 and 40, however, show that this need not be so.

2.3.5 Elementary circuit topologies.

Groups a to e of the basic circuits, shown on page 49, represent spurs and tee-offs. These are the principle circuit delineations in the mapping of the h.v. distribution circuits. Consequently the majority of the fuse faults will be found to be identified within the first five of the basic topologies. However, a further three topologies provide a refinement where a fuse fault can be identified clear of bifurcations.

A total of 319 fuse faults are shown from the 41 case studies, but some of these faults are associated with sub-stations and not shown on the case diagrams, and some were not located on the electrical maps H1-H24. This leaves 297 fuse faults distributed among the electrical diagrams accompanying the studies. The analysis of these diagrams according to the letter references representing the elementary topologies is displayed in figure 6 overleaf. Bifurcations a and c represent the majority of these faults (33% and 49% of the total respectively) and it is noted that whereas "a" represent a transformer insertion between lines of about the same surge impedance and therefore there is a discontinuity, "c" is a homogeneous system and is shown to be associated with about half of the fuse faulted circuits.

2.3.6 The prestrike effects.

Prestrike influence as a factor in fuse blowing in thunderstorms has not hitherto been considered by previous investigations of the lightning response of h.v. distribution systems. Only Uchara and Ohwa (Ref. 34, Part I) have suggested that the increase in the electric field intensity and subsequent point discharge effects would be contributing factors. Clearly, there is no evidence that the initial flashover of rod-gaps is

TABLE 6.

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	Totals	
a	3		2	1	1	2		4	1	6	3	6	1			9	2	1	1	1		4	3	2	6	1	1	5	4		4	2	1		2			1	5	10	3	98	
b					3			1	2				1	1		2	1		1		1															1				1		15	
c	3	1	3	1	1	2		8	1	14	3	4	3	5	4		7	5	1	4	2	2	9	3	4	3	2	1	5	10	2	3	2	1	2		3		4	7	7	3	145
d							1				1		1	1		1				1		1					1		2	1							1					12	
e	1								1																																	2	
f							1	1		1	2																															5	
g	1										1		1			1	1		2	2								1	1		1				1	1				1		15	
h											1					1	1																				1		1			5	
Totals	6	3	5	2	5	4	14	4	23	7	15	5	8	5	1	21	9	2	8	6	3	14	6	6	9	3	3	11	17	3	8	4	2	2	3	6	0	6	13	17	8	287	

The distribution of elementary circuits for fuse faults only.

solely achieved, in every case of a transient fault, by a simply incident surge and the doubling effect at terminations. There are reasonable grounds for taking into account a supplementary surge component which could well explain some of the anomalous fuse faults. This component is identified here as a response to the prestrike effects (Griscom, Ref. 23, Part I) and is assessed on the basis of utilising much lower critical ground voltage gradients than are currently considered.

Some evidence for the presence of the component is sought in a few examples taken from the case studies in which the responses are easily explained in terms of single travelling waves. It suggests that attention is paid to the three-fuse fault. There are only ten of these distributed between eight cases. Evidently, the three-fuse transient fault is an infrequent one, and if disassociated from the secondary effects of persistent faults to which it is sometimes attributed, an alternative explanation needs to be found.

Case 12 provides insufficient data from the electrical diagrams as the feeder is a cable and the spur is an l.v. connection which may also be a cable run (not shown on an 11kV diagram system). Case 14 however provides an interesting example. It is assumed that an indirect surge was generated in the 11kV line system nearby. References 1 and 2 are adjacent spurs with 2 associated with the farmhouse and hence the rate of change of the ground gradient would be greater for the latter and it can be assumed that the response could be quite different to reference 1 (one fuse only). Since case 18 has only three transient faults, two of which occur at the same time on a common circuit, it seems reasonable to assume that both propagation and prestrike can be considered as in case 14. Both fuse faults are only about half a mile apart and prestrike influence could have a greater effect on both faults than in the previous example.

In case 21, the three-fuse fault is isolated but linked by a single discharge with two other fuse faults. Possibly the leader head was

in closer proximity to this circuit and so had a stronger influence.

Case 31 is outstanding in that three of the eight fuse actions are 3-fuse, and significantly, two of these together with a 2-fuse outage occur at the same time. However, all are in isolated circuits as also is the third reference to a 3-fuse fault at a different time. The same conclusion is reached as to the reason for these responses as previously indicated. This also applies to cases 37 and 40 which each have a single 3-fuse operation, the latter as part of a simultaneous group response, but again both in isolated circuits.

It is to be noted that in the majority of these examples the elementary circuit topology is the homogeneous bifurcation (type (C)).

2.4 Assessment of field study.

The variation in the lightning performance year by year is very evident with some years recording a high proportion of transient faults in relation to the permanent damage to equipment. One of these years shows an exceptional number of fuse actions.

The prediction of lightning performance from past records, in terms of the relative proportions of transient and persistent faults, is seen to be difficult owing to the nebulous relationship between these group identities.

Overall fuse action and autorecloser operation is shown to be about 80% of the total lightning faults conforming to the findings of a previous investigation by the writer.

Single fuse action total more than half of the transient faults, and recloser protection is successful in nearly one fifth of the outages in this class.

In the persistent fault classification, transformers are clearly shown to be the greatest casualties.

About one half of the case studies are shown to have little or no equipment damage. The outages are, with those exceptions, all transient

faults as defined in this investigation. Thus, the contents of approximately 50% of the studies are the responses to lightning excitation of moderate intensity assumed here to be generated by indirect strokes.

The remaining studies each contain two or more persistent faults which, however, have to be considered in relation to the other faults and the general fault pattern, in each case. But for most of these examples evidence is again presented of responses predominantly due to indirect lightning strokes.

The duration of the lightning fault day as recorded by the first and last items in each study is shown to bear no relation to the number of items, or to the identity of those items. This period of time gives the information as to the duration of the electric storm excitation affecting the overhead line system.

Since there is no relation between the duration of fault conditions and the number of entries in each case study, similarity in performance in comparative cases is unlikely to accompany similar time durations, and this fact is clearly confirmed.

A topographical influence over the lightning fault pattern is demonstrated in a number of the studies, although it is not clear what contribution is also made by the disposition of the overhead line system in those cases. Fault repetition could be accounted for by this combination. Repeated faults are seen to take place throughout the series of studies showing that there is some evidence for lightning catchment areas.

The efficacy of autorecloser presence is assumed to be demonstrated in a few cases.

A prestrike component is used to illustrate that some of the fuse faults are plainly not the response to simple incident surge voltages. A number of the case studies present anomalous effects of this type. Examples of the infrequent 3-fuse fault are included in this category.

About one third of the fuse faults are linked conductively in some way but not necessarily linked by simultaneous action. In a few cases,

all the transient faults are fuse faults in one circuit only.

Simultaneous fuse action, either in common circuits or in circuits in isolation, can be expected from the majority of lightning storms irrespective of their duration, but the number of outages so involved is shown to vary considerably.

About one half of the fuse faults are identified with basic homogeneous circuits, and the other half with discontinuous topologies of varying forms.

PART III

System assessment. Pulse excitation; surge impedances; ground return; propagation analysis.

3.1 Pulse excitation.

3.1.1 The indirect surge.

Representative forcing functions for the surge analysis of some basic circuits contained within the faulted systems, are found from a sampling of table 7. Whilst it is evident that indirect lightning strokes induce voltage pulses with a variety of delineation of form, only those with the greatest rate of rise need be considered in the present context. A simple approach is to regard the induced voltage pulse as primarily aperiodic (the type A pulse) and then to include the complimentary bipolar shape (the type B pulse) as its extension and alternative, i.e. a negative loop preceding a positive loop without discontinuity. In this way the mathematical statement for the type A pulse, with a little modification, appears again in the expression for the type B pulse. Table 7 gives a summary of the induced voltage effects resulting from field measurements, together with comparative data as utilised by a few investigators in related studies.

A sampling indicates that $5/20\mu\text{sec}$ wave would be representative of a short pulse in response to a nearby ground stroke. Alternatively, one of $8/40\mu\text{sec}$ would suffice. Converting to equations of the standard form,

$$e_i = AE (e^{-at} - e^{-bt}) \dots\dots\dots(1)$$

is relatively straight forward since a and b are both real and positive and a graphical method is then available.² Consequently, the $5/20\mu\text{sec}$ pulse is found to be

$$e_i = E (e^{-0.055t} - e^{-0.445t}) \dots\dots\dots(2)$$

TABLE 7

Ref.	Origin	Source	Date	Pulse	Pulse or Wave Shape μ sec.	Min. Neg. Loop μ sec.	Max. kV.
1	Lewis & Foust	E	1930	A & B	$\frac{5}{32}$ $\frac{6}{27}$	5	Surge Tests
2	George & Eaton	E	1930	A & B	$\frac{6}{14}$ $\frac{8}{32}$	8	Surge Tests
3	Bewley	T	1932	A only	-	-	-
4	Perry	E	1937	A & B	$\frac{6}{12}$ $\frac{9}{32}$ $\frac{11}{23.5}$ $\frac{19}{36}$	7.5	98
5	Perry, Webster & Baguley	E	1939	A & B	$\frac{5}{24}$ $\frac{7}{23}$	2	80
6	Norinder	E	1939	A only	6 μ sec. only	-	-
7	Bruce & Goldie	T	1941	"	$\frac{6}{23.5}$		
8	Wagner & McCann	T	1942	"	$\frac{5}{20}$		
9	Goldie	T	1954	"	$\frac{5}{18}$ $\frac{8}{20}$ $\frac{10}{30}$ etc.		
10	Bellaschi	T	1958	"	$\frac{4}{40}$ $\frac{8}{40}$		
11	Ouyang	E & T	1961	"	$\frac{4.9}{20.9}$ $\frac{6}{19}$ $\frac{8}{31}$		Surge Tests
12	Chowdhuri & Gross	E & T	1967	B only	$\frac{18}{38}$ $\frac{14}{40}$ $\frac{11}{65}$		80
13	Electricity Council	E	1968	A & B	-		75
14	Singarajah	E & T	1972	A & B	$\frac{7}{52}$ $\frac{8}{25}$	3	77

* as defined by BS923

Legend

A - aperiodic

E - experimental

B - bipolar

T - theoretical

and the $8/40 \mu\text{sec}$ pulse as

$$e_{i_2} = E(e^{-0.024t} - e^{-0.36t}) \dots\dots\dots(3)$$

A pulse typical of the direct stroke by comparison is

$$e_{i_d} = E(e^{-0.048t} - e^{-2.4t}) \dots\dots\dots(4)$$

This corresponds to a time representation of $2/40 \mu\text{sec}$.

By the addition of a further exponential term to equation (1), and an alteration to the coefficients of each term, an expression for a bipolar pulse can now be presented, i.e.

$$e_{i_B} = E(Ae^{-at} - Be^{-bt} + Ce^{-ct}) \dots\dots\dots(5)$$

and where a negative loop precedes the positive loop without interruption, then $A + C - B = 0$. Rorden³ has applied this form of equation to various types of electrical circuits and obtained an expression which identifies the coefficients. The equation is shown as

$$e_i = ME \left[\frac{a - \alpha}{a - \beta} \cdot e^{-at} - \frac{b - \alpha}{b - \beta} \cdot e^{-bt} + \frac{(\alpha + \beta)(a - b)}{(a - \beta)(b - \beta)} \cdot e^{-\beta t} \right] \dots\dots\dots(6)$$

in which M , α and β are functions of the surge impedances of the connected circuit. Arranged for the present discussion as, for example, an overhead line terminated by a transformer, then $M = -1$, $\alpha = \beta = 0.667$, so that the corresponding bipolar pulses, utilising equations (2) and (3) earlier, now become respectively

$$e_{i_3} = E(1.179e^{-0.055t} - 5.009e^{-0.445t} + 3.83e^{-0.667t}) \dots\dots\dots(7)$$

$$\text{and } E_{i_4} = E(1.074e^{-0.024t} - 3.345e^{-0.36t} + 2.271e^{-0.667t}) \dots\dots\dots(8)$$

which suffice to show that, in principle, a bipolar wave form can be

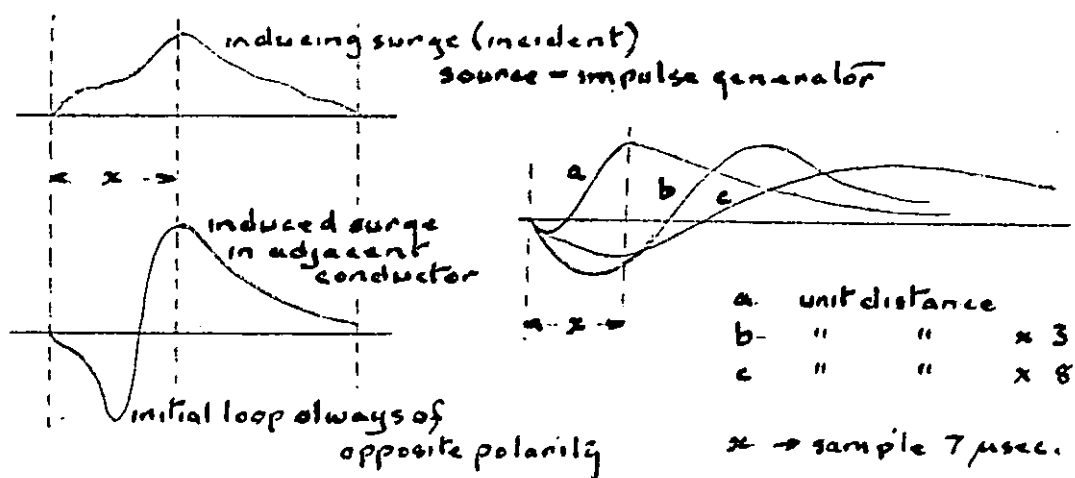
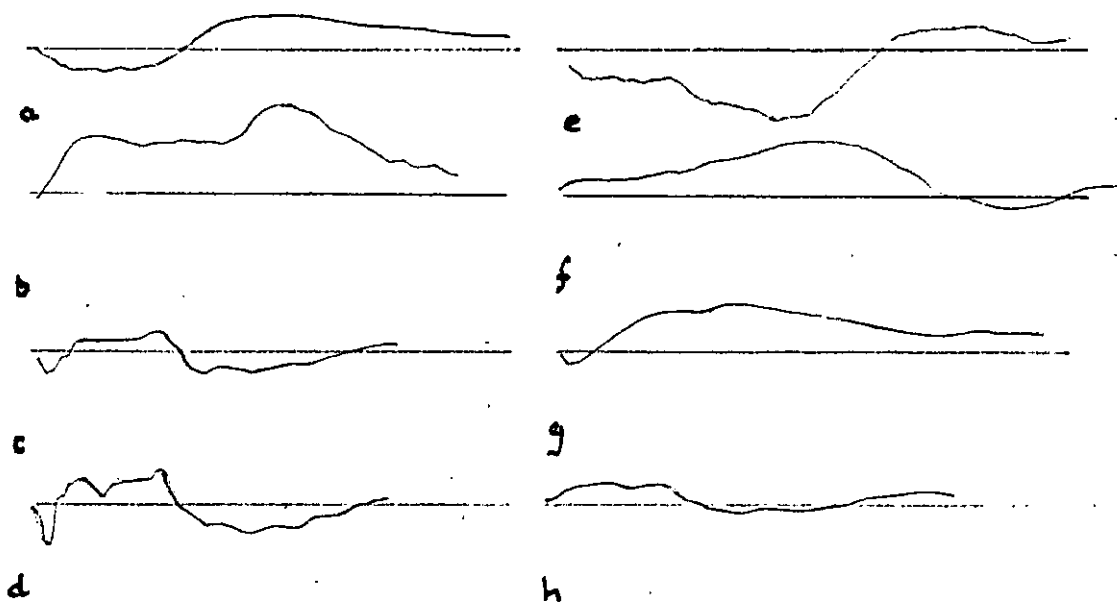
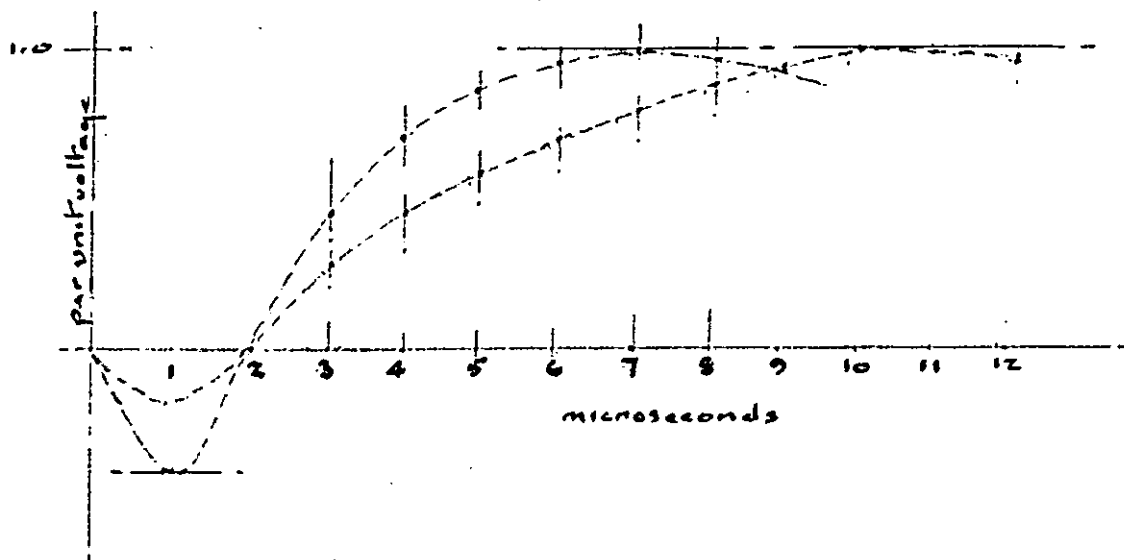
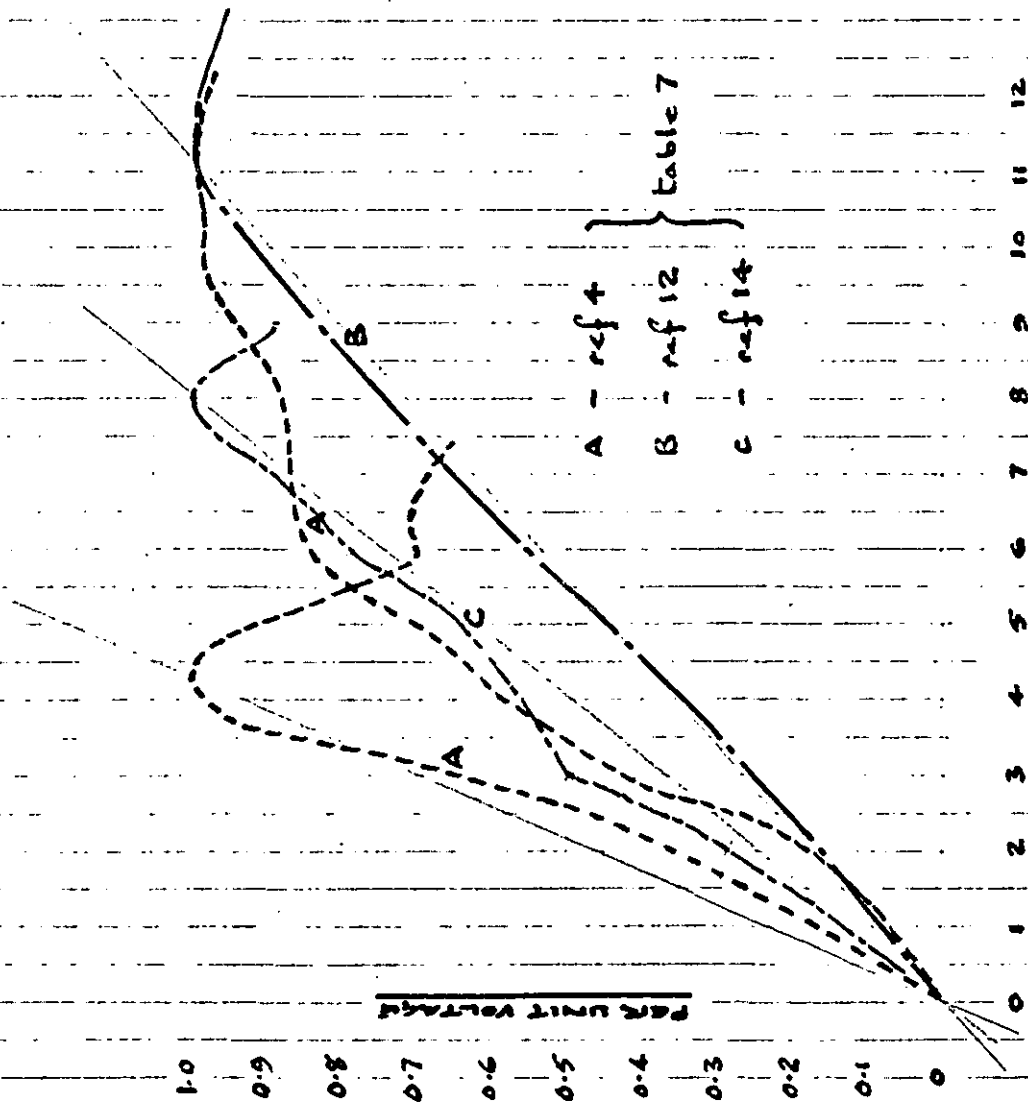
Sample Waveforms(i) Induced Pulses in Coupled Conductors.(ii) Induced Pulses from Lightning Strokes.(iii) Synthesised Pulses (from equations 7 and 8 , Page 155)

Figure 6.

COMPARISON OF WAVE FRONTS - PER UNIT VALUES

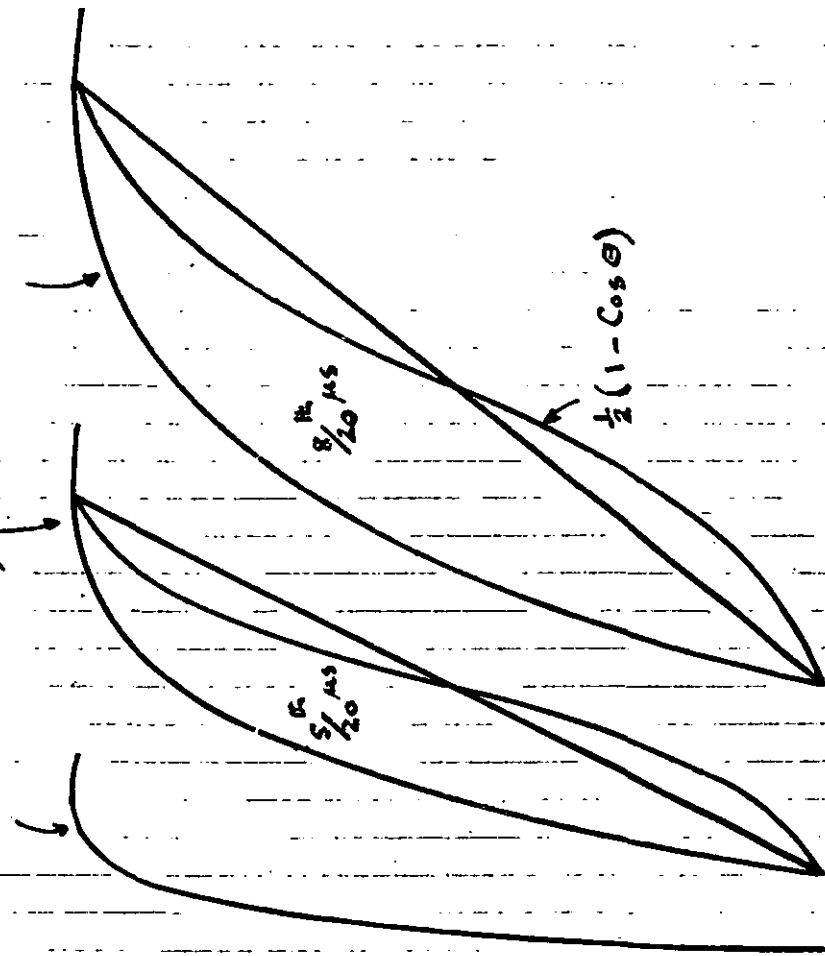


$$1.432(e^{-0.053t} - e^{-0.495t})$$

Reference 1

$$1.045(e^{-0.012t} - e^{-2.4t})$$

$$1.3(e^{-0.024t} - e^{-0.36t})$$



resolved quite easily. Equations 2 and 3 then represent the type A pulse, and equations 7 and 8, the type B pulse referred to earlier.

It is unlikely, however, that examples of the induced bipolar wave found from field measurements can be defined so simply. The positive wave front is often seen to deviate from the accepted exponential norm. The negative loop or spike may vary in such a way that the loop is seriously distorted. Sample waveforms taken from experimental work illustrate these points in figure 6, by comparison with those bipolar pulses constructed from equations 7 and 8.

In table 7, the early references to bipolar pulses, circa 1930, are those effects accorded to travelling waves on multiconductor lines in which the reversed loop response with distance travelled is exhibited. The source of energy here is an impulse generator. Nevertheless, the effect will most probably appear in some of the oscillograms obtained by Perry and his associates from the direct measurements of lightning impulses, and certainly from some of the oscillograms to be found in references 13 and 14, whilst reference 11 is in the same category as references 1 and 2.

A sample negative loop time for a bipolar incident surge is 5 microseconds based on the field measurements of Singarajah. The crest value of the loop is seen to vary greatly, for in some oscillograms it is but a few per cent of the positive maximum value and in others it may actually exceed that value. For maximum effect as part of a forcing function it is assumed here to be equal to a positive maximum induced voltage.

3.1.2 The comparison of primary pulses.

An examination of the wave fronts of a large number of induced voltage surges indicate that they frequently depart from the traditional exponential form so readily assigned to the direct stroke surge. A study of lightning stroke currents by Berger⁴ over a number of years shows that the form of the current front generally does not have an initial high rate of rise. It may rise slowly at first and increase steadily over the

main part, and so generate a near concave contour. Berger attributes this to the effect of the upward streamer and Wagner and Hileman later come to the same conclusion. It is therefore to be expected that some variation in the shape of the front of the induced voltage wave is likely to be a common feature. Figure 7 explores this variation in positive pulse fronts, but evidently linear, sinusoidal and exponential forms can be employed in the surge analysis without departing too far from the natural shapes of indirect incident surges.

The pulse tail is usually taken to be exponential but here it is seen to be very close to the linear form, and it is more convenient to use the latter in the graphical surge analysis that follows. The tail is, therefore, of the general form

$$y = -ax + b \quad \dots\dots\dots (9)$$

This equation is resolved when $a = 0.0333$ and b is 1.166 in the case of the $5/20 \mu\text{sec}$ pulse, or alternatively, if $a = 0.01562$ and b is 1.125 where the $8/40 \mu\text{sec}$ pulse is used.

The corresponding linear and sinusoidal fronts are then

$$(i) \quad y = ax \quad \dots\dots\dots (10)$$

$$\text{and} \quad (ii) \quad y = \frac{1}{2}(1 - \cos x) \quad \dots\dots\dots (11)$$

Values for a and $\cos x$ (where $x = \theta$) are to be found from figure 7.

3.1.3 The transfer of surges.

A general solution of the transmission of a lightning pulse from the 11 kV circuit of a transformer to its low voltage equivalent is seen to be complicated, but an "engineering" solution is readily available if it is assumed that the electro-magnetic component is the dominating factor. In any case, the secondary terminals are unlikely to be in an open circuit state or to have a low impedance load connected across them, so that the electrostatic component can be disregarded. Further, this

investigation is primarily concerned with the 11kV network and the magnitude (but not the waveform) of the transmitted pulse at the secondary terminals is of interest only on a bilateral basis. A recent field study, discussed in Part IV, for example, although intended as a l.v. protection study, provides information on l.v. transmitted overvoltages due to lightning storms. Hence the magnitude of the incoming surges on the h.v. side of the transformer can be estimated by means of the transfer ratio referred to in section 1.4.4.

3.2 The prestrike calculations.

3.2.1 Uniform charge distribution.

The first consideration is the descending leader head as it approaches the earth, and its influence upon the electric field gradient at ground level. Since the leader head contains considerable charge and travels at a relatively low velocity towards the ground, a simple assessment of the ground gradient can be made by an electrostatic solution using the method of images.

On the assumption that the downward leader is a vertical conductor having a uniform charge density extending over its length, the derived equation representing the field strength at a point p, having a horizontal displacement y from a point on the ground directly below the head, is

$$\mathcal{E}_c = Kq. \left[\frac{1}{(h_1^2 - y^2)^{\frac{1}{2}}} - \frac{1}{(h_2^2 - y^2)^{\frac{1}{2}}} \right] \dots\dots\dots (12)$$

in which h_1 and h_2 are the vertical heights, above level ground, of the leader head and the top of the leader channel respectively; q is the charge per unit length in the leader column and K is a constant. According to Wagner and Hileman, the current in the lightning channel can be represented alternatively as the product of the charge and its velocity of propagation

along the channel. Hence, by substitution in equation 13, and discounting the second term in the brackets since $h_2^2 \gg Kq$, the height of the leader head above a perfectly flat earth to liberate an upward streamer is simply

$$h_1 = \frac{Ki}{\xi_c v}$$

where ξ_c is the critical disruptive value of the ground gradient, noting that the maximum ground gradient must appear directly below the aerial charge and v is the velocity of propagation of the lightning current. Due to point discharge effects from ground irregularities such as grass, stones and more substantial projections, the value of ξ_c is unlikely to be as high as the 3kV/metre figure that is generally assumed. One authority⁵ has, in fact, suggested a figure of 1kV/metre as being more realistic, and even lower values for special cases.*

The application of equation 13 to the present studies appears to be unsatisfactory. All the evidence from rotating lens cameras (Schonland, Malan and associates) shows that the propagation velocity of the lowered charge is very slow and very nearly uniform over the extent of the lightning channel from cloud to ground. It has been demonstrated that it seldom exceeds a maximum rate of progression of 0.0013c (0.39 metres/ μ sec) and the subsequent leaders of a multistroke appear to be only about 0.0067c (about 2 metres/ μ sec). Although evidence at the lower end of the leader channel as it approaches the earth is not plentiful, it can be assumed that the velocity of propagation is of the same order. Consequently, if $i = 20kA$, $v = 0.39$ metres/ μ sec and ξ_c is 1kV/metre, the height of the leader head above ground to liberate the upward streamer is found to be about 920 metres or just over 3,000 ft. which seems unrealistic. At 2 metres/ μ sec, h_1 becomes 180 metres or about 590 ft., and it is clear that the stroke current is equivalent to the product of the charge and the propagation velocity at this stage of the stroke mechanism is not valid when the latter

* 0.3kV/metre has been used in the case of the lightning conductor.

parameter is very small.

3.2.2 Exponential charge distribution.

If an exponential distribution of the charge along the leader channel is envisaged such that the charge q at any height h above ground is represented by

$$q_h = q_0 \cdot e^{-\beta h} \dots\dots\dots (14)$$

where q_0 is the charge at the ground end of the channel, and β is a constant, then the total distributed charge q_t before contact is made with the ground is clearly

$$q_t = q_0 \cdot \int_0^{h_2} e^{-\beta h} \cdot dh \dots\dots\dots (15)$$

Consequently, the ground gradient at point p located as before, is found to be

$$\mathcal{E} = Kq_t \cdot \int_{h_1}^{h_2} \frac{h \cdot e^{-\beta h}}{(h^2 - y^2)^{3/2}} \cdot dh \dots\dots\dots (16)$$

Solving equation (16) for h_1 , when $y = 0$ and $\mathcal{E}_c = 1\text{MV/metre}$, indicates that h_1 is nearly 17 metres or about 56 ft., which appears more reasonable than the previous example with the linear charge distribution, and is now directly comparable with artificial discharges.

The curves, A, B and C in figure 8 are all derived from equation 16, and show the ground gradient directly below the leader head as a function of the height of the head above a perfectly flat earth for stroke currents of 20kA, 40kA and 60kA. The limiting value of \mathcal{E}_c is taken as 1MV/metre.

3.2.3 The induced voltage component.

The voltage induced in a line conductor 25 ft. (7.62 metres) above earth and distance y from the vertical projection of the descending leader head is described here as the prestrike voltage. A necessary component for the computation of this voltage is the presence of an upward streamer of some magnitude. In general, this requires isolated ground

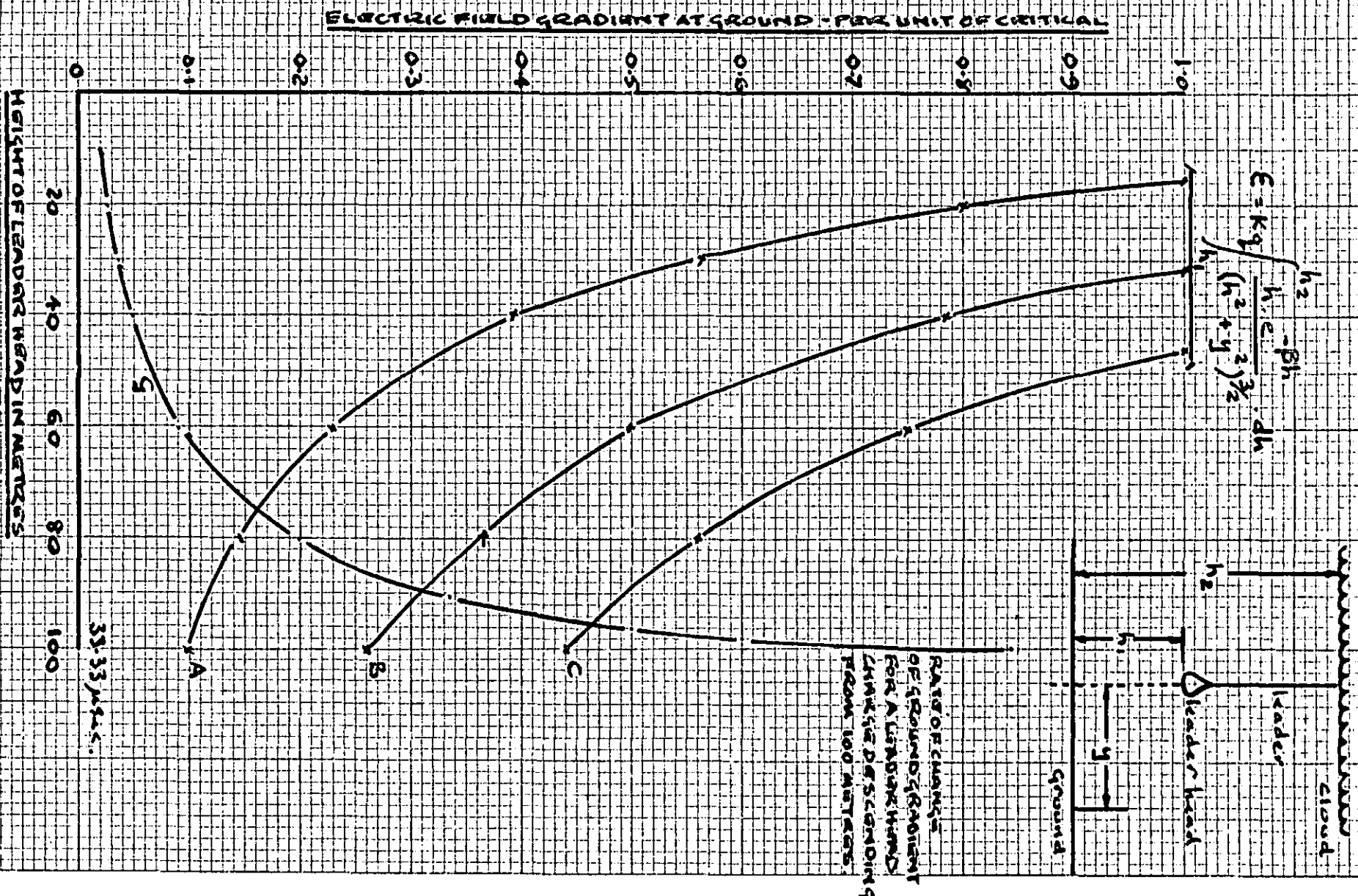
* Appendix, note 5.

objects of some elevation to be in the path of the leader head.

A full evaluation is necessarily complicated and involves the solution of a problem in electrodynamics. Consideration needs to be given to the fact that the charge content of the head must rise very rapidly with voltage and the approach to the ground. This leads to an expansion in the size of the head and to some distortion of the corona envelope, accordingly to Griscom. The presence of point discharge and corona from grounded objects, part of which contribute to the liberation of the upward streamer, influence the electric field distribution and require attention also. However, these areas of comprehension are outside the scope of the present work and only a single contribution consisting of a charge descending slowly but at a uniform rate in association with an upward streamer is analysed.

Differentiation of the electric field gradient/leader head characteristics is confined to curve A only in figure 8, and for a propagation velocity of $0.001c$, yielding the anticipated shape according to the parent curve. Thus, the rate of change of ground gradient for one coulomb charge corresponding to a stroke current of $20kA$ is shown as curve G. It now remains to assess the duration of the prestrike pulse, its waveshape and magnitude.

The bound charge on the line conductors increases rapidly with the approaching leader head and then collapses suddenly as soon as the ground streamer and leader head meet. The duration of the prestrike induced voltage pulse therefore is equal to the time taken for a prescribed length of space to be traversed by approaching vertical conductors of opposite polarity. Let it be assumed, for a first approximation, that the ground streamer moves with the same velocity as the descending head. Then the gap is closed at the uniform rate of $2v$. For a single discharge let $v = 0.39 \text{ metre}/\mu\text{sec}$, a stroke current of $20kA$, then the separation corresponding to a critical ground gradient of $1MV/\text{metre}$ is about 17 metres,



POTENTIAL GRADIENT AT GROUND SURFACE
DUE TO APPROACHING LEADER HEAD.

Figure 8

so that the pulse duration corresponding to this distance is

$$t_p = \frac{17}{2 \times 0.39} = 21.8 \mu\text{sec.}$$

Where the velocity is increased approximately by a factor of five, as with the second and subsequent leaders in the multistroke case, the pulse duration is reduced to about $4 \mu\text{sec.}$

It is tacitly assumed so far that the streamer starts from the ground surface but, if the prestrike concept is to be used, it is essential that the streamer should be liberated from a grounded object of some height above this surface. This means that the critical gradient must be attained at the top of this object. If an isolated object of height h is in the path of the leader head then the streamer is liberated when the critical gradient is reached at its tip. Some simplification is introduced here but this tends to compensate for the increased charge transfer given to projecting objects provided by the prestrike theory.

Clearly, the prestrike influence decreases rapidly with multistroke activity. It is evident also that an increase in the leader head charge, or a decrease in the critical electric field gradient required to liberate an upward streamer, has the effect of increasing the prestrike time. Since the rate of progress of the streamer also influences the prestrike duration, reference to field data relevant to the velocity of propagation of long streamers initiated by lightning discharges should provide guidance. However, the only Boys camera evidence available is that of the return stroke velocity from the ground surface where there is little or no streamer. This velocity is found to vary from about 25 metres/ μsec to 80 metres/ μsec . in which case, a prestrike period occupies less than one microsecond and its influence is of no consequence. A slow velocity of propagation of the streamer is therefore essential. The process of passing from point discharge to plasma streamer is most likely

to follow an exponential law, but in the absence of field data, it is assumed that the streamer proceeds at the same rate as that of the descending leader head. The shape of the prestrike voltage pulse induced in the line conductors is likely to be similar to the rate of change of ground gradient characteristic, and since the leader head charge in the majority of cases is negative, the induced charge is positive corresponding to the bound charge on the conductors.

To calculate the induced voltage in a conductor 25 ft. (7.62 metres) high in proximity to the ground object, an image point charge q' is considered equivalent in distance to the highest point of the object. A simple equation then defines the voltage as

$$V = \frac{q_0}{4\pi\epsilon_0} \left[(y^2 + (h - h_1)^2)^{-\frac{1}{2}} - (y^2 + (h + h_1)^2)^{-\frac{1}{2}} \right] \dots\dots(17)$$

where y defines the horizontal distance as before, of the point p located in this case to the line pole and $h = 7.62$ metres. A set of constants* is calculated from the terms within the square brackets corresponding to the height of the ground object h above level ground for 10, 15, 20 and 30 metres, and for different distances y metres. These are shown below.

Table 8

h metres	$y = 10$ metres	$y = 20$ metres	$y = 30$ metres	$y = 40$ metres
10	0.04792593	0.01213278	0.00448649	0.00207722
15	0.04041138	0.01386460	0.00577766	0.00283449
20	0.02879402	0.01318945	0.00628995	0.00331013
30	0.01510605	0.00984647	0.00593531	0.00360616

The computation of the voltage follows in table 9 from 100 metres above the ground object using corresponding ground gradients obtained from equation 15 and figure 8. It is noted that for the first 83 metres the velocity of propagation is 0.39 metre/ μ sec. Thereafter, it appears to be twice this value corresponding to the prestrike period. The distance y

* for use with alternative charge densities.

may have a lower limit subject to the attractive effect of the height h , but for the single prestrike component assessment this influence is not considered.

Table 9

h_1 metres	$h = 10$ metres				$h = 15$ metres			
100	4.79	1.21	0.44	0.21	4.04	1.39	0.58	0.28
90	5.66	1.43	0.53	0.25	4.77	1.64	0.68	0.33
80	6.95	1.76	0.65	0.30	5.86	2.01	0.84	0.41
70	8.63	2.18	0.81	0.37	7.27	2.50	1.04	0.51
60	11.02	2.79	1.03	0.47	9.29	3.19	1.33	0.65
50	14.14	3.57	1.32	0.61	11.92	4.09	1.70	0.84
40	18.69	4.72	1.75	0.81	15.76	5.41	2.25	1.11
30	23.96	6.06	2.24	1.04	20.21	6.93	2.89	1.42
20	38.34	9.69	3.59	1.66	32.32	11.09	4.62	2.27
17	47.93	12.11	4.49	2.08	40.41	13.87	5.78	2.83
16	52.72	13.32	4.94	2.28	44.45	15.25	6.36	3.12
15	57.51	14.54	5.38	2.49	48.49	16.64	6.93	3.40
14	62.30	15.75	5.83	2.70	52.53	18.02	7.51	3.68
13	67.10	16.96	6.28	2.91	56.58	19.41	8.09	3.97
12	71.88	18.17	6.73	3.12	60.62	20.80	8.67	4.25
11	76.68	19.38	7.18	3.32	64.66	22.18	9.24	4.53
10	82.43	20.83	7.72	3.57	69.51	23.85	9.94	4.87
9	91.06	23.00	8.53	3.94	76.78	26.34	10.98	5.38
8.5	100.64	25.44	9.42	4.36	84.86	29.12	12.13	5.95

kilovolts

Figure 9 indicates the shape of the induced voltage characteristic at $y = 10$ metres for varying heights of ground object. The prestrike period is shown and occupies a time of $21.8 \mu\text{sec}$ when the charge is one coulomb. The maximum prestrike voltage when y is varied from 10 metres to 40 metres is shown also, in figure 10, as a function of the height of the ground object. Figure 11 gives the prestrike characteristics for $y = 10$ metres only.

Table 9 (continued)

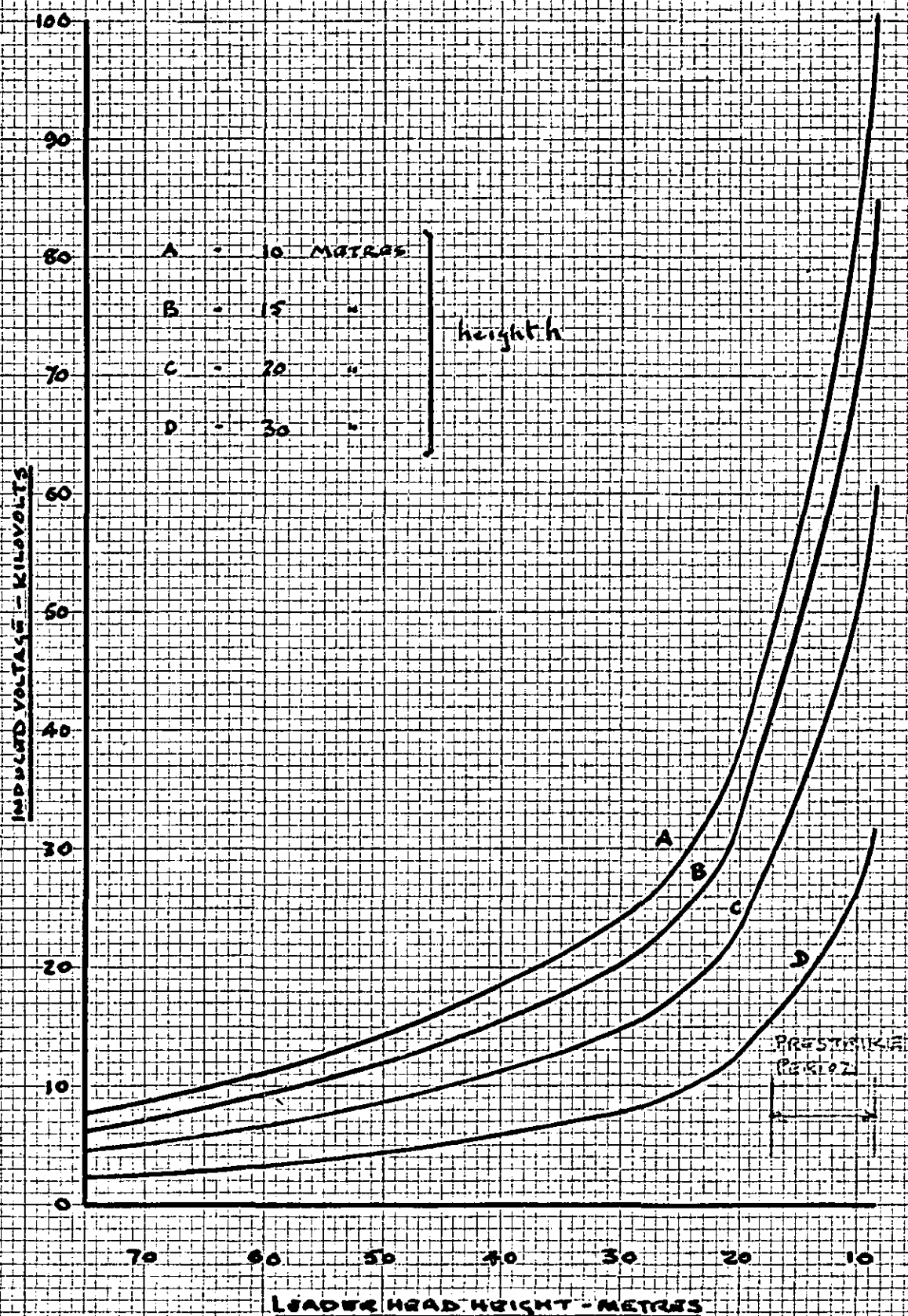
h_1 metres	$h = 20$ metres				$h = 30$ metres			
100	2.88	1.32	0.63	0.33	1.51	0.98	0.59	0.36
90	3.40	1.57	0.74	0.39	1.78	1.16	0.70	0.43
80	4.18	1.91	0.91	0.48	2.19	1.43	0.86	0.52
70	5.18	2.37	1.13	0.59	2.72	1.77	1.07	0.65
60	6.62	3.03	1.45	0.76	3.47	2.26	1.37	0.83
50	8.49	3.89	1.86	0.98	4.46	2.90	1.75	1.06
40	11.23	5.14	2.45	1.29	5.89	3.84	2.31	1.41
30	14.40	6.59	3.15	1.66	7.55	4.92	2.97	1.80
20	23.04	10.55	5.03	2.65	12.08	7.88	4.75	2.88
17	28.79	13.19	6.29	3.31	15.11	9.85	5.94	3.61
16	31.67	14.51	6.92	3.64	16.62	10.83	6.53	3.97
15	34.55	15.83	7.55	3.97	18.13	11.82	7.12	4.33
14	37.43	17.15	8.18	4.30	19.64	12.80	7.71	4.69
13	40.31	18.46	8.81	4.63	21.15	13.78	8.31	5.05
12	43.19	19.78	9.44	4.97	22.66	14.77	8.90	5.41
11	46.07	21.10	10.06	5.30	24.17	15.75	9.50	5.77
10	49.53	22.69	10.82	5.69	25.98	16.94	10.21	5.20
9	54.71	25.06	11.95	6.29	28.70	18.71	11.28	6.85
8.5	60.46	27.70	13.21	6.95	31.72	20.68	12.46	7.57

kilovolt.s

3.2 Surge impedances.

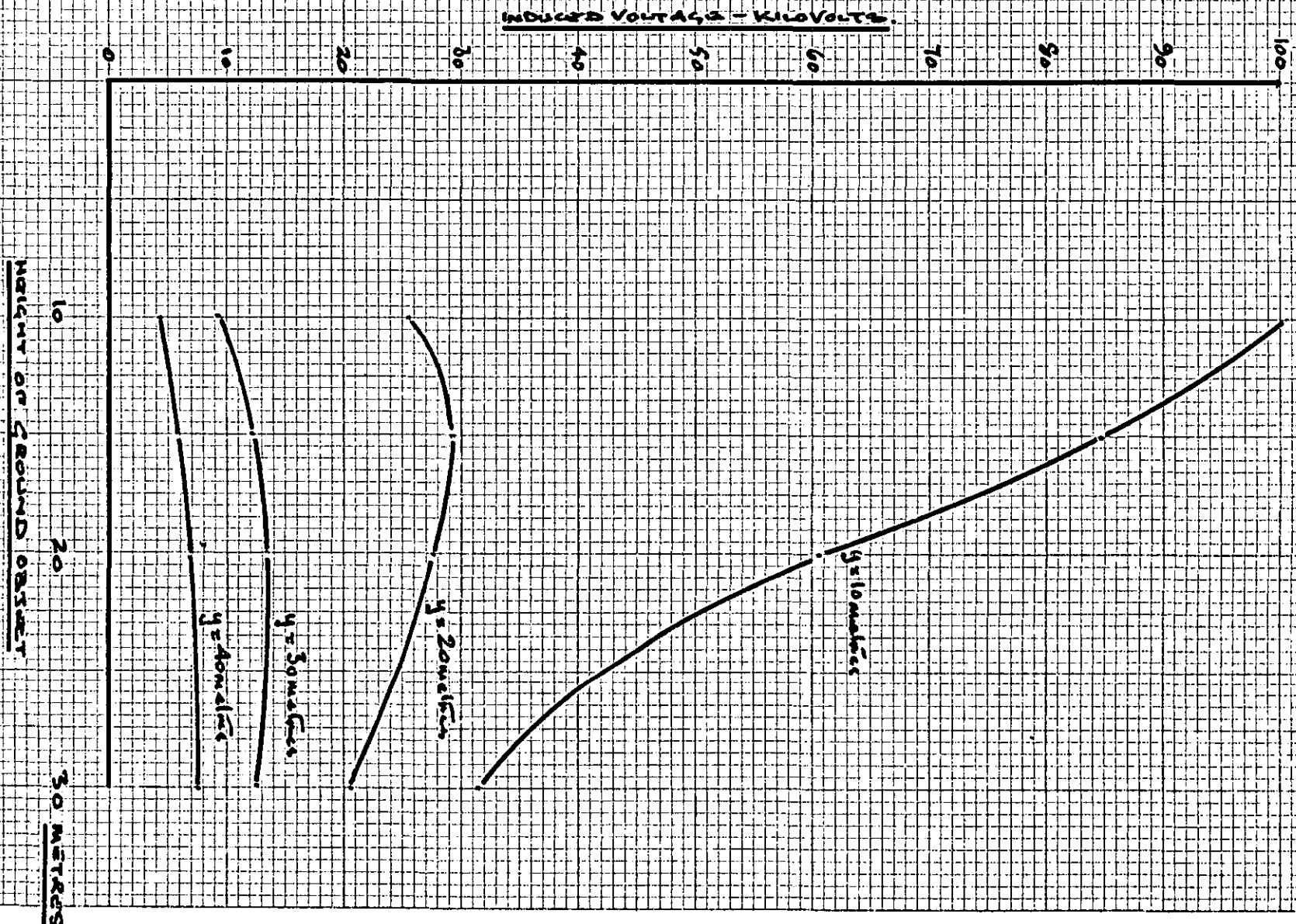
3.3.1 Overhead lines.

The surge impedance values for single conductor and three conductor overhead lines at 17 ft. and 25 ft. above ground, and for both horizontal and triangular configurations, have been previously calculated by the writer. These can be found, for the range of conductor cross-sections relevant to the 11kV system, in Table 1 on page 9 ref. 8, Part I. The calculations are based on the absence of the internal flux linkage



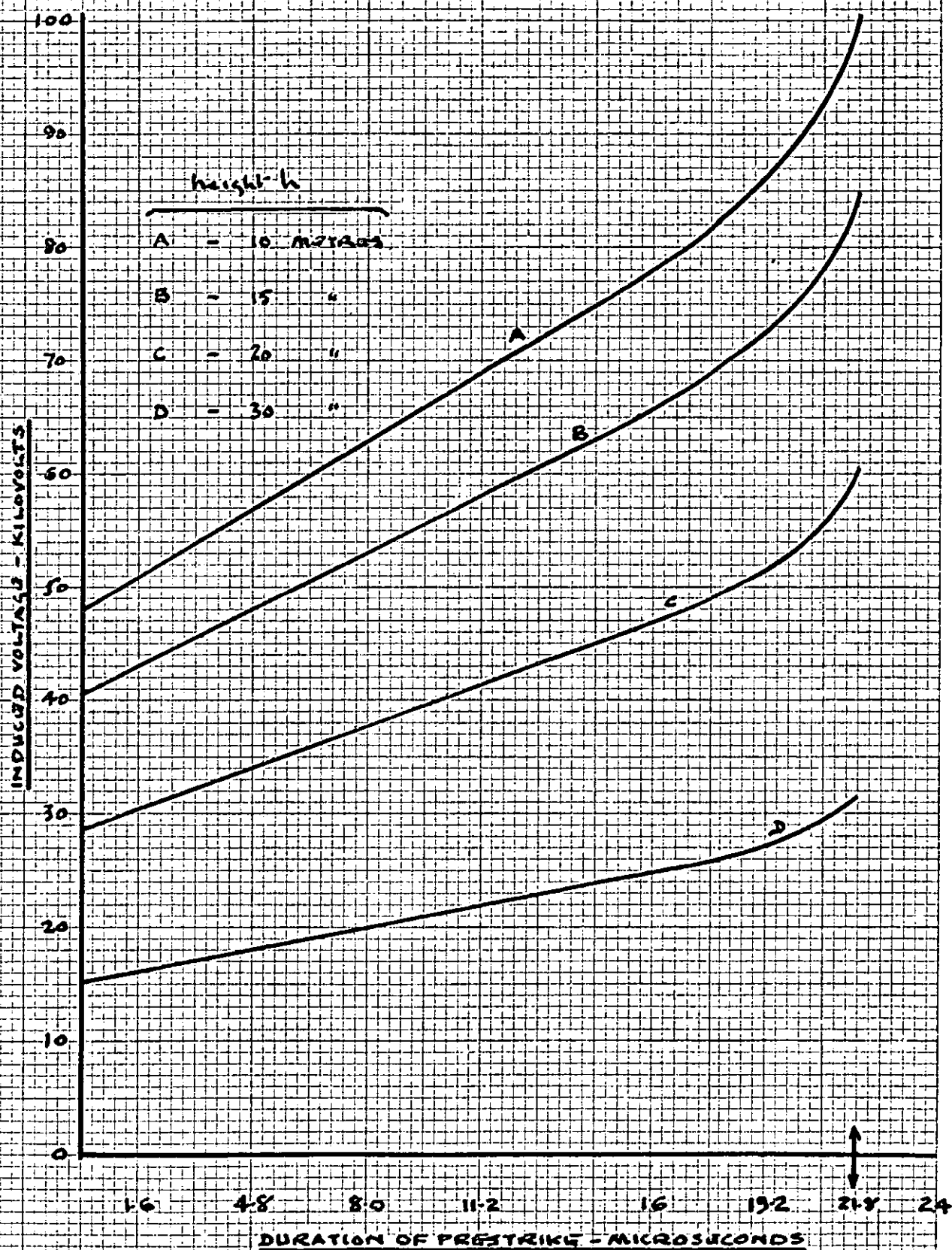
INDUCED VOLTAGE AS A FUNCTION OF HEIGHT OF LEADER
HEAD ABOVE GROUND OBJECT OF DIFFERENT HEIGHTS
FOR $h = 10$ METRES CORRESPONDING TO ONE COLUMB CHARGE

FIGURE 9



MAXIMUM PRESTAKE VOLTAGE AS A FUNCTION OF HEIGHT OF GROUND
 OBJECT FOR DIFFERENT DISTANCES y .
 CORRESPONDING TO ONE CABLEOM B. LINEAGE.

FIGURE 10



PRESTRIKE CHARACTERISTICS CORRESPONDING TO DIFFERENT HEIGHTS OF GROUND OBJECT, FOR $q = 10$ METERS AND ONE COULOMBS CHARGE.

FIGURE 11

component, due to skin effect, as the response to the short duration of the excitation. For reasons presented therein, the influence of line resistance and leakance is discounted, and hence all line conduits are considered lossless in the case of the h.v. distribution circuit.

The effect of line sag on the computation of surge impedance is examined on the following basis

(i) the calculated line sag is found to be about 7 ft. if a copper conductor of 0.1 inch^2 cross-section area is used. The line supports are taken as of equal height above level ground with an average spacing of 400 ft. The worst conditions of loading are assumed. A parabolic equation is found satisfactory since calculations reveal that divergence from the catenary solution does not begin until a span of about 700 ft. is reached.

(ii) the mean height with line supports of 25 ft. above ground; assuming a parabolic curve, is then calculated as 20.66 ft. Since the self-surge impedance of the single conductor is obtained from the equation

$$Z_0 = 60 \log_e \frac{4h}{d} \text{ ohms} \quad *$$

substitution shows that Z_0 is 476 ohms. This is a decrease of 2.26% from that obtained from the line parallel to the level ground. This sample calculation is shown to be within the impedance tolerance discussed in section 3.4 and since conductors of smaller cross section will have less sag, it is therefore considered that the effects of line sag need not be included.

The calculated critical disruptive voltage for a single conductor is about 110kV allowing for air pressure and temperature adjustments. This assumes a critical ground gradient of 3MV/metre. The visual corona level is then some 20% higher. Since the threshold voltage is directly proportional to the critical gradient \mathcal{E}_c , a reduction in the latter, as suggested in an earlier section, must lead to a critical voltage of well below 100kV. The corresponding value of the disruptive voltage

*

Reference 8, Part I.

for the three conductor horizontal system is about 170kV.

The effect of increasing the voltage above the disruptive value is to increase the corona envelope which results in

- (i) an increase in the line capacitance,⁶ which leads to
- (ii) a decrease in the self-surge impedance, and
- (iii) a decrease in the velocity of propagation of the travelling wave,

The change in the surge impedance can be estimated quite simply by taking a likely value⁶ of the propagation velocity below that of light, and substituting in the velocity equation, for the lossless case, to find the increase in capacitance. Let $v = 0.95c$, then for a conductor cross-section of 0.1 inch^2 , this gives Z_0 a value of 462 ohms which is a reduction of 5.13% on the corresponding surge impedance given in the table of reference 8 in Part I. This is in excess of the divergence angle for an overhead line discussed in section 3.4. Lower values of propagation velocity which can be anticipated, from the effects of corona, must indicate even larger percentage reductions in the surge impedance. Hence, travelling waves in the region of the corona level must be given special attention in the surge analysis.

3.3.2 Cables and Transformers.

The assessment of cable surge impedance values is subject to calculating the geometric factors according to the configuration of the cable section. These calculations are made much more difficult in the case of shaped conductors, but using the manufacturers information that an increase of 8% is allowed above the calculated value of capacitance for conductors with circular cross-sections, it is possible to estimate the effect on the surge impedances. The change in inductance is much less due to the proximity of the conductors and hence the surge impedance is decreased. The amount of reduction is well within the parameter tolerance allowed for in the surge analysis. Similarly, it is noted that both belted

and screened cable constructions are utilised in the 11kV system, but these calculated surge impedances for different conductor sizes also fall within this tolerance.

Unlike the lines and cables, the transformer does not present a linear, passive and bilateral element to travelling waves, and consequently the surge impedance at the h.v. terminals is not a constant quantity. However, an assumption is made here that as the excitation is brief, the surge impedance remains unchanged in magnitude and form over the period of interest. Utilising the propagation time of the winding and known values of series and shunt capacitances, the surge impedance can be estimated. As with the previous data, values of surge impedance have been taken from ref. 8 Part I. Since both transit time and effective capacitance vary according to the design and rating of the transformer, there is a large variation in the estimated values. In general, the higher surge impedances are assigned to lower rated equipment such as pole-mounted types and these are the majority of installations.

3.3.3. Ground return.

The calculation of the earth return path represents a complex problem which can never be exactly resolved due to the non-homogeneity of the ground, although Carson established a working formula more than 50 years ago. However, in the present study it is unnecessary to determine the impedance of the ground path in an exact manner. The elements of the overhead line system to be analysed are considered to be lossless to pulses of short duration and hence a simple assessment is all that is required.

The point of resolution begins with the electrical connection to the cross-arm. This connection has an inductance of about $16 \mu\text{H}$ according to Bellaschi,⁷ so that its ohmic value is then about 5μ to the $5/20 \mu\text{sec}$ pulse. The resistance of a single ground rod electrode is taken as 25μ but the inductance and capacitance due to the pulsed current and potential distribution are not considered.

3.4 Travelling wave analysis.

3.4.1 Choice of method and accuracy.

The Schnyder-Bergeron system, known generally as the Method of Characteristics, is employed for the surge analysis of some basic circuits related to the field study. This technique, pioneered in this country by Arlett and Murray-Shelley⁸, as devised by Bergeron⁹, is one which is carried out essentially in the graphical mode.

The choice of the method of analysis is based on the following observations:-

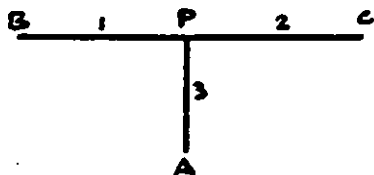
(i) For exploratory studies it is of great help to assume that the h.v. distribution network is intrinsically lossless to pulse excitation of this nature, and to introduce the effects of the earth path, corona and similar features separately.

(ii) In a study of these circuits small changes in parameters take place frequently and it is therefore paramount that the problem is easily reworked.

(iii) Physical insight as to the progress of solution is of some benefit in this type of study.

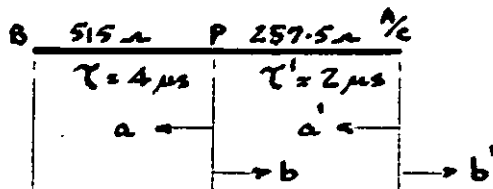
An analysis which is carried out on the drawing board satisfies the specifications above quite well and the Bergeron system provides an additional advantage in that a readout of both voltage and current is obtained simultaneously adding to the interpretation of the problem. Sufficient accuracy is obtained from the use of just two "observers" in the circuits, thereby providing the simplest interpretation of the Method of Characteristics. This fact can easily be verified by working an example and comparing with the solution by the well-known Bewley Lattice² method. The lattice system is pseudo-graphical in that the diagram merely serves as a timing device but the actual values of voltage are computed continuously from the reflection and refraction coefficients. The problem is to find the voltage response of a basic circuit type c to a 5/20 μ sec aperiodic pulse. The circuit parameters are shown as follows,

and the circuit simplification that can be utilised.



Z_0 of each section is 515Ω , $\tau_1 = 4\mu\text{sec}$. $\tau_2 = \tau_3 = 2\mu\text{sec}$

equivalent circuit



reflection coefficients: $a = 0.33$ $a^1 = 0.975$

refraction coefficients: $b = 0.0667$ $b^1 = 1.975$

incremental time $\Delta t = 1\mu\text{sec}$.

The voltage distribution is summarised in the following four general equations:

$$E_{B-P} = E_B(t) + aE_P(t - \tau) \quad (18)$$

$$E_{P-B} = a \left[E_B(t) + aE_P(t - \tau) \right] \quad (19)$$

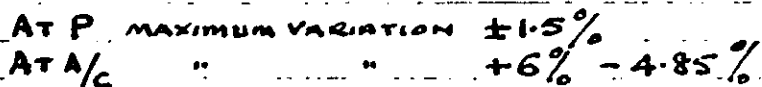
$$E_{P-A} = b \left[E_B(t) + aE_P(t - \tau) \right] - aE_A(t + \tau - \tau') \quad (20)$$

$$E_A = b \left[b \left[E_B(t) + aE_P(t - \tau) \right] - aE_A(t + \tau - \tau') \right] \quad (21)$$

The lattice solution is shown in Table 10 together with the Bergeron comparison. Using the former as the reference, the Bergeron results show a maximum variation of $\pm 1.5\%$ at terminal P, and $+6\%$ and -4.8% at terminals A and C. As the solution was performed on A4 size graph paper this appears to be an acceptable tolerance for the graphical method with only two observers.

Due to changes in cross-sections of overhead line and cable conductors, there is some variation in the corresponding surge impedance values. These changes are transmitted to the Bergeron diagrams. To limit the amount of reworking, a divergence angle is assessed for each circuit element. Thus, for a single conductor 17 ft. above ground, the range

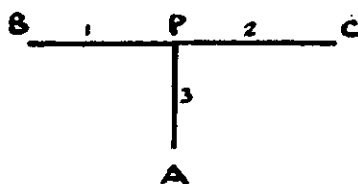
SINGLE VELOCITY SYSTEM



of surge impedances is from 506Ω to 443Ω and from the V/I characteristics, the corresponding angles are $21^\circ 36'$ and $24^\circ 30'$. Hence the divergence angle is $2^\circ 54'$. Similarly, for a conductor 25 ft. in height, this angle is $2^\circ 30'$. The divergence angle is less for the three-conductor configuration due to less difference between the maximum and minimum surge impedances. The divergence angle in the case of the single-phase cable, has a maximum of $3^\circ 24'$ and again, is less for the three-phase case. Transformer surge impedances on the h.v. side establish a divergence angle of 2.25° . Since these angles are seen to be small the Bergeron analysis can be reduced, under certain conditions, by introducing standard solutions to reiterative problems.

It is unnecessary to consider three-conductor surge response when investigating related section transit times, since the single conductor system provides an adequate model and the TEM mode of propagation is without complication. Hence, the analysis in section 3.4.2 that follows covers five of the basic circuit topologies as single conductor systems.

3.4.2 Bifurcated system (first series)



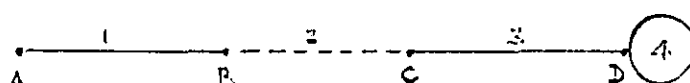
The propagation velocity is the same for all sections and is therefore the basic type c tee-off system. Each section has a surge impedance of 515Ω and the bifurcation is terminated by transformers $Z = 20k\Omega$. The surge analysis examines the responses to varying transit times in the different sections. A chart, shown in table 11, indicates the permutations made available by the adjustment in the electrical lengths, and hence 32 Bergeron diagrams are required to complete the series. The response curves, figures 12-23, are made up of:

- (i) the voltage at the terminations A and C
- (ii) the relation between the voltage and current at the junction P.

For item (i), the characteristic responses are displayed in group pairs from table 11 corresponding to units of transit time allotted to the section B-P. For item (ii), separate displays of voltage and current are necessary to avoid confusion.

It is noted that this analysis may also serve for the elementary circuit type a spur system if the transformer h.v. winding represents the section P-A, and providing that winding is given a transit time.

3.4.3 Cascaded systems.



This configuration represents the elementary circuits f, g and h.

(i) Second series.

The effects of a propagation time in the h.v. windings of the transformer Z_4 are examined by means of 4 Bergeron diagrams, and Z_4 is either 4 k Ω or 10 k Ω . The surge impedances of the conduit section are respectively $Z_1 = 443\Omega$, $Z_2 = 22$, $Z_3 = 506\Omega$. No change is made in the transit time of the two lines and the cable, which is the same for each element. The transit time of the winding is either zero or twice that of any section. Figures 24-27 show:

(a) the relation between voltage and current at the terminal B

(b) the voltage and current at the terminal C in addition to the voltage at the transformer.

It is noted that there are three propagation velocities in this example.

(ii) Third series.

A comprehensive examination of the fully connected system is made. This requires 9 Bergeron diagrams for varying transit times to be applied to line and cable sections. The transit time in the transformer winding is not included. The surge impedances from A to D are respectively $Z_1 = 480\Omega$, $Z_2 = 22\Omega$ and $Z_3 = 464\Omega$. The terminal impedance is 18 k Ω . There are nine groups of response curves which express the following:

(a) The voltage and current relationship at the terminal B.

Figures 28-30.

(b) The voltage and current relationship at the terminal C.

Figures 31-33.

(c) A comparison between voltage at C and at D.

Figures 34-36.

(iii) Fourth series.

This is a similar circuit but with slightly modified line parameters, the inclusion of a propagation time associated with the h.v. winding of the terminal transformer, and a different aperiodic impulse. The line surge impedance values are $Z_1 = 464 \Omega$ and $Z_3 = 506 \Omega$. The analysis is limited to one adjustment of transit time in each element except that for the winding which is given a double transit time. This is sufficient to compare the pattern of behaviour with the previous series. Hence only 3 Bergeron diagrams are required. These responses are confined to 37-39. Three propagation times are involved in this analysis also.

3.4.4 Further observations.

Additional analysis yields the following information, details of which can be found in the appendix.

(i) The responses to a sinusoidal front given to the incident pulse are found to be very close to those obtained with the linear wavefront and are therefore not included.

(ii) The alternative $8/40 \mu\text{sec}$ wave produces exactly the same pattern of responses at the discontinuities as the shorter pulse. The rate of rise of the voltage and current is decreased in all the circuits studied, and the total effect is extended over a longer time scale. Since the rate of rise is important, clearly the $5/20 \mu\text{sec}$ excitation is the better measure of performance in the present study.

(iii) The behaviour of a system to an incident voltage made up of a negative voltage spike preceding the positive pulse is shown to modify

the transmitted voltages in a similar manner.

(iv) The effect of corona may be included in the Bergeron diagram at a coordinate location considered to be the threshold voltage. At this point, the line characteristic therefore changes its slope and, since the surge impedance is reduced, the angle decreases. The analysis then continues in the same manner as before.

3.4.5 The three conductor system.

The effects of two and three-conductor tee-offs from the feeder in the elementary type c circuit, is covered in the appendix. It is clear that as all the propagation equations must comply with Kirchhoff's laws, the net effect of varying transit times is essentially the same as in single conductor systems. The three-phase response, associated with any conductor configuration, involves the application of a modal transformation so that the three interacting conductors can be made three independent systems. The surge analysis is carried out in the modal domain and therefore normally requires three Bergeron diagrams for each solution.*

It has been shown by Wedepohl,¹⁰ using eigen value theory, that, for lossless symmetrical systems, the symmetrical component transformation can be utilised as a modal matrix. The use of this well-known transformation is avoided by Adams¹¹ on the grounds that it is primarily a power frequency technique for use with three-phase excitation. Further, although accepting that the Clarke¹²-Kimbarke transformation is more suitable, Adams maintains that this also has deficiencies, the chief of which is associated with conductor asymmetry. However, this criticism appears to rest entirely upon the nature of the problem to be solved.

The triangular^x conductor configuration represents a symmetrical system but the horizontal arrangement is only partially symmetrical as described by Wedepohl, and here the system of impedance and admittance matrices are of the general form :-

* Appendix.

x equilateral

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \quad \text{and} \quad Y = \begin{bmatrix} Y_{11} & -Y_{12} & -Y_{13} \\ -Y_{21} & Y_{22} & -Y_{23} \\ -Y_{31} & -Y_{32} & Y_{33} \end{bmatrix}$$

A minus sign precedes the off-diagonal terms of the admittance matrix due to the final form of the charge equations. The assembly of these matrices is based on the assumption that

$$\begin{aligned} Z_{11} &= Z_{22} = Z_{33} \\ Z_{12} &= Z_{21} = Z_{23} = Z_{32} \end{aligned}$$

and $Z_{13} = Z_{31}$

If equations 1, 2 and 3 are replaced by Z_A , Z_B and Z_C respectively then it may be written that

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} Z_A & Z_B & Z_C \\ Z_B & Z_A & Z_B \\ Z_C & Z_B & Z_A \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

which resolves in an eigen value problem to find a modal transform to obtain three independent equations. However, on the basis of an approximation which will suffice to give a pilot assessment of a three-conductor response in these circuits, the alpha, beta, zero transformation has been chosen for the Bergeron analysis of the type c circuit. This transform provides the following two advantages over the use of symmetrical components:

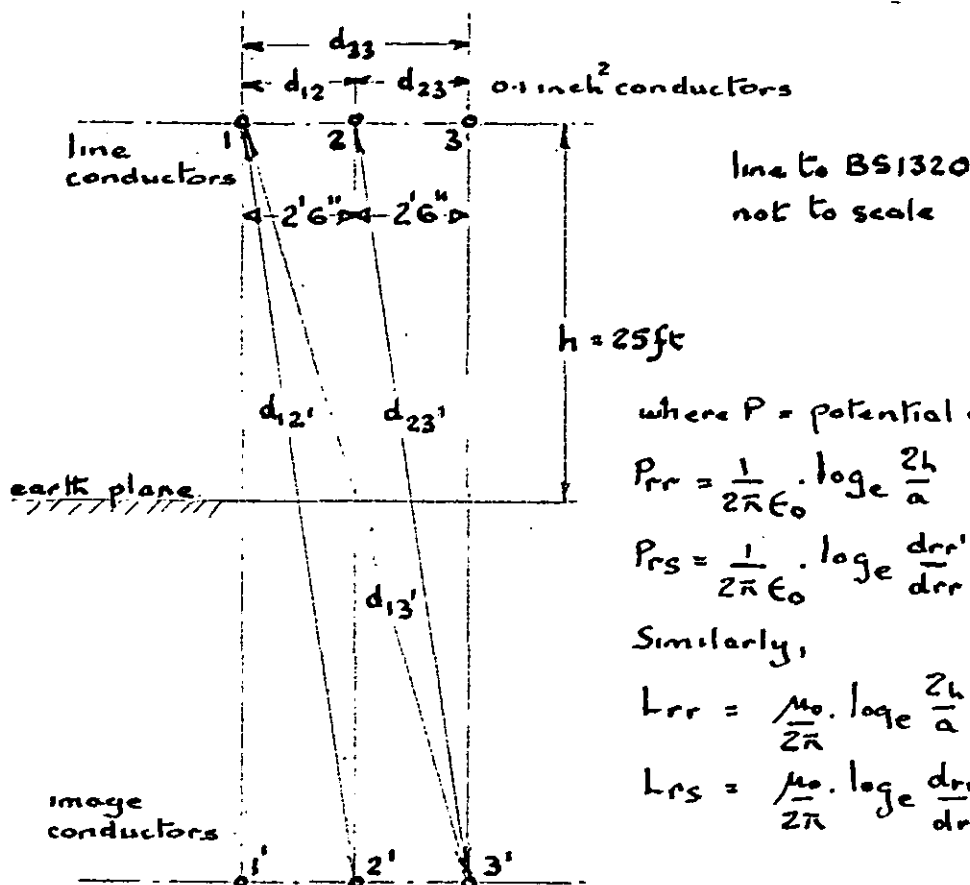
(i) It does not lead to complex numbers which, although accommodated on the Bergeron diagrams, give rise to complications.

(ii) Where the positive and negative sequence impedances are the same, as in the case of overhead lines, the application of these components generally leads to less work in the solution.

It has already been stated that the need for line transposition is relieved by the relatively close proximity of the conductors, and further, the presence of limited lengths of overhead line distribution between discontinuities also provide distinct advantages in this respect. Some degree of symmetry

is thus introduced into the problem of obtaining the responses, aided by the assumption that all three conductors are equally pulse excited.

It remains to resolve the values of the primary constants L and C of the horizontal arrangement of conductors so that the velocities of propagation and the surge impedances can be determined in the modal domain. It is tacitly assumed that the conductors have no sag and are parallel to a perfect earth plane of infinite conductivity.



where P = potential coefficient, then

$$P_{rr} = \frac{1}{2\pi\epsilon_0} \cdot \log_e \frac{2h}{a} \text{ to earth}$$

$$P_{rs} = \frac{1}{2\pi\epsilon_0} \cdot \log_e \frac{d_{rr'}}{d_{rr}} \text{ between condrs.}$$

Similarly,

$$L_{rr} = \frac{\mu_0}{2\pi} \cdot \log_e \frac{2h}{a} \text{ self induct.}$$

$$L_{rs} = \frac{\mu_0}{2\pi} \cdot \log_e \frac{d_{rr'}}{d_{rr}} \text{ mutual induct.}$$

all dimensions in metres

$d_{12} = 0.762$	$d_{11'} = 15.24$	$d_{12'} = 15.25$
$d_{23} = 0.762$	$d_{22'} = 15.24$	$d_{23'} = 15.25$
$d_{31} = 1.524$	$d_{33'} = 15.24$	$d_{13'} = 15.32$

The computation of the line constants can be reduced to some extent by using the relation $L = \frac{\mu_0}{\epsilon_0} P$. Then $L_{rr} = \frac{\mu_0}{\epsilon_0} P_{rr}$, and $L_{rs} = \frac{\mu_0}{\epsilon_0} P_{rs}$.

$$\text{Now if } E_1 = P_{11} Q_1 + P_{12} Q_2 + P_{13} Q_3$$

$$E_2 = P_{21} Q_1 + P_{22} Q_2 + P_{23} Q_3$$

$$E_3 = P_{31} Q_1 + P_{32} Q_2 + P_{33} Q_3$$

on substituting for the calculated values of P (using the diagram) and arranging in matrix form, these equations become

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} 14.6 & 2.995 & 2.3026 \\ 2.995 & 14.6 & 2.995 \\ 2.3026 & 2.995 & 14.6 \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix}$$

solving for Q_1 , Q_2 and Q_3 in terms of the potentials E_1 , E_2 and E_3

$$10^{12} \times \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} 7.25E_1 & -1.3E_2 & -0.876E_3 \\ -1.3E_1 & +7.39E_2 & -1.3E_3 \\ -0.876E_1 & -1.3E_2 & +7.26E_3 \end{bmatrix}$$

and rearranging

$$10^{12} \times \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} 5.074E_1 & +1.3(E_1 - E_2) & +0.876(E_1 - E_3) \\ 4.79E_2 & +1.3(E_2 - E_1) & +1.3(E_2 - E_3) \\ 5.084E_3 & +0.875(E_3 - E_1) & +1.3(E_3 - E_2) \end{bmatrix}$$

from which the capacitances (i) to earth, (ii) between conductors, are:

$$(i) \quad \begin{bmatrix} C_{11} = 5.074 \\ C_{22} = 4.79 \\ C_{33} = 5.084 \end{bmatrix} \mu F/\text{metre} \quad (ii) \quad \begin{bmatrix} C_{12} = 1.3 \\ C_{13} = 0.876 \\ C_{23} = 1.3 \end{bmatrix} \mu F/\text{metre}$$

Using the equations on the previous page relating the self and mutual inductances to the potential coefficients, the constants are found to be (iii) self inductances, and (iv) mutual inductances, as

$$(iii) \quad \begin{bmatrix} L_{11} = 1.63 \\ L_{22} = 1.63 \\ L_{33} = 1.63 \end{bmatrix} \mu H/\text{metre} \quad (iv) \quad \begin{bmatrix} L_{12} = 0.334 \\ L_{13} = 0.256 \\ L_{23} = 0.334 \end{bmatrix} \mu H/\text{metre}$$

Now, the M matrix is represented by

$$[M] = \begin{bmatrix} 1 & 1 & 0 \\ 1 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 1 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

and its inverse resolves as shown overleaf:-

$$[M]^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix}$$

since

$$\frac{d^2[V]}{dx^2} - [L][C] \frac{d^2[V]}{dt^2} = 0$$

where $[V]$ is a column matrix, a set of independent equations may be derived from the diagonal matrix resulting from the computation of

$$[M]^{-1} [L] [C] [M] \quad \dots\dots\dots(A)$$

and since $v = \frac{1}{\sqrt{LC}}$, the velocity of propagation is then available for each component.

Similarly, if Z_o^2 is found from

$$[M]^{-1} [L] [C]^{-1} [M] \quad \dots\dots\dots(B)$$

the three modal surge impedances can be found in the same manner. Hence it follows that when

$$[L] = \begin{bmatrix} 1.63 & 0.334 & 0.256 \\ 0.334 & 1.63 & 0.334 \\ 0.256 & 0.334 & 1.63 \end{bmatrix}$$

and

$$[C] = \begin{bmatrix} 5.074 & -1.3 & -0.876 \\ -1.3 & 4.79 & -1.3 \\ -0.876 & -1.3 & 5.084 \end{bmatrix}$$

and the inverse of this matrix is shown to be

$$[C]^{-1} = \begin{bmatrix} 0.226 & 0.078 & 0.059 \\ 0.078 & 0.250 & 0.078 \\ 0.059 & 0.078 & 0.226 \end{bmatrix}$$

then equations (A) and (B) can be resolved.

Summarising the results as modal values of v and Z_0 ,

Component	Velocity of propagation	Surge impedance
Zero	$0.408c$	$0.92 Z_0$
Alpha	$0.352c$	$0.469Z_0$
Beta	$0.352c$	$0.469Z_0$

It is now possible to carry out the Bergeron analysis on the network. A step function pulse could be applied at this stage, the response from which, by means of Duhamel's theorem, would serve as the foundation for an investigation of the effects of differing shapes of induced pulse. This is beyond the scope of the present work however, and a $5/20^{\text{th}}$ μsec linear pulse represents the forcing function. The results obtained in the modal state are transformed back into the real system by means of the operation

$$[V]_1 = [M] [V]$$



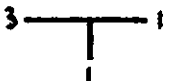
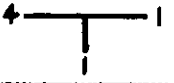
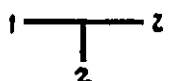
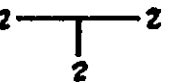


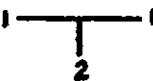
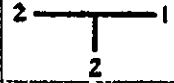
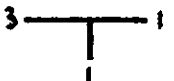
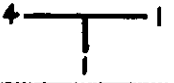
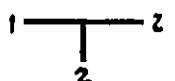
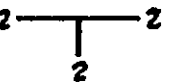



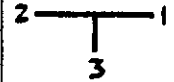

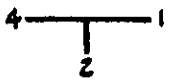
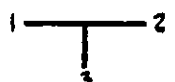
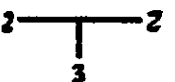
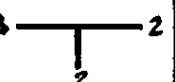
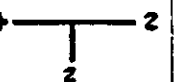

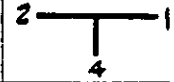

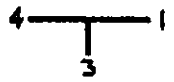
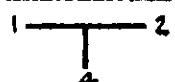
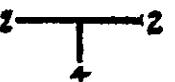
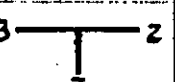
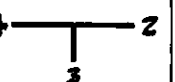




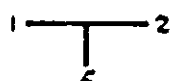


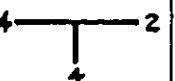







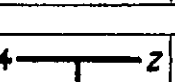




and sample responses are shown in figure 40 corresponding to group 2 in Table 11 on page 187. The overall results are seen to differ only slightly from the corresponding single conductor responses in figures 13 and 17.

Table 11

Ratio of section lengths - Type C tee-off circuit

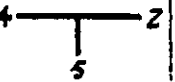
Group No.

Figure No.

1	2	3	4	5	6	7	8	Delay at P
16 	18 	20 	22 	17 	19 	21 	23 	3
								4
								5
								6
								7
								8
								9
								10
								11
								12

←
In unit section
lengths, due
to reflection
at A.

Table 11.

	14
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TEAR-OFF TERMINAL VOLTAGE GROUPS 1 AND 5

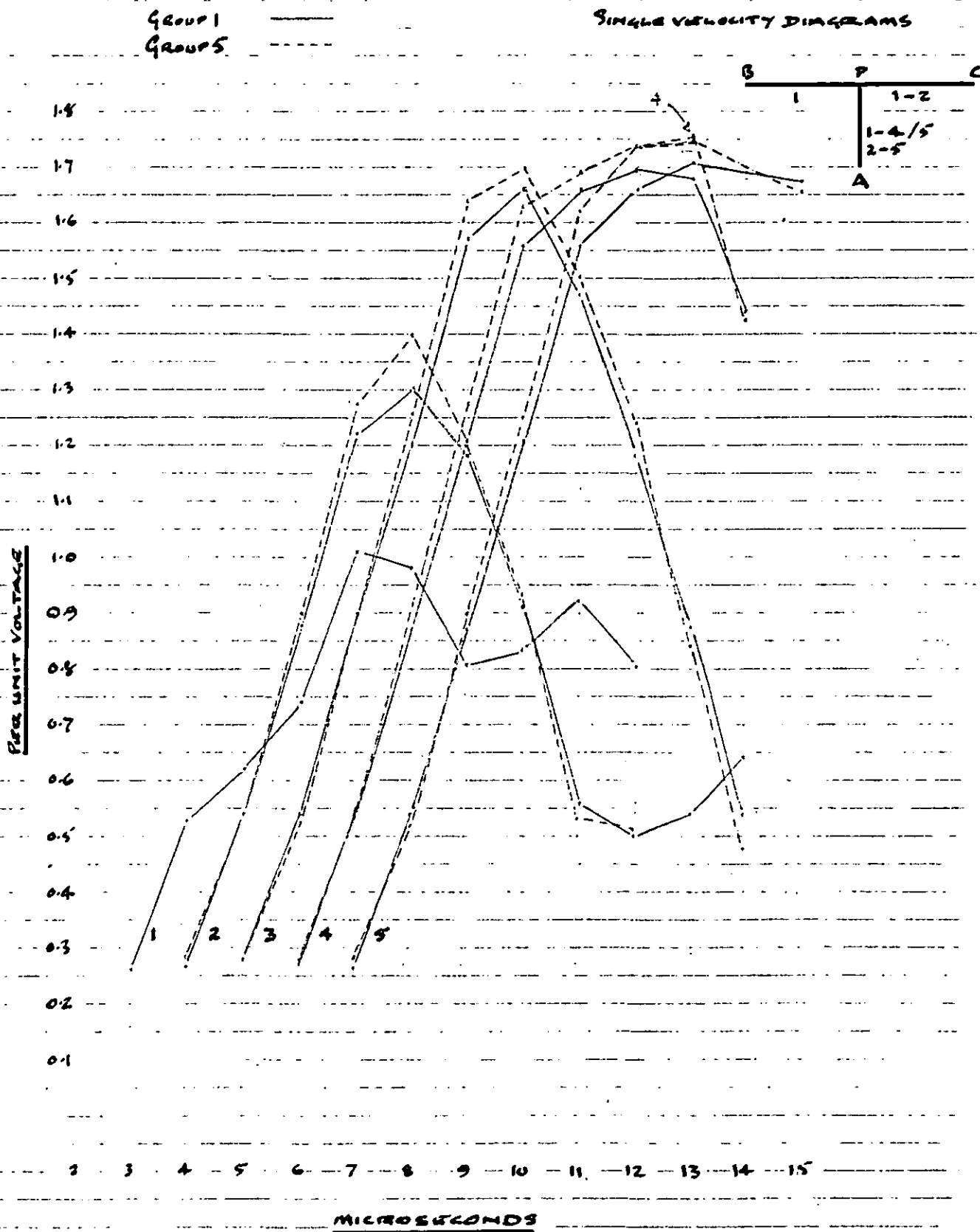


FIGURE 12

TEG-OFF TERMINAL VOLTAGES GROUPS 2 AND 6

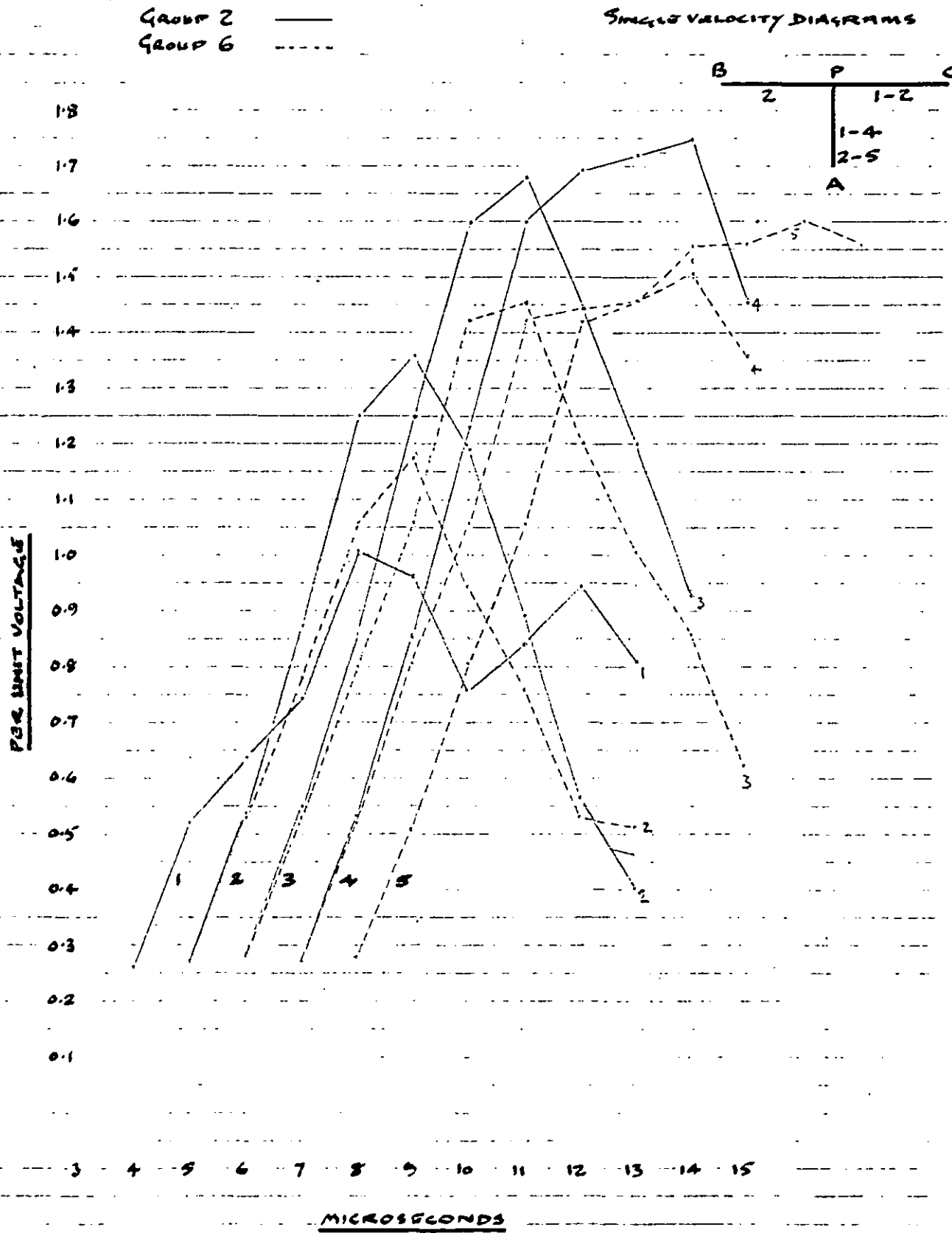


FIGURE 13

TEE-OFF TERMINAL VOLTAGES GROUPS 3 AND 7

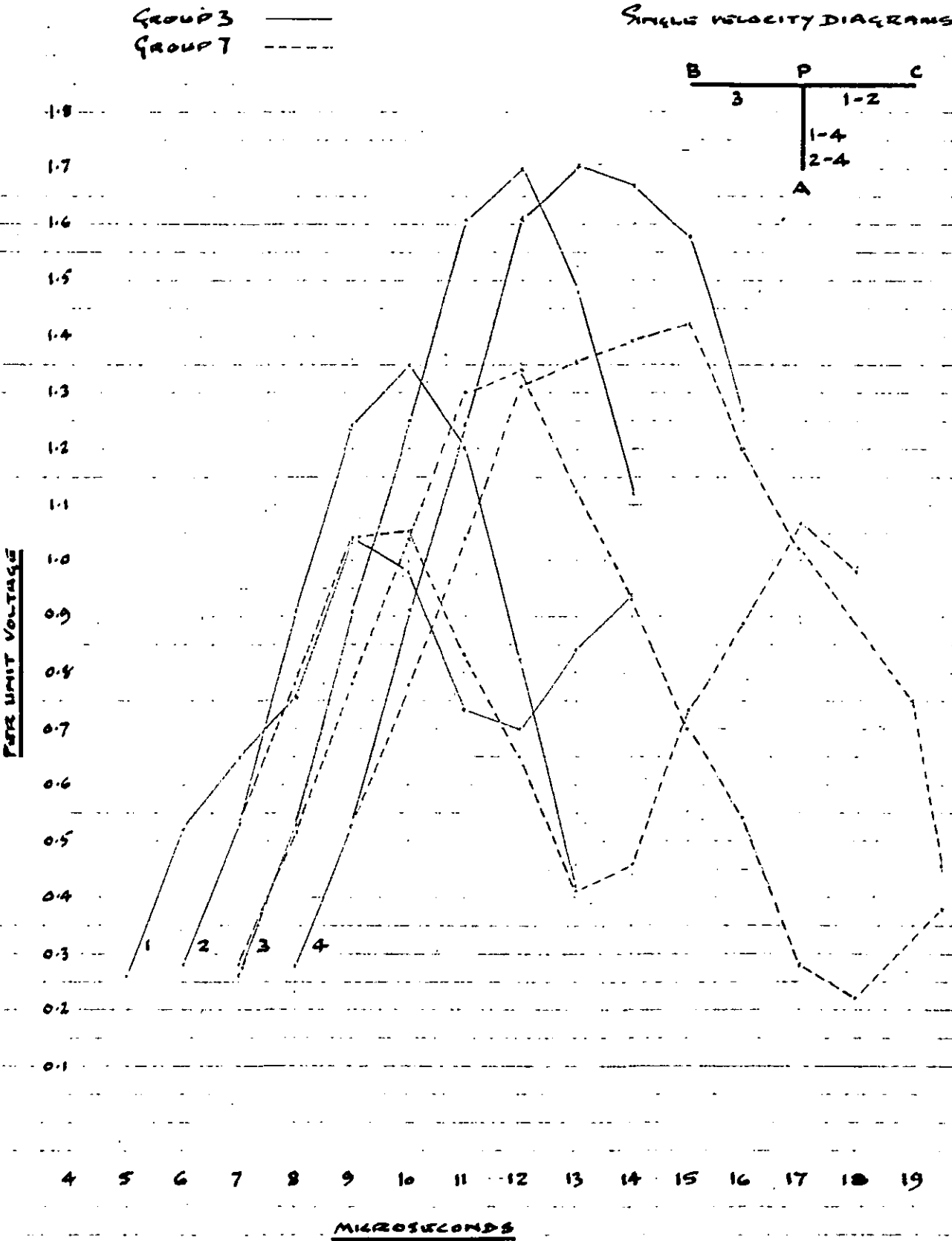


FIGURE 14

125-OPP TERMINAL VOLTAGES. GROUPS 4 AND 8

GROUP 4 ———
GROUP 8 - - - -

SINGLE VELOCITY DIAGRAMS

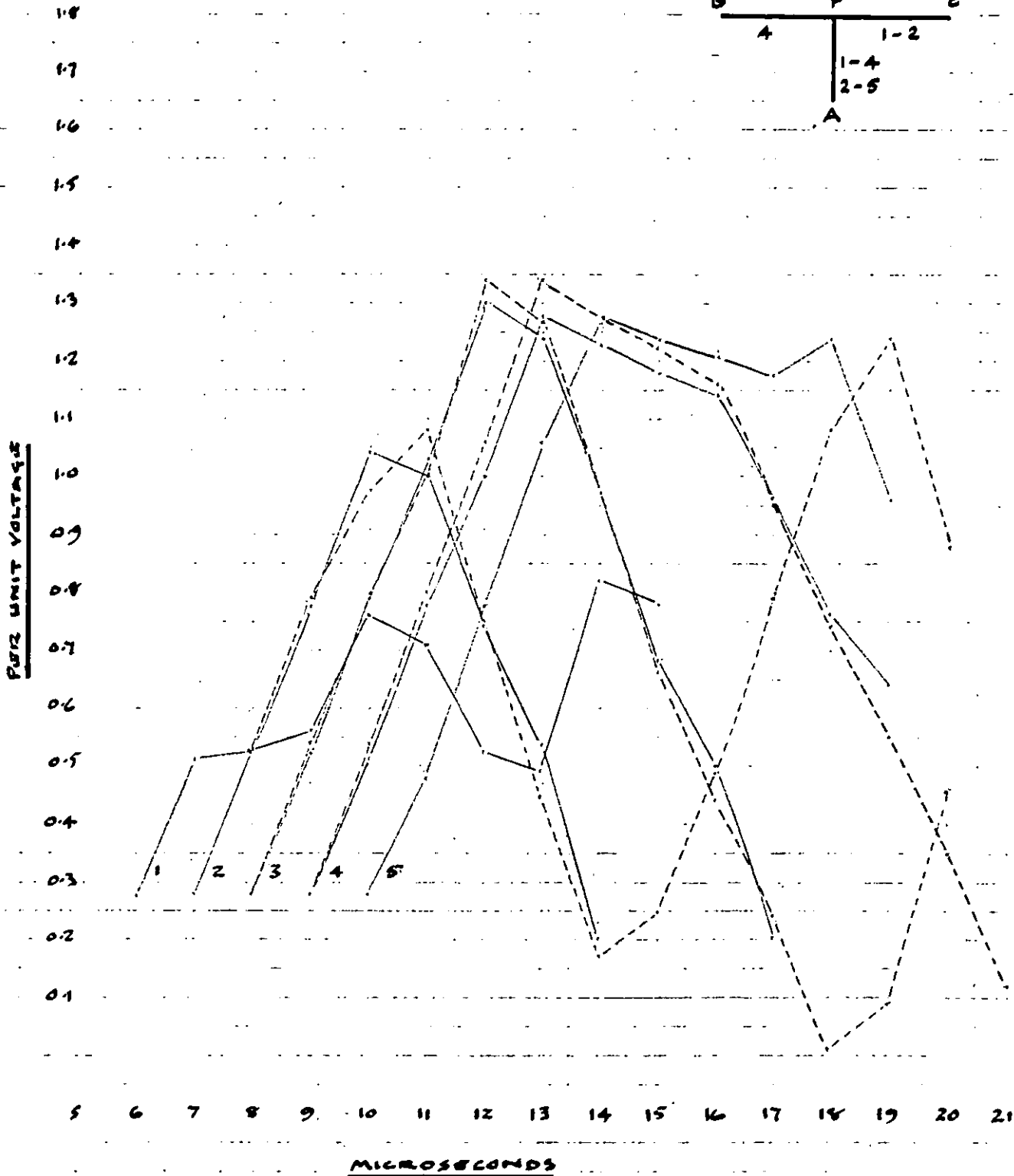
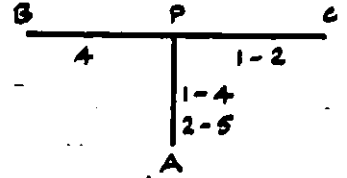
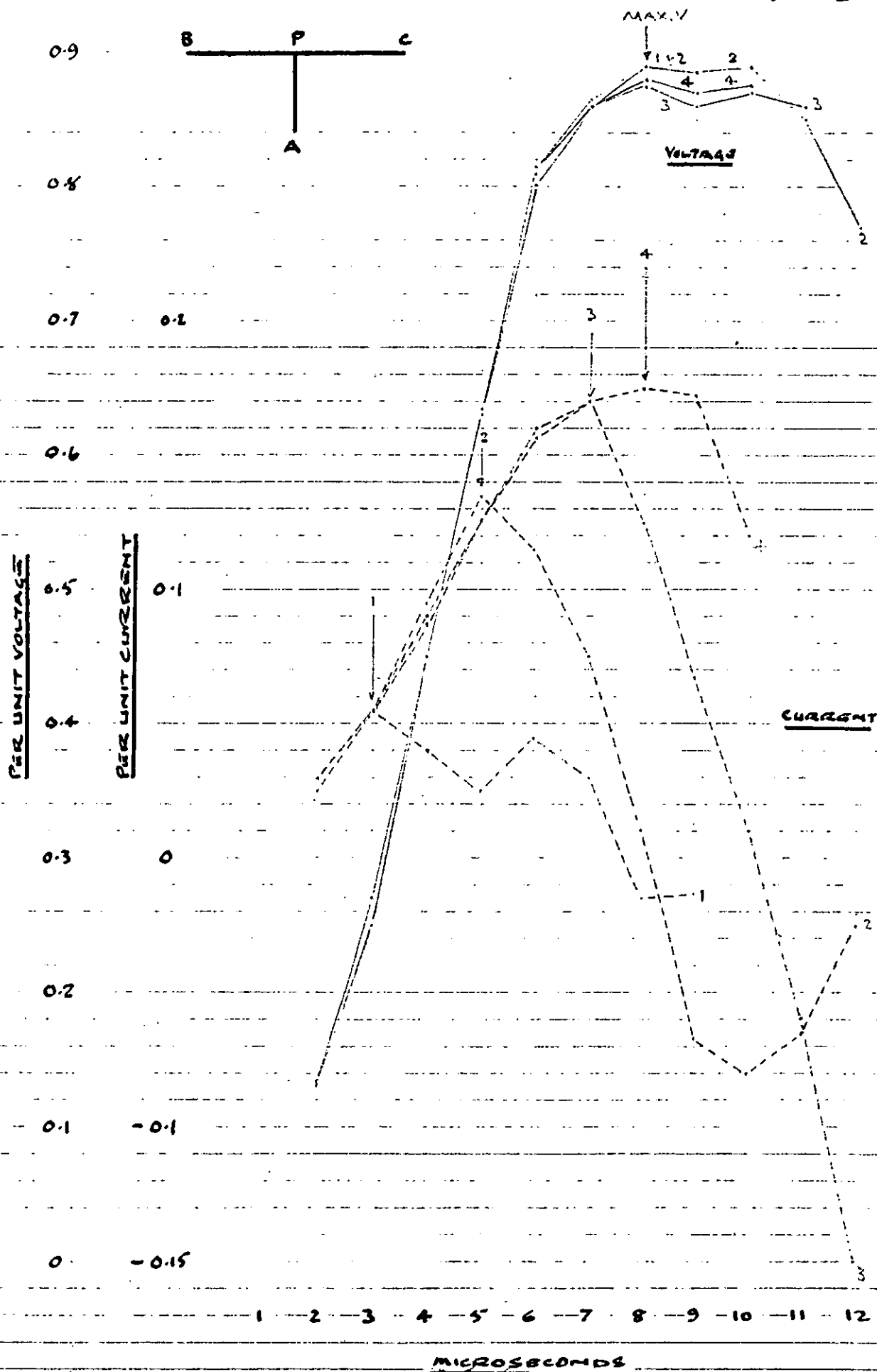


FIGURE 15

VOLTAGE AND CURRENT AT TEG-OFF TERMINAL P

GROUP I

Figure 16

VOLTAGE AND CURRENT AT TURN-OFF TERMINAL P

GROUP 2

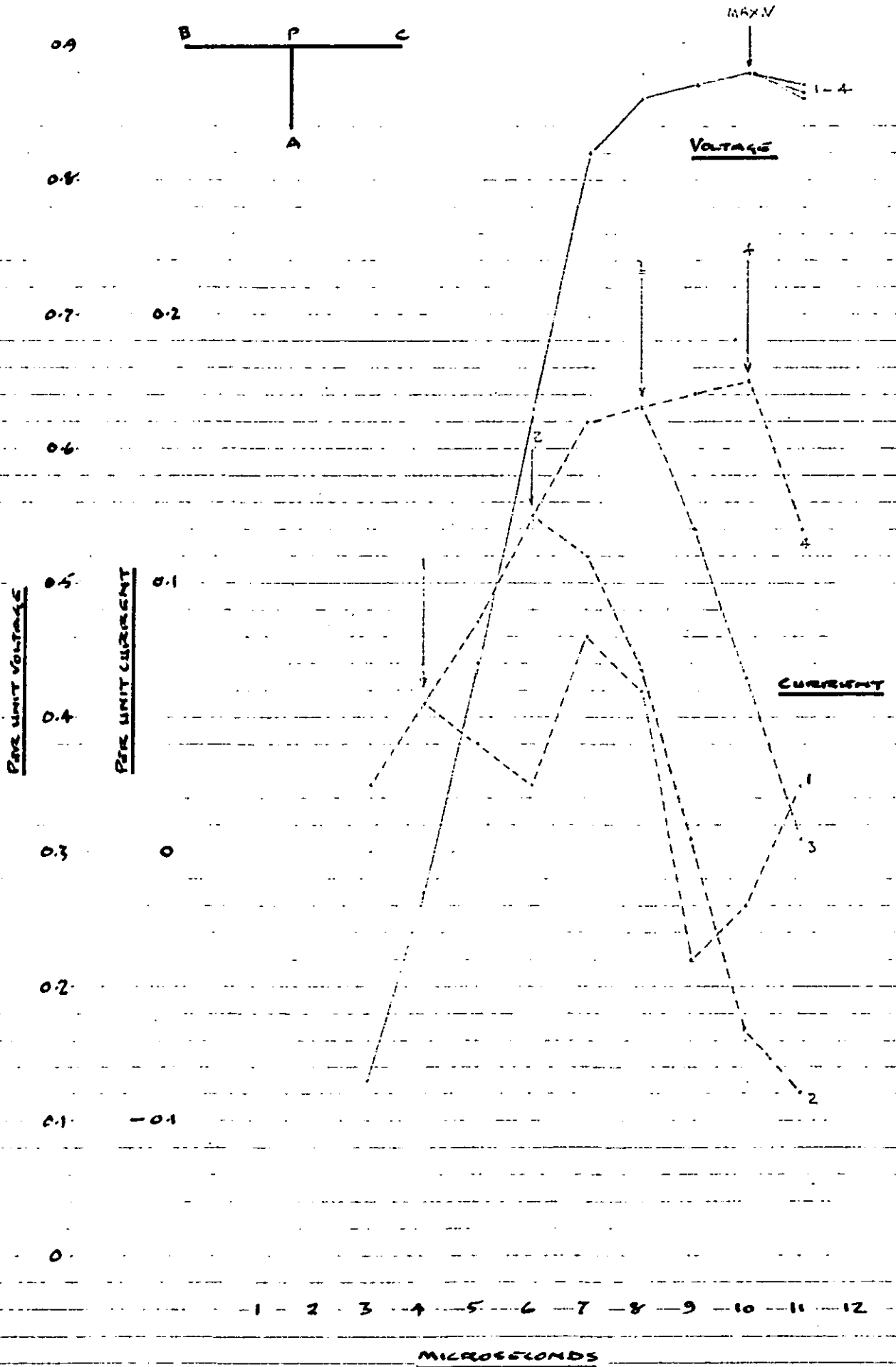


Figure 17

VOLTAGE AND CURRENT AT TEE-OFF TERMINAL P

GROUP 3

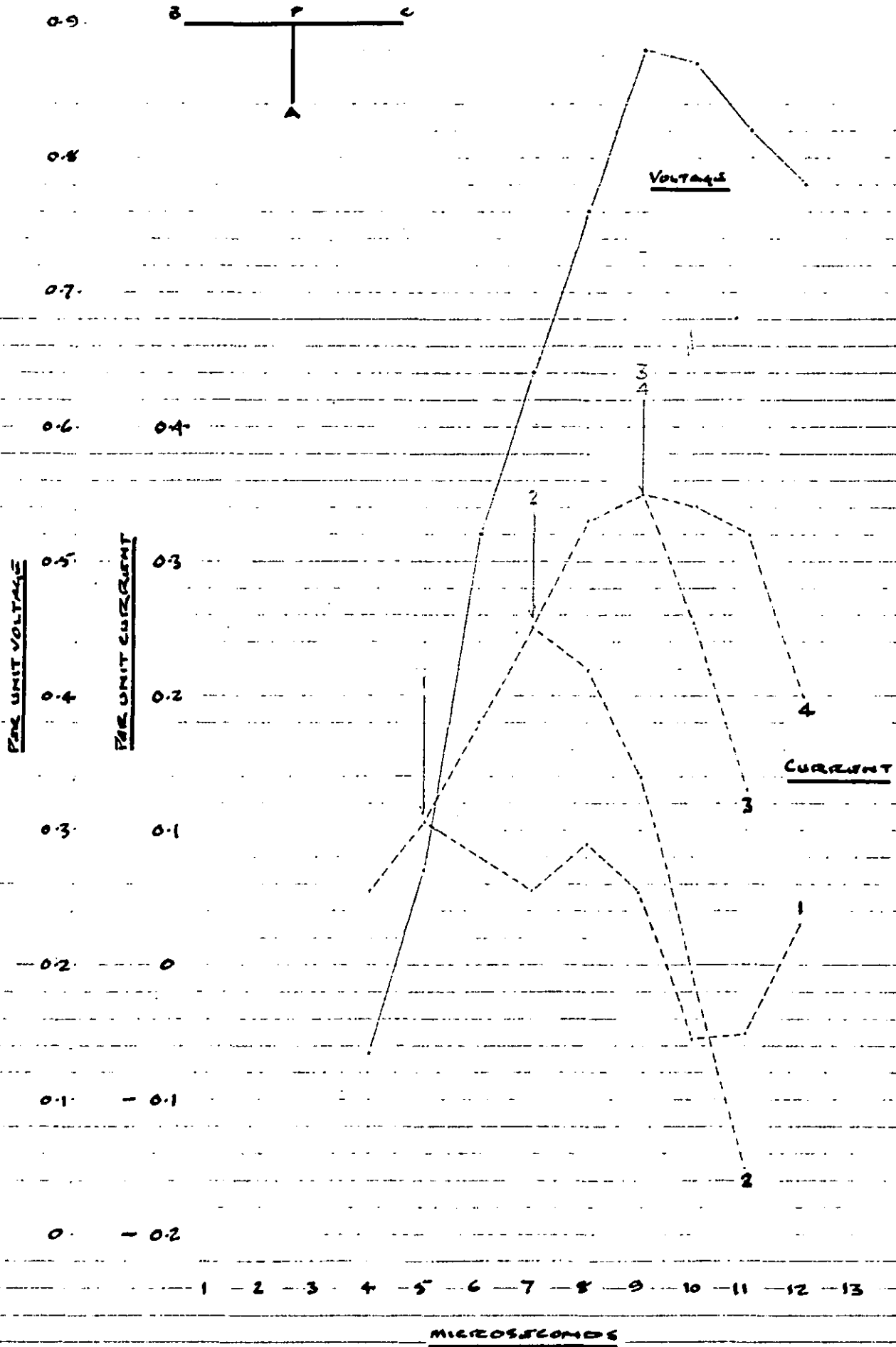


Figure 18

VOLTAGE AND CURRENT AT TEE-OFF TERMINAL P

GROUP 4

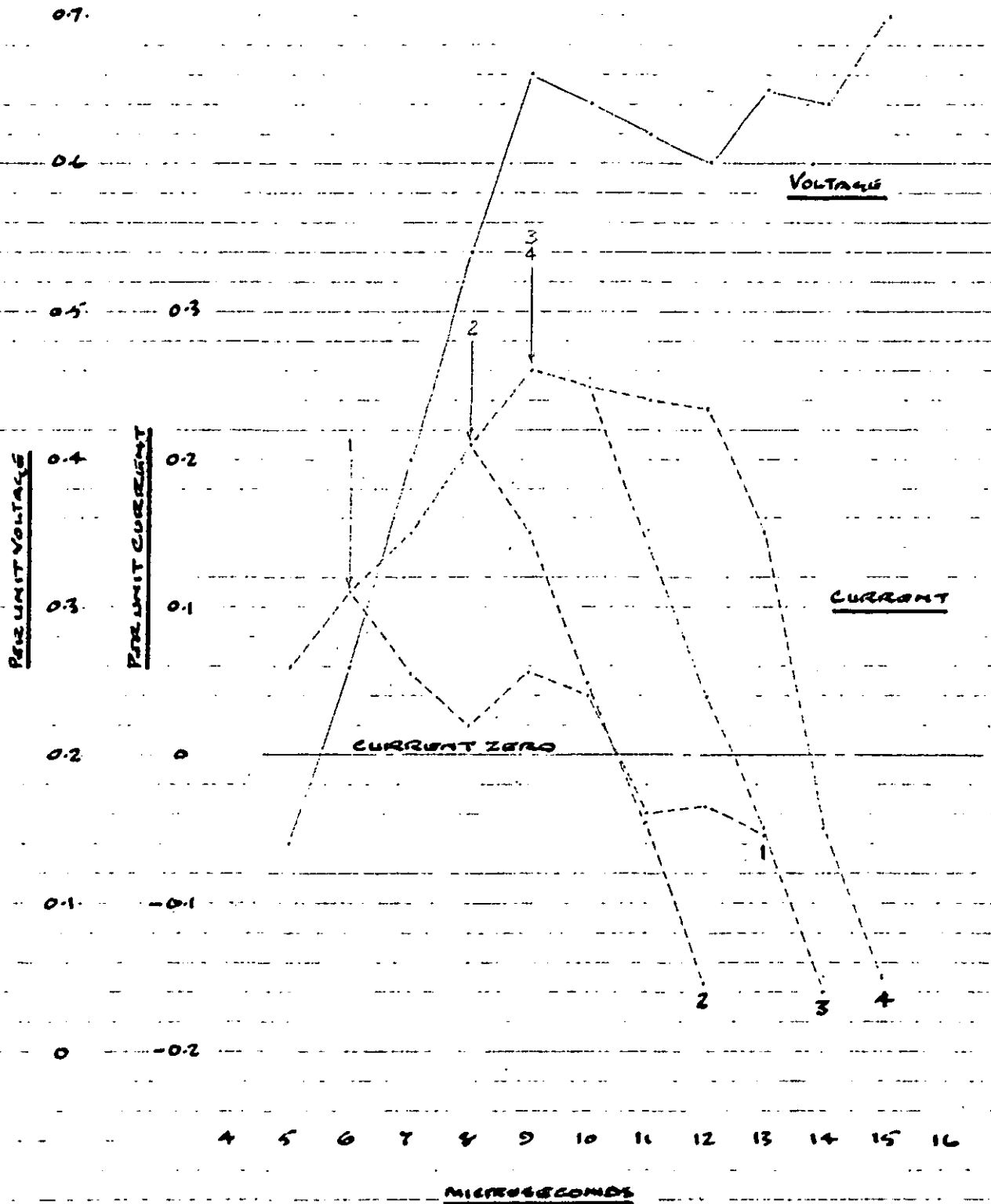
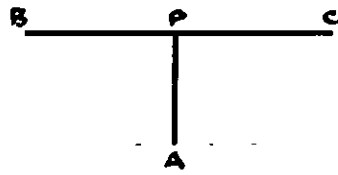


FIGURE 19

VOLTAGE AND CURRENT AT TEE-OFF TERMINAL P

GROUP 5

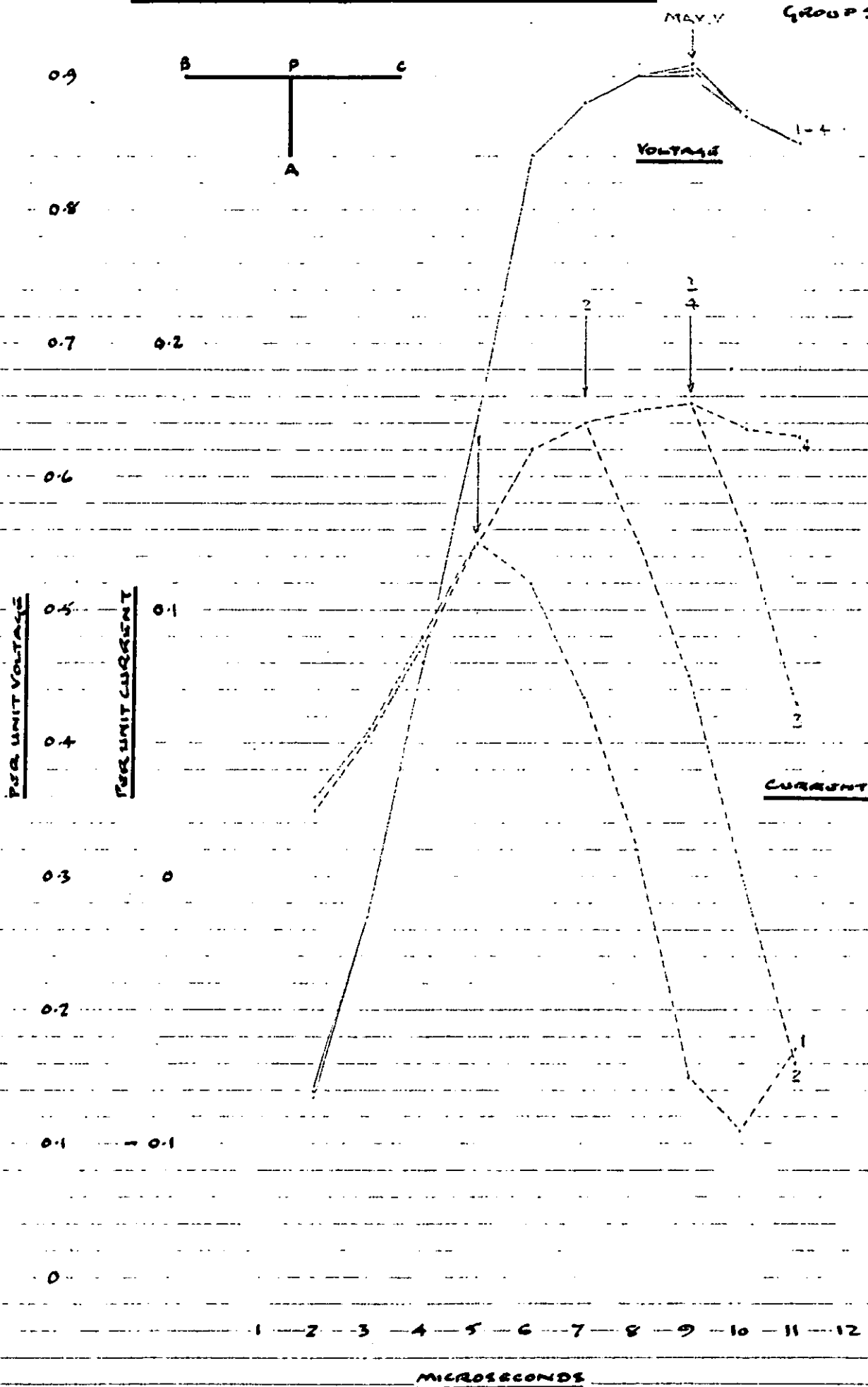
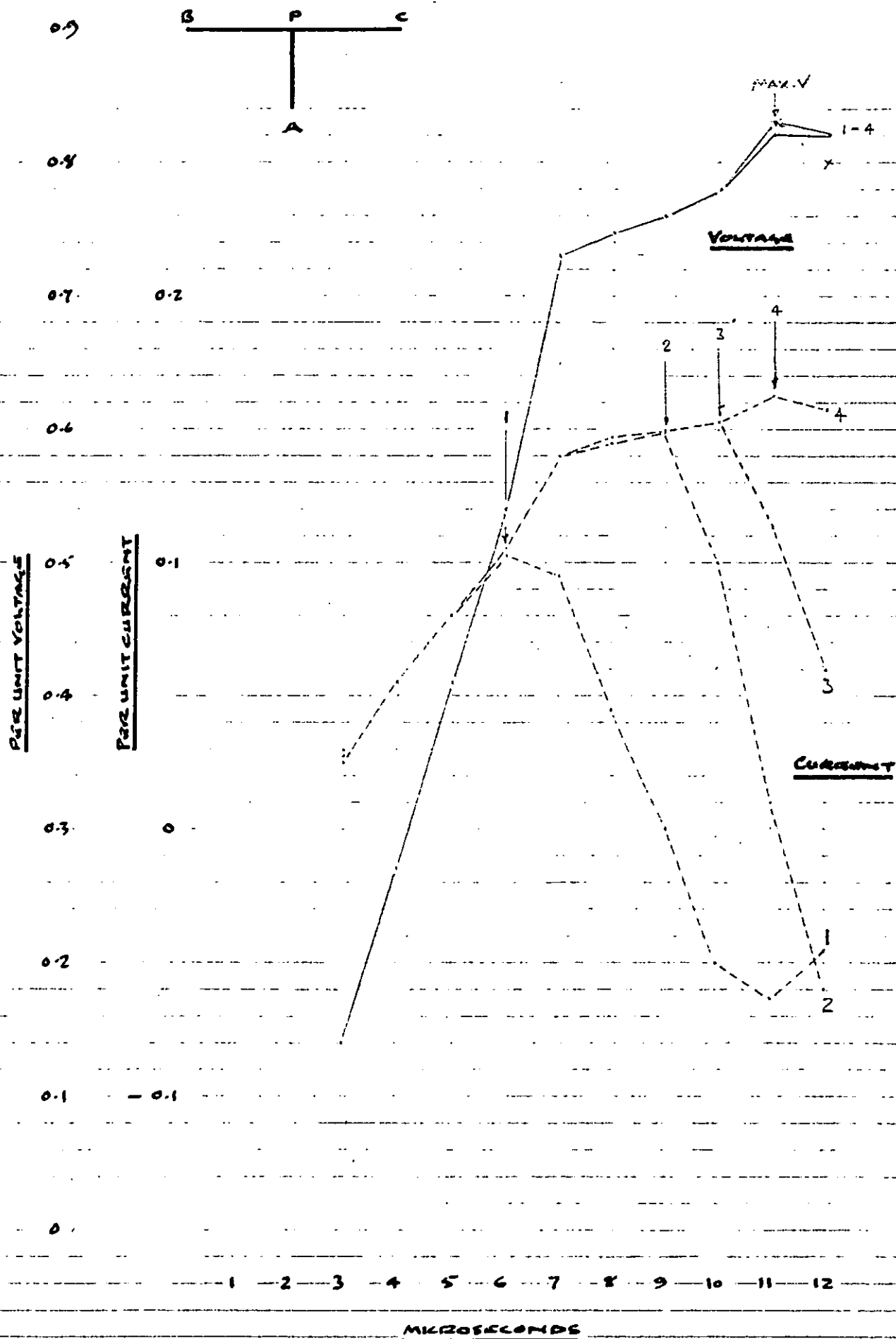


FIGURE 20

VOLTAGE AND CURRENT AT THE-OUT-TERMINAL P

GROUP 6



VOLTAGE AND CURRENT AT TURN-OFF TERMINAL P

GROUP 7

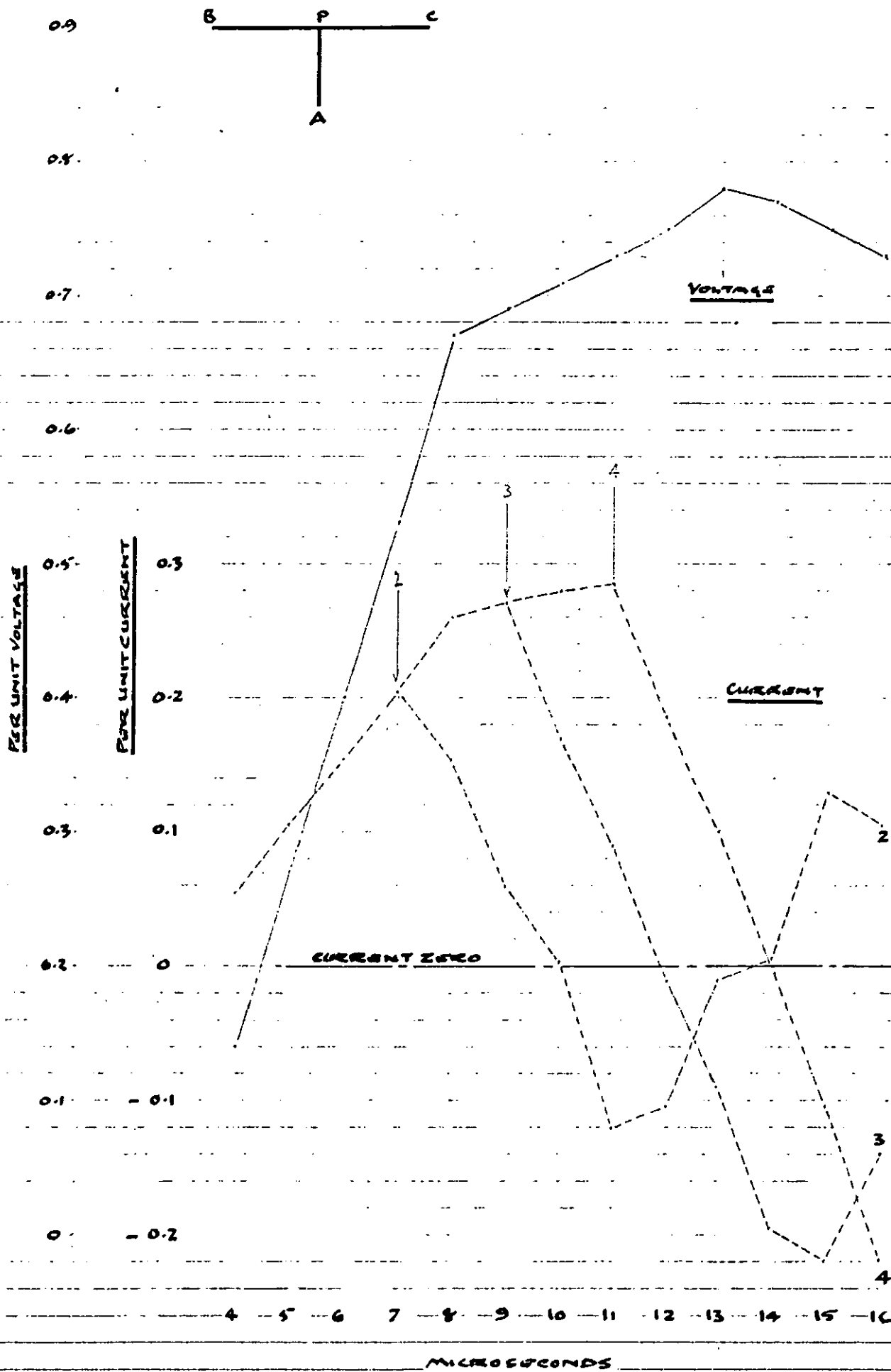


FIGURE 22

VOLTAGE AND CURRENT AT TGS-OFF TERMINAL P

GROUP 8

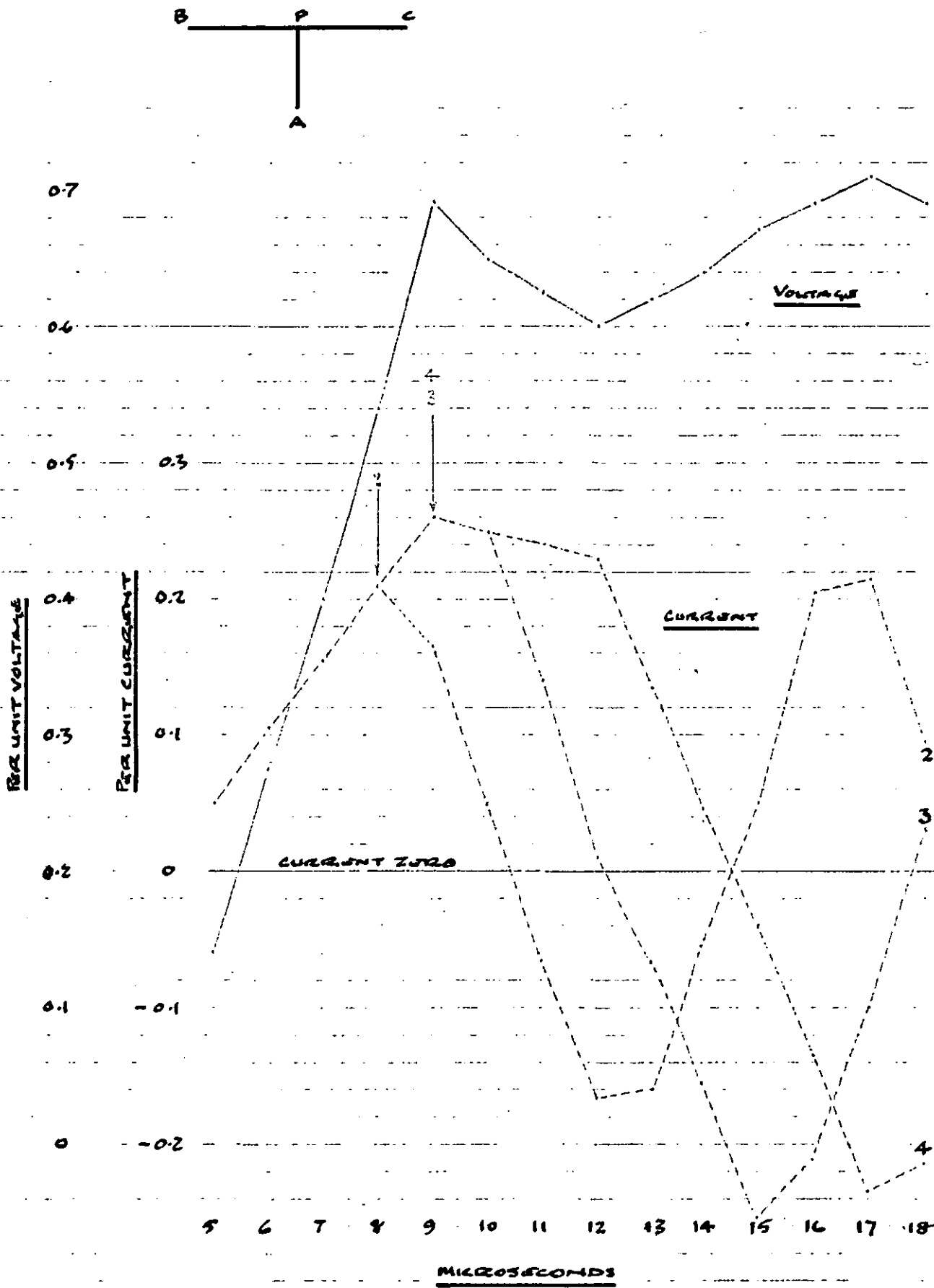
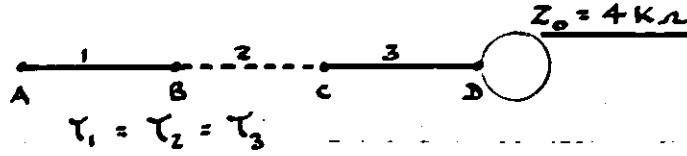


FIGURE 23

EFFECTS OF TRANSFORMER WINDING TRANSIT TIME

TERMINAL B



LEGEND:

- NO TRANSIT TIME B
- SAME TRANSIT TIME B'
- DOUBLE TRANSIT TIME B''

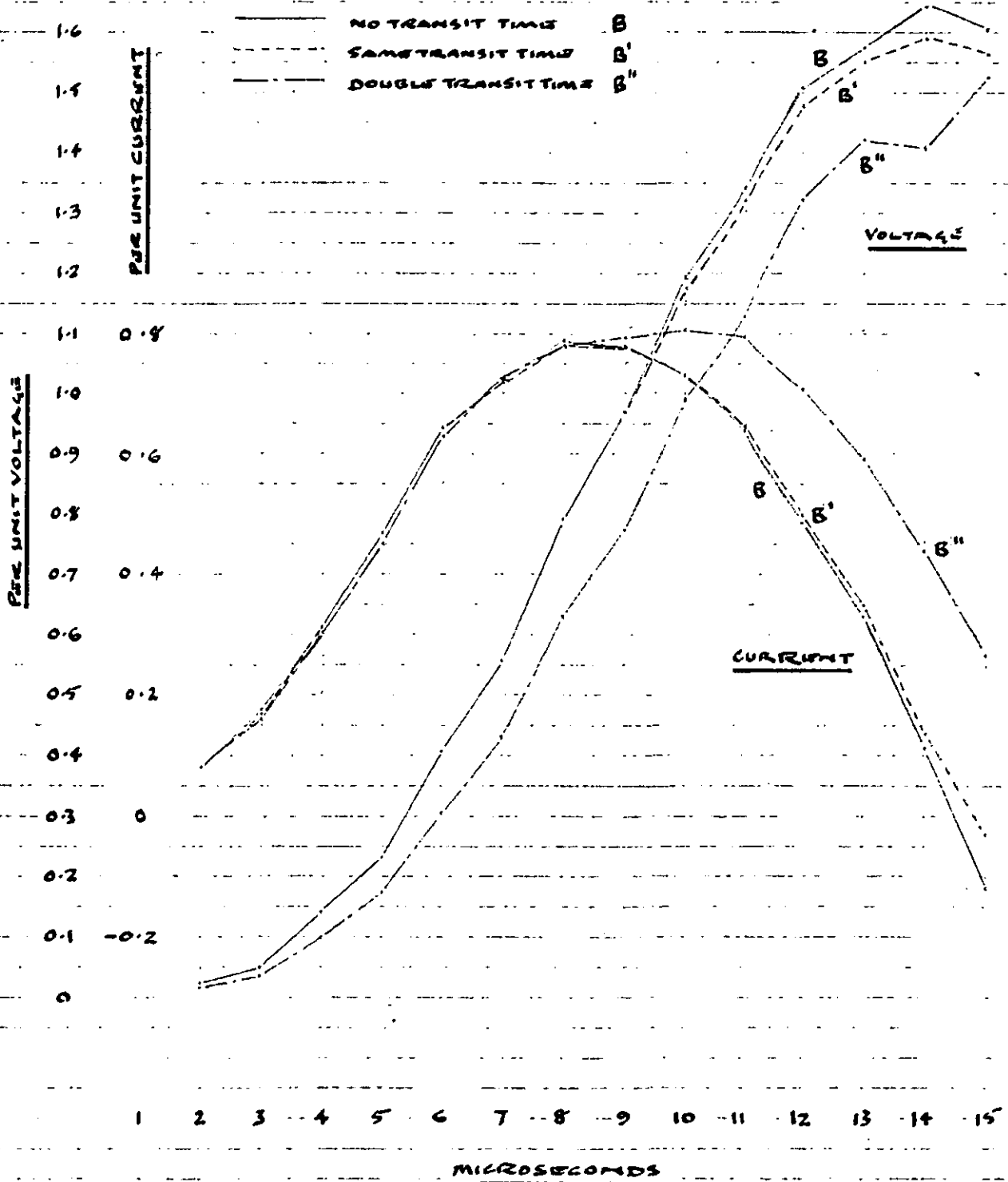
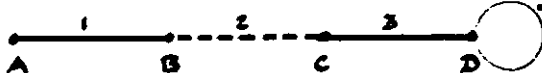


FIGURE 24

EFFECTS OF TRANSFORMER WINDING TRANSIT TIMETERMINALS C AND D

$$Z_0 = 4 \text{ K}\Omega$$

LEGEND:

- NO TRANSIT TIME
- - - SAME TRANSIT TIME
- · - DOUBLE TRANSIT TIME

VOLTAGECURRENT

PER UNIT VOLTAGE

PER UNIT CURRENT

0.2

0.1

0.05

0

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

MICROSECONDSFIGURE 25

EFFECTS OF TRANSFORMER WINDING TRANSIT TIME

TERMINAL B

$$Z_0 = 10 \text{ K}\Omega$$

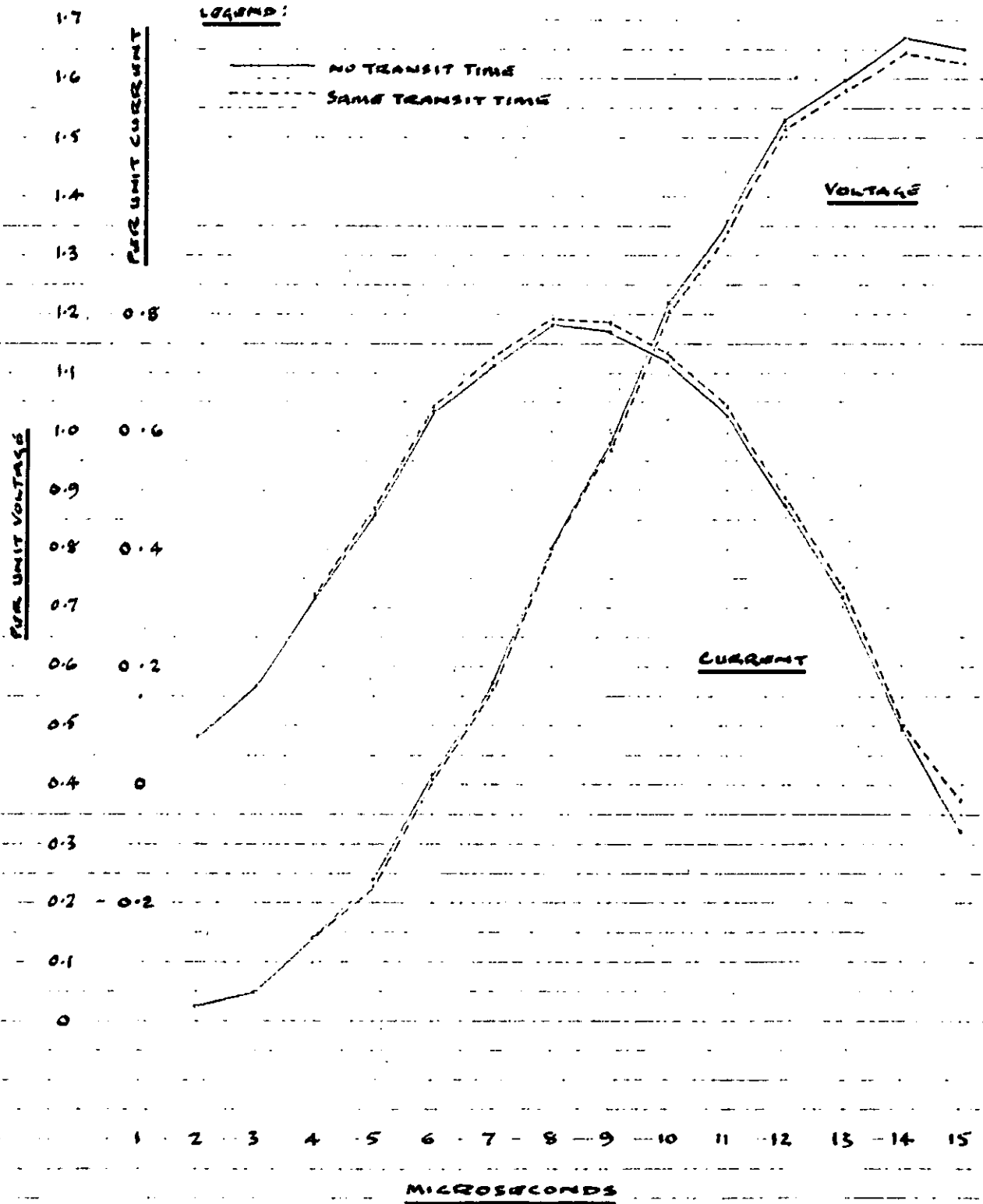
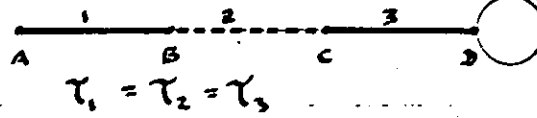


FIGURE 26

EFFECTS OF TRANSFORMER WINDING TRANSIT TIME

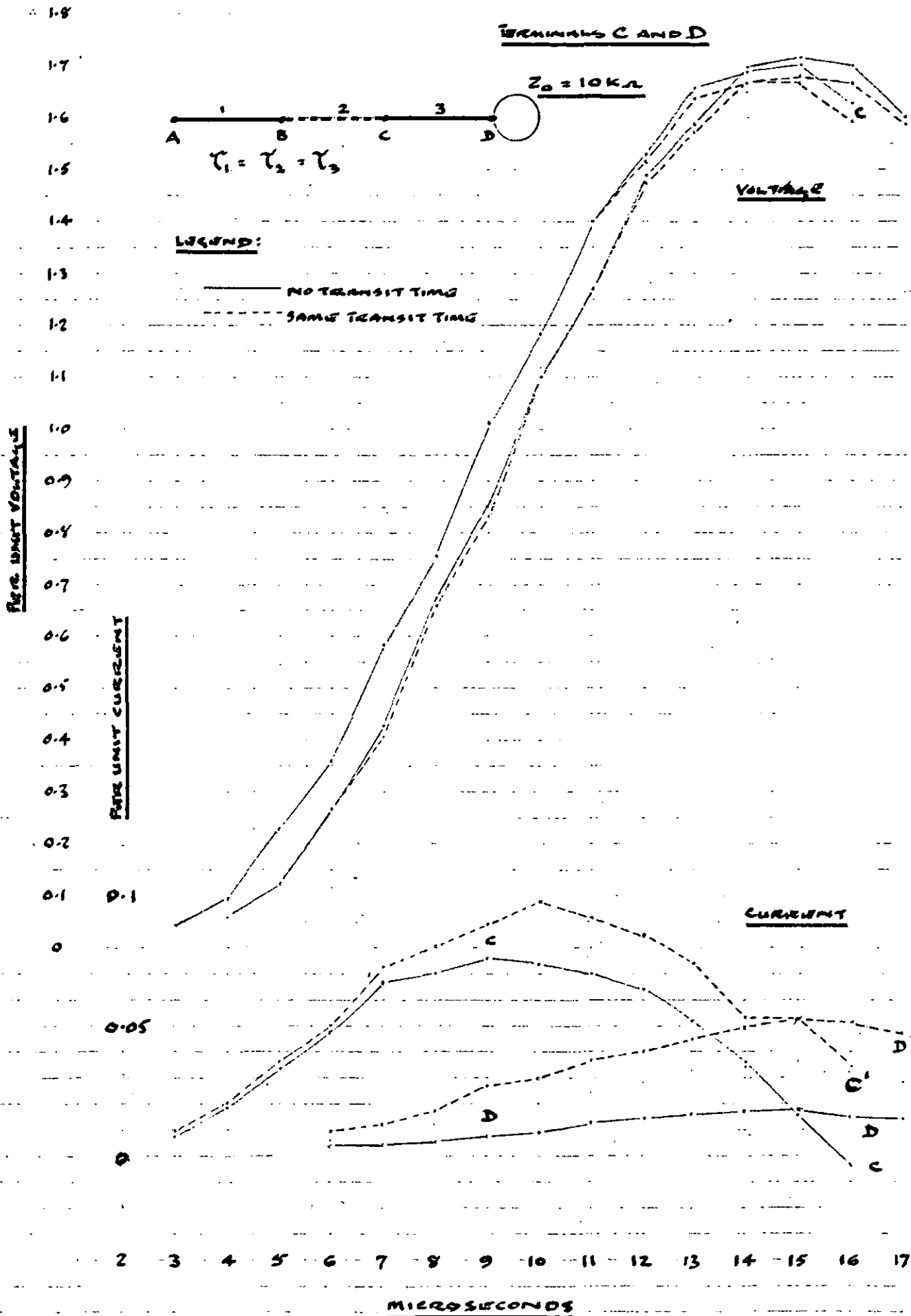
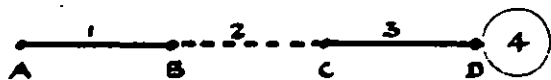


FIGURE 27

VOLTAGE AND CURRENT AT TERMINAL B FOR VARYING TRANSIT TIMES

IN LINE 1



Z_1 480 Ω EXCITATION:
 Z_2 22 Ω $\frac{5}{20}$ μ SEC. LIN. AC.
 Z_3 464 Ω FRONT AND TAIL.
 Z_4 18 k Ω

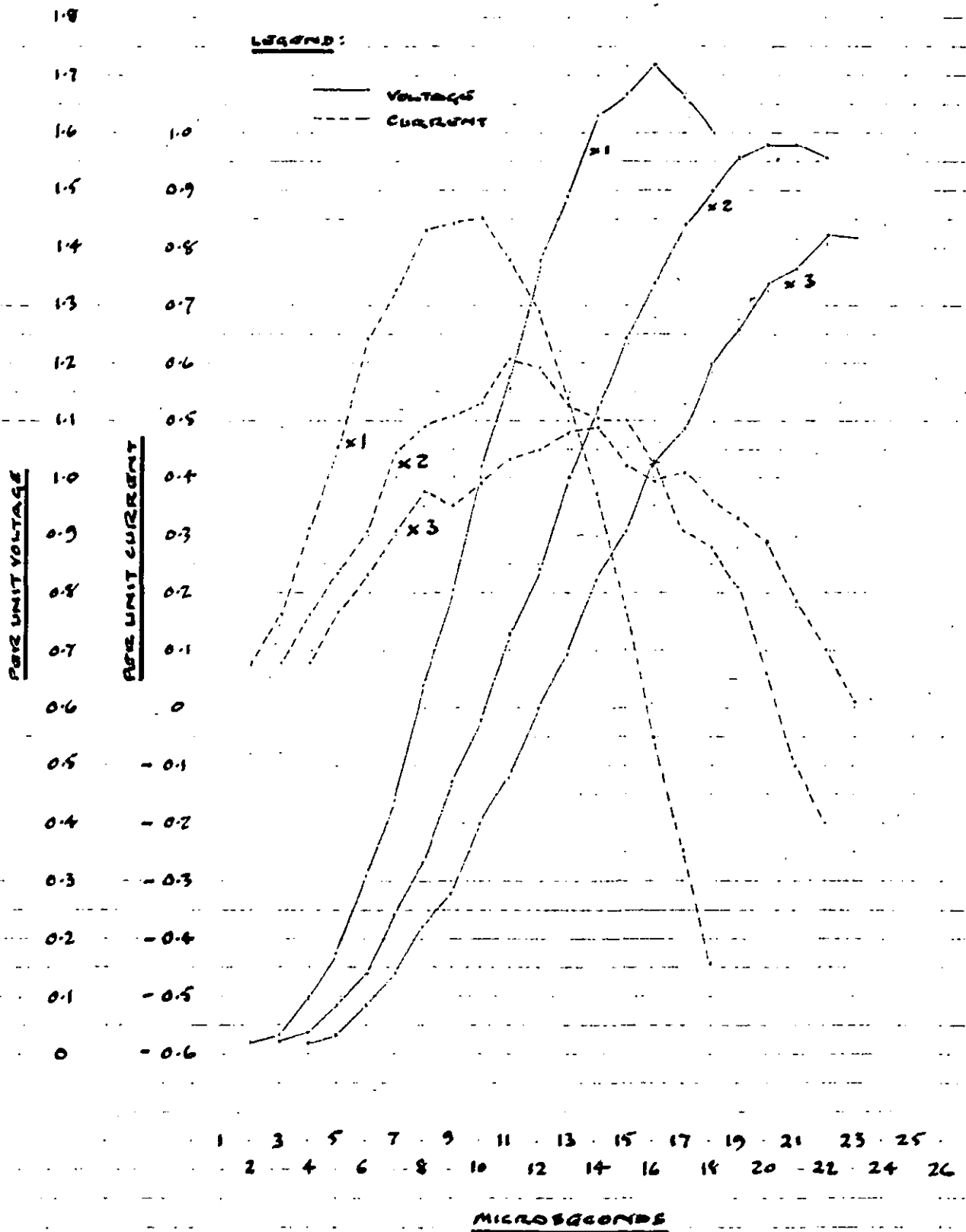


FIGURE 28

VOLTAGE AND CURRENT AT TERMINAL B FOR VARYING TRANSIT TIMES

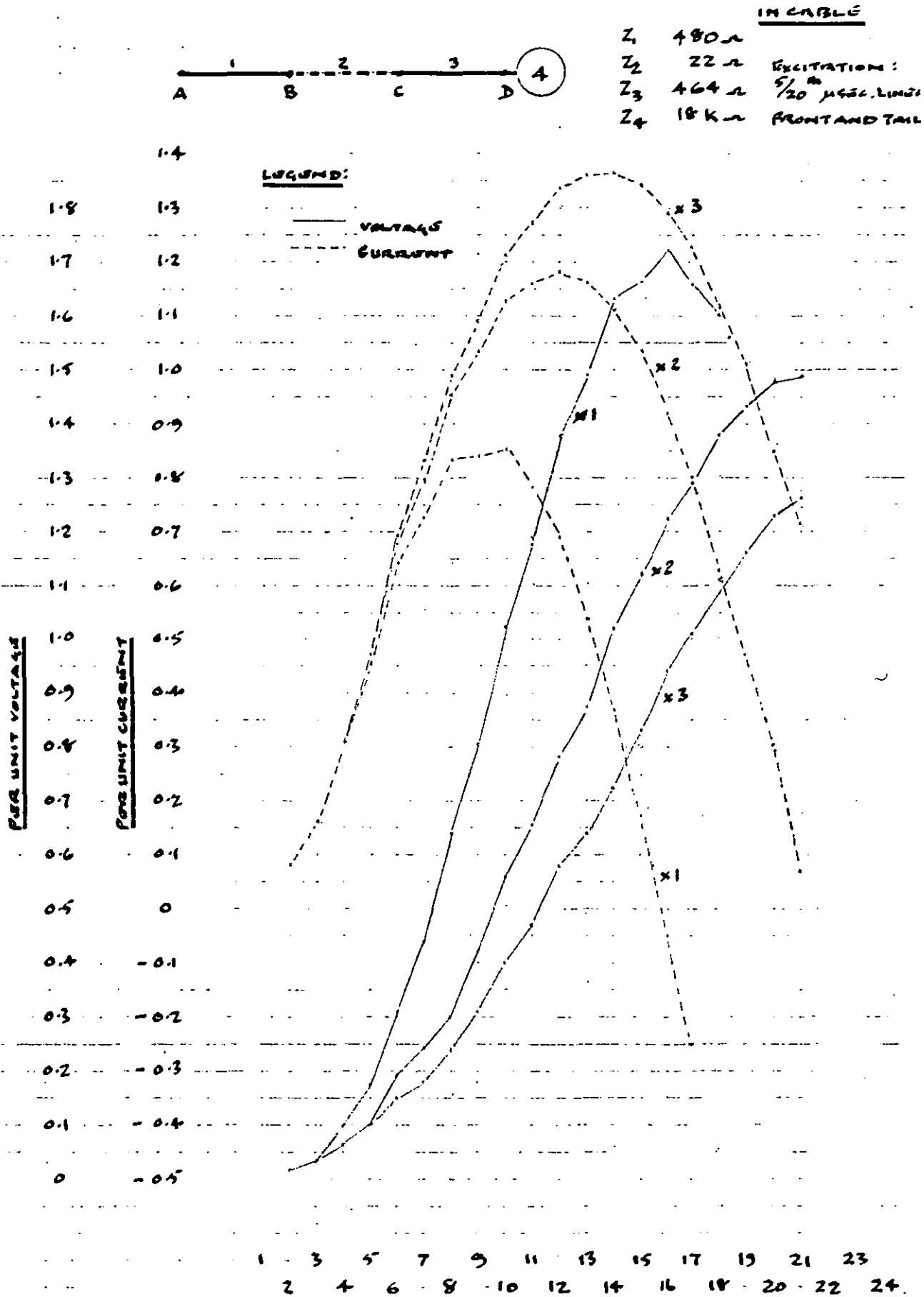
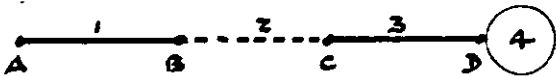


FIGURE 29

VOLTAGE AND CURRENT AT TERMINAL B FOR VARYING TRANSIT TIMES

IN LINE 2



Z_1 480 Ω EXCITATION:
 Z_2 22 Ω $5/20 \mu\text{SEC. LINE}$
 Z_3 464 Ω FRONT AND TAIL
 Z_4 18 K Ω

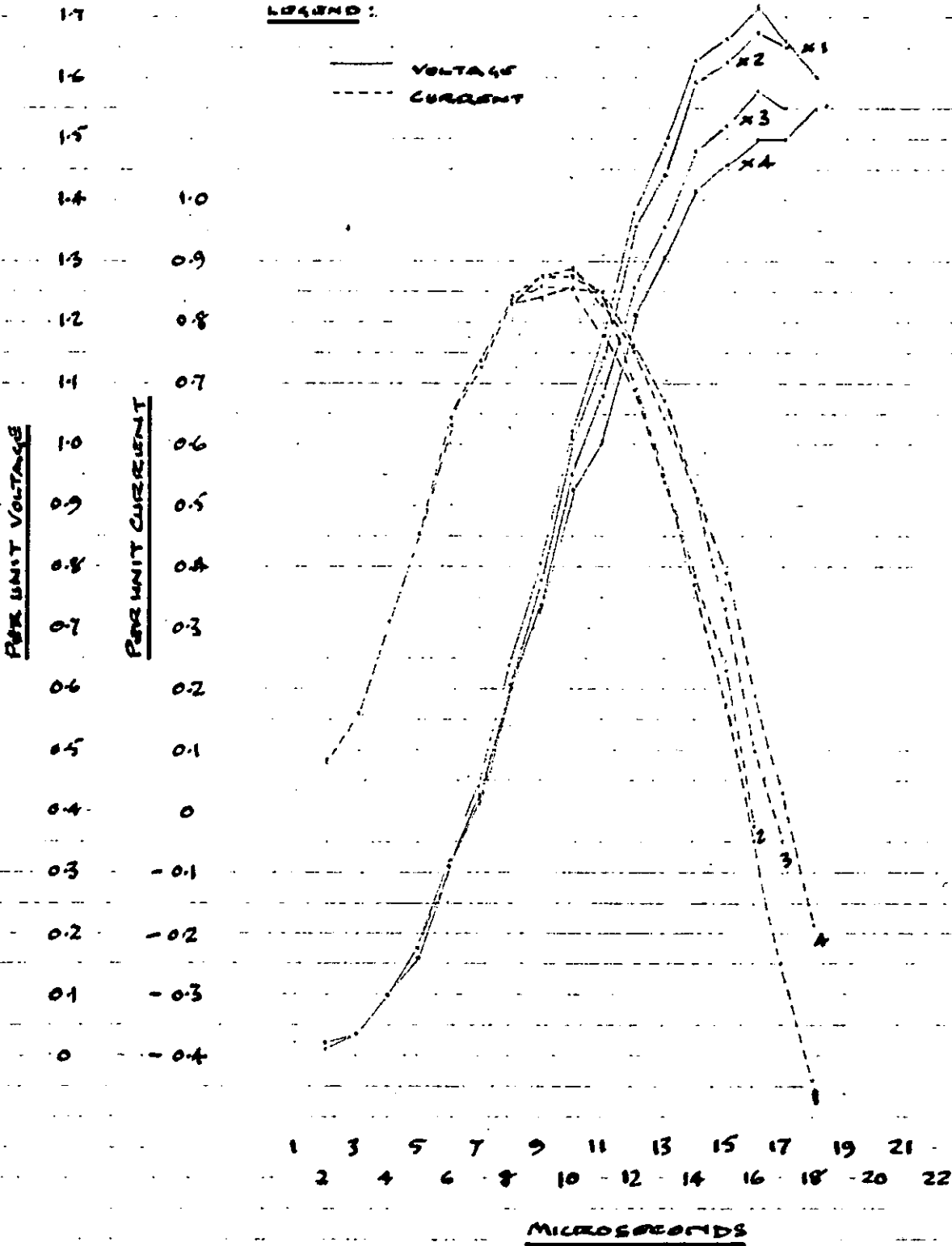
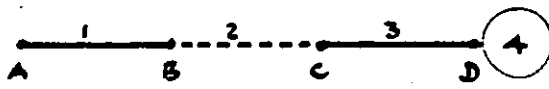


FIGURE 30

VOLTAGE AND CURRENT AT TERMINAL C FOR VARYING TRANSIT TIMES

IN LINE 1



Z_1 480 Ω EXCITATION:
 Z_2 22 Ω 5/20 μ SEC. PULSE
 Z_3 464 Ω FRONT AND TAIL
 Z_4 18K Ω

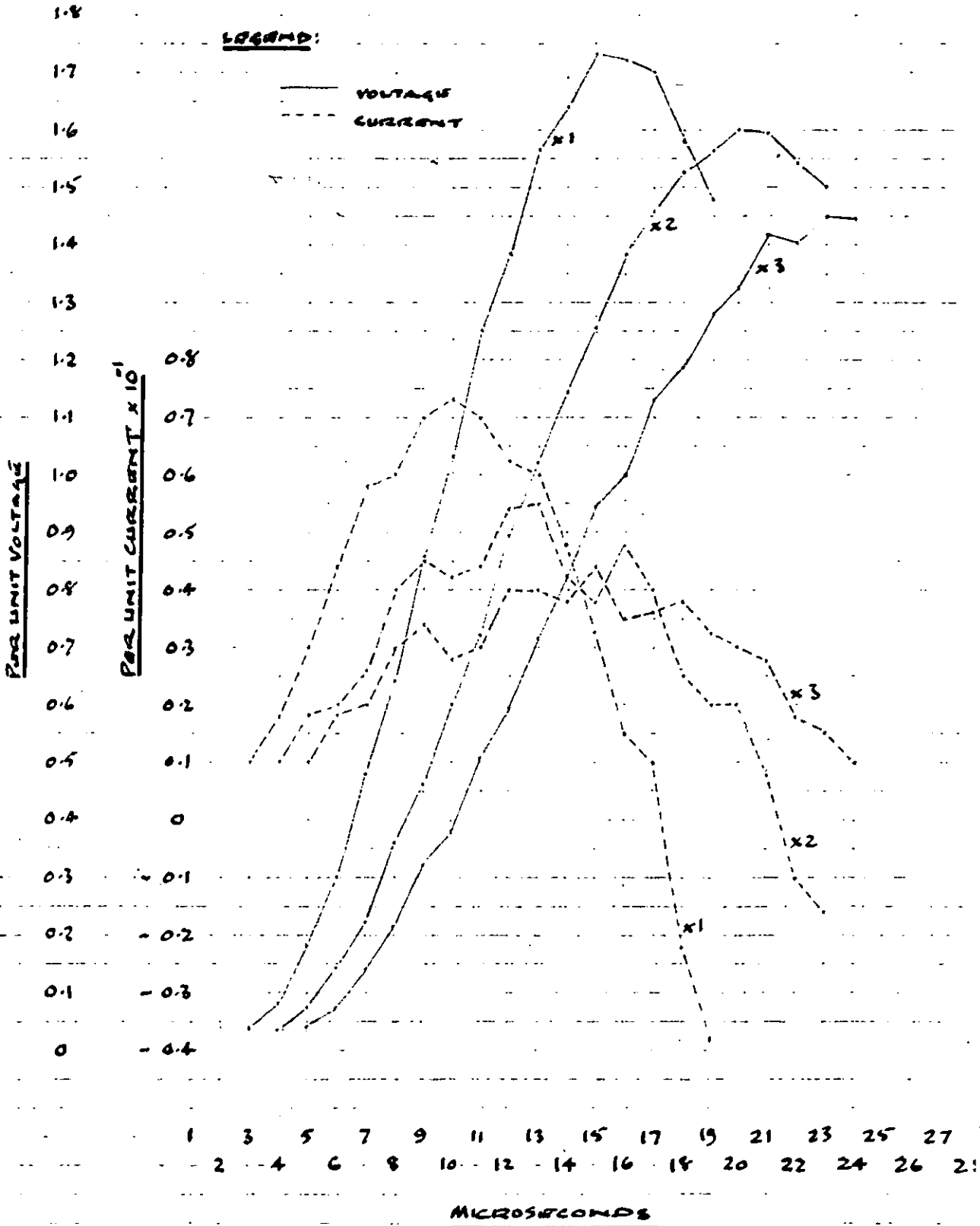
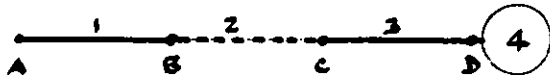


FIGURE 31

VOLTAGE AND CURRENT AT TERMINAL C FOR VARYING TRANSIT TIMES
IN CATHODE



Z_1 480 Ω
 Z_2 22 Ω
 Z_3 464 Ω
 Z_4 18 K Ω

EXCITATION:
5/10 μ SEC. LINER.
FRONT AND TAIL

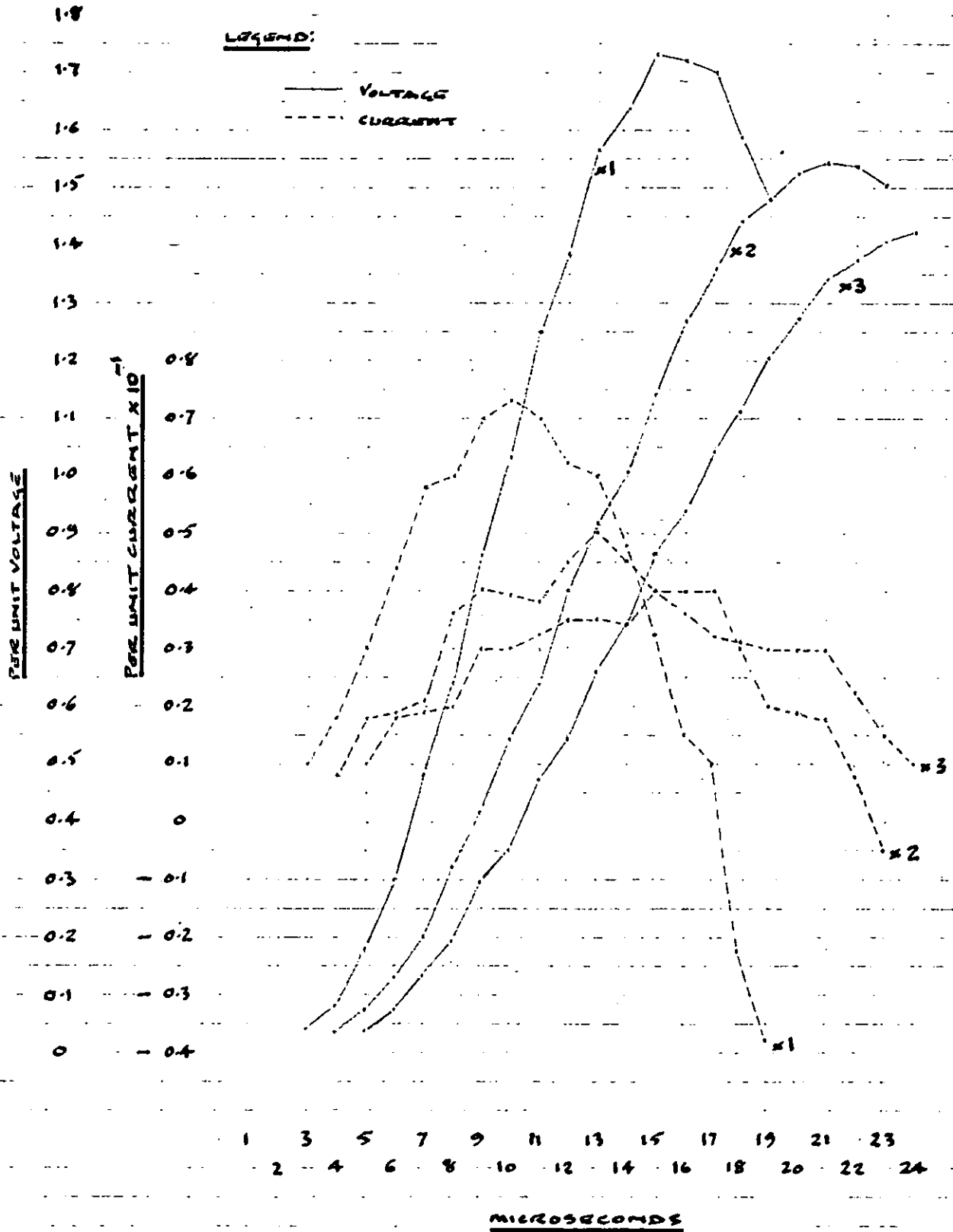
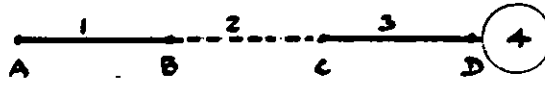


Figure 32

VOLTAGE AND CURRENT AT TERMINAL C FOR VARYING TRANSIT TIME
IN LINE 2



Z_1 480 Ω EXCITATION:
 Z_2 22 Ω $\frac{5}{20}$ Hz μ CL-LINWA
 Z_3 464 Ω FRONT AND TAIL
 Z_4 18 K Ω

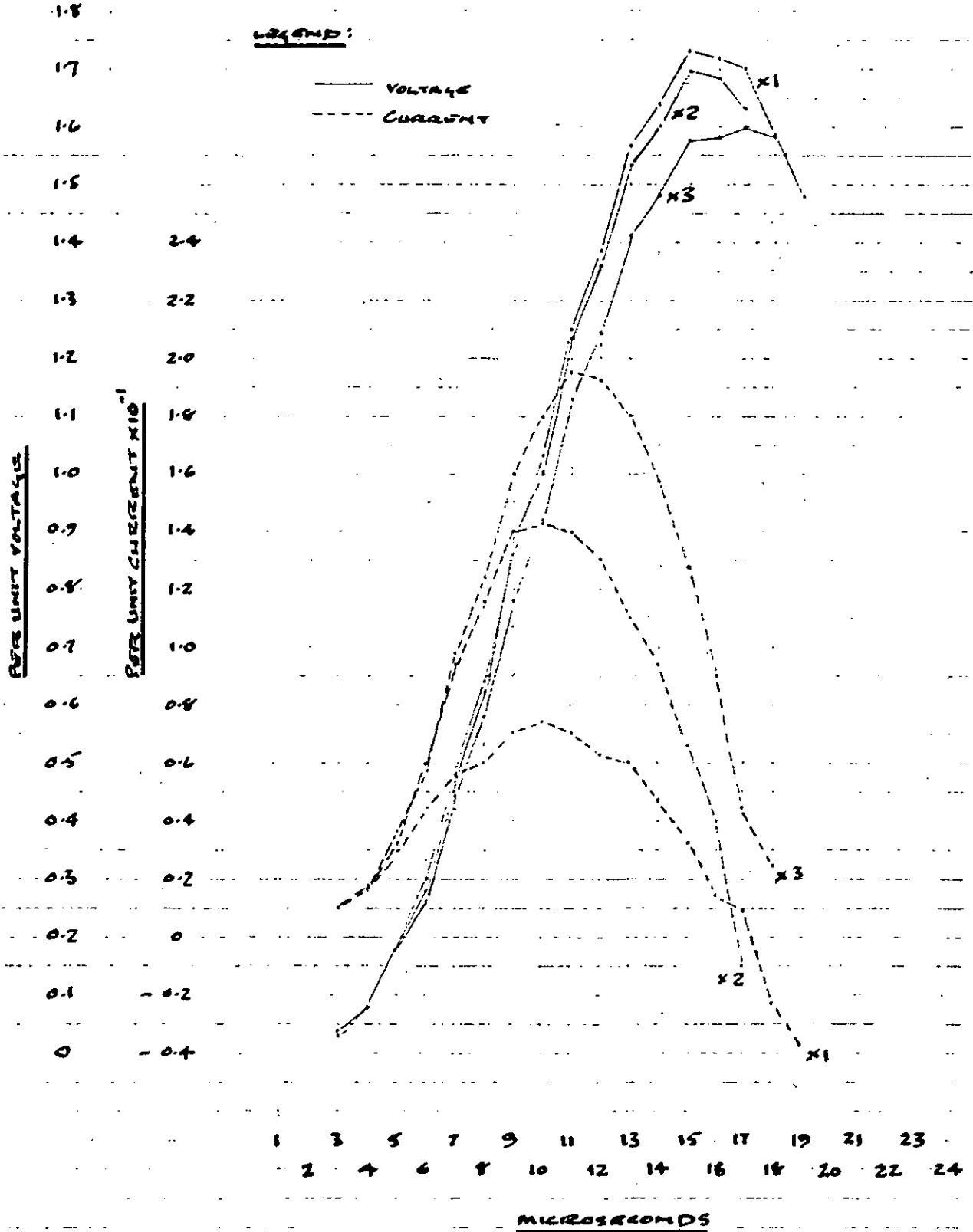


FIGURE 33

VOLTAGE AT TERMINALS C AND D FOR VARYING TRANSIT TIMES IN LINE 1

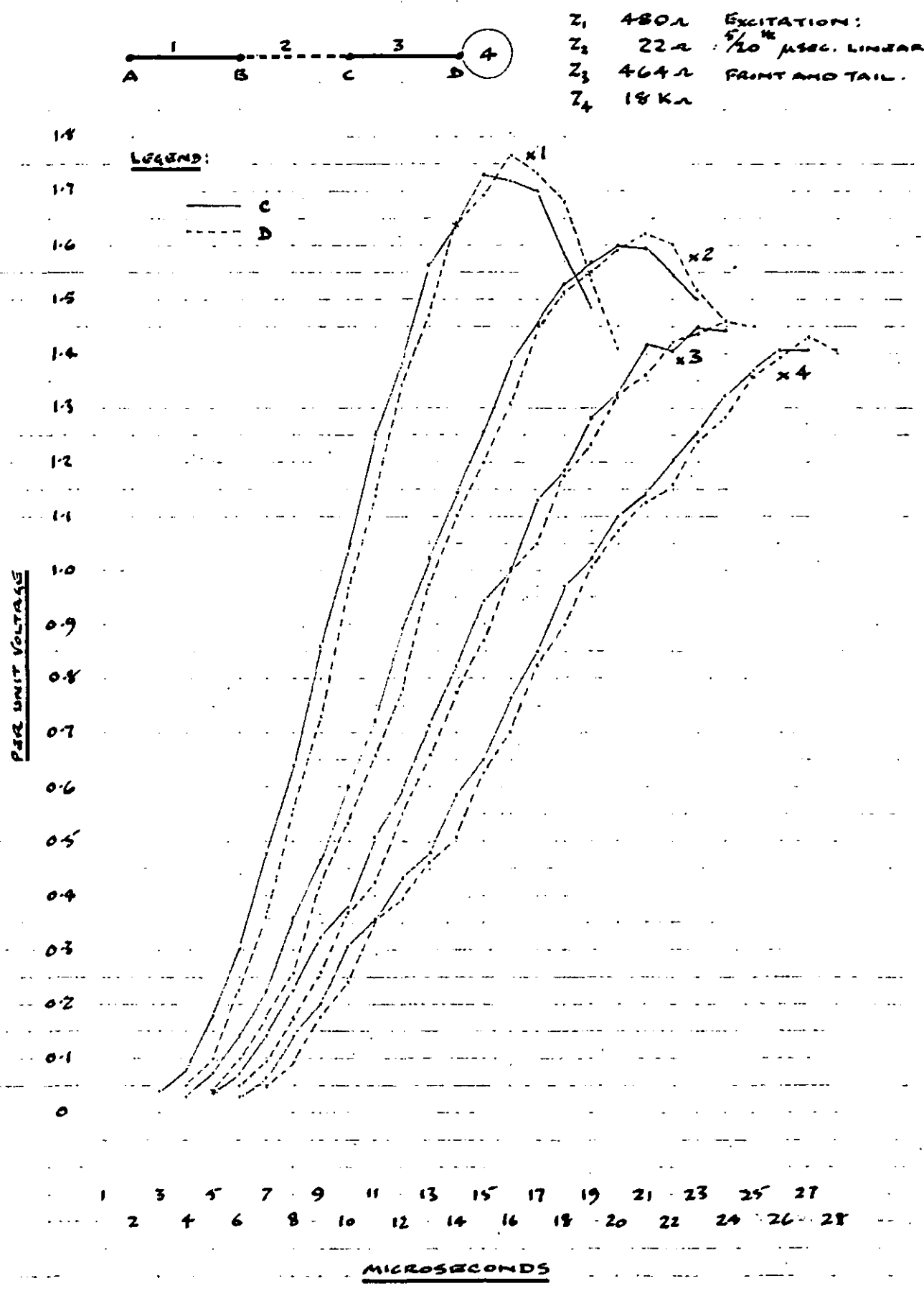


FIGURE 34

VOLTAGE AT TERMINALS C AND D FOR VARYING TRANSIT TIMES IN CABLE

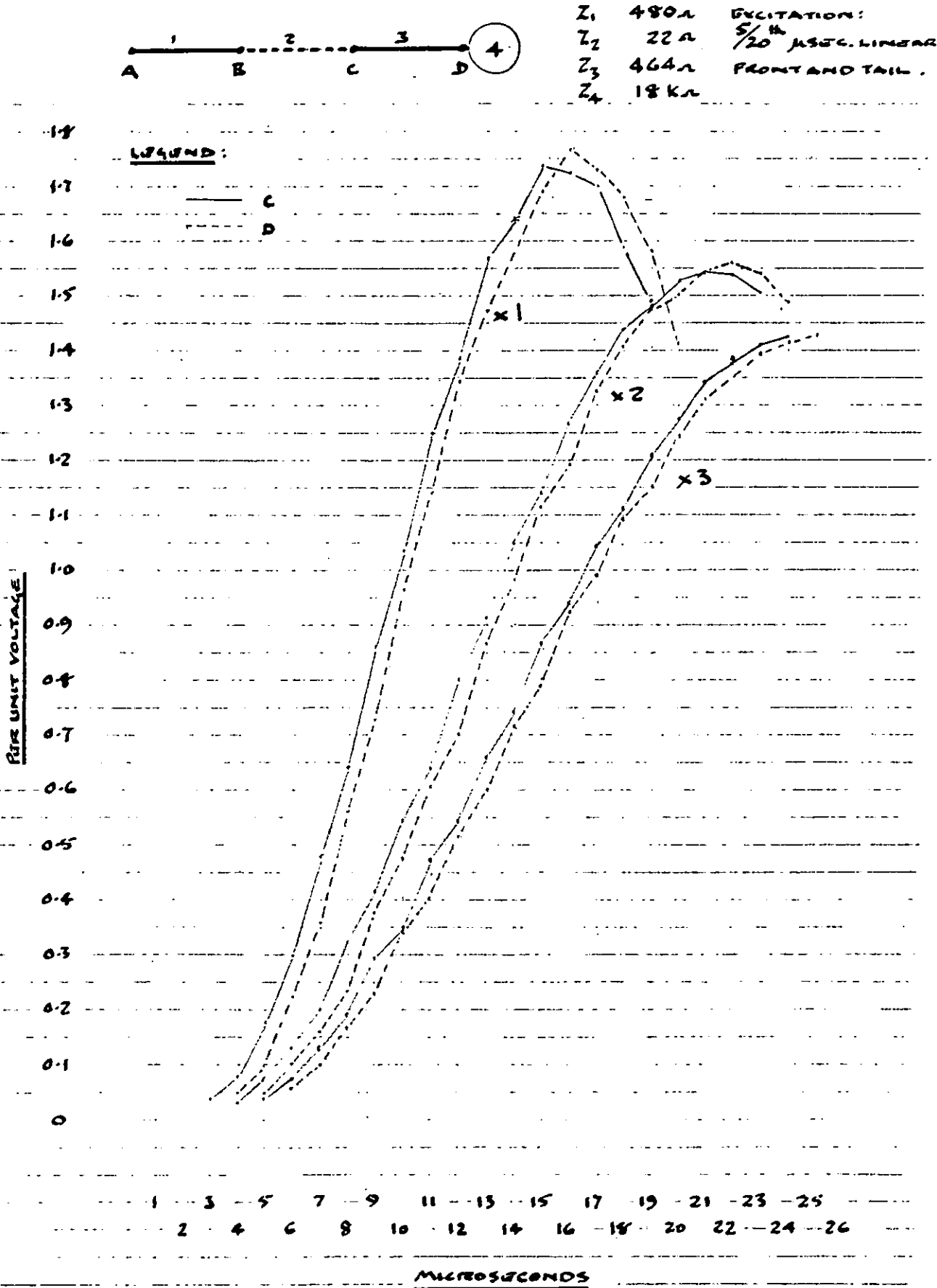


FIGURE 35

VOLTAGE AT TERMINALS C AND D FOR VARYING TRANSIT TIMES IN LINE 2

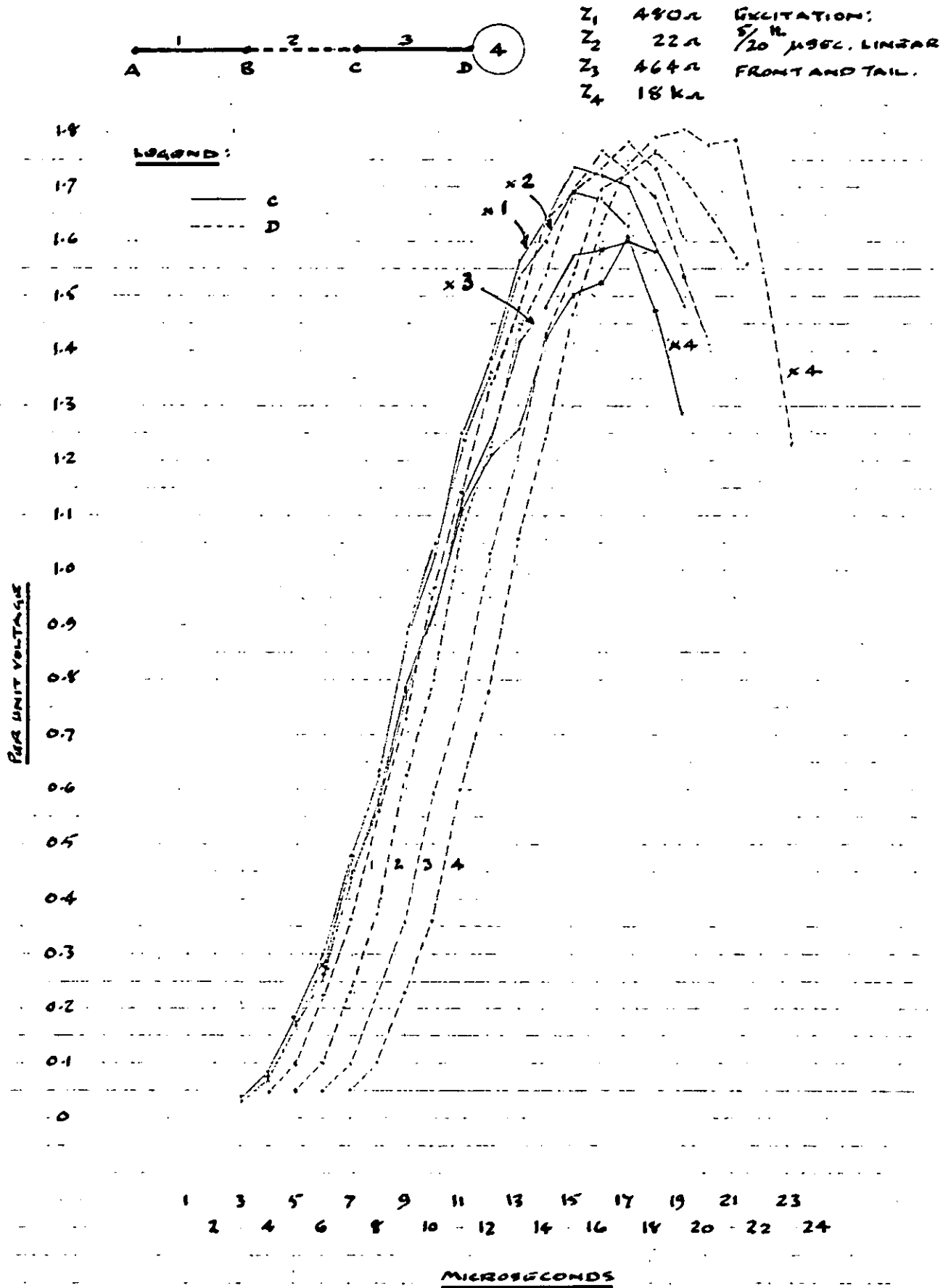
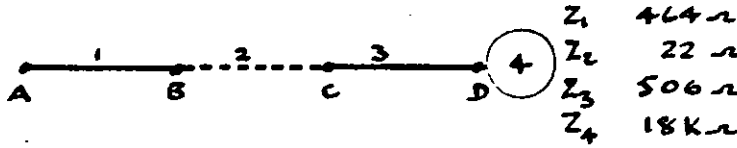


FIGURE 36

VOLTAGE AND CURRENT AT TERMINAL B FOR TWO TRANSIT TIMES IN
(a) LINE 1 (b) CABLE (c) LINE 2



EXCITATION:
5/10 μ SEC. EXPONENTIAL
FRONT AND TAIL
TRANSIT
TIME 2 μ SEC.

- a - 1 IDENTICAL TRANSIT TIMES
b - 2 DOUBLE TRANSIT TIME IN LINE 1 ONLY
c - 3 " " " " CABLE "
d - 4 " " " " LINE 2 "

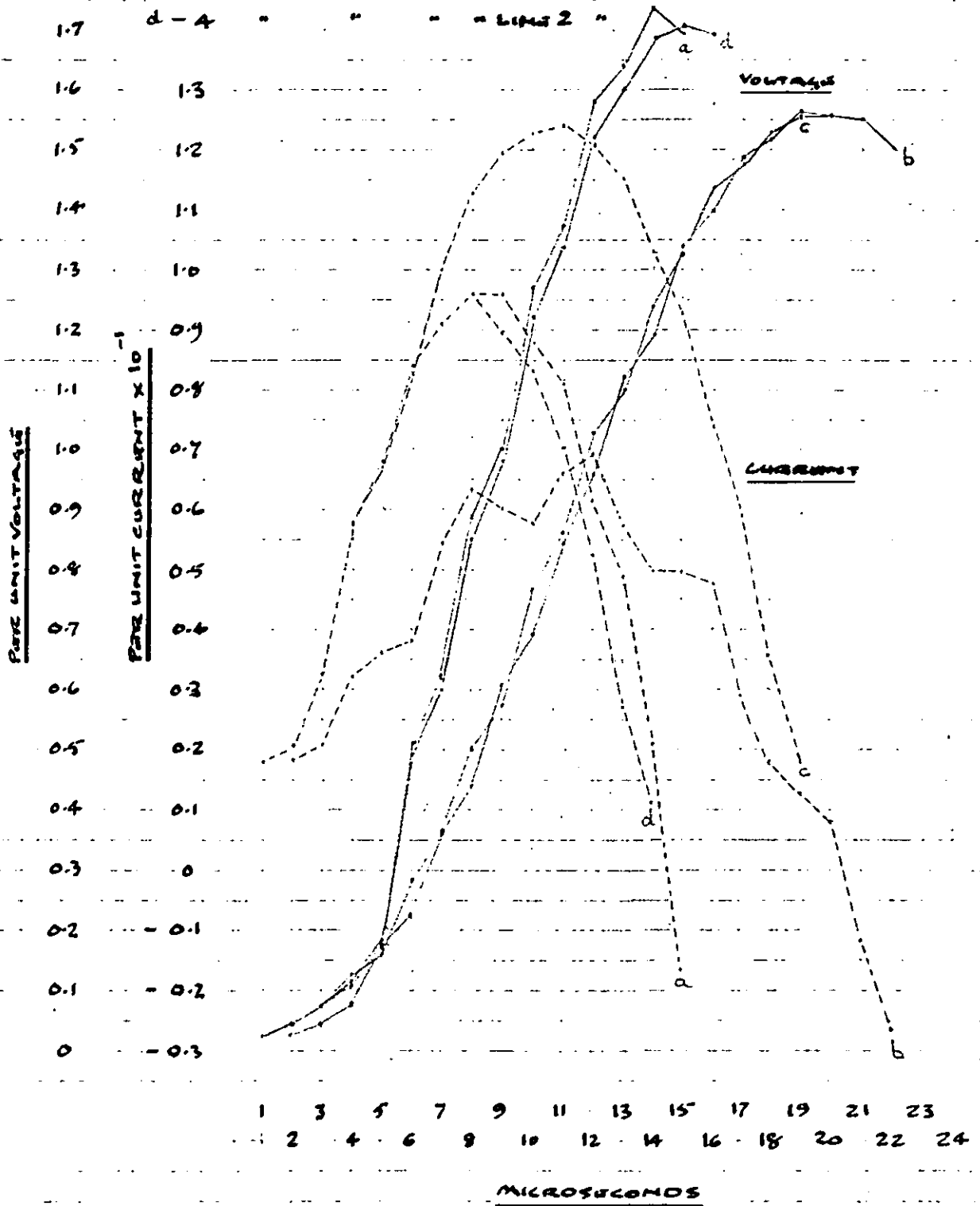
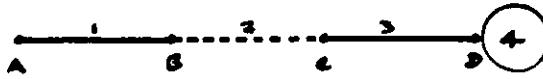


FIGURE 37

VOLTAGE AND CURRENT AT TERMINAL C FOR TWO TRANSIT TIMES IN

(a) LINE 1 (b) CABLE (c) LINE 2



LEGEND:

— VOLTAGE
--- CURRENT

Z_1 464 Ω EXCITATION:
 Z_2 22 Ω $\frac{5}{20}$ μ SEC. EXPONENTIAL
 Z_3 506 Ω FRONT AND TAIL.
 Z_4 18 K Ω

- a IDENTICAL TRANSIT TIME
- b DOUBLE TRANSIT TIME IN LINE 1 ONLY
- c " " " " CABLE "
- d " " " " LINE 2 "

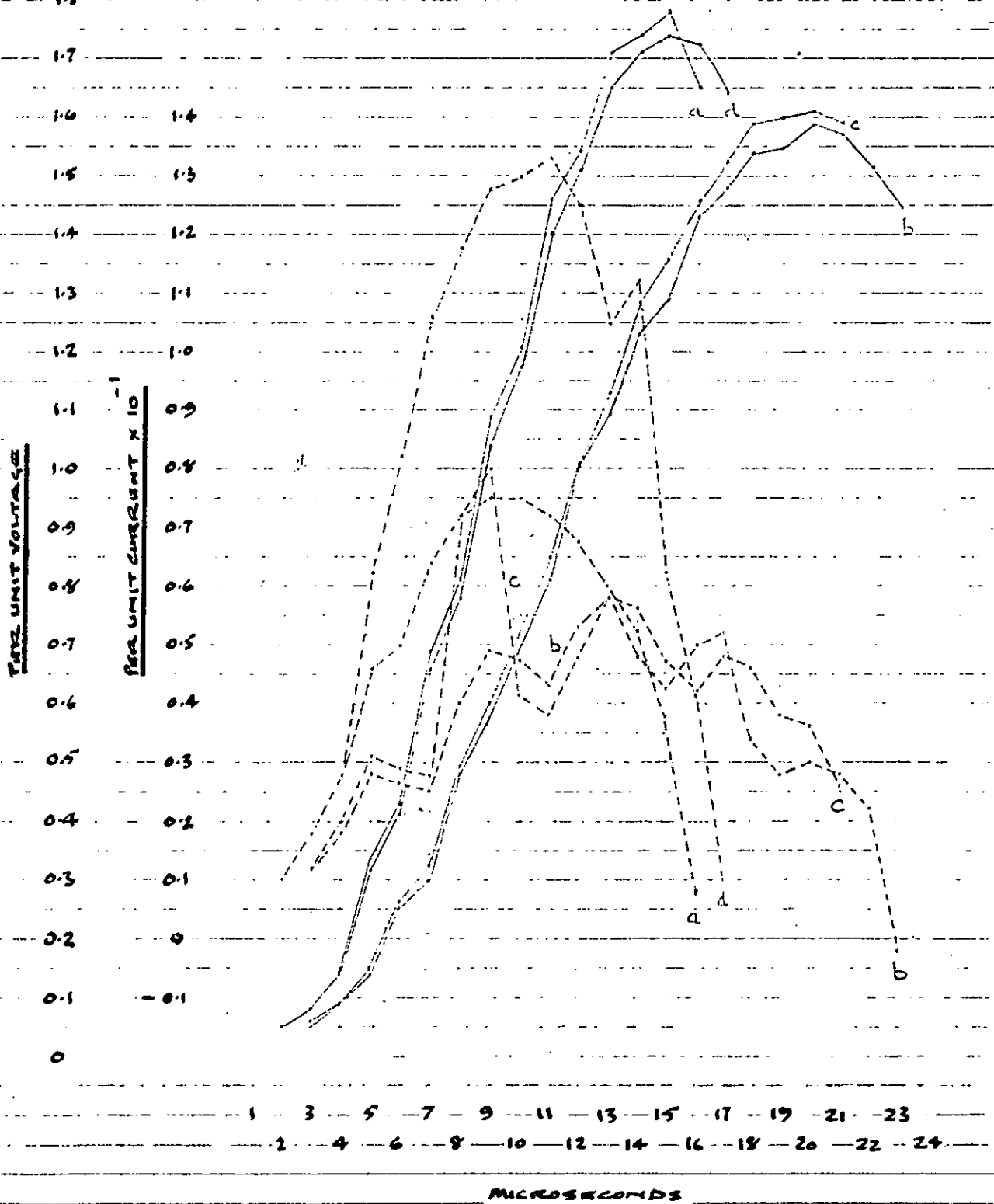


FIGURE 38

VOLTAGE AT TERMINALS C AND D FOR TWO TRANSIT TIMES IN

(a) LINE 1 (b) CABLE (c) LINE 2

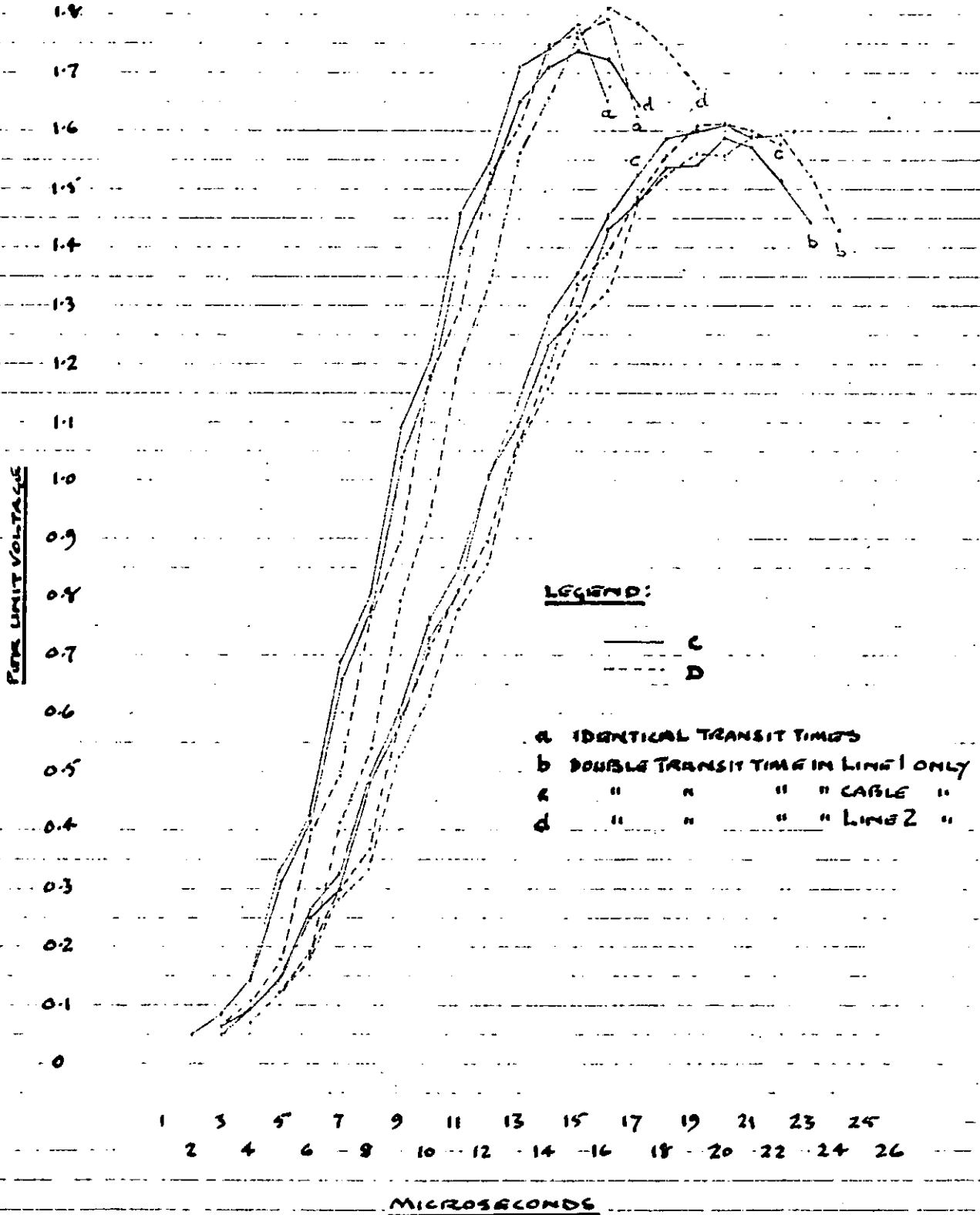
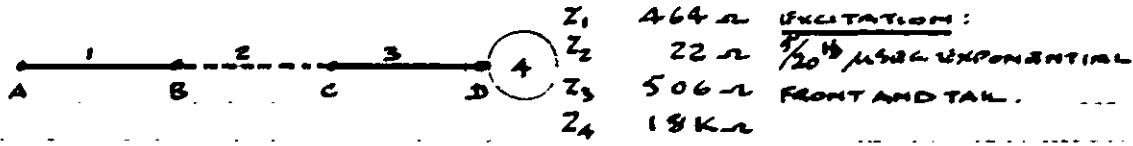


FIGURE 39

THREE-CONDUCTOR TBE-OFF TERMINAL VOLTAGES - GROUP 2
TIMING

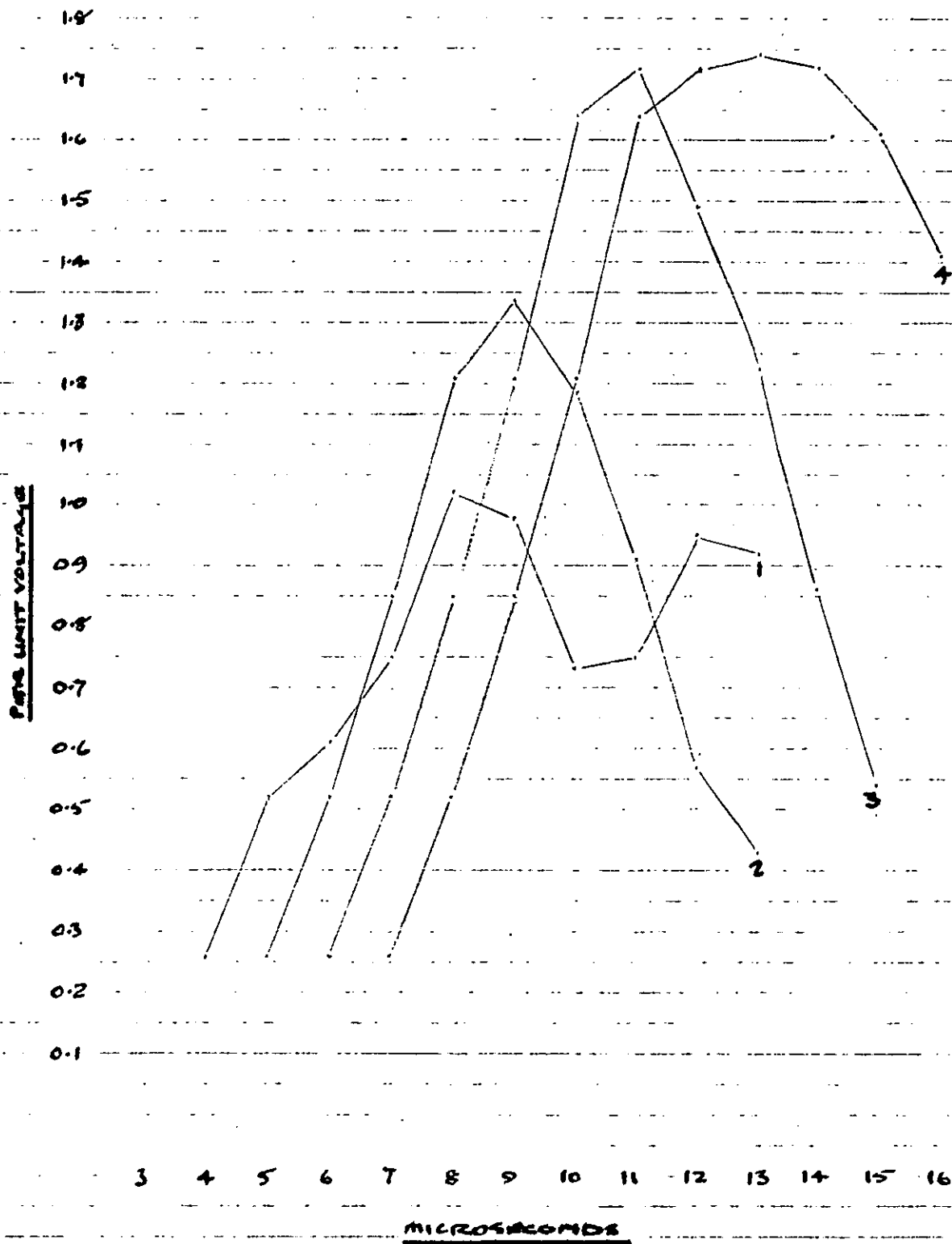


Figure 40

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PART IV.

Discussion and conclusion:- Prestrike influence and surge analysis; relationship to field study; predictable and anomalous responses; further work.

4.1 General observations.

To satisfy the final objective on page 5 of this study, it is not only necessary to account for the prevalent behaviour of the distribution network during a period of lightning excitation in relation to indirect surges, but also for the anomalous behaviour that is evident in some of the case studies in Part II.

There is clearly no difficulty in establishing the overwhelming predominance of transient faults, a large proportion of which are fuse operations. On this basis, the effect of annual variations in thunderstorm frequency and thunderstorm intensity need not be considered. Although both contribute to the total number of lightning faults, the number of transient faults is always well in excess of the number of persistent faults. Good examples of the reaction to these two excitation variables are to be seen in the records for 1971, 1973 and 1974.

Some fuse actions take place at the same time and it is shown that about one third of all the fuse faults during a storm are linked conductively. Hence, Miller's conclusion, that several rod-gaps flash over simultaneously due to voltage doubling which then leads to follow-through power frequency overcurrents, is the probable reason for the simultaneity of fuse action. It is also highly likely that this characteristic response is due solely to simple propagation effects. It is noted also that transformers provide the largest number of casualties in the persistent fault classification. Most rod-gaps are connected either at the transformer terminals or very close to them so that the high failure rate is probably linked with the

simultaneity of fuse operations in these instances.* The failure of cables, as distinct from cable boxes, likewise is to be associated with the travelling waves alone.

Again, simple fuse action in isolated circuits is to be attributed to the natural propagation processes following single ground strokes. Simultaneous fuse action, however, appears less likely to result from the widespread flashover of rod-gaps in isolation from the same cause, since the propagation conditions are now quite different. Even if this stroke is of greater severity than usual, it remains to be demonstrated that it can influence several scattered and unrelated electrical circuits as effectively as a single-conduit multi-tee-off/spur system. Simultaneous indirect strokes from widely separated cells within the thundercloud are not unknown, but they are seen to be too infrequent to account for the response. Nevertheless, they serve to explain how outages can occur at the same time in remote circuits several miles apart. Clearly, additional factors are needed to account for the raising of the surge levels in independent local circuits to produce instant reaction. Therefore it is very necessary to take into account the topographical features of the faulted areas, the disposition of the overhead lines and the prevailing wind direction during the electric storm. At the same time, an additional source of excitation may present itself in the form of the prestrike charge.

Lightning catchment areas are seen to be justified from the records of repeated faults. Some of these examples actually display the same characteristics indicating that a uniformity of response is made possible when certain topographical constraints are present.

*Transformer failures can be associated with the fuse-faulted networks in case studies 5, 9, 13, 16, 22, 29 and 40, but it is well known that faults in transformers, due to overvoltages of this nature, may not be revealed at once and a delay of a few hours or even several days is more characteristic.

4.2 The prestrike influence.

The principal source of the energy transfer by indirect action is seen to reside in the return stroke processes, but it is believed here, that prior to this taking place, some of the charge in the descending leader head as it begins to noticeably affect the ground gradient, is transferred to elevated and isolated ground objects in its path. This charge, of opposite polarity to the leader head, is assumed to reside mainly at the very tip of the objects. In this study, it is taken as a point charge. With its liberation, an overhead line in close vicinity is then subjected to a short pulse of excitation which is termed the prestrike voltage. A single tree or building of greater height than the line is all that is required to present the conditions for pre-excitation. Further, it is assumed that the prestrike component is a frequent contributor to the total pulse excitation, but it is only recognisable on some of those occasions when the associated faults appear to be more severe than would normally be expected. This may be under circumstances where, apart from the presence of those special ground features, travelling wave responses are predictable. On this basis, quite modest indirect surges in the lines due to a single stroke may well be anticipated by prestrikes of greater magnitudes. The maximum prestrike voltage depends, of course, upon the nearness and elevation of the ground object in relation to the line. With some margin between maxima of the two pulses and with only a few microseconds separating them the initial damage done by the prestrike voltage is reinforced by the main pulse with its greater rate of rise. It appears permissible therefore to attribute the prestrike influence to a few of those substantial transient faults associated with the case studies, and in some of those instances this has been done in respect of the three-fuse fault as discussed in section 2.3.6. Other examples that could be considered are some of the cases with repeated faults, but each incident requires much more site information before this could be qualified but which is not available from the fault records.

4.3 The surge analysis.

4.3.1 Terminal responses.

(a) Tee-off system. (Basic type c, single-velocity circuit).

References: Table 11 and figures 12 to 15.

General notes: The extension of section BP is the degree of remoteness of the point of excitation with respect to the tee-off at P, and to the terminations C and A. The behaviour of the voltage pulse at A is of principal interest.

Observations:

(i) The responses in groups 2 and 5, displayed in figures 12 and 13, show the highest peak values per unit voltage. In both cases the maximum value is seen to be 1.75. This then occurs when BP is one half of the length of PC and one quarter of the length of PA, or BP is twice the length of PC and one half of the length of PA.

(ii) Since the withstand value of a distribution transformer is 95 kV, an incident surge of about 60 kV is sufficient to endanger the unit.

(iii) The maximum response in either of the above two configurations is reached in about the same time.

(iv) The pulse duration lengthens with distance travelled by the surge.

(v) The responses in groups 1 and 3, corresponding to figures 12 and 14, possess characteristics which reach a maximum of 1.705 per unit voltage. Thus, an incident surge only slightly greater than that in (i) presents a similar hazard to the transformer insulation. The critical configurations are when BP is the same length as PC but one fifth of the length of PA, or BP is three times the length of PC and three quarters of the length of PA.

(vi) The rate of rise of these voltage characteristics over the principal part of the pulse are found to be about the same and in fact the gradients of most of the responses in groups 1, 2, 3, 5, 6 and 7, corresponding to figures 12 to 14, are similar.

(vii) The responses due to the configurations in groups 4 and 8 are not only generally of much lower magnitude than all other groups but their rates of rise are considerably less, in accordance with the remotest point of excitation in the section BP.

(viii) Natural oscillations of about 250 kHz are displayed in some responses in all groups, and it is likely that they are present in all pulses if the time scales are extended.

(ix) The behaviour at the terminal C is the same as at A for the equivalent ratios.

Summary: The principal groups showing maximum per unit voltage response are shown below in relation to the magnitude of an incident surge, (in kV), required to equal (A) - the withstand voltage of the transformer (95 kV), and (B) - the 50% flashover voltage of the rod-gap across its terminals (81 kV).

Groups	Max.p.u.v.	A	B
2 and 5	1.75	54.29	46.29
1 and 3	1.705	55.72	47.50
6	1.60	59.40	50.60

(b) Cascaded systems. (Basic types f, g and h mixed-velocity circuits).

References: Figures 25 and 27 related to the effects of transformer winding transit time.

(i) The terminal voltage response when a transit time is given to the transformer winding shows that an attenuation takes place although the rate of rise of the principal part of the pulse is little affected.

(ii) The effect of increasing the transit time increases the attenuation but this is seen to be a function also of the surge impedance assigned to the winding. If $Z_0 = 4 \text{ k}\Omega$ and the same transit time as the other circuit elements, the reduction amounts to about 3%, but when $Z_0 = 10 \text{ k}\Omega$ this becomes 2.3%.

(iii) With higher surge impedances given to pole-mounted units the difference is likely to be only marginal, so that the effect of winding time

is not very important and is dispensed with in the other studies.

(iv) The current response is of only small magnitude but nevertheless shows the converse effects to the voltage and is seen to increase when a propagation time is given to the winding, but less so when the surge impedance is raised.

References: Figures 34, 35 and 36 related to the examination of varying transit time in several circuit elements.

(i) The shorter lengths of line 1 and cable, and therefore the lower transit times in these sections, produce the maximum effect, but all the configurations associated with line 2 give rise to high maximum values.

(ii) The slope of the pulse over its principal part is seen to decrease with increasing length given to line 1, or alternatively, with increasing length given to the cable, i.e. the pulse lengthens with distance travelled.

(iii) The slope of the pulse remains approximately constant and independent of the length^{*} given to line 2, and since the maximum values are generally much higher than those responses due to the other two sections, the presence of line 2 evidently provides a hazard to the transformer if incident surges are of substantial magnitude.

(iv) The critical configurations for line 1 occur when both the lines are the same length and the section of cable is twice the length^{*} of either line, or line 1 is the same length^{*} as the cable and twice the length of line 2. The maximum values of the responses are then 1.765 or 1.62 per unit voltage.

(v) The critical length of the cable is the simple case when its transit time is the same as each of the lines. The maximum value attained is then 1.765 per unit voltage.

(vi) All lengths of line 2 establish high level responses from 1.765 to 1.805 per unit voltage.

Summary: The principal sections showing maximum per unit voltage response

* electrical length.

in relation to the magnitude of an incident surge to equal (A) - the withstands voltage of the transformer, and (B) - the 50% flashover voltage of the rod-gap, is given below:

Sections	Max.	A	B
Line 1 } cable } Line 2 }	1.765	53.8	45.9
Line 1	1.62	58.6	50.0
Line 2	1.78	53.4	45.5
"	1.805	52.6	44.9

4.3.2 Intermediate responses.

(a) Tee-off system. (Basic type c, single-velocity circuit).

References; Table 11 and figures 16 to 23.

At the tee-off point P, the transient current, in addition to the voltage, is of some significance. The voltage at P is the transmitted voltage and should be the same for each permutation in the group.

Observations:

(i) The highest transmitted voltage is found with group 5, but voltage pulses with maximum values of similar order are present with groups 1, 2, 3 and 4 also as distinct from the other groups.

(ii) The voltage characteristics of the first five groups have greater rates of rise over the principal part of the pulse front than the voltages representing the remaining groups.

(iii) The groups with the lower transmitted voltages have longer dwell times in the crest region of the pulse than the voltages in the remaining groups.

(iv) The highest current response occurs in group 3 where the maximum values are substantially greater than in any other group. This is observed to take place when BP is three times the length of PC and either the same length or three quarters of the length of PA.

(v) All the current responses in each group initially build up from the same point and their ultimate crest values clearly depend upon the system transit times.

(vi) In all groups, some current responses show oscillations about zero with a frequency of 100 kHz or 125 kHz. It is likely that all display this behaviour if the time scale is sufficiently extended.

(vii) Small perturbations accompany the minimum current responses in several cases prior to oscillation.

(viii) The maximum value of the current pulse is displaced in relation to the voltage when alterations take place in the transit times.

(b) Cascaded systems. (basic types f, g and h mixed high velocity circuits).

References: Figures 24 to 27 related to the effects of transformer winding transit time.

Observations:

Junction C.

(i) The highest voltage response is achieved when no transit time is given to the transformer winding. This is a maximum when the transformer surge impedance is 10 k Ω , but still lower than the corresponding maximum at the termination.

(ii) With increasing transit time in the winding, voltage attenuation increases but this is also governed by the magnitude of the surge impedance as with the terminal responses.

(iii) Larger currents are produced when the winding has the lower surge impedance but the maximum value is reached only when all the circuit elements have the same transit time. Thereafter, an increase in winding propagation time reduces the maximum current, unlike that response at the termination.

(iv) The current pulses attain their maximum values before the voltage pulses reach their maxima in all cases independent of the value given to the winding surge impedance.

(v) Double transit time given to the winding increases the time to reach the maximum value of both voltage and current responses but the voltage pulses take the longer time.

(vi) Current perturbations are established when the winding surge impedance is 4 k Ω , which appear as oscillations of frequency 0.5 MHz.

Junction B.

(i) The highest voltage response is achieved when no transit time is given to the winding of 10 k Ω surge impedance, as at junction C, but is still relatively high in comparison with the terminal voltage.

(ii) Similarly, voltage attenuation takes place with increasing propagation time in the winding as at C and D.

(iii) The voltage levels generally are not much lower than those at junction C.

(iv) The highest current response is obtained with double transit time and the lowest surge impedance, as in the terminal response.

(v) Current pulses lead the voltage pulses in the same manner, again as at junction C, but the displacement is greater at B than at C.

(vi) Current pulses build up initially from the same point in both examples of terminal surge impedance and indicate their oscillatory tendencies.

References: Figures 28 to 33 related to the examination of varying transit times in several circuit elements.

Observations:

Junction C.

(i) The shorter lengths of line 1 and cable establish the highest voltage responses. This is also true of the current responses.

(ii) Similarly, the slope of the voltage characteristic over its principal part is seen to decrease with increasing length given to line 1, and to the cable independently. i.e. the pulse lengthens with distance travelled. This is again true of the corresponding current responses.

(iii) The slope of the voltage pulse over its main portion remains

little changed for varying lengths of line 2.

(iv) The voltage levels, compared with the terminal responses, still remain high for all variations of transit time in those circuit elements.

(v) Current responses decrease when line 1 or the cable propagation times are increased, but increase considerably when line 2 is lengthened.

(vi) Maximum currents are associated with changes in the length of line 2, and these currents are considerably higher than those due to any changes in the transit times of either line 1 or the cable. .

(vii) Current pulses lead the voltage pulses by varying amounts of time when the length of line 1 or the cable is changed.

(viii) Current pulses lead the voltage pulses by approximately the same length of time when the length of line 2 is increased.

(ix) All current responses show oscillatory tendencies, and whereas the oscillation vary between 26.3 kHz to 35.7 kHz in the cases of the influence of line 1 and the cable, there is much less variation in the frequency of the responses due to changes in line 2. There are also less disturbances in the current pulse shapes.

Junction B.

(i) Maximum voltage response appears to be the same for minimum lengths given to each circuit section, but falls off more rapidly when the cable length is increased.

(ii) The voltage responses behave in a similar manner as at the previous junction, with the pulse lengthening with distance travelled either in line 1 or the cable, but remaining nearly constant for any changes in the length of line 2.

(iii) Maximum currents are associated with increases in the length of the cable section and not in line 2 as at junction C. These currents are considerably higher than when other section changes take place.

(iv) The distribution of the current responses due to changes in the length of line 1 are similar to those responses at junction C also due

to changes in line 1, and in the cable independently.

(v) The distribution of the current responses due to changes in length of either the cable or line 2 are now similar in that the current pulses build up initially from the same point. However, the cable length only has a marked influence on the subsequent maximum values, whereas alterations in the transit time of line 2 has very little effect upon the current characteristics.

(vi) Again, with a length adjustment of line 1 or the cable, the current relationship with the corresponding voltage pulse changes considerably. This is not the case when line 2 is increased in length where a fixed relationship exists. All current pulses lead the voltage pulses.

(vii) Current responses decrease with an increase in the length of line 1, but build up for an increase in the length of the cable. Thus, the effect of the cable is opposite to the corresponding responses at junction C.

(viii) The oscillatory nature of the current responses is again present and small perturbations appear in these pulses only, due to the variation of propagation time in line 1.

4.3.3 Special features.

Group 3, associated with the basic type c circuit, produces a transit time ratio that gives the highest current response at the tee-off point (section 4.3.2). At the same time, this particular configuration also establishes a very high voltage response at the transformer terminals (section 4.3.1). No other permutation results in a voltage-current reaction as efficacious, and hence this particular arrangement is to be noted. An incident pulse circa 48 kV is sufficient to flashover rod-gaps across the transformer terminals, whilst the surge current at junction P is clearly very much larger than is normally the case.

The current relationship, with the corresponding voltage, at junction points associated with all the basic circuits examined, is shown

to vary considerably according to the timing arrangements of the connected circuit elements. The maximum value of the current seldom coincides with the voltage maximum but may vary up to a period of $6\mu\text{sec}$ prior to the voltage reaching its highest value. This behaviour supplies direct evidence of the presence of standing wave pulses in these systems. According to theory, a lossless line shows antinodes at locations given by the corresponding distances $\frac{\lambda}{4}$ $\frac{3\lambda}{4}$ $\frac{5\lambda}{4}$ etc. along the line. For an aperiodic pulse of $\frac{5}{20}$ th μsec delineation, these points are respectively 1500 metres 4500 metres etc. or 5, 15 etc. microseconds of time. Where the velocity of propagation is less, as in cables and windings, these figures are of course modified accordingly. The voltage standing wave ratio can be found from the section reflection coefficient and is calculated for the simple series system as 23.4, 21.2 and 36.0. In a lossless line, both the reflection coefficient and the VSWR remain constant, and also a VSWR of 18 or more means that at least 80% of the energy of the pulse is reflected. A fortuitous combination of section lengths therefore allows the possibility of substantial antinodal surge voltages to appear between discontinuities which may serve to explain the failures of FN16 line insulators, line jumpers, pole boxes and similar line equipment. Apparatus associated with antinodal points in this manner can be regarded as weak-link structures. By definition, these are locations where system reliability is most easily affected by the secondary propagation effects.

4.3.4 Inclusion of earth path.

Let the capacitance of the transformer high voltage winding be in the region of $100\mu\text{F} \rightarrow 10\mu\text{F}$ (Bewley), and the equipment is pole-mounted, the inductance of the downlead is about $16\mu\text{H}$ (Bellaschi). The ground-rod assembly is assumed to be not greater than 25Ω resistance (Electricity Authority), neglecting the effects of its capacitance and inductance. The resulting termination is then a simple R-L-C series system to which the incident pulse is first applied. The roots of the auxiliary equation, obtained from the differential equation defining the voltage distribution when

this is equated to zero, is to be found from:-

$$m = \frac{-R \pm \sqrt{R^2 - \frac{4L}{C}}}{2L}$$

from which it is clear that $\frac{4L}{C} > R^2$ for both values of winding capacitance. Hence the roots are imaginary for a bipolar pulse as well as for an aperiodic pulse, and the response is therefore a damped oscillation. Clearly, the capacitance would have to be of more than $0.1 \mu\text{F}$, or the inductance very much smaller than $16 \mu\text{H}$ to produce any significant alteration. This is quite outside the practical range of values available for C and L . The damped oscillation is the normal response to pulse excitation in these circuits, and its duration, from the parameters above, is found to be less than $2 \mu\text{sec}$.^{*} If a significant reduction in the ground resistance is achieved, it is easily shown that the perturbations are then sustained over a substantial period of interest.

If capacitance and inductance are associated with the single ground-rod assembly, the resulting circuit is an R-L-C parallel system. With pulse excitation, again the natural response is a damped oscillation and the duration of these perturbations for realistic values of R , L and C are calculated to be less than $0.1 \mu\text{sec}$ and hence they are of no importance here.

4.4 Conclusion.

Those fuse faults directly attributed to the effects of the propagation of induced incident voltages may be regarded as predictable faults in the sense that their cause is able to be clearly determined. The case studies, and their associated circuit diagrams, give adequate evidence of this type of behaviour. Single conductor travelling wave

* These calculations are based on ground resistivity of 10^2 ohm-metre corresponding to moist soil, and a ground-rod of $\frac{5}{8}$ " diameter (1.59 cm) driven to a depth of about 15 ft. (4.57 metres).

analysis, based on the assumption that the circuits are lossless, provides a useful first stage assessment of the propagation characteristics. The employment of the Schnyder-Bergeron graphical method for the analysis supplies an economic and enlightened approach to the understanding of pulse excitation in the system, although limitations are imposed in the case of the three-conductor solution if continued in the graphical mode.

The faulted circuits are considered as being constructed from a number of basic circuit topologies whose propagation characteristics to lightning-induced pulses have been predetermined so that some indication of the overall performance can be deduced. In a few cases, this leads simply to a reiterative process as, for example, when a number of type c elementary units are linked together in series to make up a feeder with homogenous tee-off sections. The voltage response, at the points of discontinuity, is seen to behave somewhat in the same manner as the response obtained by Ouyang when a three-conductor line is excited from an impulse generator. i.e. the tee-off points are shown to generate a steep voltage rise with maximum values near to the maximum of the incident surge. In this study these responses are clearly dependent upon the length ratios. Hence, Ouyang's observation that with flashover at the terminal station (end of feeder), the reflective wave, with a steep voltage swing, is imposed on the line over a considerable distance appears to be verified. Again, it is clearly demonstrated, in the basic cascaded unit at both junctions before the terminal point, that a high level voltage pulse appears whose maximum value is very nearly as great as that of the terminal response. At the first junction from the termination too, the voltage gradient is seen to be little affected by changes in length required to connect to the transformer. This particular observation may well explain the failure of connected apparatus in similar tee-off situations. Results from the analysis for various elemental configurations indicate that the front of the pulse lengthens with distance travelled. These

confirm similar effects found in Ouyang's propagation study with a synthetic pulse excitation, and also in Singarajah's oscillograms of induced lightning voltages obtained from his field work. These effects are also to be found in references 24, 25 and 26 in Part I.

The groups of transient faults which are regarded as anomalous are those which give rise to substantial responses which are not directly attributable to direct strokes. These faults are unable to be assessed collectively since each is likely to have different environmental conditions. Therein lies the importance of the local topography. In association, are those special features which allow the prestrike charge to contribute to the pulse excitation, and due recognition has been given earlier to this latent source of induced voltage. The generation of standing wave pulses, amplified by the fortuitous arrangements of section lengths and discontinuities, to provide large antinodal voltages at points along the conduit also come within the anomalous category. The antinodes may coincide with the position of line equipment thereby regarded as weak-link structures. All the above phenomena associated with the single stroke, are not necessarily extended in the presence of multi-stroke discharges since the point of excitation may have shifted. Thus a prestrike charge is no longer present and large antinodal effects vanish. Alternatively, these manifestations may come into being during multi-discharges to ground.

Finally, the fact that rod-gap flashover is not uncommon during thunderstorms leads to a belief that induced voltages of about 40 kV at least are not too infrequent. Inspection of the field recordings in references 24, 25, 29 and 30 in Part I show that although the majority of indirect surges lie in the range of 10-30 kV, there are a few from 30-50 kV, and occasionally a surge well above this level. There is also evidence to show that substantially more bipolar surges are recorded than aperiodic surges, but it is certainly not clear how many of these are due to conductor coupling and how many are due to the influence of the upward streamer. Another source of information concerning the voltage level of the

incident surge is from measurements made on the low voltage side of the system. The automatic recording of l.v. surge voltages has been made within the last decade by Martzloff and Hahn¹ over a period of two years, from which those surges of lightning origin were identified. From this data it is possible, in a few cases, to estimate the level of the surge on the h.v. side of the transformer. The most frequent surges are found to lie between 0.6 and 1.2 kV, and more severely between 1.4 and 2.7 kV.* All the recordings showed the transferred excitation as a damped oscillation of frequency 130-300 kHz, evidently indicating that this is the eigen or natural frequency range of the l.v. circuit, in which variation is due simply to the position of the outage in the system. The calculation of the primary surges is then found to give a range from 17 to about 60 kV. On this basis and the earlier field data, the operation of rod-gaps either singly or collectively can be expected from time to time as part of the propagation response to most thunderstorms.

It is considered that the object of the research study has now been achieved, namely,

(i) that a summary of the present state of knowledge of the generation, excitation characteristics and propagation of induced voltages due to indirect lightning strokes has been given which has a particular reference to the 11 kV rural distribution network in the United Kingdom.

(ii) that a field study has been presented which covers a period of sufficient duration; is located in an area of good topographical interest possessing a high isoceraunic level (for the U.K.); and contains a substantial number of case studies pertaining to the records of lightning faults, for the characteristic behaviour of this type of supply network to be assessed.

* There are two records of 4 kV and 5.6 kV attributed to lightning, but it would seem that here the low voltage lines were directly influenced by nearby ground strokes.

(iii) that sufficient fundamental surge analysis has been performed on representative elementary circuits which can be applied to the lightning-faulted circuits in the field study to explain the predictable responses therein.

(iv) that additional factors have been considered and developed to provide reasons for certain anomalous effects which are shown to take place.

4.5 Suggestions for further work.

The Bergeron analysis of the equivalent lossless three-conductor systems is found to lead to complications on the drawing board which inhibit extending this convenient mode of solution to anything but simple problems. When considering the single conductor case with R and G absent however, the "telegraph equations" are directly integrable and an exact solution is available using D'Alembert's method. This leads to a particularly efficient algorithm for computing not only the terminal voltages, but also the incident and reflected voltages and currents along a conducting system. Branin² and Dommel³ each develop digital programmes based on equivalent impedance or admittance networks representing the input and output conditions, which may be modified for a three-conductor solution through the usual matrix procedures. Althammer and Frey⁴ show that a chain of quadripoles may be used to solve more complex supply networks, and Althammer⁵, Dwek⁶ et al⁷ develop this for the multi-conductor numerical solution in the modal state. So clearly, the present employment of the Bergeron system can be extended to three-conductor circuits with the aid of the digital computer. The networks selected from the case studies need to contain two and three-conductor spurs. The overall results, available from the propagation behaviour of indirect surges in these rural networks, then enables attention to be given to formulating more precise rules for the location of related protective apparatus.

The importance attached to the prestrike component here, also

presents a case for further development beyond the concepts used in this study and hence refine its contribution to the fault pattern. The size and shape of the corona envelope surrounding the leader head is known to change as the head comes within the effective influence of the ground below, and charge is drawn off by an elevated object. The evaluation of the effects of this charge which, although virtually stationary in space but not in magnitude, is not one to be arrived at by the method of images alone but conditioned also by a changing field. A theoretical evaluation in the dynamic state together with field experiments, the replication of which may be realised by the use of the electrolytic tank, can lead to a better understanding of the prestrike contribution and its importance.

MCMCLXXX

"Ancóra imparo"

Michelangelo Buonarroti (1475-1564).

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APPENDIXNotes pertaining to the Bergeron analysis.Note 1. Excitation.(a) The linear pulse.Front: $y = ax.$ $a = 0.2$ for $5/20$ μ sec. ref. $a = 0.125$ for $8/40$ μ sec. ref.Tail: $y = -ax - b.$ $a = 0.033$ $b = 1.166$ for $5/20$ μ sec. ref. $a = 0.0156$ $b = 1.125$ for $8/40$ μ sec. ref.(b) The exponential pulse.

$$y = A(e^{-ax} - e^{-bx})$$

 $a = 0.055$ $b = 0.495$ for $5/20$ μ sec. ref. $a = 0.024$ $b = 0.36$ for $8/40$ μ sec. ref. $5/20$ $A = 1.482$ $8/40$ $A = 1.3$

y	μ sec.	y
0.282	0.5	0.199
0.498	1	0.363
0.778	2	0.606
0.919	3	0.768
0.985	4	0.874
1.000	5	0.940
0.988	6	0.975
0.958	7	0.994
0.926	8	1.000
0.887	9	0.998
0.845	10	0.986
0.802	11	0.973
0.762	12	0.958

0.721	13	0.940
0.685	14	0.919
0.648	15	0.902
0.615	16	0.881
0.582	17	0.861
0.552	18	0.842
0.522	19	0.822
0.495	20	0.803

(c) The sinusoidal pulse front.

$$y = \frac{1}{2} (1 - \cos x)$$

$\mu\text{sec.}$	5 $\mu\text{sec.}$		8 $\mu\text{sec.}$	
	$\cos x$	y	$\cos x$	y
0.5	0.951	0.025		
1.0	0.809	0.0955	0.924	0.038
1.5	0.588	0.206		
2.0	0.309	0.346	0.707	0.147
2.5	0	0.500		
3.0	-0.309	0.6545	0.383	0.309
3.5	-0.588	0.794		
4.0	-0.809	0.905	0	0.500
4.5	-0.951	0.975		
5.0	-1.000	1.000	-0.383	0.692
6.0			-0.707	0.854
7.0			-0.924	0.962
8.0			-1.000	1.000

(d) The binolar pulse.

The positive part of this pulse is represented as either the $5/20^{\text{th}}$ $\mu\text{sec.}$ or $8/40^{\text{th}}$ $\mu\text{sec.}$ pulse shape. Preceding this, is the negative portion which should be taken as having about the same maximum value as the positive part on the basis that the most damaging response is

then obtained. The wave shape approximates in form to the equation 5 shown on page 155 in Part III.

(e) The prestrike pulse.

This also presents a negative induced voltage but spike-shaped with the sudden collapse at the instant when the leader head charge and streamer meet. There will be then a brief pause before the main excitation appears. The rate of rise of the induced voltage pulse due to the prestrike charge is shown to be less than the corresponding rate of rise of the incident surge from the return stroke process.

Note 2.

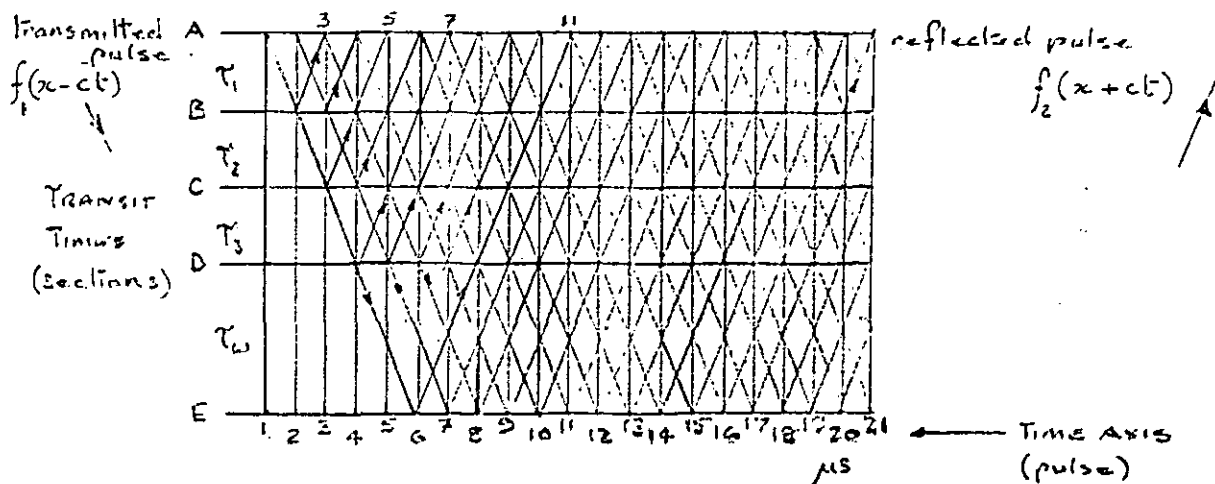
With two "observers" only, each graphical solution appears as a series of large steps. A numerical solution follows the same pattern except that there are many more steps depending upon the size of Δt used in the programme. The Bergeron solution is shown here with coordinates joined by straight lines to aid the interpretation.

Note 3.

A suitable book-keeping technique is available in the form of a timing lattice which can be drawn in such a manner that the negative slope represents a forward travelling wave and the positive slope is then a reflected pulse. The vertical axis is also drawn to scale in multiples of unit transit time.

Example: Cascaded system in second series (page 179 in Part III)

where $\tau_1 = \tau_2 = \tau_3 = \frac{1}{2}$ transit time in winding. $\frac{5}{20}$ th μ sec. excitation.



$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_T = \frac{2}{3} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_I \quad \text{and} \quad \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_R = -\frac{1}{3} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_I$$

where the suffixes I, R and T refer to the incident, reflected and transmitted pulse respectively.

Suppose, however, that the tee-off section PA is a single-phase line, then only two of the feeder conductors will be utilised. (say phases 1 and 2 of the feeder). The above equations need to be modified into two component groups, namely, the surges in the feeder, and the surges in the tee-off section PA, to satisfy Kirchhoff's laws. It can be shown that these two groups reduce to the following equations:-

For the feeder, the transmitted voltage is then

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_T = \frac{2}{3} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_I + \frac{1}{3Y_{33}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ Y_{13} & Y_{23} & Y_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_I$$

and the reflected voltage

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_R = -\frac{1}{3} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_I + \frac{1}{3Y_{33}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ Y_{13} & Y_{23} & Y_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_I$$

For the tee-off section, the transmitted voltage is

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_T = \frac{2}{3} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}$$

and

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_T = \frac{2}{3} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_I - \frac{2}{3Y_{33}} \begin{bmatrix} 0 & 0 \\ 0 & 0 & E_1 \\ Y_{13} & Y_{23} & E_2 \end{bmatrix}_I$$

and the reflected voltage

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_R = -\frac{1}{3} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_I$$

and the transmitted surge,

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}_T = \frac{2}{3} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_I - \frac{2}{3Y_{33}} \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ Y_{13} & Y_{23} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_I$$

and the reflected surge,

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_R = -\frac{1}{3} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_I$$

If an indirect stroke is close to the feeder, the system is then excited symmetrically. But if this stroke is close to the tee-off section PA, the feeder receives its excitation through two of its conductors only and hence excitation matrix now has only two terms.

The modal transform of equal voltages in all three conductors is then $[M]^{-1}[E]$

$$\frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} E \\ E \\ E \end{bmatrix} = \begin{bmatrix} E \\ 0 \\ 0 \end{bmatrix}$$

and for the two conductor excitation

$$\frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} E \\ E \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{2E}{3} \\ \frac{E}{3} \\ \frac{E}{\sqrt{3}} \end{bmatrix}$$

Equal excitation in all lines therefore represents the simplest forcing function associated with the Bergeron diagrams.

Note 5.

The total charge given by equation (15), on page 162, resolves as

$$q_t = \frac{q_0}{\beta} (1 - e^{-\beta h_2}) \dots\dots\dots (i)$$

in which β is a constant. The product of β and h_2 when realised, results in the exponential term $\rightarrow 0$, hence equation (i) is reduced to

$$q_t = \frac{q_0}{\beta} \dots\dots\dots (ii)$$

The potential gradient at p, distance y from the vertical projection of a point charge q at a height h above a flat plane is

$$\mathcal{E} = \frac{hq}{2\pi\epsilon_0 \cdot (h^2 - y^2)^{3/2}} \text{ volts/metre} \dots\dots\dots (iii)$$

so that the ground gradient due to the leader channel becomes

$$\mathcal{E}_g = \frac{q_0}{2\pi\epsilon_0} \cdot \int_{h_1}^{h_2} \frac{h \cdot e^{-\beta h}}{(h^2 - y^2)^{3/2}} \cdot dh \text{ volts/metre} \dots\dots\dots (iv)$$

and substituting for q_0 from equation (ii)

$$\mathcal{E}_g = Kq_t \cdot \int_{h_1}^{h_2} \frac{h \cdot e^{-\beta h}}{(h^2 - y^2)^{3/2}} \cdot dh \dots\dots\dots (v)$$

where $K = \frac{\beta}{2\pi\epsilon_0}$. Since the maximum ground gradient is required in the present context, equation (v) is simplified by making $y = 0$. The solution to the integral can be presented as a series i.e.

$$\mathcal{E}_g = Kq_t \cdot \left[-\frac{1}{h} + K_1(1 - \log_e 2h) + K_2h^2 - K_3h^3 + K_4h^4 \dots \right]_{-h}^h$$

where K_1, K_2, K_3, K_4 etc. are numerical constants extracted from the series components.

