LOCATION OF FAULTS IN POWER CABLES

BY FAULT-GENERATED SURGES

by

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ABSTRACT

The object of this research is to develop a satisfactory method for locating high-impedance faults in underground cables. Most methods of locating faults require that the fault-impedance be reduced to a low value before the measurement can be made. After a careful investigation of the available literature, it was decided that the most desirable method would be one utilizing the traveling-wave. Of the traveling-wave methods, the fault-generated surge method appeared to have the greatest possibilities; yet, according to the author's knowledge, this method has not been applied to power cables. In this method, the cable itself may be considered as the network that generates the required surges. The cable is initially charged to a voltage sufficiently high to establish an arc at the fault. The sudden collapse of the high voltage at the fault generates a surge which travels along the cable to the monitoring end, where it initiates a timing device and is reflected back along the cable toward the fault. The arc which is still conducting reflects the surge back to the station.
The time interval between the first and second arrival of the fault-surge at the station is recorded by the timing device and is proportional to the distance to the fault.

In mathematically analyzing the surge phenomena in cables, the La Place operational method of analysis is used. The calculations for the transient produced by the discharge of a distortionless cable are worked out in full detail. The wave-form calculated is plotted and substantiated with experimental results. The transient produced is a rectangular wave that is exponentially attenuated and whose period is $4\delta$, where $\delta$ is the one-way transmission time of the cable in seconds. It is this wave-form generated by the cable itself that is used to locate the fault.

Basically, the fault-locator developed consists of a high-voltage low-current power pack, a triggering unit, a timing-pip generator, two uniform delay lines, and a double-beam oscilloscope. The block diagram of the fault-locator and the circuit diagrams of the triggering unit and timing-pip generator are given. The operation of the circuits and the procedure for measuring cable faults are fully explained.

The fault-locator was tested on coaxial cable only, since no power cables were available. The results obtained were very satisfactory. The oscilloscope traces obtained were photographed and the experimental results discussed.
It is concluded that the fault-locator can be used without modification for locating low and medium-impedance faults, as well as high-impedance faults in power cables. If the timing-pip interval is increased, the fault-locator can also be used for locating faults on overhead transmission lines.

N. E. Hudak
U. B. C.
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# CONTENTS

## I Introduction ........................................... 1

## II Review of Literature ................................. 4

## III Investigation

### A. Theory of Wave Propagation

1. Fundamental Differential Equations ............ 8
2. Pulses Generated by the Discharge of a Lossless Cable .... 12
3. Transients Produced by a Charged Cable Shorting to Ground .... 16

### B. Reflections

1. Derivation of Reflection Operator ............ 24
2. Reflection Lattices ............................ 27

### C. Attenuation, Distortion and Velocity ........ 28

### D. Equipment

1. General Description ............................ 31
2. High-Voltage Power Pack and Line Coupling .... 34
3. Triggering and Trace-Brightening Circuit .... 36
4. Timing-Pip Generator .......................... 40
5. Delay Line ...................................... 42
6. Procedure in Measuring Cable Fault ........... 43

### E. Experimental Results ............................ 45

## IV Discussion ............................................ 48

## V Conclusions ........................................... 53

## VI Diagrams and Illustrations .......................... 56

## VII Literature Cited .................................... 66

## VIII Bibliography ........................................ 68

## IX Acknowledgement ..................................... 72
## LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Illustration</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schematic Circuit diagram of a charged cable discharging into a load resistance.</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>Current and voltage pulses generated by a lossless cable discharging into a load resistance</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Schematic wiring diagram of a charged cable discharging to ground.</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>The voltage wave generated by a distortionless cable discharging through a &quot;zero&quot; resistance as calculated from equation (82).</td>
<td>23</td>
</tr>
<tr>
<td>4a</td>
<td>Oscillogram of the voltage wave generated by an arc-discharge of a 2927-foot section of RG/8U coaxial cable.</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>Reflection Lattice—successive reflections of a charged cable discharging through an impedance</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>Block diagram showing the components of the fault-locator.</td>
<td>57</td>
</tr>
<tr>
<td>7</td>
<td>Circuit diagram of an experimental high voltage power pack coupling circuit.</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>Schematic circuit diagram of the triggering and trace-brightening circuit.</td>
<td>58</td>
</tr>
<tr>
<td>9</td>
<td>Schematic circuit diagram of the timing-pip generator.</td>
<td>59</td>
</tr>
<tr>
<td>10</td>
<td>Photograph of the fault-locator—timing-pip generator, Cossor Model 339 double-beam oscilloscope, and triggering and trace-brightening unit.</td>
<td>56</td>
</tr>
<tr>
<td>11</td>
<td>Oscillogram of a fault at the far end of a 951-foot section of RG/8U coaxial cable.</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>Oscillogram of a fault located at 951.4 feet in a 1788.2-foot section of coaxial cable.</td>
<td>61</td>
</tr>
</tbody>
</table>
Fig. 13 Oscillogram of a fault at the far end of a 1241.1-foot section of coaxial cable.

Fig. 14 Oscillogram of a fault at the far end of a 1241.1-foot section of coaxial cable and a discontinuity (20 ohms series resistor) at 289.7 feet.

Fig. 15 Oscillogram of a fault located at 289.7 feet in a 1241.1-foot section of coaxial cable.

Fig. 16 Oscillogram of a fault at the far end of a 1241.1-foot section of coaxial cable and a discontinuity (20 ohms series resistor) at 289.7 feet.
LOCATION OF FAULTS IN POWER CABLES
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I INTRODUCTION

The problem of locating faults in power cables has plagued the electric power industry since the birth of electric power cables. The need for satisfactory fault locating equipment is increasing as more and more power cables are put into service. Numerous methods of locating faults in cables have been investigated, namely, the resistance bridge, capacitance bridge, search coil, condenser-pop, standing waves, pulsed-radar and frequency-modulation. The trend in recent years has been to utilize the traveling-wave method. In this method the distance to the fault is determined by measuring the time required for a voltage or current pulse to travel along the cable between the fault and the monitoring point. Messrs. R. F. Stevens and T. W. Stringfield have divided the traveling-wave method into

1 For reference see literature cited
three categories: (1) Pulse-radar Method (2) Frequency-modulation Method and (3) Fault-generated Surge Method. In this report the fault-generated surge method will be considered.

This method unlike the pulse-radar method requires no pulse-generator and it eliminates the difficult problem of coupling the pulse generator to the cable. The surge originates at the point of fault within the cable by sudden collapse of the high voltage and travels to the station end of the cable where it starts a timing device and is reflected back down the cable toward the fault. The fault which is still conducting reflects the surge back to the station. The time interval between the first and second arrival of the surge at the station is recorded by the timing device and is proportional to the distance to the fault.

This method of locating faults is intended primarily for high-impedance faults. A fault in a cable is rarely a dead short. A fault with low voltage applied may measure between 5000 and 10,000 ohms even though well carbonized. By applying a relatively high voltage to the fault it is can be made to arc and during the arcing period the impedance of the fault drops to a very low value. Since majority of the faults are intermittent it is important that the measurement be complete in a very short time. If a highly sensitive long after-glow cathode ray tube is available or if photography
is employed the location of the fault can be determined from one flashover. However, in this investigation a constant visual pattern on the cathode ray tube was maintained by causing the cable to breakdown repeatedly.

The polarity of every consecutive echo alternates since the impedance at the monitoring end is high and the impedance at the fault while the arc is being sustained is low. The echo from the monitoring end is of same polarity as the incident echo but the echo from the fault is of opposite polarity to that incident to the fault. This reversal in polarity of consecutive echos aids in segregating the fault pips from spurious surges. The effective range of this method is limited to about 10 miles due to attenuation and distortion particularly of the high frequency components.
The requirements of the ideal fault locator were defined by Messrs. R. F. Stevens and T. W. Stringfield. The desirable qualities are: (1) The device should complete the measurement before the arc is extinguished (2) It should have a high accuracy (3) The results should be readily available (without developing photographic film) and easily interpreted. (4) The equipment should be simple, portable, rugged, and relatively inexpensive. (5) It should operate with safety to personnel and service. To fulfill the above requirements some system which utilizes the traveling waves must be employed.

The traveling-wave method can be divided into three categories: (a) The Pulse-radar (b) Frequency-modulated and (c) Fault-generated surge.

(a) PULSE-RADAR METHOD - In this method an artificially generated voltage pulse of short duration is impressed on one end of the cable. The pulse travels down the cable with velocity depending upon the cable parameters. Upon meeting the fault a portion of the incident pulse is reflected back toward the source while the remainder of the pulse continues in the same direction. One-half the time required for the return of the echo from the fault multiplied
by the velocity of propagation is equal to the fault distance. The minimum resistance of a detectable series fault is about five ohms and maximum resistance of a detectable shunt fault is about 1000 ohms. The effective range of pulse-radar method in power cables is about 10 miles.

If the impedance of the fault is high the reflection produced will not give a clear change in the trace. By applying a relatively high voltage to the fault it can be made to arc and during the arcing its impedance drops to zero. Several methods have been developed which superimpose the artificial pulses on top of a high d.c. voltage. J. P. Lozes Jr. has superimposed 3000 volt 3 micro-second test surges repeated 30 times per second on top of periodic high voltage half-second d-c pulses. When the d-c pulse is off, the trace on the screen is same as if the cable were not faulted since the fault impedance is usually much higher than the surge impedance of the cable. When the d-c pulses are applied, the fault arcs over, its "resistance" goes to zero and the test surges are reflected. With the d-c cycling on and off a continually alternating trace of the unfaulted and faulted cable is seen.

(b) FREQUENCY-MODULATION METHOD- The initial attraction of this system was the possibility of eliminating the oscilloscope and reading the fault distance directly on a milliammeter. A frequency-modulated voltage signal is
impressed on the cable which travels down the cable to the fault and is reflected back to the source. The frequency of the impressed voltage is varied at a linearly rate with time. The reflected signal arriving at the source will have a different frequency than the frequency being transmitted at the same instant. The difference in frequencies is measured by a suitable discriminator circuit and is proportional to the distance to the fault. The detailed requirements of this system were examined by Mr. F. F. Roberts. In order that short periods of time can be measured accurately the frequency of the modulated carrier and the bandwidth must be high. This is undesirable since at high frequencies the attenuation and distortion are high. Again, unless the fault impedance is reduced, the signal reflected from a high impedance fault will be small. The simple frequency-modulated system is incapable of distinguishing multiple faults. A more elaborate system involving an automatic frequency analyzer and an oscilloscope would be required. It is concluded that the f.m. method cannot compete with the pulse techniques.

(c) **FAULT-GENERATED SURGE METHOD** - Two systems of applying the fault-generated surges for locating faults on transmission lines have been developed by the Engineers of the Bonneville Power Administration. For convenience they have designated these as "Type A" and "Type B" fault-locators. In the "Type A" system the surge from the fault travels to the station end of the line where it initiates a timing device.
The surge is reflected from the station bus back down the line to the fault where it is reflected and returns to the station. The time between the first and second arrival of the surge at the station is measured by the timing device and is proportional to the distance to the fault. In the "Type B" system use is made of both surges which originate at the fault and which travel down the line in opposite directions. One of these arrives at the "near end" of the line and triggers a timing device. The other travels to the "remote end" and causes a broad-band radio transmitter to send out a timing pulse which is received at the near end and stops the timing device. The time interval measured less the correction for the radio wave is proportional to the distance to the fault. In both of these systems the fault locator is continuously monitoring the lines. The fault is recorded before the arc is extinguished thus non-sustained as well as permanent faults can be located. The "Type A" locator requires a cathode ray tube and a camera whereas "Type B" employs a electronic time interval counter. The "Type A" system requires that the coefficient of reflection at the fault be high in order to obtain a good reflected signal. In the "Type B" system no use is made of reflections.
III INVESTIGATION

A. Theory of Wave Propagation

It is desirable to calculate the shape of the pulse generated at the fault and the modifications it undergoes as it travels down the cable, also the magnitude and shape of the reflection to be expected from a discontinuity. The exact solution of the differential equations governing the traveling waves is very complex and lengthy. In order to simplify the mathematics approximations will be made.

1. Fundamental Differential Equations

Consider a short length of cable

where

\[ r \] - series resistance in ohms per unit route length

\[ l \] - series inductance in henrys

\[ c \] - shunt capacitance in farads

\[ g \] - shunt conductance in ohms
Change in voltage along $\delta x$

$$\delta e = -i \pi (\delta x) - \lambda \frac{\partial i}{\partial t} (\delta x)$$

Change in current along $\delta x$

$$\delta i = -g e (\delta x) - c \frac{\partial e}{\partial x} (\delta x)$$

In the limit as $\delta x \to 0$

$$-\frac{\partial e}{\partial x} = ri + \lambda \frac{\partial i}{\partial t} \quad \ldots \quad 1$$

$$-\frac{\partial i}{\partial x} = ge + c \frac{\partial e}{\partial t} \quad \ldots \quad 2$$

Introducing operator $\rho = \frac{\partial}{\partial t}$
equations (1) and (2) become

$$-\frac{\partial e}{\partial x} = (r + \lambda \rho) i \quad \ldots \quad 3$$

$$-\frac{\partial i}{\partial x} = (g + c \rho) e \quad \ldots \quad 4$$

Take $\frac{\partial}{\partial x}$ of (3) and substitute into (4). Take $\frac{\partial}{\partial x}$ of (4) and substitute into (3)

$$\frac{\partial^2 e}{\partial x^2} = (r + \lambda \rho)(g + c \rho) e \quad \ldots \quad 5$$
\[
\frac{\partial^2 \ddot{u}}{\partial x^2} = (r + \lambda \rho)(g + c \rho) \dot{i} \\
\]

\[\text{let} \quad \lambda = \sqrt{(r + \lambda \rho)(g + c \rho)} \]

\[\lambda = \sqrt{C \lambda + \frac{g}{c} + \rho} \]

\[\text{let} \quad \eta = \frac{1}{\sqrt{C \lambda}} \]

\[\alpha = \frac{r}{2 \lambda} + \frac{g}{2c} \]

\[\beta = \frac{r}{2 \lambda} + \frac{g}{2c} \]

Therefore, \[\lambda = \frac{1}{\eta} \sqrt{(\alpha + (\beta + \rho)(\alpha - \beta + \rho)} \]

\[= \frac{1}{\eta} \sqrt{(\rho + \alpha)^2 - (\beta^2)} \]

Then equations (5) and (6) become

\[\frac{\partial^2 e}{\partial x^2} = \lambda^2 e \]

\[\frac{\partial^2 \dot{i}}{\partial x^2} = \lambda^2 \dot{i} \]
Treating (13) and (14) as linear differential equations the solutions are,

\[ e = Ae^{-bx} + Be^{bx} \quad ...... \quad 15 \]

\[ i = Ce^{-bx} + De^{bx} \quad ...... \quad 16 \]

where \( A, B, C, \) & \( D, \) are constants with respect to \( x \) but are arbitrary functions of time. The solutions are in operational form only since \( k \) contains the operator \( p. \)

Substitute (15) and (16) into (4)

\[ C \lambda e^{-bx} - D \lambda e^{bx} = A(\gamma + \sigma p) e^{-bx} + B(\gamma + \sigma p) e^{bx} \quad ...... \quad 17 \]

Comparing coefficients,

\[ C = \frac{1}{\lambda} (\gamma + \sigma p) A \]
\[ = \sqrt{\frac{\gamma + \sigma p}{r + \lambda p}} A \quad ...... \quad 18 \]

\[ D = -\frac{1}{\lambda} (\gamma + \sigma p) B \]
\[ = -\sqrt{\frac{\gamma + \sigma p}{r + \lambda p}} B \quad ...... \quad 19 \]

Let \( \gamma \) be the surge impedance operator

\[ \gamma = \sqrt{\frac{r + \lambda p}{\gamma + \sigma p}} \quad ...... \quad 20 \]

\[ = \sqrt{\frac{\lambda}{C}} \sqrt{\frac{\frac{1}{\gamma} + p}{\frac{\lambda}{C} + p}} \]
\[ = \sqrt{\frac{\lambda}{C}} \sqrt{\frac{\alpha + \beta + p}{\alpha - \beta + p}} \]
Let \( \mathcal{Z} = \sqrt{\frac{L}{C}} \) = Characteristic impedance

Then \( \mathcal{Z} = \mathcal{Z} \sqrt{\frac{\alpha + \beta + p}{\alpha - \beta + p}} \)  

From equations (18), (19), and (20), equations (15) and (16) can be re-written,

\[ E = AE^{-kx} + BE^{kx} \]  

\[ i = \frac{1}{\mathcal{Z}} (AE^{-kx} - BE^{kx}) \]

A and B are determined from the boundary conditions.
2. PULSES GENERATED BY THE DISCHARGE OF A LOSSLESS CABLE

The nature of the transient produced by a lossless cable discharging into a resistive load (see Fig. 1) will be studied by the application of operational method analysis.

![Diagram of charged cable discharging into a load resistance](image)

**Fig. 1** Schematic circuit diagram of a charged cable discharging into a load resistance

The cable length $d$ is initially charged to a voltage $E_0$ and at time $t=0$ the switch $S$ is suddenly closed. The a-c impedance of the cable from transmission line theory is

$$Z = Z_0 \coth j \omega s$$

The Laplace transform impedance is found by substituting $\rho$ for $j \omega$

$$\mathcal{L}^{-1}(Z) = \overline{Z} = Z_0 \coth \rho \delta$$
Where $p = \frac{\partial}{\partial t}$ is the transform parameter

$\delta = \frac{a}{c}$ is the one-way transmission time of the cable

$Z_o = \sqrt{\frac{\varepsilon}{\mu}}$ is the characteristic impedance of the cable

The current transform

$$\bar{I} = \frac{E_0}{P(R_e + Z_o) \coth \delta_p}$$

$$\coth \delta_p = \frac{e^{\delta_p} - e^{-\delta_p}}{e^{\delta_p} + e^{-\delta_p}}$$

Equation (26) can be re-written

$$\bar{I} = \frac{E_0}{R_e + Z_o} \cdot \frac{1}{P} \left[ \frac{1 - e^{-2\delta_p}}{1 + m e^{-2\delta_p}} \right]$$

Let $m$ be the reflection factor at load end

$$m = \frac{Z_o - R_e}{Z_o + R_e}$$

Expand $\frac{1}{1 + m e^{-2\delta_p}}$ by binomial theorem since $|m e^{-2\delta_p}| < 1$

$$\frac{1}{1 + m e^{-2\delta_p}} = \sum_{n=0}^{\infty} (-1)^n m^n e^{-2n\delta_p}$$

Substitute equation (29) into (27)

$$\bar{I} = \frac{E_0}{R_e + Z_o} \cdot \frac{1 - e^{-2\delta_p}}{P} \left[ 1 - m e^{-2\delta_p} + m^2 e^{-4\delta_p} - \ldots (-1)^n m^n e^{-2n\delta_p} \right]$$
\[ L = \frac{E_o}{R_e + Z_o} \cdot \frac{1}{\rho} \left[ 1 - e^{-2\delta \rho} - m (e^{-2\delta \rho} - e^{-4\delta \rho}) + m^2 (e^{-4\delta \rho} - e^{-6\delta \rho}) \ldots \right] \]

Taking the inverse Laplace transform of equation (31)

\[ i(t) = \frac{E_o}{R_e + Z_o} \left\{ 1 - H(t-2\delta) - m [H(t-2\delta) - H(t-4\delta)] + m^2 [H(t-4\delta) - H(t-6\delta)] \ldots \right\} \]

where

\[ H(t-2n\delta) = 0 \quad \text{for} \quad (t-2n\delta) < 0 \]
\[ H(t-2n\delta) = 1 \quad \text{for} \quad (t-2n\delta) > 0 \]

as \( n = 0, 1, 2, 3 \ldots \)

If the load is matched to the cable \( R_e = Z_o \), the current consists of a single rectangular pulse of amplitude \( I_d = \frac{E_o}{2Z_o} \) and duration \( \tau = 2\delta \) (see Fig 2a). The effect of mismatching the load produces a series of steps into the transient discharge. (See Fig. 2b and 2c). The steps are all of the same sign when \( R_e > Z_o \) and alternate in sign when \( R_e < Z_o \). The steps are the results of reflections at the terminals of the cable due to impedance mismatch.

The reflections traverse the cable to the open end in time \( \delta \), are completely reflected and travel back to the load end in total time \( 2\delta \) where they appear as
positive or negative steps depending upon the load reflection factor. These reflections continue with constantly diminishing amplitude until all the energy initially stored in the cable is dissipated in the load resistance.

As a special case assume that load resistance is zero, then from (28) \( m = 1 \) and equation (32) becomes

\[
I(t) = \frac{E_0}{L_0} \left[ (1 - 2H(t - 2\delta) + 2H(t - 4\delta) - 2H(t - 6\delta) + \ldots) \right]
\]

This is a square wave of amplitude \( \frac{E_0}{L_0} \) and period \( 4\delta = \frac{4\alpha}{\pi} \) (See Fig. 2d).
Fig. 2. Current and voltage pulses generated by a lossless cable discharging into a load resistance. The solid line represents the voltage pulses, and the broken line the current pulses.

U.B.C. April 16, 1951
3. TRANSIENTS PRODUCED BY A CHARGED CABLE SHORTING TO GROUND

The problem is to obtain an expression for the voltage across $Z_R$ (See Fig. 3) at any instant of time after the fault occurs at $F$. $Z_S$ offers a very high impedance to high frequencies only and $Z_R$ offers high impedance to both high and low frequencies.

![Schematic wiring diagram of a charged cable shorting to ground.](image)

**Fig. 3** - Schematic wiring diagram of a charged cable shorting to ground.

The cable is initially charged to a voltage $E_0$ before the fault occurs. Assume that the "resistance" of the arc is zero. Let the parameters of the per unit length of transmission distance of the cable be $r$, $l$, $c$, and $g$. $x$ is measured from the point of fault.

Boundary conditions are

\[
\begin{align*}
\epsilon(x,0) &= E_0 \\
i(x,0) &= 0 \\
\epsilon(x,t) &= 0 \quad \text{for } t > 0 \\
i(x,t) &= 0 \quad \text{for } t > 0
\end{align*}
\]
The partial differential equations for a uniform transmission line are

\[-\frac{\partial E}{\partial x} = r i + \lambda \frac{\partial E}{\partial t} \]  \hspace{1cm}  \ldots \hspace{1cm}  1

\[-\frac{\partial i}{\partial x} = g E + c \frac{\partial E}{\partial t} \]  \hspace{1cm}  \ldots \hspace{1cm}  2

In solving equations (1) and (2) for the above boundary conditions the Laplace operational method will be used.

The Laplace transform of \(e(x,t)\) by definition is

\[\mathcal{L}[e(x,t)] = \bar{e}(\xi,t) = e(x,t) \mathcal{L}^{-1} \cdot dt\]

The Laplace transform of \(\frac{\partial}{\partial x}[e(x,t)]\) by definition is

\[\mathcal{L}\left\{\frac{\partial}{\partial x}[e(x,t)]\right\} = \mathcal{L}\left\{\frac{\partial}{\partial x}[e(x,t)]\right\} \mathcal{L}^{-1} \cdot dt\]

\[= \left[\bar{e}(\xi,t) \mathcal{L}^{-1}\right] + p \mathcal{L}\left\{e(x,t) \mathcal{L}^{-1}\right\} \mathcal{L}^{-1} \cdot dt\]

\[= -e(\xi_0) + p \mathcal{L}\left\{e(x,t) \mathcal{L}^{-1}\right\} \]

\[= p \bar{e}(\xi_0) - e(\xi_0)\]

Taking the Laplace transform of equation (1)

\[\mathcal{L}\left\{-\frac{\partial E}{\partial x}\right\} = -\frac{\partial \bar{E}}{\partial \xi} \]

\[= r \bar{Z} + \lambda p \bar{Z} - \lambda i(\xi_0) \]  \hspace{1cm}  \ldots \hspace{1cm}  38

From boundary condition (35) \(i(\xi_0) = 0\)

(38) becomes

\[-\frac{\partial \bar{E}}{\partial \xi} = (r + \lambda p) \bar{Z} \]  \hspace{1cm}  \ldots \hspace{1cm}  39
Taking the Laplace transform of equation (2)

\[ L\left[\frac{\partial \bar{v}}{\partial x}\right] = -\frac{\partial \bar{v}}{\partial x} = \bar{g} \bar{e} + \bar{c} \bar{p} \bar{e} - \bar{c} \bar{e}(x,0) \] ...... 40

From boundary condition (34) \( \bar{e}(x,0) = \bar{E}_0 \)

(40) becomes

\[ \frac{\partial \bar{v}}{\partial x} = (\bar{g} + \bar{c} \bar{p}) \bar{e} - \bar{c} \bar{E}_0 \] ...... 41

Take \( \frac{\partial}{\partial x} \) of equations (39) and (41)

\[ -\frac{\partial^2 \bar{e}}{\partial x^2} = (r + \bar{p}) \frac{\partial \bar{e}}{\partial x} \] ...... 42

\[ -\frac{\partial^2 \bar{e}}{\partial x^2} = (\bar{g} + \bar{c} \bar{p}) \frac{\partial \bar{e}}{\partial x} \] ...... 43

Substitute equation (41) into (42)

\[ \frac{\partial^2 \bar{e}}{\partial x^2} = (r + \bar{p})(\bar{g} + \bar{c} \bar{p}) \bar{e} - \bar{c}(r + \bar{p}) \bar{E}_0 \] .. 44

\[ \frac{\partial^2 \bar{e}}{\partial x^2} = \lambda^2 \bar{e} - \chi \] ...... 45

where \( \lambda^2 = (r + \bar{p})(\bar{g} + \bar{c} \bar{p}) \) ...... 7

and \( \chi = (r + \bar{p}) \bar{c} \bar{E}_0 \) ...... 46

Substitute equation (39) into (43)

\[ \frac{\partial^2 \bar{v}}{\partial x^2} = (\bar{g} + \bar{c} \bar{p})(r + \bar{p}) \bar{v} \] ...... 47

\[ \frac{\partial^2 \bar{v}}{\partial x^2} = \lambda^2 \bar{v} \] ...... 48

Treating equations (45) and (48) as ordinary linear differential equations the solutions are

\[ \bar{e}(x,\bar{p}) = A e^{\bar{h}x} + B e^{-\bar{h}x} + \frac{\chi}{\lambda^2} \] ...... 49

\[ \bar{v}(x,\bar{p}) = F e^{\bar{h}x} + G e^{-\bar{h}x} \] ...... 50
Where $A$, $B$, $F$, and $G$ are constants with respect to $x$ only and functions of $p$.

Substitute equations (49) and (50) into (39)

$$\frac{\partial \bar{e}}{\partial x} = -A e^h + B e^{-h} = (r + lp)(F e^h + G e^{-h})$$

Comparing coefficients

$$F = -\frac{Ah}{r + lp} = -\frac{A}{g} \quad \ldots \quad 52$$

$$G = \frac{B}{r + lp} = \frac{B}{g} \quad \ldots \quad 53$$

Rewriting equations (49) and (50)

$$\bar{E}(x,p) = A e^{hx} + B e^{-hx} + \frac{\psi}{\epsilon} \quad \ldots \quad 55$$

$$\bar{\zeta}(x,p) = \frac{1}{g} \left[ -A e^{hx} + B e^{-hx} \right] \quad \ldots \quad 56$$

Constants $A$ and $B$ are determined form boundary conditions (36) and (37)

Taking the Laplace transform of (37) $\bar{\zeta}(d,p) = 0$ and applying this condition to (56)

$$-A e^{kd} + B e^{-kd} = 0$$

$$B = A e^{2kd} \quad \ldots \quad 57$$

Taking the Laplace transform of (36) $\bar{E}(0,p) = 0$ and applying this condition to equation (55)

$$A + B + \frac{\psi}{\epsilon} = 0$$

$$B = -(A + \frac{\psi}{\epsilon}) \quad \ldots \quad 58$$

Solving equations (57) and (58)

$$A = \frac{-\psi e^{-2kd}}{\epsilon^2(1 + e^{-2kd})} \quad \ldots \quad 59$$
Substituting for A and B into (55) and (56) and simplifying

\[ B = \frac{-\frac{1}{\ln^2 (1 + \epsilon^{-2} \alpha d)}}{\ln^2 (1 + \epsilon^{-2} \alpha d)} \] ....... 60

Equation (61) can be rewritten as

\[ \bar{E}_{(x,p)} = \frac{\epsilon}{\epsilon^2 \ln^2 [1 - \epsilon^{-2} \frac{(2d-x) + \epsilon^{-2} \alpha d}] - \epsilon^{-2} \alpha d] - \epsilon^{-2} \alpha d}] \] ....... 61

Equation (62) can be solved by (a) the expansion theorem which gives the solution in form of a trigonometric series or by (b) the expansion in terms of the solutions for semi-infinite lines which has a physical interpretation in terms of direct and multiple-reflected waves. The rigorous pure mathematical solution of (63) consists of the application of the inversion theorem followed by contour integration. The exact solution involving contour integration will not be attempted here. Instead the solution for a distortionless cable will be obtained through the use of the expansion theorem giving the result in a trigonometric series.

Rewriting equation (63) in hyperbolic form

\[ \bar{E}_{(x,p)} = \frac{\epsilon}{\epsilon^2 \ln^2 [1 - \epsilon^{-2} \frac{(2d-x) + \epsilon^{-2} \alpha d}] - \epsilon^{-2} \alpha d]} \] ....... 63

\[ \frac{\epsilon^2}{\epsilon^2 \ln^2 [1 - \epsilon^{-2} \frac{(2d-x) + \epsilon^{-2} \alpha d}] - \epsilon^{-2} \alpha d]} \] ....... 64

\[ \epsilon^2 = (r + \lambda p)(q + c p) = \frac{\epsilon^2 (r + \lambda p)(q + c p)}{\epsilon^2 (r + \lambda p)(q + c p)} \] ....... 7
For a distortionless line  
\[ \frac{r}{\ell} = \frac{g}{c} \]  
...... 65

Equation (7) becomes  
\[ \frac{\ell}{s} = \frac{1}{\nu} \left( \frac{g}{c} + p \right) \]  
...... 66

From (46) and (7)  
\[ \frac{s}{\ell^2} = \frac{E_0}{\left( \frac{g}{c} + p \right)} \]  
...... 67

For distortionless line equation (64) is  
\[ \frac{\varepsilon}{E_0} = \frac{g}{c + p} \left[ \frac{1}{\nu} - \frac{\cosh \left( \frac{g}{c} + p \right) \left( \frac{x - a}{\ell} \right)}{\cosh \left( \frac{g}{c} + p \right) \frac{d}{\ell}} \right] \]  
...... 68

Solving second term of (68) by the expansion theorem  
\[ \phi(p) = \frac{f(p)}{g(p)} = \frac{\cosh \left( \frac{g}{c} + p \right) \left( \frac{x - a}{\ell} \right)}{\left( \frac{g}{c} + p \right) \cosh \left( \frac{g}{c} + p \right) \frac{d}{\ell}} \]  
...... 69

then  
\[ \phi(t) = \sum_{r=1}^{\infty} \frac{f(a_r)}{g'(a_r)} \frac{a_r t}{c} \]  
...... 70

First determine the zeros of the denominator of (69)  
\[ \left( \frac{g}{c} + p \right) \cosh \left( \frac{g}{c} + p \right) \frac{d}{\ell} = 0 \]  
...... 71

These are at  
(a)  \( p = -\frac{g}{c} \)  
...... 72
(b)  \( p = \pm \frac{\pi}{2c} (2n+1) \frac{a_r}{d} - \frac{g}{c} \)  
...... 73

where  \( n = 0, 1, 2, 3 \)

For the root  \( p = -\frac{g}{c} \), the denominator  \( g'(a_r) \) of (70) is  
\[ g'(a_r) = \frac{d}{dp} \left[ \left( \frac{g}{c} + p \right) \cosh \left( \frac{g}{c} + p \right) \frac{d}{\ell} \right]_{p = -\frac{g}{c}} = 1 \]  
...... 74
For the roots of \( p \) given in (73), \( g(\alpha_n) \) of (69) is

\[
g(\alpha_n) = \frac{d}{dp} \left( \frac{\alpha}{\epsilon + p} \cosh(\frac{\alpha}{\epsilon} + p) \frac{d}{d\nu} \right)
\]

\[
p = \nu \frac{\pi}{2} (2n+1) \frac{\alpha}{\epsilon} - \frac{\alpha}{\epsilon}
\]

\[
= \cosh(\frac{\alpha}{\epsilon} + p) \frac{d}{d\nu} + \frac{\pi}{2} (2n+1) \frac{\alpha}{\epsilon} \cosh(\frac{\alpha}{\epsilon} + p) \frac{d}{d\nu} \quad -- 75
\]

But \( \cosh(\frac{\alpha}{\epsilon} + p) \frac{d}{d\nu} = 0 \) for all values of \( p \) given in (73) therefore, equation (75) reduces to

\[
g(\alpha_n) = \int \frac{\pi}{2} (2n+1) \sinh(\frac{\pi}{2} (2n+1))
\]

\[
= (-1)^{n+1} \frac{\pi}{2} (2n+1) \quad ..... 76
\]

For the solution of (69) substitute (74) and (75) into (70)

\[
\phi(t) = \epsilon^{-\frac{\pi}{\epsilon} t} \sum_{n=0}^{\infty} \frac{2(-1)^{n+1}}{\pi (2n+1)} \left\{ \cosh(\frac{\pi}{2} (2n+1) (\frac{-\alpha}{\epsilon}) \int_0^\infty \cosh(\frac{\pi}{2} (2n+1)) \frac{\alpha}{\epsilon} + \frac{\alpha}{\epsilon} \right\}
\]

\[
= \epsilon^{-\frac{\pi}{\epsilon} t} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{\pi (2n+1)} \epsilon^\frac{\alpha}{\epsilon} \cos(\frac{\pi}{2} (2n+1) (\frac{-\alpha}{\epsilon}) \cos(\frac{\pi}{2} (2n+1)) \frac{\alpha}{\epsilon} + \frac{\alpha}{\epsilon} \right\}
\]

\[
= \epsilon^{-\frac{\pi}{\epsilon} t} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{\pi (2n+1)} \epsilon^\frac{\alpha}{\epsilon} \sin(\frac{\pi}{2} (2n+1)) \frac{\alpha}{\epsilon} \cos(\frac{\pi}{2} (2n+1)) \frac{\alpha}{\epsilon} + \frac{\alpha}{\epsilon} \right\}
\]

\[
= \epsilon^{-\frac{\pi}{\epsilon} t} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{\pi (2n+1)} \epsilon^\frac{\alpha}{\epsilon} \sin(\frac{\pi}{2} (2n+1)) \frac{\alpha}{\epsilon} \cos(\frac{\pi}{2} (2n+1)) \frac{\alpha}{\epsilon} + \frac{\alpha}{\epsilon} \right\}
\]

The inverse transform of the first term of equation (68) is

\[
\mathcal{L}^{-1} \left[ \frac{\epsilon}{\frac{\alpha}{\epsilon} + p} \right] = \epsilon e^{-\frac{\pi}{\epsilon} t} \quad ..... 80
\]
The complete solution of (68) is (79) minus (80)

\[ E(x,t) = \frac{4}{\pi} \varepsilon_0 \varepsilon_r \sum_{n=0}^{\infty} \frac{1}{2n+1} \sin \left( \frac{(2n+1)\pi x}{2d} \right) \cos \left( \frac{(2n+1)\pi x}{2d} \right) \quad \ldots \quad 81 \]

The voltage at any instant of time at the monitoring end of the cable where \( x = d \) is

\[ E(d,t) = \frac{4}{\pi} \varepsilon_0 \varepsilon_r e^{-\frac{3t}{8}} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \left[ \cos \left( \frac{2n+1}{2} \pi \frac{\varepsilon_r}{\varepsilon_r} \right) \right] \quad \ldots \quad 82 \]

This equation represents a square wave which has a period \( t = \frac{2d}{\pi} \) and which is exponentially attenuated by the attenuation factor \( e^{-\frac{3t}{8}} \). The plot of this curve is shown in Fig. 4. The oscillogram Fig. 4a shows the voltage generated by the discharge of a 239-foot section of RG/8U coaxial cable. The theoretically calculated voltage wave and the observed wave are very similar showing that the mathematical approximations made in arriving at equation (82) are justified.
Fig. 4. The voltage wave generated by a distortionless cable discharging through a zero resistance as calculated from equation (32).

\[ t_n = \frac{2d}{\pi} \text{ seconds} \]

Fig. 4a. Oscillogram of the voltage wave generated by an arc discharge of a 289-foot section of RG/8U coaxial cable. For circuit diagram see Fig. 3. Page 16.
A. Reflections

(1) Derivation of Reflection Operator

Consider a line of length $l$ terminated by an impedance $z_2$. At $x=0$ steady state voltage $E$ is applied through an impedance $z_1$.

\[ e_x = A e^{-lx} + B e^{lx} \quad \ldots \quad 22 \]
\[ i_x = \frac{1}{j} (A e^{-lx} - B e^{lx}) \quad \ldots \quad 23 \]

For the above boundary conditions

at $x=0$

\[ e_0 = A + B = E - \frac{z_1}{R} (A - B) \quad \ldots \quad 90 \]

at $x=d$

\[ e_d = A e^{-ld} + B e^{ld} = \frac{z_2}{\frac{R}{l}} (A e^{-ld} - B e^{ld}) \quad \ldots \quad 91 \]

Let

\[ c_1 = \frac{z_1}{\frac{R}{l}} \quad \ldots \quad 92 \]
\[ c_2 = \frac{z_2}{\frac{R}{l}} \quad \ldots \quad 93 \]

Rewriting (90) and (91)

\[ (c_2 - 1) A e^{-2ld} = (c_2 + 1) B \quad \ldots \quad 94 \]
(\rho_1 + 1) A = \varepsilon + (\rho_1, -1) B

Let \( m_1 \) and \( m_2 \) be the reflection factors at \( Z_1 \) and \( Z_2 \) respectively where

\[
m_1 = \frac{1 - \rho_1}{1 + \rho_1} = \frac{\g - Z_1}{\g + Z_1} \quad \cdots \quad 96
\]
\[
m_2 = \frac{1 - \rho_2}{1 + \rho_2} = \frac{\g - Z_2}{\g + Z_2} \quad \cdots \quad 97
\]

Solving (94)

\[
B = -A m_2 \varepsilon^{-2 \kappa d} \quad \cdots \quad 98
\]

From (95) and (98)

\[
B = \frac{-m_2 \varepsilon^{-2 \kappa d}}{1 - m_1 m_2 \varepsilon^{-2 \kappa d} i + \rho_1} \cdot \varepsilon \quad \cdots \quad 99
\]

From (98) and (99)

\[
A = \frac{1}{1 - m_1 m_2 \varepsilon^{-2 \kappa d} i + \rho_1} \cdot \frac{\varepsilon}{i + \rho_1} \quad \cdots \quad 100
\]

Substituting into equation (22) and (23)

\[
E_x = \frac{-h_x - h_2 (2d - x)}{1 - m_1 m_2 \varepsilon^{-2 \kappa d} i + \rho_1} \cdot \frac{\varepsilon}{i + \rho_1} \quad \cdots \quad 101
\]
\[
i_x = \frac{-h_x - h_2 (2d - x)}{1 - m_1 m_2 \varepsilon^{-2 \kappa d} i + \rho_1} \cdot \frac{\varepsilon}{i + \rho_1} \quad \cdots \quad 102
\]

Expanding the denominator by the binomial expansion theorem

\[
\frac{1}{1 - m_1 m_2 \varepsilon^{-2 \kappa d} i + \rho_1} = \frac{1}{1 - r} = 1 + r + r^2 + r^3 + \cdots \quad \cdots \quad 103
\]

Equations (101) and (102) become

\[
E_x = \frac{\varepsilon}{i + \rho_1} \left[ E - m_2 \varepsilon + m_1 m_2 \varepsilon^2 - h_2 (2d - x) \right] \quad \cdots \quad 104
\]
\[
i_x = \frac{\varepsilon}{\beta (1 + \rho_1)} \left[ E + m_2 \varepsilon^2 + m_1 m_2 \varepsilon + m_2 \varepsilon^2 + h_2 (4d - x) \right] \quad \cdots \quad 105
\]
The first term gives the effect of the direct wave while the second term gives the effect of the reflected wave from the far end, and the third that of the wave reflected from the near end. The above equations give the sum of the direct and reflected waves which are effective at times $t = \frac{\lambda}{\nu} \cdot \frac{2d-x}{\nu}$, $t = \frac{2d+x}{\nu}$, etc. Individually, the waves act as if each were traveling alone on an infinite line, originating at the impedance discontinuity and displaced from each other by time $t = \frac{d}{\nu}$ where $d$ is the distance between the impedance discontinuities. The wave originating at the discontinuity is determined by the incident wave and the reflection operator.
(b) **Reflection Lattices**

In analyzing the problem of successive reflections of traveling waves, use is made of reflection lattices. Consider a charged cable insulated at both ends shorting to ground through an impedance \( Z_i \), at distance \( \frac{z_i}{2} \) from one end, (See Fig. 5). The wave \( \mathcal{E} \) generated by the sudden collapse of voltage travels along the cable in both directions from \( Z_i \), and when it reaches the open end it reflects without change of shape or sign. The wave on returning to \( Z_i \), gives rise to two components; the reflected wave \( \mathcal{E} \) and the refracted or transmitted wave \( \mathcal{E} \) where \( \mathcal{E} \) is the reflection operator and \( \mathcal{E} \) the refraction operator, each being a function involving the parameters of the circuit and the time derivative \( \mathcal{P} = \frac{\partial}{\partial t} \).

The resultant voltage as a function of time at any point is the sum of all waves which have arrived up to the given instant properly displaced by the interval of their relative position on the cable. At definite intervals such as \( \mathcal{E} \) the waves arrive simultaneously from the right and left and add up by superposition. Thus, the lattice presents a clear time-distance picture of the phenomena of successive reflections and shows at a glance just what is happening at all points along the cable at all instants of time.
Fig. 5. Successive reflections of a charged cable discharging through an impedance Z.
(2) **Attenuation, Distortion and Velocity**

As a wave travels along the cable it is attenuated and distorted due to conductor resistance as modified by skin effect, leakage to ground, and dielectric losses. The distortion is eliminated if \( \frac{r}{l} = \frac{3}{c} \) and the attenuation is accounted for by a simple exponential decrement factor.

The expressions for attenuation and distortion may be derived from general voltage and current equations for a transmission line.

\[
E_x = A e^{-\frac{B}{l}x} + B e^{B l x}
\]

\[
i_x = \frac{i}{s} \left( A e^{-\frac{B}{l}x} - B e^{B l x} \right)
\]

For infinite line \( x \to \infty \)

\( B = 0 \)

For an applied voltage that is a function of time \( t \)

\[
E_{x=0} = E(t)
\]

Equation (22) and (23) become

\[
E_x = e^{-\frac{B}{l}x} E(t)
\]

\[
i_x = \frac{i}{s} e^{\frac{B}{l}x} E(t)
\]

\[
\bar{h} = \frac{1}{\nu} \sqrt{(p + \alpha)^2 - \beta^2}
\]

The accurate solution of equations (107) and (108) is difficult and so an approximation will be made. For high rates of change with time of voltage and current, \( p \) is large hence

\[
\bar{h} = \frac{1}{\nu} (p + \alpha) \sqrt{1 - \left(\frac{\beta^2}{(p + \alpha)^2}\right)}
\]

\[
\approx \frac{1}{\nu} (p + \alpha)
\]

\[
\approx \frac{1}{\nu} (p + \alpha)
\]
\[ G = \frac{E \sqrt{\alpha + \beta + \rho}}{e^{-\beta + \rho}} \]

Equation (107) and (108) reduce to

\[ E = e^{-\frac{\alpha \lambda}{\mu}} \int E(t) dt \]

\[ I = \frac{1}{L} e^{-\frac{\alpha \lambda}{\mu}} \int \left( E(t - \frac{\alpha}{\mu}) - \beta \int E(t - \frac{\alpha}{\mu}) dt \right) dt \]

The equations show that the voltage wave is propagated without distortion but is subject to attenuation of \( E \) per unit length. The current wave is subject to same attenuation but is also distorted as shown by the integral term. The attenuation factor \( \alpha \) was defined in equation (9)

\[ \alpha = \frac{r}{2\lambda} + \frac{g}{2c} \]

At high frequencies, skin effect and dielectric absorption losses change \( r, l, \) and \( g \). Capacitance \( C \) is relatively independent of frequency. The skin effect will concentrate most of the current at the outer surface of the core and inner surface of the sheath. Resistance will be increased by decreasing the effective cross section of the conductors. The self inductance of the core due to internal flux linkage will be reduced. The change in \( \alpha \) with frequency means that the high frequency components are attenuated more rapidly than the low frequency components thus creating distortion which
is not shown in equations (112) and (113). Solutions (112) and (113) are approximate since it was assumed that \( p \) is large. For single conductor cable, \(^11,12\)

\[
C = \frac{k \times 10^7}{2 \pi \varepsilon_0 \ln \frac{r_1}{r}} \quad \text{farads per meter } \quad 114
\]

\[
\lambda = \frac{2 \mu_0 (\ln \frac{r_1}{r}) 10^{-7}}{\text{henries per meter } } \quad 115
\]

(at high frequencies internal inductance is negligible)

Where \( C_0 \) - velocity of light = \( 3 \times 10^8 \) meter per second

\( K = \frac{\varepsilon}{\varepsilon_0} \) - relative permittivity of the insulation

\( \mu \) - relative permeability of the dielectric

(for most dielectrics \( \mu \) is unity)

\[
\frac{1}{\nu} = \sqrt{\lambda C}
\]

Substitute (114) and (115) into (8)

\[
\frac{1}{\nu} = \sqrt{\frac{2 \mu_0 (\ln \frac{r_1}{r}) 10^{-7}}{\frac{k \times 10^7}{2 \pi \varepsilon_0 \ln \frac{r_1}{r}}} }
\]

\[
= \frac{1}{C_0} \sqrt{K}
\]

\[
\nu = \frac{1}{C_0} \sqrt{K}
\]

The velocity of propagation along the cable depends upon the relative permittivity of the insulation. (See table below)

<table>
<thead>
<tr>
<th>Insulation</th>
<th>( K ) (Average)</th>
<th>Velocity of Propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>1.0</td>
<td>983 ft. per second</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>2.25</td>
<td>655 &quot; &quot; &quot; &quot;</td>
</tr>
<tr>
<td>Oil filled paper</td>
<td>3.5</td>
<td>525 &quot; &quot; &quot; &quot;</td>
</tr>
<tr>
<td>Varnished cambric</td>
<td>4.5</td>
<td>460 &quot; &quot; &quot; &quot;</td>
</tr>
<tr>
<td>Rubber</td>
<td>6</td>
<td>400 &quot; &quot; &quot; &quot;</td>
</tr>
</tbody>
</table>
D. THE EQUIPMENT

1. General Description

Basically the equipment consists of a variable high voltage power-pack, a triggering and trace-brightening circuit, a timing-pip generator, two delay lines and a double-beam Cossor oscilloscope. The block diagram of the equipment is shown in Fig. 6.

The cable (1) is disconnected at both ends (2 and 3) and the equipment is stationed at the near end (2). The fault at (4) is assimilated by applying a high voltage to the cable from the power pack (5). The sudden collapse of the high voltage to a very much lower value at the fault generates two traveling waves (5 and 6) which travel along the cable in opposite directions away from the fault. The traveling wave (6) is not required in this method and its effects may be eliminated by terminating the cable at the far end (3) in its characteristic impedance. The fault-surge (5) on arriving at the near end (2) meets a high-pass filter (7) which passes only the steep wave front of the traveling wave. The resistors (8), (9) and (10) form a potentiometer device for tapping a reduced value of the incident voltage wave (5). The initial negative voltage (5) appearing across resistors (8 and 9) triggers the univibrator in circuit (11) which generates two sharp negative pulses (12 and 13). Pulse (12) initiates the single stroke horizontal sweep in the oscilloscope and pulse (13) triggers the timing-pip
generator (15). The univibrator in circuit (11) also generates a longer positive pulse (16) for brightening the oscilloscope trace. The incident voltage wave (5) appearing across the resistor (8) is fed into the delay line (17), through the amplifier (18) if necessary, onto the Y₂ plate of the oscilloscope producing a vertical deflection. Both delay lines (14 and 17) are terminated in their respective characteristic impedance in order to eliminate reflections.

Meanwhile the surge (5) which started the above train of events is partially reflected from the high impedance at (2) and is on its way back to the fault (4). At the fault (4) which is still conducting the initial wave (5) is again partially reflected and travels back to the near end (2). On its second arrival the pulse (5) is again fed onto the Y₂ plate of the oscilloscope producing a second pip on the trace. The second pip is displaced from the first pip by a distance proportional to the return route travel time of the surge between the equipment at (2) and the fault at (4). The second and succeeding arrivals of wave (5) have no effect on the univibrator in circuit (11) so that the horizontal sweep of the oscilloscope is not interrupted.

The timing pips produced by timing-pip generator (15) are fed onto the Y₁ trace of the oscilloscope simultaneously with the echoes on the Y₂ trace. These are of fixed frequency and are therefore a means of measuring equal time intervals on the horizontal trace.
In order to keep the trace visible on the cathode ray tube the output of the power pack (5) was arranged to assimulate the fault repetitively. If a long after-glow screen is available or photography is used a single flash-over of the fault is sufficient to locate it.
2. High-Voltage Power Pack and Line Coupling

In order to maintain the trace visible on the oscilloscope the power pack was connected to produce a voltage that would repeatedly cause the fault to flash-over. For experimental purpose the voltages used were:

(a) 0 - 1200 volts D. C.
(b) 0 - 1750 volts peak half-wave rectified 60-cycle sine wave.
(c) 0 - 1750 volts peak full-wave rectified 60-cycle sine wave.
(d) 0 - 4600 volts A. C. 60-cycle

At first, a D. C. voltage was used and the power pack was coupled to the cable through the coupling circuit shown in Fig. 7. The repetition frequency of the flash-over was determined largely by the time constants of the current limiting resistor R and the shunting condenser C. The condenser C was intended as a reservoir of energy which would discharge into the cable once the flash-over occurred and maintain the arc while the fault-surges are traveling up and down the cable. The 4 mh. radio frequency choke coil was used to prevent the fault-surges from shorting to ground through C. It was found necessary to place a 250 ohm damping resistor in series with the r.f. choke to eliminate the oscillations which were generated by shock exciting the choke each time the fault flashed over. After experimenting with this coupling circuit it was found that L and C could be omitted.
Fig. 7. Circuit diagram of an experimental high voltage power pack coupling circuit
Satisfactory results for any of the four voltages available were obtained by connecting the power pack directly in series with the cable through a 100,000 ohm non-inductive resistor. The repetition frequency of the flash-over, in case of d. c., depends upon the time constant of the current limiting resistor and the capacity of the cable and also upon the magnitude of the flash-over voltage. In case of a.c. voltages the repetition frequency is determined predominantly by frequency of a.c. voltage. The current limiting resistor is a voltage regulator whose value should be high to keep the fault current low so that the fault will flash-over repetitively, and not conduct continuously.
3. **Triggering and Trace-Brightening Circuit**

The triggering and trace brightening circuit permits the first impulse from the fault to trigger the horizontal sweep and simultaneously brighten the trace, but blocks the subsequent echoes so they do not interfere with the horizontal sweep. Basically the circuit consists of a diode limiter, a univibrator and a cathode follower. The complete circuit is shown schematically in Fig. 8. In the quiescent condition, $V_2$ in the univibrator is conducting strongly (a plate current of 11 ma), $V_3$ and $V_4$ are non-conducting. The cathode of $V_1$, the diode limiter, is held positive relative to the anode by the cathode bias potentiometer which can maintain a positive potential 0 - 150 volts on the cathode. The diode will conduct only when the cathode is driven far enough negatively so that the anode is positive relative to the cathode. This means that only an input signal which has a negative voltage greater than the positive bias on the cathode will cause $V_1$ to conduct and upset the balance of the univibrator. The biasing potentiometer can be set so that either a large or small negative pulse will trigger the univibrator.

When $V_1$ conducts a negative signal is impressed on the grid of $V_2$ which stops $V_2$ from conducting sending the plate of $V_2$ positive. The high positive voltage on the plate of $V_2$ is impressed on the grids of $V_3$ and $V_4$ causing both tubes to conduct very strongly. While $V_3$ is conducting,
its plate is driven about 150 volts negative. This negative voltage is impressed on the grid of $V_2$ through the coupling condenser $C_1$ which stops $V_2$ from conducting until $C_1$ discharges through $R_1$. Once $C_1$ has discharged through $R_1$, $V_2$ begins to conduct again and $V_3$ is cut off and the circuit returns to the quiescent period awaiting the next disturbance. The time constant is about 725 micro-seconds. During this period of time the echoes appearing on $V_1$ have no effect on $V_2$ since $V_2$ is already cut off. Thus the univibrator responds to the first negative pulse and blocks all succeeding pulses for a period of 725 microseconds.

The negative pulse generated at the plate of $V_3$ is differentiated and applied to the "Synch" terminal of the oscilloscope for triggering the horizontal sweep. The Puckle time base in the Cossor Model 339 oscilloscope can be started and stopped by an external trigger voltage applied to the "synch" terminals when the internal self-repeating voltage is short circuited. When the "synch" terminal is discharged and the beam flies back to the left side of the screen and remains there until the "synch" terminal is driven positive at which time the horizontal sweep begins. The negative pulse should only be of sufficient duration to discharge the condenser in the Puckle time-base circuit. Since the Synchronizing pulse has a steep leading edge and less steep trailing edge, the "synch" potentiometer on the oscilloscope is used as a vernier to vary the time at which
the horizontal sweep will begin. The "synch" potentiometer determines what percentage of the "synch" is applied to the grid of the buffer tube. As soon as the grid of the buffer tube returns to less than 12 volts negative the buffer tube starts conducting and the horizontal sweep is initiated. The horizontal sweep can be delayed as much as 10 micro-seconds for the fastest sweep and the effective length of the trace can be expanded simply by rotating the "synch" control clockwise.

The negative pulse for triggering the timing-pip generator is taken from the plate of $V_3$. Since the fly-back on the oscilloscope is not blacked-out, the timing pips appear on the fly-back trace and interfere with those on the forward trace. To avoid this interference the negative triggering pulse is delayed 6.1 microseconds by 335 cms of General Electric Company uniform delay line to make certain that the fly-back is complete before the timing-pips appear on the trace.

The positive pulse generated at the plate of $V_2$ is applied to grid of the cathode follower $V_4$. The output of the cathode follower, a 500-microsecond 90-volt positive pulse, is fed onto grid $A_4$ of the cathode ray tube through a 0.01 microfarad condenser shunted by a 0.1 megohm resistor. This large brightening pulse is applied each time the horizontal sweep is triggered to make the trace visible at high writing
speeds. This brightening pulse cannot be applied continuously as it would burn the fluorescent coating on the cathode ray tube.
4. **Timing-Pip Generator**

On the Cossor Model 339 double-beam oscilloscope, whose horizontal sweep is not linear with time, the most convenient way of measuring equal time intervals is by placing timing pips on the $Y_1$ trace. The timing pips appear on the $Y_1$ trace simultaneously with the fault-surge pips on the $Y_2$ trace and are locked in step by the initial fault-surge so that the sweep can be expanded and the position of the echoes measured more accurately.

The timing-pip generator is a modified Hartley oscillator which was built by T. K. Naylor. It was remodeled so that it could be triggered from the univibrator. The schematic circuit diagram is shown in Fig. 9. $V_{6A}$ is a shunting triode which is conducting during the quiescent period and biasing the oscillator triode $V_{6B}$ beyond cutoff by means of the common cathode resistor $R_{24}$. The 500 ohm resistor $R_{31}$ was added to unbalance the operating characteristics of $V_{6A}$ and $V_{6B}$ and the grid of $V_{6A}$ was biased 33 volts positive to insure that $V_{6A}$ is conducting continuously except when triggered by a large negative pulse from the univibrator. The sine wave output of $V_{6B}$ is clipped by the asymmetrical cathode follower ($V_{7A}$). A second cathode follower, a buffer triode $V_{7B}$, drives a differentiating circuit which differentiates the rectified sine wave from $V_{7A}$. This peaked wave is impressed on a small inductance ($L_4$) which tends to square
the pips by reducing the amplitude and increasing the width of the peak.

The frequency of the timing pips is 4.47 megacycles so the pips are spaced 0.224 microseconds apart. They are 0.03 microseconds wide and 18 volts in amplitude. These pips are indistinguishable at low sweep speeds but are only 12 mm apart on the fastest sweep.

A 6.1 microsecond General Electric Company uniform delay line is used between the timing-pip generator and the triggering circuit so that the timing pips do not appear on the flyback trace and be confused with those on the forward trace.
5. **Delay Line**

As the minimum time required to initiate the horizontal sweep on the oscilloscope is about 4 microseconds, the fault-surge had to be delayed before being applied to the Y2 deflector plates. It was thought desirable to see several microseconds of the trace before the first fault-surge arrived and so the pulse was delayed another 6 microseconds. The delay was accomplished by 550 cms of General Electric Company uniform delay line. The inner conductor is a long thin coil wound on a 3/16 inch diameter Saran flexible plastic tubing and the outer conductor is a metal braid surrounding the inner one. The inner winding is made of AWG No. 40 copper wire, formex insulated, 109 turns per centimeter and insulated from the outer conductor by a 0.0015 inch cellulose acetobutyrote tape single wrap, 50 per cent overlap. The characteristic impedance of the line is 1100 ohms and the delay is 1 microsecond in 55 cms. The voltage rating is 5000 volts D. C. The attenuation per microsecond is 2 to 3 decibels at 2 megacycles per second and 4 to 6 decibel at 4 megacycles per second.

The delay line is correctly terminated at each end by a 1100 ohms carbon resistor in order to avoid reflections.
6. **Procedure For Measuring The Cable Fault**

Make certain the cable is disconnected at both ends and free from stray induced voltages. Connect the power pack to the cable through a current limiting resistor using either 60 cycle a.c. or full-wave rectified a.c. voltage. Connect the various units of the fault-locator as shown in Fig. 6 using short lengths of coaxial line. The resistors in the detecting circuit (7) are chosen so that the maximum voltage appearing across the triggering circuit does not exceed 300 volts and 200 volts across the delay line. The potentiometer on the diode limiter is set half-way. On the oscilloscope set **plates-amplifier** switch to A. C. plates, condenser to position "9", trigger maximum counterclockwise, synch, brilliancy and velocity half-way, amplitude maximum clockwise, \( Y_1 \) and \( X_2 \)-shifts so that \( Y_1 \) beam is above \( Y_2 \), and and the \( X- \) shift so that the resting spot of the beam is just off to the right of the screen. Keep increasing the voltage on the cable by increasing the variac setting in the high voltage power-pack until the fault begins to flash over. Adjust **focus** and rotate velocity and **Synch** clockwise to expand sweep. Examine the \( Y_2 \) trace carefully. If the deflections are small, the output of the delay line is fed onto the \( A_1 \) terminal of the oscilloscope and amplified. The internal amplifiers are cascaded by setting the **plates-amplifiers** switch to 2-HFY\(_1\). The gain is increased by rotating \( A_1 \) and \( A_2 \) **Gain** clockwise. The amplifiers will
produce one-half of their full scale deflection without distortion when cascaded. Overloading produces distortion.

After the fault has been approximately located on the compressed sweep, the trace is expanded by setting condenser to position "10" and rotating Synch and Velocity slowly clockwise. The X-shift is used to examine any portion of the expanded trace. The distances between the echoes on the expanded trace are measured in terms of the 0.224 microsecond timing pips. All measurements are made to the beginning of the pulse and not the peak.
E. EXPERIMENTAL RESULTS

Since no power cables were available all experiments were carried out on three lengths of coaxial cable. Two lengths, one 289.7 feet long and the other 951.4 feet long, of RG/8/U cable and a third length 837.8 feet long which resembles very closely the RG-63/U cable, were used. The specifications of the cables used are listed below.

RG-8/U General purpose medium-size flexible cable.

Inner conductor - 7/21 AWG copper
Dielectric material - polyethylene
Shielding braid - copper
Protective covering - vinyl
Nominal diameter of dielectric - 0.285 in.
Nominal outside diameter - 0.405 in.
Maximum operating voltage rms - 4000 volts
Nominal capacitance - 29.5 μF/ft.
Nominal impedance - 52.2 ohms
Velocity of propagation - 655 ft/μ sec.
Lengths of cable used - 289.7 feet and 951.4 feet
RG-63/U Medium size low-capacitance air-spaced-dielectric cable.

Inner conductor - 1/22 AWG copperweld
Dielectric material - air and polyethylene
Shielding braid - copper
Protective covering - vinyl
Nominal diameter of dielectric - 0.285 in.
Nominal outside diameter - 0.405 in.
Maximum operating voltage rms - 1000 volts
Nominal capacitance - 10 μf/ft
Nominal impedance - 125 ohms

Velocity of propagation - 311.5 ft/μ sec.
Length of cable used - 337.8 feet

The photographs of the oscilloscope traces are shown in figures 11 to 16 inclusive. The distances between the successive fault-pips on the trace were measured in terms of the timing-pips on a fully expanded trace and then averaged. The distance to the fault was calculated by one of two methods;

(a) from the velocity of propagation of the wave in the cable and the timing-pip interval.
(b) from the ratio of the distance to the fault to that of a known discontinuity.
The results obtained are tabulated in the table shown below.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Reference</th>
<th>Average Distance to the fault measured in timing-pip</th>
<th>Measured distance to the fault in feet</th>
<th>Actual Distance to the fault in feet</th>
<th>Error in feet</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fig. 15</td>
<td>3.8</td>
<td>278</td>
<td>289.7</td>
<td>-11.7</td>
<td>4.03</td>
</tr>
<tr>
<td>2</td>
<td>Fig. 15</td>
<td>9.1</td>
<td>828</td>
<td>837.8</td>
<td>-9.8</td>
<td>1.17</td>
</tr>
<tr>
<td>3</td>
<td>Fig. 11</td>
<td>13.1</td>
<td>961</td>
<td>951.4</td>
<td>+10.4</td>
<td>1.09</td>
</tr>
<tr>
<td>4</td>
<td>Fig. 12</td>
<td>13.0</td>
<td>954</td>
<td>951.4</td>
<td>+3.4</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>Fig. 13</td>
<td>16.6</td>
<td>1218</td>
<td>1241.1</td>
<td>-23.1</td>
<td>1.85</td>
</tr>
<tr>
<td>6</td>
<td>Fig. 16</td>
<td>17.0</td>
<td>1247</td>
<td>1241.1</td>
<td>+5.9</td>
<td>0.47</td>
</tr>
<tr>
<td>7</td>
<td>---</td>
<td>21.75</td>
<td>1745</td>
<td>1788.2</td>
<td>-43.2</td>
<td>2.41</td>
</tr>
</tbody>
</table>

Sample Calculation

**Method (a)**

\[ d = \frac{N \times v T_0}{2} \]

where \( d \) = distance to the fault in feet
\( N \) = number of timing-pips to the fault
\( v \) = velocity of propagation in feet per microsecond
\( T_0 \) = time interval between timing-pips in microseconds

Consider Trial 3

\[ d = \frac{655}{2} \times (0.224)(13.1) \]

= 961 feet

**Method (b)**

\[ d = \frac{N_1}{N_2} (\ell) \]

where \( N_1 \) = number of timing-pips to the fault
\( N_2 \) = number of timing-pips to the end of the cable
\( \ell \) = length of the cable in feet

Consider Trial 1

\[ d = \frac{3.8}{17} (1241.1) = 278 \text{ feet} \]
IV DISCUSSION

The results obtained on coaxial cable are indeed gratifying. No power cables were available and so the performance of the fault-locator on single-conductor or three-conductor cables could not be tested. The oscillograms, figs. 11 to 16 inclusive, appear to be out of focus because the trace at high sweep speeds is rather dim, particularly for photography, and a time-exposure was necessary. In taking the photographs the time-exposure for the compressed sweep was 6 seconds and 15 seconds for the expanded sweep. At the highest sweep speed the writing speed of the cathode-ray beam is about 3.5 centimeters per microsecond. To make the trace visible at such high sweep speeds external brilliancy control was necessary. It can be seen from the oscillograms that the trace is well behaved since it remained fixed in position and amplitude during the time-exposure. The traces are free from spurious reflections and easily interpreted.

The effects of a 20-ohm series resistor placed at a cable junction are shown in Figs. 14 and 16. The cable junction itself did not produce a noticeable deflection in the trace and so a large impedance discontinuity was placed at a known point to study its effect on the surge phenomena. It will be noted that the resistor attenuates the traveling surge very rapidly and that its position on the trace aids in determining the distance to the fault.
The high-pass filter or differentiating circuit (7) in Fig. 6 plays a large role in determining the wave shape appearing on the trace and the accuracy of the measurement. The wave produced at the fault is a square wave exponentially attenuated whose period is $\frac{4d}{V}$. Fig. 4a shows the square wave generated by the discharge of a 269.7-foot section of cable when the condenser (19) (See Fig. 6) in the high-pass filter circuit (7) is 150 μfd and resistor (10) is removed. Fig. 15 is the discharge of the same cable but the condenser (19) was reduced to 16 μfd to differentiate the square wave. A capacitor acts like a short circuit at the first instant, but finally, if the wave is sufficiently long the capacitor becomes fully charged and thereafter acts like an open circuit. Resistor (10) should be kept low so that the amplitude of the fault-surges appearing on the Y2 trace are large. For a large fault-surge the leading edge is steep and the beginning of the wave is more accurately determined. For precise measurement between the fault-pips it is important that the toe of the pulse be accurately determined. Fig. 16 is a special case where an a.c. breakdown voltage was applied to the cable and the high-pass filter (7) in Fig. 6 was improperly proportioned. When resistor (10) was removed from circuit (7) the triggering impulse was exceedingly large. The triggering unit was initiating the horizontal sweep on both the positive and negative fault-surges. There are two traces superimposed upon one another, one trace resulting from a flash-over of
the fault on the positive half-cycle of the sine wave and the other on the negative half-cycle. When the 5000 ohm resistor (10) was replaced, the a.c. breakdown voltage gave the same trace as the d.c. breakdown voltage. If the circuit (7) is correctly proportioned the trace is the same for either a.c. or d.c. breakdown voltage.

In the experiments conducted the fault was assimilated either by driving a nail through the armour until it nearly touched the centre conductor or by placing a spark-gap at the cable junction and applying a high voltage to generate an arc. A constant visual trace on the oscilloscope was maintained by repetitively causing the fault to flash over. After considerable amount of experimenting it was concluded that the most effective means of coupling the high-voltage power pack to the cable was through a high value (150,000 ohms) non-inductive series resistor. This current limiting resistor (20)(see Fig. 6) together with the capacity of the cable, the fault breakdown voltage, and the applied voltage determine the repetition rate of the arc. The repetition rate for a large 60 cycle a.c. applied voltage was greater than 120 cycles for short lengths of cable since the cable could be re-charged several times in half a cycle. The magnitude of the resistor (20) was maintained at a high value to limit the supply current to the order of 10 milliamperes so that the fault will not conduct continuously once it has flashed over. For an applied voltage of 200 volts, it was found that with a resistor (20) of 150,000 ohms the sparking
at the fault appeared to be periodic (about 125 sparks per second) and the trace on the oscilloscope was stationary and very clear. With a resistor (20) of 25,000 ohms the sparking at the fault was rapid and erratic (about 250 sparks per second) and the trace was stationary but slightly blurred.

The distance to the fault may be determined by either method (a) or method (b) as outlined previously. Assuming that the velocity of propagation along the cable remains constant, the accuracy with which the fault is located depends primarily upon the steepness of the wave front appearing on the trace. The rise time of the leading edge of the impulse can be improved by choosing the parameters in the high-pass filter (7) such that the fault-pips appearing on \( Y_2 \) trace are large in amplitude. As the pulse travels along the cable its leading edge is flattened due to attenuation and distortion causing the pulse to appear delayed. For accurate results it is important that all measurements be made to the toe of the pulse.

This method of locating faults was intended primarily for high-impedance faults. The complete burning-down of the fault is unnecessary and undesirable. The arc generated at the fault provides the necessary surge and also reduces the fault-impedance to a very low value so that a good reflection is obtained from the fault. From the oscillograms it is seen that the arc conducts strongly for a period about six times the one-way transmission time of the longest length of unfaulted cable. The fault impedance during the arcing period is low. This is verified by the reversal in
polarity of every consecutive echo and by the absences of spurious reflections from beyond the fault. These facts are borne out very clearly in Fig. 12. It is not until the arc begins to fade that spurious reflections from beyond the fault appear on the trace. Since the arcing period varies directly with the length of the cable and is of sufficient duration to reflect several echoes nothing is gained by using an external source of current to maintain the arc conducting for a longer period. The energy stored within the cable before the discharge takes place is sufficient to locate the fault.

This fault-locator can easily be used to locate medium and low-impedance faults simply by placing the fault-locator at one end and repetitively discharging a large condenser into the other end of the cable. The repetition rate of the discharge need not be periodic since the triggering unit will initiate the horizontal sweep from the first negative impulse that arrives at the monitoring end. The repetition rate should be sufficiently high to give a clear visual trace on the oscilloscope. The fault-locator can also be used as an echo-ranger to "sound-out" the impedance discontinuities by placing the equipment at one end of the cable and a spark-gap at the other end.
A fault-locator has been developed for locating high-impedance faults in power cables by using the fault-generated surge. The results obtained in the laboratory experiments are highly satisfactory. It is regretted that no power cables were available to test the fault-locator under adverse conditions. However, there is every reason to believe that its performance in field will be just as effective as it is in the laboratory. The equipment is simple, rugged, portable, inexpensive and results are readily available and easily interpreted.

The accuracy and the effective range of this method of locating faults depends greatly on the type of oscilloscope that is available and on the distortion of the wave in the cable. For accurate measurement it is important that the horizontal sweep be highly expandible. The average accuracy obtained in the experiments conducted is within 1.3%. Due to attenuation and distortion particularly of the high frequency components, the effective range is limited to about 10 miles.

This fault-locator can be used to locate both transient and permanent faults. For transient faults the equipment must be coupled continuously to the cable and the transient disturbance photographed. For high-impedance permanent faults the voltage required to cause the fault to flash over can be either a.c. or d.c. The cable is coupled
to the high-voltage power pack by means of a high value non-inductive series resistor. The arc generated at the fault provides the surge necessary to locate the fault and also reduces the fault impedance to a very low value so that a good reflection is obtained. The length of time during which the arc conducts strongly is of sufficient duration to obtain several clear reflections so that no external source of current is required to maintain the arc. The trace is free from spurious reflections from beyond the fault until the arc begins to fade. The arc begins to fade after about the third reflection and the trace begins to show spurious reflections. The fault-pips are equally spaced along the trace and alternate consecutively in polarity. The sweep can be compressed to examine the trace in its entirety or expanded to examine any portion in detail. A constant visual trace on the oscilloscope was maintained by causing the fault to flash over repetitively.

This fault-locator can be used for locating medium and low-impedance faults by placing it at one end of the cable and repetitively discharging a large condenser into the other. This equipment can be used to study switching transients, and measure velocity of propagation, attenuation, and distortion of travelling waves in cables. The surges can be generated by an external source or a spark-gap placed at the end of the cable. If the timing-pip interval is increased, the fault-
locator can also be used for locating faults on overhead transmission lines.

The observed voltage wave (See Fig. 4a) and the theoretical calculated voltage wave (Fig. 4) are very similar showing that the mathematical approximations made in the theoretical calculations are justified. Other phases of the theory have also been verified.
Fig. 10. Photograph of the fault-locator—
Timing-pip generator, Cossor model 339
double-beam oscilloscope, and the triggering
and trace-brightening unit.

(One-tenth full size)
Fig. 6. Block diagram showing the components of the fault-locator

U.B.C. April 18, 1951
TRIGGERING AND TRACE-BRIGHTENING CIRCUIT

Fig. 8. Schematic circuit diagram of the triggering and trace-brightening circuit

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April 18, 1951
TIMING-PIP GENERATOR

Fig. 9. Schematic circuit diagram of the timing-pip generator

U.B.C.
April 18, 1951
Fig. 11. Oscillogram of a fault at the far end of a 951-foot section of RG/8U coaxial cable.

Top - compressed trace

Bottom - expanded trace (the timing-pip interval is 0.224 microseconds)
Fig. 12. Oscillogram of a fault located at 951.4 feet in a 1788.2-foot section of coaxial cable.

Top - compressed trace

Bottom - expanded trace (the timing-pip interval is 0.224 microseconds)
Fig. 13. Oscillogram of a fault of the far end of a 1247.1-foot section of coaxial line.

Top - compressed trace

Bottom - expanded trace (the timing-pip interval is 0.224 microseconds)
Fig. 14. Oscillogram of a fault at the far end of a 1241.1-foot section of coaxial cable and a discontinuity (20 ohms series resistor) at 289.7 feet
Fig. 15. Oscillogram of a fault located at 289.7 feet in a 1241.1-foot section of coaxial cable. This is an expand trace showing only the first two wave forms. The timing-pip interval is 0.224 microseconds.
Abnormal Trace

Fig. 16. Oscillogram of a fault at the far end of a 1,241.1-foot section of coaxial cable and a discontinuity at 289.7 feet. The breakdown voltage used was 60 cycle a.c. The timing-pip interval is 0.224 microseconds.


