PB275815

RI 8257

Bureau of Mines Report of Investigations/1977

AC Impedance Measurements Used To Locate Faults in Mining Power Cables

UNITED STATES DEPARTMENT OF THE INTERIOR

BIBLIOGRAPHIC DATA SHEET	1. Report No. BuMines RI 8257	2.	3. Recipient's Accession No.

4. Title and Subtitle

A.C. Impedance Measurements Used to Locate Faults in Mining Power Cables

5. Report Date: 1977

6. Performing Organization Code

7. Author(s)

Richard Hammer and George J. Conroy

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Pittsburgh Mining and Safety Research Center
Bureau of Mines, USDI
4800 Forbes Avenue
Pittsburgh, PA 15213

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Agency Name and Address

Bureau of Mines, USDI
2401 E Street, NW
Washington, DC 20241

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstracts

Various a.c. methods which can localize faults in portable trailing cables and other cables are considered. They include the Murray Loop, capacitance value measurement, inductance measurement, phase comparison recordings, and standing wave measurement. Judgements regarding suitability rank of the various methods were not attempted; however, the Murray Loop method proved to be a feasible and easily implemented method for locating certain high resistance short circuits.

17. Key Words and Document Analysis. 17a. Descriptors

Electrical power, trailing cables, fault locating

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Distribution Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited by NTIS.	UNCLASSIFIED	23
	20. Security Class (This Page)	22. Price
	UNCLASSIFIED	A02-A01

FORM NTIS-35(10-70)

US COMM-DC 40329-P71

INSTRUCTIONS FOR COMPLETING FORM NTIS-35 (10-70) (Bibliographic Data Sheet based on COSATI Guidelines to Format Standards for Scientific and Technical Reports Prepared by or for the Federal Government, PB-180 600).

1. **Report Number.** Each report shall carry a unique alphanumeric designation. Select one of the following types: (a) alphanumeric designation provided by the sponsoring agency, e.g., FAA-RD-68-09; or, if none has been assigned, (b) alphanumeric designation established by the performing organization e.g., FASEB-NS-87; or, if none has been established, (c) alphanumeric designation derived from contract or grant number, e.g., PH-43-64-932-4.

2. Leave blank.

3. **Recipient's Accession Number.** Reserved for use by each report recipient.

4. **Title and Subtitle.** Title should indicate clearly and briefly the subject coverage of the report, and be displayed prominently. Set subtitle, if used, in smaller type or otherwise subordinate it to main title. When a report is prepared in more than one volume, repeat the primary title, add volume number and include subtitle for the specific volume.

5. **Report Date.** Each report shall carry a date indicating at least month and year. Indicate the basis on which it was selected (e.g., date of issue, date of approval, date of preparation.

6. **Performing Organization Code.** Leave blank.

7. **Author(s).** Give name(s) in conventional order (e.g., John R. Doe, or J.Robert Doe). List author's affiliation if it differs from the performing organization.

8. **Performing Organization Report Number.** Insert if performing organization wishes to assign this number.

9. **Performing Organization Name and Address.** Give name, street, city, state, and zip code. List no more than two levels of an organizational hierarchy. Display the name of the organization exactly as it should appear in Government indexes such as USGRDR-I.

10. **Project/Task/Work Unit Number.** Use the project, task and work unit numbers under which the report was prepared.

11. **Contract/Grant Number.** Insert contract or grant number under which report was prepared.

12. **Sponsoring Agency Name and Address.** Include zip code.

13. **Type of Report and Period Covered.** Indicate interim, final, etc., and, if applicable, dates covered.

14. **Sponsoring Agency Code.** Leave blank.

15. **Supplementary Notes.** Enter information not included elsewhere but useful, such as: Prepared in cooperation with . . . Translation of . . . Presented at conference of . . . To be published in . . . Supersedes . . . Supplements . . .

16. **Abstract.** Include a brief (200 words or less) factual summary of the most significant information contained in the report. If the report contains a significant bibliography or literature survey, mention it here.

17. **Key Words and Document Analysis. (a). Descriptors.** Select from the Thesaurus of Engineering and Scientific Terms the proper authorized terms that identify the major concept of the research and are sufficiently specific and precise to be used as index entries for cataloging.
    (b). Identifiers and Open-Ended Terms. Use identifiers for project names, code names, equipment designators, etc. Use open-ended terms written in descriptor form for those subjects for which no descriptor exists.
    (c). COSATI Field/Group. Field and Group assignments are to be taken from the 1965 COSATI Subject Category List. Since the majority of documents are multidisciplinary in nature, the primary Field/Group assignment(s) will be the specific discipline, area of human endeavor, or type of physical object. The application(s) will be cross-referenced with secondary Field/Group assignments that will follow the primary posting(s).

18. **Distribution Statement.** Denote releasability to the public or limitation for reasons other than security for example "Release unlimited". Cite any availability to the public, with address and price.

19 & 20. **Security Classification.** Do not submit classified reports to the National Technical Information Service.

21. **Number of Pages.** Insert the total number of pages, including this one and unnumbered pages, but excluding distribution list, if any.

22. **Price.** Insert the price set by the National Technical Information Service or the Government Printing Office, if known.

BuMines RI 8257

Report of Investigations 8257

AC Impedance Measurements Used To Locate Faults in Mining Power Cables

By Richard Hammer and George J. Conroy

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES

This publication has been cataloged as follows:

Hammer, Richard

AC impedance measurements used to locate faults in mining power cables / by Richard Hammer and George J. Conroy. [Washington] : U.S. Dept. of the Interior, Bureau of Mines, 1977.

19 p. : ill., diagrams ; 27 cm. (Report of investigations - Bureau of Mines ; 8257)

Bibliography: p. 17-19.

1. Electric cables - Fault location. 2. Mining machinery - Electric equipment. 3. Electricity in mining. I. Conroy, George J., joint author. II. United States. Bureau of Mines. III. Title. IV. Series: United States. Bureau of Mines. Report of investigations - Bureau of Mines ; 8257.

TN23.U7 no. 8257 622.06173

U.S. Dept. of the Int. Library

CONTENTS

ILLUSTRATIONS

TABLES

AC IMPEDANCE MEASUREMENTS USED TO LOCATE FAULTS IN MINING POWER CABLES

by

Richard Hammer[1] and George J. Conroy[2]

ABSTRACT

Various alternating current (ac) methods can localize faults in mining power cables. Several methods considered by the Bureau of Mines in this report are the Murray loop for short circuits, wherein a bridge provides proportional distance to the fault; capacitance measurements for open conductors; inductance measurements for shorted conductors; phase comparison, high speed recordings of voltage and current in the faulted state are compared with normal voltage and current with the difference being a function of impedance change and impedance change being a function of fault location; and standing wave measurements, detecting the resonance of the length of cable to a fault (either short or open). Portable capacitance bridges are presently available for the second method, and the fourth method is well developed for use on large power distribution systems.

Because it utilizes pulses rather than ac, the time domain reflectometer (TDR) method of fault locating was not included in this investigation. However, a comparative evaluation between this versatile method and the Murray loop might prove advantageous in locating high resistance faults.

INTRODUCTION

Information was drawn from a literature search on fault location. Of the 32 papers listed in the bibliography, 12 papers had direct relevance to ac methods of fault location.

The following hardware tests were made:

1. The inductance of a shorted wire and capacitance of an open wire were measured under various conditions. The results show some unexplained trends, but were reproducible and linear with distance.

[1] Electrical engineer, formerly with Pittsburgh Mining and Safety Research Center, Industrial Hazards and Communications, Bureau of Mines, Pittsburgh, Pa.

[2] Supervisory electrical engineer, Pittsburgh Mining and Safety Research Center, Industrial Hazards and Communications, Bureau of Mines, Pittsburgh, Pa.

2. An ac Murray loop fault locator was tested under various conditions. All fault distances were accurate within ±18 percent; most results were within ±7 percent. Here, also, the errors exhibit unexplained trends.

3. Impedance bridges were tested. The Hewlett-Packard[3] vector impedance meter was found unsuitable for impedance measurements on cables. An Anderson bridge, for measuring inductive reactance, was constructed and tested. It worked, but it was not used for making cable measurements because the General Radio impedance bridge proved to be the more efficient.

DISCUSSION AND RESULTS

AC Murray Loop

The Murray loop is an adaptation of the Wheatstone bridge. A simple Wheatstone bridge is shown in figure 1.

In the dc case, when the detector is nulled it can be equated as

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}.$$

In the ac case, the battery is replaced with an ac source and resistors replaced with impedances.

Now at null you have

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}, \tag{1}$$

where $Z = R + jx$,

$z = R + j2\pi fL$,

f is frequency in Hz,

and L is conductor inductance in henrys.

Since impedance is complex, having two components, two separate conditions must be met to achieve balance. Substituting the complex expressions for the Z's in equation 1 yields

$$\frac{Z_1}{Z_2} = \frac{R_1 + jX_1}{R_2 + jX_2} = \frac{R_3 + jX_3}{R_4 + jX_4} = \frac{Z_3}{Z_4},$$

$$(R_1 + kX_1)(R_4 + jX_4) = (R_3 + jX_3)(R_2 + jX_2),$$

and

$$R_1R_4 + j(R_1X_4 + R_4X_1) - X_1X_4 = R_2R_3 + j(R_3X_2 + R_2X_3) - X_2X_3.$$

[3]Reference to specific trade and company names is made for identification only and does not imply endorsement by the Bureau of Mines.

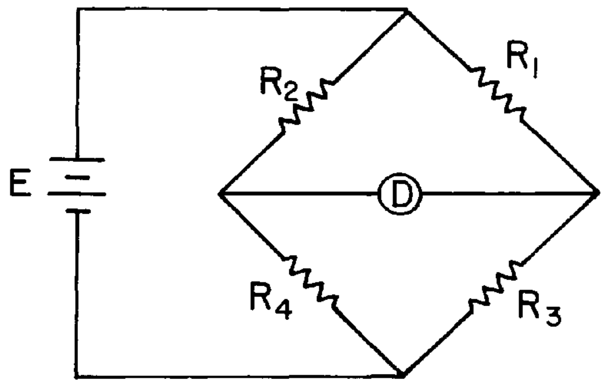

FIGURE 1. - Wheatstone bridge circuit.

Equating first the real components, then the imaginary components, yields equations 2 and 3 as follows:

where $R_1R_4 - X_1X_4 = R_3R_2 - X_2X_3,$ (2)

and $R_1X_4 + R_4X_1 = R_3X_2 + R_2X_3.$ (3)

As a digression, the Murray loop can locate faults of the specific type shown in figure 2.

Phase conductors 1 and 2 must equal each other in resistance and inductance per unit length; that is, they must be the same size wire. The fault resistance can be any magnitude that is significantly less than insulation resistance (less than 10,000 ohms).[4] This is because the fault is connected in series with the power source; it has no impact on the ratios of equation 1.

The faulted cable becomes arms 3 and 4 of the bridge, as shown in figure 3. In this cable, both series resistance and series inductance are linear

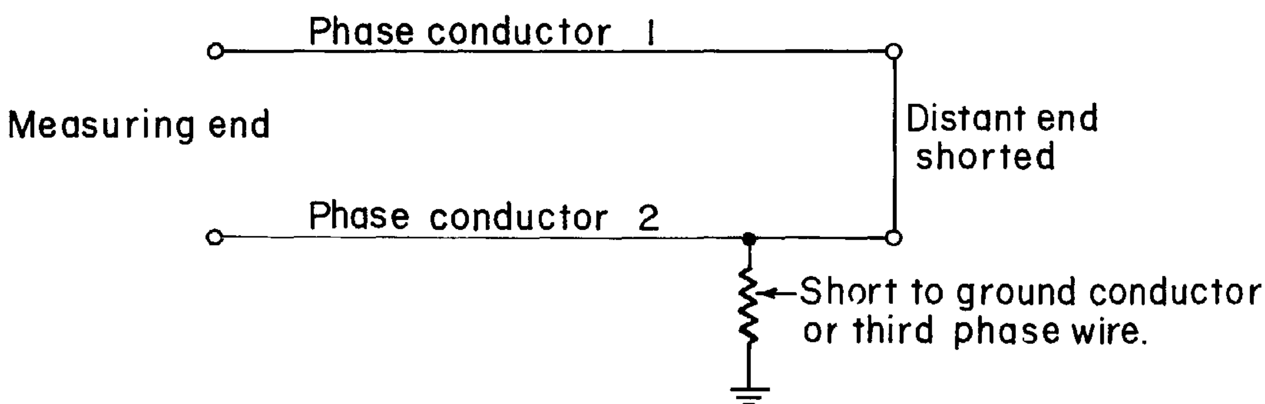

FIGURE 2. - Short circuit fault in mine cable.

[4]See the section headed Murray Loop--Fault Resistance.

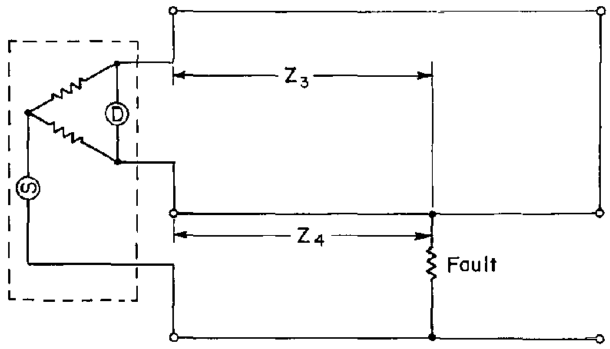

FIGURE 3. - Faulted cable connected to form bridge.

functions of conductor length. This leads to a key assumption regarding the impedances Z_3 and Z_4:

$$\frac{R_3}{R_4} = \frac{L_3}{L_4}. \tag{4}$$

Now this relation allows the use of simple resistances in arms 1 and 2 of the bridge, because if $X_1 = X_2 = 0$, equations 2 and 3 reduce to

$$R_1 R_4 = R_3 R_2,$$

and

$$R_1 X_4 = R_2 X_3,$$

it follows that

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} = \frac{X_3}{X_4} = \frac{L_3}{L_4}. \tag{5}$$

Thus, both the real and imaginary components of equation 1 are balanced with one adjustment--that is, setting the ratio $R_1 : R_2$. This is a great simplification.

Conveniently R_1 and R_2 can be made from one slide wire potentiometer,[5] as in figure 4. At null, the distance x along the slide wire from the tap to end "b" represents the distance along the cable from the fault in conductor 2 to the measuring end (see fig. 2). If null is attained with the tap in the middle ($x=\ell$) then the fault is located exactly at the distance end of the cable. A null point closer to end "a" ($x=\ell$) indicates a fault in the other power conductor.

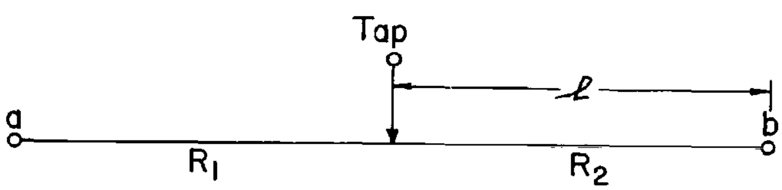

FIGURE 4. - Representation of slide wire potentiometer.

[5] See section headed Impedance of the Bridge Arms--Relative Magnitudes.

The resultant relation is

$$S = \frac{X}{\ell} L,$$

where ℓ = one-half the total length of slide wire,

S = distance to fault along the faulted conductor,

L = cable length,

and X = shortest distance to an end of the slide wire,

then the faulted conductor is the one connected to the end associated with X.

The Murray loop has been used as a dc fault locator (16),[6] but the ac application following from assumption 4 and equation 5 was not referenced in the available literature.

Assumption 4 Examined

The assumption that $\frac{R_3}{R_4} = \frac{L_3}{L_4}$ is not strictly true. Mutual inductance is not proportionately distributed between arms 3 and 4 of the bridge. This affects the ratio L_3:L_4. Note the current flow arrows in the diagram given in figure 5.

By examination

$$\frac{L_3}{L_4} \text{ (ignoring mutual inductance)} \neq \frac{L_3}{L_4} \text{ (actual - incorporating mutual inductance)},$$

and

$$\frac{L_3}{L_4} \text{ (actual)} \neq \frac{\text{length of arm 3}}{\text{length of arm 4}}.$$

In this case, a simple slide wire will not completely achieve a null. To balance the bridge, a reactive element must be inserted in the slide wire side.

While testing the Murray loop, a decade capacitor was connected so that it could parallel either R_1 or R_2 and achieve balance. If it parallels R_1, and achieves balance, then equation 6 would hold exactly; otherwise, a broad null would lead to error in fault location.

[6] Underlined numbers in parentheses refer to items in the bibliography at the end of this report.

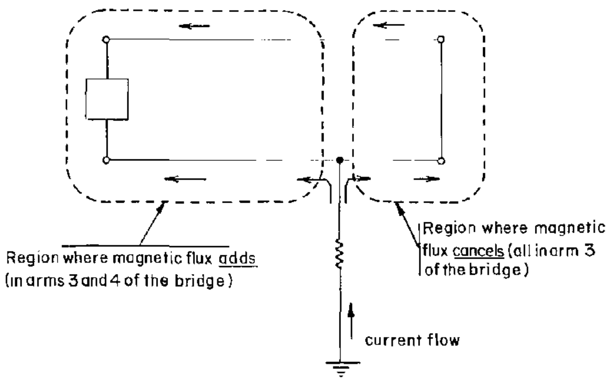

FIGURE 5. - Current flow in bridge circuit.

The experimental data thus obtained do not confirm or refute equation 6. It was impossible to predict which resistor would require the balancing capacitor. The effect of mutual inductance is apparently much less than the effect of noise and such factors as contact resistance that could also affect balance.

The value of capacitance (c) used to achieve balance was therefore ignored because it is of secondary importance, and to include its balancing action with regard to the cable's distributed capacitance would have unnecessarily complicated the equation.

Murray Loop--Fault Resistance

The Murray loop can locate shorts of resistance less than 10,000 ohms. This is because conduction through the insulation may be ignored as long as it is small compared with conduction through the fault; but when fault conductance is small it must be considered parallel to many other conductances through the insulation to ground. In this case the Murray loop does not work unless appropriate corrections are made (12).

If a Murray loop measurement is made on a cable that is free of shorts or other low resistance paths to ground a null will be obtained, and the fault distance calculated will represent the average location of all conductance through the insulation to ground.

The preceding two paragraphs consider only dc conduction. Obviously there is an ac impedance analog. This study does not reach into that area.

Impedance of the Bridge Arms--Relative Magnitudes

In this study R_1 and R_2 were fabricated with a slide wire. A good linear precision wire-wound potentiometer would be easier to use. However, the practicality of a potentiometer may be limited by the following consideration. As stated in references 11 and 18, a Wheatstone bridge works best when its arms have roughly the same resistance. The resistance of the cable loop (arms 3 and 4 of the bridge) is likely to be less than 1 ohm and the slide wire (arms 1 and 2) should be of the same order of magnitude. The slide wire used had about 5 ohms end-to-end. Precision potentiometers of less than 50 ohms were not found listed in any catalogs and were thus not obtainable during the course of the present investigation.

A 1,000-ohm commercially available precision potentiometer was tested in the ac Murray loop fault locator, and a clear null point was obtained. Therefore, it is possible that proper design would permit satisfactory use of this type of component as a viable replacement for the slide wire, even if lower resistance units are not available.

Murray Loop Versus Varley Loop

For trailing cable fault location, the Murray loop is superior to the Varley Loop. The Varley loop method requires two separate readings, the Murray loop requires only one. This difference results from the way the methods are designed. The Murray loop method varies the ratio $R_1:R_2$; this indicates $R_3:R_4$, which in turn indicated fault distance. The Varley loop uses fixed values for R_1 and R_2 and a rheostat connected in series with the cable. The resultant equations have two unknowns; a solution requires one reading in each of two configurations.

Test Procedure

The Murray loop test circuit is shown in figure 6. A short was inserted at one of the lead locations in a 182-ft-long cable. The tap on the 58.2-cm-long slide wire was adjusted to get a minimum signal on the oscilloscope. C and S_1 were adjusted to reduce the signal still further. The slide wire tap was given a final adjustment. Tap distance from node A or B (whichever was closer) was measured. Fault distance in feet was calculated by multiplying tap distance by the factor

$$\text{Ratio} = \frac{L}{\ell} = \frac{182}{0.5\times 58.2} = 6.25\ \frac{\text{ft}}{\text{cm}}.$$

This procedure was repeated 2×3×4×2 times, that is:

Two fault values, 0 ohm, and 47 ohms.

Three fault locations, 60, 100, and 150 feet.

Four frequencies, 100, 1,000 and 10,000 Hz, and dc.

Two configurations,[7] first with the red phase connected to node A, black connected to node B, and second, the reverse of this. Three additional readings were made at a frequency of 100,000 Hz. The test results are given in tables 1-2.

[7] Changing the configuration should not change the results. This serves as a double check on the system's symmetry.

TABLE 1.--Murray loop data: Red phase connected to node A, black phase connected to node B

	Fault distance[1]								
	B cm[2]	Results, 60 ft	Capacitor,[3] µf	A cm[4]	Results, 100 ft	Capacitor,[3] µf	B cm[2]	Results, 150 ft	Capacitor,[3] µf
0 ohm short:									
DC	10.4	65.0		18.7	116.9		23.8	148.8	
100 Hz	10.0	62.5	0	17.9	111.9	2A C	23.4	146.3	2A C
1,000 Hz	9.5	59.4	0C	15.1	94.4	8A	21.6	135.1	2.3A
10,000 Hz	9.8	61.3	0.14A	15.4	96.3	0.03B	24.6	153.8	0.34A
47 ohm short:									
DC	10.2	63.8	0	17.8	111.3		23.6	147.6	
100 Hz	10.2	63.8	0.4A	17.7	110.7	0.4B C	23.1	144.5	2B C
1,000 Hz	9.4	58.8	0.01A	15.1	94.4	5A	21.4	133.8	2A
10,000 Hz	10.0	62.5	0.45A	15.9	99.4	0.8B	24.5	153.2	0.15

[1]Calculate fault distance, tap cm times 6.254.
[2]B cm = tap cm from node B.
[3]Capacitance needed to null:
A indicates capacitor connected between tap and node A.
B indicates capacitor connected between tap and node B.
C indicates broad and vague null with respect to capacitance.
[4]A cm = tap distance in cm along the slide wire from node A.

TABLE 2.--Murray loop data: Red phase connected to node B, black phase connected to node A

	Fault distance[1]								
	A cm[2]	Results, 60 ft	Capacitor,[3] µf	B cm[4]	Results, 100 ft	Capacitor,[3] µf	A cm[2]	Results, 150 ft	Capacitor,[3] µf
0 ohm short:									
DC	10.6	66.3		16.9	105.7		24.6	153.8	
100 Hz	10.8	67.5	C	16.5	103.2		23.6	147.6	0C
1,000 Hz	9.0	56.3	10A	14.5	90.7	10B	19.9	124.5	4A
10,000 Hz	9.0	56.3	0.11B	15.8	98.8	0.34A	23.2	145.1	0.63B
100,000 Hz	7.6	47.5	0.07B	16.9	105.7	0.03B	23.0	143.8	0.11B
47 ohm short:									
DC	10.6	66.3		17.1	106.9		24.6	153.8	
100 Hz	10.5	65.7	0C	16.5	103.2	3A C	24.3	152.0	
1,000 Hz	8.8	55.0	0C	14.4	90.1	10B C	19.8	123.8	3A
10,000 Hz	10.0	62.5	1.6B	15.4	96.3	0.23B	23.6	147.6	1.6B

[1]Calculate fault distance, tap cm times 6.254.
[2]A cm = tap distance in cm along the slide wire from node A.
[3]Capacitance needed to null:
A indicates capacitor connected between tap and node A.
B indicates capacitor connected between tap and node B.
C indicates broad and vague null with respect to capacitance.
[4]B cm = tap cm from node B.

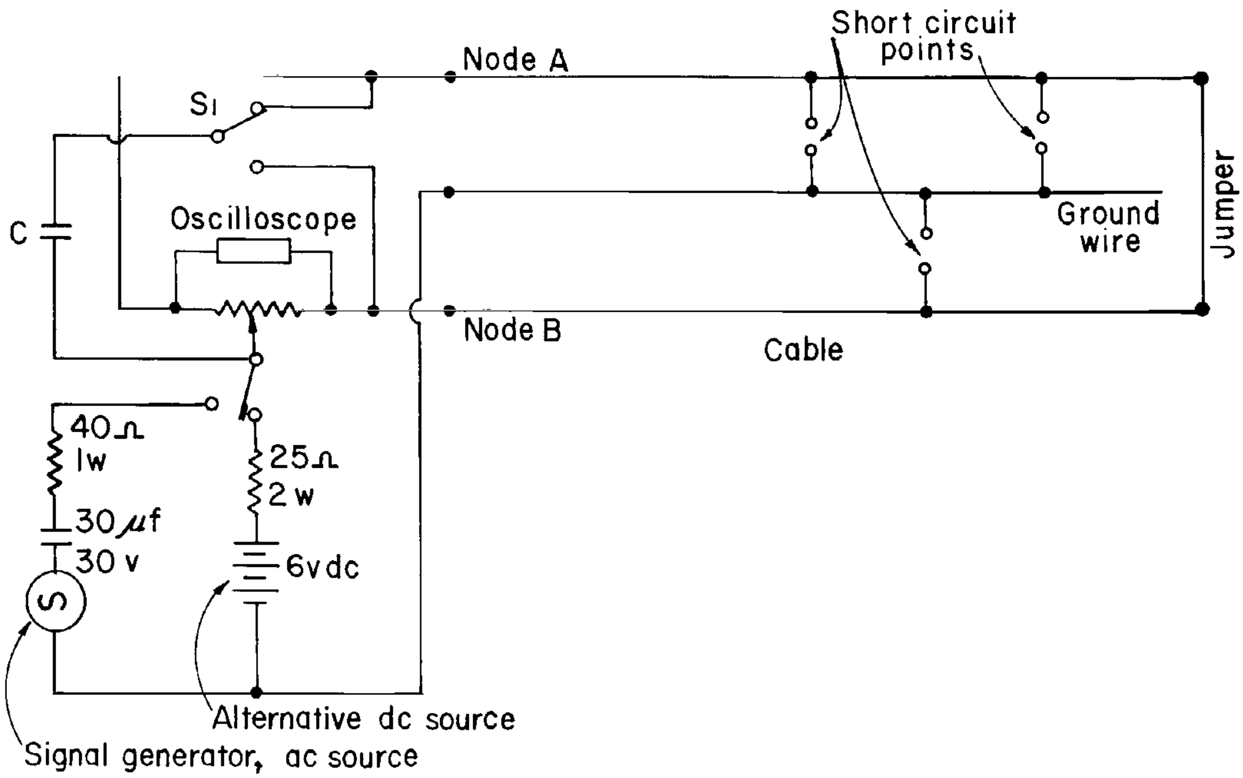

FIGURE 6. - Diagram of Murray loop test circuit.

Null Accuracy of the Murray Loop Data

The null point on the slide wire became sharper and more distinct at high frequencies. The exact location of the null point could be established within ±4 cm at 100 Hz, whereas at 10,000 Hz, it was found to an accuracy of ±0.1 cm. Direct current measurements gave about the same results as did 100 Hz.

Cable Inductance

The inductance of a 2-strand No. 18 lamp cord was measured with a General Radio impedance bridge under a variety of circumstances as follows:

1. At each of seven distances to the short, 10, 40, 80, 125, 200, 230, and 250 feet (±2 feet).

2. With two different sized shorts, 0 and 1 ohm.

3. At two frequencies, 1,000 and 6,000 Hz.

4. In two configurations, with the distant end open and with the distant end shorted.

The total cable length was 250 feet (±2 feet).

The General Radio bridge gave two numbers, R and Q. Inductance was calculated as

$$Q = \frac{X}{R},$$

$$X = QR \text{ ohms},$$

$$\omega L = QR \text{ ohms},$$

and

$$L = \frac{QR}{2\pi f} \text{ henrys}.$$

Impedance was calculated as

$$Z = \sqrt{X^2 + R^2}$$

$$Z = \sqrt{(QR)^2 + R^2},$$

and

$$Z = R\sqrt{Q^2 + 1} \text{ ohms}.$$

Phase angle was calculated as

$$\phi = \arctan Q.$$

Notes on Cable Inductance Data

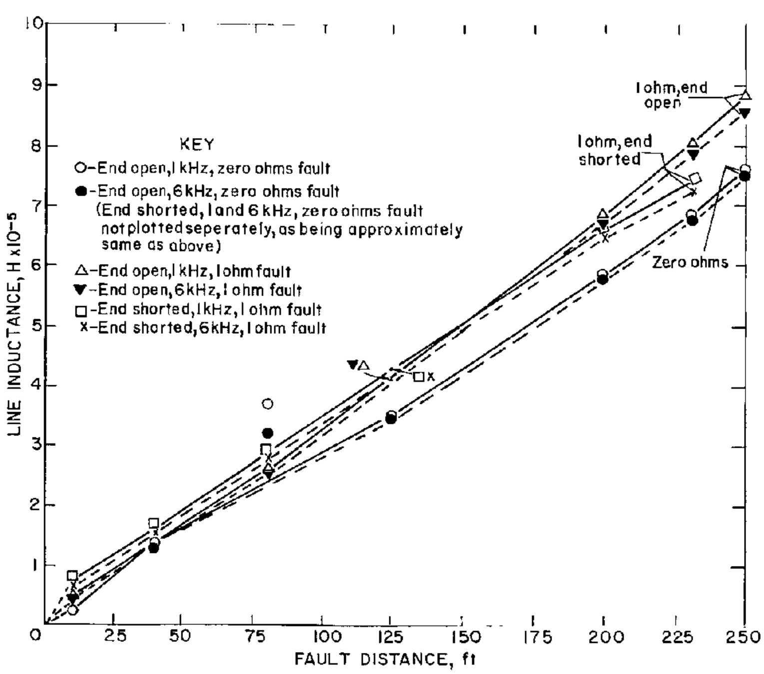

FIGURE 7. - Total inductance versus distance to fault.

Only one graph was made from these data (fig. 7). It displays good linearity, and some unexplained trends, that is, the four straight lines diverge. Inductance is to decrease when frequency increases from 1 to 6 kHz; this may be due to proximity and skin effects (9). No explanation is offered for why L changed significantly as a function of fault resistance. Tabular data is presented in table 3; obviously these data contain enough information for many more studies.

An anomaly occurred at 80 feet for measurements at 1 and 6 kHz, with fault resistance of zero ohm and the cable end open.

TABLE 3.--Inductance of lamp cord data

Short value	Units	Fault distance, feet: 10, 1 kHz	10, 6 kHz	40, 1 kHz	40, 6 kHz	80, 1 kHz	80, 6 kHz	125, 1 kHz	125, 6 kHz
0 ohm:									
Open distant end.......	R.....	0.1400	0.1375	0.5288	0.4516	1.074	0.7963	1.676	1.607
	Q*....	.141	.141	.166	.188	.214	.256	.130	.135
	L.....	.314	.309	1.4	1.35	3.658	3.24	3.47	3.45
	Z.....	.141	.180	.536	.681	1.10	1.46	1.69	2.07
	L/ft..	3.15	3.09	3.5	3.38	4.57	4.06	2.77	2.76
	R/ft..	14.00	13.8	13.22	11.3	13.43	9.95	13.41	12.9
	ϕ**...		40.2		48.4		56.9		39.0
Short distant end......	R.....	.1402	.1375	.5293	.4524	1.077	.7962	1.671	1.605
	Q.....	.140	.141	.166	.187	.214	.256	.130	.135
	L.....	.312	.309	1.4	1.35	3.67	3.24	3.46	3.45
	Z.....	.142	.180	.537	.680	1.10	1.46	1.69	2.07
	ϕ.....		40.2		48.3		56.9		39.0
1 ohm									
Open distant end.......	R.....	1.207	1.200	1.582	1.571	2.128	2.083	2.727	2.593
	Q.....	.027	.026	.054	.054	.077	.079	.095	.099
	L.....	.519	.497	1.36	1.35	2.61	2.62	4.12	4.09
	Z.....	1.21	1.21	1.58	1.65	2.13	2.31	2.74	3.02
	L/ft..	5.19	4.97	3.40	3.38	3.26	3.27	3.30	3.27
	ϕ.....		8.87	3.09	18.0		25.4		30.7
Short distant end......	R.....	.9331	.983	1.293	1.331	1.790	1.801	2.320	2.251
	Q.....	.127	.045	.078	.073	.099	.096	.116	.117
	L.....	1.89	.704	1.61	1.55	2.82	2.75	4.28	4.19
	Z.....	.941	1.02	1.30	1.45	1.80	2.08	2.34	2.75
	ϕ.....		15.1	4.46	23.7		29.9		35.1

Short value	Units	200, 1 kHz	200, 6 kHz	230, 1 kHz	230, 6 kHz	250***, 1 kHz	250***, 6 kHz
0 ohm:							
Open distant end.......	R.....	2.642	2.417	3.044	2.751	3.284	3.006
	Q*....	.139	.150	.142	.155	.145	.158
	L.....	5.84	5.77	6.88	6.79	7.58	7.56
	Z.....	2.67	3.25	3.07	3.757	3.32	4.14
	L/ft..	2.92	2.89	2.99	2.95	3.03	3.02
	R/ft..	13.21	12.1	13.23	12.0	13.14	12.0
	ϕ**...		42.0		42.9		43.5
Short distant end......	R.....	2.641	2.415	3.042	2.750		
	Q.....	.139	.150.	.142	.155		
	L.....	5.84	5.77	6.87	6.78		
	Z.....	2.67	3.25	3.07	3.76		
	ϕ.....		42.0		42.9		
1 ohm:							
Open distant end.......	R.....	3.693	3.389	4.095	3.724	4.303	3.943
	Q.....	.116	.124	.123	.131	.129	.136
	L.....	6.82	6.69	8.02	7.76	8.83	8.53
	Z.....	3.72	4.22	4.13	4.74	4.34	5.09
	L/ft..	3.41	3.34	3.49	3.38	3.53	3.41
	ϕ.....		36.6		38.2		39.2
Short distant end......	R.....	3.047	2.811	3.265	2.955		
	Q.....	.137	.145	.143	.154		
	L.....	6.64	6.49	7.43	7.24		
	Z.....	3.08	3.73	3.30	4.02		
	ϕ.....		41.0		42.0		

Units: L = Henrys x 10^{-5}; L/ft = Henrys x 10^{-7}; R/ft = ohms x 10^{-3}; ϕ = degrees.
*At 6 kH, Q(actual) = 6xQ(reading). These data are Q(reading). See reference 32.
**Not computed for every reading.
***250 feet is the end of the cable. Thus it is meaningless to describe the distant end as open or short.

The one resistor used as a short was measured on the bridge. The results are R = 1.075 ohms and Q = 0.003 ohm.

Actual Versus Measured Inductance

The vector impedance of the cable is expressed in terms of a magnitude and a phase angle. It is not satisfactory to assume that the vector is the sum of just two other vector-series resistance and series inductance; instead we must consider four vectors, including shunt capacitance and shunt leakage.

For example, a vector impedance may be measured and found to be as shown in figure 8A. A mistake occurs when the vertical component is all attributed to inductance, as in figure 8B. The truth is more accurately represented by figure 8C.

The General Radio impedance bridge will make this mistake. Its output is expressed in terms of L and Q (Q=tan ϕ), or in terms of R and Q. These

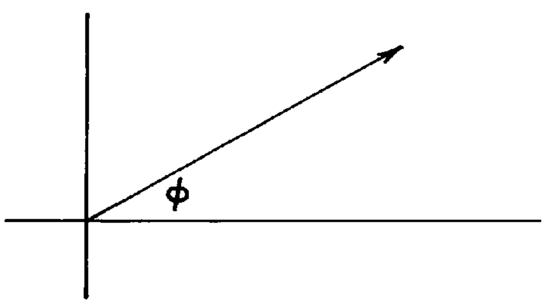

FIGURE 8A. - Vector impedance.

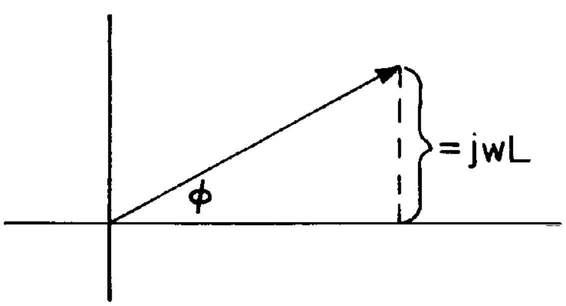

FIGURE 8B. - Reactive component of impedance, neglecting distributed capacitance.

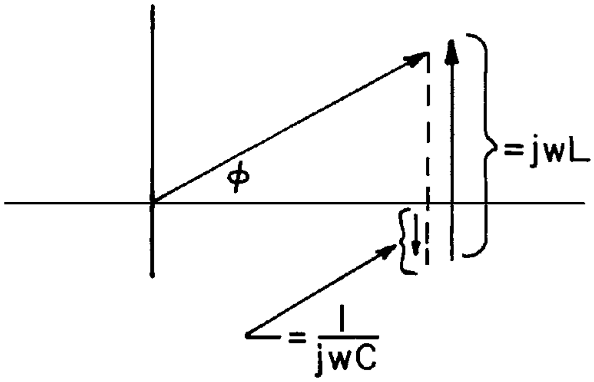

FIGURE 8C. - Reactive components of impedance considering distributed capacitance.

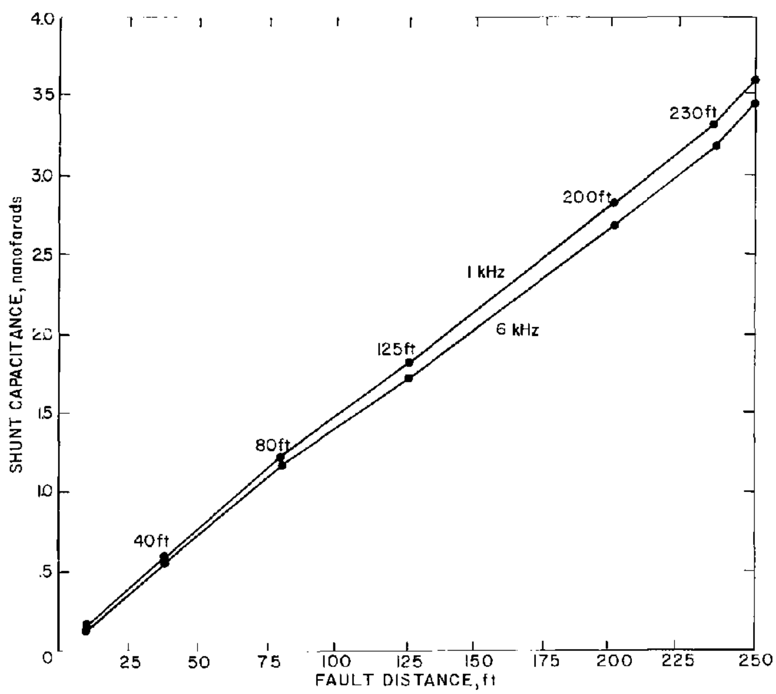

FIGURE 9. - Shunt capacitance versus distance to open circuit fault.

readings of L or R are good only if the inductor measured has no capacitance or leakage. Power cables have capacitance and leakage.

This obviously bears on the experimental measurements of inductance in lamp cord, that were conducted as part of this study. To check, measured values of L were compared with corrected values of L, and the correction factor turned out to be insignificant. In most cases it did not change any of the first three significant digits in the value of L.

Although these particular experimental results were not changed, anyone who intends to measure the "inductance" of a wire should be aware of this hazard. At higher frequencies it would be more important, at the reasonant frequency, for instance $X_C = X_L$. Note that the measurement of capacitance in a cable runs into an analogous problem.

Capacitance to an Open Fault

The capacitance of the No. 18 lamp cord with an open fault was measured with a General Radio impedance bridge under various conditions: 7 fault distances, 2 frequencies, and 2 configurations with distant end open and distant end shorted.

One plot of these data is shown in figure 9 with the tabulated data presented in table 4. Note that the 1- and 6-kHz lines diverge, more capacitance being measured at the lower frequency. This may be due to permittivity changing with frequency (9).

TABLE 4. - Capacitance of lamp cord data

Parameter	Distance to open fault							
	10 feet		40 feet		80 feet		125 feet	
	1 kHz	6 kHz	1 kHz	6 kHz	1 kHz	6 kHz	1 kHz	6 kHz
OPEN DISTANT END								
C..........	1.495	1.409	5.993	5.720	12.44	11.79	18.11	17.34
D..........	.049	.0106	.0422	.0084	.0402	.0083	.0435	.0088
C/ft....:...	1.495	1.409	1.498	1.43	1.555	1.474	1.449	1.387
SHORT DISTANT END								
C..........	1.484	1.405	5.849	5.600	12.09	11.55	18.41	17.36
D..........	.048	.0100	.0457	.0082	.0485	.0088	.0395	.0087

Parameter	Distance to open fault					
	200 feet		230 feet		250 feet	
	1 kHz	6 kHz	1 kHz	6 kHz	1 kHz	6 kHz
OPEN DISTANT END						
C..........	28.43	26.75	33.42	31.89	36.21	34.28
D..........	.049	.0102	.0448	.0088	.0432	.0085
C/ft.......	1.422	1.3388	1.453	1.387	1.45	1.37
SHORT DISTANT END						
C..........	28.84	26.69	33.68	31.97	-	-
D..........	.0453	.01	.0425	.0087	-	-

C = total capacitance, farads $\times 10^{-10}$.
D = dissipation factor (dimensionless).
C/ft = capacitance per foot, farads $\times 10^{-11}$.

Requirements for Other AC Fault Locating Methods

Except for the Murray and Varley loops, every ac method for locating faults requires a predetermined knowledge of some physical properties of either the cable under test or an equivalent cable for comparison. The standing wave method requires konwledge of wave propagation velocity. The phase comparison method requires knowledge of the normal phase angle between voltage and current. The capacitance and inductance methods require knowledge of capacitance or inductance per unit length. Other ac methods which require a "prefault" knowledge of cable properties are described in references 10, 17, 27-28. None of these methods are particularly practical because it is unlikely that mining cable properties will be measured before a fault occurs.

Constraints on Cable End

Most ac methods of fault location require that the distant end of the cable be connected in one particular way. The Murray and Varley loop methods require that the faulted conductor be shorted to another phase conductor at the distant end and that there be no connection (infinite resistance) between the ground conductor and phase wires. The method of measuring inductance requires that the distant end be open. These methods are impractical in situations where the distant end connects to a machine and cannot readily be disconnected.

The standing wave method, on the other hand, does not demand any particular connections at the distant end nor does the method of measuring capacitance to an open end. This latter observation is empirical; it follows from the experience on the lamp cord that was conducted for this study.

Equations for the Inductance and Capacitance of Two-Conductor Wires

The following equations are based on consideration of the parameters as shown in figure 10. The inductance of the two conductors forming the cable loop is given by

$$L = 4 \times 10^{-7} \left[1/4 + \log_n \left(\frac{D}{r} \right) \right] \text{ henrys per meter.}$$

where D = distance between conductor centerlines,

R = radius of conductor.

Source: Page 26 of reference 25.

The capacitance between the two conductors is

$$C = \frac{\pi k}{\log_n \left(\frac{D}{r} \right)} \text{ farads per meter.}$$

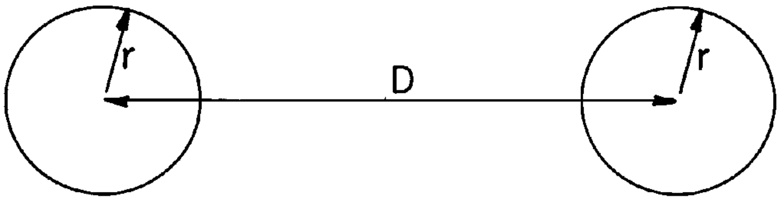

FIGURE 10. - Inductance and capacitance of two-conductor wires.

Where K is permittivity of the insulation for the lamp cord, K is assumed to be approximately 3Ko, where Ko is the permittivity of free space:

$$K_o = 8.85 \times 10^{-12}.$$

To check validity, these equations were used to calculate the inductance and capacitance of the lamp cord. The dimensions of the No. 18 lamp cord, as measured are

$$D = 0.32 \text{ cm and } r = 0.053 \text{ cm}.$$

Then $L = 8.19 \times 10^{-7}$ henrys per meter = 2.5×10^{-7} henrys per foot,

and $C = 46.39 \times 10^{-12}$ farads per meter = 14.1×10^{-12} farads per foot.

These numbers approximate the experimentally measured inductance and capacitance which were about 3.2×10^{-7} henrys per foot and 14×10^{-12} farads per foot, respectively.

CONCLUSIONS

The ac Murray loop method has shown to be a technically feasible approach to trailing cable fault location. To reduce the method to practice, further investigation would be required to accomplish the following objectives:

1. Discover the sources of error in the Murray loop method. With the trends accounted for, it would be possible to attain enough accuracy (±5 percent) for mining applications.

2. Estimate the retail cost of an ac Murray loop fault locator. The cost would determine whether it could displace, or act as a companion to, TDR devices.

3. Test existing ac bridge fault locators that measure the capacitance or inductance of faulted cables and determine whether or not these devices have any advantages over TDR.

4. Research the properties of transmission lines as they relate to fault location. A technique for locating faults may be found in the dependence of capacitance, inductance, and propagation velocity on frequency.

5. Test the standing wave method on mining cables. This will require the use of radio frequencies, but may be serviceable.

BIBLIOGRAPHY

1. Allen, N. A. Fault Localization on Cables. Electr. Rev., v. 99, Oct. 1, 1926, pp. 532-533.

2. Atkins, W. T. J. Automatic Fault Recording. Electrician, v. 112, Apr. 27, 1934, p. 561.

3. Baker, H. M., and J. R. Cressey (assigned to H & B Engineering Corp.). Method and System for Locating Faults in Utility Electrical Power Systems. U.S. Pat. 3,559,176, Jan. 26, 1971.

4. Baker, H. S. Method of Locating Faults in Buried Lead-Covered Cables. Electr. World, v. 82, No. 16, Oct. 20, 1923, pp. 815-816.

5. Biggerstaff, W. F. A Transmission Line and Radiating System Measurement. Inst. Radio Eng., v. VC-9, No. 1, May 1960, pp. 75-79.

6. Bolton, K. G. W. Experience With Modern High Voltage Cable Fault Location Methods. Electr. Rev., v. 187, No. 14, Oct. 2, 1970, pp. 477-480.

7. Electrical Review. New Techniques for HV Fault Location and Recording. V. 184, No. 11, Mar. 14, 1969, pp. 377-378.

8. Ferris, L. P., and R. G. McCurdy. Telephone Circuit Unbalances. Trans. Am. Inst. Electr. Eng., v. 43, Oct. 13-17, 1924, pp. 1331-1347.

9. Figiel, F. J. Fault Locating Experiences at Con Edison. Conf. Record on Underground Distribution, Chicago, Ill., 1966, pp. 303-310.

10. Gale, P. F. A New Digital Cable Fault Location Technique. Electr. Rev., v. 189, Dec. 3, 1971, pp. 811-814.

11. General Radio Company (West Concord, Mass.). Type 1608-A Impedance Bridge. 1969, p. 51.

12. Grover, C. Notes on A.C. Bridge Methods for Localizing Cable Faults. Distribution of Electricity (London), v. 14, April 1942, pp. 532-535.

13. Hague, B. (rev. by). Alternating Current Bridge Methods. Sir Isaac Pitman and Sons, Ltd., London, 5th ed., 1957, 650 pp.

14. Hennebarger, T. C., and P. G. Edwards. Bridge Methods for Locating Resistance Faults on Cable Wires. Bell Syst. Tech. J., 1931, pp. 382-407.

15. Kazansky, V. E., and A. P. Kusnetsov. Fault Locating Test Sets. Energy Internat., v. 8, No. 10, October 1971, pp. 19-21.

16. Lantz, M. J. Simplified Method for Calculating Intermediate Faults on Mutually Coupled Transmission Lines. IEEE Trans. on Power Appar. Syst., v. 75, No. 26, October 1956, pp. 964-967.

17. _____. New Method for Locating Transmission Line Ground Faults. AIEE Trans. on Power Appar. Syst., v. 81, pt. 3, June 1962, pp. 134-136.

18. Maloney, C. A. Locating Cable Faults. IEEE Trans. on Ind. Appl., v. 1A-9A, No. 4, July/August 1973, pp. 380-394.

19. Numakeura, H., and R. Tukamoto. New Method of Fault Localization of Power Cable. Electrotech. J., v. 4, March 1940, pp. 55-58.

20. Owen, D. Alternating Current Measurements. John Wiley & Sons, Inc., New York, 1953, 120 pp.

21. Palmer, W. T., and M. E. Tufnail. A.C. Methods of Fault Localization in Telephone Cables. Post Off. Electr. Eng. J., v. 23, April 1930, pp. 42-54.

22. Patterson, L. Trends in Electrical Power Line Fault Location and Protection. Aust. J. Instrum. Control, April 1972, pp. 28-39.

23. Rangachar, H. V. A Graphical Method for the Determination of Fault Currents. Electrotechnics, No. 24, 1952, pp. 99-107.

24. Savage, N. Digital Programs for Calculation of Transmission-Line Impedances. AIEE Trans. on Power Appar. Syst., v. 79, No. 3, February 1961, pp. 1229-1235.

25. Shinozaki, H., and T. Kousumi. Detection of Fault Locations on Power Cables. Electr. Eng. in Japan, v. 88, No. 1, January 1968, pp. 27-33.

26. Stevens, D. R., G. E. Ott, W. C. Pomeroy, and J. R. Tudor. Frequency Modulated Fault Locator for Power Lines. IEEE Trans. on Power Appar. Syst. v. 91, No. 9, 1972, pp. 1760-1768.

27. Stevenson, W. D., Jr. Elements of Power System Analysis. McGraw-Hill Book Co., Inc., New York, 2d ed., 1962, p. 388.

28. Summers, S. D. Effective Resistance and Inductance of 3-Conductor Shipboard Power Cables. Trans. Am. Electr. Eng., v. 67, 1948, pp. 1345-1350.

29. Susuki, A. Locating Faults on Submarine Cable by a Diagramatic Measuring Method. Nippon Electr. Communication Eng., No. 5, March 1937, pp. 37-42.

30. Urmston, J. The Electrical High-Pressure Testing of Cables and the Localization of Faults. Inst. Electr. Eng. J., v. 69, 1931, pp. 983-1003.

31. Vaughan, W. C. Transmission-Line Calculations. Wireless Eng., v. 24, November 1947, pp. 314-322.

32. Zelikin, B. D. A Method for Detection of Sustained Earth-Faults in Rural Overhead Lines Protected by Peterson Coils. Inst. Electr. Eng., J., v. 95, October 1948, pp. 617-619.

☆U.S. GOVERNMENT PRINTING OFFICE: 1977-703-001/9

INT.-BU.OF MINES,PGH.,PA. 22626