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MAINTENANCE TESTING OF NAVY UNDERGROUND HIGH VOLTAGE CABLES.(U)

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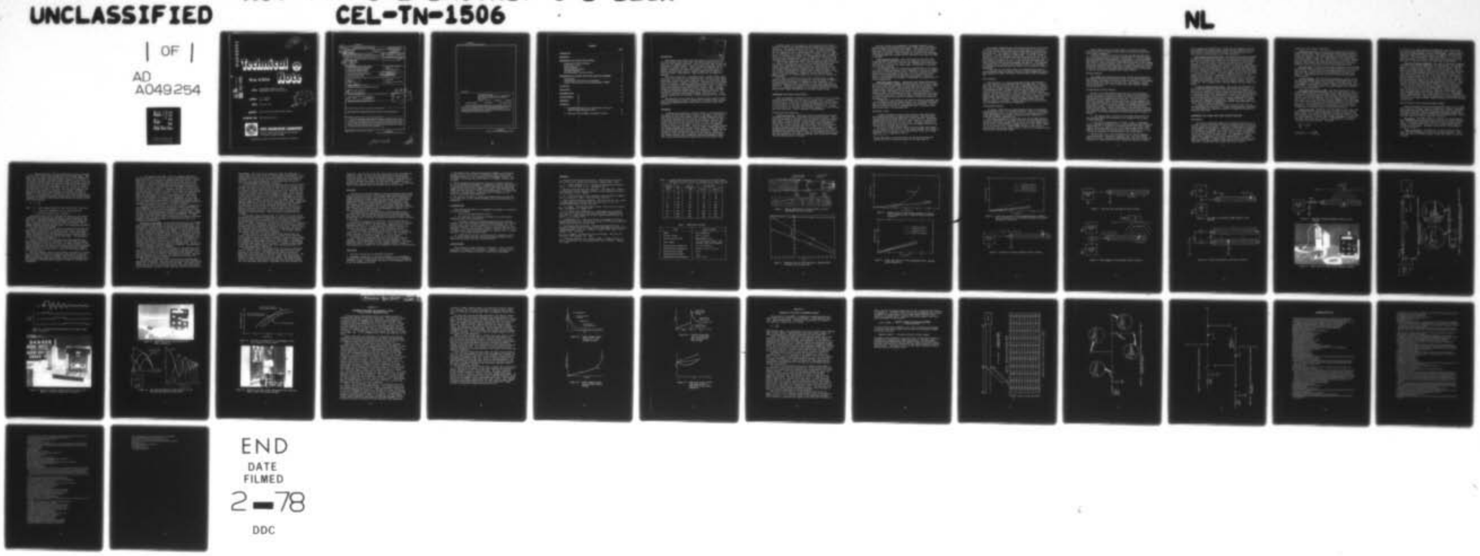

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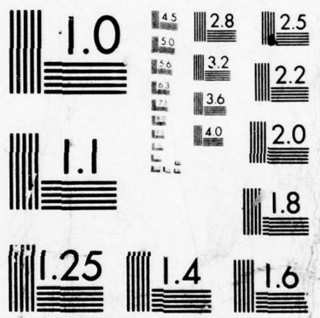

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Technical Note

TN no. N-1506

title: MAINTENANCE TESTING OF NAVY UNDERGROUND HIGH VOLTAGE CABLES

author: J. L. Brooks
G. B. Beck

date: November 1977

sponsor: Naval Facilities Engineering Command

program nos: YF53.534.006.01.036

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CEL-TN-1506 (14)	2. GOVT ACCESSION NO. DN587020	3. RECIPIENT'S CATALOG NUMBER Rept.
4. TITLE (and Subtitle) (6) MAINTENANCE TESTING OF NAVY UNDERGROUND HIGH VOLTAGE CABLES.		5. TYPE OF REPORT & PERIOD COVERED (9) Final Jul 1974 - Sep 1976
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) J. L. Brooks and G. B. Beck		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS CIVIL ENGINEERING LABORATORY Naval Construction Battalion Center Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62760N; YF53.534.006.01.036
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Facilities Engineering Command Alexandria, Virginia 22332		12. REPORT DATE (11) November 1977
		13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 36p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distirubtion unlimited.

(16) F53534

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(17) YF53534006

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

High voltage cables, underground cables, hi-pot tests, fault location, insulation tests.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Methods of testing high voltage underground cable were investigated in order to find an alternative to the DC high-potential (hi-pot) test for cable maintenance testing. The search for such a method proved fruitless, however. The problems of using the DC hi-pot test are discussed, and a recommended procedure of testing is presented. In addition, a new method of locating cable faults is described and recommended.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391 111 .

Library Card

Civil Engineering Laboratory
MAINTENANCE TESTING OF NAVY UNDERGROUND HIGH VOLTAGE CABLES (Final), by J. L. Brooks and G. B. Beck
TN-1506 39 pp illus November 1977 Unclassified

1. High voltage cables 2. Cable testing I. YF53.534.006.01.036

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INTRODUCTION

Underground high voltage electrical cables (5 to 15 kV), an integral part of Naval shore facilities, distribute necessary electrical power for fleet support operations. Most of the time, they do this with a minimum of trouble; however, as with all physical systems, cables are subject to occasional failure. These failures are sometimes due to improper installation of cables and splices or can be the result of gradual insulation deterioration, possibly aggravated by physical or electrical abuse. Unfortunately, these failures are invariably unexpected.

When power cables fail, a prolonged outage, usually results, causing a loss in work time for the using activity. For Naval fleet support operations, an electrical power outage may result in a particular activity's being unable to fulfill its mission. One solution to this problem would be to provide a redundant distribution system so that if any part fails, an alternate cable is immediately available. This, of course, is financially infeasible except for the most critical loads. Instead, preventive maintenance programs must be developed to reduce the number of inservice electrical power outages due to insulation failure. In addition to preventive maintenance programs, rapid and accurate fault-location methods must be developed to reduce the time and cost of cable repair.

The objective of this study was to develop state-of-the-art acceptance and maintenance testing techniques and to evaluate fault-location devices for underground high voltage cables installed at Naval shore facilities.

BACKGROUND

In modern Naval shipyards, electrical energy is used extensively in the repair and servicing of Naval vessels of all types. Electricity is distributed to the piers by means of high voltage underground cables. Most of the operations are non critical, and power failures are more of an expensive nuisance than a serious mission problem. However, some ships' electrical service facilities are so critical that any power outage in excess of a few minutes is cause for alarm, and immediate corrective action must be taken. These facilities are normally provided with backup equipment such as dual service cables, standby generators, and automatic switch gear; however, a test procedure is needed that may be used to predict the service life of the facilities. Cables, in particular, offer the most frustration in that they are inaccessible, fail without warning, and are expensive and time-consuming to repair. This is true of the noncritical loads as well as the critical loads.

The most common test procedure for cable testing is the DC high potential (hi-pot) test, which measures the leakage current of the cable insulation. The appropriateness of this test as a cable maintenance test has been the subject of debate for years: many users claim that the test damages the cable, and therefore they refuse to use it; others use it occasionally, but without confidence. Clearly, what is needed is either an alternative test method or a recommended procedure for using the hi-pot test equipment where it may be applicable. In addition, an improved method is needed for finding the fault after it has occurred.

High voltage underground cable rated over 600 volts must be shielded [1]. Many of the cables now in service were manufactured with lead sheaths and oil-impregnated paper insulation. A more popular high voltage cable makes use of polyethylene as the insulation with a covering of semiconducting sheath. A manufacturer's specification on typical, modern, underground distribution cable is shown in Figure 1. This type of cable (two-conductor, concentric, neutral construction) is generally accepted as standard design and is available for nominal 5-to 35-kV systems.

Such cable is suitable for direct burial, which allows a higher ampacity rating than duct installations do. The vulcanized or chemically cross-linked polyethylene, a comparatively new insulation, is a thermosetting material that will not melt or drip under high overload conditions. Although used extensively for primary underground distribution, it is somewhat more expensive at the present state-of-the-art than high molecular wieght polyethylene for the same voltage rating.

UNDERGROUND HIGH VOLTAGE CABLE TESTING

Many test methods to determine a cable's suitability for its intended use have been developed over the years for various uses: to detect insulation flaws in new cable, to detect shipping or installation damage, to detect defects in splicing or termination workmanship, and to detect any deterioration of the cable system during its useful life. Because of the variety of test methods, the following categories of cable testing have been identified: proof, acceptance, and maintenance.

Conventional Test Techniques

Cable Proof Testing. Cable proof tests are performed by the cable manufacturer as part of an established quality-control program. These tests are performed in the plant, and a certificate of test is available upon demand. In proof testing, an overpontential is impressed on the cable and the results observed. Either a high voltage alternating current (AC) or direct current (DC) can be used. If an AC hi-pot test is used, the results observed can be due to either (a) the leakage current generated between the conductor and the sheath or (b) the radio frequency noise (corona test) produced. If a DC hi-pot test is used, the results observed can be due to either (a) the leakage current or (b) the time required for the cable to discharge itself by internal leakage after the high potential is removed.

The test criteria are documented in published standards of the Insulated Power Cable Engineers Association (IPCEA) and of the National Electrical Manufacturers Association (NEMA). Test methods and limits depend upon the insulating materials used in the construction of the cable and are specified. These standards are revised as the technology in insulating materials advances and are available from either the IPCEA or the NEMA.

Cable Acceptance Testing. After new cables are installed, but before the cable is placed in service, an acceptance test on the cable is performed to insure that it has not been damaged during installation. This test is a DC hi-pot test which, again, is performed in accordance with the IPCEA standards.

A DC acceptance test will reveal gross imperfections of the insulation, such as deep perforations of the insulation of the use of improper materials or practices used in splices. This test is usually an installation contract requirement to guarantee to the user that the cable, splices, and terminations have been properly installed. This test method is used because the equipment is lightweight and portable and the test straightforward.

Cable Maintenance Testing. Underground high voltage cable maintenance testing presently requires disconnecting the cable from the source and load so that the overpotential may be impressed on the cable, using the DC hi-pot test method. This disconnection, which constitutes a planned outage, requires scheduling of the test at a time that will cause the least interference in the affected activity's mission. A planned outage is an inconvenience at best. Some missions are so critical, however, that those in charge of these activities state that there is *never* a time when power may be disconnected to perform a preventive maintenance test.

In addition to the financial loss caused by idling of personnel and loss of production during a planned outage, cost of personnel and equipment to perform such maintenance testing must be considered. Private industry estimates the cost at approximately $400 a circuit per test; most of this cost is for personnel [2].

Reluctance to Test

A common misconception about hi-pot testing is the belief that a good cable may possibily be damaged during testing. This belief persists because the following experience is often reported: maintenance personnel perform DC hi-pot test on a cable, return it to service, and several days or weeks later the cable fails. The usual conclusion is that the cable was good before the test but was damaged during the test because the test voltage was too high.

DC hi-pot testing, properly applied, does NOT damage good insulation or shorten its service life. Such testing, however, will weaken an incipient fault and thus will cause cable failure if the test voltage magnitude is to an appropriate level.*

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*On the other hand, it has been proved that AC hi-pot testing does shorten the life of electrical insulation [3] (see Figure 2).

The probable explanation for cable failure soon after a hi-pot test is that an incipient fault existed in the cable prior to the test but the voltage was not sufficiently high to break down the incipient fault during the test. For comparion, Figure 3 shows the leakage current for two cables - a faulty cable and a sound cable. If the test voltage is limited to 50 kV, the incipient fault may escape detection; but if the test voltage is raised to 60 or 75 kV, the incipient fault will start to break down and eventually arc over. After the fault has broken down, it can be located by fault-locating equipment and repaired. The advantage of breaking down an incipient fault during the test is that personnel are prepared to locate and repair the fault, and no in-service outage is experienced.

It was shown in one 10-year study of 45 manufacturing plants of a large corporation that the periodic testing of cable systems resulted in the elimination of 90% of in-service cable failures of that corporation [4].

Record Keeping

Good records of all hi-pot testing must be kept and consulted to correctly interpret each subsequent test of the same cable. Figures 4 and 5 show the test records of two similar underground cables. Figure 4 shows that the leakage current with this cable increased gradually and in approximately equal increments from the time the cable was installed until the ninth year of service. Figure 5 shows a disproportionate increase from the seventh year test to the ninth year test. Both cables, however, show the same amount of leakage at the end of 9 years of service. These figures demonstrate the need for records of each cable's test history. The cable in Figure 4 should be judged "sound", while the cable in Figure 5 is "unsound". Without the records of previous years, this determination would have been impossible.

Testing Specifications

At present, IPCEA does not provide specifications for maintenance-testing voltage levels or for testing frequency. There is considerable debate regarding correct voltage levels to use for maintenance testing. A new IEEE standard is currently in preparation that should help to establish reasonable guidelines [5].

The latest proposal for voltage test levels by the IEEE Insulated Conductors Committee (ICC) was made in 1973 at a steering group session. The ICC project leaders agreed that the new DC test level formula was to be 70% of the rated system Basic Impulse Insulation Level (BIL), rounded off to the nearest 5 kV. Although IPCEA has not, at this writing, approved these new voltage levels, Table 1 would be the resulting voltage test levels if 70% BIL was adopted.

Class I service would be normal service for noncritical loads. Class II would be for critical loads, where an in-service outage would have serious consequences.

Information from the literature on hi-pot testing indicates that, if it is to be effective, hi-pot must be performed in a well-structured and well-documented testing program. In particular, a rigid and demanding acceptance test of the cable system immediately after installation will uncover a large percentage of potential failures due to poor workmanship in the installation process [4,6]. If acceptance tests are followed by periodic testing at sufficiently high voltages, cables having faulty insulation will be detected during these tests rather than failing while in service (resulting in untimely loss of that service).

Testing Frequency

The optimum test frequency has not been clearly established due to the sparsity of published testing histories, but one user reported that most failures were found in the first 5 years of cable life. The probability of failure after that was very small [4]. This suggest frequent testing during the first 5 years after installation and less frequent testing thereafter.

New Maintenance Testing Concepts

Because of the many problems associated with cable maintenance testing, an extensive literature search covering an international spectrum of journals was pursued in an effort to discover an alternative test method to the conventional DC hi-pot test. In addition to the extensive literature search, several electrical utility companies, two major cable manufacturers, and three major test equipment manufacturers were surveyed to obtain the latest technical reasoning regarding cable maintenance testing. No viable substitute for the conventional DC hi-pot test was found. Several interesting low voltage test procedures were described; however, they were discounted because evidence indicates that modern cross-linked polyethylene insulation may have two modes of failure:

1. The expected mode of failure is the gradual deterioration of the insulation which can be measured by low voltage as well as high voltage techniques.

2. The newly recognized mode of failure is due to a phenomenon called "treeing" which demonstrates an abrupt breakdown under an applied high voltage [4,7]. Treeing is a system of minute cracks whose growth depends on the environment as well as the applied high voltage. This type of failure sheds considerable doubt on the credibility of all low voltage test methods for cable maintenance test effectiveness.

The DC hi-pot test is used universally by the utility companies, cable manufacturers, and private industry alike - all with varying degrees of success. Nothing of significance was found which offered an alternative to conventional DC hi-pot testing for the type of cables used in underground installations. Though very low frequency AC hi-pot testing methods are gaining popularity for testing insulators and rotating machines, this method is not suitable for cables because of the large reactive current caused by the cable capacitance.

Extra Sensitive DC Hi-Pot Tests. One interesting innovation brought to light by the literature search was the description by some Japanese authors of an improved power supply for a conventional DC hi-pot tester [8]. The authors were able to increase the sensitivity of the hi-pot equipment to 0.2 μA, instead of the usual 10 μA, by use of a voltage regulator in the power supply that, in effect, removed the normal voltage fluctuations in the output high voltage DC. Thus, they obtained a move sensitive leakage current reading. Two of these devices were fabricated; the first provided 0 to 25 kV for 6.6-kV cables, and the second provided 0 to 50 kV for 22-kV cables. The units weighed 33 lb each and were used extensively in the field in conjunction with the partial discharge method of fault location. Some 1,500 circuits of 6.6-kV to 77-kV cables of different insulations were tested over a period of years using this equipment with favorable results. The test method, however, is still a hi-pot test, and it appears that hi-potting remains the only viable test method.

In Situ AC Leakage Current Tests. CEL proposed one alternative to the conventional DC hi-pot test by CEL early in the investigation: to monitor the AC leakage current with built-in electronic sensors while the cable was operating at normal voltage and with normal load connected. A feasibility study of this technique was conducted, but the practicality of the method proved to be doubtful [9]. It was found infeasible for practical application because of the stringent requirement of constant load to obtain meaningful measurements. Attempts were made to modify the method to eliminate or minimize the constant load requirement, to no avail; the test method was abandoned.

It appears that no viable alternative to the DC hi-pot test for field maintenance testing exists. To assist Naval personnel responsible for cable maintenance, Appendix A presents a recommended procedure for using the hi-pot test.

UNDERGROUND HIGH VOLTAGE CABLE FAULT-LOCATING TECHNIQUES

Requirements

In the past, underground cable fault locating has been more of an art than a science; but today with better equipment, fault locating can be done rapidly and accurately. Therefore, an investigation of the more modern methods and equipment was conducted in order that an instrument or combination of instruments for fault location could be recommended for use by Naval personnel. The criteria used to select the most appropriate test method and instrument were: (1) independence of cable characteristic impedance, (2) universal application to all types of faults, (3) minimum of operator skill, and (4) speed of operation. To make this selection, all known conventional fault-location techniques applicable to underground high voltage cables were reviewed.

Conventional Fault-Location Techniques

Relaxation Oscillator. The relaxation oscillator fault-location method requires only a current-limited high voltage supply and pulse counter for operation. This method depends on the internal resistance of the power supply and the cable capacitance to form a relaxation oscillation (shown in Figure 6). The frequency of oscillation depends upon the capacitance of the cable, which in turn is a function of the length of cable between the connected end and the fault. This test method has several deficiencies and has never gained popularity.

Burn and Trace. The burn and trace method requires a heavy DC high voltage power supply to break the fault down, then burn it to a virtual short circuit. A current detection instrument makes use of the fact that the sheath current splits in two directions at the fault (see Figure 7). This method also has several deficiencies and has never gained popularity.

Ion Path Pulsing. The ion-path pulsing method is similar to the burn and trace method except that the detection instrument detects the electromagnetic field caused by the ion path at the fault point. The electromagnetic field method is shown in Figure 8 and may be detected at ground level. This method requires two power supplies and, therefore, has never gained popularity.

Time Domain Reflectometer (TDR). The TDR test method is a low voltage method, popular for locating faults in signal circuits but with serious deficiencies when used on power cables. The TDR uses a short, fast pulse to propagate down the cable and reflect back from any discontinuity, such as a low impedance fault (see Figure 9) [10]. However, that portion of the incident pulse reflected depends on the fault impedance rather than on the cable characteristic impedance. For high impedance faults, the reflected protion of the pulse is so small that it becomes lost in the system noise, preventing use of this test method. Consequently, this method also has never gained popularity.

Murray Loop Test. The Murray loop test method is one of the classical bridge-type test methods that work very well on low resistance ground faults. The circuit configuration is shown in Figure 10. The faulty conductor and an equal length of good conductor of the same type are joined together at one end, and a bridge arrangement is set up at the other (test) end, with a battery, a galvanometer, and variable resistances R_a and R_b attached. At balance,

$$\frac{R_a}{R_b} = \frac{L + y}{x}$$

from which $x = 2L \frac{R_b}{R_a + r_b}$

If the fault is a high-resistance-to-ground type, very little current will flow through the bridge in the arrangement shown. In that case, the battery and galvanometer should be interchanged. Readings should be taken with forward and reverse currents to compensate for stray earth potentials. This test method is often used; however, it is a low voltage test method and, therefore, cannot detect the intermittent breakdown type of fault which occurs only under high voltage stress.

Capacitor Discharge (Thumping). The capacitor discharge (thumping) method is by far the most popular fault-location method. The equipment required is bulky and must be mounted in a vehicle; however, the test method is straightforward and simple, as shown in Figure 11. The DC high voltage supply charges up the capacitors until the spark gap breaks over; then the cable charges suddenly to the capacitor voltage. The cable fault breaks down, and all of the stored energy in the capacitor bank discharges through the fault. This occurs with a loud bang and physical jerking of the cable at the location of the fault. Test personnel traversing the length of the cable aboveground can hear the noise and feel the ground tremble when approaching the fault location. Under favorable conditions an experienced "thumper" team can locate a fault within a few feet, which accounts for the popularity of the method.

The major deficiency of the thumper method of fault location is that the process to trace the entire length of a faulted cable is tedious, time-consuming – and therefore, expensive. One thumper manufacturer recommends sampling the surface route every 10 ft. Each sample requires approximately 1 min, so approximately 1-1/2 hr are required to check 1,000 ft of cable. Additional deficiencies include nonapplicability to cables routed under buildings, submarine cables, and vertical building installations.

Digital Universal Fault-Locating Equipment (DUFLE)

These conventional fault-location methods have been in use for many years by public utilities, industry, and the Navy. However, with modern electronics, more sophisticated and portable fault-location techniques have become available. The most promising new technique requires an instrument called the Digital Universal Fault-Locating Equipment (DUFLE), which was selected by CEL for laboratory evaluation.

Description. The DUFLE (Figure 12) consists of a digital measurement instrument and capacitive voltage divider with an interconnecting cable. The measuring instrument contains the logic circuitry, digital display, a voltage-tunable oscillator, and a battery supply with an internal battery charger. Equipment specifications for the DUFLE are presented in Table 2.

Theory of Operation. The DUFLE has two distinct modes of operation: the high voltage mode and the line resonance (LR) mode. Both modes make use of the digital display to give the distance to the fault in yards.

1. High Voltage Mode – The high voltage mode requires a portable, auxiliary, low current, high voltage capacitor discharge supply. This mode is used to locate the high resistance faults or the intermittent faults that only appear when high voltage is applied to the cable. In this mode of operation, the high voltage source is connected to one end of the cable, and the DUFLE is connected through the voltage divider to the other end of the cable (see Figure 13). The voltage is raised on the cable until the fault breaks down; when this occurs, the cable is virtually short circuited at the fault, and the stored energy in each part of the cable begins to dissipate. In so doing, a waveform is generated in the part to which the DUFLE is connected, as shown in Figure 14. This waveform is characteristic of a shorted transmission line, and its properties determine the wave shape. The period τ between crossovers is related to the distance from the fault to the end of the cable by the equation:

$$D = \tau \frac{V}{4}$$

where D = cable length between the fault and the end of the cable

V = velocity of propagation for the cable under test

τ = time period between zero crossovers

The digital logic circuit calculates the distance to the fault D automatically and presents the information in yards digitally on the front panel. The pulse waveform is characteristic of the cable; however, it is initiated by the sudden discharge of energy through the fault, which may cause the first cycle or two to be erratic. To circumvent erroneous readings that may result, two switch positions may be used to double-check the readings.

The first switch position is called the normal position where the measurement of the period τ is delayed by three cycles. The elapsed time is then measured over the next four cycles. This delay avoids slight inaccuracies due to the nonsinusoidal form of the early part of the wave and allows a much more precise measurement. This measuring period is illustrated in Figure 15.

In the second switch position (called the short position) the measurement of the period τ is delayed by one cycle; then the elapsed time is measured for the next two cycles. As shown in Figure 15, the reading obtained with the switch in the short position should be approximately one-half the value obtained in the normal position. Readings taken in the short position serve as a check on the readings taken in the normal position.

Since the operator cannot see the waveform, the check is to insure that the proper waveform is being generated and contains a sufficient number of cycles to calculate a reading. The DC switch position is useful when testing cables with branches (this will be explained later). The capacitance discharge impulse generator (Figure 16) is small and lightweight.

2. Line Resonance (LR) Mode - The line resonance (LR) mode of operation utilizes a built-in low voltage, sine wave oscillator and is useful only for low resistance or open-circuited line faults. A front panel meter is used to measure relatively the voltage output of the oscillator to determine voltage peaks and valleys as the oscillator frequency is varied. The capacitive discharge impulse generator and voltage divider are not used in this mode. The DUFLE is connected to the cable as shown in Figure 17. When the frequency of the oscillator is increased from an initial low value, the voltmeter will vary through peaks and valleys as shown in Figure 18. For a very low resistance fault, the reading will rise to a first maximum at the frequency at which the cable behaves as a quarter-wave transformer. For an open circuit, the voltmeter will decrease to a minimum for the same condition. By measuring the time period of the oscillator frequency when it is tuned to the first peak or valley, the DUFLE automatically calculates and digitally presents the distance to the fault in yards.

In either mode of operation, the correct velocity of propagation of electromagnetic waves for the particular type of cable tested must be set on the DUFLE. The volocity of propagation, a variable, is a function of cable construction and the frequency of the test signal. Figure 19 shows the relationship between velocity of propagation and frequency for three of the most common types of cable construction. In those instances where the type of cable construction is not known, a procedure is given in the instruction manual for determining the velocity of propagation experimentally.

Evaluation of the DUFLE. The principal characteristic of the DUFLE to be verified is the accuracy of the fault-location measurement. The manufacturer's stated accuracy is ±2% over the operational range of 20 to 40,000 yd. The importance of the measurement accuracy becomes apparent when considering the longer cable lengths. To verify the accuracy, a series of laboratory experiments was conducted. Both modes of operation were observed with precise lengths of type SD submarine cable used. This type of cable was selected because of the rigid dimensional tolerance control used in its manufacture. This type of cable demonstrates a precise surge impedance and velocity of propagation. In addition, it features a solid copper sheath so that its coaxial transmission line characteristics may be accurately predicted mathematically. By the use of several samples of different lengths as "standards," the measurement accuracy of the DUFLE could be determined.

In the LR mode, the accuracy of the DUFLE was determined by using open circuit and short circuit line terminations, and then tuning the oscillator for respective maximum and minimum voltage readings. In the high voltage mode, the accuracy was determined by utilizing a spark gap and high voltage source to simulate the intermittent breakover and discharge type of insulation failure.

Two sources of inaccuracies were associated with the DUFLE while operating in the LR mode. The first was the discovery that considerable warmup time is required to stabilize the instrument. This shows up as a phase-velocity drift from the initial setting. The phase velocity must be set according to the type of cable under test prior to fault-location measurements. The drift due to warmup time alone was sufficient to cause a 6% error in fault location. After further investigation, it was observed that most of the drift occurred immediately after turning the instrument on. After an hour the unit had stabilized sufficiently to avoid the drift problem completely, if the proper phase velocity is reset and measurements made within 15 minutes.

The second source of inaccuracy was observed when the fault distance readout for an open-circuited cable was compared to that obtained from the same line short-circuited at the far end. These two readings should be identical; however, they differed by as much as 8%. Apparently this was caused by insufficient isolation between the input circuit and the internal oscillator circuitry that develops the output digital readings. A tuned quarter-wave line acts as an impedance transformer, so that an open-circuited line appears as a short circuit to the DUFLE and a short-circuited line appears as an open circuit to the DUFLE. The extremes of impedance appear to affect the distance readings of the DUFLE. Conversely, when the phase velocity of the line is being measured with the DUFLE, the same error will be present, depending upon whether the line is open-circuited or short-circuited. About all that can be done by the operator to minimize this error is to obtain phase-velocity readings from both the open- and short-circuited line and to average the two readings for the actual tests. This will yield an answer within 4% accuracy.

In the high voltage discharge mode, the source of inaccuracies was determined to be simply the irregularities associated with the initiation of the characteristic pulse generated by the insulation breakdown and the nonsinusoidal form of the early part of the waveform as shown in Figure 14. These irregularities are expected in any kind of arc discharge, and the manufacturer recommends taking 10 readings and averaging them to determine the best estimate of the distance to the fault. This procedure was tried many times on different lengths of the SD submarine cable in the laboratory with surprisingly good results. The averaged readings were always within 5% of the actual distances.

Another difficulty in using the DUFLE became apparent when the theory of operation was considered and was verified in the laboratory. In both modes of operation, erroneous readings are obtained when readings are attempted on cables containing one or more branches. The degree of error depends upon the number of branches, their length in relationship to the main cable length, and their location. A special study was made to determine the expected errors from cables containing branches; the results are summarized in Appendix B.

The DUFLE was taken to the Miramar Naval Air Station in California where it could be used on actual high voltage cables by public works personnel at the station. The DUFLE unit was demonstrated and the operational theory explained to the high voltage test electricians. The DUFLE was left with the electricians for 1 month, when CEL personnel returned to answer questions and review progress. The DUFLE was again left for a period of 2 more months, with the electricians who, during that time, had ample opportunity to experiment with the instrument (see

Figure 20). The reaction of the test electricians to the instrument was favorable; however, no real life cable failures occurred during the field test period. Two additional problems, however, became apparent during the field tests: first, the digital readout is difficult to read in direct sunlight; and second, the instruction book supplied by the manufacturer is not well-written from the user's viewpoint. A simplified, user-oriented handbook would be necessary for use in the field.

DISCUSSION

The search for alternate methods of testing underground high voltage cable has not been fruitful. The in-depth study of monitoring the cable leakage currents with built-in sensors while the cable is operating at normal voltages and currents shows that this concept has limited Naval applications because of the strong dependence of the method on load conditions. Two possible applications are at Naval hospitals, which have redundant electrical power service, and nuclear ship piers, where the cables would be unloaded or very lightly loaded at periodic intervals. Even in these limited applications, the mathematical analysis is, at best, encouraging but not conclusive.

The disturbing fact that polyethylene insulation demonstrates a nonlinear type of failure renders low voltage test methods unsuitable. This leaves the high voltage test methods as the only acceptable ones; the DC hi-pot test is the best for testing the quality of cable insulation in the field.

For DC hi-pot testing to be effective, it must be performed in a well-structured, documented testing program. In particular, a rigid and demanding acceptance test of the cable system immediately after it is installed will uncover a large percentage of potential failures that could be caused by poor workmanship in the installation process.

Hi-pot maintenance testing may include determining if incipient faults exist on a cable and forcing those faults to fail during the test rather than while the cable is in service. In any case, correct DC hi-pot testing will reduce the number of in-service outages.

The search for an improved cable fault location device was very sucessful. The Digital Universal Fault Location Equipment (DUFLE) represents a major improvement in fault locating techniques. The theory behind this divice is sound and it will probably require a second or third generation of hardware for this technique to reach its full potential.

CONCLUSIONS

1. DC hi-pot testing does not harm good insulation.

2. Management should base the decision on whether or not maintenance testing is to be performed on the cost and seriousness of an unexpected in-service outage. If maintenance testing is to be implemented, the DC hi-pot test method must be used.

3. The high-voltage, impulse-tracing method (thumper) is the present technique used to locate faults in underground high voltage cables. Although the method is time consuming and the equipment bulky in size and weight, this method has proved itself to be simple, reliable, and accurate.

4. The new method of fault location, known as the Digital Universal Fault-Locating Equipment (DUFLE), is lightweight, accurate, and versatile. It could speed the location of many faults by reducing or eliminating completely the surface route length to be traced. This generally will reduce the time required to locate faults substantially. To locate high resistance or arcing faults, it must be used in conjunction with a capacitive discharge impulse generator.

5. The location of faults in cables with branch circuits is more difficult than with circuits without branches; special procedures must be implemented.

RECOMMENDATIONS

The following procedures are recommended as minimum in a structured cable-testing program.

1. The DC hi-pot method should be used.

2. An acceptance test should be performed on the cable system immediately after cable installation.

3. Maintenance should be performed frequently on the following schedule: the first maintenance test should be performed after 6 mo and no later than 12 mo of service; annually for the following 4 yr; and biannually thereafter with detailed records of each test kept for later comparison. The test voltage levels in Table 1 should be used until the new IEEE standard "Guide for Making High Direct Voltage Test" is issued; thereafter, the standard should be used.

4. A DUFLE should be used in conjunction with a portable capacitive discharge impulse generator where maintenance personnel wish to improve and accelerate the fault-location process.

ACKNOWLEDGMENTS

The assistance provided by Messrs J. Franchi, M. Eaton, and Drs R. Staab and D. B. Chan of CEL; and Messrs J. McCurry, J. Koletar, and G. Shoemaker of NAS, Miramar, California is gratefully acknowledged.

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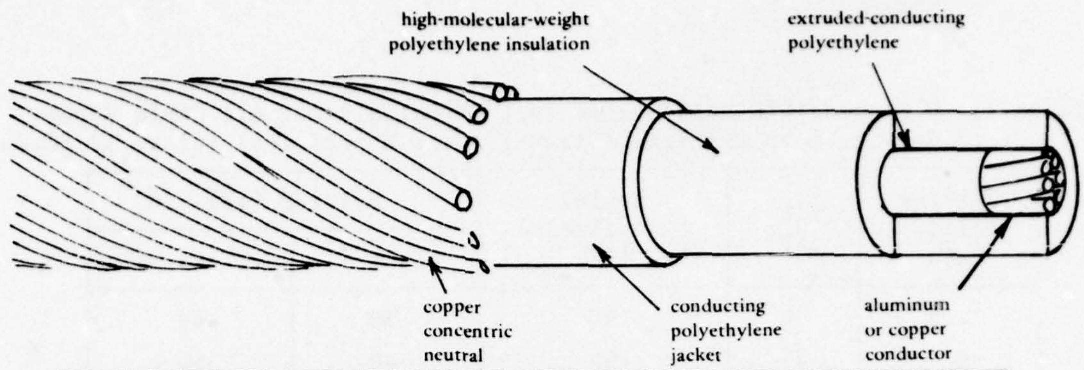
Table 1. Proposed IEEE Maintenance Test Potentials for All Cable Types Serving Both Critical (Class II) and Noncritical (Class I) Loads

Service Voltage (kV)	BIL (kV)	Initial Installation (kV)	Service (kV)	
			Class I	Class II
2.5	60	40	30	40
5	75	50	40	50
8.7	95	65	50	65
15	110	75	55	75
23	150	105	80	105
28	170	120	90	120
34.5	200	140	105	140
46	250	170	130	170
67	350	245	185	245

Table 2. DUFLE Specifications

Item	Specifications
Range	20 to 40,000 yd
Divider Voltage	500 V to 30 kV
Interconnecting Cable	Approximately 5 yd
Power Supply	12 1.25-V NiCad D cells, with internal 120-V, 60 Hz charger
Measuring Unit Dimensions	10 x 14 x 8-1/4 in.
Voltage Divider Dimensions	16-1/4 x 7-1/2 x 4-3/4 in.
Measuring Unit Weight	22 lb
Voltage Divider Weight	4 lb
Shipping Space Requirements	3 ft^3, 33 lb



Size AWG/MCM	Stranding	Insulation Jacket (mils)		Jacket, Outside Diameter (in.)	Neutral No./AWG Size	Weight (lb/1,000 ft)	Ampacity	
							Duct	Direct Burial
3/0	19	175	30	0.95	25 x 12	1,265	358	255

Figure 1. Typical manufacturer's specifications for 15-kV underground distribution cable.

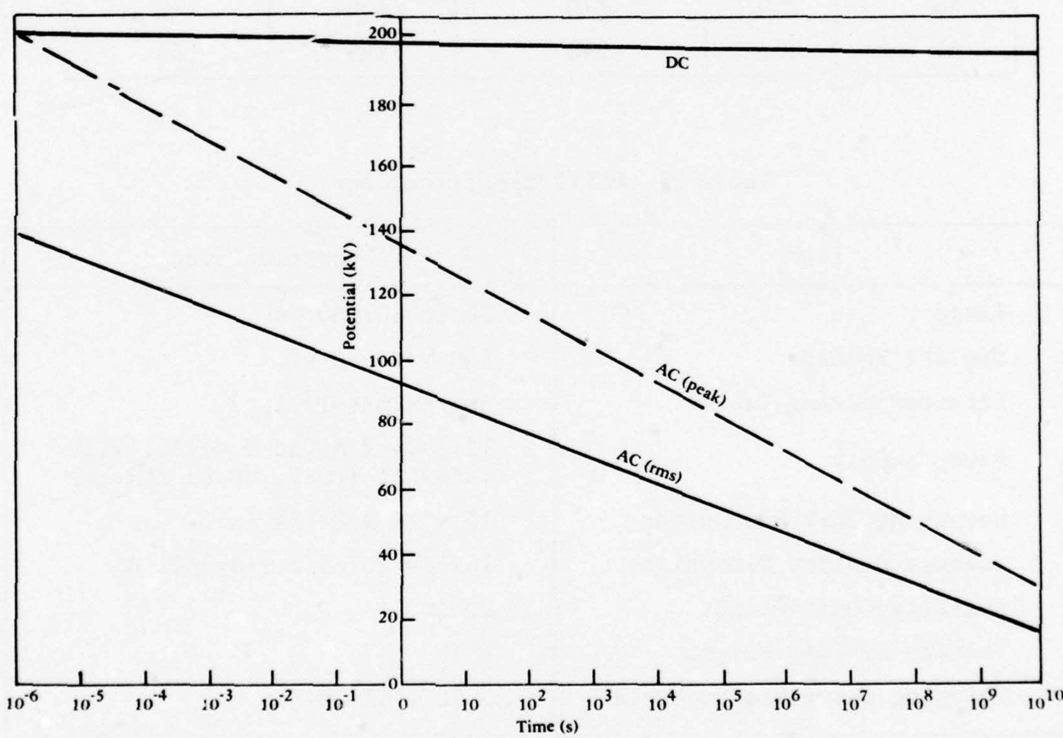


Figure 2. Endurance test of 15-kV insulation, comparing high voltage AC and DC potentials.

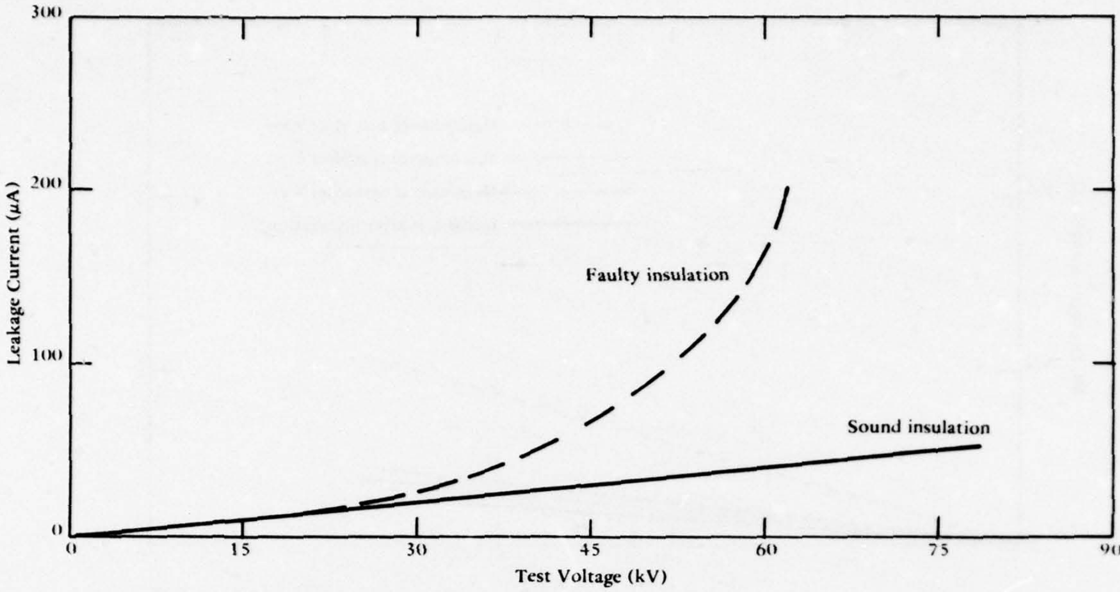


Figure 3. Leakage current versus applied voltage, for typical 15-kV underground cable, comparing faulty and sound insulation.

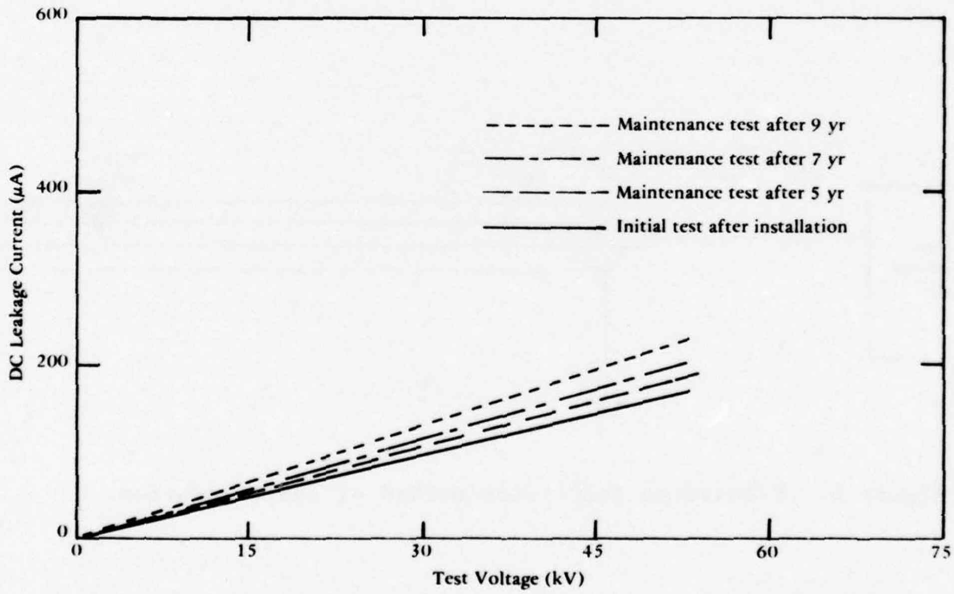


Figure 4. Hi-pot test record of 15-kV underground cable, showing normal degradation.

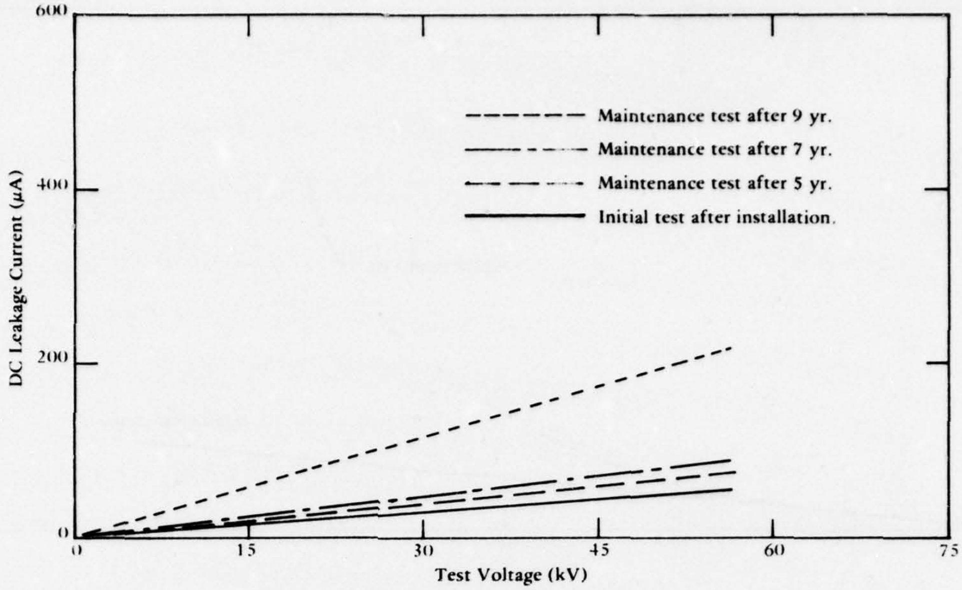


Figure 5. Hi-pot test record of 15-kV underground cable, showing unusual degradation of the insulation between the seventh and ninth yr of service.

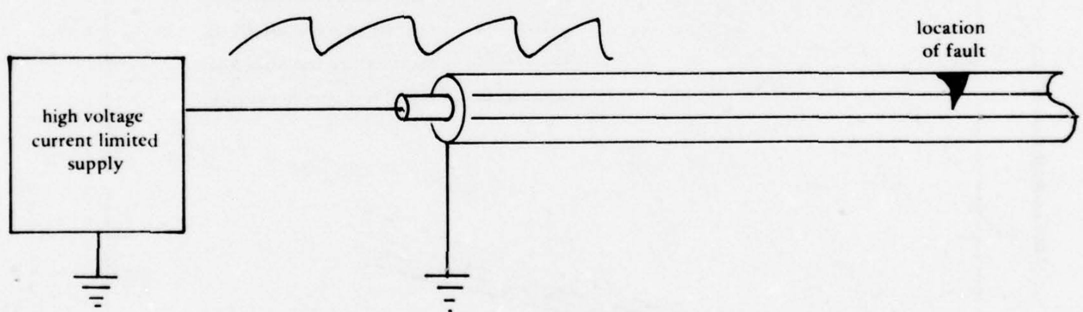


Figure 6. Relaxation oscillator method of fault location.

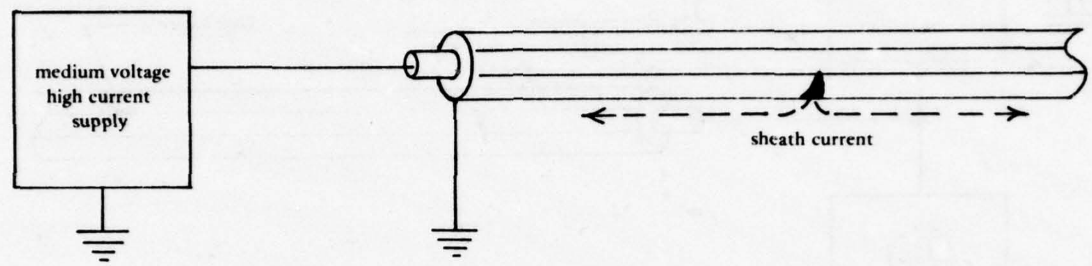


Figure 7. Burn and then trace mode of fault location.

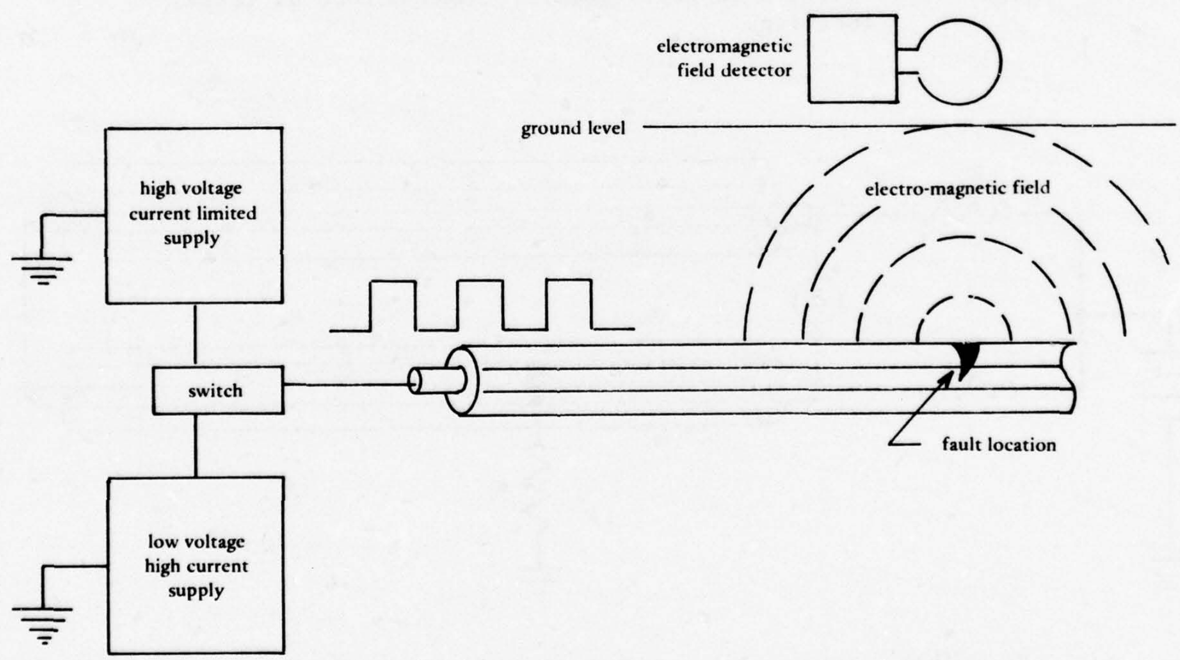


Figure 8. Electromagnetic field method of fault location.

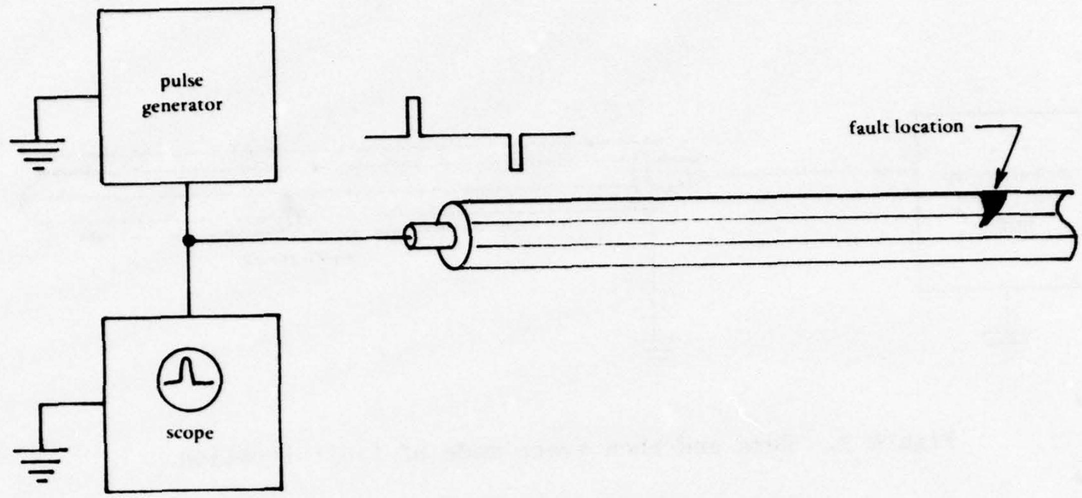


Figure 9. Time domain reflectometer (TDR) method of fault location.

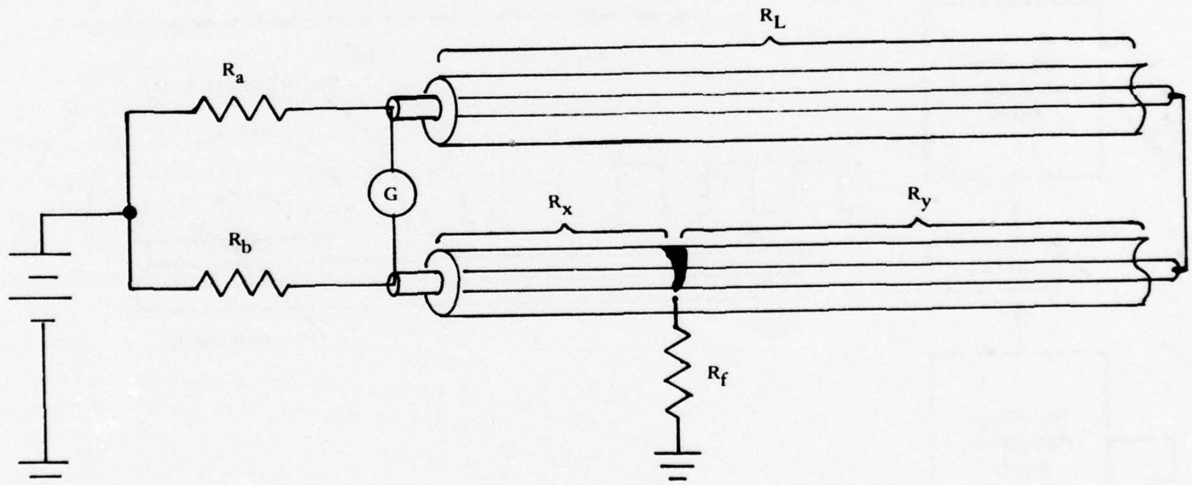


Figure 10. Murray loop method of cable fault location.

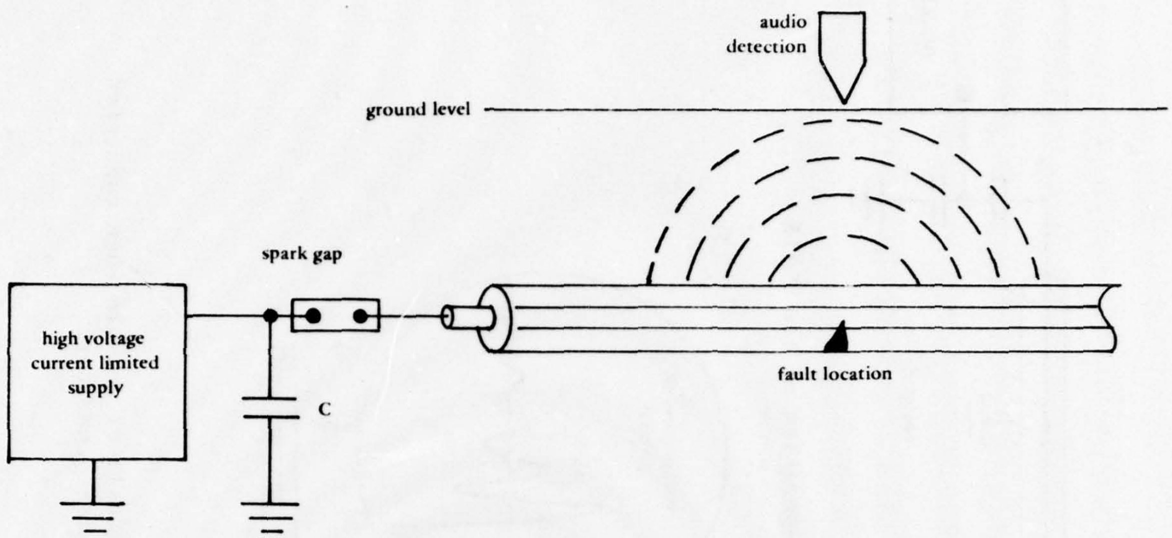


Figure 11. Capacitor discharge (thumper) method of fault location.

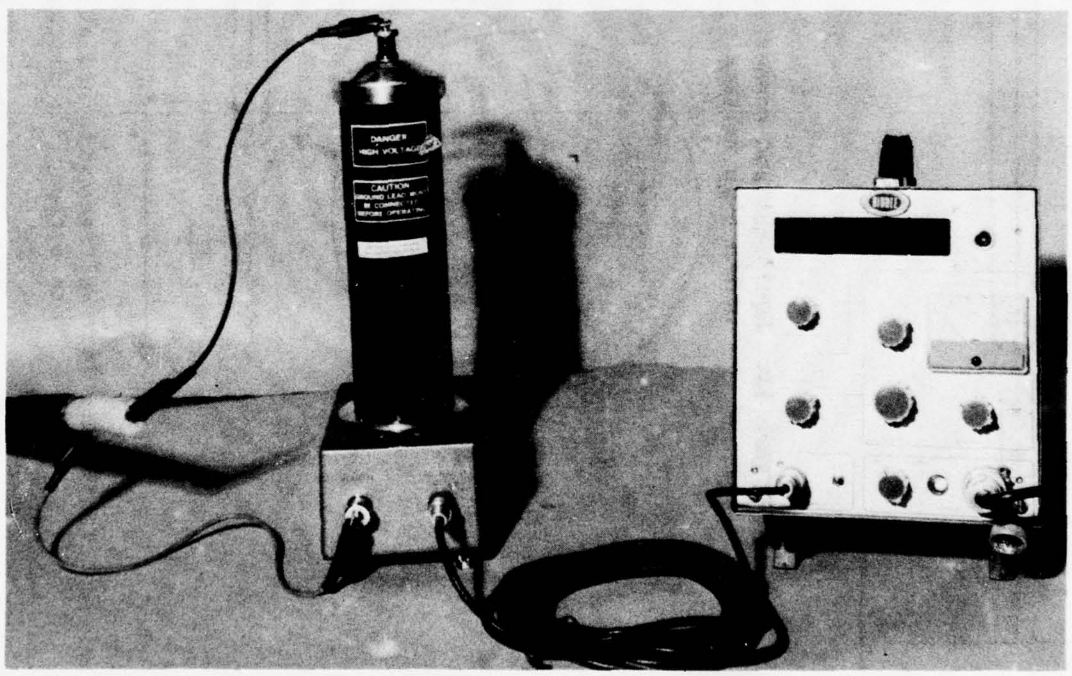


Figure 12. Digital Universal Fault Locator Equipment (DUFLE).

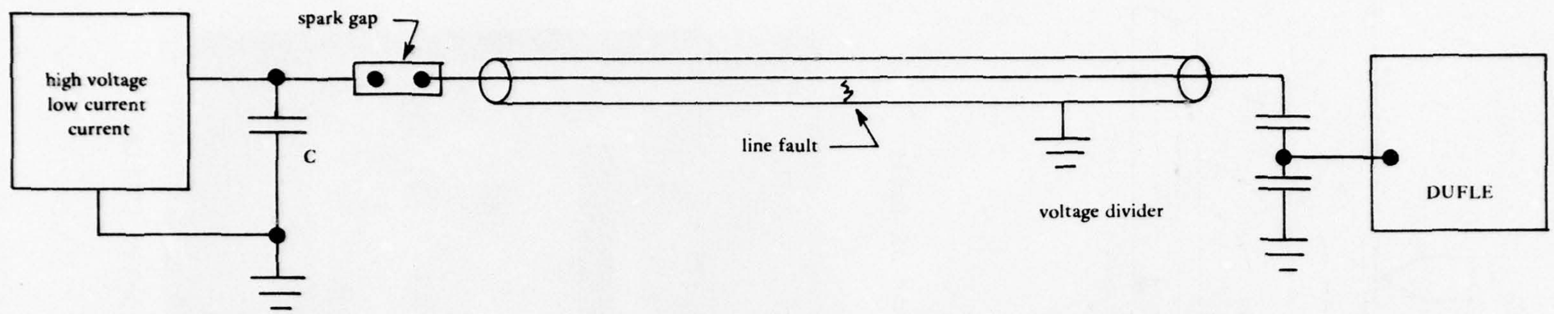


Figure 13. Equipment and connections for operation of the DUFLE in the high voltage mode.

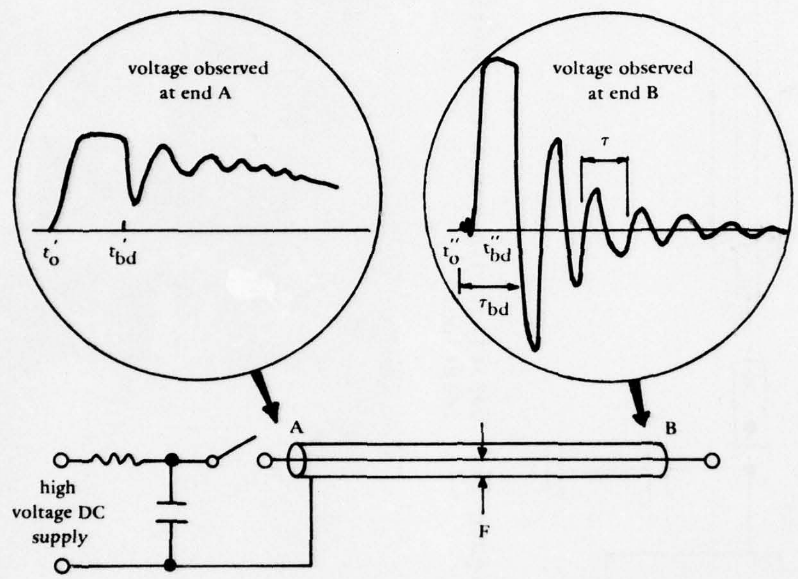


Figure 14. Voltages obtained at the terminals of a cable when connected to a capacitor discharge impulse generator.

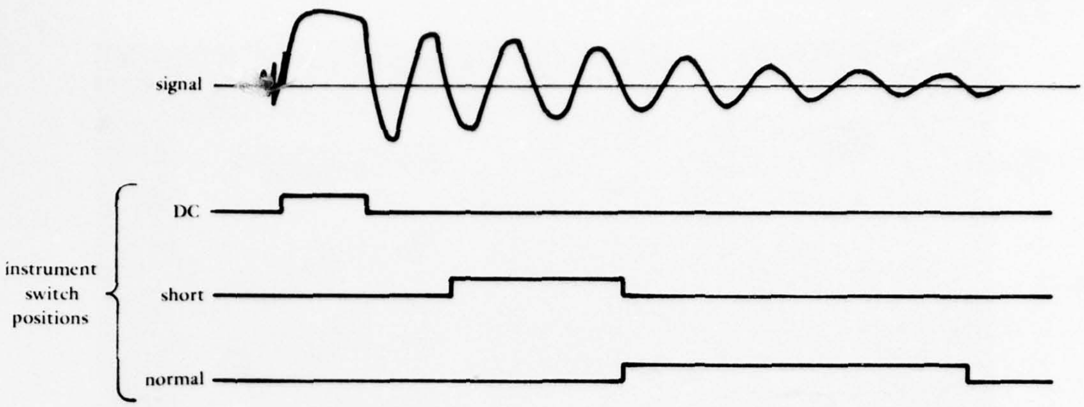


Figure 15. The three measuring periods for the high voltage mode of operation.

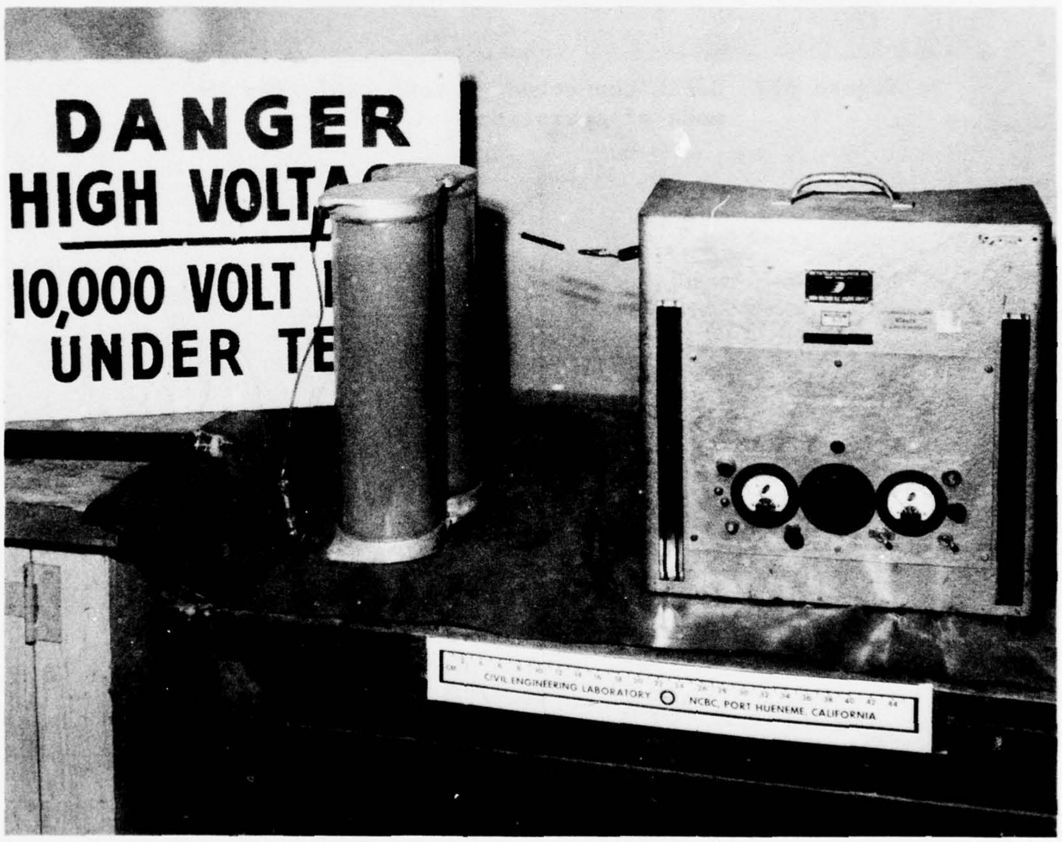


Figure 16. Capacitor discharge impulse generator used with the DUFLE in the high voltage mode of operation.

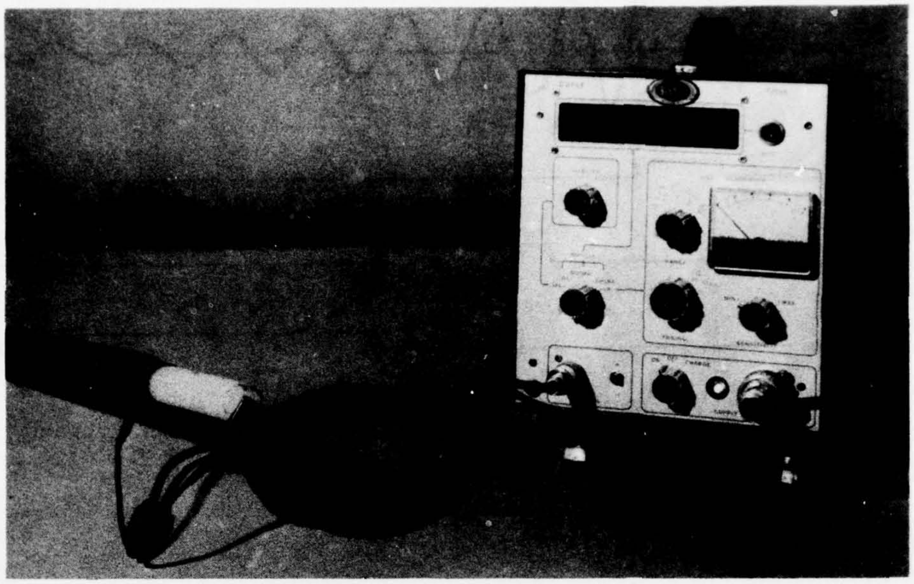


Figure 17. DUFLE connected to test cable for LR mode of operation.

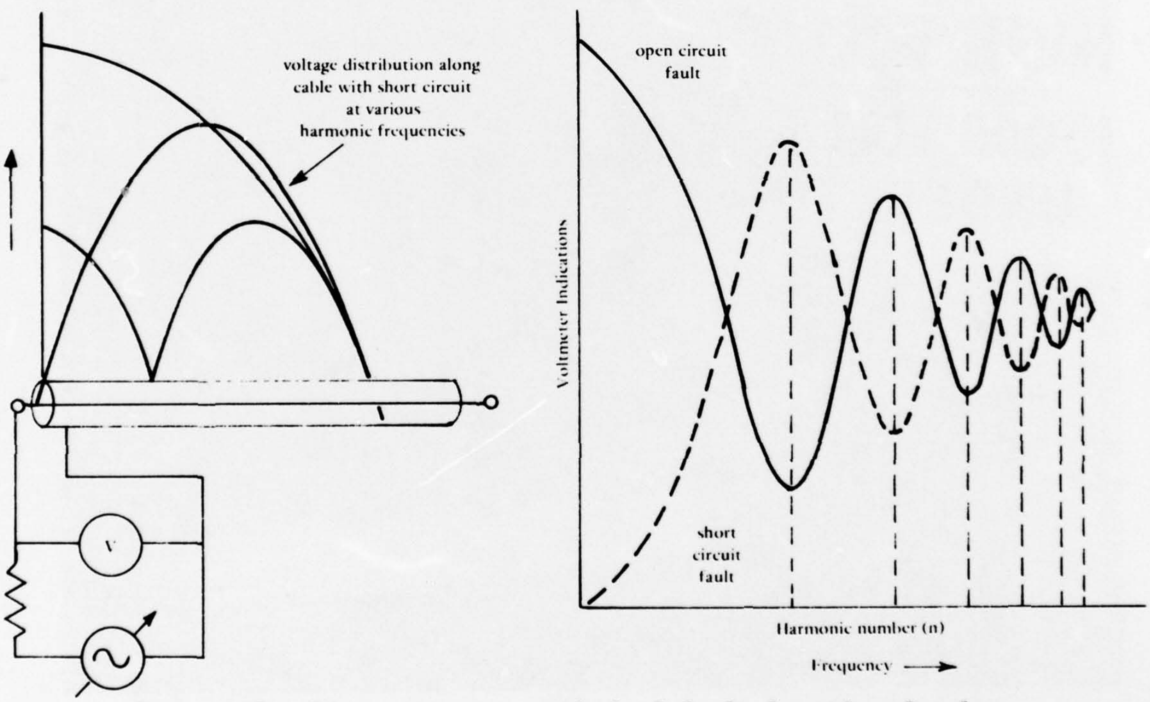


Figure 18. Line resonance method of fault location for low resistance and open-circuited faults.

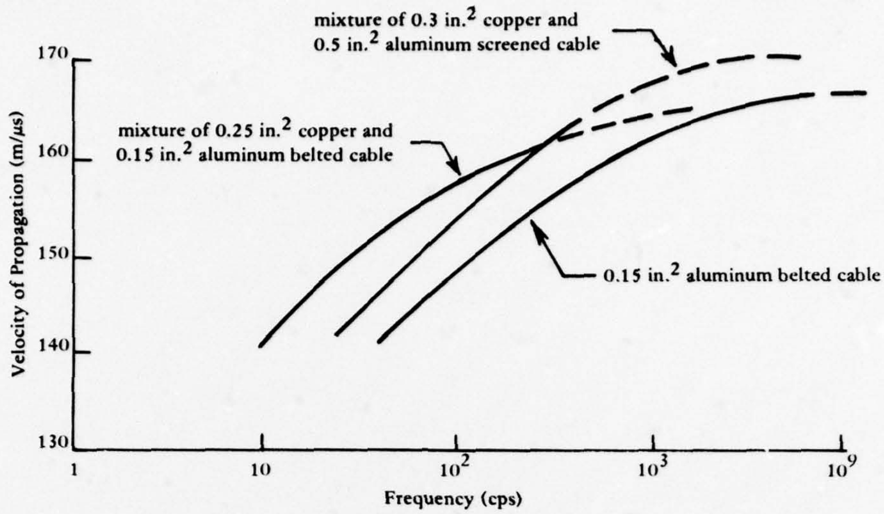


Figure 19. Velocity of propagation of electromagnetic waves for a variety of 11-kV cables.

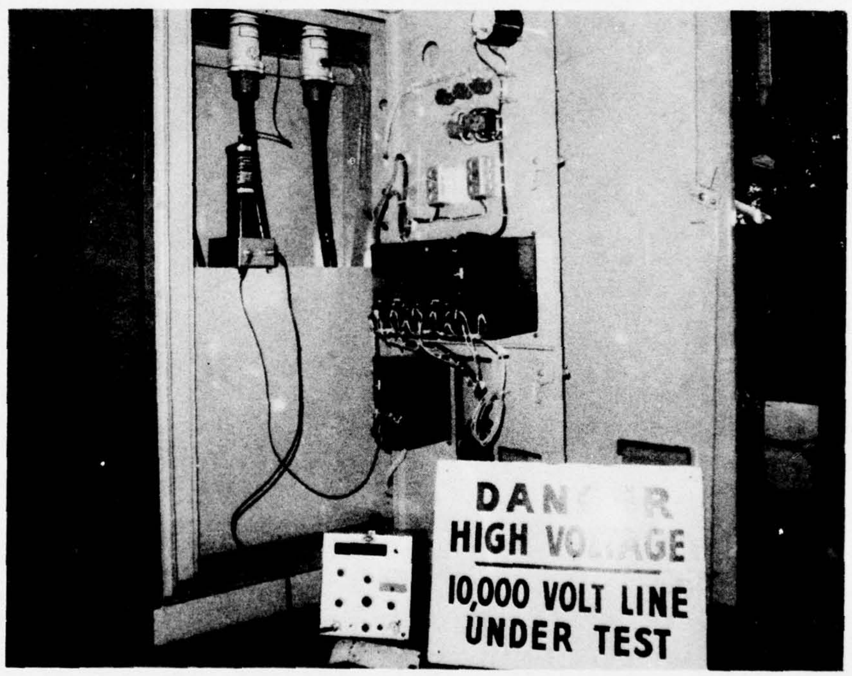


Figure 20. Field test of high voltage underground cable using the DUFLE at Naval Air Station, Miramar.

Appendix A

RECOMMENDED PROCEDURE FOR MAINTENANCE TESTING OF HIGH VOLTAGE UNDERGROUND CABLE

DC high potential maintenance tests are performed primarily to determine the condition of the cable insulation. An experienced operator working within the framework of a good maintenance program can frequently predict an impending cable failure and often make a good estimate of the future operating life of the cable. The exact voltage at which breakdown will occur is not particularly important, but the relative condition of the insulation at, and somewhat above operating voltage is of primary interest. Two tests are recommended to achieve this result: the "leakage current versus voltage test" and the "current versus time" test. It is recommended that both be performed and in that order.

Before these tests are performed, all terminations and loads are disconnected from the cable being tested; the shield and unused phase conductors are grounded; and the high voltage lead of the hi-pot tester is connected to the center conductor of the cable under test.

Then the voltage is slowly raised in discrete steps, allowing sufficient time at each step for the leakage current to stabilize. Each time the voltage is raised, the leakage current will jump high, then slowly decrease with time until a steady minimum value is reached. The initial high value of current for each step is called the charging current and is dependent primarily upon the capacitance of the cable under test. The lower steady-state current consists of the actual leakage current and the dielectric absorption current, which is relatively minor (see Figure A-1) [11]. The value of the leakage current is noted at each step of voltage; as the voltage is raised, a curve of leakage current versus voltage is plotted, as shown in Figure A-2. As long as this curve is a straight line (equal increments of voltage giving equal increments of current, points A and B of Figure A-2), the cable under test is considered to be in good condition. At some point the current will begin rising at a more rapid rate (point C, Figure A-2). This will show up on the plot as a knee in the curve. It is very important that the voltage increments be small enough so that the starting point of this knee can be observed. If the test is carried beyond the start of the knee, the current will increase at a much more rapid rate and breakdown will soon occur (point D, Figure A-2). Unless breakdown is actually desired, it is wise to halt the test as soon as the beginning of the knee in the curve is observed.

With a little experience, the operator can extrapolate the curve and estimate the point of breakdown voltage. This extrapolation procedure enables the the operator to anticipate the breakdown voltage without actually damaging the insulation. The important thing to watch for is the rate of change of current as the voltage is raised, much information may be obtained from the value of the current. A comparison of the leakage current from phase to phase or a comparison with the leakage current values obtained on tests made with the same equipment on prior occasions will give an indication of the condition of the insulation.

In general, higher leakage current is an indication of poorer insulation. However, this is a matter difficult to evaluate from a single test and, therefore evaluation under these circumstances should not be done.

On long cable runs having high capacitance, the time for current stabilization with each step in voltage may be several minutes to an hour. To minimize the testing time under these conditions, it is recommended that a reading be taken after each voltage step at fixed intervals. For example, voltage could be brought up to the first step, allowed to remain there for 5 minutes and then the current reading taken. The voltage is then raised to the next step, again 5 minutes is allowed and the current reading taken. This procedure is continued throughout the test. While this method will not give the true leakage current at any point, it will still give the properly shaped curve and will permit the same evaluation.

When the final voltage step is reached, the hi-pot tester is left on and a new current versus time curve is plotted (see Figure A-3). This is done by recording the current at fixed intervals as it decays from the initial high charging value to the steady state leakage value. This curve for good cable should indicate a continuous decrease in leakage current with time or a stabilization of the current without any increase during the test. Any increase of current during this test would be indicative of failing insulation, (see Figure A-4) and the test should be terminated.

After the last reading has been taken, the high voltage should be shut off. The kilovoltmeter on the hi-pot instrument will indicate the actual voltage present on the cable as the internal circuitry permits the charge to gradually bleed off. After the voltage reaches zero, an external ground is put on the cable, which is then disconnected. The cable should be kept grounded since the effect of absorption currents may cause a buildup of voltage in the cable under test until after it has been grounded for some time.

During the current versus voltage test, a rapid rise in current may occur - not because of defects in the cable insulation but because of surface leakage or corona at the cable ends. The better commercial hi-pot testers incorporate internal circuitry to bypass this stray current so that it does not interfere with the leakage measurements. By proper use of the guard circuit and a corona ring when necessary, excellent low level leakage current measurements may be made. The technique consists of providing a separate path for these stray currents, bypassing them around the metering circuit, and only feeding the leakage current to be measured through the metering circuit.

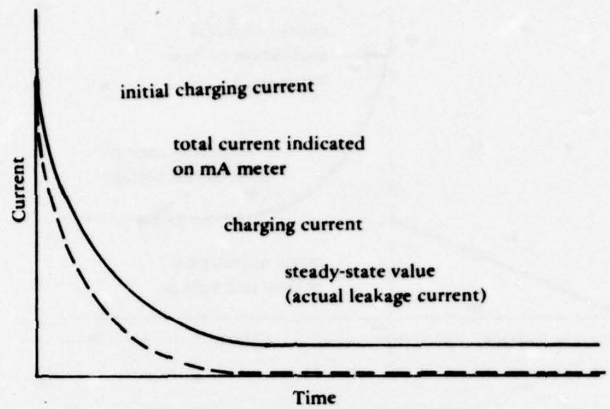


Figure A-1. Cable leakage current response to a step voltage increase.

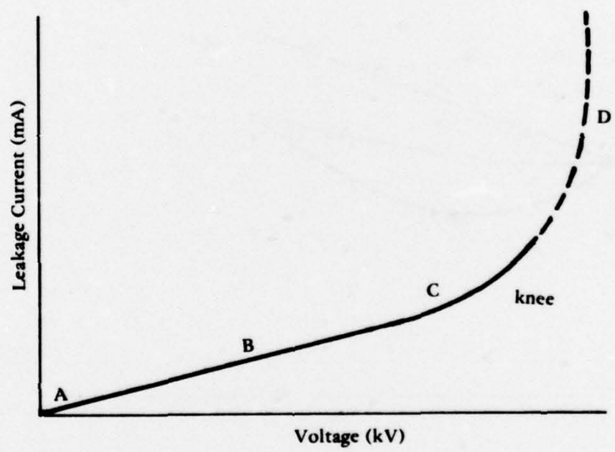


Figure A-2. Cable leakage current plotted versus applied voltage.

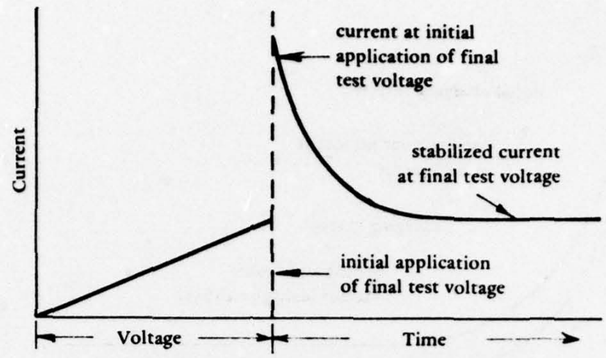


Figure A-3. Current versus time test to be performed upon reaching full test voltage.

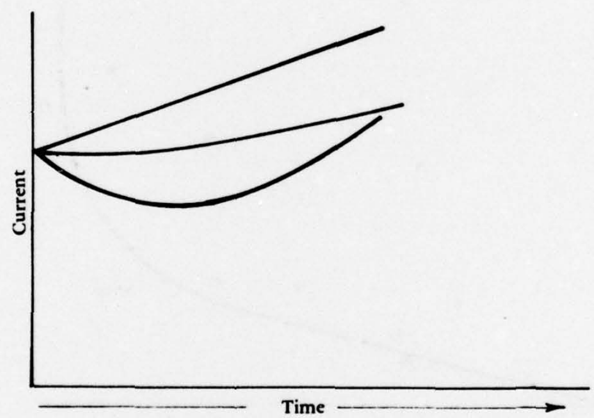


Figure A-4. Stabilized current versus time characteristics, indicative of poor cable insulation.

Appendix B

OPERATION OF THE DUFLE ON BRANCHED CIRCUITS

The operation of the DUFLE is slightly more complicated when the cable under test has branch circuits attached. In both modes of operation - high voltage and LR - the period of osciallation is related to the length of a single cable, as follows:

$$D = \frac{V\tau}{4}$$

When branches exist, this relationship is altered, and the actual relationship is quite complex. Some practical steps can be taken, however, to avoid the problem; the following discussion will point these out.

First, the physical layout of the cable must be known, either from experience or installation drawings. All loads must be disconnected, and each branch identified and each length measured. If the velocity of propagation for the cable is not known, a special procedure must be used which will be described later. With the velocity of propagation assumed known, then the capacitive discharge impulse generator should be connected to the main cable and each branch circuit examined with the DUFLE, using the DC switch position. The branch which does not show a DC component to the pulse contains the fault. This effect is shown in Figure B-1.

The DUFLE will correctly indicate the distance to a fault on a branched circuit if it is connected to the branch which contains the fault. This is true of either mode of operation. If it is not possible to connect the DUFLE to the faulty btanch (for example, when the fault lies between two branches as shown in Figure B-2), the system must be simplified by breaking down one of the splices and the DUFLE connected as shown in Figure B-3.

If there is only one branch, the error in distance measurement to the fault may be estimated by using Table B-1, which contains correction factors for an open-circuited, branched cable (illustrated in the accompanying diagram). If the cable and the branch lengths are known, the correction factor may be extracted from the table. On an open-circuited, branched cable, the reading will always be high using the DUFLE in the LR mode. The severity of the error is a function of the branch length and its location on the main cable. In many instances, however, the error is small, and the reading obtained is close enough. This method is only good for open-circuit faults, however, where the LR mode is used. The table is not applicable to short-circuited cables or cables with a high-resistance, intermittent fault. The table may not be used at all for cables containing multiple branches; with this type of cable each branch length must be tested separately.

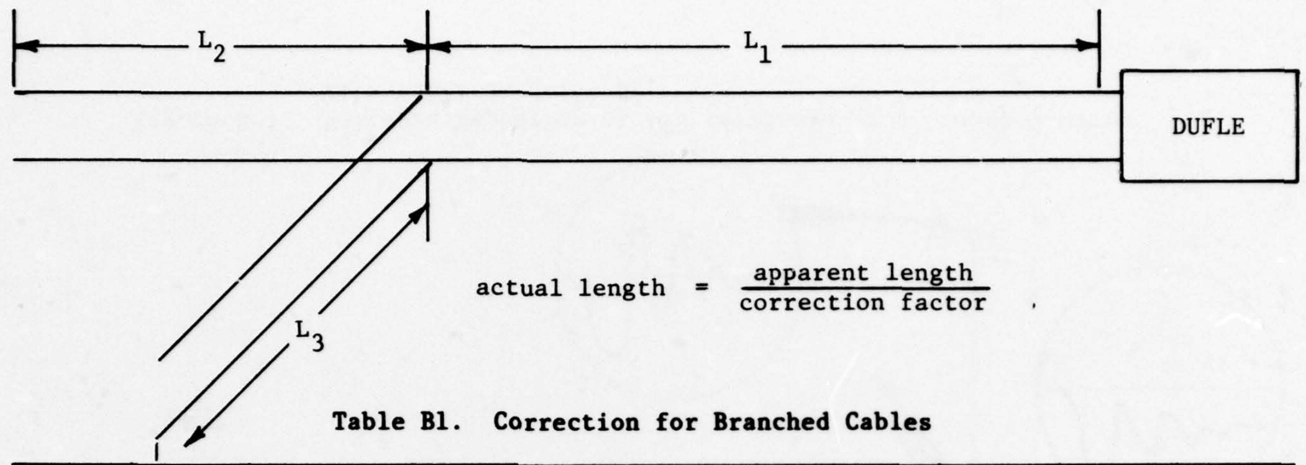
The velocity of propagation for the branched cable may not be known. In such a case, a special procedure may be used to determine the unknown velocity. If an alternate cable of the three-phase branched line is known to be good and the lengths of the cable and its branch are known, then the following procedure may be used to determine the velocity of propagation. As shown in Table B-1 and the accompanying cable diagram, the DUFLE will always present a line length greater than the actual length on a branched cable. Therefore, the actual length of the cable may be determined by the equation

$$\text{actual length} = \frac{\text{apparent length as measured with DUFLE}}{\text{correction factor}}$$

In this case the actual lengths L_1, L_2, and L_3 are known so the proper correction fabtor may be found from the table and the apparent length calculated as follows:

$$\text{apparent length} = (\text{correction factor})\ (\text{actual length})$$

The DUFLE is then connected to the good cable, and the phase velocity is adjusted while observing the length presentation. When the length presented by the DUFLE reached the apparent length as calculated above, the phase velocity knob is released and the output switched to read the phase velocity. This phase velocity is then used to perform the fault-location tests on the faulty cable.



actual length = $\frac{\text{apparent length}}{\text{correction factor}}$

Table B1. Correction for Branched Cables

Normalized Branch Length $\frac{L_3}{L_1 + L_2}$ (first column)

1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.100	1.096	1.089	1.078	1.065	1.050	1.035	1.021	1.010	1.002	1.000
1.200	1.190	1.175	1.155	1.130	1.102	1.073	1.045	1.021	1.005	1.000
1.300	1.284	1.261	1.232	1.196	1.157	1.114	1.071	1.034	1.008	1.000
1.400	1.377	1.347	1.309	1.265	1.215	1.159	1.102	1.049	1.012	1.000
1.500	1.471	1.434	1.389	1.336	1.276	1.209	1.138	1.069	1.017	1.000
1.600	1.565	1.522	1.470	1.411	1.342	1.265	1.181	1.095	1.024	1.000
1.700	1.659	1.611	1.533	1.488	1.412	1.327	1.232	1.129	1.036	1.000
1.800	1.754	1.701	1.638	1.567	1.486	1.394	1.291	1.175	1.057	1.000
1.900	1.899	1.792	1.725	1.649	1.564	1.467	1.357	1.233	1.096	1.000
2.000	1.945	1.883	1.813	1.774	1.649	1.544	1.430	1.302	1.158	1.000

Normalized Distance to Branch From Far End $\frac{L_2}{L_1 + L_2}$

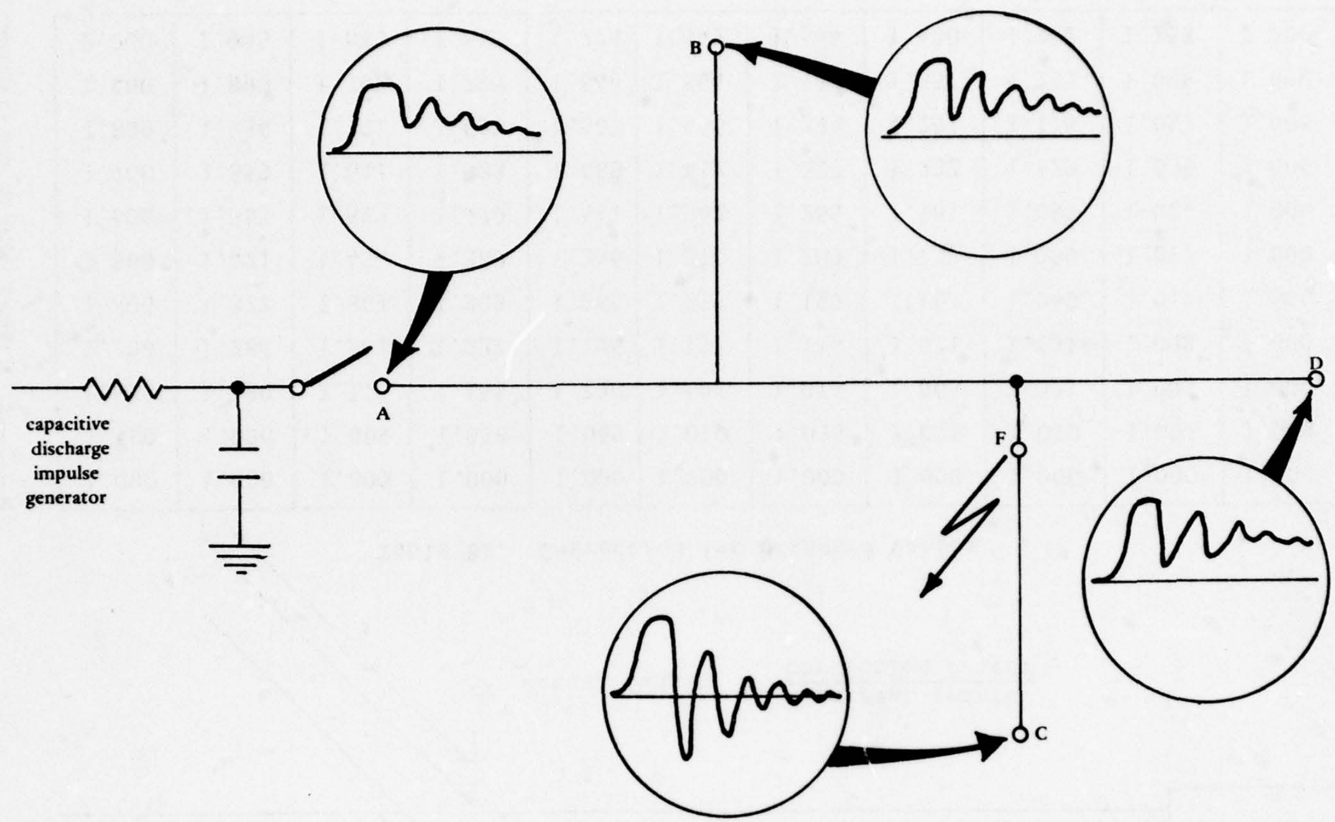


Figure B-1. Voltages appearing at the terminals of a branched cable with fault at point F.

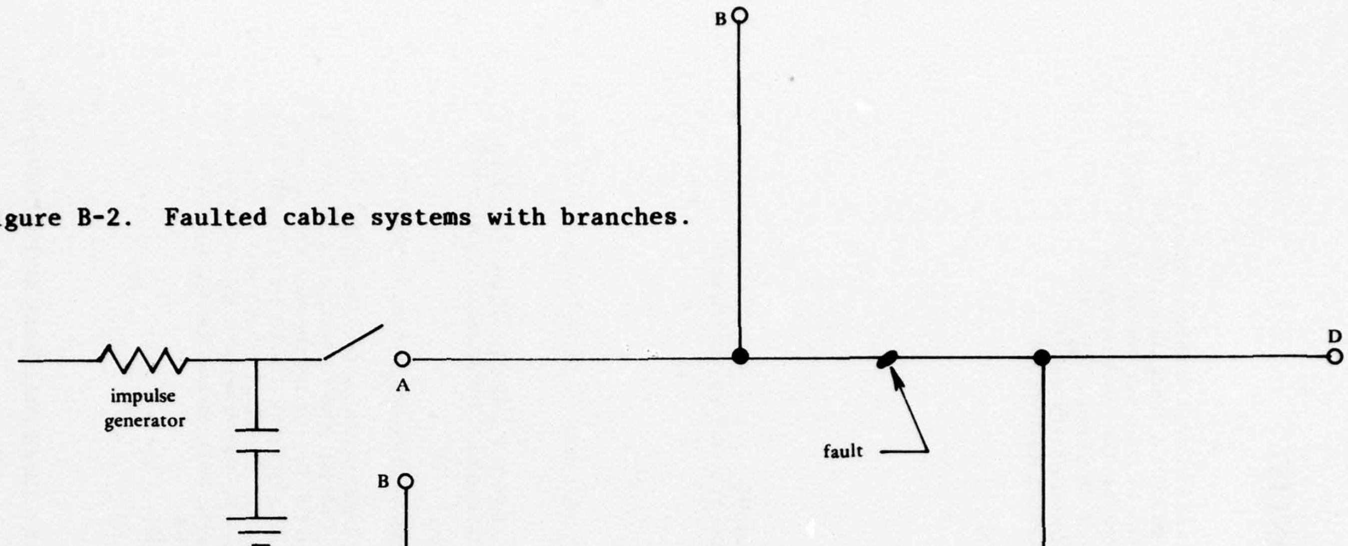


Figure B-2. Faulted cable systems with branches.

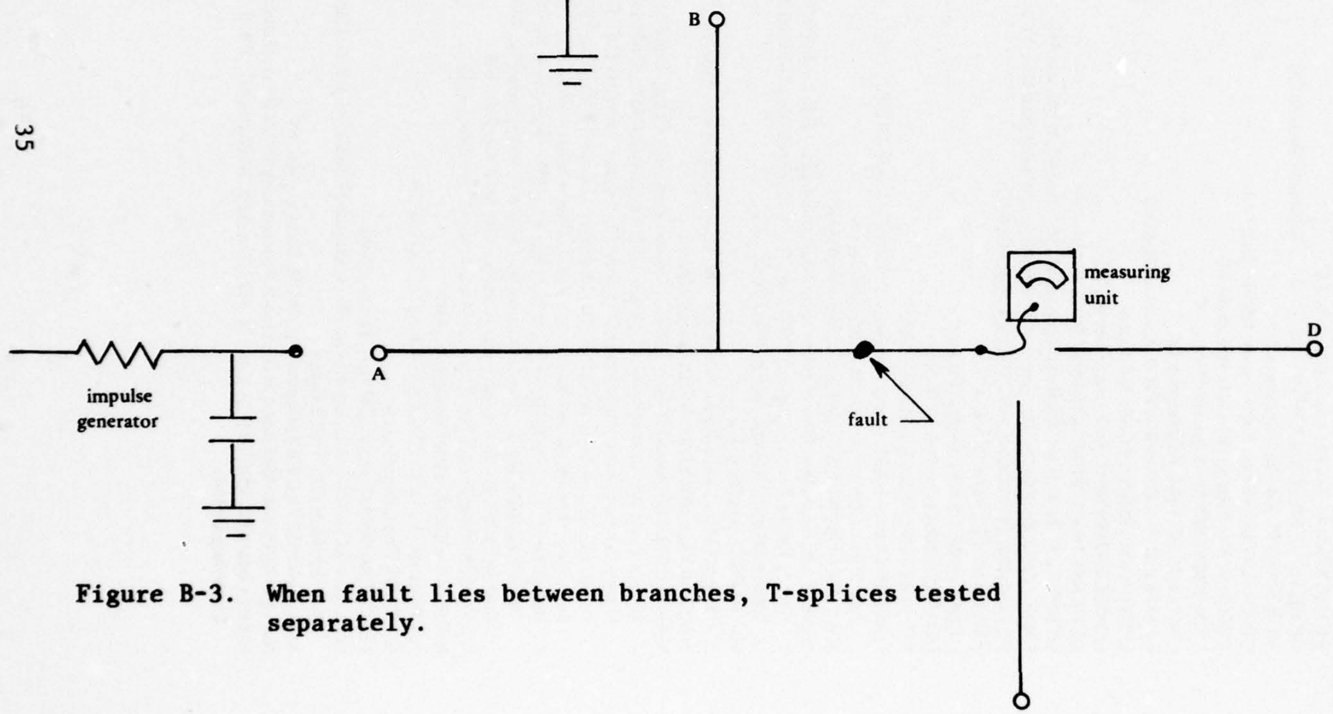


Figure B-3. When fault lies between branches, T-splices tested separately.

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