15 kV class underground cable fault tester
by Clair Karl Nystrom

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
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Abstract:
Utility power companies which service residential customers with 7200 VAC underground cable circuits (15 kV Class Cable) that fault (circuit interrupter activated) are faced with determining circuit integrity prior to energizing the circuit. Current testing techniques involve energizing the circuit with a new fuse. If the fuse holds, the faulted circuit is cleared. If fused, however, the circuit is systematically sectionalized until the faulted section is localized and isolated. This sectional troubleshooting process produces line surges on adjacent customer circuits, causing such inconveniences as the necessity of rebooting computers, and stresses on the power system, lighting, and appliances.

Power cable testing equipment presently exists which could be used to pretest the circuit, however, the equipment may not be economically feasible or convenient to use. The object of this study is to investigate an economically feasible, portable tester which can pretest a faulted circuit and report the approximate distance to a detected fault.

A review of applicable literature; power industry products; cable and connected transformer characteristics; circuit simulation and fault analysis is included.

A micro-controlled prototype using a TDR time-to-digital technique to determine cable/fault distance, coupled with a high-voltage impulse generator (thumper) is designed and demonstrated. Modular circuit design, implementation, test results, and parts lists are outlined. The test results reported are for various cable circuit conditions: open circuit, short circuit, high-impedance fault, minimum resistive termination that results in a nofault detection, maximum resistive termination that causes a detected fault, high-impedance fault with a transformer, minimum resistive termination that results in a nofault detection with a transformer, and maximum resistive termination that causes a detected fault with a transformer.

This thesis concludes with a brief summary of the study, conclusions drawn from the prototype results, and resulting recommendations.

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APPROVAL

Of a thesis submitted by

Clair Karl Nystrom

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Utility power companies which service residential customers with 7200 VAC underground cable circuits (15 kV Class Cable) that fault (circuit interrupter activated) are faced with determining circuit integrity prior to energizing the circuit. Current testing techniques involve energizing the circuit with a new fuse. If the fuse holds, the faulted circuit is cleared. If fused, however, the circuit is systematically sectionalized until the faulted section is localized and isolated. This sectional troubleshooting process produces line surges on adjacent customer circuits, causing such inconveniences as the necessity of rebooting computers, and stresses on the power system, lighting, and appliances.

Power cable testing equipment presently exists which could be used to pretest the circuit, however, the equipment may not be economically feasible or convenient to use. The object of this study is to investigate an economically feasible, portable tester which can pretest a faulted circuit and report the approximate distance to a detected fault.

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This thesis concludes with a brief summary of the study, conclusions drawn from the prototype results, and resulting recommendations.

CHAPTER 1

INTRODUCTION

Utility power companies which service residential customers with 7200 VAC underground cable circuits (15 kV Class Cable) that experience a fault condition (circuit breaker activated) are faced with determining circuit integrity prior to energizing the circuit. The testing technique currently used by most power companies to evaluate a faulted circuit involves energizing the circuit with a new fuse and, if the fuse holds, then the circuit fault is cleared. However, if fused, the circuit is systematically sectionalized, re-fused and re-energized until the faulted section is localized and isolated. This sectional troubleshooting process causes undesirable stress on the power system, and line surges on adjacent customer circuits, resulting in added stresses to motors, lighting, and appliances, and often necessitating rebooting of computers.

Utility power company service personnel need a portable device that can be quickly connected to any de-energized residential circuit to determine if a fault exists. If a fault is detected, the approximate distance from the testing location to the fault needs to be determined.

Purpose

The purpose of this study is to evaluate the feasibility of developing an economical and conveniently portable underground cable tester which has the ability to determine fault/no-fault conditions (with estimated distances to detected faults) of de-energized circuits, thus eliminating the risk to customers' property which is inherent in the commonly used sectional troubleshooting process.

Assumptions And Limitations

For convenient portability, it is assumed the cable tester to be under 1.0 cubic foot in size and less than 50 pounds in weight. For cost considerations, a market value of less than $3000 is assumed to be feasible. For normal/fault test reliability, 80% or better is assumed. For fault location, accuracy of within 5 feet (ft) is assumed.

Summary Of The Remainder Of This Thesis

Chapter 2 discusses a limited literature review of patents, technical journals, power industry publications, periodical product advertisements and manufacturer's product literature which address underground cable fault detection processes and equipment. Chapter 3 identifies system characteristics that need to be addressed, including which process to use when performing a cable test; which instrumentation technique to use for sensing a fault; and, the fault location process and portable power requirements. Chapter 4 presents analytical data on system component characteristics, a summary of high-voltage (HV) switch devices, instrumentation concerns, a fault location process, portable power requirements and prototype results. Chapter 5 summarizes this study, states conclusions to the data reported in Chapter 4, and makes recommendations for future study.

CHAPTER 2

LITERATURE AND INDUSTRY REVIEW

Introduction

A literature search was performed to determine what technological and/or industrial techniques were available or being used to meet this need of power companies as outlined in the previous chapter. The search was limited to appropriate U.S. patents listed in the last five years; technical journals (IEEE Transactions on Instrumentation and Measurement, IEEE Transactions on Circuits and Systems, and IEEE Transactions on Power Delivery); indices to power industry publications; periodical product advertisements over the past seven years; and manufacturer's product literature.

Patents

Of the 25 related patents found, No. 5,210,498 is the most applicable to this project. Titled "Detector for Locating Underground Cable and Faults Therein Using High-Powered Electromagnet", it describes a method for above-ground fault location by transmitting an inducted signal into the cable and monitoring the signal on the surface.

Technical Journals

Pintelon [1] proposes that a Gaussian, frequency-domain, maximum likelihood estimator can determine the transfer function of a linear, continuous-time, two-port system with time delay. The estimator can be used to locate a discontinuity in a cable. Fault location was based on the Time Domain Reflectometry (TDR) principle. The cable was stimulated with a short duration pulse. The stimulus and first reflection were sampled and the first F spectral line determined by the fast Fourier transform (FFT) is sent to the estimation algorithm. The propagation velocity of the cable was required to determine the final location of the fault. A simplified analytical model reported by Abullma'atti [2] involves the modeling of a resistively or capacitively (RC) loaded line based on finding the approximate poles of the transfer function. This transfer model claims to make it easier to implement a computer-aided analysis, however, it is not as accurate as other published techniques.

A transient propagation analysis through nonuniform structures and uniform lines was reported by Schutt-Aine [3]. The analysis uses a scattering parameter formulation in the time domain to establish closed-form algorithms for current and voltage variables in the line. The technique was applied to microstrips, uniform, and tapered lines.

A digital signal process (DSP) algorithm was developed to estimate the location of a fault by a line parameter estimation technique, Van Biesen [4]. This process was applied to sampled TDR data of a known unfaulted cable for calibration of line parameters and compared with a faulted line to locate the discontinuity. The technique requires the knowledge of the propagation speed for accuracy. The process is reported to resolve accuracy's of 30 cm, using a 20 MHz-8 bit sampler.

Makoto [5] reports a nonlinearity measuring method using two frequencies to determine electrical circuit components. Two currents of different frequencies were introduced into a device which selectively measured the multi-order of nonlinearity distortion from the harmonics present. The technique was applied to passive devices to demonstrate the results.

Fiber optic technology has been applied to locate cable faults, Kawai [6]. This technique requires a fiber optic distributed temperature sensor (FODT) composite cable. The premise is that a temperature rise occurs from the arc at a ground fault location. Detection of the temperature rise is based on the Raman backscattering light which is temperature-dependent and composed of Stokes light and anti-Stokes light (incident). Accuracy was reported to be one meter (m) within a maximum measuring distance of ten kilometers (km).

A continuous monitoring location system was developed for a 66 kilovolt (kV) underground cable using an optical-to-electrical (O/E) converter and a fast, 16 megasamples per second (Msps), analog-to-digital converter (ADC), Inoue [7]. The system topology includes a 1000 m segmented cable section with fast, 1 MHz bandwidth, optical current transformers (CT) mounted at each end. Optical fiber interconnects the CTs to the O/E converter, ADC, and CPU. When a ground fault happens the surge current flows from the point of the fault to both ends of the cable. The system monitors the time delay of the surge current from each end and determines the fault location. The reported location error of the system is less than 10 meters in a 1000 meter cable length.

The characterization of fault-generated traveling waves and properties was empirically determined for underground residential distribution (URD) cable systems, Wiggins [8]. Some of the characteristics of the fault wave are reported as a damped square, sinusoid, or alternating pulse waveform. A wave peak amplitude of 10 kV / 300 Amps(A) near the fault, and 20 kV / 10 A near the open end was measured for a 15 kV tree-retardant cross-linked polyethylene (TRXLP) primary cable with a surge impedance of approximately 34 ohms (Ω). The waveform risetime of 20 nanoseconds (ns) at the open end (no transformer) was measured to be 60 ns at 1,100 ft from the fault, 100 ns at 1847 ft from the fault, and 20 ns at the open end, 90 ft from the fault. The maximum frequency component is 50 MHz near the fault. The fault duration ranged between a maximum of 80 microseconds (μs) and a minimum of 4 μs. The cable propagation velocity varies from 440 ft/μs to 570 ft/μs for URD cables and 503 ft/μs for TRXLP. A U.S. patent (No. 5,206,595) has been issued for digital circuitry of a calculator-sized fault locator unit intended to be installed at the padmount.

There is an automated fault locating system which implements a two-step procedure, Steiner [9]. The first step determines the fault between two transformers and the second step pinpoints the fault. The process for the first step involves the operator entering estimated distances between all connected transformers into the testing device, and performing a TDR test. The automated testing device determines the fault location between two transformers. The second step involves the operator isolating the cable section and reconnecting the test device at one end of the section. Another TDR test is generated to estimate the fault location within 2% accuracy. An antenna is then placed on both sides of the suspected fault location and another TDR test is generated. The test device calculates the relative distance to the fault from the antenna. This process determines the fault within 250 centimeters (cm). The defense for this process is that the wave propagation rate is not predictable enough to get precise accuracy's in finding the location. The demonstration site was at Purdue University. Details of the antenna design and some empirical data are reported by Weeks [10].

Industry Publications

Power industry periodical/s: ELECTRICAL WORLD

Product Advertisements

Searching the last five years of ELECTRICAL WORLD for related advertised fault locators revealed the manufacturer/suppliers listed in Table 1.

Table 1. Cable Tester Manufacturer - Supplier List

AVO International Biddle Instruments 510 Township Line Road Route 22 North Blue Bell, PA 19422-2795 800-366-5543	Hipotronics, Inc. PO Box 414 Bethlehem, PA 18017 215-837-9803 Brewster, NY 10509-0414	HDW Electronics, Inc 5897 Colony Drive 800-727-4476

Product Literature

Manufacturer's product literature was reviewed for the equipment detailed in Table 2, Table 3, and Table 4.

Table 2. Cable Fault Locators

SOURCE	MFG/MODEL	DESCRIPTION	COST
HDW Electronics	W204/M501	VLF Cable Test Set. 0.1 Hz bipolar pulse wave.	$ 56,100
HDW Electronics	T3000/M219-SW	Digital Time Domain Reflectometer / Arc Reflection Filter. Requires 'thumper'. Accuracy 1% of range.	$ 16,440
Hipotronics	M602	HV Reflecting Pulse fault locator Requires 'thumper'. Accuracy 1% of range.	$ 14,750
HDW Electronics	System 1000	Analog Time Domain Reflectometer with Arc Reflection Filter. Requires 'thumper'. Accuracy 2% of range.	$ 10,800

Table 3. Cable Fault Tracers

SOURCE	MFG/MODEL	DESCRIPTION	COST
AVO International	Biddle / SFL-2000	Dual purpose locator and tracer. Uses 11.11 Hz for locating and 7776.4 Hz for tracing.	$ 4,450
HDW Electronics	T16/9	Digiphone. Acoustic / electro-magnetic pickup for pinpoint fault location.	$ 3,100
Hipotronics	FD202C	Acoustic/electro-magnetic pickup for pinpoint fault location.	$ 2,800

Table 4. Cable 'Thumper's

SOURCE	MFG/MODEL	DESCRIPTION	COST
HDW Electronics	T19.1	7.5/15 kV, 800 J	$ 10,500
Hipotronics	CF30/15-8C	900 J	$ 7,400

Of the products listed in Table 1, none meet the industry's need for hand portability, size, weight, and overall cost.

CHAPTER 3

METHODOLOGY

Introduction

The purpose of this study is to evaluate the feasibility of developing a small hand-portable, underground cable tester which can determine fault/no-fault conditions of de-energized circuits and estimates the distance to the fault while residential transformers are connected, and which also meets portability (size under 1.0 cubic feet), weight (under 50 pounds) and cost (under $3000) constraints.

System Component Characteristics

The first design issue addressed is which parameter(s) (voltage, current, resistance, impedance, etc.) in the cable circuit to instrument such that faulted and normal conditions can be discriminated. Since the objective is to determine the integrity of the power circuit while de-energized, low DC voltage and low current measurements could be used to calculate the resistance of the circuit, with a predetermined low resistance value being an indicator of a fault. However, this testing technique is limited to low-voltage breakdown faults and to direct short-circuits due to the primary resistance of the attached transformers being of the order of one ohm (see Appendix A.) It is evident, from the literature review, that the more difficult and frequent fault condition is the highresistance breakdown in which the circuit faults only when the nominal operating voltage, 7200 VAC (10.2 kV peak), is applied. This fault condition is most frequently caused by an inter-electrode insulation compromise (aging process, absorption of water, mechanical deformation, etc.). In order to test the cable under these conditions, a high-voltage needs to be applied to the cable in such a manner as to not have adverse effects to equipment or appliances on the customer's side of the transformer. It is proposed that a measurable "fast" (>600 Hz) energy pulse can be used to charge a cable to near peak voltage while having minimal effect on power customer's equipment. In light of the above, several cable testing issues posed in Table 5 are evaluated by use of published component electrical characteristics, analytical analysis, cable model simulation (PSPICE), and prototype results in the Chapter 4.

Table 5. Cable Testing Issues

CABLE ISSUES	
1	What are the15kV Class Underground Cable electrical characteristics?
2	What are the energy requirements to fully charge the cable to near peak voltage?
3	What are the normal and faulted cable energy impulse responses?
4	What are the residential pad-mounted transformer characteristics relative to a 'fast' energy pulse response?
5	What is the effect of an energy pulse on the customer's side of the transformer?

A testing technique is next examined.

Testing Technique

An embedded controller is used to interface the user and testing components, as shown in Figure 1.

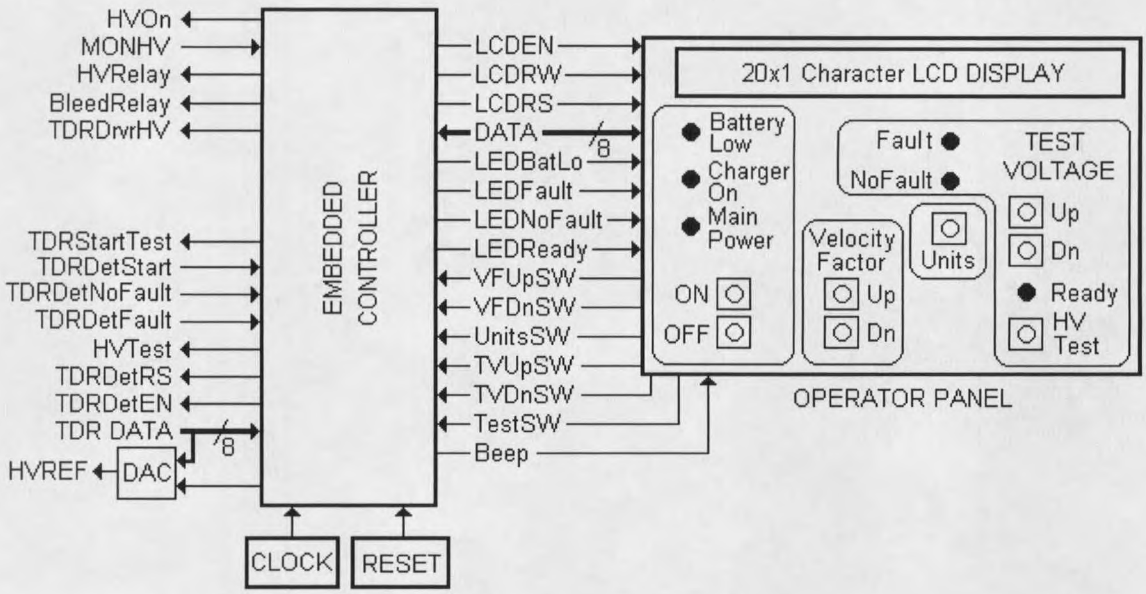

Figure 1. Operator Panel and Embedded Controller Block Diagram

The operator panel includes functional groupings of status and control switches. In the primary power group, Main Power On is indicated by a green LED and controlled by the ON and OFF switches. A yellow LED indicates when the charger is connected (Charger On) and a red LED lights when the battery condition is too low to continue. In the velocity factor group, two switches, Up and Dn, are used to select a velocity factor between 50% and 100%. A Units switch is used to select between displayed distances in feet or meters. In the Test group, two switches, Up and Dn, are used to select the high-voltage (HV) test voltage and a yellow LED, Ready, indicates when the HV Test switch can be pressed. Two LEDs, a red Fault and a green No Fault, are used to indicate the results of low or high-voltage cable tests. The LCD display shows the velocity factor, distance, and HV textual values and a graphical display indicates a relative battery charge condition. A beeper is provided as user feedback to switch selections.

Fault Location Process

Literature review revealed that Time Domain Reflectometry (TDR) is a popular technique used to determine fault distance. This technique works on the principle that energy traveling in a medium, cable in this case, takes an increment of time to traverse distance and continues until a discontinuity, change in impedance, of the medium is encountered. When the discontinuity is an open ended cable the energy reflects in the same polarity and traverses the medium in the opposite direction. If the discontinuity is a short-circuit, however, the energy reflects in the opposite polarity (energy conservation met for boundary conditions in both cases). If the instrumentation point in the system is at the cable tester, then time variations in the reflected energy could determine if the cable is faulted (reverse polarity) as well as the approximate distance to the fault (one-half the time between start of the test pulse to the detected reflection).

The TDR process, depicted in Figure 2, connects to the test cable through the TDR CONNECTOR and is used to determine the test cable's low-voltage response. The TDR TRANSMITTER produces test pulses with sufficient energy supplied from the TDR SUPPLY to transverse the cable circuit in both directions and be detected by the TDR RECEIVER/DETECTOR. The output of the TDR RECEIVER/DETECTOR produces a HI signal for the test pulse and its unfaulted reflection or a LO signal when a fault is detected in the cable circuit. The TIME-TO-DIGITAL CONVERTER latches the state of the reflected pulse (HI or LO) and measures time by counting clock ticks between the test pulse and the reflected pulse. The TDR DATA is presented to the processor for scaling and displaying to the user. For high-voltage testing, a Thumper is added.

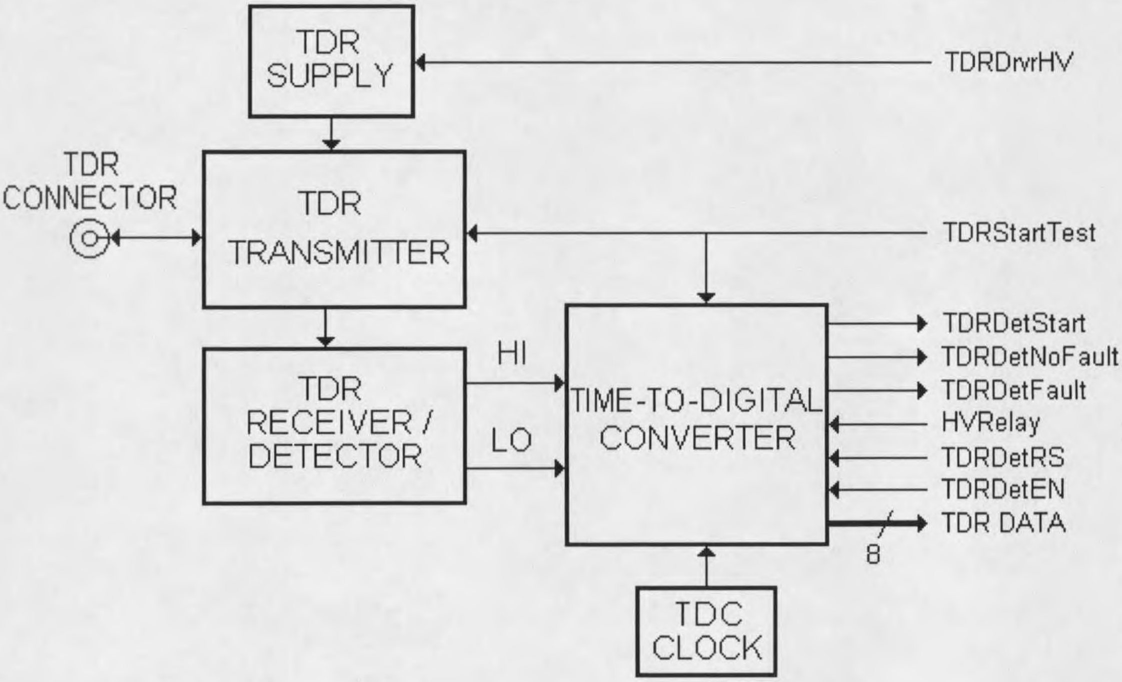

Figure 2. TDR Block Diagram

A Thumper is a device used by the power industry to assist service personnel in locating the position of a faulted cable. The Thumper presents high-voltage pulses which create a "thump" sound at the site of a breakdown in an isolated cable circuit. Thumpers are also used to “burn” the fault location to such an extent that physical destruction occurs, aiding in locating the position. Thumpers are generally large, heavy, and