IDENTIFICATION AND REPAIR OF INTERMITTENT CABLE FAULTS IN NUCLEAR POWER PLANTS

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ABSTRACT

The nuclear industry uses cable circuits as an integral part of a plant's reactor protection system (RPS), instrumentation and control (I&C) and power distribution systems. The reliability of these systems is critical for continued operation of the world's aging nuclear fleet, as well as for safe shutdown of the reactor. When intermittent faults occur in cable circuits, the symptom of the problem often appears and disappears in milliseconds while the aftereffects can result in spurious alarms and automatic actuation of safety systems. Problems are compounded when component degradation causes a cable circuit to transmit inaccurate information that does not represent actual plant operating conditions.

The root cause of intermittent cable circuit operation can include degradation of cable and connectors from heat, humidity, radiation, and vibration. Unlike hard faults (which are constant open or short circuits), intermittent faults are defined as a temporary change in impedance that may only last for a few milliseconds. While less disruptive than hard faults, signal spiking from intermittent faults can often lead to alarm conditions and reactor trips. A soft fault is defined as a subtle variation the electrical characteristics of the circuit that still permit the continued operation of the circuit. A soft fault may be a precursor to a hard fault due to continued degradation of the fault over time.

The focus of this paper is the description of a cable testing system that can be connected to an active, low frequency circuit and continuously monitor electrical characteristics using the time domain reflectometry (TDR) technique until an intermittent impedance change occurs. This technique uses the difference in frequency response of the circuit and the TDR to isolate the TDR signature from the active circuit data [1]. When a momentary impedance change occurs that exceeds a preconfigured limit threshold, the distance to fault data is automatically overlaid with the healthy baseline reference and stored in a database for diagnosis and repair.

Key Words: intermittent fault, cable degredation, neutron detectors

1 INTRODUCTION

All nuclear power plants (NPPs) rely on cable circuits to transmit instrumentation and control (I&C) signals and power to equipment important to plant operation. Cable failures have long been known to plant operators as precursors to reactor trips, inadvertent actuation of safety systems, limiting conditions for operation (LCOs), and spurious transients. As NPPs age worldwide, researching the effects of age-related degradation in safety systems and their associated cables is becoming a higher priority for long term plant reliability [2]. All NPPs, and other types of industrial facilities, suffer from intermittent faults in cable circuits. Accordingly, the Nuclear Regulatory Commission (NRC) has been increasingly concerned with cable qualification and condition monitoring particularly in NPPs that will operate beyond 60 years [3]. The need for an intermittent fault and health monitoring system for energized circuits has been expressed by industry contacts from many nuclear utilities [4]. The focus of this paper, and the research and development (R&D) described herein, is a recently developed system for identifying and locating intermittent faults in energized cables.

2 BACKGROUND

A cable circuit consists of three basic components: (1) a sensor or end-device, (2) cables that connect the end device to processing electronics or power source, and (3) connectors such as splices, junction boxes, and structural penetrations [5]. Any degradation in a circuit signal path, such as loose connections, equipment failure, or environmental stresses affect the reliability of the entire system. Many low voltage I&C circuits are used to transmit low frequency analog signals in a 4-20 milliAmp current loop. Other sensors, such as resistance temperature detectors (RTDs) and thermocouples (T/Cs) directly measure a process such as pressure, level, or flow and output small amplitude current and voltage changes to measurement electronics. Neutron detector circuits typically transmit low voltage and currents, in the tens of micro-volts range, in the form of high frequency pulses that are 100-200 nano-seconds wide. These pulses are then measured as discrete neutron measurements or cumulatively as a DC voltage to indicate neutron flux level. The primary challenge in detecting intermittent faults in vairous nuclear power plant I&C circuits is actively monitoring the test signal at the same time that the intermittent fault occurs.

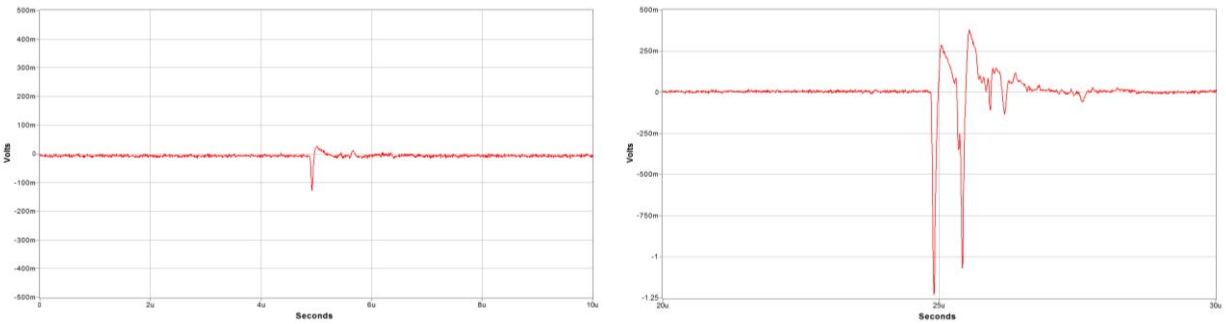
Any sensor that transmits small amplitude signals across long cable lengths are susceptible to noise interference and signal spiking as a result of intermittent faults in the cable shield, conductor, or connections. Cable failures have long been known to plant operators as precursors to spurious transients, inadvertent actuation of safety systems, limiting conditions of operation, and even reactor trips. Testing methods such as TDR and frequency domain reflectometry (FDR), mentioned in NRC Reg. Guide 1.218, *Condition-Monitoring Techniques for Electric Cables used in Nuclear Power Plants [6]*, can diagnose previously undetectable faults which lead to these failures.

3 INTERMITTENT FAULT EFFECTS ON CABLE CIRCUITS

Unlike hard faults (which are constant open or short circuits), intermittent faults are defined as a temporary change in impedance that may only last for a few milliseconds. While less noticeable than hard faults, signal spiking from intermittent faults can often lead to alarm conditions and reactor trips. A soft fault is defined as a subtle variation in the electrical characteristics of the circuit that still permit the continued operation of the circuit. A soft fault may be a precursor to a hard fault due to continued degradation of the fault over time. Following are three examples of intermittent cable faults in operating US NPPs [7]:

1. Intermittent ground problems in the circuits of five power supplies produced voltage dips which lasted only about 40 milliseconds but affected 600 annunciators. Years of troubleshooting has yet to reveal the root cause of this problem.
2. Containment pressure signals input to reactor protection system produce high and high-high alarms intermittently due to electromagnetic interference. Years of normal plant troubleshooting efforts could not determine the root cause of the problem until EMI/RFI experts were called in who simulated the problems off-site in a laboratory and helped determine the root cause.
3. Neutron detector channels would spike anytime the reactor building temperature rose above a threshold. After three years of troubleshooting, the root cause of the problem was identified to be faulty connections internal to the containment penetration.

The effect of intermittent faults on normal circuit operation is dependent on the frequency content of the signal to the nuclear plant measuring equipment. For example, a typical pressure transmitter signal output has frequency content below 100 kHz. Sensor response time measured in kHz is not susceptible to radio frequency interference (RFI) in the MHz to GHz frequency spectrum. However, in the case of neutron monitoring equipment, a single discrete intermittent fault can produce electrical noise with high frequency ringing that may be incorrectly measured as a sudden increase in neutron flux (Fig. 1). This false



Neutron output from detector (128 mV)

Electrical noise on detector cable (1.25 V)

Figure 1. Neutron measured as negative voltage pulse by detector (left), and intermittent electrical noise ringing on the same detector cable (right).

information can initiate automatic safety systems and cause an unplanned reactor shutdown. Fig. 1 shows two graphics measured on the source range neutron detector circuit in a US NPP. The plot on the left shows a typical pulse generated by a neutron passing through the ionizing gas volume of the detector. The plot on the right shows electrical noise on the detector cable with ringing that would be counted as several neutron events in quick succession. The goal of this technology is identifying the location of the degradation in the cable circuit that allows this noise to couple into the detector cable.

Electrical noise occurs on neutron detector circuits in a myriad of ways, which complicates troubleshooting efforts by nuclear plant personnel. For example, high frequency electrical noise can be coupled onto the shielding of the detector cable, and then onto the central cable conductor at a degraded connector. Or, mechanical looseness and vibration can intermittently make and break a circuit creating a voltage spike with ringing at each fault event. Certain types of neutron detectors are particularly susceptible to metal whisker growth across the detector electrodes. When small metal whikers almost completely bridge the detector electrode gap, arcing can produce erroneous indications of neutron activity. If left untreated, metal whisker growth can ultimately short circuit the neutron detector.

4 TECHNIQUES FOR CHARACTERIZING CABLE CIRCUITS

By performing a series of tests on a de-energized electrical/electronic cable, the condition of the cable and other components of the system can be determined. The results of the tests may be compared to baseline data, data from similar circuits, manufacturer's specifications, other measurements of the same system, and/or values calculated from circuit characteristics [8]. These comparisons are used to identify changes in the integrity of insulation, conductors, connectors, terminations and other circuit components. The following test techniques were applied to live cable circuits in a laboratory environment on representative cable circuits. An example of this test setup is shown in Fig. 2.

Figure 2. Developing techniques for testing live cables in nuclear power plant circuits.

Time Domain Reflectometry (TDR) — This non-destructive test is applied using a fast-rise time pulse that is transmitted between cable conductors, shield, or ground plane. Changes in impedance are reflected as a proportion of the incident voltage. The propagation delay of the incident pulse is converted to distance using the velocity of propagation of the cable type. TDR can identify potential defects in low voltage (LV) and medium voltage (MV) cable, and requires training and experience to analyze the test results.

The TDR test works on a live circuit that is not sensitive to high frequency signals. Most industrial plant sensors are low frequency devices that can be decoupled from the TDR signal online. Directional coupling devices and filters have been used to reduce the impact to the system electronics and input impedances of the TDR test equipment. Adjustments to TDR parameters such as repetition rate, amplitude, or duty cycle can prevent interference with most signal types.

Frequency Domain Reflectometry (FDR) — This non-destructive test is applied using an incident wave of varying frequency that is transmitted between conductors, shield, or ground plane of a cable circuit. Frequency domain phase changes in the reflected wave are caused by impedance changes. Distance to fault is calculated by performing an inverse fast fourier transform (FFT) on the reflected signal and using the velocity of propagation for the cable under test. This test is applicable to LV and MV cables and identifies and locates potential cable defects. FDR is more sensitive than TDR to certain types of impedance changes, such as with insulation degradation resulting from thermal aging. However FDR requires more training and experience to analyze data than the TDR technique.

The FDR test technique can be applied to live cable circuits. One limitation is the strength of the FDR signal relative to the signal strength in the circuit under test. If the signal is very small, then the FDR test can interfere with the signal if applied at sufficient amplitude to return a meaningful reflection. When applied to circuits with very small signal amplitude, the FDR signal strength may be reduced to the point that the FDR measurement becomes susceptible to noise and/or interference by the circuit's primary signal.

Impedance (Capacitance, Inductance, and AC Resistance) — The AC impedance of an electrical circuit is measured to determine whether an electrical circuit is changing due to the degradation of the insulating materials, which influences capacitance, or the degradation of the electrical wiring, which influences inductance. AC impedance is a combination of the resistance, inductance, and capacitance of the circuit, and must be defined at a given frequency.

AC impedance measurements for a particular electrical circuit are evaluated to determine if they are as expected for the type of circuit being tested. Imbalances, mismatches or unexpectedly high or low impedances between the cable leads would indicate problems because of cable degradation, possibly from faulty connections and splices or physical damage. Abnormal capacitance measurements are usually indicative of a breakdown in the insulation dielectric properties of the cable. Abnormal inductive measurements may be due to changes in the inductive properties of the electrical end device, cable conductors or connections, or they may be due to changes in the capacitive properties of the circuit.

Waveform Acquisition – When a circuit is spiking or acting erratically with long durations between events the issue may be EMI coupling or an intermittent cable fault. Prior to characterizing a system, it is recommended that the signal to noise ratio of the system be determined by recording the signal out of the system at its lowest analog level. This data can be used to trend the system output and the electrical noise levels. Electrical noise may be either a transient burst that will last only a few milliseconds, or continuous noise that repeats at a regular rate, usually some multiple of the fundamental frequency of 60 Hz. Multiple acquisitions may be performed to differentiate between transient noise and periodic noise. When applied to live cable circuits, this waveform information can differentiate between the normal operation of the signal on the channel as compared to the transient created by intermittent operational issues. For example, this information is useful when determining if electrical noise is being erroneously counted as neutron activity on neutron detector circuits.

5 LOCATING INTERMITTENT FAULTS IN LIVE CIRCUITS

A technological benefit of the novel approach described in this paper is the ability to perform diagnostic testing and analysis on live cable circuits; thereby monitoring impedance mismatches during normal operating conditions. Because no part of the circuit is required to be disconnected during fault detection, the device under test may remain in service with no disturbance to the plant operation. Therefore, the system has the ability to monitor and trend long-term cable circuit operation, including degradation in connections and end devices. For example, injection of a test signal into a live circuit in a nuclear power plant requires a very well-designed electronic isolation system and a means to generate and apply the test signal to the circuit under test.

First the Live Cable data acquisition process starts with the immediate acquisition of a normal circuit response using the following reference measurements: waveform capture, impedance, and reflectometry measurements. Then the system is set to monitor the circuit continuously, sending this periodic pulse down the circuit and comparing each consecutive measurement to the baseline until a difference is detected that exceeds a pre-defined threshold. The data is then automatically stored by the system and the location can be determined directly from the measured reflectometry data. When the threshold between the current data and reference data is exceeded, the additional measurements are then acquired according to the test configuration. Upon completion of the specified measurements, the live cable monitoring will terminate or continue based on the data acquisition operating mode. There are four types of data acquisition modes available for a live cable test configuration:

Single Shot	Acquires a single record of measurement data when the limit tolerance is exceeded.
Continuous	Acquires measurement data each time the limit tolerance is exceeded until the operator stops the acquisition cycle.
Step Trigger	Acquires measurement data when the limit tolerance is exceeded. After the specified number of step violations occurs, the limit tolerances are increased by the step percentage.
Update	Acquires measurement data when the limit tolerance is exceeded. After the specified number of step violations occurs, the reference measurements are updated.

6 PROTECTING LIVE CIRCUITS FROM INTERFERENCE DURING TESTING

Preventing the electronic test equiment from loading down the live circuit and preventing the test signal input from interfering with the NPP measurement equipment are two important considerations that were addressed under this R&D. When testing an energized circuit, the Live Cables Test System (LCTS) is teed into the energized circuit to send the reflectometry pulses along the cable under test. The pulses are then directed toward the load and away from the measurement electronics. This is accomplished by adding series inductance to direct the reflectometry impulse toward the field cable and end device and block the reflectometry signal from interfering with the nuclear plant measuring equipment.

This was accomplished by developing custom coupling and isolation test adapters that are placed in series with the signal cable of the circuit under test. For example, Fig. 3 is an illustration of a circuit board design that has been impedance matched to 75 Ohms for neutron detector circuits with BNC connectors to tee the LCTS cable into the signal cable. The isolation capacitors and series inductors are integrated into this printed circuit board (PCB).

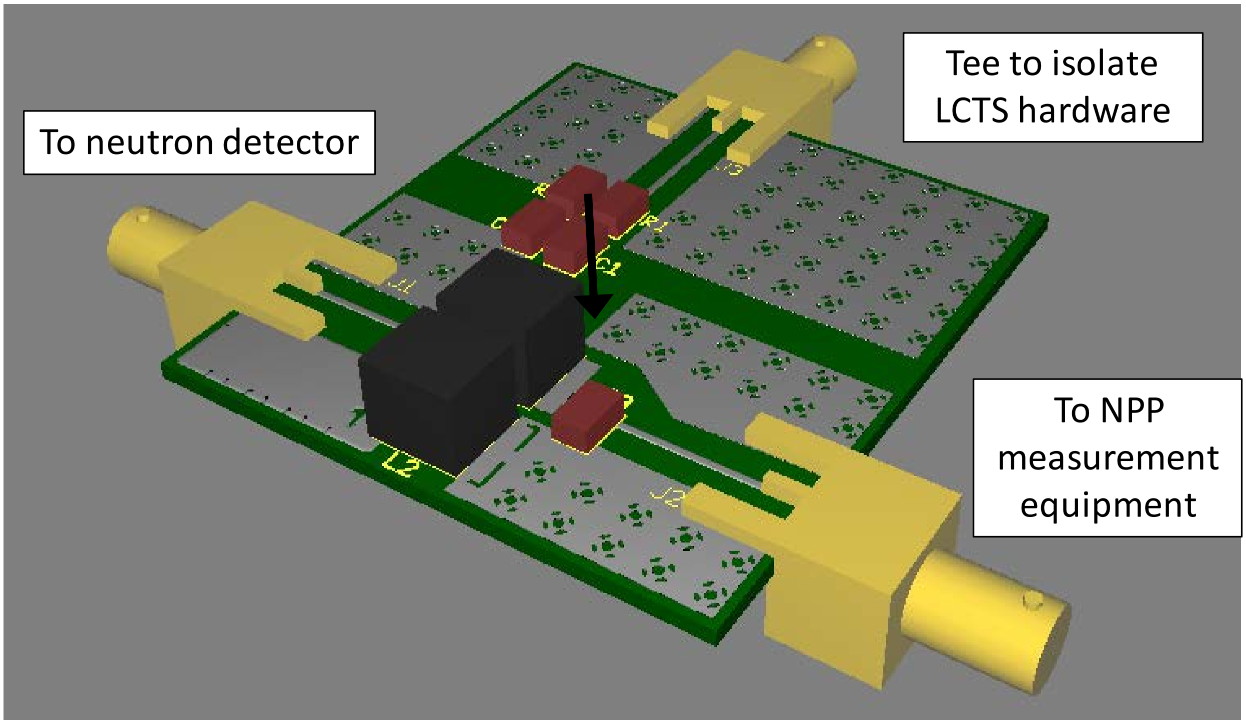


Figure 3. Circuit illustration of coupling and isolation mechanism.

7 REFLECTOMETRY MONITORING OF LIVE NEUTRON DETECTORS

There are several types of neutron detector circuits that are used to monitor reactor power and neutron flux levels for the various types of nuclear power plants. The types of nuclear plants used in the US are pressurized water reactors (PWR) that are manufactured by Westinghouse, Babcock and Wilcox, and Combustion Engineering Companies. The boiling water reactor (BWR) plant types in the US are made by the General Electric Company.

All nuclear reactors have a reactor protection system (RPS) that is designed to automatically and safely shut down the reactor to prevent the release of radioactive materials. An integral component of the RPS are neutron detector circuits. These are located outside the reactor pressure vessel in PWRs and inside the reactor vessel in BWRs. The neutron flux monitoring system typically consists of a control cabinet with measurement electronics and high voltage power supply, coaxial or triaxial shielded cables, a signal amplifier, and the neutron detector. Each of these NPP types have subtle differences in the design of the neutron flux monitoring system.

For simplicity in this report, a generic type of radiation monitoring circuit will be used to describe the testing methodology that may be applied to all types of neutron flux monitoring circuits. Fig. 4 shows a neutron detector circuit with the the HV supply circuit going out on the center conductor of one cable with a return on the center conductor of the signal cable.

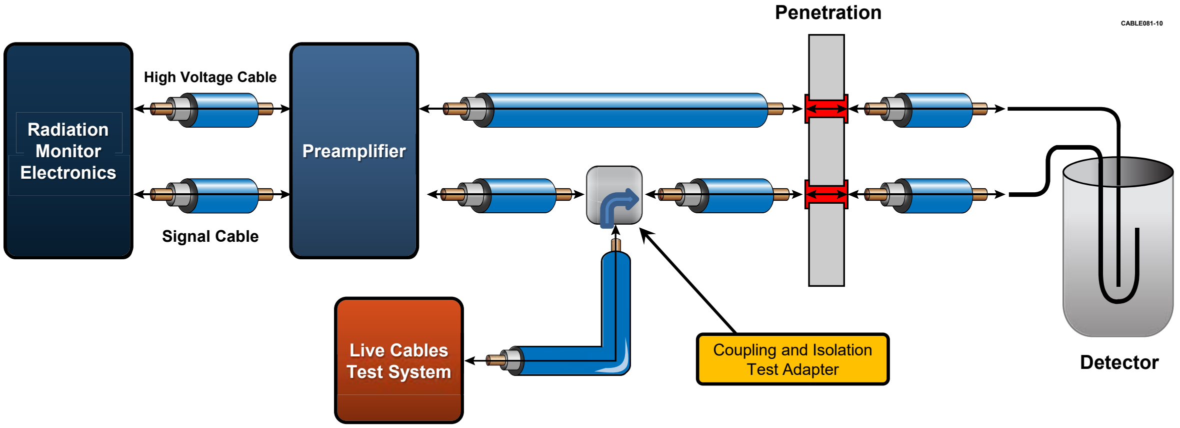


Figure 4. Neutron detector circuit configuration showing LCTS connections.

In neutron detector circuits, a high voltage and low current DC excitation voltage is sent to the detector, and low voltage and low current output pulses are sent back to the plant measurement equipment from the detector. A souce range detector measures each neutron impact as a discrete event. As reactor power increases from source range to intermediate and power ranges, these discrete neutron pulses become so frequent that they are counted as a DC signal level representing neutron flux. A loose or intermittent connection will prevent this signal from being correctly measured by the plant processing electronics.

Both a source and intermediate range neutron detector circuit have been assembled in the AMS laboratory for use as a test bed for this R&D project (Fig. 5). The source range detector has a typical operating voltage up to 1,800 VDC. The intermediate range detector is typically operated at 800 VDC.

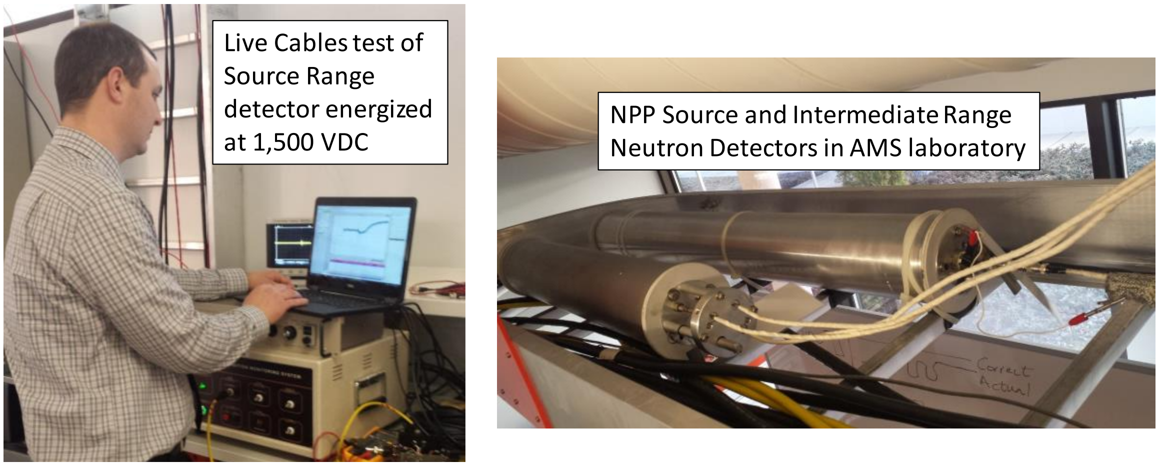


Figure 5. Laboratory testing source range neutron detector live at 1,500 VDC.

The following reflectometry plot is an example of an intermittent open circuit fault detection in a source range neutron detector circuit that is energized at a normal operating voltage of 1,500 VDC. The circuit components include the source range neutron detector with integral mineral-insulated shielded cable, 75-feet of shielded coaxial cable, the LCTS intermittent fault detection equipment, a high voltage power supply, a custom-made coupling and isolation device, and an oscilloscope to monitor the detector output. The data in Fig. 6 shows the healthy baseline reference TDR signature of the intermediate range detector circuit in blue, with the intermittent fault signature overlaid in red. The shaded region is the TDR threshold boundary that will trigger data acquisition when the circuit impedance exceeds the user-configurable limit. A vertical black line automatically marks the distance to the impedance change, thereby alerting the user that a fault was diagnosed and where the problem is located in the circuit.

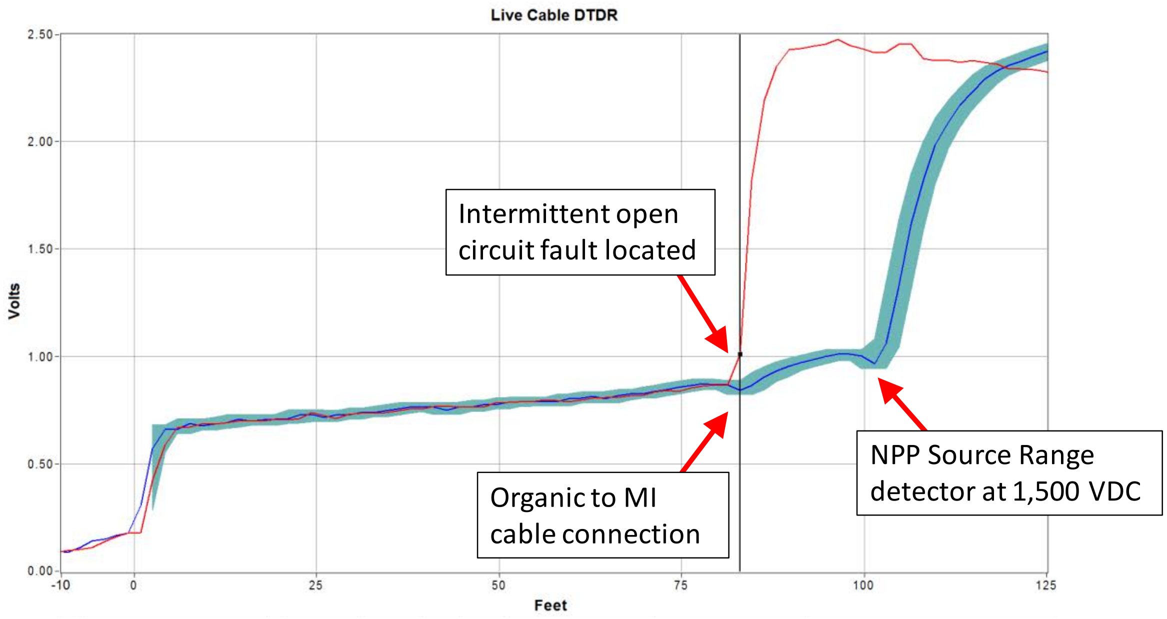


Figure 6. Intermittent fault location in an energized source range neutron detector circuit at 1,500 VDC normal operating voltage in AMS laboratory.

8 FIELD TRIALS OF LCTS IN OPERATING US NPPS

The LCTS hardware was recently used to repeatedly acquire reflectometry data on a de-energized power range neutron detector circuit in an operating US NPP (Fig. 7). There are impedance changes that are typical of neutron detector circuits, such as the test connection, the containment penetration, and the mineral insulated cable leading to the neutron detector connection. These characteristic impedance signatures are used as landmark references when interpreting the location of circuit problems, and they are annotated in the distributed impedance plot in Fig. 8. Reflectometry signatures are expected to be very repeatable when acquired successively, so any deviations from one signature to the next would trigger an automatic acquisition of an impedance anomaly.

Figure 7. Field trials of LCTS hardware and software in an operating US NPP.

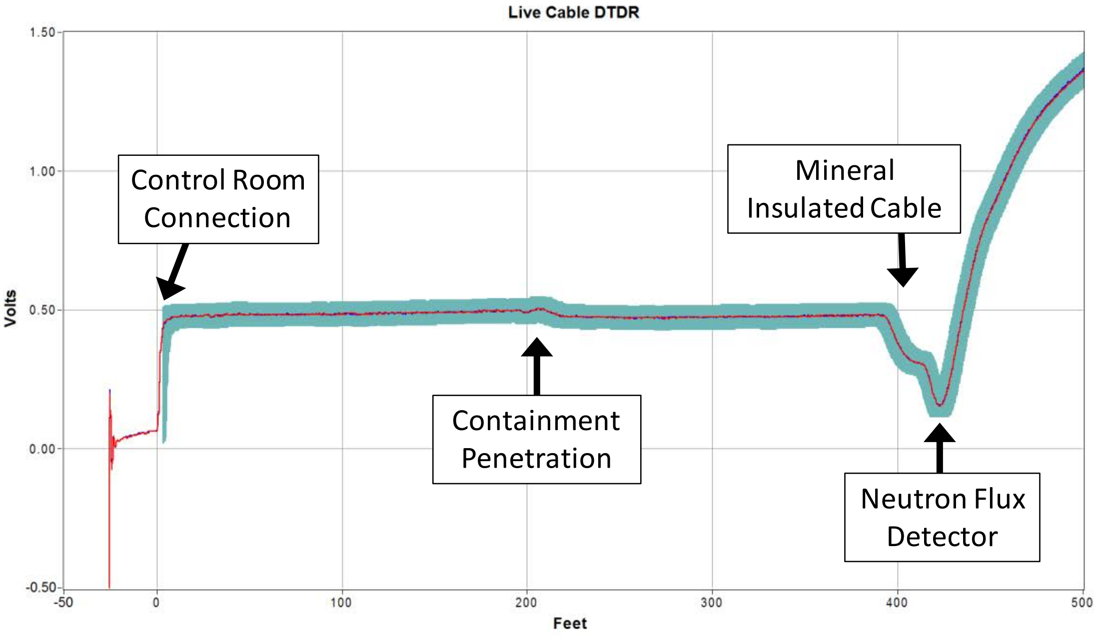


Figure 8. LCTS data acquired on a de-energized power range neutron detector in a US NPP.

When performing cable testing field services, the circuit will first be de-energized and placed into test mode. Then the detector cable will be disconnected at the location of the preamplifier assembly, or in the case of a power range neutron detector, inside the control room. A capacitive coupling adapter will be teed into the signal cable, with a series inductance installed between the test equipment and the preamplifier. The neutron detector circuit can then be restored to normal operational voltage and the LCTS will actively monitor the detector signal cable for intermittent faults, signified by momentary impedance changes. Any anomalies are automatically acquired and saved to the database archives for timely diagnosis and repairs.

9 CONCLUSION

Performing online diagnostics will reduce outage times and maintenance costs which in turn reduces the cost to the electrical utility. The detection of faults in the normal operation of safety-related or otherwise critical circuitry will enable wide-ranging risk reduction due to improved diagnostics, accurate representation of environmental effects, and trending capabilities. Dealing with the symptoms of intermittent connections can be a drain on the resources of the NPP and locating the intermittent connection can be a difficult and time-consuming task.

Additionally, installation and maintenance practices can affect the development of intermittent connections. As such, the prototype product of the research described in this paper has been successful in demonstrating that intermittent faults are detectable through online monitoring of live cables. This research has also revealed that significant challenges must be overcome to allow for continuous online monitoring of live cables in an operating nuclear power plant. A substantial part of the remaining work will be devoted to development and testing of these systems to ensure that the test equipment is benign to the function of the plant circuits and will not affect the plant operation. This verification and validation work is currently in progress through laboratory simulations of various high voltage, low current NPP circuits, such as neutron detectors and radiation monitors.

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