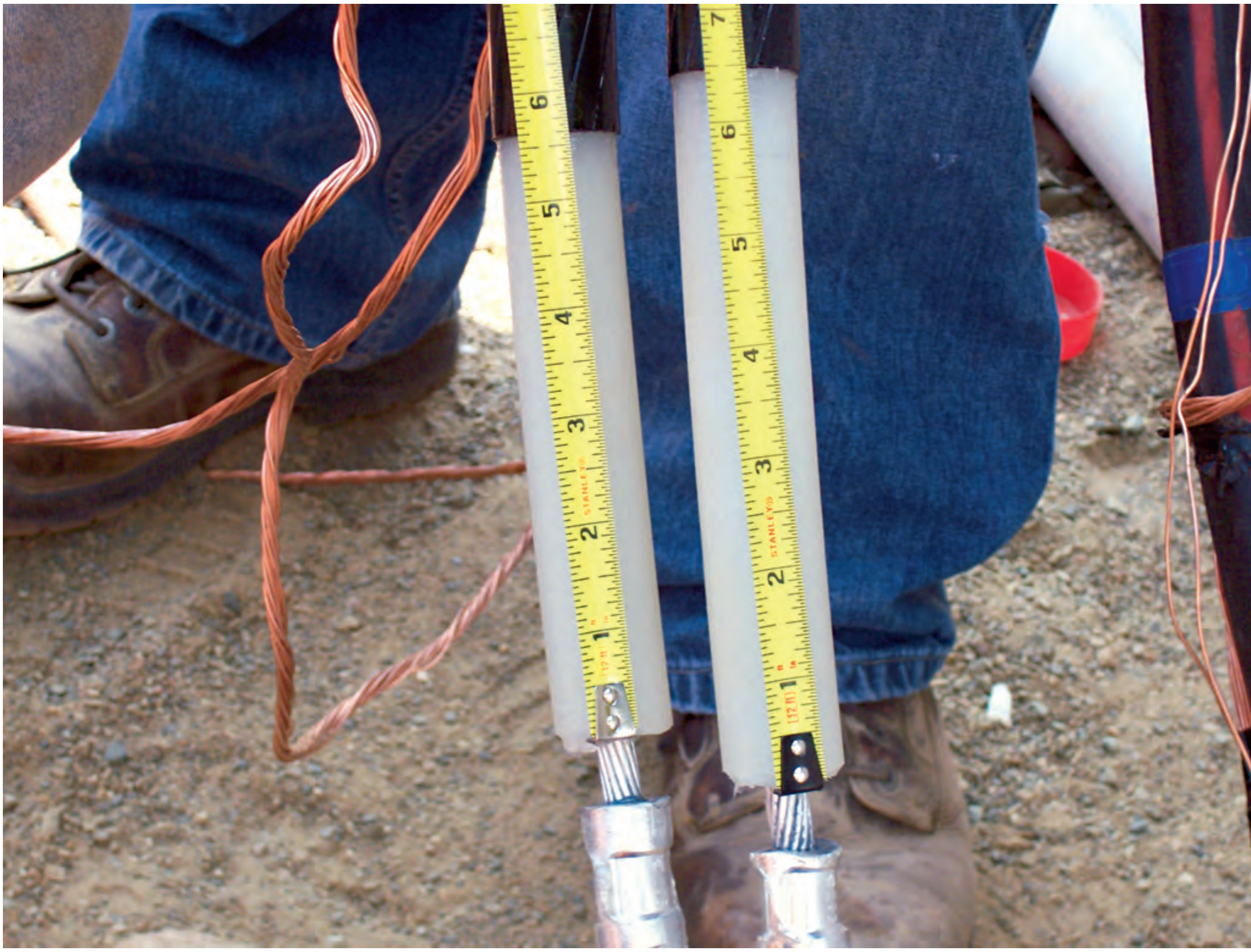

Specifying Cable System Reliability

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Power cable diagnostics enable consulting engineers to specify and commission cable systems

Consulting engineers have been specifying DC Hi-Potting to commission newly installed power cable systems for the past century. While this cable test is very popular, the question remains whether it is effective in locating cable system defects that may cause future cable system failures? If not, is there an adequate alternative to ensure that the cable system is free of defects and has been properly installed per the requirements of IEEE cable system standards? Here, I will address this topic based on experience obtained over the past ten years. But first, some history.

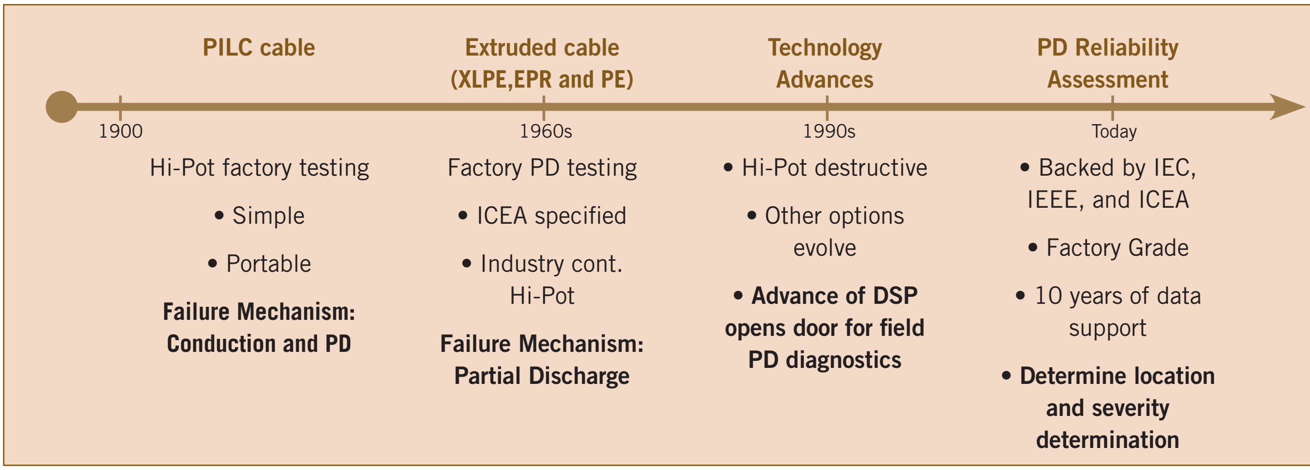


Figure 1. Timeline of cable system testing

HISTORY OF CABLE TESTING

The origin of shielded power cable (5-kV-rated cable and above) testing goes back approximately 100 years, when paper-insulated lead-covered (PILC) cable was first installed in the rapidly expanding United States electrical distribution grid. While it was not fully understood at the time, the primary failure mechanisms of PILC cable falls into two categories: PILC cable will fail either thermally, mostly due to moisture ingress, which tends to increase insulation conductivity (approximately 40% of failure incidences); or it fails due to the electrical phenomenon known as partial discharge (approximately 60% of failure incidences).

The development of the DC Hi-Pot test (now categorized by IEEE as a Type 1 Destructive Withstand Test) by the cable manufacturers was very successful in causing conductive defects to fail in the PILC cable. However, at that time the technology to detect partial discharge activity in the cable did not exist. Since the DC Hi-Pot test equipment was inexpensive and simple to use, it was quickly adopted for field use throughout the electrical industry.

When extruded dielectric cable (i.e. HMWPE, XLPE, EPR) was introduced in the 1960s, the cable manufacturers were aware that the primary failure mechanism of this type of insulated cable was partial discharge (over 95%). In order to implement cable manufacturing quality controls it was necessary to develop the means to detect this electrical phenomenon in their factories. While the factory partial discharge test—known as a corona test back in the ‘60s—was able to detect partial discharge in their cable, it involved expensive equipment and required a fabricated shielded environment to conduct the test.

The NETA Testing Specs

The National Electrical Testing Assn. *Maintenance Testing Specifications* was developed for use by those responsible for the continued operation of existing electrical systems and equipment to guide them in specifying and performing the necessary tests to ensure that these systems and apparatus perform satisfactorily, minimizing downtime and maximizing life expectancy.

The NETA Acceptance Testing Specifications is a document to assist designers, specifiers, architects, and users of electrical equipment and systems in specifying required tests on newly-installed power systems and apparatus, before energizing, to ensure that the installation and equipment comply with specifications and intended use as well as with regulatory and safety requirements.

NETA’s specifications include topics such as Applicable Codes, Standards, and References; Qualifications of the Testing Agency; Division of Responsibility; General Information concerning Testing Equipment; Short Circuit Analysis and Coordinating Studies; System Function Tests; and Thermographic Surveys.

A major featured section includes tests to be performed on Switchgear and Switchboard Assemblies, Transformers, Cables, Metal-Enclosed Busways, Switches, Circuit Breakers, Network Protectors, Protective Relays, Instrument Transformers, Metering and Instrumentation, Grounding Systems, Ground Fault Systems, Rotating Machinery, Motor Control, Direct Current Systems, Surge Arresters, Capacitors, Outdoor Bus Structures, Emergency Systems, Automatic Circuit Reclosers and Line Sectionalizers, Fiber-Optic Cables, and Electrical Safety Equipment.

Therefore, the DC Hi-Pot test continued as the most recognized option for field cable system integrity testing, even though it was known by the manufacturers to have limited value. In fact, "from the work of Bach (TU Berlin), we know that even massive insulation defects in extruded dielectric insulation cannot be detected with DC at the recommended voltage levels." (IEEE 400, section 4.2) In addition, "A major objection to Type 1 field tests is the concern that application of elevated voltages without any other accompanying diagnostic measurements trigger failure mechanisms that will not show during the test but which may cause subsequent failures in service." (IEEE 400, Section 4.3)

This left a significant void in the industry's ability to effectively test new or existing shielded power cable systems until the mid-nineties when Dr. Matthew Mashikian, an innovative engineering professor at the University of Connecticut was able to utilize evolving digital signal processing technologies to replicate the cable manufacturers' factory test in practical field applications (Figure 1, p.27).

This technology, known as off-line 50/60 Hz partial discharge diagnostics, has been developed over the past 10 years in the utility industry and has evolved into a robust condition assessment and predictive diagnostics solution for power cable.

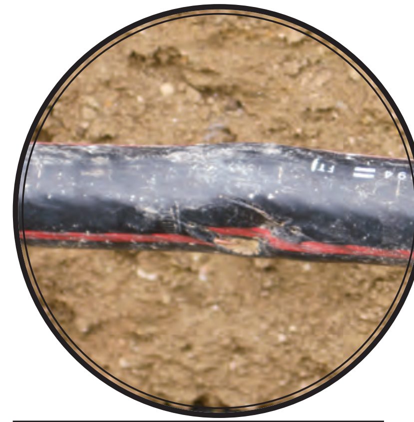
PARTIAL DISCHARGE DIAGNOSTICS

Off-line 50/60 Hz partial discharge diagnostics offers a major advantage over traditional DC and AC withstand test, because it enables the cable owner to pinpoint the exact defect location providing the details necessary to take precise action without destroying the cable. Type 2 non-destructive off-line partial discharge diagnostics also provides a second major advantage which is the ability to determine the future performance of the cable system.

During its service life, a cable will be subjected to overvoltage conditions caused by switching, lightning and other transient events. Any test conducted at operating voltage will be unable to simulate in the cable system the conditions which may produce partial discharge during operation. Therefore, in order to effectively predict the future performance of the cable system, a partial discharge test at a reasonably elevated voltage must be conducted, as stipulated by IEEE and ICEA. IEEE 400 section 7.4 states that "if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory [off-line 50/60 Hz PD diagnostics test on the cable and accessories], it is the most convincing evidence that the cable system is in excellent condition." Hence, each component of the system, the cable, joints and terminations have their own acceptable level of discharge (see Figure 2 below) defined by IEEE and ICEA.

Because the offline 50/60 Hz partial discharge diagnostic approach is non-destructive and predictive, it represents a significant breakthrough for consulting engineers designing applications where reliability of critical loads is important. It is now possible for cable system installation quality levels to be quantified, and therefore, specified by owners and consulting engineers. The power of this technology is evident when it is realized that certain defects subjected to a IEEE 400 Type 1 destructive withstand test did not fail, yet were located without failure by the IEEE Type 2 non-destructive partial discharge technology.

Consulting engineers developing specifications for facilities such as data centers, casinos, hospitals, industrial sites and other critical-load facilities are now empowered to establish specific installation quality parameters based on IEEE and ICEA standards (see Figure 2) to assure that their cable system designs meet the required reliability level desired by their user clients.



The above defect was not detected by IEEE 400 Type 1 withstand test. It was detected and located by the IEEE 400 Type 2 off-line 50/60 Hz PD diagnostics. This type of diagnostic provides a second advantage: the ability to determine the future performance of the cable system.

IEEE Standard	Thresholds
IEEE 48-1996 Terminations	No PD ≥ 5pC up to 1.5Uo
IEEE 404-2000 Joints	No PD ≥ 3pC up to 1.5Uo
IEEE 386-1995 Separable Connectors	No PD ≥ 3pC up to 1.3Uo
ICEA S-93-639-2000 MV Extruded Cable	No PD ≥ 5pC up to 4Uo

Figure 2. IEEE and ICEA standards for allowable partial discharge in various cable system components

Testing Technology

The non-destructive diagnostic test from Imcorp is based on pulse reflectometry and time-of-arrival techniques. At the core of the technology is an expert system that uses cutting edge digital signal processing techniques and high performance electronics. This system empowers the user to locate defects and make decisive recommendations for maintenance. The technology makes use of the power frequency (50/60Hz) to excite defects in the cable being tested. Power frequency testing exactly replicates service conditions and allows comparisons to be made to standard factory tests. In laboratory tests and comparative field tests, the technology has proved itself especially in the presence of high ambient noise.

Acquisition of the cable topology allows the user to locate cable joints and neutral discontinuities, and to determine the cable length. Sensitivity calibration allows the subsequent test to be compared to the baseline cable factory test. The HV diagnostic tests apply continuous 50/60 Hz voltage to the cable for a few seconds. During this time, the system takes measurements and stores the data. The operator turns off the high voltage and analyzes the data with the help of the proprietary software system. A preliminary report and recommendations are produced on site.

A TEST CASE

A utility asked us to perform a PD test on a 1,405-ft. long, 25-kV Class, 1000 kcmil XLPE feeder cable. According to the PD test results, multiple defects in the cable insulation were present. The utility then asked a manufacturer of a VLF voltage source to perform a VLF Hi-Pot on the cable.

If any of the condemned phases survived, the PD test would be repeated on those phases.

THE SETUP

According to the manufacturer of a VLF source, a 25-kV class cable should be tested with 0.1Hz VLF at 3xUo for 30 minutes. This may be confusing for some because 3xUo equals 3x13.2 kV rms, or 39.6 kV rms. The IEEE guide for VLF Hi-Pot field testing (IEEE 400.2) recommends 23 kV rms for 25-kV cables. During the experiment, the manufacturer of the VLF source explained that even though their equipment only produces a maximum of 23 kV rms, they claim that only the peak voltage needs to reach ~40 kV to have an effective VLF Hi-Pot. The manufacturer made the following statements:

Electrical tree growth rate is 472 mils/hr or 12mm/hr in XLPE insulation.

A VLF Hi-Pot left on for 30 minutes will grow any significant defect to failure in a 25-kV class cable.

If the cable fails within the 30 minute Hi-Pot test, the cable is "bad."

If the cable survives the 30 minute Hi-Pot test, the cable is "good."

Only 3% to 4% of cables that test "good" will fail within the next three years.

It is recommended that the 30 minute VLF Hi-Pot be repeated after a failed cable is repaired to ensure reliability.

THE RESULTS

Each phase was VLF Hi-Pot tested independently. The results follow:

'A' phase survived 31 minutes of VLF HIPOT.

'B' phase failed after 20 minutes of VLF HIPOT application.

'C' phase failed after a prolonged dwell time of 37 minutes. (The operator of the test lost track of time and forgot to stop the Hi-Pot at 30 minutes.)

As for the PD Diagnostic test results, the only cable which could be retested was 'A' phase, since the other two phases failed during the test. 'A' phase was known to have three cable PD (defects) sites from the previous test. In addition to three sites, the second PD test showed seven new sites after the 30 minute VLF Hi-Pot test.

The three original PD sites appeared at a test voltage closer to operating voltage after the VLF Hi-Pot demonstrating deterioration at each location. Note that the comparative PD tests were carried out within minutes of the VLF Hi-Pot to ensure that the most accurate comparison could be made.

FINALCONSIDERATIONS

While IEEE 400 Type 1 withstand test (DC and AC Hi-Pot) provide some value when testing older PILC cables, they may not be effective in locating defects in extruded dielectric insulated cables. Furthermore, they may unknowingly trigger failure mechanisms that may cause subsequent failures in service.

On the other hand, IEEE 400 Type 2 non-destructive off-line 50/60 Hz partial discharge diagnostics provide valuable information concerning the quality and workmanship of a newly installed or aged cable system. This information includes detecting cable defect locations and determining their severity in accordance with the preset acceptable limits (see Figure 2). Therefore, corrections can be made to assure that the cable system is in excellent operating condition before the system is placed into service.

What does all of this information add up to for the consulting engineer? As mentioned at the beginning, consulting engineers have been specifying DC Hi-Potting to commission newly installed power cable systems for the past century. But it's time to consider whether there is an alternative to this type of testing. There is an adequate alternative that ensures that the cable system is free of defects and has been properly installed per the requirements of IEEE cable system standards. END