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## *Featured in this Issue:*

- Strategies for Field Testing Medium Voltage Cables
- Unconventional Diagnostic Methods for Testing Generator Stator Windings
- The Electro-Chemical Basis of Manhole Events

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FEATURE ARTICLE

# *Strategies for Field Testing Medium Voltage Cables*

**Key words:** Partial discharge, cable testing, failure, reliability, condition assessment

**Wally Vahlstrom**

*Emerson Process Management, Electrical Reliability Services, Inc. Pleasanton, CA*

*Guidelines are presented for assessing the serviceability of medium-voltage cables. Part 1 reviews available test methods, Part 2 discusses failure mechanisms, and Part 3 provides test suggestions.*

## Part 1—Available Test Methods

### A. Introduction

In power systems where failures and power outages are unacceptable, preventative maintenance activities must be a priority; but what is the best way to monitor the condition and maintain the integrity of medium-voltage (MV) cables within such a system? Should we follow the recommendations of the National Fire Protection Association (NFPA) 70B *Recommended Practice for Electrical Equipment Maintenance* standard, or the recommendations of the Institute of Electrical and Electronics Engineers (IEEE) 400-2001, *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems* standard, which discusses six testing options? Should we use the IEEE 400.1, 400.2, or 400.3 standards? Should we consider other tests? Some cable test equipment manufacturers and cable testing service providers are adamant that only their methods are effective and appropriate. In fact, some claim that some equipment or methods will damage the cable and decrease its remaining service life. How should we choose among the various options?

There are many factors to consider. How old is the MV cable system and what is its current condition? Is it paper insulated lead covered (PILC) cable or does it have extruded insulation, such as cross-linked polyethylene (XLPE), tree retardant cross-linked polyethylene (TRXLPE), or ethylene propylene rubber (EPR)? (In the remainder of this paper the generic abbreviations XLPE and EPR will be used for simplicity to refer to these two basic insulation types). What is the load on the cable and what is its rating? Has the system been exposed to significant voltage transients? We would like to know the nature of any previous failures—were they really cable failures or were they splice or termination failures? If practical, we might want to dissect the failures. Did the failures occur in risers? Were they in duct locations or in cable tray? What was the nature of the environment where the failure occurred—was the operating temperature especially high or low; was it a wet or contaminated location? We would want to consider such information when evaluating the wide variety of available preventative maintenance options.

### B. Cable Testing Standards

In the United States there are more than ten industry standards that provide information about field-testing MV cable and components. The IEEE 400 standard (including the 400.1, 400.2, and 400.3 series) might be the most widely used, but there are several others, including those available from the National Electrical Manufacturers Association/Insulated Conductors Engineers Association (NEMA/ICEA), the Association of Edison Illuminating Companies (AEIC), NFPA, and the InterNational Electrical Testing Association (NETA).

What do the industry standards recommend? For more than 50 years, the most widely accepted test method was the dc Hipot test. The IEEE 400.1 standard provides test voltages for dc Hipot testing and indicates this is still an acceptable method for testing PILC cables; dc Hipot testing is also recognized as acceptable for new EPR and XLPE cables, but in the last 10 to 15 years, much has been written about how dc Hipot testing can cause damage to and premature failure of field-aged EPR and XLPE cables. As a result, many standards are either silent regarding dc Hipot testing of field-aged EPR and XLPE cable,

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or they recommend other types of testing. The IEEE 400-2001 standard provides the following cautions about dc Hipot testing: “Testing of cables that have been service aged in a wet environment (specifically XLPE) with dc at the currently recommended dc voltage levels…..may cause the cables to fail after they are returned to service….. The failures would not have occurred at that point in time if the cables had remained in service and not been tested with dc….. Furthermore.….we know that even massive insulation defects in extruded dielectric insulation cannot be detected with dc at the recommended voltage levels.” For additional detail regarding field-testing of MV cable, the reader should refer directly to the IEEE 400-2001 standard. (It should be noted that standards mentioned here, including the IEEE 400 series, are continuously undergoing review and updating).

## C. IEEE 400 test methods

A short summary of the advantages and disadvantages of each of the six optional tests, as outlined in the IEEE 400-2001 standard, follows:

### *Method 1: DC Hipot*

Advantages

- Relatively simple and light test equipment, in comparison to ac, good portability.
- Input power supply requirements readily available.
- Extensive history of successful testing of laminated dielectric cable systems and well established database.
- Effective when the failure mechanism is triggered by conduction or by thermal influence.
- Effective on interface joint and termination problems, and termination surface problems
- Purchase cost generally lower than that of non-dc test equipment for comparable kilovolt output.

Disadvantages

- Blind to certain types of defects such as clean voids and cuts.
- May not replicate the stress distribution existing with power frequency ac voltage. The stress distribution is sensitive to temperature and temperature distribution.
- May cause undesirable space charge accumulation, especially at accessory-to-cable insulation interfaces.
- May adversely affect future performance of water-tree-affected extruded dielectric cables.
- Leakage current readings may have wide variations because of atmospheric conditions, and lack of control of charges at termination lugs.

### *Method 2: AC Hipot*

Advantages

- Readily available at $V_o$ (normal line voltage).

Disadvantages

- Heavy equipment, expensive for voltages above $V_{o.}$
- Does not assess condition of insulation.

### *Method 3: VLF (Very Low Frequency) Hipot*

Advantages

- Because of continuous polarity changes, space charges cannot develop.
- Cables can be tested with an ac voltage up to three times the normal phase to ground voltage.
- Works best when eliminating a few singular defects from otherwise good cable insulation. Can be used to “fault” the cable defects without jeopardizing the cable system integrity.
- When a cable passes the recommended 0.1Hz test, it can be returned to service.

Disadvantages

- When testing cables with extensive water tree damage or ionization of the insulation, it is often inconclusive. Additional tests that measure the extent of insulation losses are then required.
- Long testing times required.

### *Method 4: Tan-Delta (also known as dissipation factor testing)*

Advantages

- Tan-delta measurements permit assessment of aging or damage in the cable insulation.
- Cables are tested with an ac voltage up to $3V_{0.}$
- All tests are performed at operating or lower frequencies.
- Suitable for extruded and laminar types of insulation.
- If a cable fails the test it can be returned to service until repaired or replaced.
- Regular tan delta measurements will establish a cable deterioration history.

Disadvantages

- When a cable passes the test it is not possible to declare the cable insulation sound, because a localized defect in a long cable may not be detected.
- A breakdown test is necessary to identify any large defects in the insulation.

### *Method 5: Partial Discharge*

Advantages

- Modest size, weight and cost.
- Useful for both laminar and extruded insulation types.
- Frequencies in the range 0.1 to 60 Hz are available.
- Measures and pinpoints defects.

Disadvantages

- Trained operators required.
- One large PD site may mask others.
- Mixed dielectrics generate confusing results.

### *Method 6: Oscillating Wave (OSW)*

The IEEE 400 OSW standard states: “Most of the tests carried out so far are of an experimental nature.” Consequently, it seems reasonable to conclude that OSW has not yet been developed sufficiently to be considered a routine or fully recognized field test. The standard goes on to say: “These test procedures were intended to obtain breakdown as a criterion for comparison.” The last step in the test procedure states: “Proceed until breakdown occurs.” Thus the IEEE 400 OSW procedure always results in failure of the cable under test. It seems that, at present, the OSW method is primarily a laboratory test technique, and needs further development to become a practical field test. Consequently OSW will not be discussed further here.

As stated previously, the IEEE 400 standards are undergoing continuous review and updating. Future revisions of these standards are likely to be concerned with low voltage dc leakage current measurements, the application of lower VLF Hipot and tan-delta test voltages, and commercially available damped ac (previously OSW) test methods.

## D. Online vs. offline tests

Test methods that require the cable system to be taken out of service are referred to as offline tests, whereas those that may be performed while the cable system remains energized are referred to as online tests. Hipot and tan-delta tests must be performed offline, whereas partial discharge tests can be performed online or offline.

## E. Type 1 vs. Type 2 tests

Tests can also be generally categorized as withstand tests or as condition assessment tests. The purpose of withstand tests is to cause the cable system to fail at defects or areas of deterioration so that such areas can be identified. The cable can then be replaced or repaired and returned to service. Withstand tests usually involve voltage overstress—applying a voltage higher than normal operating voltage to force areas of deterioration to fail during the test. Those who favor such test methods have concluded it is better to cause a failure during testing, make repairs, and return the cable to service, than to experience a failure and unplanned outage during normal system operation. Opponents of withstand testing argue that overstressing the insulation could cause damage and unnecessarily reduce the remaining service life of good insulation. Withstand methods such as dc Hipot, ac Hipot and VLF Hipot testing may provide data that indicate a trend, but their primary purpose is to cause any defects to fail.

The purpose of condition assessment tests is to produce test data without causing failure. Methods such as tan-delta or partial discharge testing are designed primarily to produce quantitative and trend-indicating data. Condition assessment testing may require application of higher than operating voltages, but the overvoltage is not applied for the purpose of causing defective areas to fail. In the case of online partial discharge testing, the test is performed at normal line voltage with no interruption in service. It results in zero abnormal voltage stress to the cable system.

The current version of the IEEE 400 standard defines Type 1 tests as field tests “…intended to detect defects in the insulation of a cable system in order to improve the service reliability after the defective part is removed and appropriate repairs are performed…” In the discussion above, such tests are referred to as withstand tests.

The IEEE 400 standard describes Type 2 field tests as “... intended to provide indications that the insulation system has deteriorated…” It describes Type 2 tests as diagnostic. In the discussion above, such tests are referred to as condition assessment tests.

Testing new cable that has been spliced to cable which has been in service for several years presents a unique challenge. Whereas it is necessary to specify tests appropriate for each component when formulating maintenance and testing programs, usually tests which will avoid overstressing the field-aged cable are specified.

# Part 2 – Damage and Deterioration Mechanisms

## A. Introduction

We consider now the main mechanisms by which MV cable systems can deteriorate or be damaged. They are mechanical and installation damage, operational damage, and age-related deterioration.

## B. Mechanical and Installation Damage

Cable system components can be damaged mechanically during handling in the factory, shipment, handling at the warehouse or job site, during installation, and by dig-ins or other physical means (settling of the earth, etc.) during operation. Such damage can involve cuts, scrapes, excessive sidewall force, and possibly the intrusion of water into the strands of the core conductor. Cuts, scrapes, and excessive sidewall force may be immediately catastrophic and prevent the cable from being successfully energized, or they may result in damage to the jacket, the insulation shield, or outer portion of the insulation on XLPE or EPR cables. Once in service, damage to the insulation shield or insulation is likely to produce partial discharge and lead to failure. Damage to the jacket may allow water to permeate the space between the jacket and insulation shield and result in corrosion of the metallic shield. Failure to connect the metallic shield properly can also lead to failure. The voltage and current normally carried to ground by the metallic shield may produce leakage current and tracking if not correctly connected or if left unconnected. Tracking can erode the insulation shield and insulation, eventually leading to significant deformation of the stress gradient and failure of the cable. Water intrusion into the conductor of PILC cable can be a serious problem, because intrusion of moisture into the oil-impregnated paper insulation may lead to increased leakage current, localized thermal runaway and eventual failure. The presence of water in the strands of XLPE or EPR cable may be a problem if the internal pressure causes the water to migrate from the cable along the interfaces and exit at a splice or termination. The water would provide a conductive path from the cable core conductor (operating at phase voltage) along the interfaces, and exiting at the joint between the outer layer of insulation semicon on the cable and the outer layer of semicon on the splice or termination (ground potential). Short circuit and failure are then likely.

Physical damage to the lead sheath of PILC cable could allow oil to leak out and/or provide a path for water to enter and be absorbed into the insulation. Loss of oil would probably lead to voids and result in partial discharge when the cable was energized. As mentioned above, intrusion of moisture into the insulation is likely to cause increased leakage current, localized thermal runaway, and eventual failure.

Medium-voltage cable system designs are quite complex. Whereas all designs include a metallic core conductor insulated from ground by some type of dielectric, many different materials and constructions have been used over the years. A typical cable design includes: the core conductor (copper or aluminum), a semiconducting conductor shield, the insulation (most typically oil impregnated paper or extruded EPR or XLPE), a semiconducting insulation shield, and a metallic shield (usually lead, copper tape or copper wires). The cable may have an overall jacket made of PVC, polyethylene, neoprene, or other extruded materials. The splices and terminations are equally complicated and must be specifically designed to make a watertight, electrically and mechanically compatible connection to the cable. Whereas the cable and pre-molded connecting devices can be manufactured very accurately by machine in a tightly controlled factory environment, terminations are manually assembled and fitted to the cable under field conditions. Consequently, splices and terminations are likely sources of defects leading to cable system failures. Whereas cables, splices, and terminations can all suffer from occasional manufacturing defects, the manually assembled components will generally have a considerably higher failure rate because of the difficulty of ensuring quality control during the field assembly/installation process.

Dig-ins, fires, and other forms of accidental damage are also likely to cause failures over the life of cable systems.

## C. Operational Damage

Operational damage can occur when the cable system is exposed to severe load cycling, overloads, or short-circuit currents. Load cycling can result in linear expansion and contraction of the cable and can cause work hardening and cracking of the lead sheath or chaffing of EPR or XLPE cables. Load cycling may have a more severe impact on splices and terminations because they may be physically restrained and may therefore experience significant compressive or tensile forces. Such forces may cause components within the splice or termination to shift, resulting in voids or gaps at insulating and semiconducting interfaces which could lead to partial discharge. Overloads and short-circuit currents can have similar or even greater effects. They can produce high temperatures that lead to deformation of XLPE and EPR cable materials and result in gaps or voids. In severe cases, the deformation may allow migration of core conductor within the insulation, or migration of shield wires into the insulation semicon, or even into the insulation (especially where the cable passes through bends or where there is significant sidewall force caused by pressure from adjacent cables, supports, or restraints). Gaps and voids produce partial discharge. If no gaps or voids are created but the insulation/conductor geometry is changed by overheating, the damage may not lead to partial discharges, but may reduce the dielectric strength of the insulation. In extreme cases, this may lead to localized leakage current. Heat generated by overloads or short-circuit currents within PILC cable is likely to produce localized charring, leading to increased leakage current and reduced dielectric strength.

## D. Age-Related Deterioration

Age-related deterioration of PILC can result in waxing or depolymerization of the impregnating oil, migration of the oil (especially away from riser sections and splices), and decomposition of the paper. Such deterioration can result in voids which will produce partial discharge or result in local charring, increased leakage current, and reduced dielectric strength. Age-related deterioration of EPR and XLPE cable can result in loss of adhesion between the insulation and semicon insulation screen, leading to gaps or voids at this interface and partial discharge. The most frequently discussed form of age-related deterioration of EPR and XLPE cable is water treeing, resulting from moisture permeation of the insulation in the presence of electrical stress (a phenomenon known as dielectrophoresis). According to the IEEE 400.3 standard, “water trees do not generate partial discharge.” Water trees may take many years to grow sufficiently large and dense to reduce the dielectric strength of the insulation significantly. However, given sufficient time, well-developed water trees may be converted to electrical trees (especially if accelerated by lightning or other overvoltages) and produce partial discharge. Figure 1 provides a simplified graphical representation of hypothetical deterioration in water treed XLPE or EPR cable. In this example, hypothetical PD inception and extinction voltages are plotted over the life of the cable. The graph depicts two scenarios: one in which the cable is subjected to four overvoltages, and one in which there are no overvoltages. It should be noted that water trees will also reduce the dielectric strength of cable insulation. Although not shown, the impulse withstand capability of the cable will also decrease as the size and density of water trees increase with time. Corrosion of the metallic shield of EPR and XLPE cables can lead to problems similar to those discussed previously in the context of improper or missing connection of the metallic shield. The voltage and current normally carried to ground by the metallic shield may produce leakage current and tracking if the metallic shield becomes ineffective or disappears completely because of corrosion. The resultant tracking can erode the insulation shield and insulation, eventually leading to significant deformation of the stress gradient and failure of the cable.

## E. Combined Installation, Operation and Age-Related Deterioration

Consider a large, utility-sized new XLPE or EPR cable system, installed but not tested. We would expect a number of failures over the life of the system. Assume no acceptance or maintenance testing, only repair of failures. During the first year or so, several splice and termination failures would be expected. As noted earlier, splices and terminations are field- assembled and are therefore prone to an “infant mortality” failure rate (see Figure 2). A few early failures caused by installation damage would also be expected. In the years between initial installation

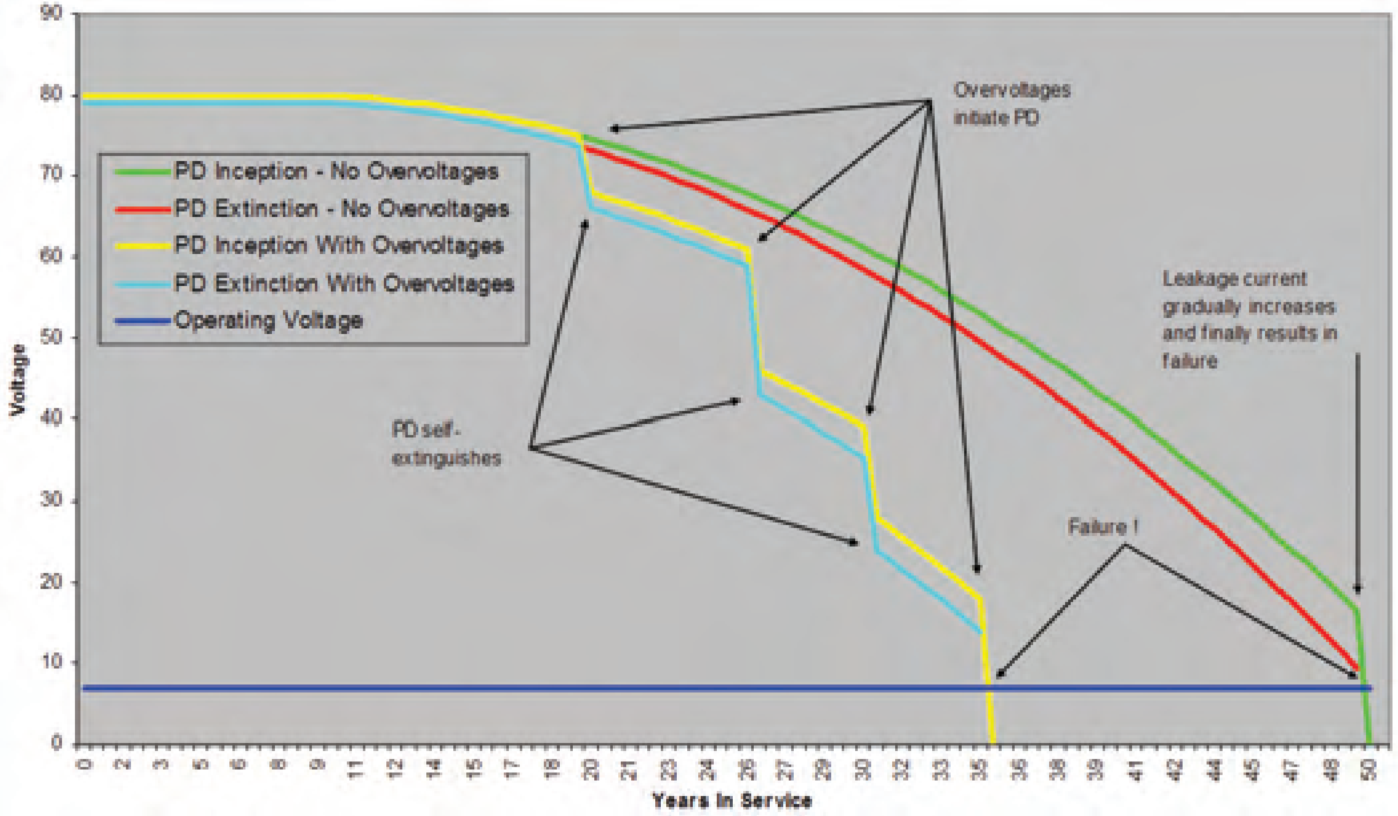

*Figure 1. Simplified depiction of hypothetical reduction in PD inception and extinction voltage for XLPE or EPR cable caused by water treeing.*

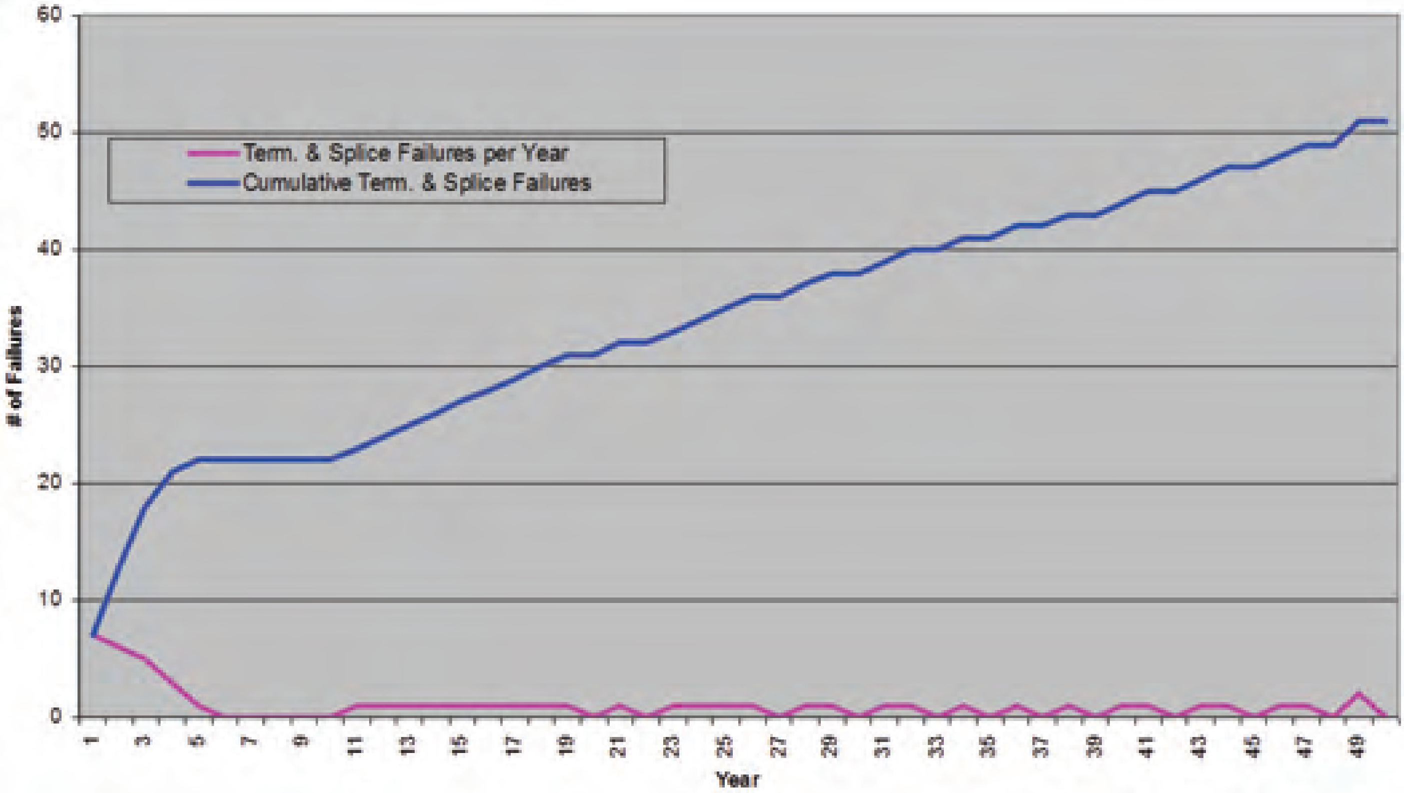

*Figure 2. Hypothetical XLPE/EPR cable system failure profile—Termination and splice failures (only). Several splice/termination failures occur early, followed by a few at a nearly constant rate as the system ages.*

and end-of-life, occasional termination failures caused by contamination, physical stress caused by load cycling, workmanship issues during installation, or some combination of these, would be expected, along with dig-ins or other mechanically-induced failures. As the system nears end-of-life, a significant increase in the number of cable failures caused by the conversion of water trees to electrical trees would be expected (see Figure 3). The combination of termination and cable failures is shown in Figure 4.

Similar graphs depicting scenarios for PILC cable systems are shown in Figures 5–7. PILC cable systems are generally more reliable than EPR or XLPE systems, and are not subject to water treeing.

## Part 3 – Choosing a Test Method

### A. Matching Test Methods to Types of Deterioration

To choose the best test method, it is important to understand the types of damage or deterioration each of the available tests will detect. It is also important to understand the type of data each test will provide; partial discharge cannot be identified by dc Hipot testing, a disconnected or corroded neutral conductor cannot be identified by tan delta testing, and a damaged jacket cannot be found by partial discharge testing. Clearly, not all testing methods are appropriate or useful for all cable types. Table 1 provides information regarding the types of cable system defects which can be identified using various test methods. It lists each of the common types of damage or deterioration, and suggests which types of test would be most effective in assessing the relevant damage or deterioration.

### B. Matching Test Methods to Types of Cable System Installation

In Table 2, cable systems and conditions are listed, along with the test methods which would be most effective in identifying the types of damage or deterioration for each system/condition combination. If a neutral corrosion problem were suspected in a 20-year old cable, a time domain reflectometry (TDR) test would be preferred to a VLF Hipot test. On the other hand, if baseline data were to be acquired so that future trends could be monitored in a just-installed cable system, partial discharge and tan-delta testing would be preferred to dc Hipot testing. Likewise, if water tree deterioration was suspected in a 25-year old XLPE cable system, tan delta testing would be preferred. However, it should be noted that tan-delta testing would be effective in detecting large numbers of large water trees, but probably not effective in detecting small numbers of small water trees.

Table 2 provides a simplified strategy for determining which test types would be most appropriate under given circumstances.

### C. An Example

Assume that a cable system has been in service for more than 40 years, and that sections have been added at various times over

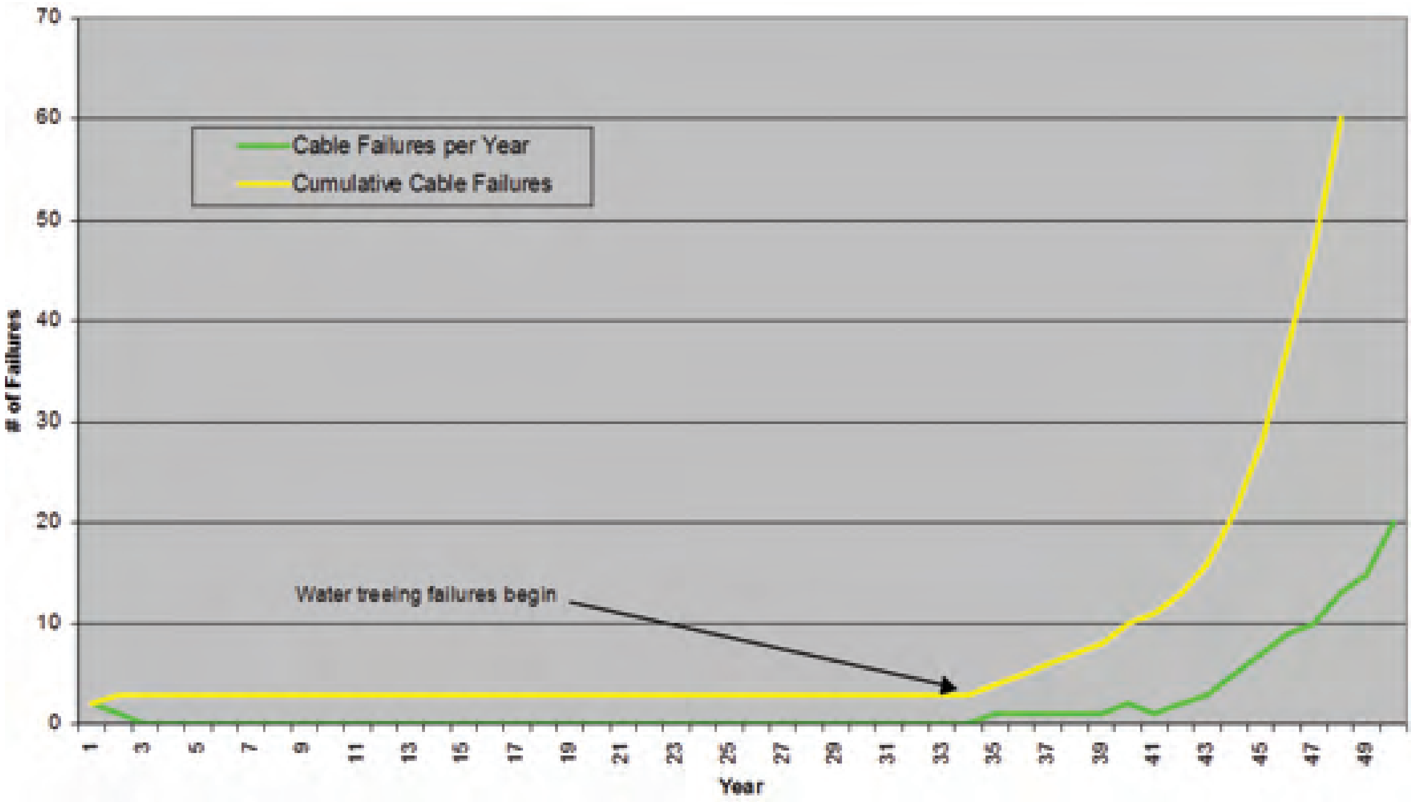

*Figure 3. Hypothetical XLPE/EPR cable system failure profile—Cable failures (only). Two failures occur early, with very few until near end of life when water trees convert to electrical trees.*

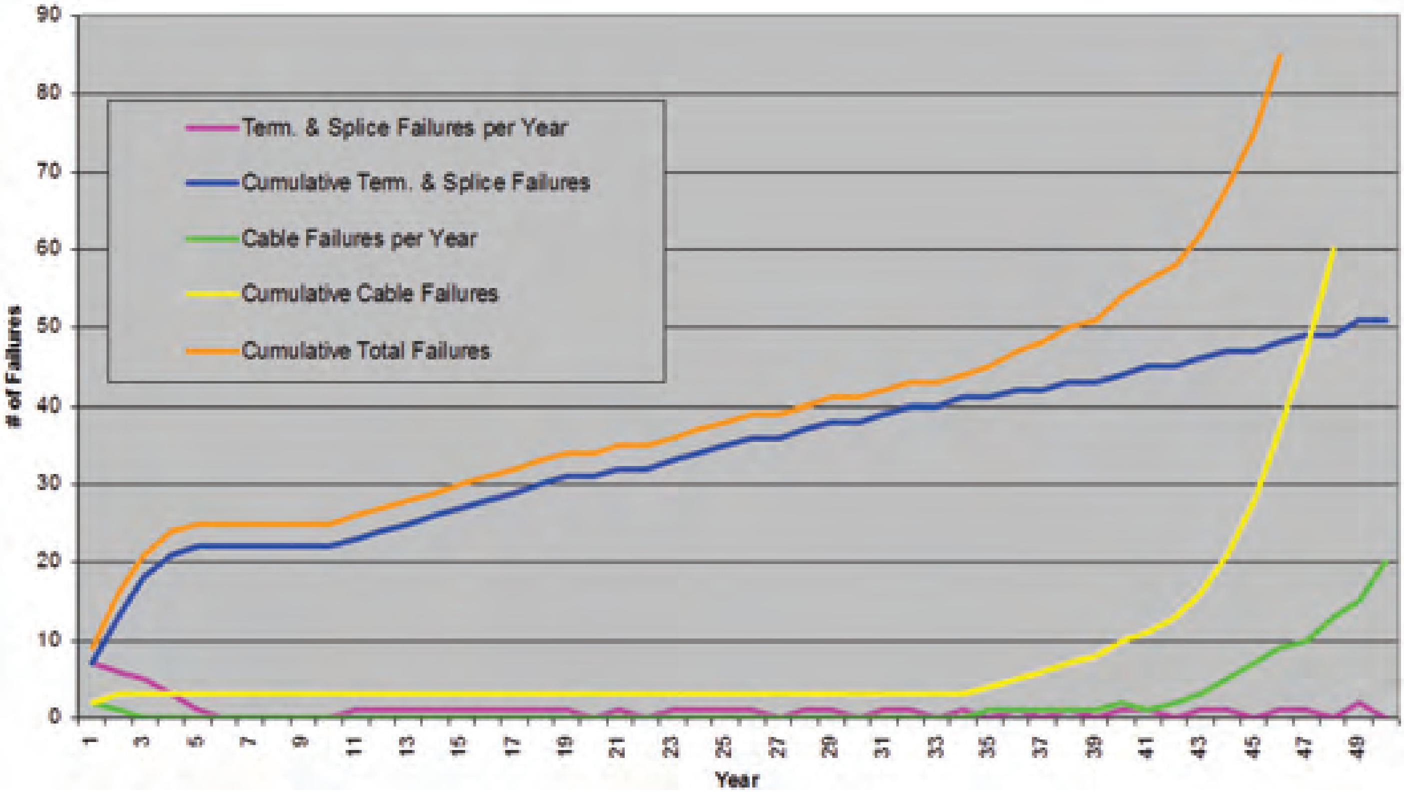

*Figure 4. Hypothetical XLPE/EPR cable system failure profile—Cumulative failures from all causes. The failure rate is dominated by termination failures until near end of life when water trees convert to electrical trees.*

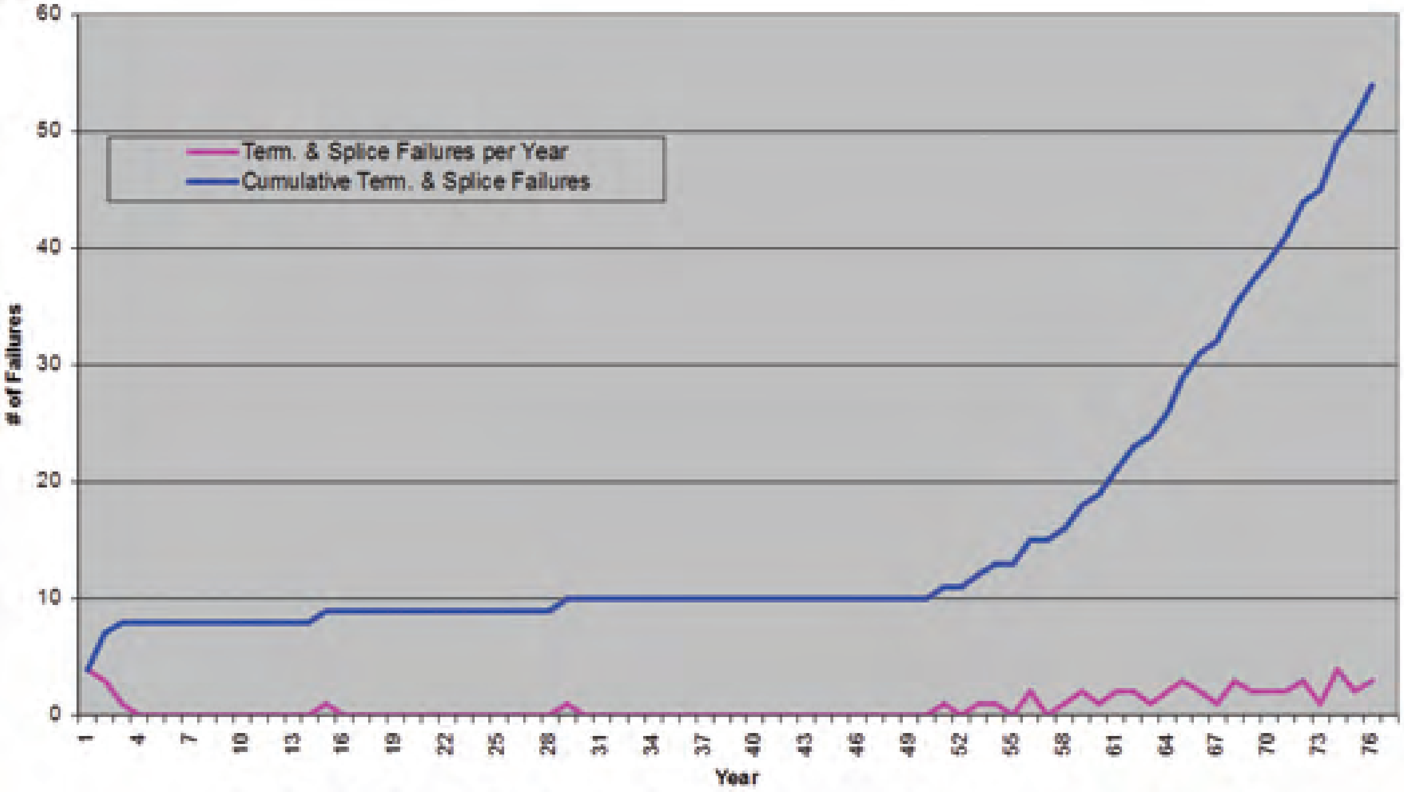

*Figure 5. Hypothetical PILC cable system failure profile—Termination and splice failures (only). Several splice/termination failures occur early, followed by a few at a nearly constant rate as the system ages.*

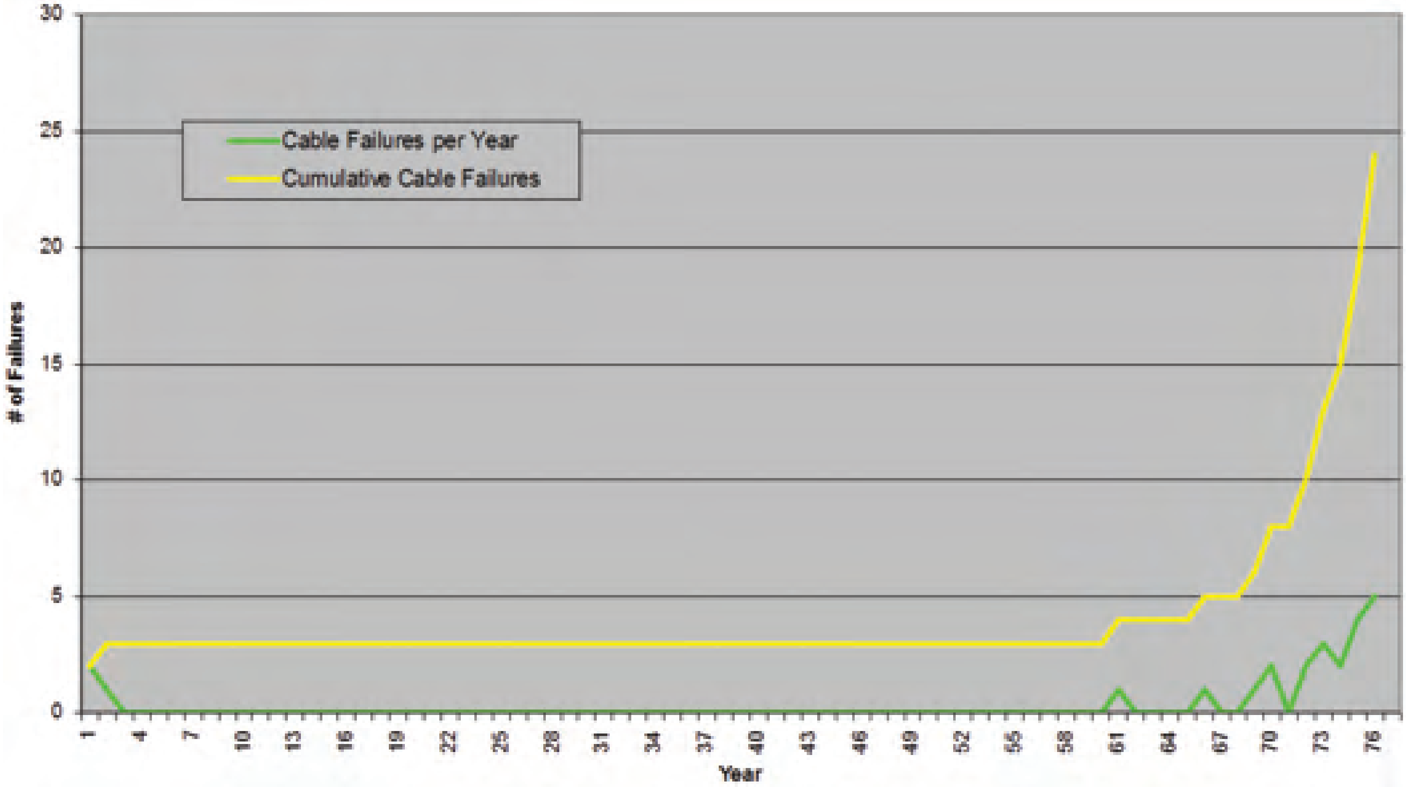

Figure 6. Hypothetical PILC cable system failure profile—Cable failures (only). Two failures occur early, with very few until near end of life.

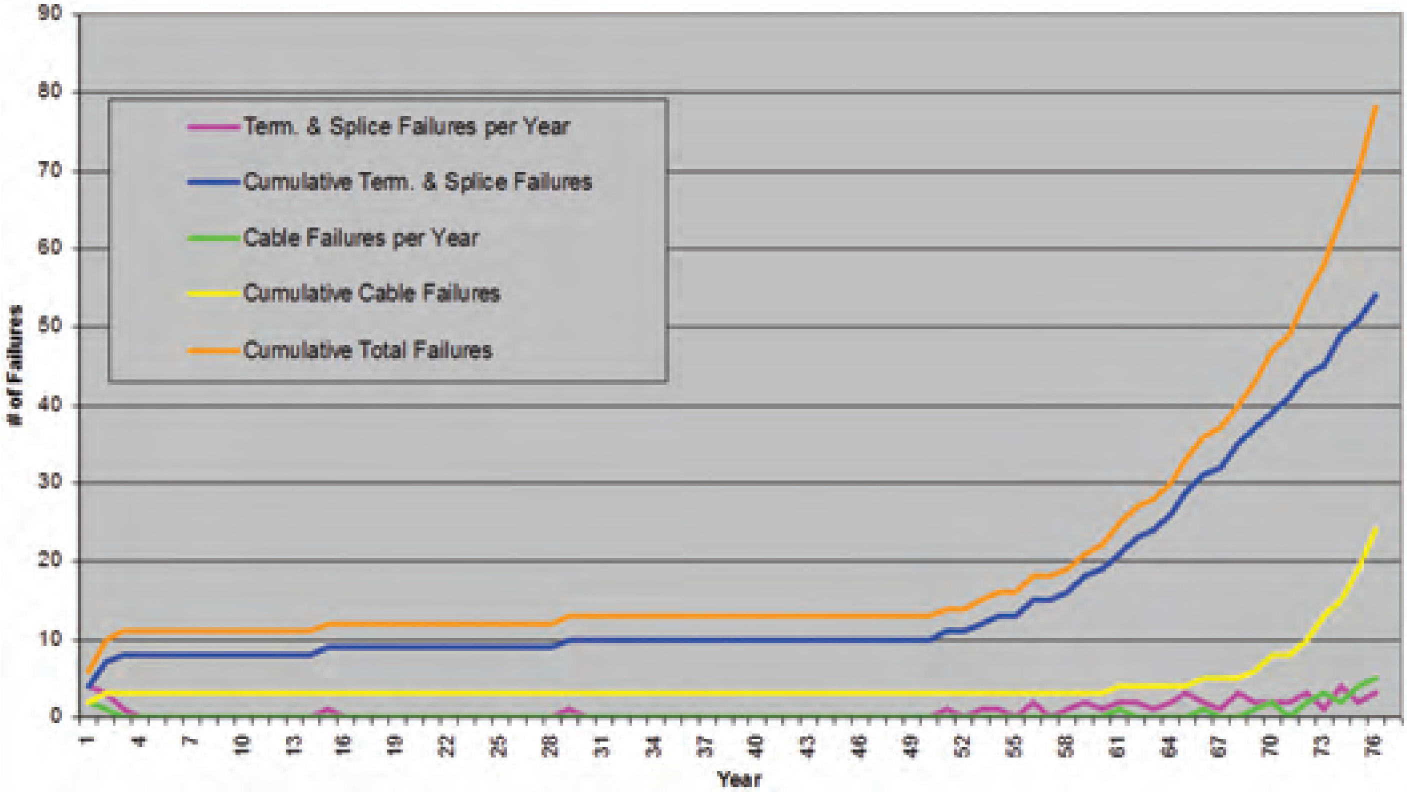

Figure 7. Hypothetical PILC cable system failure profile—Cumulative failures from all causes. The failure rate is dominated by termination failures until end of life.

**Table 1. Cable System Deterioration Assessment Test Methods: Cross-Linked Polyethylene (XLPE) and Ethylene Propylene Rubber (EPR) Cables.**

| Deterioration or defect | Failure mechanism | Test methods likely to detect such deterioration | |
|---|---|---|---|
| | | Cable | Terminations and joints |
| 1. Physical abuse of the cable during installation or dig-in or other physical stress during operation. Causes tears, gouges, cuts, gaps, cracks, tears, or punctures in, or deformation of semicon or insulation. Poor workmanship or physical abuse of the termination resulting in incorrect overlap or gaps at interfaces, or nicks in the insulation. | Such imperfections typically result in non-uniform electric fields, involve voids, and produce PD. Continued PD will erode, carbonize, and cause the insulation to fail. | PD | PD or TEV<br>(Because these defects are typically inside the termination, not on the surface, ultrasound will be a less effective detection method.) |
| 2. Contamination on terminations. Improper spacing of unshielded portions of terminations. | Contamination and improper spacing can result in surface discharges and tracking. Tracking leaves a carbonized pat h and results in increased electric field stress concentration, increased carbonization and eventual failure. | N/A | PD, TEV, or ultrasound |
| 3. Improperly connected, damaged, or corroded drain wire or corroded or damaged metallic shield. | Discontinuities in the metallic shield or drain wire can result in leakage current concentration that will produce tracking across the surface where the shield or drain wire is discontinuous. Tracking leaves a carbonized path, results in increased electric field stress concentration and increased carbonization and eventual failure. | PD or TDR | PD, TEV, or TDR<br>Ultrasound if problem is at termination. |
| 4. Water trees. | A. Water trees will generally not directly cause failure but will reduce dielectric strength. Water-treed insulation has a lower dielectric strength and is susceptible to failure by lightning or other transient overvoltage.<br>B. Water trees do not produce PD. Water treed cable may operate for years without failure.<br>C. In time, water trees will grow larger and convert to electrical trees. | Tan-delta | N/A<br>(Cables are more susceptible to water trees than terminations.) |
| 5. Electrical trees resulting from water trees. | Electrical trees produce PD. Continued PD will erode, carbonize, and cause the insulation to fail. | VLF to cause the weak spot to fail.<br>PD<br>(However, it should be noted that much literature indicates that XLPE or EPR cable insulation exposed to continued PD will likely fail in only days or months). | N/A<br>(Cables are more susceptible to electrical trees resulting from water trees than are terminations.) |
| 6. Overload | Heat produced by the overload causes physical and chemical deterioration of the dielectric and leads to physical deformation, decreased insulation resistance, increased leakage current, carbonization of the leakage current path, and failure. The deterioration process may result in PD if it produces a void or gap in the insulation or semicon materials. (Terminations and splices tend to be more susceptible to this form of deterioration than cable runs.) | PD<br>VLF to cause the weak spot to fail. | PD or TEV<br>VLF to cause the weak spot to fail. |
| 7. Damaged jacket | Damage of a jacket on EPR or XLPE cable will probably not result in failure but may allow water to enter and cause corrosion of the metallic shield. | Insulation resistance. (The measurement would be made between metallic shield and ground.) | N/A |

Types of tests
Insulation resistance – Such tests are typically made with a 500 V insulation test unit.
PD – Partial Discharge testing. This type of testing can be performed either online or offline.
Tan-delta – Tan-delta, dissipation factor, power factor, dielectric spectroscopy, or oscillating wave type testing are all claimed to be able to detect water treeing in XLPE or EPR cables. These tests must be performed offline.
TDR – Time Domain Reflectometry This type of testing must be performed offline.
TEV – Transient Earth Voltage testing. This type of testing involves capacitive coupling and detects the RF signals produced by partial discharges. Must be performed online.
Ultrasound – Ultrasonic testing. This type of testing must be performed online.
VLF – Very Low-Frequency Hipot testing. This type of test must be performed offline.

**Table 1 (Continued). Cable System Deterioration Assessment Test Methods: Paper (and Oil) Insulated, Lead Covered Cables.**

| | | Test methods likely to detect such deterioration | |
|---|---|---|---|
| **Deterioration or defect** | **Failure mechanism** | **Cable** | **Terminations and joints** |
| A. Oil migration caused by elevation changes along cable run or incomplete impregnation of the paper. Hole or crack in lead sheath (see B below) allows oil to leak out. | Leads to voids that produce PD. Continued PD will erode and carbonize the insulation, and result in failure. | PD<br>Hipot may also be used to measure leakage current and cause the weak spot to fail. | PD or TEV<br>Hipot may also be used to measure leakage current and cause the weak spot to fail. |
| B. Physical abuse to cable during installation or dig-in or other physical stress during operation (such as repeated thermal expansion/contraction caused by load or temperature cycling) causes cracks or gaps in the lead sheath and allows water to leak in, locally permeating the paper insulation. | Leads to localized insulation deterioration, decreased insulation resistance, increased leakage current and eventual failure. | Tan-delta<br>Hipot to cause weak spot to fail. | Tan-delta<br>Hipot to cause weak spot to fail. |
| C. Poor workmanship or physical abuse of the termination results in incorrect overlap or gaps at interfaces, or nicks in the insulation. | Such imperfections typically result in non-uniform electric fields, involve voids and produce PD. Continued PD will erode, carbonize and fail the insulation. | N/A | PD or TEV<br>(Because these defects are typically inside the termination, not on the surface, ultrasound will be a less effective detection method.) |
| D. Contamination on terminations. | Contamination can result in surface discharges and tracking. Tracking leaves a carbonized path, results in increased electric field stress concentration and increased carbonization and eventual failure. | N/A | PD, TEV, or ultrasound |
| E. Overload | Heat produced by the overload causes physical and chemical deterioration of the dielectric. Leads to decreased insulation resistance, increased leakage current, carbonization of the leakage current path and failure. The deterioration process may result in PD if it produces a void or gap in the insulation or semicon materials. (Terminations and splices tend to be more susceptible to this form of deterioration than cable runs.) | Hipot to cause weak spot to fail.<br>PD may also be an option. | Hipot to cause weak spot to fail.<br>PD or TEV may also be an option. |

Types of tests
Hipot – dc Hipot, ac Hipot or VLF Hipot. These tests must be performed offline. (dc Hipot should not be performed on field -aged XLPE or EPR cable.)
PD – Partial Discharge testing. This type of testing can be performed either online or offline.
Tan-delta – Tan-delta, dissipation factor, power factor, dielectric spectroscopy, or oscillating wave type testing are all claimed to be able to detect water treeing in XLPE or EPR cables. These tests must be performed offline.
TEV – Transient Earth Voltage testing. This type of testing involves capacitive coupling and detects the RF signals produced by partial discharges. Must be performed online.
Ultrasound – Ultrasonic testing. This type of testing must be performed online.

the years. Assume also that the oldest cables are PILC and have a very good record, but the majority of failures have involved hand-taped terminations in the 20 to 25-year old EPR circuits. Under these circumstances, row three of Table 2 recommends PD testing to detect possible termination contamination or insulation deterioration, and tan delta testing to detect possible water treeing. VLF Hipot testing would also be an option. Partial discharge testing would identify terminations producing PD, and would also provide trend data.

## Conclusion

Without intervention, medium voltage cable systems will deteriorate, fail, and cause power outages. For most users, power outages are unacceptable. It is therefore critical that cable system owners develop a reliable method for periodically assessing the condition and serviceability of their cable systems, allowing for corrective action before failures occur. However, deciding which tests to perform can be a major challenge, because there are many cable types, a large number of deterioration mechanisms, and many available test methods. This article attempts to clarify the issues involved in condition assessment of cable systems. It outlines the available test methods, reviews deterioration and failure mechanisms affecting the common cable types, and, in Tables 1 and 2, provides simplified guidelines for deciding which tests will provide the best condition assessment information for each situation.

**Table 2. Testing Recommendations.**

| Cable System/Condition | Which Tests to Perform | |
|---|---|---|
| | **Recommended** | **Optional** |
| Cross-Linked Polyethylene (XLPE) and Ethylene Propylene Rubber (EPR) Cable | | |
| Newly installed<br>Possible defects: 1, 2, 3, or 7 | PD to establish baseline value and to detect possible termination workmanship defects or cable installation damage. | Tan-delta to establish baseline value.<br>TEV or ultrasound to detect possible termination workmanship defects.<br>Hipot to cause failure of possible insulation defect.<br>TDR to establish baseline value and to identify possible discontinuous shield wire or missing drain wire connection.<br>Insulation resistance test of jacket. |
| After 5 to 20 years of operation<br>Possible defects: 1, 2, 3, or 6 | PD to detect possible termination contamination or termination or cable insulation deterioration. | TDR to identify discontinuous shield wire or missing drain wire connection.<br>TEV or ultrasound to detect possible termination contamination or deterioration.<br>VLF to cause failure of possible insulation deterioration. |
| After 20 years or more of operation<br>Possible defects: 1, 2, 3, 4, 5, 6 | Tan-delta to detect possible water treeing.<br>PD to detect possible termination contamination or termination or cable insulation deterioration. | TDR to identify possible discontinuous shield wire or missing drain wire connection.<br>TEV or ultrasound to detect possible termination contamination or deterioration.<br>VLF to cause failure of possible insulation deterioration. |
| Paper (and Oil) Insulated, Lead Covered Cable | | |
| Newly installed<br>Possible defects: B, C, D | PD to establish baseline value and to detect possible termination workmanship defects or cable installation damage. | Tan-delta to establish baseline value.<br>TEV or ultrasound to detect possible termination workmanship defects.<br>Hipot to cause failure of possible installation damage or termination workmanship defects. |
| After 5 or more years of operation<br>Possible defects/deterioration:<br>A, B, C, D, E | PD to identify possible sites of oil migration/ loss or age-related deterioration. | Hipot to cause failure of possible insulation deterioration.<br>TEV or ultrasound to detect possible termination contamination or deterioration.<br>If an overload is known or suspected, Hipot to cause failure of possible insulation deterioration.<br>If oil leaks (and resulting water ingress) are known or suspected, tan-delta. |

Defect designations and types of tests are defined in Table 1.

Wally Vahlstrom (M ’85) has a B.S. degree in electrical engineering from California State University, Fresno, and an M.S. degree in engineering from the University of Santa Clara. He is a registered professional Electrical Engineer. Professional affiliations include the National Association of Forensic Engineers (NAFE), the American Council for Electrical Safety, and the Lightning Protection Institute. Mr. Vahlstrom spent more than 25 years at Pacific Gas and Electric Company, where he held positions including Chief Electrical Engineer and Director of Engineering. He is presently Director, Technical Services for Emerson’s Electrical Reliability Services, Inc., in Pleasanton, CA. He has held this position for more than 10 years and is responsible for failure investigation work, field labeling and conformity assessment services, and power system studies and reliability analysis.