Power Cable Testing

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Visual inspection of the cable installations, conduit, manholes, and so on, and electrical maintenance testing are the major maintenance routines for cable systems.

Visual Inspection

Visual inspection can be completed on energized installations. However, if cables are touched or moved they should be de-energized. Cables in vaults, substations rooms, manholes, and at other areas need to be inspected on a yearly basis. This inspection needs to include:

1. Oil leaks, soft spots, and insulation swelling
2. Physical damage, sharp bends, and excessive and prolonged tension
3. Cracked jackets of nonleaded cables
4. Poor earth connections, metallic-sheath bonding deterioration, corroded cable supports, and continuity of main earthing system
5. Soft spots in terminations and splices
6. Corona tracking
7. Potheads should be inspected for oil or compound leaks
8. Inspect the manhole for spalling concrete and standing water

Aerial cables need to be inspected for mechanical damage that is made by vibration or deterioration of support and suspension mechanism. Inspection needs to be made of cables for insulation abrasion and cable being bent or pinched.

Cable Failures and Their Assessment

Power cables can get damaged due to many reasons. Some of the typical reasons are presented below.

Mechanical Issues

Mechanical issues can happen due to breaks and problems of sheath material, mechanical punctures by people or heavy machines, or cracks due to sharp bending or vibration. Regardless of the mechanical damage that happens in the cable sheath, the entrance of moisture will start slow deterioration of insulation material which will finally end in cable failure. Hence, it is important to protect the cable either from direct or indirect mechanical damage. This can be eliminated or minimized by proper selection, installation, and maintenance of power cable systems.

Sheath Corrosion

Sheath corrosion can happen due to the following factors:

- Acidity and alkali in conduits
- Dissimilar soil issues
- Soil chemical contamination
- Galvanic issues

Sheath corrosion will allow moisture to enter the insulation system and cause an eventual damage. Sheath corrosion can be avoided by proper usage of cathodic protection, application of insulating paints, ensuring proper drainage, and removing chemical contamination source.

Moisture in the Insulation

Moisture entrance into the insulation system will deteriorate the power cable, and all precautions have to be taken to stop such entrance. Damage due to moisture can be discovered by the following symptoms:

- Whitish powder on aluminium conductor
- Resistance to tearing of tapes
- Bleached or soggy paper

- Visible water
- Stain on the inside surface of the sheath

Cable Heating

Increased heat rise in the cable will cause insulation degradation. Heat can be caused by overloading, increased ambient temperatures, insufficient ventilation, manual heating due to cables being installed too close to each other, or external heat sources. Attention needs to be taken not to surpass cable insulation system temperature. This can be accomplished by first identifying the different environmental and operating factors that will affect the proper selection of the cable insulation and conductor size. Once correct selection and installation are done, routine cable maintenance and inspection will ensure safe and long service.

Fire and Lightning Surges

Fire in conduit or manholes can cause cable damage and failure in adjacent manholes and junction boxes. Barriers can be placed between big groups of conductors to prevent fire damage. Lightning arresters need to be installed to protect the cable where it is connected to overhead lines to minimize cable failures due to lightning surges.

Electrical Puncture

Once the insulation is weakened due to any of the presented reasons, it may electrically fail. At the point, the insulation system cannot confine the electrical current flow to the conductor inside the insulation system. Failure may be line-to-earth or three line-to-earth or line-to-line faults. Apparently, if the failure is caused by a short circuit, it will be cleared by the circuit protective device. Some of the not-so-easy-to discover electrical failures can be:

- Lack of compound in the insulation
- Sheath bulging
- Polymerized compound (wax)

- Tree design marking

The cable failures can be further grouped into two classes as follows:

- Inherent causes
- Non-inherent causes.

Inherent Causes

Inherent causes can be organised as follows:

- Sheath or jacket issues
- Insulation failures
- Conductor failures

Sheath or Jacket Issues

Sheath issues happen due to:

- Eccentric lead thickness less than 85%
- Thin lead (splits under pressure)
- Cracked, embrittled, soft sports, bulge, cuts, bruises, or gauges
- Structural defects: radial splits, laminations and gas pockets

Insulation Failures

These failures happen due to the following:

- Workmanship defects. These can be detected by the following:
    - Soft walls
    - Torn tapes
    - Wrinkling or creasing of tapes

    - Knotted or misplaced fillers
    - Excessive registrations

- High dielectric loss. These can be detected by the following:

    - Can be discovered by PF at 60°C or higher
    - Scorching or carbonizing of paper
    - Happens in one or more areas

- Incomplete saturation. These can be detected by the following:

    - Paper is void of the compound
    - Scarcity of the compound in spaces between adjacent tape edges and surfaces

- Unstable compound. These can be detected by the following:

    - Apparent change in the compound
    - Wax, in case of mineral oil Ionization: These can be detected by the following:
        - Strings or flakes of darkened wax containing carbon
        - Carbonized paths (tree design)

Conductor Issues

Conductor issues can be detected by the following:

- Sharp corners
- Irregular strands
- Strands burrs
- Incomplete strands
- Poor brazing

Non-Inherent Issues

Sheath corrosion - Corrosion typically progresses either to complete penetration of the sheath or sheath weakness, so that the sheath breaks open.

Electrical breakdown happens due to moisture admission. Sheath corrosion can happen due to:

- Negative potential (cathodic), shown by heavy deposit of lead oxides coloured red, yellow, or orange
- Positive potential (anodic), shown by rough, pitted surface and very thin white crystal deposits
- Chemical action
- Local galvanic action

Chemical Action

Chemicals such as alkali affect cable insulation, which comes about from incompletely cured concrete, acetic acid, rotting wood, jute, and other materials. Typically, these can be discovered by the chemical known to be present for a specific installation.

Local Galvanic Action

Galvanic corrosion may happen in the presence of an electrolyte and some other metal that is electrically connected to the sheath. Such issues are discovered by corroded sheath and may be identical with either type of corrosion depending on whether the sheath is anode or cathode.

External Fire and HV Surges

These problems are caused by fire and lightning strikes and surges.

Overheating

This mainly happens due to cable heating. Most likely that it is overloaded or exposed to external heat and high temperature.

Mechanical Issues

Mechanical problems can happen due to:

- Injury during installation
- Vibration
- External effects
- Contraction and expansion

Other Issues

These can be grouped as:

- Compound migration on a slope or riser
- High internal pressure
- Moisture let in through defective joints, terminations, and bonds

Medium-Voltage Cable Field Testing

Diagnostic Checks and Cable Degradation

The goal of any diagnostic check is to discover, in a nondestructive way, a potential issue that may exist with a cable, so that corrective action can be done to prevent a possible in-service cable failure. This check applies to cable systems comprising of the cable itself and the related accessories such as splices and terminations. Field diagnostic tests can be done on cables during different stages of their existence. The IEEE std 400-2001 discusses these tests as follows:

- Installation test: Done after the power cable is installed but before any accessories (joints/splices and terminations) are installed. These checks are supposed to discover any manufacturing, transport, and installation issues that may have happened to the cable.

- Acceptance test: Done after the installation of all cable and accessories, but before energizing the cable with system voltage. It is supposed to discover installation problems in both the cable and cable accessories.

- Maintenance tests: Also known as after-laying tests that are done during the cable system operating life. Its goal is to verify the condition and check cable system service ability so that appropriate maintenance actions can be done. The IEEE std 400-2001 organizes cable field tests into two main groups, Type 1 and Type 2 tests.

Type 1 field tests: These tests are typically done at elevated voltages and are a pass/fail type test. The typical high-potential (hi-pot) test is an example of a Type 1 field test. The cable either passes or fails the test. However, it provides limited knowledge of the cable condition other than whether the cable system withstood the voltage for the duration of the test or not. This test is useful in that it is normally able to root out severe cable issues. Nevertheless, many defects may pass unnoticed during a pure voltage-withstand test.

Type 2 field tests: These cable diagnostic tests are done at test voltages above and/or below the normal operating cable voltage. These tests verify cable system condition and try to establish the remaining service life. Two categories of Type 2 cable diagnostic are available:

- Tests that discover and locate discrete defect areas in a cable system

- Tests that check the complete (integral) cable condition

Recently, a number of research projects have focused on field cable diagnostic tests.

This was done due to the fact that many of the new PE and XLPE cable systems installed in the late 1960s, 1970s, and early 1980s were failing. Typical DC hi-pot testing was not only found to be ineffective in trying to discover the failure issues before cable failure happened, but the presence of these elevated DC test voltages was also found to be damaging to PE and XLPE service-aged cables. Therefore, focused effort to understand and diagnose the root cause of these cable failures in was undertaken. To check which cable diagnostic technique to apply to a specific cable system, the type of cable insulation is an important criterion. Cables are organized into two main cable insulation groups:

- Extruded/solid dielectric cable: These cables are whose insulation is extruded on the conductor and include cables, such as PE, XLPE, and EPR cables.

- Laminated cable: These are cables whose insulation is made up of laminated layers, such as PILC cable.

The research investigating extruded dielectric insulated cable premature failures, pointed to water tress and partial discharges (PDs) in the insulation void cavity as the main cause of these cable damage. Water trees are tree-like structures which develop and mature in extruded cables. Water trees do not happen in laminated insulated cables because these laminated cables do not have cavity voids as the extruded insulated cables. The extruded solid dielectric cables are sensitive to voids during cable manufacturing. After these cables are installed in the ground, the voids over time will fill-up with water or water vapor. Hence, water filled voids in the extruded insulation are known as water trees because these voids when inspected under a microscope resemble like a tree. Studies indicated that water treeing is the crucial degradation form that may afflict older XLPE and high-molecular weight PE-extruded cables. Water treeing is self-propagating dendritic pattern of electro-oxidation, which decreases extruded insulation AC and impulse breakdown strengths. It is the main degradation mechanism of extruded medium-voltage power cables. Even though carefully studied, the initiation and growth mechanisms of water treeing are not yet clear. Water treeing is not a single mechanism but complex interaction of chemical, electrical, and mechanical processes that depend on the material and applied stresses. The visible manifestation of water treeing is strings of water-filled micro-cavities. Water trees do not create partial discharges (PD) by themselves. Nevertheless, water trees can lead to electrical trees as a result of a lightning impulse, or used AC voltage, or during fault locating activities, or during DC high-voltage (HV) testing. Generally, electrical trees are more difficult to begin than to develop, so that an electrical tree, once started, tends to develop to failure by PDs. Hence, it can be concluded that growing water trees do not create PD signals, unless they give rise to an electrical tree. Any PDs at a water tree suggest the existence of one or more electrical trees at that water tree. In order for water trees to develop in extruded insulated cables, four factors need to exist in extruded cable insulation. These factors are water in void cavity, time, electrical field and entry point into the power cable. Water trees slowly migrate across the insulation, finally bridging adjacent voids across the cable insulation. Thousands of trees develop to make electro-oxidized channels which are very small in diameter. Intuitively, as water tree channels start to bridge the insulation, the losses dissipated through the insulation rise and lead to cable failure. This loss can be understood by measuring the dissipation factor (DF). Even though other techniques are available to understand the degree of water treeing in cables, the most typically used technique is the measurement of DF (or PF) of the cable insulation. A perfect cable can be electrically modelled as a single capacitor. Longer cable means the bigger the capacitance of this capacitor. As water trees begin to bridge the cable insulation, this capacitor now starts to have some resistive (water tree) paths in parallel with it. Finally, the resistive loss component (in-phase component) of the total current loss increases and it can be detected by measuring the DF or the PF of the cable. The DF measurements can be cross compared with previous test measurements and trended to understand the cable health. In completing a DF test, the applied voltage is typically stepped up from below operating voltage to slightly above operating voltage. Cables with improper insulation have bigger DF ($\tan \delta$) values than normal, and will show bigger changes in the tangent delta values with changes in applied voltage levels. Healthy cables have low individual DF ($\tan \delta$) values and small changes in DF ($\tan \delta$) values with higher applied voltages levels. Typically, a very low-frequency (VLF) HV test is used as the voltage excitation source to complete the DF (tan δ) tests. VLF as an energizer source is done for two reasons:

- The increased load capacity in field applications in which 60 Hz is too bulky and costly

- The increased sensitivity and effectiveness of measuring DF in the low frequency range for extruded cable.

DF (tan δ) testing is also independent of the cable length, as it is a ratio of resistive losses to capacitive losses (the cable itself). Since XLPE and certain EPR cables have very low DF (tan δ) values when in proper condition, the DF (tan δ) value resolution of the measurement equipment needs to be at least 1×10^{-4} to obtain correct results. Also, a guard circuit to drain off surface leakage currents at the terminations needs to be used to provide true DF (tan δ) results during a measurement. Typically, this requires VLF test equipment with a virtual ground return, instead of a solidly earthed VLF generator.

PD is known as a localized electrical discharge that partially bridges the insulation between two electrodes/conductors. It is important to note that this is a partial breakdown in the cable insulation. Hence, it would not be detectable using conventional fault location instruments. PD can happen from a number of areas within a cable installation, such as within electrical tree channel, gas voids, along an interface and between the concentric neutral to outer semiconducting layer. When PDs happen within the XLPE insulation section, total cable failure is imminent. During cable off-line field testing with PD instruments, it is possible to increase the applied voltage to discover one or multiple PD sites that may only discharge above certain voltage levels. The voltage at which a site begins to partially discharge is known as the PD inception voltage (PDIV). If the PDIV values reach close to system-operating voltage levels, the cable will most probably break down. The insulation erosion by PD activity leads to what is known as an electrical tree. The PD and subsequent electrical trees quickly lead to total cable failure within XLPE cables. Nevertheless, it needs to be clear that certain materials are more resistant to PD than others. For instance, joints and terminations have a big ability, at least for a while, to fend off PDs in their insulation. Hence, the location of the PD site is an important aspect to understand whether that site will lead to imminent failure or not. Typically, PD measurements on cables are done by cable manufacturers as a final quality control test. Typically, PD tests are done in a shielded PD free test room. It is only within the last years that technology developments have allowed this diagnostic method to be used in the very noisy field environments. The capability to discover and locate sites of PDs down to 10pC in cables in the field is now available. It has to be pointed out that there are no PDs related with water trees by themselves unless the water trees become electric trees. Hence, unless water tree in the cable becomes an electrical tree PD testing is not able to discover it. Electrical trees and water trees have totally different characteristics, and the diagnostic processes used to discover them are also totally different. In many situations, cables with very poor DF test results, show the presence of serious water treeing, show no PD activity. PD is useful in isolating installation defects in the cable system and especially in the accessories. Nevertheless, PDs must be present in order to detect any PD. For instance, a wet splice may have a high leakage current but may not show any PD. So, which technique needs be used to discover the health of the cable system? The used diagnostic technique will depend on a number of factors, including the type of insulation, the age of the cable, maintenance strategy, etc. In order to understand the condition of a new installation, a PD check is very efficient in isolating installation defects that may have happened. A poorly installed splice or an outer shield compromised during the cable installation will lend itself more to a PD test than a tan δ test, since no insulation aging would be present in the new power cable. For older installation maintenance testing, a tan δ would be of most useful to understand the degree of cable insulation aging. If the cable is very critical in nature and even a single cable fault is to be avoided, then a combination of a PD and a tan δ test is the best possible option. Most utilities are concerned about spending large amounts of unnecessary resources fixing cables that have a succession of repetitive failures. This is especially true if the cable is globally deteriorated. The utilities would rather replace such a cable at the outset. In such a case, a tan δ test will be most useful. Even though it may not discover a singular defect in an otherwise good cable, it will discover a globally aged cable that could be the source of many future failures. As in most efficient maintenance strategies, a combination of more than one diagnostic test is typically the best way of establishing the condition of a cable system. Cable diagnostic systems that include a combination of both tan δ and PD diagnostic measurements in one integrated test instrument are now available to fulfil all these needs.

Safety Practices and Earthing

When testing power cables, personnel safety is of crucial importance. All cable and equipment tests need to be completed on isolated and de-energized systems, except where specifically needed and approved. Certain switches may be connected to a cable end with a role to disconnect the power cable from the rest of the system. The capacity of the switch to sustain the VLF test voltage while the other end is under normal operating voltage need to be shall be verified with the manufacturer. The safety procedures shall include the following requirements:

- IEEE std. 510-1983
- Applicable user safety operating processes
- Applicable state and local safety operating regulations
- NFPA 70E Standard for Electrical safety requirements
- Protection of utility and customer property while conducting the test, one or more cable ends will be remote from the testing site. Hence, before testing is started, the following actions need to be completed:
    - Cable ends under test need to be cleared and protected
    - Cables need to be de-energized and earthed
    - At the conclusion of HV testing, attention needs to be given to discharge cables and cable systems including test instruments

Cable installations can be considered de-energized and earthed when a conductor and metallic shield are connected to system earth point at the test site and, if possible, at the far end of the power cable. When conducting a test, a single system earth point at the test site is advised. The cable shield or concentric conductor of the tested cable is connected to a system earth point. If this connection is missing, deteriorated, or has been removed, it needs to be fixed. A safety earth cable needs to connect the instrument case with the system earth point. If the test instrument is a HV instrument, the safety earthing cable needs to be at least a braided or stranded #2 AWG copper cable capable of transferring anticipated fault current. Only after the safety earthing cable is connected, the conductor-to-earth connection can be removed. In the case local ground is needed for the test equipment, the case ground needs to stay connected to the system earth point in order to maintain an acceptable single-ground potential. Attention needs to be taken to make sure that all earthing connections cannot be disconnected by accident.

Cable Testing Procedures

Once a new power cable has been installed and before it is energized, acceptance proof testing (HV tests) need to be completed. Generally, acceptance proof test are done at 80% of final factory test voltage. Also, routine maintenance HV tests can be done in the field on installed cables, similarly as maintenance tests. The maintenance HV tests are done at 60% of final factory test voltage. Tests that can be completed in the field for acceptance and maintenance purposes are described in the following paragraphs.

Insulation Resistance and DC Hi-Pot Testing

In the past, insulation resistance and DC HV (hi-pot) tests were completed for acceptance (proof) and maintenance testing of cables. When examining power cables with DC voltage, it needs to be clear that DC voltage creates within the cable insulation system an electrical field determined by the conductance and the cable insulation system geometry. Nevertheless, the normal service voltage applied to cable is AC 60 Hz voltage. Therefore, during normal service conditions the AC voltage produces an electrical field that is determined by the dielectric constant (capacitance) of the insulation system. Hence, the electric stress distribution with DC voltage is different from AC voltage electric stress distribution. Also, conductivity is affected by temperature to a bigger extent rather than the dielectric constant. Hence, comparative electric stress distribution under DC and AC voltages will be differently impacted by insulation temperatures changes. The DC voltage tests are efficient in discovering failures that are caused by thermal mechanism. The value of the DC voltage diagnostic tests for extruded-type insulation are limited since failures under service AC voltage conditions are most likely to be created by PDs in the extruded insulation voids rather than by thermal processes. However, the DC voltage diagnostic verifications are very useful for laminated-type insulation system where the failure is most likely to be caused by thermal process. The current industry trend is to minimize the application of the DC hi-pot tests on extruded insulation.

AC Hi-Pot Testing

Cables and cable accessories can also be field tested with 60 Hz AC voltage, even though this is typically not done because of the requirement for heavy and costly test equipment that may not be available or transportable to a field site. The typical field tests done on cables are DC hi-pot or VLF tests, such as one-tenth of hertz frequency tests in lieu of AC hi-pot tests. Nevertheless, if AC hi-pot acceptance and maintenance tests are to be done on power cables, then it needs to be kept in mind that this test is not very practical in the field. Also, the AC hi-pot test can only be completed as go-no-go test. Hence, it may create extensive damage in the case the cable under test fails. On the other hand, AC hi-pot test has a distinct benefit over other tests that stress the insulation comparably to normal operating voltage. Also, this test replicates the factory test completed on the new power cable. When completing the AC 60 Hz hi-pot test attention needs to be given to the adequacy of the test equipment for successfully charging the test specimen. The AC test equipment needs to have proper volt-ampere (VA) capacity to provide the needed cable charging current requirements of the tested cable. The VA capacity of the AC hi-pot test equipment can be calculated with the following formula:

$$VA = 2\pi f c E^2 \quad \text{or} \quad kVA = 2\pi f c E^2 \times 10^{-3}$$

where

c is capacitance (μf/mile)

f is the frequency (Hz)

E is the test voltage (kV) of the test set

The test voltage values suggested for acceptance and maintenance tests are 80% and 60%, respectively, of the final factory test voltage.

PF and DF Tests

PF and DF tests can be completed on shielded cable installations to determine insulation degradation to decrease in-service cable failures. PF tests for shielded or sheathed cables and accessories are diagnostic testing methods for field testing of service aged cable installations. For lossless insulation, the cable capacitance (C) per unit length can be calculated using the following formula:

$$C = 2\pi k e_0 \ln\left(\frac{d_i}{d_c}\right)$$

where

k is the insulation dielectric constant
e_0 is the permittivity (capacitance) of air
d_i is the diameter over the insulation
d_c is the conductor diameter

For power cables with conventional insulating materials, the cable conductance (G) per unit length can be calculated using the following formula:

$$G = 2\pi f C \tan\delta$$

The quantity tan δ presents the losses in the insulation when exposed to an electric field and is known as DF or the insulating material loss angle. Table 1 gives typical values of dielectric constant k and tan δ.

Table 1. Typical values of dielectric constant k and tan δ

Type of Insulation	k	tan δ
Impregnated paper	3.5	2.3×10^{-3}
Impregnated PPP	2.7	0.7×10^{-3}
PVC	5.8	0.7×10^{-3}
XLPE	2.3	0.1×10^{-3}
HDPE	2.3	0.1×10^{-3}
EPR	2.8	3.5×10^{-3}

When a voltage V is applied to the loss-free insulation dielectric, the total current (I_T) taken by the dielectric is the sum of the capacitive charging current (I_C) and loss current (I_R). The angle formed by the current I_T and I_C is δ, and the angle formed by the I_T and voltage E is q where cos q is the dielectric PF. The DF (tan δ) test allows inspection of an insulation system at operating voltage level and frequency. The tan δ test can also be completed at frequency different than 60 Hz, such as at VLF of 0.1 Hz during proof test completed at such frequency. According to IEEE std. 400-2001, tests completed on 1500 miles of XLPE insulated cable have established a figure of merit for XLPE at tan $\delta = 2.2\times10^{-3}$. In the case the measured tan δ is bigger than 2.2×10^{-3}, then the cable insulation is degraded by moisture in the form of water trees, and it is suggested that extra hi-pot tests, such as VLF test be completed to discover cable insulation defects. The tan δ test for each conductor with respect to ground should be done. The evaluation needs to be based upon comparative analysis with previously completed tests or correlated with test results of similar types of cables.

VLF Tests

Very low frequency (VLF) test is completed with an AC voltage at frequency ranging from 0.01 to 1 Hz. VLF tests can be grouped as withstand or diagnostic test. In other words, it may be done as a proof test for acceptance or as a maintenance test for examining the cable condition. For the withstand test, the tested insulation must withstand applied voltage that is bigger than the service voltage across the insulation for a specified period of time without insulation breakdown. The magnitude of the withstand voltage is typically bigger than that of the operating voltage. If the VLF test is done as a diagnostic test, it is done at lower voltages than withstand tests. Hence, it may be considered as nondestructive test. Diagnostic testing helps to determine the relative amount of cable system degradation, and by comparison with previous test records, whether a cable installation is likely to continue to perform correctly. It needs to be noted that values of the diagnostic quantity measurements collected during VLF tests may not correlate with those collected during power frequency tests. For instance, the PF and DF tests are completed at power frequency (60 Hz) which is much bigger than at 0.1 Hz, and PD may differ in terms of magnitude and inception voltage. At the time cable system insulation is in an advanced degradation stage, the VLF diagnostic tests can cause breakdown of the cable before the test can be completed. The VLF withstand test for cable systems can be completed with the following waveforms:

- Sinusoidal waveform
- Cosine-rectangular waveform
- Alternating regulated positive and negative DC step voltages
- Bipolar rectangular waveform

The diagnostic test using VLF methods for cable systems are:

- VLF differential dissipation factor measurement (VLF-DTD)
- VLF loss current harmonics (VLF-LCH)
- VLF partial discharge measurement (VLF-PD)
- Spectroscopy (VLF-DS)
- Dissipation factor (tan δ) measurement (VLF-DF)
- VLF dielectric
- VLF leakage current (VLF-LC)

The most typically applied, commercially available VLF test frequency is 0.1 Hz. Other commercially available frequencies are in the range of 0.0001– 1 Hz. These frequencies may be beneficial for inspecting cable systems where the cable system length surpasses the limitations of the test system at 0.1 Hz, even though there is evidence that testing below 0.1 Hz may increase the risk of failure in service once the test is completed. The internal impedance of the test set can limit the available charging current, preventing the tested cable to reach the required test voltage. Cable manufacturer may be consulted when choosing an initial test voltage level and testing time duration for a particular cable length. VLF test voltages with cosine-rectangular and the sinusoidal wave shapes are most typically applied. While other VLF wave shapes are available for cable system testing, recommended test voltage levels have not been specified. During a VLF test an electrical tree at the site of an insulation defect is forced to penetrate the insulation. Inception of an electrical tree and channel development time depend on test signal frequency and amplitude. For an electrical tree to totally penetrate the insulation during the test duration, VLF test voltage levels and testing time durations have been determined for the two most typically used test signals, the cosine-rectangular and the sinusoidal wave shapes.

The installation and acceptance voltage levels are based on worldwide most-used practices of between two times rated voltage and three times rated voltage for cables rated between 5 and 35 kV. The maintenance test level is around 80% of the acceptance test level. One can decrease the test voltage another 20% if more test cycles are done. Table 2 and Table 3 present voltage levels for VLF withstand examination of shielded power cable systems using cosine-rectangular and sinusoidal waveforms.

Table 2. VLF test voltages for cosine-rectangular waveform

Cable rating phase to phase RMS voltage (kV)	Installation phase to earth RMS voltage/peak voltage	Acceptance phase to earth RMS voltage/peak voltage	Maintenance phase to earth RMS voltage/peak voltage
5	12	14	10
8	16	18	14
15	25	28	22
25	38	44	33

Table 3. VLF test voltages for sinusoidal waveform

Cable rating phase to phase RMS voltage (kV)	Installation phase to earth RMS/Peak voltage	Acceptance phase to earth RMS/Peak voltage	Maintenance phase to earth RMS/Peak voltage
5	9/13	10/14	7/10
8	11/16	13/18	10/14
15	18/25	20/28	16/22
25	27/38	31/44	23/33
35	39(55)	44(62)	33(47)

For a sinusoidal waveform, the RMS is 0.707 of the peak value if the distortion is less than 5%. The suggested testing time ranges from 15 to 60 min, even though the average testing time of 30 min is typically used. The real testing time and voltage may be determined by the supplier and user. They are dependent on the testing philosophy, cable installation, insulation condition, how frequently the test is done, and the chosen test technique. When a VLF test is interrupted, it is suggested that the testing timer is reset to the original time when the VLF test is restarted. The tan δ test may be completed with VLF equipment at 0.1 Hz sinusoidal to monitor the aging and degradation of extruded insulated cables. The tan δ test gives an assessment of the water tree damage in the cable insulation. The tan δ measurement with 0.1 Hz sinusoidal waveform gives comparative evaluation of the aging condition of PE, XLPE, and EPR-type insulation systems. The tan δ test needs to be completed at normal operating service voltage to prevent insulation breakdown. The tan δ test completed at 0.1 Hz sinusoidal waveform is typically determined by water tree damage in the insulation system and if the tan δ measurement is bigger than 4×10^{-3}, the service-aged cable needs to be examined for replacement. If the tan δ measurement is lower than 4×10^{-3}, the cable should be additionally examined with VLF at three times the service voltage for 60 min.

The pros and cons of VLF testing are presented below:

Pros

The 0.1 Hz cosine-rectangular waveform has polarity changes similar to those at power frequency. Because of the sinusoidal transitions between the positive and negative polarities, traveling waves are not created, and because of continuous polarity changes, dangerous space charges are less likely to be created in the insulation.

- Leakage current needs to be measured.

- Cables may be examined with an AC voltage roughly three times the rated conductor-to-earth voltage with a device comparable in size, weight, and power requirements to a DC test set.

- The VLF test can be used to examine cable installations with extruded and laminated dielectric insulation.

- The VLF test with cosine-rectangular/bipolar pulse and sinusoidal waveform works best when trying to discover a few defects from otherwise good cable insulation.

Cons

- When examining power cables with extensive water tree degradation or PDs in the insulation, low frequency withstand testing alone may not be conclusive. Extra diagnostic checks that measure the extent of insulation losses will be needed.

- Cables need to be taken out of service for testing.

PD Test

A PD is an electrical discharge that happens in a void within the extruded cable insulation, at interfaces or surfaces such as shield protrusion and the insulation or in a water tree within cable insulation when exposed to relatively HV. PD manifests as a series of PD pulses during each half cycle of an AC waveform. The rise time of the PD pulses is in the order of nanoseconds to tens of nanoseconds. The PD pulses tend to set an electromagnetic field which expands in both directions along the cable with a propagation velocity that is based on the cable insulation dielectric constant. PD features are dependent on the type, size and defect location, insulation type, voltage, and cable temperature. The insulation of full reels of extruded cables is tested for PDs at the factory at power frequency. This test is chosen to discover small imperfections in the insulation such as voids or skips in the insulation shield layer. It seems logical to complete PD measurements on newly installed and service-aged cables to discover any damage made during the installation of new cable or in-service degradation of cable insulation due to PDs.

Two techniques that can be used for discovering PDs from installed cables in the field. They are on- and off-line detection system. There are several commercial off-line systems available for measuring PD in medium-voltage systems (up to 35 kV). The online measuring system is based on measuring PDs at the cable-operating voltage. In the case of offline system, the PD measurements are completed at a higher voltage than cable-operating voltage. This is due to the fact that the off-line testing demands the power cable to be de-energized which results in cessation of any active PD activity. In order to start the PD activity again in the de-energized cable during off-line testing, a higher voltage is demanded to restart the PD activity. The test equipment for PD testing for online or off-line comprise of the power supply, sensors and noise reduction, signal detection, and signal processing instruments. The power supply can be 60 Hz voltage, oscillating voltage, or VLF (0.1 Hz) voltage source. The sensors can be inductive couplers, capacitive couplers, or an antenna along with noise treatment and amplification instruments. The signal detection and processing instruments include digital oscilloscope, spectrum analyzer, wave form digitizer and time-domain reflectometer (TDR). Even though it is difficult to complete a PD measurement in the field because of external noise, this test can be done in the field where conditions warrant it is worth the time and cost to do so. The PD test provides the most convincing validation whether the power cable is in good condition and suitable for operation or needs to be fixed or replaced. The PD test is beneficial for both the laminated and extruded cable insulation installations. This test can be completed at power frequency or at any other frequency, such as 0.1 Hz (VLF). To complete an off-line PD test the cable is disconnected from the network at both ends and correctly isolated. A voltage source and a coupling instrument, or sensor, are connected at one of the ends, whereas the remote end is left disconnected. The coupling instrument could be capacitive or inductive. The coupling instrument is connected to the PD detecting and processing systems. Variations of this arrangement include a measuring system with sensors at both ends and means to communicate the far end data to the near end processing devices or, in the case of a branched system, sensors installed at the end of each branch. Multi-terminal testing also has the benefit of higher sensitivity in the PD testing of very long cable lengths as the pulse travel distances are considerably shorter and consequently the related attenuation of pulse amplitude is lower. The following steps are completed:

- Low-voltage TDR is used to find cable joints and other irregularities
- Sensitivity check
- PD magnitude calibration
- PD testing under voltage stress
- Test record evaluation and documentation

Sensitivity Check

The objective of this step is to find the value in pico-coulomb (pC) of the smallest PD signal detectable under the test conditions. In extruded dielectric cables PD activity in the range of several pCs is needed, otherwise inadequate detection sensitivity may mask the existence of severe defects with low PD magnitudes. Inability to discover low levels of PD may end in false-negative situations that are expected to lead to unexpected post-testing service failures. Also, incorrectly identified PD can lead to false-positive situations leading to unnecessary cable replacement. Hence, a calibrated pulse, such as 5 pC, is injected at the near end. The PD estimator discovers and records the response. If the reflected signal cannot be detected above the filtered noise level, a bigger signal, such as 10 pC, is injected. This process is repeated until the reflected signal can be detected. This determines the smallest PD signal that can be resolved under the test conditions.

PD Magnitude Calibration

The calibrated pulse generator is connected to the cable remote end. A big signal, such as 50 or 100 pC, is injected. The corresponding signal recorded at the near end is evaluated by integrating it with respect to time. The constant k is adjusted until the PD magnitude read is 50 or 100 pC. The instrument is now calibrated for measuring the apparent charge, q, of the PD.

PD Testing under Voltage Stress

Off-line tests can be completed using different voltage sources. There is a solid technical justification for testing up to 1.5 to 2.5 times of rated voltage to ensure that the PDIV of the cable is sufficiently high to start the PD activity. There is an increased risk of creating damage at defects in aged cable systems that are innocuous at operating voltage if testing is completed at voltages bigger than 2.5 times of rated voltage. There is also an increased risk of failures during the PD testing. Nevertheless, some utilities will request testing up to a maximum of three times of rated voltage on new cables, either on the reel or newly installed, to make sure that there was no damage during transportation or installation. Also, some utilities will test up to three times of rated voltage, although there is a considerably higher chance of failure during the testing, of the following cable systems:

- Cable circuits with generic defects that may create big failure rates. For example, some silane-cured cables can create severe corrosion of aluminum conductors.

- Cable installations that are being considered for silicone injection, the rationale being that all power cables with electrical trees will fail at bigger test voltages. The bigger test voltages could also create new electrical trees.

- Cable installations that may have suspect accessories and/or cables to ensure operation during high load periods. The voltage in power frequency tests may be applied for up to a maximum of 15 min to make sure that electrons are available in cavities to start PD. Nevertheless, once PDs are discovered, the voltage needs to be applied long enough to collect sufficient data up to a maximum of 15 s.

For example, the following steps are done for voltage stress testing. The voltage is quickly increased to the cable operating level (1.0 p.u.) at which it is kept for several minutes as a conditioning step. The voltage is increased to its maximum value (such as 2.0 or 2.5p.u.). It then is returned to zero as fast as possible. During this stress cycle, several data sets are collected. Each of these sets encompasses an entire 60 Hz period. The rising and falling parts of the voltage help determine the PDIV and PD extinction voltage (PDEV), respectively. It needs to be clear that off-line testing using bigger voltages than cable operating voltage may be a destructive test. In conclusion, it is not possible to standardize a specific test procedure at the current time for either online or off-line tests. This may be possible as more information is obtained. For off-line tests, the amplitude of the test voltage can be varied. For heavily aged systems, a maximum test voltage of 2p.u. is recommended. As the anticipated condition of the cable improves, the test voltage may be increased to as much as 2.5p.u. New cable installations, either on the reel or newly installed, may be tested to a maximum of 3p.u. at the concurrence of the cable owner and cable manufacturer. The test duration needs to be sufficiently long to allow the availability of electrons to start PDs, but once PDs are discovered, the voltage needs to be applied long enough to obtain sufficient PD data.

PD Test Data Assessment and Documentation

The PD test factory needs to provide report of the tested cables and the PD test results to the end user. Also, the PD test provider needs to give appropriate recommendations and possible corrective action that should be taken. The test results report needs to include the value of PD detection sensitivity and a reference to the technique used in obtaining this value. The PD site location results need to also be given with an assessment of the accuracy limits within which these results can be interpreted under the conditions of the specific test. This becomes very important where the location is at or near a splice. Information that has to be included in the report is:

Cable system identification:

- Cable section identification
- Cable manufacturer name
- Cable insulation
- Cable voltage class
- Conductor type and size
- Operating voltage
- Year put in service
- Cable length
- Location of splices
- Termination type (switching cabinet live-front/dead front, pole-top, premolded, heat-shrink, etc.)
- Neutral type (concentric wires, metal tapes, size and flat strap)
- Construction type (aerial, jacketed, unjacketed, duct, direct buried etc.)
- If available splice type

PD test results

- Test date.
- Date of the most recent completed test.
- Splice location.
- Cable length.
- Background noise level.
- Test voltage levels.
- At each test voltage level, the location of each PD site, along with the accuracy limits.
- At each voltage and site location, the number of PD events per second or per cycle of a sinusoidal excitation voltage.
- Minimum resolvable PD signal pC magnitude and how it was found. If the

sensitivity is lower than anticipated, provide the justification.

- At each voltage and site location, a phase-resolved PD representation provided the excitation voltage is sinusoidal. Mention the number of cycles included in the phase-resolved diagram.
- Any other diagnostic results pertinent to the used test method.
- An indication of the severity of the PD behavior, if PDs are discovered, and suggestions on possible corrective action to be done.
- Variations of this 3D representation are also possible. Others prefer a set of two-dimensional representations, presenting PD location with PDIV, and apparent charge (pC) versus phase angle for each PD site, at each voltage level, and PD repetition rate for each PD site at each voltage level.
- The reporting format may vary. For example, some prefer reporting individual PD events in a three-dimensional (3D) form with location, pC level, and phase angle at which each PD is started.
- For a frequency-domain measurement, include the spectral features and the estimated location for each PD site. Specify the accuracy limits.

AC Resonance Test

The resonant test systems are used to check power cable and other electrical instruments with AC voltage at power frequencies (50 or 60 Hz). This technique has the advantage over other test techniques, of stressing the insulation similar to normal operating conditions. Previously, to checking electrical equipment at power frequency required bulky and costly test equipment that was not portable for on-site field testing applications. The resonant test installations were made so that they can be handled easily on-site. This technique can be used to examine cable consisting of either XLPE, oil-impregnated paper and EPR, or a combination of these insulating materials. As the name suggests, this test technique is based on applying AC at the operating frequency (50 or 60 Hz) as a test source using the principle of resonance. Resonance can be described as the condition at which the net inductive reactance cancels the net capacitive reactance at operating frequency. The resonant circuit must have both capacitance provided by the tested cable and inductance provided by the test set reactor.

When resonance happens, the energy absorbed at any moment by one reactive element is exactly same to that released by another reactive element within the system. Therefore, energy pulsates from one reactive element to the other. Hence, once the system has reached resonance condition, it needs no additional reactive power since it is self-sustaining. The total apparent power is then simply equal to the average power dissipated by the resistive elements in the inductor and cable installation. Either parallel or series resonant circuits are typically used for completing this test. The series resonant test consists of a voltage regulator (autotransformer type) that is connected to the supply voltage. The regulator gives a variable voltage to the exciter transformer. The exciter transformer is supplied by the voltage regulator output. This transformer increases the voltage to a usable value by the HV portion of the circuit. The HV reactor L and the load capacitance C represent the HV portion of the circuit. The inductance of the HV reactor can be changed by changing iron core air gap. The load capacitance C consists of the load capacitance. When testing, the HV reactor is adjusted so that the impedance of L corresponds to the impedance of C at the frequency of the supply voltage. Hence, the circuit is tuned to series resonance at 50 or 60 Hz.

The Q of the basic resonant circuit or with a low loss test specimen is usually 50 to 80. The HV reactor is made for a minimum Q of 40. The system Q is made around the projected load. In case of a flashover during testing on the HV side, the resonant circuit is detuned and the test voltage instantly decreases. The short-circuit current is limited by the HV reactor impedance. This means that the short-circuit current of a series resonant system with a Q of 40 is 2.5% of the load current to which it is tuned. The series resonant mode is appropriate for sensitive PD measurements. Harmonics from the supply are better suppressed than in parallel mode. The parallel resonant configuration gives a more stable output voltage with test specimens, such as big generator windings, or other specimens with corona losses. The test voltage rate of rise is stable in parallel mode, independent of the tuning degree and the Q of the circuit. Also, parallel mode allows the test set to be energized to full voltage without a load. This is beneficial for calibrating the instrumentation and checking for the test equipment PD level. The test voltage rate of rise is stable in parallel mode, independent of the degree of tuning and the Q of the circuit. The average power absorbed by the system will also be at a maximum at resonance. The typically used measure of the quality in a resonant circuit is the quality factor, or Q. The power source of resonant circuits operating in the resonant mode is used to supply the dissipated energy.

Q is roughly equivalent to the ratio of the output kVA to the input kVA. Given the load kVA demands and the Q of the test system, the input power can be determined by dividing the kVA by the Q. The correct operation mode must be selected according to the test objects and the measurements that need to be completed. The parallel resonant mode gives a more stable output voltage with test specimens, such as large generator windings, or other specimens with corona losses. Resonant test installations are available that use variable inductance and variable frequency resonant and pulsed resonant test sources. A quick overview of the variable frequency resonant test installation is as follows.

The resonant test installation with variable frequency typically consists of the frequency converter, the exciting transformer, the coupling capacitors, and HV reactors with fixed inductance. The frequency converter produces a variable voltage and frequency output which is applied to the exciter transformer. The exciter transformer excites the series resonant circuit consisting of the reactor's inductance L and the cable capacitance C. The resonance is adjusted by tuning the frequency of the frequency converter according the expression:

$$f = \frac{1}{2\pi}(LC)^{1/2}$$

The tuning range of the test installation is calculated by the converter's frequency range:

$$\frac{C_{max}}{C_{min}} = \left(\frac{f_{max}}{f_{min}}\right)^2$$

Summary of Testing Techniques

The objective of summarizing cable testing techniques is to cite the pros and cons of these techniques so that the reader can quickly select the test technique best suited for his application. The cable testing techniques can be grouped into three categories:

Hi-pot withstand checks

General condition assessment (GCA) checks

PD checks

These checks can be viewed from the perspective of being destructive or non-destructive. Any test that uses the test source voltage to be greater than the in-service operating voltage could be classified as destructive test because during testing the cable insulation will be exposed to a greater voltage than what it will see in service. Hence, all hi-pot withstand tests would fall into this category. Nevertheless, during a hi-pot test, if the voltage is applied in a steps and the leakage current is observed, then the test may be classified as being non-destructive. The reasoning for this is that the test can be stopped before the insulation gets to a failure point since at every step of voltage application the leakage current is being observed and evaluated before continuing to the next step. An application of this test technique is the step-voltage DC hi-pot withstand test. The same cannot be stated for AC hi-pot withstand test since there is no possibility to assess the leakage current. Hence, this test would be considered as go-no-go test and destructive. The GCA tests and PD tests are classified as non-destructive since the voltage used during these checks is either the same, or lower than, or slightly above the in-service operating voltage. The pros and cons of the tests are as follow:

Hi-pot withstand checks

Under this group, cable tests that use HV source are mentioned. These tests are: DC hi-pot tests, AC hi-pot, AC resonant test, and VLF test. The pros and cons of the test that use hi-pot voltage source are:

DC hi-pot check

Pros:

- Has been used for a long time
- Very portable and convenient for field application
- Low power demands
- Is a good for conductive type failures

Cons:

- Demonstrated to create space charge which aggravates failures in aged extruded cable long after the test's conclusion

- Cannot discover high impedance failures such as voids and cuts

- Stress distribution is not the same as in-service conditions

- Cannot be cross compared to factory tests

60 Hz hi-pot and AC resonant checks

Pros:

- Is appropriate for conductive and high impedance failures
- Does not induce space charge, therefore decreases the propagation of failures in extruded cable
- Replicates steady-state in-service conditions
- Can be cross compared to factory tests

Cons:

- Very costly and not practical for field tests
- Highest power demands except for AC resonant test
- Grows certain type of failures

VLF hi-pot checks

Pros:

- Portable for field evaluation
- Relatively low power demands
- Is a good for conductive-type failure and high-impedance failures
- Does not induce as much space charge as DC hi-pot in aged extruded cable
- Causes some failures to quickly expand resulting in shorter test time

Cons:

- Aggravate failures in aged power cable without failing them
- Does not replicate service conditions
- Cannot be directly cross compared to factory tests
- Not suggested for aged power cable with multiple failures
- Stress distribution is not the same as in-service conditions
- Does not replicate normal stress distribution conditions with wet regions

GCA Evaluation

GCA checks are those which assess the overall health of the cable insulation. These tests include: DF/ tan δ /PF, PD tests, dielectric spectroscopy, depolarization-return voltage, and depolarization-relaxation current. Each of these checks has their own pros and cons. Generally, the following can be stated for PF/DF and PD checks:

PF/DF (tan δ)

Pros:

- Considered as non-destructive to cable insulation
- Tests are completed at in-service voltage levels
- Monitor the overall condition of the cable insulation
- Efficient in discovering and assessing conduction-type failures
- Can be cross compared to factory tests
- Portable for field testing

Cons:

- Need prior cable types and data for cross comparison
- Temperature dependant in extruded cables
- Cannot discover high-impedance failures such as cuts, voids, and PD
- Cannot discover singular failures in extruded insulation, such as water tree
- Not an efficient test for mixed dielectric or newly installed cable installation
- Equipment is expensive in comparison to hi-pot equipment

PD Tests

Two type of PD tests are considered, that is online PD testing and off-line PD testing. PD diagnostics evaluations are considered to be efficient in discovering defects in shielded power cables.

PD Diagnostics Evaluation

Pros:

- Considered as non-destructive
- Can discover high-impedance failures such as void, cuts and tracking

- Can be completed online in limited applications
- Efficient at discovering defects in mixed dielectric systems

Cons:

- Needs a trained analyst to assess measurements
- Limited to power cables with a continuous neutral shield
- Not efficient for branched network installations
- Cannot discover or locate conduction-type failures

Online PD Evaluation

Pros:

- Discover and find some accessory defects and some cable defects
- Done while circuit is energized
- Does not need an external voltage source

Cons:

- Cannot be applied to long directly buried power cables
- Cannot be cross compared to completed factory tests
- Not a calibrated test, hence the test results are not objective
- Finds only 3% or less of cable insulation defects in extruded cable
- Needs access to the cable every few hundred feet depending on the cable type
- Not efficient by statistically significant data correlating results to actual cable system defects or failures
- Demands that manholes are pumped to access cable

Off-line PD Evaluation

Pros:

- Can discover electrical trees with PDs
- Gives onsite report of the test results
- Replicates steady-state and transient operating situations
- Can examine up to 1 to 3 miles of power cable depending on the cable type
- Finds all defect sites in one test from one cable end
- Is efficient with mixed dielectric power cables
- Can be quickly compared to factory baseline tests

Cons:

- Need circuit outage for test completion
- Equipment is costly in comparison to other tests