Cable Types, Design, and Associated Insulation Faults

Addressing the task of power cable diagnostics and fault location, the energy industry now offers a wide range of tools using various cable testing methods. The choice of the right method and the most appropriate instrument greatly depends on a number of factors, including the test purpose, the type and age of the cable, environmental factors, and the anticipated cable fault type.

Before moving on to the main hipot testing techniques, it is important to introduce the basic information on power cables, namely their types and typical structure, and explain the associated types of cable errors.

Power Cables: General Notes on Types, Design and Application

The power cable market can be segmented into three areas based upon the voltage class of the cable: the medium voltage class with cables 6 kV to 69 kV, the high voltage cable class with cables 69 kV to 150 kV, and the extra high voltage with cables greater than 150 kV. The medium voltage cable dominates in the underground cable market segment.

Insulated power cables are used for the transmission and distribution of electricity both for industrial and commercial, and various underground applications.

In a typical medium voltage cable, copper and/or aluminum wires, stranded and/or solid, are used as the conductors. These conductors are covered with an extruded polymeric stress-control layer, often referred to as the permashield or conductor shield, made of semi conductive compounds. The insulation layer immediately surrounds and is fully bonded with the conductor shield. The insulation shield encases the insulation and in some cases may be composed of the same semi conductive material as the conductor shield.

Figure 1 - Examples of power cables

The copper neutral wires are wound around the insulation shield, and are usually covered with a thermoplastic polyethylene jacket, which ensures mechanical protection from the external environment, and also reduces moisture intrusion into the cable, thus preventing a premature cable failure.

There are two basic categories for cables, the extruded dielectric and the laminated style cable. Examples of the extruded dielectric cables include the cross-linked polyethylene, or polyethylene XLPE or PE style cables, and ethylene propylene rubber (EPR) style cables. In its turn, the paper insulated lead covered (PILC) type is a representation of the typical laminated style cables.

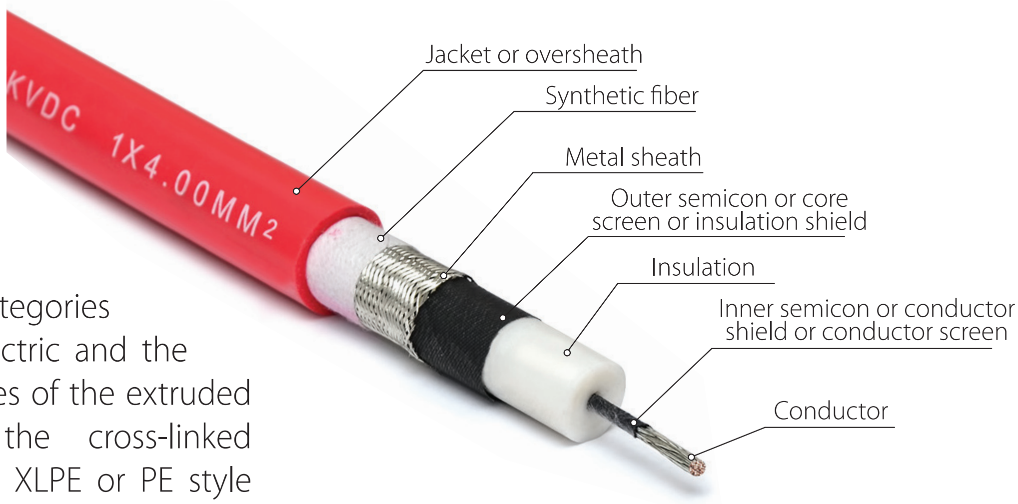

Figure 2 - Structure of a power cable

Aging Characteristics: Treeing

Water tree degradation is a major problem for medium voltage extruded dielectric cables, particularly the service age XLPE and PE style cables. It is perhaps the worst degradation process of the power cable insulation and contributes to the failure of the cable. Water trees are formed and grow in the presence of moisture, impurities or contamination, and electric field over time.

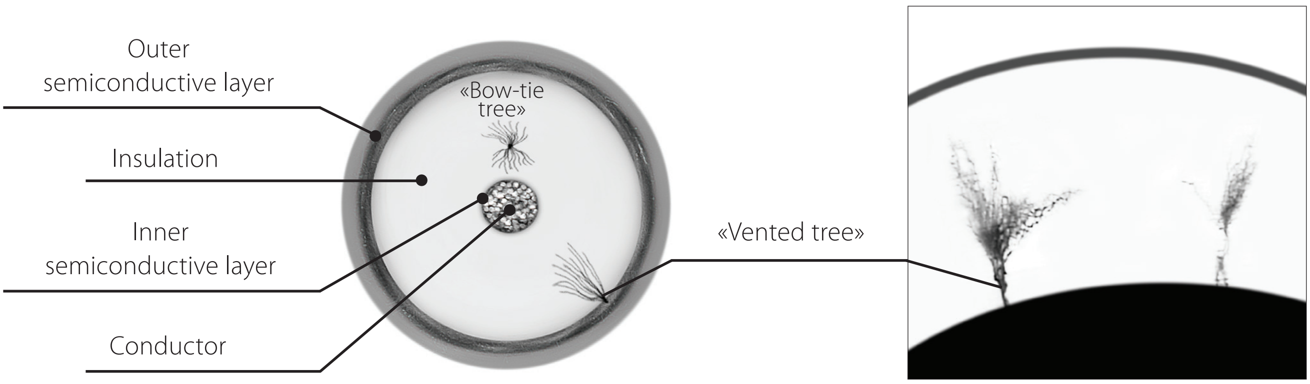

Figure 3 – Types of water trees

There are generally two types of water trees, namely the bow tie tree and the vented tree.

Bow tie trees are water trees that grow from the insulation outward toward the surfaces of the insulation. These trees grow in the direction of the electric field, in both directions toward the two electrodes, the centre conductor of the cable and the concentric neutral surrounding the cable.

While having a faster growth rate compared to the vented trees, bow tie trees are not capable of growing to large sizes and usually do not grow to a size significant enough to cause a failure in the insulating system.

Vented trees are water trees that grow in the direction of the electric field, from the surface of the polymer inward into the insulating system. Vented trees have a lower initial growth rate as compared to the bow tie tree. However, they are capable of growing right through the entire insulation thickness.

So, vented trees are definitely the more problematic of the tree series, leading service age cables to eventual electrical failure or a fault mode.

In the case of extruded dielectric the treeing is a result of water and grass contamination and is referred to as a water tree.

In laminated cables the most common cause of the tree effect is from the drying of the oil and then the burning of the insulating layers of paper. As the insulating layers of paper burn, they leave behind carbon deposits, which are conductive. So, in time, as the papers begin to burn, leaving behind little carbon deposits, a conductive path is created through the insulation, again, causing a cable failure. This type of treeing is referred to as a carbon tree.

Timely conducted testing procedures can help notice the loss of cable insulation integrity, spot signs of its deterioration caused by aging, and therefore prevent cable failure.

Withstand or Hipot Cable Testing

Withstand or hipot testing is used to evaluate the condition of cable insulation during installation, acceptance, or maintenance testing. As a result of a hipot test, at the point of an insulation defect an electrical tree will start to progress, create the insulation breakdown and make it possible for the technician to pinpoint the faulted place.

There are several methods for the field testing of underground electric power cables which are grouped under the category of Type 1 Tests. These are intended to detect defects in the insulation of the cable system in order to improve the service reliability after the defective part is removed and appropriate repairs are performed. These tests are usually achieved by application of moderately increased voltage across the insulation for a prescribed duration of time. Such tests are categorized as a pass or fail, go or no go type of a test.

Type 1 Tests typically involve one of the following:

1. the insulation resistance test performed with a standard megohmmeter, also known as undervoltage test;
2. the DC high potential test or DC hipot test;
3. the very low frequency high potential test (VLF hipot test);
4. the AC high potential test which is performed at power frequency (50 hertz or 60 hertz).

Figure 4 - HVTS 70/50

Undervoltage Tests Utilizing DC Voltage

Undervoltage tests are typically performed with a megahometer. Since the test uses voltages under the rating of the insulation, the test is considered to be a nondestructive test and does not produce any of the harmful effects associated with a high voltage DC test. Insulation tests electrically stimulate the insulation and measure the response. Depending upon that response conclusions are drawn about the condition of the insulation.

What is important to understand is that if perfect insulation existed, there would be no flow of electrical current through the insulation to ground, but since no insulation has infinite resistance, there is always some leakage current flowing through the insulation. While a small amount of current leaking through a good insulation is not a problem, difficulties arise when the insulation begins to deteriorate, and the leakage current begins to increase.

The insulation resistance test measures the resistance of the insulation material to the flow of the leakage current, helping to assess the condition of the insulation. This type of test allows to measure either the resistance or the flow of the leakage current.

Overvoltage Testing Utilizing DC Voltage

For years high voltage DC testing has been a traditionally accepted method for judging the serviceability of MV cables. DC hipots or DC high potential tests have worked well as a withstand and condition assessment test for paper insulated lead-covered PILC cables. When plastic insulation cables were first introduced, DC was still the preferred measurement method.

As time moved on, plastic insulated cables became more abundant and began showing aging effects and service aging. DC continued to be the dominant test, but concerns began to grow over the effectiveness of this test. Studies showed that while not causing any damage to new cables, DC hipot testing has a detrimental effect on service age cables on account of accelerating treeing effects.

Currently, most standards continue to include DC testing as an acceptance test on newly installed extruded dielectrics, and almost all of the recommended practices have abandoned the use of DC testing for maintenance purposes, or particularly when the cable has reached service age (is over five years of age).

To locate a cable fault with DC hipot testing, the technician needs to find the point where current leaks through the faulted insulation, and for electricity to leak, it requires a conductive path. In other words, two wires should be exposed, or there should be a wire and some other metal like the cable shield. So, in hipot testing, voltage is increased to cause leaking or arcing between exposed wires or cables, which helps to catch errors that otherwise would be missed.

Concerns Associated With DC Testing

DC hipot testing is believed to be harmless to new solid dielectric cables as their insulation is homogenous and allows for an even distribution of electric stress. Also, DC can be safely applied for the installation, acceptance, and maintenance testing of cables with laminated-type insulation.

The most common concerns over DC hipot testing are related to aged cables. Applied to the non-homogenous insulation of such cables, DC is likely to cause space charging at the weak points of the insulation, a very typical problem for extruded cables. In their turn, accumulated space charges can result in electrical treeing and eventual insulation breakdown.

Another limitation of DC withstand testing is the fact that the test polarity cannot be changed during a single test, and no partial discharge can be initiated. Yet, without the partial discharge analysis some of the severe cable insulation defects may be overlooked.

Nevertheless, DC withstand testing is effectively applied to detect insulation errors to do with cable accessories or environmentally-affected interfacial and surface leakage issues.

Cable Temperature, Test Voltage & Duration

For a DC hipot test to provide accurate results, the cable or cable system under test should be at ambient temperature. This means that if the cable temperature is increased due to having been subjected to substantial load, some time should be allowed for the cable to cool down.

The DC hipot test should be started with test voltage that is up to 80 per cent higher than the cable's rated ac rms phase-to-phase voltage. It should then be raised, either continuously or in steps, and brought to the maximum test voltage in the time interval of 10 to 60 seconds (this interval may have to be increased for longer cable systems under test); the maximum test voltage should then be maintained for 15 minutes.

Figure 5 - Test transformer TIOG-100

Field test voltages for shielded MV power cables

System voltage, kV rms, phase-to-phase	System BIL, kV crest	Acceptance test, kV dc, phase-to-ground	Maintenance test, kV dc, phase-to-ground
5	75	28	23
8	95	36	29
15	110	56	46
25	150	75	61
28	170	85	68
35	200	100	75

Testing Method

DC withstand testing is performed offline, on a disconnected cable or cable system under test. In case of multiconductor cables, each conductor is tested individually. The other conductors and shields should be grounded. The test lead of the hipot tester is connected to the first conductor under test, and the initial test voltage is supplied and gradually raised to the maximum level.

If the test voltage is increased continuously, it should be done at an even rate. If the test voltage is increased in steps, at least five steps should be made; at each step the technician should wait for the current level to stabilize, with current readings taken at the end of each step, 2 minutes after reaching the maximum test voltage, and at the end of testing.

Figure 6 - Connection setup for DC testing

In most cases steady or decreasing current readings received when fixed voltage was applied indicate that the insulation of the object under test is in an acceptable condition.

A reliable indicator of the insulation quality is the resistance of one of the tree circuit conductors compared to the resistance of the other two conductors. If the ratio of insulation resistance exceeds three to one for cables over 1000 m, it is a sign of the insulation quality deterioration.

Advantages and Disadvantages of DC Withstand Testing

The benefits of the DC dielectric breakdown test include the following:

- The lower output capacity of a DC test system compared to an AC test instrument makes DC testing safer for the technician;
- The DC withstand test is much safer for the technician than AC testing on highly capacitive objects under test;
- DC withstand testing is used to detect insulation errors to do with cable accessories or environmentally-affected interfacial and surface leakage issues;
- DC hipot testers accurately display the amount of true leakage current of the cable or cable system under test.

Yet, DC withstand testing has a number of drawbacks:

- The cable or cable system under test has to be discharged after testing;
- DC withstand testing is potentially destructive for the insulation of service age cables;
- Some serious insulation errors cannot be revealed with DC dielectric breakdown testing.

To sum up, DC hipot testing is still widely applied for the acceptance testing of newly-installed cables. Yet, when it comes to maintenance testing done in the field, VLF hipots are more commonly used.

AC versus DC Testing

AC withstand testing is typically used by cable producers when performing the installation testing of new cables. The AC hipot test is a Pass/Fail or Go/No-Go test, during which the technician raises the test voltage to a certain maximum value to check whether the object being tested can withstand the applied voltage, and therefore passes the AC test, or fails it. AC hipot testing is widely used to

Figure 7 - AC hipot test set HVAC-50/60R

see whether the equipment complies with the applicable standard.

In contrast, DC testing provides more information on the cable or cable system under test, giving the ability to measure leakage current and calculate the insulation resistance.

Another difference is the size, and therefore cost, of AC testers and DC testers, with the former being substantially larger and more expensive than their DC analogues. This is explained by the fact that AC testers supply a much larger charging current than DC testers do.

The strong advantages of DC over AC testing are that DC testers are smaller, more affordable, safer due to supplying less current, and give information on real leakage current. On the negative side, with DC testers there is a need to ramp up the test voltage and to discharge the object under test after testing.

The benefits of AC versus DC testing are that AC testing does not require ramp voltage and the object being tested does not need discharging. However, due to their size AC test sets are usually not practical for field testing; besides, the high current they supply present a safety hazard for the operator.

Figure 8 - HVTS 70/50L

AC DC Hipot Testers by KEP

Understanding that today's cable testing conditions require flexibility in terms of hipot testing method choice, KEP offers the portable test systems AC DC Hipot Tester HVT-70/50 with oil-insulated high voltage unit and AC DC Hipot Tester HVTS-70/50 with SF-6 insulated high voltage unit.

KEP's high voltage test systems HVT-70/50 and HVTS-70/50 perform DC high potential testing of power cables (IEC 60502-2) up to 70 kV, power cables accessories (IEC 61442) as well as AC high potential testing, up to 50 kV at 50 Hz, of switchgear, reclosers, dielectric insulators, high-voltage dischargers (arresters), busbars and other dielectric materials with relatively low electric capacitance.

The main features of the HVT-70/50 and HVTS-70/50 AC DC hipot testers include:

- AC (up to 50 kV) and DC (up to 70 kV) modes
- Compact and portable desig
- Exceptionally high safety level due to the new safety interlock and two-operator mode features
- Internal memory
- Auto and manual modes
- Wireless test data exchange with a PC via optional Bluetooth

VLF Withstand Testing

What is VLF Hipot Testing

The very low frequency (VLF) withstand cable test is essentially a type of AC hipot test conducted at a frequency rate of 0.01 to 1.00 Hz. Due to a significant drop in the operation frequency compared to AC hipot testing, done at 50 or 60 Hz, a VLF hipot tester is much smaller than a typical AC hipot test set, and thus is applicable for field usage.

Figure 9 - VLF 60 Cable insulation Tester

Main VLF Hipot Testing Parameters: Waveform, Voltage, Duration

The typical waveforms for VLF testing include the sinewave, squarewave, and cosine-rectangular (trapezoidal) wave. The sinewave, or sinusoidal voltage, is the same as the voltage used by AC power systems. Out of the three mentioned waveforms, the sinewave is found to be the most efficient for cable testing as it causes the electrical tree to progress at the fastest rate, which results in shorter test times.

IEEE 400.2 guide stipulates that the test voltage should be 2.0 to 3.0 times the cables' normal line to ground voltage. Since maintenance testing is done on service age cables, the recommended voltage is 80 per cent of that used for installation/acceptance testing. If there is a need to perform several test cycles, it may be reasonable to decrease the testing voltage by a further 20 per cent. The table below reflects the IEEE 400.2 guidelines as to the optimal testing sinewave voltage for 5 kV to 35 kV cables.

VLF test voltage for MV cables

Cable rms voltage	Installation rms / peak voltage	Acceptance rms / peak voltage	Maintenance rms / peak voltage
5 kV	9 / 13 kV	10 / 14 kV	7 / 10 kV
8 kV	11 / 16 kV	13 / 18 kV	10 / 14 kV
15 kV	18 / 25 kV	20 / 28 kV	16 / 22 kV
25 kV	27 / 38 kV	31 / 44 kV	23 / 33 kV
35 kV	39 / 55 kV	44 / 62 kV	33 / 47 kV

The advised testing time is 60 minutes at 0.1 Hz on new cables, and 30 minutes at 0.1 Hz on service age cables; it is recommended that the withstand testing time during maintenance testing should be extended to 60 minutes at 0.1 Hz if the circuit in question is of special importance.

VLF Testing Method

VLF testing is performed on offline cables, that is, the cable under test should be disconnected from the power system, and properly grounded. The VLF tester is then connected to the cable under test, and the required test voltage is set.

If the cable under test passes the VLF testing, the voltage should be decreased to zero, the cable under test and the VLF instrument should be discharged, and the cable should be grounded.

If the cable under test fails the test, the test voltage drops down to zero on its own. The VLF tester should be switched off for the cable and the tester to discharge, and the cable should be grounded. After that, the fault or faults can be found with fault locating instruments and repaired, or the respective cable sections are replaced.

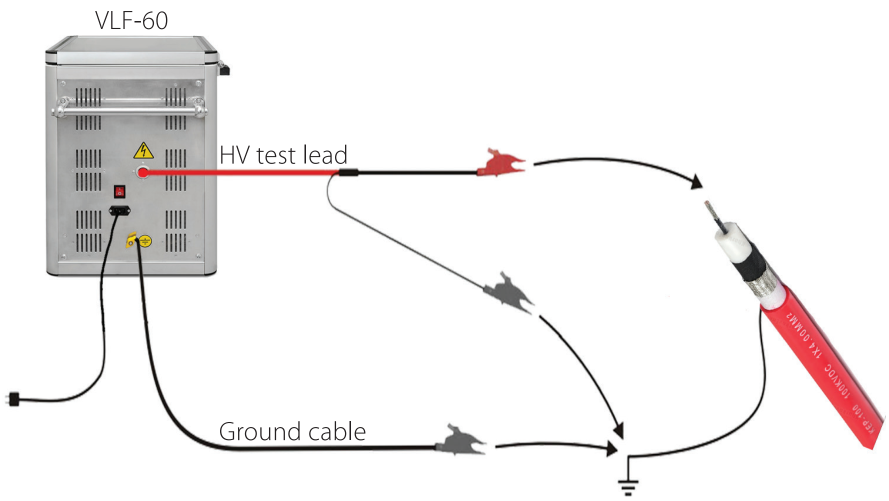

Figure 10 – Connection setup for a VLF cable

Advantages and Disadvantages of VLF Cable Testing

The strong points of VLF cable testing include the following:

- VLF cable testing is applicable for extruded polyethylene, laminated paper, and mixed insulation;
- the small size of the VLF test set is perfect for field testing;
- VLF hipot testing can be done on both new and service age cables, which means that it can be used for installation, acceptance, and maintenance testing;
- With the right voltage and testing time, VLF testing is not destructive for less severe insulation defects that could remain dormant for a long time and not impede the cable

performance. Yet, it is efficient for locating more severe insulation defects that are likely to cause cable faults in the nearest future;

- Combined with standard cable diagnostics equipment, a VLF test set can be used for diagnostic testing.

At the same time, the difficulties associated with VLF hipot testing are these:

- VLF withstand testing may not provide conclusive results if the insulation is significantly damaged by water treeing or has partial discharges. In this situation, it is recommended that VLF testing should be combined with other diagnostic testing methods;
- VLF testing with very high testing voltage at a frequency below 0.01 Hz may cause space charges in extruded polyethylene insulation;
- VLF cable testing is done on offline cables only.

To sum up, although VLF withstand testing is attributed to destructive cable testing as it causes severe defects to initiate treeing and break down the insulation, the VLF test nevertheless does not harm good insulation. So, VLF hipot testing performed with alternating sinusoidal voltage best meets the testing purpose of locating and removing severe defects in insulation that is mostly of good quality.

VLF-60 AC Hipot by KEP

The VLF-60 Cable Insulation Tester by KEP is a very low frequency high voltage test set that ensures efficient testing and fault location on medium voltage cables.

Main features of the Cable Insulation Tester VLF-60:

- Efficient non-destructive cable withstand testing
- Portable, perfect for field testing
- Test capacity of 10 µf
- Fully automatic testing cycle
- Automatic discharging
- Easy maintenance due to solid-type insulation system
- Breakdown voltage measurement and load recognition
- Easy-to-use software
- Does not need an external PC
- LCD touch screen