Water Tree Degradation And How to Manage It

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1. Introduction

As distribution systems around the world transitioned from PILC to XLPE insulation, they have become vulnerable to water tree degradation. The resulting reduction of system reliability grows steadily year by year. In North America the transition was more then 30 years ago and the water tree problem has become the leading cause of dielectric failure.

Cable manufacturers have largely learned how to build cables that are much more resistant to water trees. A good cable today should perform reliably for many decades. But, the pressure on manufacturers to reduce cable costs sometimes leads to quality problems that will not become apparent until years after the cable is installed. Cables manufactured with defects can show reduced reliability from water trees in as little as 5 years.

Once a poor quality cable is installed, water tree degradation will slowly reduce system reliability. The tools system managers have to manage the results are few. The extremes of management tactics include wholesale cable replacement or living with the problem and just repairing failures as they occur.

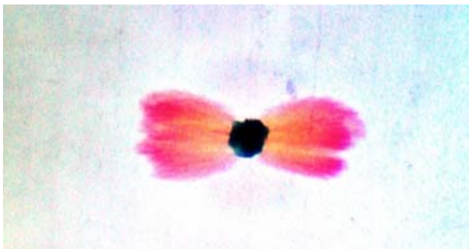
System managers in North America and Europe have been using a method of insulation restoration for many years. The need for this technology is now spreading across the rest of the world following the path of the transition to XLPE 15 and 20 years ago.

2. Water Tree Growth

AC stress within homogeneous XLPE insulation of distribution cables is many times lower then levels that can lead directly to breakdown. However, small defects on the surface or in the bulk of the insulation will act as electrical stress risers and focus the stress to very high levels. This will lead to electro-oxidation of amorphous regions in the XLPE and as a consequence a change of properties from hydrophobic to hydrophilic. This promotes condensation of water vapor to form microscopic water filled voids between the XLPE molecules. This encourages further electro-oxidation and condensation causing the phenomenon to grow in the direction of the stress. The resulting cloud of voids grows in the shape of a tree and is therefore called a water tree. But, the voids are not interconnected so there is no open channel or trunk to the tree.

Without the defect to focus the stress or water to condense, a water tree will not grow. If either could be controlled after installation, water tree degradation could be controlled and system reliability would be maintained. However, after installation the defects are a permanent fact of life and there are few options to reduce the stress.

Cables can be manufactured and installed completely dry. However, if not protected with a full metal sheath (such as extruded lead), water vapor in the surrounding environment will diffuse into the XLPE until it reaches equilibrium. Most soils and ducts contain close to 100% relative humidity. Consequently, in a few years the insulation will approach 100% saturation. Therefore, there is ample water in the insulation of most cables for water tree growth. Even the humidity in ambient air can be sufficient to promote water tree growth in above ground insulated cables.



Bowtie water tree growing from dust particle in 6-year old XLPE insulation.

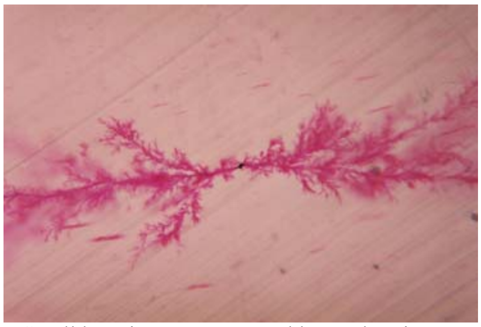
Efforts to keep water out with PE or PVC jackets, water swellable compounds, strand filling materials, or water blocked accessories have little effect on eventual water concentration in the XLPE.

3. Transition to Electric Tree

The XLPE within the water tree is still a good insulator. But, it has a lower resistance to discharge then the surrounding insulation. If the stress across the insulation exceeds the reduced discharge resistance of the water tree, a partial discharge is initiated. This discharge will burn an open channel in the insulation called an electric tree.

The resistance to discharge in the electric tree's channel (inception voltage) is lower then in the undamaged water tree. Further discharging is therefore more likely. While discharging, the electric tree will lengthen which lowers the inception voltage further. A small electric tree may exist in a cable for some time as long as the extinction voltage is well above the operating voltage. But, if the extinction voltage drops below the operating voltage, the discharge will continue and lead to failure within hours.

There is a strong correlation between water tree length and AC breakdown strength. As the water trees grow longer over many years, the cable gets progressively weaker. Eventually, the resistance to discharge is reduced far enough that even minor transient voltage events such as switching or grounding will initiate an electric tree.



Small bowtie water trees and large electric tree several centimeters from cable fault

4. Detecting Water Trees

Directly detecting water trees insitu is difficult because water trees have minute electrical signatures. Test systems generally rely on the cumulative property of a characteristic from many water trees to reach detectable levels. But, if there are only a few very bad water trees, the technologies will average the condition over the entire insulation volume and therefore occasionally underestimate the severity of the cable's aging.

Water trees can be indirectly measured by applying high AC voltage at various frequencies including VLF. The high stress will initiate a partial discharge. If the high voltage is maintained, the electric tree will rapidly grow across the insulation and produce a fault. This is an AC breakdown test or withstand test. This is like having a patient exercise on a treadmill. If the patient has a heart attack, you have confirmed the patient had a weak heart. A variation is to use PD equipment to detect the discharge and immediately shut the test down. This leaves small electric trees behind.

High voltage DC has been used for years for commissioning of new or re-worked circuits to detect large defects such as knife cuts. But the voltage level required for this testing injects space charge that will make water trees more susceptible to discharge when placed back in service. High voltage DC may be valuable for testing new cables. But it is not appropriate for commissioning craftwork on aged cables.

When applied at lower voltages, DC can be useful in measuring the aging condition of a cable either through leakage current measurement or through measuring the rate of space charge injection (or release).

The only definitive way to directly measure water trees is to send a cable sample to the laboratory for water tree inspection. Water tree staining and visualization can be done on a sample only a few centimeters long. Samples from fault locations should be regularly inspected for water trees to identify trends. AC breakdown study can effectively measure the effect of water trees. But, it requires many meters of cable and a high voltage laboratory. It is therefore generally only used as a research tool.

The easiest way to gauge the severity of aging in an XLPE system is to analyze failure history. All cable (and accessory) failures should be documented and categorized by cable type (age, manufacturer, size, etc) and failure type (external damage, accessory, or otherwise unknown insulation failure). A review of this information along with a few lab tests of failure samples will reveal certain classes of cable that are having water tree issues.

5. Managing System Reliability

Managing the effect of water tree degradation is a matter of balancing the value of system reliability against the cost of the remedy. When an XLPE insulated system is young, almost all cable related outages come from mechanical damage. Reliability improvements at this stage focus on reducing the threat posed by excavations along the cable route. Relatively small investments can produce significant improvements.

As the underground system ages, the frequency of outages stemming from water trees increases adding to the baseline of outages from other causes. At first the water tree related faults are a small fraction of the whole reliability issue. The cause of these few faults is frequently labeled as unknown and no action is necessary. Even if they are recognized, the cost of proactive intervention is unreasonable. As the system ages further, the percentage of cables with critical water tree problems increases and eventually water trees can become the leading cause of outages.

To maintain the system reliability at a reasonable level while the water tree problem grows necessitates an ever increasing attention to their resolution. Focusing on installing higher quality cables today can help years from now. But for the cables in the ground, the options are limited to replacement and restoration.

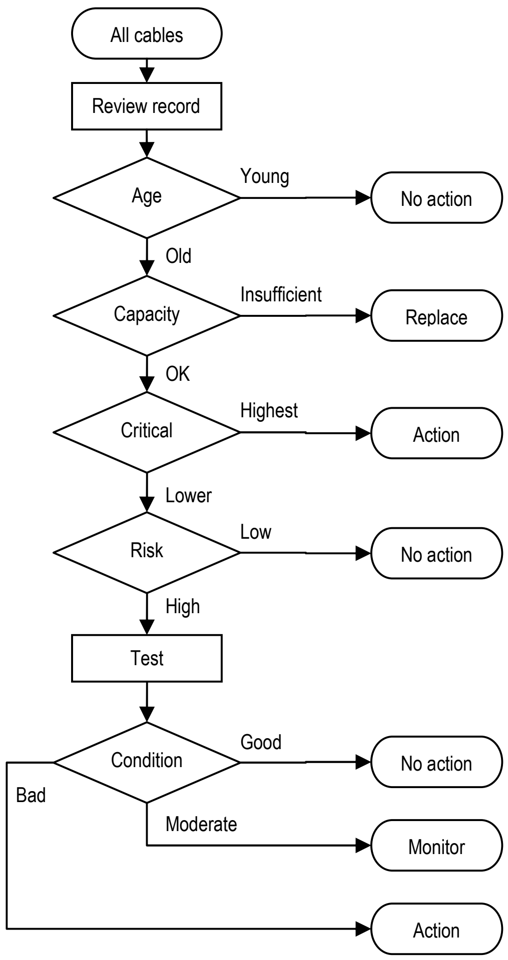
6. Prioritization

Circuits within the aging system must be evaluated to assign a criticality factor associated with the real and perceived cost of an interruption. This is combined with an estimate of the probability of a fault to derive a priority.

Many of the highly critical circuits within a system are already identified through intuitive cues. These are circuits with large customers that are particularly sensitive to outages (industrial complexes, police facilities, government buildings, and healthcare facilities). Other circuits that are intuitively critical are the backbone circuits which would have a large area impact or have no backup (ring main circuits or radial circuits).

The rest of the system must also be assessed to identify where reliability of a particular circuit has higher value. This can be a gigantic task. But, since the water tree problem is age related, the scope of the assessment can be greatly narrowed by setting an age limit. Unfortunately, records of cable age are not always available. In this case a geographic approach looking at the age of development can be helpful.

The first step in judging a circuit's potential to fail is reviewing it's history. The cable's age is a central factor in water tree related reliability. But, of equal importance is the original quality of the cable when it was installed. Records should be reviewed to identify groups of cables that should have similar quality issues (manufacturer, insulation type, date manufactured, cable construction).



Prioritization

Failure records must be reviewed to identify particular cables with low reliability. If a cable has had an otherwise unexplained insulation failure, it has a very high risk of failing again. Analyzing all failure records along with the associated original cable record will expose groups which had original quality issues and are now at high risk of failure. This leads to recognizing marker factors in the original cable records. Sorting the other aged cable records by these markers will reveal groups that have not yet failed but should be suspect.

Testing is expensive and can lead to further problems. Therefore, testing should be limited to only the high risk circuits identified through the record analysis. Testing programs should begin with passive or online systems to narrow the field for further testing (or action). Second level testing can include offline systems with low risk or more destructive systems such as PD measurement.

The reliability of the system related to insulation degradation is dynamic. As the years pass new groups will reach critical age and some groups will drop from the list when they are replaced or restored. The benchmarks in the decision process will also change as the availability of funds, political pressure, acceptable risk, and the number of circuits that need attention change.

7. Restoration

When a particular circuit or group of cables reaches the top of the priorities list, its circumstances must be reviewed to determine which course of action which achieves the desired result. The factors that will be weighed in this review include the full cost of the action, the disruption it causes, the availability of funds, and how the use of resources will impact other projects.

In the early stages of system degradation, the higher cost of a few cable replacements can be justified considering it also provides the opportunity to upgrade the capacity or quality of the cables, joints, terminations, ducts, or manholes. However, as the water tree problem becomes more pervasive, the number of circuits that must be addressed can overwhelm the available resources. At that point restoration becomes favorable because the lower cost and higher speed of application allows more circuits to be addressed with the same resources.

Restoration is a process of adjusting the chemistry and electrical properties of the cable's insulation insitu. More specifically, a unique silicone fluid is injected through the length of the conductor which then diffuses into the polyethylene, undergoes a chemical transformation, and raises the resistance to discharge. This results in the prevention of faults.

8. Treatment Process

The actual steps used for treatment vary widely to match the circuit and circumstances. Weather treating from termination to termination or from joint to joint, the process can look very different. But, there are basic steps common to all.

A. Preparation

Circuits are de-energized long enough to modify or replace the terminations (or joints) with equipment that provides an injection access port at both ends of the circuit.

B. Pneumatic Testing

Pressurized air or nitrogen is injected into one end of the cable. If flow is detected coming out the far end, the flow path is established. The entire length is then pressurized to detect any potential leaks. This assures the terminations and any intermediary joints will inject without difficulty.

C. Joints

Any pre-existing joints on the circuit are carefully identified with a TDR. Most are not designed to contain internal fluid pressure (although some will). Additionally, some types of joints contain materials that are not compatible with the restoration fluid. If the joints on the circuit are a type that is not compatible or they fail the pneumatic testing, they will be replaced with kits that are designed for treatment. These jointing kits are available for installation on critical circuits that may be treated in the future.

D. Energize or Not

The injection equipment and most termination modifications are designed to allow injection while the cable is energized. However, for an added margin of safety, cables are frequently treated while out of service. When treating from joint to joint or from joint to termination, the circuit must remain out of service.

E. Vacuum

A small tank is connected to one end of the cable and a pump is used to establish a moderate vacuum. This removes air or nitrogen from the conductor to enhance the completeness of the fluid fill. It also assists with moving fluid through the cable.

F. Fluid Injection

At the opposite end from the vacuum tank, a small tank is connected and pressurized to inject a small amount of a desiccant fluid. This will lead the restoration fluid through the conductor cleaning out water and contaminants.

Following the desiccant, a tank of silicone restoration fluid is connected to the inlet end of the cable and it is pressurized with air or nitrogen to the injection pressure. This forces the fluid out of the tank and through the cable. The pressure used depends on factors such as the length of the cable, the available time, joints, and elevation changes. Most injections are completed at 3 or 4 bar. The most common injection equipment is certified to operate up to 8 bar and equipment rated for 23 bar is available for special applications.

G. Completion

Injection time is highly dependent on the conductor compression. For example: 500 meters of typical compressed conductor may complete in 12 hours. The same length of highly compacted conductor may take 3 days. All three phases are tested and treated simultaneously. Circuits over 5 km have been treated in one piece.

Injection is complete when clean silicone fluid comes through into the vacuum tank at the far end. The injection tanks are removed and the terminations are permanently plugged to contain the fluid.

9. Preventing Faults

Phenylmethyldimethoxysilane is the unique molecule that has been used for restoration for nearly 20 years. Its properties make it uniquely suited for cable restoration.

- In bulk form it is a very low viscosity liquid which allows it to be injected through great lengths of cable at low pressure.
- It is a relatively small molecule and diffuses easily through solid XLPE.
- It reacts (polymerizes) with water molecules. In this reaction the water is consumed and the silicone molecule grows larger.
- The polymerized molecule moves more slowly through the insulation.
- The polymerized molecule remains reactive with water.
- It has a very high dielectric strength.
- It is a strong water tree retardant.

Once the conductor of a cable is filled with the fluid, the restoration of the insulation begins. Over a period of months the silicone molecules diffuse through the conductor shield and into the XLPE insulation. There it encounters resident water molecules. Two silicone molecules react with one water molecule to form the beginning of a silicone polymer chain. In the process the water molecule is consumed and a methanol molecule is produced. This methanol molecule diffuses quickly out of the cable and dissipates into the environment. When the short silicone polymer chain encounters additional water and silicone molecules, the process repeats.

Since the concentration of water in the insulation is highest in the micro-voids of the water tree, more reactions occur there. Additionally, the polymerization of the silicone makes the molecule larger and dramatically slows its diffusion. As a consequence, the silicone molecules that diffuse through a water tree find ample water to react with and then they essentially lock themselves in place. This leaves a large concentration of silicone in the water tree.

After polymerization the molecules continue to consume water long into the future keeping the insulation dry. The CableCURE molecule is also a strong water tree retardant preventing future growth.

After treatment the water in the micro-voids of the water tree has been replaced with a high dielectric strength silicone polymer that has particular qualities that prevent discharges. As a consequence, the cable can withstand higher transient voltages without the initiation of electric trees.

Restoration interrupts the usual progression from water tree degradation to electric tree and then failure by blocking the discharge that creates the electric trees.

When compared to replacement, a treated cable can perform with nearly the same reliability. 21,000 km of severely degraded cable has been treated in almost 20 years. More then 99% of this cable is still in service without failure. This matches or in some cases exceeds the record of newly installed cable.

10. Conclusions

The frequency of cable failure today is a function of the quality of cables that were installed decades ago. Once the cable is installed, few of the factors that influence water tree degradation can be changed. To maintain an acceptable level of system reliability, managers must assess and prioritize the cables within the system and apply the available tools accordingly. Cable replacement is suitable in the early stages of system degradation or when more capacity is required. As the degradation continues, restoration becomes increasingly viable to maintain the desired level of system reliability with finite resources.