USING NEW TECHNOLOGY AND ASSESSMENT METHODS TO A RELIABLE MAINTENANCE STRATEGY OF MV CABLES

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ABSTRACT

This paper presents an integrated approach to the maintenance strategy of the medium voltage underground grid of the Greater Lisbon area. This strategy, implemented by EDP Distribuição over the last 6 years, aims to reduce the cable failure rate. This assessment, completed through pilot projects and innovative tests, has also included reviewing and improving cable and accessory technology and analysing faulted cables and accessories on laboratory. Diagnosing the network, by using online monitoring solutions improves the asset manager's decisions, as it allows investment decisions – either replacing or extending the life of an asset – to be based on real data.

INTRODUCTION

The Medium Voltage (10kV and 30kV) underground grid of the Greater Lisbon area spans over 6000 km, serving a population of over 2 million people. This grid is composed of cables with impregnated paper insulation and cables with extruded insulation, with different ages and conditions. Many of these cables are close or have even surpassed their predicted lifetime and some cables are even breaking down long before this time. The immediate consequence is an increasing failure rate. This rate, which has been around 7 faults/100km/year, can be associated with a low reliability of the XLPE cables, many of which are in fact now completing 30 years.
These facts, together with the growing demand (by both population and regulator) for better network performance and cost-effective maintenance solutions, pose a challenge to the DSO, as it has to daily manage, maintain and develop an ageing grid. The fact that this grid includes the Portuguese capital and largest city, Lisbon, makes reliability and resilience more pressing matters to the system operator. EDP Distribuição, as the main Portuguese DSO, has been taking steps to establish a maintenance strategy based on a reliable assessment of the underground MV grid and also on the introduction of innovative technologies. Although the current review focuses on the Greater Lisbon area grid, some of initiatives carried were applied nationwide.

EDP Distribuição has tackled the issues concerning the grid by frequently organizing workshops and seminars, as broad discussion forums with service providers, manufacturers and scholars, gathering ideas and new solutions to launch innovative projects and initiatives.

The first workshop was in October 2010 and it was totally devoted to the MV underground network. More recently, in 2012, other workshops have followed, such as one on Distribution Substations and another one on Automation and Control.

In accordance with the conclusions yielded from the cited workshops, EDP Distribuição has launched several initiatives, as pilot projects and also as definitive improvements to the underground grid components. The solutions we have tested over the past 6 years can then be divided into four categories, according to the phase of the life-cycle to which they were applied, as the diagram in Figure 1 suggests.

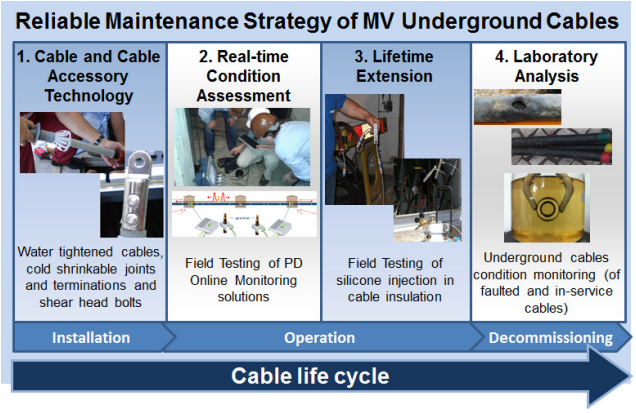

Figure 1 – EDP Distribuição's approach to the MV underground cables' life cycle.

The initiatives carried concern **Cable and Cable Accessory Technology**, **Real-Time Condition Assessment**, **Lifetime Extension** and **Laboratory Analysis,** all of which are detailed hereinafter.
Another noteworthy initiative, not detailed ahead, was the creation of a diagnosis and test manual of MV underground cables, accompanied by personnel training, which contributed significantly to the improvement of our knowledge of the cables.

CABLE AND CABLE ACCESSORY TECHNOLOGY

The first phase considered in the life cycle is the installation of new cables in the grid. The choice of the applied cable – and its accessories – plays a significant role in the performance of the entire grid.
Much like other global electrical utilities, the technology of the cables installed in the Portuguese grid has gradually evolved in the 1980s from paper insulated lead

cables (PILC) to polymeric insulated cables (PE and XLPE) with PVC outer sheath. After a few years, some issues with the polymeric insulated cables started to arise, the most relevant being water diffusion through plastic, which lead to water treeing, electrical treeing and, ultimately, insulation breakdown.
One of the most important topics discussed in the 2010 workshop was a diagnosis of the network components, conducted by EDP Labelec between 2004 and 2010, which, among other tests, examined the contamination agents present in medium voltage cables. The result of this analysis showed that water, traces of moisture , water treeing or a combination of these were present in over 60% of the cables, thus confirming the reliability issues identified in the cables.
As a response to this problem, EDP Distribuição had already started (back in 2008) to study, specify and redefine the standards for new cables to install in the Portuguese grid. As a result of these efforts, in 2010 a new generation of XLPE cables (called LXHIOZ1(be) according to the Portuguese Norm NP665) was introduced in the medium voltage grid. This cable differs from its predecessor in two very important constructing aspects:

- Water-swelling tape over the copper sheath;
- Outer sheath in polyolefine (PO) material.

The goal of the changes introduced is to prevent absorption and penetration of water (guaranteed by the PO sheath) and circulation of water inside the cable (assured by the water-swelling tape) and therefore significantly reduce premature ageing caused by water treeing. Figure 2 shows this LXHIOZ1(be) cable, where the layers, numbered radially from 1 to 8, are as follows: 1)-Conductor; 2-Conductor screen; 3-XLPE insulation; 4-Insulation screen; 5-Metallic screen; 6-Longitudinal water tightness tape; 7-Outer sheath; 8- Semiconducting cover.

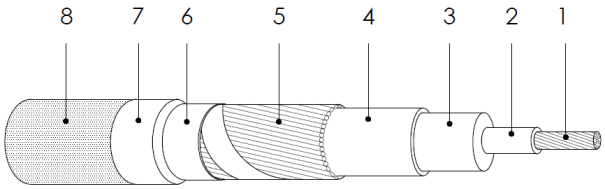

Figure 2 – LXHIOZ1(be) cable

In addition to this cable, EDP Distribuição has also tested a cable that offers radial water tightness (as well as longitudinal) via an aluminium foil bonded to the outer sheath and a better behaviour with water treeing due to its insulation in XLPE-WTR (Water Tree Retardant). It also guarantees water tightness to the conductor. This cable was tested to be used in terrains of particularly high phreatic surfaces, where water penetration to the cable is more likely to occur.

Cable accessories also play a significant role in the overall performance of the underground grid. The aforementioned diagnosis conducted by EDP Labelec also focused on the analysis of joints and terminations removed from the grid. It showed that 52% of these joints had severe defects caused by poor workmanship (such as irregular and undue cuts, punctures and dirtiness).
As a result, a project to study and propose new, more reliable accessories was launched. The objective was to test accessories that were easier to install and less likely to include workmanship errors - less dependent on the workers' ability – whilst, at the same time, having proven quality and reliability.
Therefore, cold-shrink joints and terminations, slip-on terminations and also shear head bolt connectors and cable lugs were deployed on the MV network on selected locations, on both 10kV and 30kV cables.
The cold-shrink concept is based on pre-expanded silicone rubber tubes with removable plastic cores that are easily removed once the components are properly positioned. This creates a safe and tightened seal around the cable, as the rubber tends to return to its original size. The slip-on technology offers the same installation ease but in this case the rubber piece is not pre-expanded and so the assembly is carried out by sliding the body onto the prepared cable using slip-on auxiliary plastic devices.

These two types of accessories, used on joints and terminations, require no heat source, as the traditional heat-shrink do. The following advantages are noted:

- The installation involves fewer steps;
- It requires less physical effort;
- It requires almost none special tools (like heat sources);
- It takes less time, as the operation can start immediately after installation (there is no cooling time).

The shear head bolt through connectors and cable lugs – tested as alternatives to the traditional compression devices – are mechanical splice connectors or terminals that use, as fasteners, bolts that shear off when proper torque is achieved. These connectors prevent the use of crimping tools, reducing the risk of using an inadequate die.

REAL-TIME CONDITION ASSESSMENT

One of the most significant aspects to improve identified during the workshops promoted at EDP Distribuição, is the high fault rate of the MV underground network caused, in a large part, by asset ageing.
This ageing results in the deterioration of the insulation of the cables, characterized by water and electrical treeings, which ultimately leads to the fault. The problem is the lack of reliable knowledge of the current condition of the cables, which means that we do not possess, presently, an indicator of the condition of the cable insulation and, consequently, of the probability of a fault in that cable.

If available, the information of the real condition of a given cable can be used to determine, with a significant degree of confidence, if the cable has weak spots in the insulation and, if so, if it is prone to fail soon.
Furthermore, this data can be taken into account to consider and plan the replacement of the cable, before a fault occurs, thus avoiding the consequences associated with the fault.
On the other hand, the result of the test can show a good condition of a cable, thus avoiding unnecessary replacement investments and giving EDP Distribuição a useful tool for more discerning and informed investment decisions.

The **Partial Discharge (PD) activity** on a cable has been used, to a large extent, to serve this purpose of detecting early warning signs of deterioration of the MV cables. For more than 15 years the offline tests to cables have been performed on newly installed cables, as a part of the asset commissioning process. The offline PD test requires the cable to be completely taken out of service.

As a more advanced alternative, the **On-line Partial Discharge** test is performed with the cable in-service in normal working conditions and so it offers important advantages, when compared to the offline PD test, such as:

- Power supply is not interrupted during the test;
- The cable is tested in real operating conditions;
- The partial discharge record is continuous and in real-time (and not just a "snapshot" as in an offline test).

To test the effectiveness and usefulness of the On-line PD monitoring EDP Distribuição has trialled, for a period of 6 months in 2012, two On-line PD monitoring systems: "Smart Cable Guard" from DNV GL and "4 Phase PD Test and Monitoring Solutions" from HVPD Ltd, UK [1].

The **SCG ® (Smart Cable Guard)** is the **DNV GL** solution, and it presents a very wide experience and a proven track record in several utilities around the world. Each SCG ® system consists of two measurement units, one at each end of the assessed cable, in either a substation or a RMU (Ring Main Unit). Each of these measurement units includes a Sensor/Injector Unit (SCG - SIU) and a Controller Unit (SCG - CU). The SIU contains a sensor to measure pulses from the cable and an injection device to inject pulses into the cable [2]. The CU controls the measurement sequence and collects the data, uploading it to the Control Centre at DNV GL for interpretation, via a GPRS communication card. The system was then left unattended for the duration of the trial, and EDP Distribuição were given access to a secure web site were we could follow up on any PD activity and risk values in the circuits assessed.
In Lisbon, 4 of these units were installed, monitoring the condition of 4 cables for which EDP Distribuição had some concerns, caused by their relevance in the grid and a fault record history.

The **HVPD Ltd (High Voltage Partial Discharge)** solution adopted by EDP Distribuição was the appliance of the first 3 phases of the HVPD's 4-phase asset management, designed to detect, locate, diagnose and monitor PD activity in the MV electrical grid.
The first phase, the "PD Surveying Stage", is a survey to detect PD Activity and it is performed using a simple screening device (the "HVPD-PDS Air™"). This small portable device includes three PD sensors: a transient earth voltage (TEV) sensor to detect local electromagnetic activity inside metal clad plant switchgear; an airborne acoustic (AA) sensor for detection of discharges into air and an external sensor, the HFCT (High Frequency Current Transformer) sensor, to detect PD activity in cables by attaching it to the earth connections of in-service MV (or HV) cables.
The second phase is the "PD Diagnostics and Location Stage" in which the HVPD-Longshot™ Unit is used. This portable test device is suitable for short duration on-line PD testing. It uses the same sensors used in phase 1whilst also recording data from four channels. The software included provides automatic PD activity diagnosis. Mapping techniques are then used to locate the PD activity along the cable, when present.
The third phase is the "Short Term Monitoring of PD Trends" which is achieved using the HVPD Multi™ and Mini™ monitors to detect and analyse continuously the PD activity in several circuits at the same time through multiple channels (4 in the Mini-Monitor™ and 16 in the Multi-Monitor™) grading the PD activity in each channel in a colour scale according to the level of the PD activity. The Mini-Monitor™ is designed for RMU or secondary substations and the Multi-Monitor™ is used mainly for primary larger substations. Through these monitors it is possible to determine (using HFCT sensors) the existence of PD and also, through a statistical algorithm that determines the direction of the discharges, the PD sources (cable or substation switchgear).
These three phases were performed consecutively and, in the last phase, the monitors were left for a period of time (2 to 3 weeks) on a location, after which the results were analysed and the equipment was moved to a different location. Using this method, we were able to monitor three primary substations. Figure 3 shows a few images of the On-line tests.

Figure 3 – Overview of the On-Line PD Tests (HVPD and DNV GL).

LIFETIME EXTENSION

Water treeing and the consequent electrical treeing is one of the most common and well-known insulation breakdown processes. This breakdown leads to a failure which represents service interruption and reparation costs.
In a cable with a fault record history – even if it has not reached its predicted life time yet – the replacement of the cable is usually considered, which carries a high cost to the electrical utility.
There is, however, another solution to postpone the costly replacement: the **extension of the lifetime** of a cable through the injection of silicone.
This process, applicable only to polymeric-insulated cables (such as XLPE cables), consists in injecting a silicone fluid into the conductor strands of the cable. This fluid diffuses from the conductor strands into the solid dielectric material and, once inside the insulation, it repairs the damage caused by existing water trees and other dielectric defects, by filling in the insulation microscopic gaps.

EDP Distribuição has tested the **CableCure®** solution from UtilX on two occasions, in 2006 and in 2008, in different circuits, both with a fault history record.

The full process can be divided in five different stages:
The first stage is the diagnosis and preparation of the cable, in which the conditions of the cable are assessed, by performing flow and pressure tests. The length of the cable and the presence of joints are confirmed by TDR (Time Domain Reflectometer) and the joints, if existent, are replaced by special ones, provided by UtilX.
The second stage is the injection of a strand desiccant as a purging and drying agent.
The third stage is the injection of the silicone fluid (Siloxane) on one end of the cable, which can take up to 30 hours (depending on the length of the cable) to reach the other end.
The fourth stage is the appliance of vacuum. A vacuum tank removes the excess water inside the cable, hasten the fluid through and ensure a thorough fill.
The fifth and final stage is the chemical process that occurs with the diffusion of the silicone fluid to the insulation. The Siloxane fluid reacts with the water in the voids and fills them with a dielectric oligomer, repairing the damage. Since the molecules of the resulting oligomer are 47 times larger than water molecules, they lock into place and retard the growth of new water trees.

The CableCure® technology has been used for more than 25 years and it has been applied to more than 38.000 km of cable. This proven track record backs the 20 year minimum lifetime extension guaranteed by UtilX.
The cost for the 2008 intervention, on a 640m long cable, was around 12.000€.

LABORATORY ANALYSIS

As a way of knowing the health of the MV cables and in which manner they breakdown, EDP Distribuição has introduced laboratory tests on the insulation of cables, to detect water, air gaps or other contaminants inside the cable. These agents often indicate the presence of water treeing which will eventually lead to a full insulation breakdown.
The tests are performed in small samples of cables since from faulted cables and from in-service cables that were intervened. Furthermore, other tests were conducted on joints to assess the conditions of these accessories, to detect, for example, poor workmanship.
This means we tested cables and joints from a wide range of ages and conditions (not just from faulted cables).
It should be noted that these tests are made in addition to the standard type and routine tests performed on new cables in factory.

The laboratory test on cables consists in cutting a small portion of the cable (around 5cm) in a helical shape, so every portion is 0.6/0.7 mm thick. This portion is then immersed in glycerine at 130ºC and the whole set is backlit to observe contaminants or damages to the insulation (as shown in Figure 4). When such problems are detected, the portion is thoroughly inspected.
The joints, on the other hand, are fully opened and traces of water, dirtiness and signs of poor execution are screened (Figure 4).
The result of the full diagnosis of the cable/joint indicates not only the presence of the contaminants in the insulation but it also defines, according to a risk matrix, the severity of the condition of the cable and, consequently, the priority to replace the cable. This information is useful to plan the investment according to real data.

These "Underground Cable Condition Monitoring" tests are performed since 2011 and in the period from 2011 to 2013 some 180 tests were carried to the cables in the Greater Lisbon area.
The tests were conducted with EDP Labelec, an EDP company specialized in performing laboratory and field tests on electrical utilities' assets.

Figure 4 – Joint analysis (left) and cable insulation diagnosis (right).

CONCLUSIONS

The integrated approach to the maintenance strategy of the underground Medium Voltage grid in the Greater Lisbon area has allowed EDP Distribuição to gain, over the last 6 years, a significant know-how of the behaviour of the cables.

The introduction of **water tightened XLPE cables** will contribute to a reduction of the insulation breakdown caused by the presence of water inside the cable. The experience gained by the installation of the cable is positive but it should be noted that 4 years of use is not enough to reach a definitive conclusion of its reliability. The wider application and the accumulated experience throughout the coming years will determine the conclusions of the performance of the cable.
The field tests of **cold-shrink joints and terminations, slip-on terminations** as well as **shear head bolt through connectors and cable lugs** from various manufacturers allowed us to note differences and similarities between them, as well as test the contractor field teams' reaction to these accessories.
By using these accessories, some of the issues detected with heat-shrinking (like incomplete shrinkage) and with compression connectors and cable lugs (inappropriate and inadequate compression dies) are eliminated, thus lowering the likelihood of defects in the installation of cable accessories and, consequently, increasing the reliability of these network components. The overall time was also significantly reduced – an approximately 30% time save – and the contractor team also handled the new equipment very well, denoting its simplicity and effectiveness. The conclusion of our analysis was that despite the higher cost of these accessories, the aforementioned advantages justify their installation.
Our efforts, and conclusions, and the positive overall response to the tested equipment, lead to the redefining of the standards for cable accessories at EDP Distribuição, supported by the emission, in early 2014, of a new internal norm for these accessories.

Monitoring On-Line the condition of cables is a very promising approach, even though the trial period of 6 months was proven to be too short for these systems. During the trial period some PD activity was detected but no significant event was registered. And even though none of the analysed cables failed we expected to witness more PD activity, due to the age and foreseen condition of the cables.
Once installed, DNV GL's solution can be regarded as a service, in a sense that SCG ® is almost a turnkey solution: the monitoring and interpretation of the results is provided by the DNV GL's Control Centre. Despite the fact that the monitored cables did not display significant PD events, SCG ® is widely regarded as a very accurate technology and is used in several utilities worldwide.
The HVPD 4-phase approach is more dependent on the operators' experience. The detection of the presence of PD events, in the survey stage (phase 1) and in the PD trend monitoring stage (phase 3) was successfully achieved and displayed encouraging results in the detection of presence of PD events in cables. On the other hand, the accurate location of the PD sources along a cable has shown to be harder for inexperienced operators. The valuable cooperation of HVPD engineers helped to better interpret the results of the tests.

Extending the lifetime of the XLPE cables for at least 20 more years can prove to be a cost-effective solution, as the cost of the "rejuvenation" of a cable is merely a fraction (around 30%) of the cost of the replacement. Using a technology with a remarkable worldwide track record, as the CableCure® solution has showed, adds reliability to the process and sets the stage for future initiatives and even for a broader application as a viable alternative to cable replacement.

The **laboratory analysis** revealed the presence of water or other contaminants in around 65% of the cables. According to the severity of the contamination and also due to the importance of the circuit to which the cable belongs, 15% of the cables were given a recommendation to be considered for replacement in the near future. The thorough examination of cable joints confirmed the results of the aforementioned diagnosis conducted by EDP Labelec: the two main "enemies" of underground network components are water and poor workmanship. To a certain extent, these conclusions validate the implementation of the new water tightened cable and of the "fail-proof" cable accessories stated previously.

Analysing better and improving all the phases of the cable life cycle will certainly lead to more insightful investment decisions, based on real data about the cables.

The overall conclusion of these initiatives is that assessing integrally all the phases of the cable life cycle, from the review of the cable and the accessories introduced to the analysis of faulted components is a very promising approach and one that EDP Distribuição will follow to reach a reliable maintenance strategy and improve the performance of the MV underground grid.

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