Introduction

Historically, maintenance criteria to prevent failures in Medium-Voltage underground cables were limited to the own experience and knowledge of the power network. In practice, this was translated to controlling the number of failures in different cables types or cables sections and of their technology, the statistics of age and use.

Such information induced to investments which not always conduced to the expected profit in terms of the target: to reduce the number of failures and to improve the quality of the service.

Current trends in the privatization of the Power Distribution Systems Sector, with the major demands on maintenance profit and improvement of high quality service have driven ENDESA DISTRIBUCION to the search of new technologies to reach the objectives.

The next question is still valid:

“When is profitable to change a cable?”

In the Century XXI we keep formulating the questions: Why do cables get damaged? Do we know when a cable has aged? Are we capable to tell which sections aged and to what extent?

Additionally, the natural evolution of the utilities does not permit to know accurate data for each section of cable, such as:

- Type of cable
- Manufacturer
- Setup date
- Geographic maps of each section and its parts
- History of damages and faults.

Besides, many resources are required to obtain and keep great amounts of data.

Objectives

Therefore there is a need of a diagnosis system which provides an “x-ray” of the cable just as it is “here and now”, independent of the data of the cable and of its history. We need a quantifiable diagnosis for the determination of the zones of a faulty cable section, which lead up to priority actions, independently of the technology of the cable section since this information is not always known. Additionally, experience shows that there is not a total correlation among the technology of a cable and its probability of failure in a short-term.

Premises of the diagnosis:

- The results should be objective and scalable.
- To Provoke the least stress for the cables.
- Operating simplicity of the process.

The whole process should be compulsorily profitable.

Diagnosis Methods.

Current technologies.

In the next block we show the known diagnostic methods for cables, classified in terms of the information they offer:

Choosing a diagnostic method.

The methods who give a vision of the global state of the cable, do not fulfill a fundamental target: to locate the problems of the cables. This is an essential issue in the maintenance of a distribution network.

Given an industrial frequency, the peak voltage corresponding to the RMS value $U_0$, is equal to $\sqrt{2}U_0$.

The measurement systems based on oscillating waves submit the cable to peak voltage of $2U_0$, compared to $\sqrt{2}U_0$, the peak value of the VLF (very low frequency) system.

Besides, the application time of the voltage is limited to the load time of the cable (some seconds) in the oscillating wave case. In the VLF system, the charge is maintained all during the measurement of PD.
On the other hand, the measuring frequency with oscillating waves is closer to the nominal frequency of the network, thus, the test results are obtained under conditions similar to the working conditions.

Considering the features of the equipment based on such technologies, we decided to implant a maintenance process for Middle Voltage underground cables with the support of a Diagnosis laboratory of Partial Discharges, measured with the use of oscillating waves.

### Cables Diagnosis

**Cable Selection Criteria**

Until now, underground cable replacement decisions were made after knowledge of damage. Insulation tests were carried out during the repair process, being mainly corrective. Furthermore, the predictive plans of cable replacement associated the damage risk level to the technological nature of the cable (manufacturer's specifications, damage statistics, etc.), not by means of an individual diagnosis.

Besides, in the Power network may exist MV cables with a specific level of insulation adequate to the original exploitation needs, but less reliable to the present service voltage, representing a greater risk of damages.

The method proposed here focus the cable diagnosis on its behavior and/or function carried out in the network (Market fed, Impact facing a damage, etc.), evaluating objectively its reliability. The result of the diagnosis constitutes a new priority parameter: the risk of damages based on the PD value and frequency. This is decisive to propose the cables replacement or elimination by reconfiguration.

Thus, the main cables selection criteria are the following:

**Criterion 1 - Cables with repetitive damages (reference value > 2 damages/year).** The result of the diagnosis applied to this group of cables will lead up to decide the replacement of the section or sections diagnosed as with the highest level of risk.

**Criterion 2 - Cables with major responsibility.** The diagnosis has preventive character and is oriented fundamentally to the cables whose function in the network is, among others:

- MV Feeders of Distribution Centers whose damage can suppose blackouts of market by failing to guarantee the condition (n-1).
- Circuits head MV Cables, or cables interconnected with other whose fault can suppose interruptions of market supply by not remaining guaranteed the condition (n-1).
- Cables feeding critical service supplies.

In any case the selection priority is given by:

- Magnitude of the supplied market (Power, number of customers, etc.)
- Fail to supply energy (FSE) – expected TIEPI¹ in case of damage.

The result of the diagnosis can lead up to 2 possible decisions: the replacement of the part or to assume the risk.

**Criterion 3 - Cables in networks in process of reconfiguration (due to saturation, growth of demand, etc.)** The diagnosis permits to know the reliability of the cables that are kept in service during the reconfiguration process and which are not supposed to be replaced as a consequence of the process.

**Criterion 4 - Cables with technology whose specific rate of damages has been evaluated.** The trace of damages in the cables permits to determine the rates of damages for each type of technology (material / type of insulation / level of insulation). It permits to identify those cables whose rate overpasses a specific statistical reference value considered a threshold. The given types of installed cables that register these rates should be detected in order to determine its degree of risk, thus letting make a decision as for its replacement.

**Measuring Method.**

The diagnosis equipment identifies and assigns the magnitude to the diverse PD that can be produced in a section of cable,

¹ TIEPI: “Tiempo de Interrupción Equivalente a la Potencia Instalada”. In Spain, measure of the breakdown time equal to the installed Power.
along its length, providing a map with the PD along the same one.

Diagnosis Results Example

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It is indispensable to carry out a prior calibration, consistent in the injection of a reference pulse, equivalent to the one that would produce a PD of predetermined magnitude in the extreme of measurement. This operation is carried out by injecting a specified sign, depending on the insulation type of the cable. The pulse will travel along the cable which behaves like a guide of wave, to the open and opposite extreme, where will suffer a reflection and will be detected again in the extreme of measurement with a softened value, determined by the characteristic of the line.

By means of the calibration, the curve of exponential attenuation pertaining to the reference pulse is determined. This curve will be used as a reference to analyze the PD and to assign its magnitude.

The technique of measurement of the distance to the extreme of test where the pulse of PD is produced is analogous to the one used in classical reflectometry, keeping in mind that in the case of PD the pulse is not injected in the line but generated in some point of it.

Software identifies the point where the PD is produced, the number of times that occurs on that point during the process of measurement and its magnitude in pC.

Diagnosis is carried out according to a sequence of softened pulses oscillating with a frequently close to the service frequency and with maximum peak of the first semi-wave (negative) of increasing values: 0.5, 1, 1.5 and 2 U0.

The diagnosis also permits to identify and differentiate punctual problems in accessories or points with damages possibly caused by external agents, summarizing the corrective response to actions upon those singular points.

Analysis and criteria of action.

There are three parameters to define the degree of critical risk of the different PD that can be detected and to decide consequently, the order of the interventions to be carried out in the network. The parameters are:

1- Voltage level in which appears the PD.
2- Magnitude of the PD in pC.
3- Number of repetitions of the PD in a same place during the process of measurement.

Knowledge of the dielectric material, location and origin of the joints (initially laid on or due to damages), and laying on conditions of the cable to be diagnosed are of great help.

The PD value in terms of the type of insulation gives a first approach of the result.

For extruded polymers insulation (PVC, CPE, XLPE, EPR) a value over 50 pC is considered as insulation damage. For impregnated paper insulation, a scale is considered: over 50,000 pC, damaged insulation; from among 10,000 and 50,000 pC risk of progression of the PD in a relatively brief time and requires maintenance actions upon the section of network; and among 2,000 and 10,000 pC a new test of PD should be carried out on the section in a reasonable time (1 year) to follow the evolution of the PD level. Waiting times remain uncertain and they will require great experimentation.

Dielectric Material | PD level (pC) | observe | risk | damaged
--- | --- | --- | --- | ---
Extruded | > 50 | • | • | •
Paper | 2,000 – 10,000 | • | • | •
 | 10,000 – 50,000 | • | • | •
 | > 50,000 | • | • | •

The analysis of the PD activity maps, in terms of dimension and frequency within the same section and in comparison with other sections was performed. As a result, the following scale for the frequency at which the PD appear, for a given part and measurement process, gives a qualitative measure of fault risk:

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>low risk</th>
<th>medium risk</th>
<th>high risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 3</td>
<td>4 - 6</td>
<td>&gt; 6</td>
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The Voltage level while the test has been carried out and PD activity has been detected, represents another risk indicator: It
is more dangerous if PD activity is present with low levels of voltage, given that its permanent presence in service will lead up to a fast evolution of the insulation damage, which may finally cause a breakdown under usual service stress.

Through the evaluation of all these factors observed in the distinct PD maps, either in the same location or different locations, one can state Preventive Action Plans in terms of priority, within three categories:

- Immediate Action
- Put into Schedule Action
- Stand By

With the use of this final classification, people responsible of the network maintenance have valuable information upon the degree of urgency and the order of application on the development of corrective actions before great defects are shown (preventive maintenance).

Practical application of the Diagnosis

Once implanted, depending on the group of cables, the process offers diverse benefits:

Cables with repetitive damages (Criterion 1): Maintenance resources optimization dedicated to the replacement of cables, being able to act upon a greater number of cables by replacing only those sections with major risk of suffering damages and redistributing the expenses for other maintenance actions. Furthermore, the fault reduction turns into a better quality service.

Cables with high level of responsibility (Criterion 2): In this case the actions upon selected cables with major risk, prevent major faults; the investment on the repair comes compensated by the benefit of the Quality of Service (TIEPI, FSE). These actions are specially profitable in zones of great concentration of Power or zones of high Service Quality demand.

Cables in networks in process of reconfiguration (Criterion 3). The knowledge of the state of these cables permits a correct decision making on replacement costs and investments of maintenance projects and/or external demands. It also gives a good guess of how to redistribute initially considered service costs into investment costs.

Cables with technology of low reliability (Criterion 4): In this case diagnosis has shown that there is not a direct correlation among the known risk of failure due to the technology with the effective risk of failure of a given cable, and of the final presence of damage.

The application of this process permits selective actions upon the cables with major objective risk of suffering damages, in a predictive mode, focussing on those sections of greater incidence, as opposed of replacing the whole group of cables.

All in all, it leads up to a decrease of the so called Cost / Profit binomial understood as:

- Cost: cost of Diagnosis process implant
- Profit: maintenance costs reduction by selective replacement actions and faults reduction, with the consequent increase of the Quality of Service.

Applying the mentioned process, we obtained the systematic diagnosis of all the sections of a feeder distribution line of the 25kV network, with responsibility.

As a practical case we show the results and conclusions for two of these sections among distribution centers.

Section 1. Cable with repetitive faults. The preventive maintenance program suggested replacement of the part.

length: 1000 m. 
extruded insulation
8 damages distributed uniformly all along.
Replacement cost: 150 000€.

Diagnosis: DP values suggest a stand-by action, so the cable is not replaced.

Section 2. Cable with history of no observed faults. The preventive maintenance program suggested to discard the cable as for replacement.

length: 370 m. 
1 subsection of oil impregnated paper insulation
1 subsection of extruded insulation (30 m.)
1 mixed joint

Diagnosis: DP values suggested an Immediate Action for the paper insulation end, a programmable Action over the mixed joint, and a stand-by Action over a 70 m. portion due to observed PD activity.

Cost of preventive actions: 1 500 €

Results of the execution of the diagnosis by DP were:

- To derive the budget of Section 1 to other sections and lines in more critical conditions.
- To determine corrective actions in Section 2 that assure the quality of service with a minimal cost.

Difficulties of the process.

Our experiences during the implantation of the Partial Discharges PD fault location in cables in service confirm the
main difficulties of the lack of practical experience in the field.

For the selection of a specific diagnosis system, ENDESA DISTRIBUTION tested diverse field laboratories of diverse technologies. Even in this first phase we observed an important dispersion of technologies, both in the electro-technical aspect (voltages, frequencies, etc.) and in the analysis results, where very complex data processing procedures are used with no standard type of norm or guide. Because of that, it is very difficult to guess the behavior of each one upon the resolution of our problems. In fact, only a comparative experimental study would let us weight up how does each one match our own needs and possibilities.

This is specially evident with the measuring options (with or without disconnection of the MV cables from its corresponding equipment), the equipment ergonomics, in the capture of data, the data analysis and submitting results. In general, there are obvious differences all along the diagnosis process.

Though the standards and the technology developed by the diverse manufacturers are converging, a great dispersion still exists.

In the data capture process, manufacturers establish calibrations and filters that affect the subsequent analysis. Differences in these parameters are appreciated, apart from the associated to different technologies.

Also, data analyses associate the use of filters, parameters and systems for search, comparison and integration. Practice shows that one must be scrupulous otherwise would lead up to divergent results. Likewise, when using correctly the diverse laboratories results are not homogeneous, even though all give intrinsic correct results.

It is to expect an advance in the future in this sense, having available equipment that give objective and homogeneous results, providing the Power Distribution System Utility with diagnoses of MV cables comparable and independent to the applied technology. That would permit without doubt a better management of the maintenance.

**Conclusions**

The system provides a detailed knowledge of the state of cables insulation, especially useful in studies of network reconfiguration, as well as laying on new facilities.

It permits a better resource assignment by acting selectively upon specific portions of cable sections. It permits a trustworthy predictive maintenance allowing to act before mayor damages appear. The issue is of practical application on cables of great responsibility.

It also brings an alternative to the current insulation field test methods, suitable for the quality assurance on new cables and their parts.

The current state of the technology and standardization of these equipment imply an important dependence on the manufacturer, from which is indispensable to have an adequate technical support.