REE’s research and development projects related to predictive maintenance based on monitoring of critical parameters in high voltage underground cables.

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ABSTRACT
In order to increase the useful life of underground circuits, it is very important to identify and monitor, if possible, the critical elements and parameters of the installations, so that their condition can be controlled.

Two different projects have been developed within the REE research and development strategy, in order to achieve the target of online monitoring two different critical parameters related to underground lines: partial discharges and sheath currents.

The added value of these projects consists in making possible to assess the current condition of the installation by means of continuous online monitoring. As a result, maintenance design plans are more adequately adapted to reality.

KEYWORDS
Continuous monitoring, condition based maintenance, partial discharges, sheath currents, underground lines.

INTRODUCTION
Underground lines have increasing importance for utilities in order to guarantee the energy supply, especially in urban areas. Due to their specific characteristics, performing visual inspections is not always feasible or convenient, in addition, the effects of aging of the underground lines are often not visible externally, until the fault is irreversible.

Any system capable of monitoring continuously the critical parameters of the cable lines may provide useful information to check the state of the assets. REE has developed two different prototype systems to face the problem of continuous monitoring partial discharges (PD) and sheath currents (SC) in existing underground lines [1].

The analysis of the data obtained by these systems can help to prevent future failures and to introduce a condition based maintenance practice, in order to improve the reliability of existing grid components.

PARTIAL DISCHARGES MONITORING SYSTEM
The project of online monitoring of partial discharges (PD) was the result of an association between REE and DIAEL (High Voltage Electrical Insulation Diagnosis). This system has been installed in an underground cable system of the electricity transmission network in the metropolitan area of Madrid.

This pilot R&D initiative will allow us to know the insulation condition of underground cable systems under different network conditions and external factors that could affect their integrity.

The monitoring system employs PD measuring units placed in the cable system accessories (terminations and joints). Each PD measuring unit has HFCT (High Frequency Current Transformer) sensors installed around the ground connection cables of the accessories and communicates with the other units and with a control and analysis unit by fiber optic links. Every data acquisition is synchronized and sent to the control and analysis unit for analysis.

The system includes a software tool to discriminate between PD pulses and noise signals, to estimate the PD measurement sensitivity, to identify and locate existing PD sources and to correlate each PD source with its associated defect.

Pilot PD Monitoring System

Four PD Measurement Systems (MS) have been installed along 1662 meters of 220kV cable system. A Control Analysis System (CAS) has been installed in the substation to manage the MS units. The first MS unit has been installed in correspondence of the terminations of the high voltage (HV) cables in the substation. The next two synchronized MS units were installed in two HV joint bays. The last MS unit was installed in correspondence of the other terminations on a high voltage tower.

![Figure 1: PD Monitoring System](image)

The rack cabinet containing the CAS unit has been installed in a building near the substation. The measurement systems were housed in boxes with an appropriate protection level for each location. For each MS unit three HFCT sensors, developed for outdoor environment, have been installed around grounding connection of the cable sheath.

Communication and Synchronization

Synchronized acquisitions are managed by the CAS to acquire the PD events by all the distributed sensors with
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the same time reference. This information allows the automatic localization of each PD pulse detected by sensors to be performed. Communication and synchronization between CAS and MS units are done by means of optical fiber links. An optical fiber line complying REE specifications has been laid along the cable route using the existing channeling.

Figure 2: Sensor installation.

Power supply for MS units

The power supply for MS units was provided in different ways avoiding low voltage cable lying along the HV cable route. At the substation site, an auxiliary transformer was used. In the joint bays, existing low voltage supplies were employed. An autonomous power system was developed to supply the MS installed on the HV tower. The system is composed by solar panel, inverter, battery and charger.

PD Analysis

In order to detect PD pulses under background noise, the monitoring system includes an automatic powerful filtering tool based on wavelet transform and statistical analysis. This technique permits to find automatically all the PD travelling along the cable system. An automatic PD mapping can be determined using the arriving time to each MS unit [2].

PD Location

Preliminary automatic diagnosis using the monitoring system shows PD sources located at both ends of the cable system [3]. In figure 3, concentrations of PD pulses appear located at the substation and at the HV tower.

Figure 3: Automatic PD Location along cable system.

PD Discrimination & PD Pattern identification

Discrimination analysis using PD waveform parameters for located PD pulses on each cable end shows different PD sources [4][5]. Floating potential and external surface discharges were identified analyzing the phase resolved PD pattern of each discriminated PD source.

Identification of physical phenomena for each PD source determines a good insulation condition of the HV cable system. All the PD sources detected during the monitoring period were not related with internal insulation problems.

Table 1: PD sources detected during monitoring.

<table>
<thead>
<tr>
<th>External Surface PD Patterns Located at Substation</th>
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</thead>
<tbody>
<tr>
<td>First phase</td>
</tr>
<tr>
<td>Second phase</td>
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<tr>
<td>Third phase</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>External Surface PD Patterns Located at HV Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>First phase</td>
</tr>
<tr>
<td>Second phase</td>
</tr>
<tr>
<td>Third phase</td>
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</tbody>
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<table>
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<tr>
<th>Floating Potential PD Patterns Located at HV Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>First phase</td>
</tr>
<tr>
<td>Third phase</td>
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</tbody>
</table>

PD Evolution

The technique employed in this project reveals the location of each PD source and allows its evolution along the monitored period to be followed independently for each PD source. PD activity is measured by two indicators: amplitude and rate. The evolution of these indicators can be analyzed to determine the start date of the phenomena and the severity of the insulation degradation process [6][7].

Figure 4: Evolution analysis for External Surface PD source. a) Amplitude versus rate along 10 days. b) Hourly rate distribution during monitored period.

Correlation between PD activity and HV system condition

Power and voltage were monitored by REE on this HV cable system. Ambient temperature has been monitored by MS units as well. This information has been used to try to correlate the PD activity indicators with other quantities. It was expected that a voltage increase could be related with a PD activity increase. For this reason an analysis was carried out to look for events where the voltage could affect the PD activity.

As can be seen in figure 5 a, most of PD activity peaks are related with power peaks, but such correlation was not found for all peaks. PD activity peaks were found as well when the voltage increased (see figure 5 b), confirming the already known behaviour of surface PD activities.

Autonomous Measurement System

Lying an optical fiber cable and low voltage power line along an already installed HV cable systems can be very expensive. For this reason, autonomous devices were developed for of this research project.
Autonomous communication and synchronization devices

A technical study to evaluate possible alternatives to the optical fiber was performed in this project. The best alternative to maintain the same functionalities of the PD monitoring system is replacing fiber optic by GPS + GPRS technology.

The GPS (Global Positioning System) provides a time reference with enough accuracy (<10ns) to perform PD location along HV cable systems with a location uncertainty less than 5 m. The GPRS (General Packet Radio Service) permits to control and transmit optimized information from MS to CAS unit. Sensor information must be processed on MS before being sent to CAS unit. GPRS network fee must be compared with the cost of the optical fiber installation to determine the most interesting solution.

Autonomous power supply

In this pilot project, an alternative to the low voltage line was implemented successfully with the solar panel system. This solution is very convenient for HV towers and locations where solar energy is viable. To provide power inside joint bays for the MS, a power supply based on a current transformer to obtain energy from HV cables was also developed. The solution includes current transformer, control and rectifier electronic board and a battery to assure uninterrupted power during all day for the MS unit.

The power generated by the current transformer depends on the load of the HV cable system. To assure a minimum power, the autonomous system was developed with a modular design to permit the connection of several cores working together. Next table shows the power obtained depending on the HV cable load and the number of connected cores.

<table>
<thead>
<tr>
<th>Accessory-</th>
<th>Sensor 1</th>
<th>Sensor 2</th>
<th>Sensor 3</th>
<th>Sensor 4</th>
<th>Sensor 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB-ACT</td>
<td>93%</td>
<td>10%</td>
<td>1%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>DG-ACT</td>
<td>87%</td>
<td>16%</td>
<td>14%</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>SJ-ACT</td>
<td>69%</td>
<td>26%</td>
<td>8%</td>
<td>4%</td>
<td>5%</td>
</tr>
<tr>
<td>CB-SCR</td>
<td>103%</td>
<td>11%</td>
<td>4%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>SP-SCR</td>
<td>66%</td>
<td>3%</td>
<td>5%</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>SP-ACT left</td>
<td>62%</td>
<td>25%</td>
<td>25%</td>
<td>6%</td>
<td>4%</td>
</tr>
<tr>
<td>SP-ACT right</td>
<td>94%</td>
<td>23%</td>
<td>12%</td>
<td>5%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Table 2: Sensor sensitivity relation.

Sensor 0 has the highest sensitivity. For this reason, all the results are given in percentage ratio using sensor 0 as the reference in each bonding condition.

The main conclusion of the test is that the installation of HFCT sensors over coaxial cables outside of the link.
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Onsite test – Sensor number optimization

Another subject studied in this project is the optimization of the number of sensors. The methodology implemented is based on the empirical measurement of attenuation of real PD pulses travelling along the cable system.

To determine which sensors can be not installed, a minimum attenuation level must be defined in order to assure a minimum level of detection. Automatic PD location is performed by means of measuring each PD pulses at least by two sensors on different locations.

Figure 8: Pulse attenuation analysis.

Pulses of real PD originated on the substation have been analyzed (figure 8). The sensor on the joint place 557 meters away from PD source detects the PD with a 15% of the original energy and the sensor placed 1086 meters away detects the PD with an energy value of 2%.

Data Acquisition

The elements of the system installed on-site are sensors, Nodes and transmission boxes. The sensors employed in the pilot project are commercially available current transducers, temperature and humidity sensors.

The current transducers were chosen in order to have proper accuracy and being able to withstand the short-circuit current for this installation. Other requirements are: range of current intensity, stability, need (or not) of external power supply, size and geometry (split core or not). Various sensor configurations were considered in order to measure SC in different parts of the system, also considering different bonding systems of the underground lines. As regards the joint bays, sensors had to be introduced inside the sheath connection boxes (link boxes), and in order to do that new boxes had been designed and tested. Figure 9 shows an image of the current sensors inside the link box.

Figure 9: Sensors inside a new sheath connection box (link box) during the qualification tests.

The signals generated by the sensors are acquired by the Nodes (electronic acquisition and transmission devices, [9-11]) that send the acquired data to the transmission box (central telecommunication unit based on a modem), located in the joint bay or close to the terminations. Each Node is powered by an integrated magnetic energy harvester. Figure 10 represents a picture of the Nodes installed in a joint bay.

Figure 10: Nodes installed on power cables in a joint bay.

It is noteworthy that there is no wiring between the modem and the acquisition device (Nodes) providing the system with great installation flexibility. Figure 11 depicts the installation layout for the transition tower and for a
Joint bay.

**Telecommunication**

Another challenge of the R&D project was sending data from different test points of the underground line to a remote central server without using a fiber optic line. In fact, some existing REE underground HV lines do not have optical fiber, so an autonomous telecommunication system had to be developed.

The Nodes use radio to communicate among them and with the transmission box, which sends acquired data to the remote server by a GPRS modem. The local radio communication system is a Personal Area Network, based on IEEE 802.15.4 protocol [12], on which a proprietary standard had been developed with custom features [9–11]. As regards the communication over internet with the central server, different challenges were faced: the modem had to be robust enough to work in a harsh environment, with low power consumption and narrow bandwidth. The system sends every few seconds (10 s in the pilot project) a short length data packet, providing a nearly continuous condition monitoring.

**Data Management**

Measured data relevant to SC and other quantities is sent to a central server in order to be turned into information and to obtain valuable results and conclusions. The central server is based on a Cloud computing solution with high availability, i.e. a load balancer switches the communication, both for users and modems, between two synchronized server machines in order to guarantee continuous operation. On each server runs an application to receive data from modems (data capture) and a web interface (web server) that allows data to be browsed in real-time from any place in the world by using an internet connection.

The software system has been designed also to make possible the installation of a local server machine (not Cloud based), in order to avoid sending data over internet in case of isolated installations or for data protection purposes. All the records are stored and linked to associated metadata (company name, line, substation, etc.) and the web interface provides an easy and friendly tool for data browsing. The web application features a map-based representation of monitored assets, synoptic view, table view of installed sensors and other data representation functions. Graphics such as time based plot (for actual readings and averaged values), correlative plot and map distribution of measured quantities can be obtained through the web application as well.
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CONCLUSIONS

The added value of these projects consists in making possible to assess the current condition of a HV power line by means of continuous online monitoring. Through proper analysis of obtained information it is possible to design a model of any given circuit according to its specific features. As a result, maintenance design plans can be adapted to real asset conditions.

REFERENCES


