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OPTICAL FIBER SENSING APPLICATIONS FOR THE ELECTRIC UTILITY

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CHAPTER 1. INTRODUCTION

In recent decades, the global energy sector has undergone a significant transformation driven by the urgency to address climate change and move towards a more sustainable economy. This evolution has involved a shift in the paradigm of electric power production, where renewable energies are gradually replacing polluting sources.

In this context, the digitalization of electrical grids plays a fundamental role, demanding an advanced telecommunications network to efficiently and securely manage the generation, distribution, and consumption of electricity.

Optical fiber, thanks to its capacity to transmit large volumes of data at high speed and with low latency, has become an indispensable technology in modern telecommunications networks. In addition to facilitating data transmission and control of the electrical grid, fiber also enables advanced sensing solutions, which are essential for real-time monitoring of various critical parameters of the electrical grid, facilitating predictive maintenance and efficient operation of the electrical infrastructure.

However, the aging of optical fiber presents a challenge, as it can affect data transmission quality and sensor accuracy. Therefore, controlling aging is essential to ensure proper maintenance of optical fiber and extend the lifespan of associated telecommunications and monitoring systems, enhancing the security and reliability of the telecommunications network.

Iberdrola, one of the largest electric companies in the world, has an extensive optical fiber network integrated into its electrical infrastructure, which includes both high-voltage overhead power lines and shared underground ducts. The main motivation for this project lies in the need to optimize the operation and maintenance of Iberdrola's optical fiber network through the use of advanced "optical fiber sensing" technologies. To this end, the applications of optical fiber sensors in telecommunications grids, methods to control and mitigate the aging of optical fibers, and as an added value, the extrapolation of the obtained data for application in the operation and maintenance of the electrical grid will be explored and evaluated.

Through this project, a comprehensive vision will be provided to Iberdrola's Telecommunications Department on the potential applications and benefits of fiber optic sensing technology to improve the digitalization of the electrical grid and, ultimately, the transition towards a more sustainable energy future.

CHAPTER 2. STATE OF THE ART

Optical fiber is an advanced technology that allows the detection and measurement of various physical and environmental parameters with great precision and reliability. Among the parameters that can be measured are temperature, pressure, mechanical stresses, and vibrations over long distances [1].

The main advantages of fiber optic sensing systems include their high sensitivity, immunity to electromagnetic interference, ability to cover long distances without the need for signal regeneration, and the possibility of having multiple measurement points on a single cable.

These fiber optic systems have applications in a wide range of areas, such as monitoring critical infrastructures, intrusion detection, seismic surveillance, and telecommunications network management [1].

An emerging and particularly interesting application is the use of optical fiber in the electrical environment. This approach allows continuous monitoring of the electrical grid, improving operation and maintenance by providing real-time data on the condition of the cables. The ability to detect changes in temperature, mechanical stresses, and other conditions along power lines can prevent failures, increase efficiency, and reduce downtime.

This new approach arises thanks to the intrinsic characteristics of fiber, such as its dielectric nature, high security against intrusions and espionage, resistance to temperature and humidity, as well as the ease of system expansion. However, the implementation of optical fiber in electrical environments presents significant challenges, such as the need for electrical-to-optical signal conversion, homogeneous infrastructure requirements, specialized installation techniques, and costly repairs in case of damage, highlighting the importance of designing systems with diverse routes to minimize interruptions [3].

The main fiber optic-based monitoring systems currently in use are detailed below [2]:

- **Optical Time Domain Reflectometry Systems:** Used to measure signal attenuation and detect discontinuities along the fiber.
- **Distributed Temperature Sensing Systems:** Employed to provide detailed information about temperature distribution along the fiber.
- **Distributed Acoustic Sensing Systems:** Used to detect and measure acoustic vibrations in real time along the fiber.
- **Distributed Vibration Sensing Systems:** Used to detect and measure vibrations along the fiber.
- **Distributed Temperature & Strain Sensing Systems:** Allow measurement of both temperature and mechanical strain in real time along the fiber.

CHAPTER 3. MOTIVATION

Iberdrola shows special concern for the lifespan and performance of optical fiber cables. In recent years, the company has conducted thorough audits of decommissioned optical fiber cables to analyze the causes that have led to the modification of optical and mechanical parameters and consequently the aging of the cables. Table 1 presents the main identified problems.

Detected Problem	Description
Excessive attenuation	Higher-than-expected signal loss, which may indicate physical damage or cable aging.
Broken or damaged fibers	Physically broken or damaged fibers within the cable, which may result from mechanical stress or mishandling.
Humidity inside the cables	Presence of humidity or water inside the cable, which can affect light transmission.
Overgrowth	Anomalous growth of the optical fiber.
Contamination	Presence of dust, dirt, or moisture in connectors and splices, affecting transmission performance.
Chemical contamination	Presence of chemical residues on the cable's sheath, making it conductive, causing burns, eliminating anti-tracking protection, and accelerating the failure process due to tracking.
IH Ion absorption	Presence of hydrogen ions absorbed by the cable materials, affecting performance.
Microbends and Macrobends	Bends or curves in the cable causing signal loss.
Faulty connectors	Problems at connection points due to wear, poor installation, or contamination.
Poor quality splices	Poorly executed splices causing significant signal loss.
Aging of materials	Deterioration of cable materials over time due to environmental factors such as temperature, humidity, and UV exposure.
Electromagnetic fields	Impact on the cable sheath due to proximity to electromagnetic fields.
Gel accumulation	In vertically arranged cables, splice boxes fill with gel due to gravity-induced sliding of the material.
Rodent damage	Physical damage caused by rodents or other animals.
Sag effect	This phenomenon reduces the drag distance between conductors and the nearby environment (trees, other overhead lines, etc.).
Lightning impact	When lightning strikes an overhead optical fiber cable, one of the metallic threads in the cable can be cut and start falling, reducing the electrical distance to the conductor.
Repairs	Caused by the introduction of additional splice sections.

Table 1. Main causes of deterioration in optical fiber cables

The use of optical fiber sensors in telecommunications networks represents a technological innovation with significant potential to improve the efficiency and reliability of optical fiber infrastructures. This technology addresses and prevents detected problems, especially in a dynamic and increasingly complex environment. Additionally, the results obtained in telecommunications could be extrapolated to the electrical field, an application of particular interest to Iberdrola. However, there is currently no solution on the market that meets all the specific needs and requirements of an advanced network. This situation underscores the importance of conducting a detailed study to identify and evaluate the most promising technologies that can be implemented.

The main reasons justifying the project are presented below:

- **Improved Fault Detection and Response:** Optical fiber sensing solutions allow for early identification of network problems, which can significantly reduce response times and associated costs with service interruptions, thereby improving operational efficiency.
- **Optimization of Predictive Maintenance:** With accurate and real-time data, predictive maintenance strategies can be implemented, extending component lifespan and reducing operating costs.
- **Improvement of Smart Grids:** Incorporating advanced detection technologies is a crucial step towards the transition to smart grids, which require more sophisticated monitoring and control.

CHAPTER 4. PROJECT OBJECTIVES

The project objectives are structured into several phases, each contributing to the overall goal of identifying and proposing viable optical fiber sensing solutions for Iberdrola's electrical grid:

- **Understanding Differential Technical Aspects**
  Conduct a detailed study of the differential technical aspects of fiber optic sensing technologies, including their operating principles, advantages, and limitations.

- **Identification of Market Alternatives**
  Research the various options available in the market for implementing optical fiber sensing, considering both the technical and commercial aspects associated with each alternative.

- **Evaluation of Identified Market Alternatives**
  Evaluate the identified market alternatives, considering their suitability for application in electrical environments, their level of technological development, and their technical feasibility.

- **Proposal of Viable Solutions**
  Focus on the solutions that present the most interest and relevance, conduct pilot tests with these alternatives and analyze the obtained data.

- **Development of Equipment Evaluation and Predictive Maintenance Models**
  Analyze the main causes of deterioration of fiber optic cables and identify the critical events that need to be monitored to control the aging of the fiber optic and carry out real-time and predictive maintenance. Develop an inspection points plan to standardize the tests to be performed with each supplier, ensuring consistency and comparability in the results obtained. Develop evaluation models powered by the data collected during standardized tests with two objectives: 1. Measure the capability of fiber sensing equipment to detect events of interest to Iberdrola and pass the tests, helping to select the best equipment. 2. Characterize the optical link and assess the aging of the fiber, in order to perform predictive maintenance of the fiber optic network using temperature, vibration, and elongation data provided by the different equipment.

In this context, the project aims not only to evaluate existing technologies but also to provide a solid foundation for Iberdrola to adopt and implement optical fiber sensing technologies in its electrical grid both in the short and medium term, significantly contributing to the operational efficiency of its infrastructure.

CHAPTER 5. ALIGNMENT WITH THE SDGS

This project aligns with several Sustainable Development Goals (SDGs) established by the United Nations [4]. Below is a detailed explanation of how each goal relates to the project:

- **SDG 7: Affordable and Clean Energy**
  The implementation of fiber optic sensing technologies directly contributes to promoting SDG 7 by improving the efficiency and operation of Iberdrola's electrical grid. This ensures a more stable supply and facilitates access to affordable energy for communities and businesses.

- **SDG 9: Industry, Innovation, and Infrastructure**
  By exploring and analyzing new fiber optic sensing technologies to enhance Iberdrola's electrical infrastructure, this project drives innovation in the energy sector and promotes the development of more resilient and efficient infrastructures, significantly contributing to the advancement of SDG 9.

- **SDG 11: Sustainable Cities and Communities**
  Improvements in the operation and maintenance of Iberdrola's electrical grid, thanks to the implementation of fiber optic sensing technologies, ensure a safer, more reliable, and sustainable electrical supply. This advancement directly impacts SDG 11 by enhancing the quality of life for communities that rely on this electrical supply.

- **SDG 12: Responsible Consumption and Production**
  By optimizing predictive maintenance and reducing electrical service interruptions, energy waste is minimized, and the efficiency of electrical consumption is improved. This approach promotes a more responsible and sustainable production and consumption model, advancing SDG 12.

In summary, the project aims not only to enhance the operational efficiency of the company but also to align with the Sustainable Development Goals, thereby contributing to global sustainable development.

CHAPTER 6. WORK METHODOLOGY

In this project, having a solid methodology is fundamental to guide all the actions that make up the project, ensuring coherence and efficiency in the process and facilitating the achievement of the main objective.

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- **Literature Review**
  An exhaustive review of the existing literature on fiber optic sensing technologies and their application in electrical networks will be conducted.

- **Meetings**
  Meetings with Manufacturers
  Meetings will be organized with representatives of different supplier companies, to obtain detailed information about the equipment offered by each and their experience in various application fields.

  Knowledge Exchange Meetings
  Additionally, meetings will be scheduled with other electrical companies to exchange information on advancements in the context of fiber sensing.

- **Pilot Tests**
  Depending on the maturity level of the equipment from the contacted suppliers, a pilot test will be coordinated with them in a real environment prepared by Iberdrola for this purpose: the fiber optic cable that connects the Fuencarral and Majadahonda substations. This environment, including both aerial and underground sections, will facilitate the collection of valuable data.

- **Data Analysis**
  A comprehensive study of the systems will be conducted to determine what type of relevant information can be extracted from the data obtained in each of the pilot tests. The final objective of this analysis is to develop a model that identifies which solution provides the greatest value in monitoring the fiber optic network to perform real-time and predictive maintenance.

Finally, a detailed schedule will be presented, setting the start and end dates for each activity, as well as important milestones throughout the project. This provides a clear guide for temporal planning and ensures effective tracking of the project's progress.

Tarea	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13
	13/05 - 19/05	20/05 - 26/05	27/05 - 02/06	03/06 - 09/06	10/06 - 16/06	17/06 - 23/06	24/06 - 30/06	01/07 - 07/07	08/07 - 14/07	15/07 - 21/07	22/07 - 28/07	29/07 - 04/08	05/08 - 11/08
State of the Art - Summary of Iberdrola's Regulations on fiber optic cables and their installation													
State of the Art - Sensor technology in fiber optic systems. DTS, DAS, DVS, OTDR systems, and other systems.													
Systems using sensors for fiber optic cable analysis. Evaluation of available solutions. Distinction between experimental and commercial solutions. Analysis of capabilities and technological maturity.													
Comparison of Commercial Systems Using Sensors for Fiber Optic Cable Analysis													
Real Cases: Testing of Manufacturer A System and Testing of Manufacturer B System.													
Data Obtained. Reports Provided by the Analyzed Systems													
Conclusions													
Project Review													
Final Delivery													

CHAPTER 7. RESOURCES TO BE USED

This chapter analyzes the resources necessary for the successful execution of the project, including tools, equipment, personnel, and other crucial elements to achieve the objectives outlined in previous chapters.

- **Collaboration with Companies and Organizations**
  Collaboration with manufacturers of fiber optic sensing technology will play a crucial role in the project. These companies will have the opportunity to present their technological solutions and share their experience in the application of these solutions. This interaction will provide valuable information for the analysis and selection of the optimal technology.

- **Available Infrastructure**
  Iberdrola's existing infrastructure will be fundamental for conducting pilot tests. This infrastructure includes a variety of resources, such as equipped laboratories, electrical testing facilities, and especially Iberdrola's electrical network connecting the Fuencarral substation with the Majadahonda substation. This resource will provide a real environment for the implementation and evaluation of the proposed equipment, allowing the analysis of its performance under real operating conditions.

- **Tools and Equipment**
  To execute the activities proposed in the project objectives, highly specialized tools and equipment will be required. This includes optical fiber measurement devices, spectrum analyzers, and other key instruments. Additionally, specialized software will be used for the detailed processing and analysis of data collected during the project.

CHAPTER 8. BIBLIOGRAPHY

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