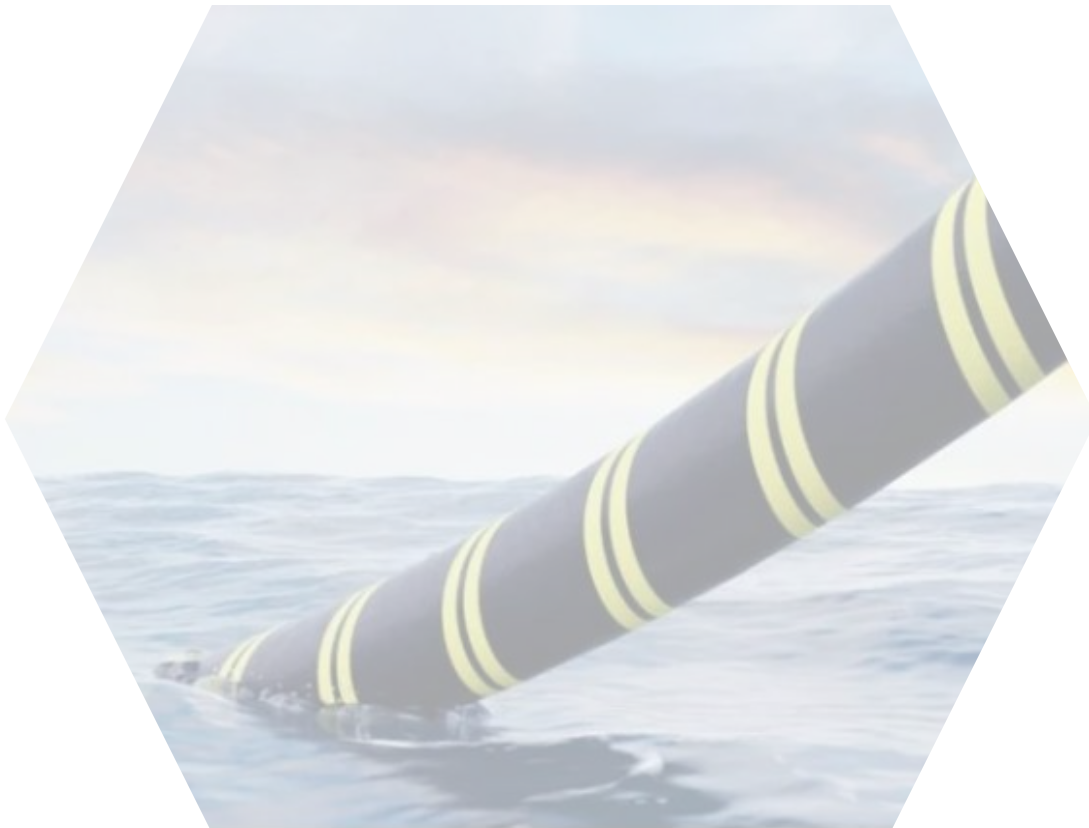




D3.3



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EasyDC-FOS

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EXECUTIVE SUMMARY

This deliverable (*D3.3 Specification of enhanced monitoring and fault location systems*) describes the requirements and development specifications for the design of the enhanced monitoring and fault location systems – short: *Monitoring System* – based on fibre optics. It presents the results of Task T3.3 and sets the criteria for monitoring at least 125 km fibre length in 525kV HVDC cables, and ensuring accurate fault detection using DTS, DAS, Point Vibration Sensors, and PD analyzer.

The report comprises three main areas. First, the EasyDC Use Cases are briefly described and requirements on the Monitoring Systems and its elements are derived. Those requirements cover measurement performance, operational conditions, installation requirements, communication, data transfer. Next, the requirements of the two Use Cases and general market requirements of the target applications are summarized. Lastly, detailed development specifications are derived from the requirements to set quantitative benchmarks for the hardware development and testing.



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ABBREVIATIONS AND ACRONYMS

[illegible]

1 INTRODUCTION

This deliverable (*D3.3 Specification of enhanced monitoring and fault location systems*) sets requirements for the design of the enhanced monitoring and fault location systems – short: *Monitoring System* – based on fibre optics. The resulting report includes criteria for monitoring at least 125 km fibre length in 525kV HVDC cables, and ensuring accurate fault detection using DTS, DAS, Point Vibration Sensors, and PD analyzer.

The success will be measured by the completeness and clarity of the specifications provided. The specifications need to address critical parameters for the measurement performance, communication, and data transfer, as well as environmental parameters, as outlined in T3.3. Additionally, the alignment of these requirements with the project objectives and technological advancements will serve as indicators of successful specification development.

T3.3 will set the implementation requirement benchmarks for PDs, DTS, DAS, and vibration detection systems. This will serve to set a series of objectives regarding fault localisation discrimination (as per system element), precision vs total monitored distance, and real-time for new fault location systems on >525KVDC systems. Monitoring parameters such as frequency bandwidth, sensitivity, real-time, and communications between new PD passive sensors and their integration in future PD analysers oriented to present AC Cables will be assessed, including the objectives of a feasibility study to evolve them to DC cable systems.

Finally, T3.3 will collect requirements for monitoring systems, including but not limited to installation, number of required fibres and type for each system, real time, storage data capacity, communications to cloud and SCADA's, edge and cloud processing functions, operational requirements, regulations, maintenance and aftermarket. WP6 will feed on the resulting digital toolkit (D3.3, M4) to technically develop and implement the passive sensors.

There will be two main content parts that structure the work on task T3.3 and this deliverable.

- 1) **Input requirements** on the Monitor System (total) and its Elements (the different sensors or interrogators), as well as the Edge Node. They are taken from the end users (TSOs), and specifically for the Use Cases. Furthermore, requirements between Elements of the Monitor System can be included, e.g. from interrogators to the sensors, or for communication to the edge node.
- 2) **Specifications** of the Monitor System (total) and its Elements (the different sensors or interrogators), as well as the edge node. These are the development goals for WP6 and party WP7. They will be mainly based on 1) but can also include more general market requirements.



2 Brief Description & Requirements of the Use Cases

To understand the requirements on the different Monitoring System Elements and the integrated Monitoring System, the expected measurement performance and installation requirements for the Use Cases are briefly described in this section. See 'Annex 1 – Description of the Action Part B' for more details on the Use Cases.

Note that the detailed planning of the Use Cases is done in T3.4 and reported in D3.4. This chapter focuses on requirements for the development of the Monitoring System and its Elements in WP6 and WP7.

2.1 Use Case I: Designing a Testbed for validating the health monitoring and fault location techniques in field applications

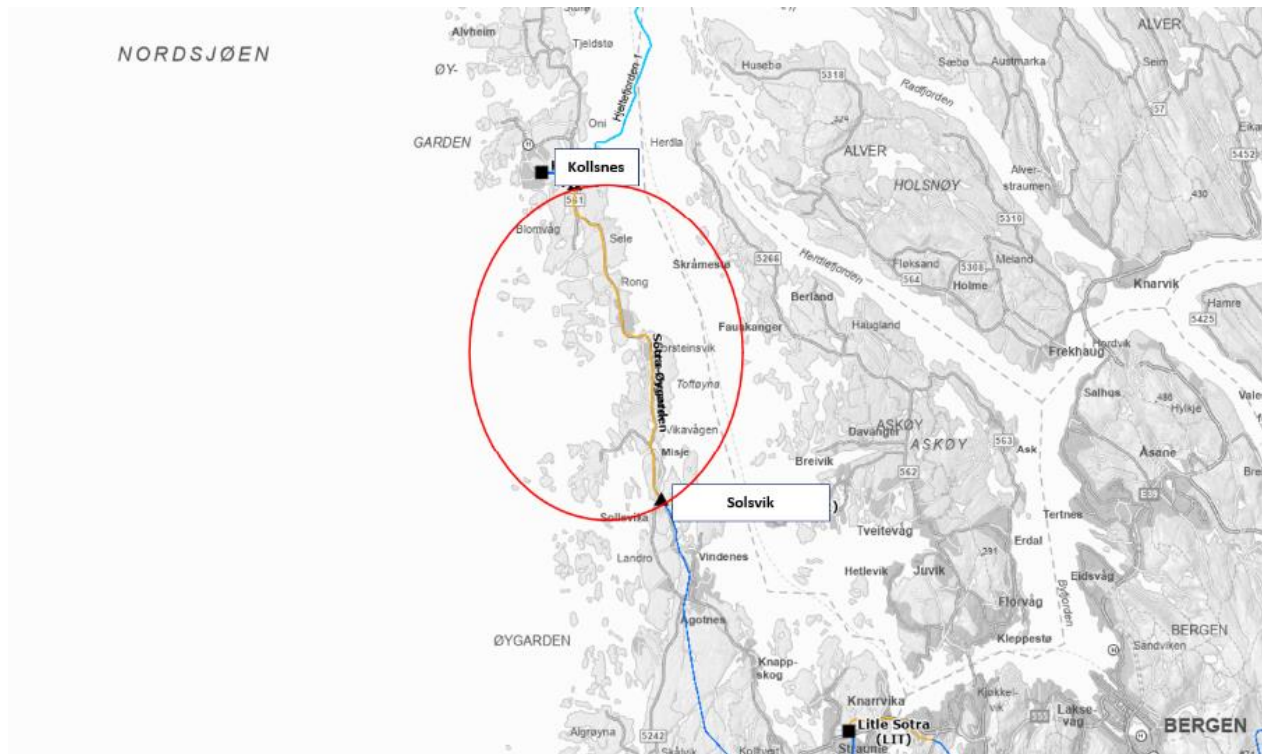


Figure 1: The Øygarden 2 project [1]

The deployment and installation of the sensors and condition monitoring interfaces will utilize the planned activities of the new 420kV cable system installation project, which will take place in Øygarden municipality, in 2025 (please refer to Figure#1). Øygarden is located close to Bergen city in Vestland county which is the 2nd largest city in Norway and close to critical infrastructure such as many Oil & Gas offshore fields. The latter ones are supplied directly from onshore substations located to Kollsnes and Lindås close to the Øygarden area. At the same time many

projects such as full-scale carbon capture and storage are in development in the area as well as early phase studies/projects like the 1GW offshore wind park west of Kollsnes and the Hydrogen factory at Mongstad.

More specifically, Øygardkabel 2 utilizes a Cross-Linked Polyethylene (XLPE) 420kV AC underground cable system connecting Solsvik-N Blomøy will have planned installation during 2025. The cable system is approximately 15km long and consist of 5 major sections (15 minor sections) in a cross-bonding configuration. The cable will be installed on four islands connected by bridges. The cable will be installed inside and below the different bridges connecting the 4 islands. The cable system will also include a fibre-optic infrastructure that can be utilized to integrate the different sensor and monitoring technologies that will be developed in this project. The cable system will be operated at 300kV for the first few years and operated at 420kV at a later stage.

Statnett will integrate the different sensor & monitoring systems in a pilot test bed with approximately 15 cross bonding cable joint locations to monitor the cable and its accessories such as joints during a long-term term test. For monitoring purposes, an external fibre optic cable (6 Single Mode + 6 Multi Mode) will be available. Regarding the installation of sensors and other condition monitoring devices/accessories such as interrogators or optical current transformers there are two options available:

- Each of the 15 XB locations will have a XB pit for installation of passive components/sensors.
- Adding sensors and related equipment at the cable's termination locations.

STATNET Validation Site will have the following instruments installed:

- DTS interrogators related to the thermal capabilities of the cable
- DAS and vibration interrogators for detecting the fault location within the cable system
- PD Analyzer to measure partial discharges related to the ageing of the cable insulation
- Edge infrastructure that will function as an aggregator of all the data, as well as have the possibility to execute the algorithms in it, enhancing real-time and an easier way for STATNET to operate all the functionalities.

2.1.1 Measurement performance DTS

The DTS system should have a sample spacing of ≤ 1.0 m, for the fibre length ~ 15 km defined for the Statnett case.

The DTS system should have a spatial resolution of ≤ 2 m, for the fibre length ~ 15 km defined for the Statnett case.

The DTS system should have a temperature measurement error of maximum ± 1.5 °C, for the fibre length ~ 15 km defined for the Statnett case.



The DTS system should have a measurement time of maximum 30 minutes, for the fibre length ~15km defined for the Statnett case.

When optimizing the DTS system performance for the relevant fibre length, the following order of priority shall be applied:

- Spatial resolution
- Temperature measurement error,
- Sample spacing
- Measurement Time

2.1.2 Measurement performance DAS

- Measurement range: 15 km
- Spatial resolution: 10 m

2.1.3 Installation requirements

- Control room:
 - The Statnett case will provide one cabinet location for at least 2 racks at one end of the cable system for the EasyDC-FOS project. The maximum cabinet size is 800 x 800 x 2000 mm and will be accessible in the front and the back.
 - Each cabinet installation position will have a 230V 16A outlet available for EasyDC-FOS.
 - The control room is temperature-controlled to maintain a constant temperature of 20°C.
- Joint bays:
 - Joints are direct buried and not accessible after installation.
 - Linkboxes are accessible at every joint location inside a XB pit as indicated in the drawing.
- Outdoor terminations
 - The terminations are located outside with ambient temperatures ranging from -20°C to 35°C.

- FO placement:

- o There are various installation methods used along the 15 km stretch. For most of the underground (UG) sections, the fibre optic (FO) cable is installed as described below.

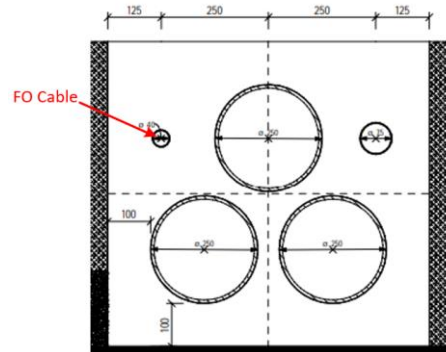


Figure 2: UG Cable cross section with FO cable

2.1.4 Communication, alarm and events

- o Alarms generated by both DTS and DAS must be capable of being transmitted to Statnett's SCADA system using standard protocols, such as IEC-61850.

2.1.5 Cable and Operational

- o Cable type: 2500mm² CU Enameled, XLPE 220/400(420)kV
- o Maximum current carrying capacity at 90 °C according to laying conditions, I_{max}: 1925 A
- o During the first years the cable system will be operated at U_m 300kV level. After that operated at U₀/U(U_m) = 220/400(420) kV

2.1.6 Fibre compatibility

- o For monitoring purposes, an external fibre optic cable (6 Single Mode, G652.D, and 6 Multi Mode, G651.1) will be available
- o If an optical switch is used, the MTBF of the switch should be > 10 million switch cycles.

2.2 Use Case II: Demonstrate condition monitoring methods in HVDC underground and submarine transition joints

COBRACable [2] is a 700 MW interconnector cable system from Denmark to the Netherlands, consisting of app. 15 km of underground cable at Danish side and 300 km of submarine cable. The cable system was commissioned in 2019, hence the sensor deployment will be of a retrofittable scheme. Below is a figure of the cable route, where it is evident that the cable system from Danish side is of land-submarine-land-submarine type, due to the crossing of the island Fanø – the end termination is marked red and the three transition joints are marked purple.



Figure 3: Map of the COBRACable at the Danish side [2]

To be noted: Only availability to the bonding cables/leads entering the link box, and not the joint itself, as the interconnector must be kept online during the mounting of the monitoring equipment/sensors. The link box and connecting bonding leads can be accessed by excavation while the COBRACable is in-service.

No fibres are available at the cable termination, as the fibre tube and its 48 SM + 6 MM fibres are separated from the power cable before the termination

2.2.1 Description of the testing environment & facilities and integration areas of the solutions to be tested

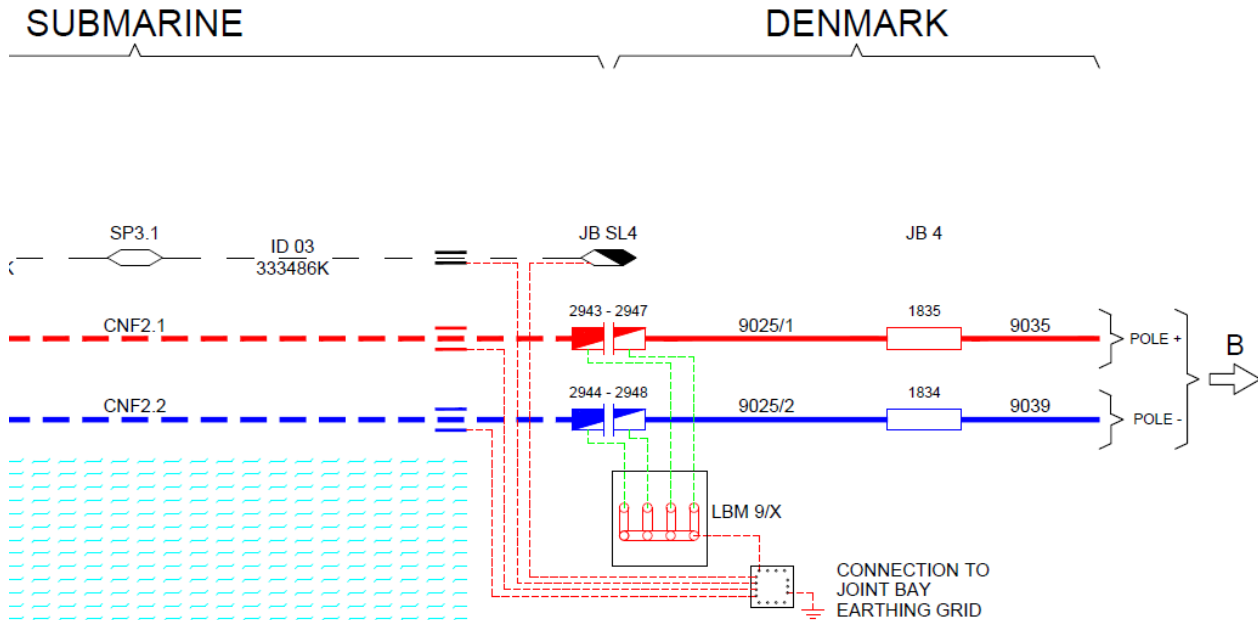


Figure 4: Schematic layout of the COBRACable at the Danish side

The COBRACable utilizes a 320 kV, bipole HVDC, cross-linked polyethylene (XLPE) combined underground and submarine cable system connecting the Danish town Endrup (substation EDR) with the Dutch Eemshaven substation. On the Danish land side (mainland + island), the cable system consists of 14 cable sections of each app. 1500 m length, 12 straight joints, 3 transition joints, and 1 end-termination joint.

Neutral earth bonding of the metal sheath (aluminium on land) is done at two straight joints and all three transition joints, where the latter also bonds the submarine lead sheath and steel armour wires to earth. 48 standard single mode (SM) and 6 multi mode (MM) fibres are paralleled the land cable part in separate fibre tube, until the mid-part of the Fanø island, after which the submarine cable is fitted with 48 SM fibres of G654LL (low loss) type in separate armoured tube, bundled to the two HVDC cable poles.

Simultaneous joint bonding lead access and fibre access (splicing) is only available at the three transition joints, dictating the possible locations for retrofitting of sensors to the bonding leads (no retrofitting to the joints themselves is allowed). All the bonding cables and link boxes connecting the bonding cables to earth are buried underground together with joints themselves and must hence be dug free for access and mounting of any equipment. Of the three transition joints, the most accessible is the one on the east side of the Fanø island, and a schematic of the electrical layout can be seen in the figure below. The bonding leads connecting the lead and aluminium sheaths of the submarine and underground cable parts, respectively, are single-core, insulated with cross-section of 120 mm² (dotted green), while the submarine steel armour and fibre optic armour are bonded using 120 mm² earthing conductors (dotted red).

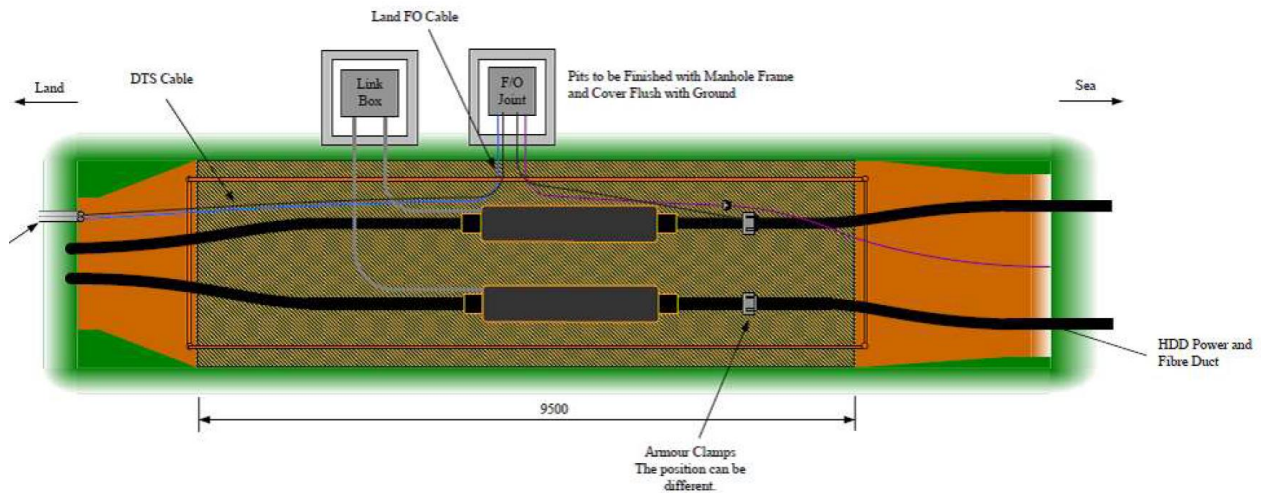


Figure 5: top view of the joint bay at the land-subsea transition

2.2.2 Measurement performance DTS

- Measurement range: 125 km
- Spatial resolution: 10 m
- Measurement time: < 20 min
- Temperature resolution: 2.0 °C

2.2.3 Measurement performance DAS

- Measurement range: 125 km
- Spatial resolution: 20 m

2.2.4 Measurement performance Point Vibration Sensor

- Measurement range for 1 sensor: 50km
- Vibration wave amplitude: x5-100 cable diameter
- Frequency band: 1 to 5 kHz

2.2.5 Measurement performance Partial Discharge Analyzer

- Minimum sensitivity: 1 to 10 pC
- Frequency band HVAC: 50 kHz to 1 GHz
- Frequency band HVDC: 10 kHz to 200 MHz

2.2.6 Installation requirements

- Two racks of size: 800x800x2000 mm (two racks might be OK for Energinet).
- 230 VAC, 10 A

2.2.7 Fibre compatibility

- ITU-T G.654 LL
- Number of available fibres: 5

2.2.8 Communication, alarm and events

- If remote access to the PC/interrogator is needed, then it must be isolated from the remaining communications network of each TSO (ENER/STAT), e.g., by using 3G/4G modem for remote access.
- The Edge Infrastructure must meet the communication requirement to the end user, enabling alarm and event management of the assets deployed in the field.

3 Summarized Requirements

This chapter presents the requirements on the different elements of the Monitoring System. They are deducted from the two Use Cases above, and general market requirements of the target applications. Development specifications will be derived from these requirements.

3.1 Long-ranged DAS and DTS

3.1.1 General DTS and DAS Interrogator Requirements

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)	Target applications
Housing size	19 inch rack type	19 inch rack type	19 inch rack type
Input voltage	230V AC (16A)	230V AC (10A)	110V AC 230V AC 24-48 VDC
Communication	MQTT with the edge node	MQTT with the edge node	Various protocols
Operational temperature range	The DTS/DAS interrogator unit should be able to operate in ambient temperatures ranging from 0°C to 40°C.	10-30°C (should be app. 20 °C)	0 to +50°C
Operating humidity range	The control room is temperature/humidity - controlled to maintain a constant temperature of 20°C.	20-95 %	0 to 95%, non condensing
Laser safety class	The laser source of the DTS instrument shall have laser safety Class 1 or Class 1M (ref. IEC 60825).	Usually Class 1/1M, but Class 3R can be accepted for e.g. Raman pump amplification.	Class 1 or 1M

3.1.2 DAS Measurement Performance

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)	Target applications
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Distance range	15 km	> 125 km	From 10 km to > 125 km for long-range applications
Spatial resolution	≤ 10 m at 15 km	≤ 20 m at 125 km	2 m to 40 m, depends on distance
Spatial sampling interval	≤ 1 m	≤ 5 m	0.5 m or higher
Optical fibre channels (simultaneously)	1	1	1 or 2
Fibre compatibility	Single mode G.652.D	Single mode G.654 LL	Various SM fibres

3.1.3 DTS Measurement Performance

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)	Target applications
Distance range	15 km	> 125 km	> 100 km for long-range applications
Spatial resolution	≤ 2 m at 15 km (prioritize spatial resolution over measurement time)	≤ 10 m at 125 km	2 m to 20 m, depends on distance
Spatial sampling interval	≤ 1 m	≤ 2 m	0.5 m or higher
Temperature resolution	± 1.5 °C at 15 km	≤ 2.0 °C	≤ 2 °C at fibre end
Temperature range	-10°C to 100°C	-10°C to 100°C	-20°C to 100°C
Measurement time	≤ 30 min	≤ 20 min	≤ 30 min for long ranges
Optical fibre channels (simultaneously)	1	1	1 or 2
Fibre compatibility	Single mode G652.D	Single mode G.654 LL	Various SM fibres

3.2 Interrogator for PD and Vibration Sensors

3.2.1 General Vibrations & PD Interrogator Requirements

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)	Target applications
Housing size	19-inch rack type	19-inch rack type	19-inch rack type
Input voltage	230V AC (16A)	230V AC (10A)	24V DC
Communication	MQTT with the Edge Modbus TCP with PD Analyzer	MQTT with the Edge Modbus TCP with PD Analyzer	Various protocols
Operational temperature range	Ambient temperatures ranging from 0°C to 40°C.	10-30°C (should be app. 20 °C)	0 to +50°C
Operating humidity range	The control room is temperature/humidity - controlled to maintain a constant temperature of 20°C.	20-95 %	0 to 95%, non condensing
Laser safety class	Class 1 or 1M	Usually Class 1/1M, but Class 3R can be accepted for e.g. Raman pump amplification.	Class 1 or 1M

3.2.2 Vibration & PD Interrogator Measurement Performance

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)	Target applications
Distance range	15 km	> 125 km	50 km for long-range applications
Measurement time			≤ 30 min



Optical fibre channels (simultaneously)	1	1	1 or 2
Fibre compatibility	Single mode G652.D	Single mode G.654 LL	Various SM fibres

3.3 PD Analyzer

3.3.1 General PD Acquisition Device Requirements

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)	Target applications
Housing			128x210x34 mm with DIN rail accessory IP 50
Power supply			12 - 24VDC / VAC 8W
Communication	HTTP(S) with the Edge Modbus TCP with interrogator	HTTP(S) with the Edge Modbus TCP with interrogator	Various protocols
Operational temperature range	Ambient temperatures ranging from 0°C to 40°C.	10-30°C (should be app. 20 °C)	-10 to +50°C
Operating humidity range	The control room is temperature/humidity - controlled to maintain a constant temperature of 20°C.	20-95 %	Up to 90% RH, non-condensing
PD channel characteristics			2 channels Input range from +/- 5mV to +/-25V 100MS/s 20MHz bandwidth



Communication			Gigabit Ethernet
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3.3.2 PD Acquisition Device Performance

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)	Target applications
Sampling frequency			100MS/s 20MHz bandwidth
Number of PD channels	2	2	2
Input range of PD channels			+/- 5mV to +/-25V
Memory depth			2MS per channel
Communication			Gigabit Ethernet

3.4 Edge node / Software / GUI

Groups	Parameter	Both Use Cases	Target applications
General infrastructure	In cloud (remote platform for Edge Nodes control and application deployment)	Include a 4G connection in the Edge Nodes (just outgoing connections). Some domains/names must be reachable on the network or must be whitelisted by the firewall (domain/port/type/protocol): • prod.bmq.barbaraiot.com 7883 TCP MQTTS • prod.bmq.barbaraiot.com 9883 TCP MQTTS • prod.bmq.barbaraiot.com 80 TCP HTTP • prod.vpn.barbaralabs.com 51822 UDP WIREGUARD • prod.ota.barbaraiot.com 443 TCP HTTPS • prod.images.barbaraiot.com 443 TCP HTTPS • de.icr.io 443 TCP HTTPS • 0.pool.ntp.org 123 UDP NTP	

		• 1.pool.ntp.org 123 UDP NTP There are also some domains that must be accessible if you want to access Docker image repositories: • auth.docker.io 443 TCP • registry.docker.io 443 TCP • registry-1.docker.io 443 TCP • registry-2.docker.io 443 TCP • index.docker.io 443 TCP • dseasb33srrn.cloudfront.net 443 TCP • production.cloudflare.docker.com 443 TCP • Modbus TCP 5502	
General infrastructure Installation requirements	"On-premises"	The same domains/names than the previous requirement must be reachable on the network if the platform installation needs to be installed in the TSOs own network. The difference is that these domains must only be reachable in the moment of installation or actualization.	
Resilience & Redundancy	Level of uptime required for Edge Devices and Applications	99.993 %	Target Service Availability
Resilience & Redundancy	System stability	Application for the notification alarms of down services.	Health-check Application
Resilience & Redundancy	Telemetry	Temperature, System Load, RAM, Disk control.	Disponibility dashboard
Resilience & Redundancy	Recuperation Time Objective – RTO	Time passed since the incident was received in support: 4 hours. Time from when the incident is assigned until it is resolved: 48 hours.	Incident Response. Incident Clousure.
Compliance & Regulatory	ISO 27001	Be compliant with ISO27001 and have an Infromation Security Management System. Consider the following controls of the SoA (Statment of Applicability): • A.8 Asset management • A.9 Access Control • A.12 Operations security	Information Security management system

		• A.14 System acquisition, development and maintenance • A.16 Information security incident management	
Compliance & Regulatory	IEC 62443-4-2 (component security requirements)	Be compliant with at least a security level 3: protection against intentional misuse by sophisticated means with moderate resources, and reasonable motivation is permitted. Consider the requirements (D7.1) for the Fundamental Requirements: • Identification and authentication control (IAC) • Use control (UC) • System Integrity (SI) • Data Confidentiality (DC) • Restricted data Flow (RDF) • Timely response to events (TRE) • Resource availability (RA)	Security levels & Fundamental Requirements
Data Handling	Data retention	30 days	
Data Security	Data encryption	All data, both at rest and in transit, must be encrypted using industry-standard algorithms, such as AES-256 and RSA, to safeguard against unauthorized access and disclosure.	
Data Security	Access to the data	Files and processes must be segregated to prevent unauthorized access and data breaches.	File system isolation
Data Security	Secure outgoing channels	The infrastructure must ensure data transmitted from the device is protected.	Protected communication channels
HW	HW differentiated capabilities	Obtain a range of three equipment with differentiated capabilities (processor, memory, latencies, external signals, GPU) that can cover the needs of the greatest variety of data capturing and algorithm needs.	
Security & Cybersecurity	No root access	The infrastructure must prevent unauthorized access to the system's root privileges, both via SSH and Docker.	SSH connection
Security & Cybersecurity	Access control	The Edge Platform must be able to assign different roles and permissions to users based on their job functions.	Role-based Access Control (RBAC)

Security & Cybersecurity	Access control	The Edge Platform must be able to provide multiple forms of identification to strengthen access control	Multi-factor Authentication (MFA)
Security & Cybersecurity	Access control	The Edge Platform must enable authentication and authorization through TLS certificates.	TLS certificates
Security & Cybersecurity	No incoming communication channels	The Edge Platform must prevent unsolicited connections from malicious actors.	
Security & Cybersecurity	Suspicious activities monitoring	The Edge Platform must continuously monitor for anomalies and suspicious activities, enabling the user to detect and respond to potential security threats.	System integrity monitoring
Security & Cybersecurity	Vulnerability patching	It must be ensured the prompt vulnerability patching with a 72-hour policy for critical vulnerabilities.	
Security & Cybersecurity	Secure communication	The Edge Platform must enable a virtual private network (VPN) for secure communication between the remote platform and the deployed Edge Nodes.	VPN
Security & Cybersecurity	Traceability	The Edge Platform must show logs of all the applications deployed in the Edge Node. This must include access, location, reading/writing/deleting/changing of data and quantity), errors and deviations.	Log traceability
Security & Cybersecurity	Unique Certificates	Each Edge Node must be equipped with unique cryptographic certificates, providing a robust authentication and authorization mechanism within the communication system	Unmatched identity management
Security & Cybersecurity	Closed ports	The infrastructure must restrict network traffic to authorized communications only.	
Security & Cybersecurity	Firmware integrity	Trusted Platform Modules (TPMs) can be leveraged to verify the integrity of firmware and encryption keys, providing an extra security layer.	TPM Support
Security & Cybersecurity	Secured and signed OTA (Over-the-Air) updates	Firmware updates are delivered securely and with integrity, preventing unauthorized modifications and ensuring the safety of the device.	Signed OTA updates
AI algorithms	No processing of personal data	The models and algorithms to be deployed on the Edge doesn't contain any personal data.	

AI algorithms	Securing training data and model	The infrastructure must maintain the security of models and training data regarding confidentiality, integrity and availability.	
AI algorithms	Management	The Edge Platform must be able to allow the deployment, deletion, restarting, training of the AI algorithm in the Edge Node.	
AI algorithms	Dockerized software	Barbara Edge applications must be packaged in ZIP files before they can be deployed on the Edge node. The ZIP directory structure must include a file docker-compose.yaml in the root. It is also strongly recommended to include a ./persist folder.	
AI algorithms	Docker restart policy	• No [Allowed]: The container is never restarted, regardless of the reason for its stop. • On-failure [Allowed]: The container is restarted if it returns an error status. • [Allowed]: The container is restarted in all cases except when it is stopped uncontrolled. • Always [NOT allowed]: The container is always restarted. This restart policy is not allowed, and an error will be displayed in the dashboard if the user has uploaded an application with this policy configured in docker-compose.	
AI algorithms	Docker security restrictions	• Mounts of bind volumes are allowed, if the mount point (side of the host) starts with ./persist/, ./appconfig or ./sys/ • Privileged containers are not allowed • Administration-related capabilities are not allowed	
AI algorithms	Data Sovereignty	Data privacy must be ensured, avoiding Access to user data. Algorithms data remains under the full ownership and control of the algorithm owner.	Sanboxes, Docker spaces
Operational	Required bandwidth	Minimum 12Mbps	
Operational	Required latency	Objective < 50ms	
Operational	IP management and communication with TSOs	Need for data capture of current data and environmental data: • IEC 61850 • Modbus	

	corporate network		
Operational	Communication between partners	MQTT allowed via Edge Node	
Operational	Lumiker's interrogator communication and needs	Modbus TCP 1 month of historical data	
Operational	AP Sensing DAS and DTS	Receiving alarms via Modbus. Data through SNMP/Syslog. Sensing needs (20kHW, 8Mbits/sec)	
Operational	Ampacimon PD analyzer – communication and needs	The PD acquisition device shall send acquired data to the Edge Node using HTTP(S) protocol The PD acquisition device shall command the PD interrogator using Modbus TCP The PD analyzer platform shall be deployed either in the edge node or in the remote platform. Next connections and protocols are expected in the PD analyzer platform: - TCP 5233: HTTP acquisition device to Edge Node - TCP 7233: HTTPS acquisition device to Edge Node	
Operational	Persistency	Autonomous operation in case of loss of communication	

3.5 Fault Localization Performance

This section briefly presents the goals of the Fault Localization Performance of the combined Monitoring System.

The sensing results from the Vibrations sensors and the DAS interrogator are aggregated in common fault localization algorithms running on the Edge Node to identify the location of fault created by internal flashover (e.g. from prolonged partial discharges).

The methodology and algorithms behind this are explained in detail in Deliverable D3.2, Section 2.2.3. In short, LMKs Vibration Sensors detect a possible fault between two joint locations (1 and 2) using the analysis of vibration patterns. If a potential fault is detected, the cable segment is analysed for the exact location of that fault using DAS data with high spatial resolution.



Target goals for the fault localization performance are

- A fault localization spatial accuracy in the order of 20 m which is the targeted spatial resolution of the DAS measurement.
- Response time of a few minutes, with the goal of being as fast as possible. A minimum viable goal is a response time shorter than 30 min.

Due to the novel combination of technologies and algorithms, the complexity of the algorithms and data processing load is hard to estimate.

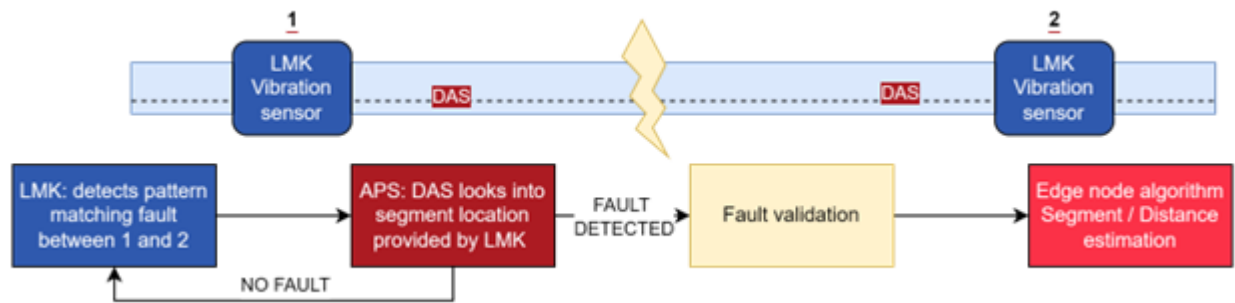


Figure 6: Fault location algorithm scheme combining Vibration Sensor and DAS data.

4 Interrogator Development Goals

This section will give a brief description of the development goals of each interrogator development carried out in WP6. It lists specifications for the hardware development as derived from the requirements listed in the summary in Chapter 3.

Note that straightforward conversions from general requirements to specifications are not listed below, unless they create specific hardware or software requirements in sub-assemblies or components. For example, the 19-inch rack housing size or the environmental operational temperature are not listed below.

4.1 DAS and DTS Interrogators

APS will develop a new generation Rayleigh-based DAS and Brillouin-based DTS measurement systems that cover >125 km (long) HVDC cable corridors for underground and submarine applications. Demonstration of the upgraded technology will be achieved first in a controlled environment (at laboratory level) and then coupled together with the development of rugged interrogators for industrial applications. The resulting amplified range DTS and DAS prototypes enable the continuous observation of vibrations, acoustics, temperature, and strain along at least 125 km in HVDC cables, enabling the identification and mitigation of noise patterns from the environment. This information is critical for cable fault localization and thermal modeling.

Based on results of a proof-of-concept study on laboratory level, DAS and DTS interrogators will be designed and developed. Components will be sourced, layouts designed, and integration of multiple sub-modules performed for various optical, electrical and functional subsystems: lasers and pulse shaping, transmitter and receiver optics, optoelectronic detection, analog electronics for signal conditioning, HW for data acquisition and processing, housing design and mechanics, power dissipation and cooling. The data processing algorithms will be implemented on suitable data processing hardware.

Parameter	Specification	Comment, Connection to requirements
Loss budget	> 20 dB	One-way loss budget of the sensing fibre for which the required measurement performance is achieved. Corresponds to at least 125 km range in ultra-low loss fibres such as used in the Use Case 2.
Minimum pulse length	10 ns	To achieve spatial resolution down to 1 m for DTS and down to 2 m. In DAS, the effective spatial resolution is usually given by a gauge length that is larger than the pulse length. Sets requirements on the speed of the pulse creation hardware and electro-optics.

Pulse forming speed	< 5 ns rise/fall time	To achieve down to 10 ns short pulses (full width half maximum, FWHM).
Digitizer sampling speed	> 200 MS/s (< 5 ns sampling interval)	To achieve a corresponding spatial sampling interval of 0.5 m fibre length or smaller.
Parallel fibre channels	2	Pulse creation, signal acquisition and data processing must be capable of the simultaneous measurement of two optical fibres.
Fibre connection	2x E2000 APC	Connection to single mode sensor fibres
Internal operational temperature range	0 to +65°C	Based on 0 to 50° environmental temperature range. Heat dissipation of hardware increases internal temperature. Components must be sourced and qualified for this temperature range.

The Brillouin-based DTS rely on the temperature dependency of the Brillouin backscattering spectrum for distributed temperature measurement. The requirements on measurement performance set specifications on the measurement and analysis of the Brillouin spectrum. 1 MHz frequency shift corresponds to roughly 1°C temperature change.

Parameter	Specification	Comment, Connection to requirements
Brillouin frequency measurement range	> 200 MHz	To enable > 120 °C temperature measurement range, with margin for the spectral width of the Brillouin peak and strain-induced frequency shifts.
Brillouin peak frequency estimation resolution	0.1 MHz	To achieve a minimum limit of 0.1°C temperature measurement resolution.
Brillouin peak frequency estimation resolution	< 2 MHz	@ 20 dB loss in 20 min measurement time. To accommodate Use Case requirements.

4.2 Interrogator for PD and Vibration Sensors

The interrogator is a crucial component in optical sensing systems, serving as the interface between optical sensors and data acquisition or monitoring equipment. For interferometric sensors, the interrogator's primary function is to detect and process the interference patterns generated by the sensors, converting them into meaningful electrical signals or digital data for analysis.



- Partial Discharge (PD) Interrogator:** The PD interrogator is designed to detect rapid changes in the intensity of the optical signal caused by partial discharge events. It converts these optical signals into electrical signals for real-time monitoring, enabling the detection of insulation failures in high-voltage cables. In AC systems, the data is transmitted to an AMP PD analyzer, which processes the data and uses an algorithm to determine if a fault is present. In DC systems, the data is processed on an LMK server to identify PD events. In both cases, the analysis results are then uploaded to the Edge for aging algorithms. This innovative approach effectively addresses the challenge of reliable PD detection in DC systems, where no dependable method currently exists.
- Vibration Interrogator:** The vibration interrogator processes changes in optical signal intensity to detect and correlate different vibration frequencies, enabling precise identification of potential issues along the cable. If an anomaly is detected, the interrogator starts to monitor different sensor pairs located along various sections of the cable. This approach allows an algorithm on Lumiker's server to determine the specific section of the cable where the fault is located. Once the faulty section is identified, only the information about that section is transmitted to the Edge for a more detailed analysis using DAS data specific to that area. This step enables fault validation and precise localization of the issue. The integration of the interrogator with the DAS system enhances monitoring algorithms, improving the accuracy of distributed monitoring and allowing for quicker responses to potential problems within the cable infrastructure. Additionally, Lumiker's server provides comprehensive maintenance information by analyzing the sensor readings taken in pairs. This approach not only allows for real-time detection and localization but also facilitates predictive maintenance strategies, leveraging advanced algorithms developed under WP6 to optimize monitoring and improve cable infrastructure management.

Understanding these functional requirements is essential when specifying the interrogator's characteristics for each application. Ensuring the interrogator meets the specific requirements of PD detection or vibration monitoring is key to achieving accurate and reliable performance in high-voltage cable systems.

Vibrations Interrogator characteristics		
Channels		1 – 8
Max. number of sensors per channel		>15
Max. sampling frequency		1-5kHz
Central wavelength		1500nm – 1600
Max measurement distance with 1 sensor		50km
Supported Sensors Type		Vibration
Fibre optic connection		FC/APC
Communications to the edge		MQTTS
Climatic tests	Operation temperature	0°C +50°C
	Humidity	Up to 95% without condensation



Power Supply	Auxiliary voltage	24 Vdc
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PD Interrogator characteristics		
Channels		1 – 8
Max. number of sensors per channel		50
Max. sampling frequency HVAC		50kHz - 1GHz
Max. sampling frequency HVDC		10kHz - 200MHz
Central wavelength		1500nm – 1600
Output options		Analog signal
Max measurement distance		>50km
Supported Sensors Type		PD
Fibre optic connection		FC/APC
Communications to the edge		MQTTS
Communications to PD Analyzer		Modbus TCP
Climatic tests	Operation temperature	0°C +50°C
	Humidity	Up to 95% without condensation
Power Supply	Auxiliary voltage	24 Vdc

4.3 Vibration Sensor

4.3.1 State-of-the-art, Vibration sensor

Vibration detection is a key tool for monitoring the condition of high-voltage (HV) cables and their surrounding environment. In direct current (DC) transmission systems, which operate under extreme conditions and where partial discharge (PD) detection is challenging, **vibration monitoring** provides a complementary method to identify structural and environmental issues affecting the cable.

Traditional Vibration Detection Methods

Traditionally, vibration sensors used for HV cables have relied on accelerometers and piezoelectric sensors to detect mechanical vibrations at specific points. However, these methods are limited when applied to long, hard-to-access systems, such as underground or submarine cables, as they require active power and are confined to a limited number of measurement points.

Advances in Fibre Optic Vibration Sensors

In recent years, fibre optic sensors have gained popularity in vibration detection for critical infrastructure. These sensors are immune to electromagnetic interference (EMI), require no active power at measurement points, and enable distributed monitoring over long distances. Additionally,



placing sensors at critical points, such as joints, enhances fault location accuracy by providing high-precision data to the distributed monitoring system as they can effectively detect anomalies at these key locations where most defects tend to originate.

Fibre optic vibration sensors detect changes in the intensity or phase of the optical signal in response to mechanical vibrations, providing a continuous profile of the cable's condition. In these sensors, optical intensity change occurs because of phase shifts induced by the accelerations experienced by the sensor during vibrations, allowing precise detection of mechanical disturbances that may indicate an imminent fault in the system.

Proposed Innovation in the EasyDC-FOS Project

The EasyDC-FOS project seeks to develop a new vibration detection system specifically designed for HVDC cables. This system will employ a specialized fibre optic sensor that enables precise detection of vibrations at critical points along the cable, including joints and terminations. Innovation lies in the sensor's ability to capture the amplitude of vibrations, allowing it to distinguish between normal vibrations and signals indicative of faults, such as structural damage to the cable or its insulation. The vibration data will complement PD detection systems, offering a more comprehensive assessment of HVDC cable conditions and enabling predictive maintenance strategies.

4.3.2 Vibration sensor specifications

This section sets the high-level specifications for the point vibration sensor development in Task T6.2.

These sensors are designed to detect subtle vibrations that traditional electrical sensors might miss. By leveraging the principles of light interference, they can detect minute changes in optical path length caused by vibrations, providing high accuracy and resolution.

Key characteristics essential for the sensors developed in this project include:

- **Frequency Measurement Range:** Capturing vibrations from very low to high frequencies enables the detection of various mechanical phenomena affecting the cable system.
- **Sensitivity and Resolution:** High sensitivity allows for the detection of minute vibrations, while high resolution ensures accurate quantification of vibration amplitudes.
- **Operating Conditions:** The sensor must function reliably across a wide temperature and humidity range typical of HV environments.

Including these specifications ensures that the optical vibration sensor can effectively monitor the cable system's condition, enabling predictive maintenance and preventing potential failures.

Specification Table of the Optical Vibration Sensor for HV Cables

Parameter	Unit	Value
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Type of Measurement	--	Vibration Detection in Cable Connections and Terminations
Frequency Measurement Range	Hz	0.1 Hz – 5 kHz (adjustable according to requirements)
Central Wavelength	nm	1510 – 1590 nm
Operating Temperature Range	°C	-20 °C – +50 °C
Operating Humidity Range	%	0% – 95% (non-condensing)
Optical Connector Type	--	FC/APC, SC/APC, or customizable

4.4 Partial Discharge Sensors

4.4.1 State-of-the-art of PD sensor

High-voltage insulation systems, particularly cross-linked polyethylene (XLPE) cables, are essential for the reliability of DC transmission lines due to their superior insulation properties. However, continuous electrical, thermal, and mechanical stress degrades this insulation over time, posing significant risks of unexpected failures. Early detection of this degradation is therefore critical for maintaining reliable operation. Partial discharge (PD) activity, occurring when localized dielectric breakdowns in the insulation release high-frequency pulses along the cable, is one of the most effective indicators of insulation degradation.

Traditional Methods for Partial Discharge Detection in AC Systems

Traditional PD detection methods have been primarily developed for alternating current (AC) systems, where PD events exhibit periodic patterns that are easier to detect and analyze. These methods typically rely on offline electrical measurements, requiring disconnection from the network. Inductive and capacitive sensors, such as High Frequency Current Transformers (HFCTs) and Transient Earth Voltage (TEV) sensors, capture high-frequency PD pulses in ranges from 100 kHz to 500 MHz and 1 MHz to 100 MHz, respectively. While effective in AC systems, these offline techniques interrupt service and limit continuous monitoring, making them unsuitable for real-time condition-based maintenance.

Advances in Online Partial Discharge Monitoring in AC Systems

Advancements in online PD monitoring now enable continuous detection of PD in AC cables without system disconnection. These methods are invaluable for Condition-Based Maintenance (CBM), providing real-time assessments that allow maintenance only when necessary. Continuous data capture lets engineers analyze PD activity trends to make informed maintenance decisions, maximizing cable lifespan and minimizing service interruptions. However, these techniques are primarily developed for AC applications, where the periodic current simplifies PD detection.

Challenges in Partial Discharge Detection in DC Systems



Detecting PD in direct current (DC) systems poses unique challenges absent in AC systems. PD events in DC cables are less predictable and lack periodic patterns, making identification more difficult. Moreover, space charge accumulation within DC insulation distorts the electric field, complicating PD signal interpretation. Unlike AC systems, where regular voltage cycles aid PD tracking, DC systems require sophisticated detection methods to distinguish PD events from background noise. Currently, there are no reliable commercial sensors specifically designed for PD detection in DC systems.

Development of New Technologies for PD Monitoring in DC Systems

Addressing these limitations, the EasyDC-FOS project aims to develop new PD monitoring solutions specifically for HVDC cables. It plans to integrate optical PD sensors with extended frequency ranges (up to 200MHz) and high sensitivity (<10 pC), deployable along long HVDC corridors, including underground and underwater routes. These optical sensors are immune to electromagnetic interference (EMI) and allow non-intrusive, passive monitoring, making them ideal for the demanding environments of HVDC systems.

A key innovation in this project is that the optical PD sensor will be designed to modulate the intensity of the optical signal based on the frequency of the partial discharges. This will be achieved through the combined use of a High Frequency Current Transformer (HFCT), which detects high-frequency PD signals, and a custom-designed optical sensor developed specifically for the EasyDC-FOS project. By adjusting the optical signal intensity in response to PD frequencies, this sensor setup will enhance detection accuracy, enabling more precise monitoring of insulation condition and early identification of potential faults in HVDC systems.

4.4.2 PD sensor specifications

This section sets the specifications for the PD sensors development in Tasks T6.4 and T6.5.

These sensors are designed to provide immunity to EMI, high sensitivity (detecting discharges as low as 10 pC), and can cover different spectral regions in the HF and VHF bands to obtain a global broad frequency response. These features allow them to capture subtle PD events and provide early warnings of insulation degradation, crucial for reliable long-term monitoring.

Important characteristics of these sensors include:

- **Partial Discharge Measurement Range and Sensitivity:** Ability to detect a wide range of PD magnitudes, including very low-level discharges (<10 pC), is crucial for early detection and intervention.
- **Frequency Response Range:** A broad frequency range covered by the sensing devices ensures that the sensor can capture PD signals can be captured regardless of their frequency content.
- **Accuracy and Resolution:** High accuracy and fine resolution are necessary for reliable PD quantification and trend analysis.

- **Operating Conditions:** The sensors must maintain performance under the environmental conditions encountered in HV installations.

By specifying these characteristics, the optical PD sensors can effectively contribute to the condition-based maintenance strategies, enhancing the reliability and safety of HV cable systems.

Specification Table of the Optical Partial Discharge Sensor for HV Cables

Parameter	Unit	Value
Type of Measurement	--	Online Partial Discharge (PD) Detection
Partial Discharge Measurement Range	pC	< 10 pC
Sensitivity	pC	10 pC
Resolution	pC	1 pC
Frequency Response Range	Hz	10 kHz – 200 MHz in DC 50 kHz – 1 GHz in AC
Central Wavelength	nm	1510 – 1590 nm
Operating Temperature Range	°C	-20 °C – +50 °C
Operating Humidity Range	%	0% – 95% (non-condensing)
Optical Connector Type	--	FC/APC, SC/APC, or customizable

4.5 Other elements of the system

In addition to the optical interrogator and sensors, it is essential to specify other components crucial for the optimal functioning of the system. Elements such as the Optical Box/Switching Fibre (OB/SF) play a fundamental role in the interconnection and operation of the optical sensors. Defining the specifications of this component ensures compatibility, efficiency, and reliability of the overall system.

Specification OB/SF

Parameter	Value
IP	IP67/68
External material	GRP
Operating temperature	-20°C a 60°C
Storage temperature	-40°C a 70°C
Dimensions	360,5 x 180 x 173 mm

5 CONCLUSIONS

In T3.3 of WP3, requirements on the fibre optic Monitoring Systems and Fault Location Algorithms are gathered, based on the specific EasyDC Use Cases as well as for the targeted markets in general.

This report lists requirement criteria for monitoring > 125 km long HVDC cables on each individual Element of the Monitoring System (DTS, DAS, Vibration sensors, PD Analyser, Edge Node, Fault location algorithms) that set benchmarks for the hardware and software development. Requirements have been set regarding:

- measurement performance (e.g. spatial resolution, DTS temperature resolution, PD frequency detection bandwidth, ...),
- operational parameters, such as installation requirements in the Use Cases, or compatible fibre types.
- environmental parameters, such as temperature and humidity ranges in the Use Cases and general market needs,
- communication protocols for data transfer between the interrogators and the Edge Node, as well as from to the TSOs systems

This complete set of requirements is aimed at the projects objective of developing a new enhanced Monitoring System based on fibre optics for long HVDC cables. Use Case 2 (COBRACable) fit well to this goal. The requirements and specifications set by this Use Case and the target applications reflect this.

Additionally, the applicability of the developed solutions is broadened by considering requirements for short HVAC cables, given by Use Case 1 (Øygarden 2).

Detailed hardware specifications are derived from the requirements and thereby set benchmarks to improve the technology basis of the fibre optic interrogators and data processing developed in this project.



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