774
B1 INSULATED CABLES
Learning from experiences

Session 2022

PD, temperature and acoustic measurement of Eleclink HVDC interconnector – anticipate failures to minimize service disruption and impact on train circulation

1) Alessandro PISTONESI* 2) Diego LA CASCIA 3) Giuseppe FISCELLI

1) Prysmian Powerlink, Italy 2) 3) Prysmian Electronics, Italy

1) alessandro.pistonesi@prysmiangroup.com 2) diego.lacascia@prysmiangroup.com
3) giuseppe.fiscelli@prysmiangroup.com

SUMMARY

Eleclink project is unique in its kind being the first HVDC interconnector laid in air in a railway tunnel, more in specific the Channel Tunnel between Folkestone (UK) and Coquelles (FR), in close proximity to the running train. This makes the maintenance activity, both ordinary and extraordinary, difficult from a technical point of view and extremely onerous from a financial point of view, as any intervention requires the rail traffic to be stopped for a significant amount of time.

This paper describes the features of an innovative asset management monitoring system, fully conceived, designed, built and installed for this specific interconnector, with the aim of anticipate an incoming issue, minimize the disruption to train circulation and reduce the outage duration thus lowering the risk of a fault and consequent unplanned outages. This is achieved thanks to Partial Discharge, Distributed Temperature Sensing, Real Time Thermal Rating and Distributed Acoustic Sensing monitoring systems. Even if this paper is mainly focused on the HVDC portion of the project, it is here also described the monitoring system of the HVAC portion laid between Folkestone and Sellindge (UK) where the SVL (Sheath Voltage Limiters), the Sheath current and the Earth current are monitored as well.

KEYWORDS

HVDC cables, HVAC cables, Monitoring System, Partial Discharge (PD), Distributed Temperature Sensing (DTS), Real Time Thermal Rating (RTTR), Distributed Acoustic Sensing (DAS), Sheath Voltage Limiter (SVL), Fiber Optic Cable (FOC).

1. INTRODUCTION

Interconnectors are increasingly becoming a key component of the electrical grids. Connecting the different national grids, interconnectors ensure the stability, reliability and quality of the energy flow, thus improving the security of the supply. They allow the exchange of surplus energy generated in excess with renewable sources (solar, wind) when it's not needed locally and, on the contrary, to import energy when needed if less energy is generated because of adverse weather condition. This helps mitigating energy generation intermittency, which is typical of renewables sources. Allowing a more efficient exchange of energy, interconnectors contribute to reduce its cost to the end user and reduce the need of peaking generation capacity, contributing to the decarbonization.

Interconnectors are made with overhead lines and cables, both submarine and underground. Compared to overhead lines cable systems present many advantages such as limited environmental impact, and some disadvantages one of the major being cost and time required to repair it in case of fault. Following this event, the first phase is the fault location to exactly pinpoint the damage. Depending on the fault and the consequent cable system condition this phase can take up to some weeks. The highest accuracy in locating the fault is needed because some damages, both on underground and submarine cable systems, can't be identified with a visual inspection from outside and avoided cutting the cable in the wrong position shall be avoided. As for the fault location, repairing the defect can take several weeks. During this time the cable system will not be available, causing potential disruption to the end users and financially affecting the cable system owner. In this scenario, the ability to identify an anomaly which might worsen in time leading to a failure brings a huge benefit to all the involved stakeholders. This benefit is even more relevant when the intervention to repair a fault is difficult, or lengthy, or impact other services such as rail traffic, or when it can only be executed during specific and limited time slot. This is very much the case of the Eleclink Interconnector, in which the cable is laid for approx. 51 km in air into the Channel tunnel near the running train. The repair of a fault on this cable systems requires the trains circulation to be stopped with disruption to the rail traffic and related financial losses (Eurotunnel carries around 22 million passengers per year by train). There are different systems which may be used to assess the status of the interconnector, identify and asses a defect, monitor its development in time and predict when it will evolve in a fault. These systems typically measure the Partial Discharge, the cable system temperature and the sound which may be caused by an impact on the cable.

2. GENERAL DESCRIPTION OF THE INTERCONNECTOR

Eleclink interconnector runs across the Channel tunnel between France and the United Kingdom, connecting the HVDC Converter Station (CS) of Peuplingues (Fr) and Folkestone (UK). It is then connected to the grid by mean of an HVAC cable line on each side. The whole scheme is depicted in Figure 1 below.

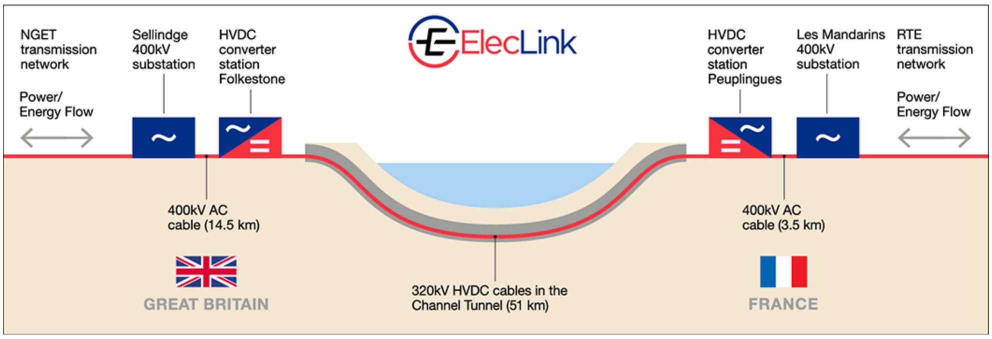

Figure 1 – Schematic interconnection of Eleclink project

The convertor technology is based on Voltage Source Convertors (VSC) to provide connections to XLPE cable with a rated voltage of +/- ~320kV DC and it allows a transmission of 1000MW with low losses. The HVDC cable connecting the 2 CS is mainly laid into the rail tunnel in close proximity to the running train. It is a 2500 mm^2 aluminum conductor, XLPE extruded insulation, longitudinally welded aluminum sheath as radial barrier against the ingress of water and a plastic outer sheath with reaction to fire qualified as Euroclass B1ca-S1a-d0-a1, as shown on Figure 2 below.

An extruded layer is applied over the outer sheath to allow the sheath test in the different phases of the cable installation and facilitate the fault location in case of failure. Between the tunnel portal and the CS, both in France and in the UK, the cable is buried, and the conductor is made of copper in order to avoid the system derating. Parallel to the HVDC cables, six ancillaries cables are laid:

- Four FOCs with 32 fibers each
- One Earth Continuity Conductor (ECC)
- One Low Voltage alternating current (LVac).

Figure 2 – In tunnel HVDC cable

The purpose of the FOC is to support communication between the CS, detect the cable temperature as part of the DTS system, detect the acoustic signal as part of the DAS system and send the signal collected by the PD Sensors, installed on the HVDC cable joints, to the PD monitoring system installed in the two CS. The purpose of the ECC is to provide the HVDC cable a dedicated earthing point separated to the one serving the rail service as requested by Eurotunnel. The purpose of the LVac is to provide power supply to the Monitoring System components installed on each PD Monitoring Point along the entire route. The whole cable system is laid into the North tunnel on a dedicated rail system bolted to the tunnel concrete wall. Inside the tunnel, which is roughly 50 km long, the cables are laid in lengths of 2.5 km each. Every 2.5 km there are 2 HVDC cable joints, one per each pole, 2 FO joints, each one connecting 2 FOCs, 1 LVac joint and 1 ECC joint. Outside the tunnel portal, there is a transition joint connecting the HVDC aluminum cable to the copper one. The HVDC line is terminated on both sides on outdoor termination installed within the CS. The project includes also the HVAC cable connection in the UK connecting Folkestone CS to Sellindge SS. Its cable is 2500 mm^2 copper conductor, XLPE extruded insulation, longitudinally welded aluminum sheath as radial barrier against the ingress of water and a plastic outer sheath with an extruded semiconductive layer to allow the sheath test in the different phases of the cable installation and facilitate the fault location in case of failure. The HVAC line is terminated on both side on GIS termination. One distinctive feature of this interconnector is its very low environmental impact in terms of visual impact, low noise, negligible magnetic fields, no overhead lines and no undersea lines.

3. DESIGN OF THE MONITORING SYSTEM

The Monitoring suite is composed by PD, shields currents, earth currents, SVL, DTS and DAS monitoring. Its design takes in account the peculiarity of the route - the DC portion is laid mainly in air and the AC one is buried underground - and it ensures that the whole cable system is constantly and thoroughly monitored and any anomaly immediately detected and communicated to the Client via the SCADA protocols. The different components of the monitoring system are installed directly on the accessories, in the substation and in the CS. Fiber Optic cables are laid along the power cables, 2 on the AC portion and 4 on the DC one. Their purpose is to transmit the digital data acquired by the MP along the lines to the servers in the CS. The LVac cables present on the AC route and on the DC one are connected to the substations and the CS, in order to feed the different monitoring components installed along the routes.

The design of the LVac distribution systems powering the Monitoring Systems on both the HVAC and the HVDC separate circuits has been carried out and has mainly covered:

- the LVac cables and related protections,
- the earthing connections,
- the EMC solution for the LVac cables installation inside the two Converter Stations,
- the induced voltages from the HV cables to the LV cables.

The design has brought to the same LVac backbone cable type in both systems. This LVac backbone cable is a 400 V ac 5/cores (3 phases plus neutral plus earthing) screened 6 sq.mm cable with the following CPR classification against the fire: B2ca-s1a, d0, a1.

The LVac supply power over a distance of 20+ km is ensured by:

- the very low value of the power consumption of each monitoring point (approx 10 W each, single phase);
- spreading the MPs over the three phases (each MP requires a single phase power supply);
- the insertion of the isolating transformes along the circuit (one every 5 km);
- the very low value of the electrical resistance of the 6sq mm cable (3,3 Ohm per km).

The concept of the Partial Discharge Monitoring System is described below.

As shown in Figure 3, on the AC route, each accessory has its own dedicated Monitoring Point (MP) which is composed by PD sensor installed on the cable in close proximity to the accessory, whose purpose is to capture the PD signals [1], [2], [3]. The captured PD signals are then acquired by the PD acquisition device and transmitted by mean of a FO cable to the Asset Management processing unit installed in Folkestone CS, where the signals are assessed. Still on the AC route the shields and earth currents are captured by Rogowski coils and the SVL status by infrared sensors. All these data are then acquired by the acquisition devices (named DLog) and then transmitted via FO cable to the processing unit in Folkestone CS.

On the DC route, each joint has its own dedicated MP which is composed by 2 PD sensors installed both sides of the accessory in close proximity to it, whose purpose is to capture the PD signal [1], [2], [3]. In particular, two sensors are placed 3 meters from the center of the joint (at both ends). The PD acquisition in DC is based on the "gating" concept: when a PD event occurs inside the joint, it reaches the PD sensors around the joint with a very small-time difference (Gate Time Threshold). If a pulse is generated outside the joint, it will travel along the HV cable and it would reach the two sensors, around the joint, with a time difference comparable to the time that a signal takes to drive through the joint. The instrument used (named Gate) is able to evaluate the time different of the signals received by the sensors and provide an alarm in case of values lower than the Gate Time Threshold.

As shown in Figure 4, the signal captured by each sensor is then acquired by the PD acquisition device and transmitted by means of the FO cable to the Asset Management processing unit installed in Folkestone CS, where it is assessed. On the termination one only sensor is installed, and the signal is then acquired by the g PD acquisition device.

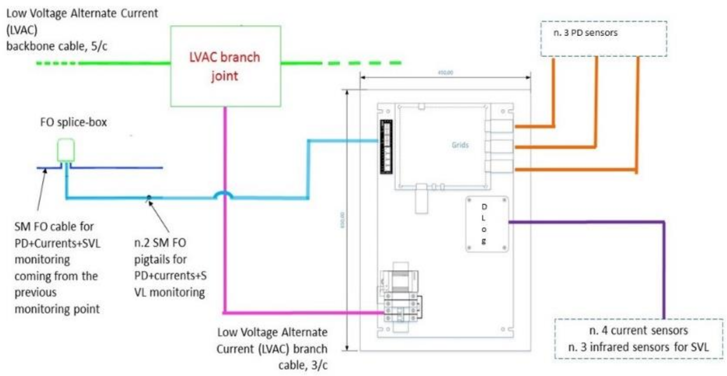

Figure 3 – MP concepts on the AC route

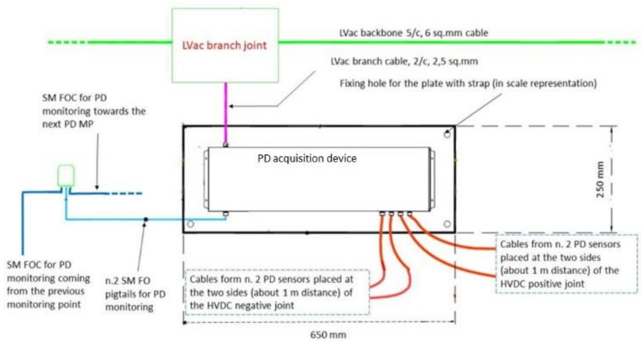

Figure 4 – PD monitoring system design in tunnel

The concept of the Distributed Temperature Monitoring System is described below.
On the AC route, the temperature monitoring along the HV cables is performed by 1 DTS interrogator installed in Folkestone CS which monitors the temperature of the FO cable laid in contact with the central phase of the HVAC power cable. On the DC route the temperature monitoring along the HV cables is performed by 2 DTS interrogators, one of which placed in UK CS and one in FR CS. This ensures the redundancy of the whole temperature monitoring system. In addition to the DTS, the two routes are also equipped with the RTTR algorithm which produces as output the cables conductor temperature profiles starting from the temperature measured by the DTS interrogators.
The DTS accuracy is better than 2°C at the farthest distance, with a measurement time of 30 minutes and spatial resolution of 5 m.

The concept of the Distributed Acousting Monitoring System is described below.
The two DAS are installed one in each Converter Station (Figure 5). They utilize the FOCs laid along the power cables to detect any acoustic disturbance occurred near or onto the cable system. The vibration modifies the light impulse transmitted into the FO cables, this change is then analyzed by the processing units placed in the two CS. Both DAS monitor the DC portion of the cable system, allowing a complete redundancy for the system. The system one installed in Folkestone CS also monitor the AC route. The design of the monitoring systems was executed taking in account the peculiar environment in which their devices are installed and operate. More in specific, the equipment into the tunnel respects the strict EM emission requirement to avoid any disturbance to the train communication and guidance system. Similarly, the EM emission caused by the trains is filtered to avoid any interaction with the monitoring system and consequent false reading.

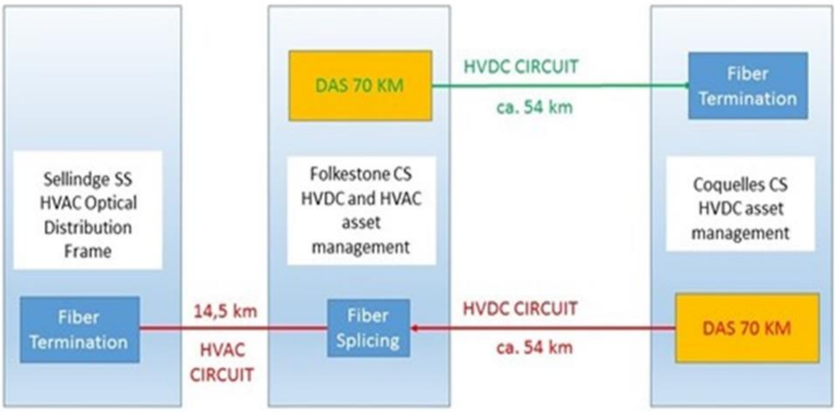

Figure 5 – DAS monitoring system schematic design

4. INSTALLATON OF THE ASSET MANAGEMENT MONITORING SYSTEM

The final locations of the MPs, sensors and associated fiber optics and LVac cables are totally different between the AC and DC routes. In the former case the HV cable joints are buried along the AC route connecting Folkestone CS with Sellindge SS (route length is 14 km, three phase circuit) while in the latter case the HVDC joints (two phase circuit) are installed inside the Channel tunnel (length 51 km). For this reason, the installation approach is totally different and therefore the two routes are analyzed in different subsections.

In the HVAC route, there are 14 MP’s on this side: one in the Folkestone C.S., one in the Sellindge S.S., and 12 along the path between the two Stations. On the SS’s the MP are installed near the GIS terminations. Along the route the other MP’s are located near the HV joints. At all locations, the MP’s are connected to the earth link pillar. As shown in Figure 6, a custom steel frame was used to secure the MP box to the link pillar. This accessory allows the pillar to be used as an anchorage point without any changes to the pillar itself. In fact, the original screws of the link box were used. Sensors to monitor earthing and bonding lead currents and SVL status were installed directly inside the link pillar. Four Rogowski current sensors and three SVL sensors are shown in Figure 7.

Figure 6 – MP installation

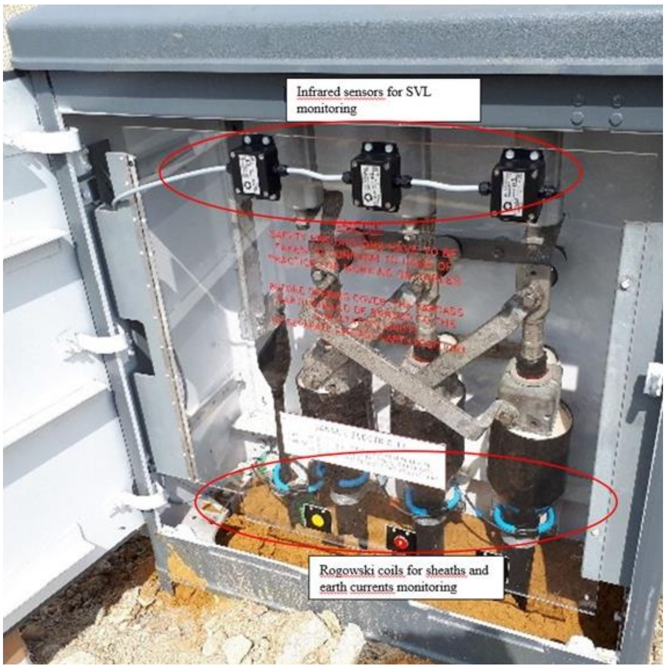

Figure 7: Rogowski and infrared installation

The partial discharges sensors were installed above the HV cable, near the HV joints. This activity was performed during the installation of the joints, before burying the cables (Figure 8). In addition, FO and LVac cables were laid in the same trench. Installation of the PD sensors in the SS was easier: the sensors are attached to the cable, at the base of the GIS termination (Figure 9).

Figure 8: PD sensors installation

Figure 9: PD sensor installation below the GIS terminations

In the HVDC route, only the PD sensors were installed along the DC line. The works into the terminations and on the first couple of joints close the terminations are similar to the works along the AC line. On the terminations the sensors have been placed at the base of the outdoor terminations and their cable have been connected to the PD acquisition device placed inside the MP (Figure 10a). On the joint locations, 4 sensors have been installed before to bury the HV cable (Figure 10b). The installation conditions of the monitoring systems placed inside the tunnel have been much more complex than usual. In fact, the access to the tunnel has always been limited to few hours per week when the train transit was interrupted. The final location of the cables and therefore of the entire monitoring system is on a high part of the tunnel at a proper distance from the train path. In order to optimize at best these time slots dedicated to the installation, an ingenious system has been devised based on a rail placed on the tunnel wall where a set of carriages (Figure 11) run and on which the HV cables and the ancillary cables are fixed. In this way it was possible to assemble all the cables outside the tunnel and then transport them inside through the above-mentioned sliding system. This operation was carried out in parallel from two fronts: English and French.

Figure 10: a) Monitoring Point under the DC outdoor termination   b) PD sensors placed on the HV joints

The only time we worked in the tunnel was during the installation of the last 2 joints (and related MP) in the middle of the tunnel. The biggest hurdle was the organizational one: the activities were carried out by different teams belonging to different companies. A civil engineering company installed the infrastructure inside the tunnel, the metallic parts of the rail/carriages and the HV and ancillary cables to the translating structure. At the same time jointers performed the cable splicing operations while monitoring staff installed the monitoring system components and performed the connections of the optical fibres and power cables. Once all the teams had finished their various tasks the entire cable-joining-monitoring system structure was hauled into the tunnel. All this happened every week until the completion of the 19 sections.

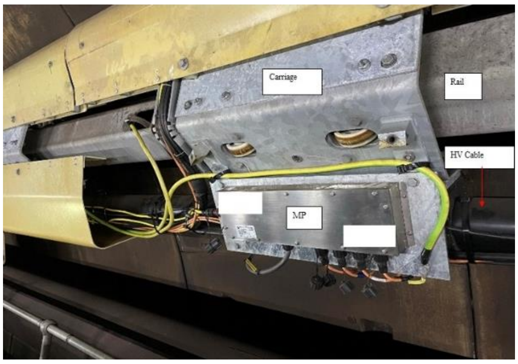

Figure 11: Carriages

The fastening of the monitoring box and the FO junction boxes has been realized through steel plates fixed on the carriages (figure 12). In this way it has been possible to assemble and test all the apparatuses before the insertion in the tunnel. All these systems have been designed and implemented on Eleclink interconnector, as described in this paper.

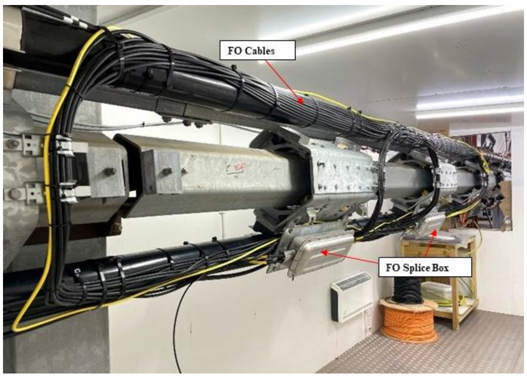

Figure 12: FO splice boxes and cables installed on carriages

5. OPERATION OF THE MONITORING SYSTEM

In service, the asset management monitoring system ensures a comprehensive and constant monitoring of the Interconnector. This system is basically made of the three systems perfectly complementing each other as each one is monitoring a different signal which might be generated by the cable system: partial discharge, temperature and acoustic. The PD system detects an electrical signal, a discharge, which is generated into the cable or in an accessory. PD are also generated by external sources and are very common, for example, in the SS where they're created because of corona effect by the equipment present there. All the PD generated externally could be summarized as "noise". All the PD captured by the system are assessed with the aim of discriminating the external to the internal one. The monitoring system automatically filters the noise and the signal considered potentially dangerous are highlighted and trigger an alarm. The ability for the system to filter the noise is crucial on this cable system. The train power supply system with the pantograph sliding on the overhead line causes many discharges which massively increases the noise level into the tunnel. Not having an effective filter would cause the system reacting to too many false signals. Once a concerning PD is detected this is analyzed by the system and those indicating a possible issue in the cable system are highlighted. This gives the possibility to further assess their characteristics, which often describe the issue affecting the cable system, and predict the defect development. In the case that the system detects a critical PD activity [4], [5], [6], it sends an alarm to the Client control room via the SCADA protocol. The temperature monitoring system provides real time measurement of the power cable temperature every 0.5 m of its length. This system tracks temperature variations depending of cable load conditions and also detect anomalies, such as hot spots. Temperature is an important parameter to monitor. In fact, operating a cable above its rated temperature will decrease its lifetime and hence its reliability; moreover, the presence of temperature hotspots might signal either a reduction of heat exchange capacity between the power cable and its surrounding which in turn limits the current rating of the cable; or a degradation of the cable which might lead to a fault. The system generates alarm and warnings in case the measured temperature exceeds pre-set threshold values. Real time temperature values at points of interest and the alarm signals are sent to the Client control room through SCADA protocol. This allows a prompt investigation and the possibility to intervene on time before the cable system performance and reliability is affected. DAS monitoring is even more meaningful for this specific cable system, which is installed in air for a length of 51 km in close proximity to a train which is running to a speed of 160 km/h. The HVDC cables as well as the FO, LV cable and the monitoring equipment are protected by fiberglass shields which avoid any accidental impacts with debris projected by the fast running train. The shield also protects the cable system during the tunnel operation when many labors work around the cable system handlings various tools. The DAS is capable to detect acoustic activity in proximity of the cable and distinguish possible threats from normal signals, such that of a passing train. The DAS is also monitoring underground sections of the projects. In this case, the DAS alarm algorithm is configured to identify excavation events. Due to the nature of acoustic monitoring, after installation, the system requires a learning phase to identify the normal acoustic activity of the installation. During this phase it also possible to make tests of events that the Client wish to be alarmed that are not already present in the DAS event library. When a threatening event is recognized, similarly to temperature monitoring, an alarm is triggered and sent to the Client control room via Scada protocol. Another important functionality of the whole monitoring system, i.e. PD, DTS and DAS, is assistance in the key and delicate operation of fault location. In fact, PD are often associated with a defect which may evolve in a failure [1], [2], [3], [4], [5], [6]. Hence, recording an abnormal and/or increasing level of PD just before a fault is an indication of where the fault might have occurred. Similar concept applies to the DTS, a localized increment of a temperature might indicate a local issue which lead to the failure. Finally, the DAS is configured to identify the acoustic signature of a cable breakdown and provide its position. DAS can also be used during fault pinpointing operation.

6. CONCLUSIONS

The system equipped to the Eleclink UK/FR interconnector is the first ever able to detect Partial Discharges in the HVDC cables and has been fully conceived, designed, built and installed for the specific Eleclink interconnector. The system is also able to detect the temperature and the acoustic noise of the HVDC cables themselves, representing this way a cutting-edge technology for the identification of faults and of pre-faults. The dimension and flexibility of the monitoring components allow their installation even on difficult scenario, as the one on the Channel Tunnel described in this paper. Their implementation on a cable system increases its reliability, support the operator optimizing the maintenance planning and shorten the out of service in case of fault. All this becomes even more relevant when the interconnector shares the same infrastructure as in the case of Eleclink interconnector since the intervention on the cable system affects another key service such as the rail service between the two countries. This demonstrates as the installation of the here described Monitoring Systems extends the benefits well beyond the interconnector operation and the end users.

BIBLIOGRAPHY

[1] P. Romano, G. Rizzo, A. Imburgia, F. Viola, G. Ala, R. Candela, "Investigation on partial discharges in HVDC cables after polarity reversal events," (IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP, October 2020, pages 292-295);

[2] G. Rizzo, P. Romano, A. Imburgia, M. Albertini, S. Franchi Bononi, S. Siripurapu, G. Ala, "The effect of Transient Over Voltages on the Partial Discharges activity in HVDC joints," (AEIT HVDC International Conference, May 2021, pages 1-6);

[3] P. Romano, A. Imburgia, G. Rizzo, G. Ala and R. Candela, "A New Approach to Partial Discharge Detection Under DC Voltage: Application to Different Materials," (IEEE Electrical Insulation Magazine, March-April 2021, vol. 37, no. 2, pages 18-32);

[4] G. Rizzo, P. Romano, A. Imburgia and G. Ala, "Partial Discharges in HVDC Cables - The Effect of the Temperature Gradient During Load Transients," (IEEE Transactions on Dielectrics and Electrical Insulation, October 2021, vol. 28, no. 5, pages 1767-1774);

[5] A. Imburgia, P. Romano, G. Ala, M. Albertini, L. De Rai, S. Franchi Bononi, E. Riva Sanseverino, G. Rizzo, S. Siripurapu, F. Viola, "Effect of Polarity Reversal on the Partial Discharge Phenomena," (IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP, October 2020, pages 378-381);

[6] P. Romano, G. Rizzo, C. Consolazione, R. Candela and G. Ala, "The Partial Discharge Behavior of Different Materials Under DC Periodic Stress," (IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP, October 2019, pages 661-665)