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HVDC transmission cables in the offshore wind industry: reliability and condition monitoring

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The deployment of high-voltage direct current (HVDC) transmission in the offshore wind industry is increasing, due to its economic and operational attractiveness.

HVDC cables are critical components of these transmission systems, but a lack of suitable condition monitoring systems in the market for these links render such systems vulnerable where undetected cable defects may exist.

Summary of findings

- Difficulties encountered with previous HVDC transmission installations in the offshore wind industry have led to a reduced investment confidence.
- HVDC transmission cables in the offshore wind industry require a high level of reliability and no suitable condition monitoring system is available for this critical asset at present.
- Investigations into HVDC cables' ageing mechanisms are underway, but insufficient knowledge sharing means that consistent approaches to health monitoring are not being established.

Recommendations

- Industry expertise in condition monitoring systems and applied research and development (R&D) resources should be used to develop a platform on which online cable condition monitoring can be based.
- The performance and reliability of HVDC cables can be enhanced by the development of novel online condition monitoring and diagnosis systems, which will help to improve system availability and reduce operating costs.
- The development of a standard approach to condition monitoring: smart grid solutions and technologies should provide a platform on which online cable condition monitoring can be based.

At present, the UK has 5GW of installed offshore wind generation capacity. These wind farms are located relatively near to the shoreline and are connected to the grid using high voltage alternating current (HVAC) transmission. HVAC transmission equipment is widely available and expertise related to its maintenance is readily available and well-established.

In the future, however, offshore wind farms are likely be located more than 100 miles from shore, such as Dogger Bank. Due to the large amount of power generated and their relatively remote location, such developments will require the use of High Voltage Direct Current (HVDC) transmission. At such distances, HVDC transmission technology is preferable to HVAC transmission, due to reduced power losses and economical attractiveness.

Problems and challenges

Globally, the number of operating offshore wind farms using HVDC transmission systems is limited.

All such farms are located in Germany, with further connections in the planning process or due to be commissioned in other European countries.

Early adopters of HVDC transmission have faced numerous problems, leading to significant time and financial losses. This has resulted in reduced investor confidence where, in some cases, additional financial agreements have been needed to guarantee investment and define liabilities, notably in the case of BorWin 1[1] and BorWin 2[2].

The key issues encountered in HVDC systems are mostly related to the system operation, control and protection[3]. HVDC export cables are also a critical component of the transmission system and make up the largest capital cost in the entire HVDC transmission system. Failure of the HVDC export cable can lead to a complete shutdown of the wind farm, resulting in significant repair costs and loss of revenue.

According to industry data, cables are the root cause of the most frequent and largest insurance claims against offshore wind developments[4]. For example, when a fault occurs within a submarine cable system, it is necessary to initially locate the fault and then raise the cable from the seabed in order to carry out repair. Operations such as these are extremely expensive[5] and logistically difficult, as this involves expert intervention to accurately pinpoint the location of the fault and deployment of expensive cable lift/repair vessels to carry out the repair.

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1 Tijdo van der Zee, 'Offshore substations should have a standard size of 900MW, *The Offshore Wind Industry*, Vol 3 (July 2012)

2 *TenneT and Mitsubishi Corporation extend partnership in German offshore grid connections,* Tennet, 6 March 2012, available online at http://www.tennet.eu/nl/news/article/tennet-and-mitsubishi-corporation-extend-partnership-in-german-offshore-grid-connections.html

3 Wensky, D., 'FACTS and HVDC for grid connection of large offshore wind farms", EWEC 2006, Athens, 27 February-2 March 2006

4 *Cable Burial Risk Assessment Methodology: Guidance for the Preparation of Cable Burial Depth of Lowering Specification*, Carbon Trust, February 2015

5 'Moyle Interconnector: Repairs Cost £31M', BBC Northern Ireland, 17 October 2012, available online at http://www.bbc.co.uk/news/uk-northern-ireland-19969955

At present, there is no suitable state and condition monitoring system available in the market for HVDC cables.

A recent survey on condition monitoring undertaken by HVPD Ltd found that while a range of experience in power quality parameters monitoring exists within the sector, it is not apparent whether or not that same experience exists in the case of fault and reliability monitoring.

Further challenges are associated with testing. Testing of HVDC cables is carried out in compliance with international recommendations during the delivery and commissioning process[6,7].

However, failures have been recorded, in spite of Council on Large Electric Systems (CIGRE) studies[8] highlighting the high reliability of the internal design of HVDC subsea transmission cable systems.

Furthermore, as extruded HVDC subsea cables are a relatively new transmission technology, there is a lack of understanding about how these particular cables age electrically under HVDC voltage stresses and also a lack of evidence regarding their reliability.

As a result, a range of studies aimed at investigating the reliability of HVDC cables is being carried out.

These studies are particularly focused on space charge formation and measurement while others are investigating partial discharge (PD) in HVDC systems.

Techniques to locate incipient faults in HVAC power cables are well-established and are generally carried out by assessing PD activities in the cable. However, under HVDC conditions, PD activity is less directly associated with causing insulation degradation and breakdown. It can be considered an indicator of defects or weak spots during manufacturing, rather than a primary cause of degradation in itself.

A draft International Electrotechnical Commission (IEC) standard, which specifies test methods and requirements for HVDC power transmission cables with extruded insulation and their accessories for rated voltages up to 320kV for land applications, has recently been released[9].

However, the standard does not mention PD testing in HVDC cables, although in other IEC standards[10] relevant to HVDC equipment such as converter transformers, smoothing reactors and bushings, PD measurement is widely covered in routine tests including DC voltage withstand testing and polarity reversal testing.

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6 *Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500kV*, CIGRE Technical Brochure 469, 2012

7 *Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500kV*, CIGRE Technical Brochure 469, 2012

8 *Update of service experience of HV underground and submarine cable systems*, CIGRE Technical Brochure 379, 2009

9 *HVDC power transmission cables with extruded insulation and their accessories for rated voltages up to 320kV for land applications – test methods and requirements*, IEC 62895, 2014

10 *Converter transformers - Part 2 & 3*, IEC 61378, 2001- 2015, *Power transformers – Part 6: Reactors*, IEC 60076, 2007 and *Bushings for DC application*, IEC 65700, 2014

The accumulation of space charge in polymeric HVDC cables can also affect the long term reliability of the HVDC cable and could lead to insulation failure. A wide range of measurement techniques are available to mitigate this risk, including the pulsed electro-acoustic (PEA) and pressure wave propagation (PWP) method. These techniques are mature and are extensively used during the development tests of HVDC cables.

Insulation defects in cables subjected to constant DC voltage are different to those which arise under an AC excitation regime.

The continual polarity reversals in an AC field tend to induce any discharge activities through the insulation system of the cable and this forms one of the cornerstones of HVAC diagnostic techniques. In contrast, a constant, unipolar DC electric field tends to inject charge into the insulation, where it can accumulate and cause only intermittent PD activity deemed to be less damaging to the cable's insulation material.

Where do we go from here?

Every aspect of the HVDC transmission system can impact upon the reliability of the system.

In addition to the existing HVDC cable quality control tests and processes already discussed, the assessment of the performance and reliability of HVDC cables could be enhanced by the development of online condition monitoring and fault diagnosis systems.

This requires applied research, case studies and demonstration of reliability. These processes can also be costly, time consuming and difficult to achieve, due to market competitiveness and confidentiality obstacles.

However, it is possible that some of the existing online fault location and monitoring systems used for HVAC transmission could be applied to HVDC.

Some of these HVAC monitoring systems, such as fibre optic distributed temperature sensing, online PD detection and location and time domain reflectometer (TDR) measurements for faults pre-location and fingerprinting, are becoming integral parts of the operator control system.

Some existing HVAC cable condition monitoring systems have proved their capabilities in providing early warnings of faults, helping to reduce the number of costly unplanned outages, which, in turn can translate into a reduction of operation and maintenance costs.

Based on the same principle, and in an attempt to investigate HVDC cable health monitoring, a recent project deployed a continuous monitoring system on an operating HVDC cable interconnector[11]. Using non-intrusive sensors installed at the termination of the HVDC cable, the system succeeded in detecting AC and DC harmonics leakage from the different quadruple valves at the HVDC cable termination. However, measurement of signs of cable degradation phenomena such as PD events were not found.

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11 *HVDC-OLPD – On-line High Voltage Direct Current Cable Monitor*, HVPD, available online at http://www.hvpd.co.uk/industries/renewables/hvdc-olpd/

The deployment of condition monitoring systems can sometimes be limited by cost considerations, when the cost is considered to be a surplus to the capital cost of the asset. However, even equipment considered to be of secondary or accessory role can affect the operation of the entire transmission system.

Additionally, false alarms generated by condition monitoring systems can also be a constraint. These false alarms not only increase the number of unnecessary site visits and prolong downtime, but also cause genuine alarm signals to become dubious and untrustworthy in the case where a potential fault may occur. Consequently, the reliability of these condition monitoring systems needs to be proven.

The main impediments to the implementation of condition monitoring systems for HVDC transmission include cost, precise and reliable data interpretation and persuading operators to act on results.

As such, approaches towards encouraging the implementation of monitoring systems should include:

- The development of low cost sensors and monitoring systems capable of assessing potential HVDC cable faults.

- More engagement from cable manufacturers and grid platform developers to assist in the design of relevant specifications for the condition monitoring system.

- The development of a standard approach to condition monitoring where smart grid solutions and technologies should provide a platform on which online cable condition monitoring can be based.

The continuous development of large MW scale wind turbines at increasingly greater distances from the shoreline will inevitably lead to the deployment of more HVDC transmission systems.

Therefore, in order to enable such deployments and reduce the risk of system failure, there is a pressing need to implement more remote condition monitoring systems to reduce the requirement for offshore access, increase reliability and reduce operational costs.

ORE Catapult's approach

In the UK, costs and associated risks with HVDC technology are approached and assessed cautiously. In a bid to address these issues, ORE Catapult has delivered different numerous projects related to HVDC technology, including cost analyses and technology assessments.

While ORE Catapult acknowledges the industry's understandable caution with regard to HVDC, the increasing need to ensure the successful development and implementation of the technology in the offshore wind industry will ultimately act as a driver to accelerate a solution.

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Recommended reading

Tijdo van der Zee, 'Offshore substations should have a standard size of 900MW, *The Offshore Wind Industry*, Vol 3 (July 2012)

TenneT and Mitsubishi Corporation extend partnership in German offshore grid connections, Tennet, 6 March 2012, available online at http://www.tennet.eu/nl/news/article/tennet-and-mitsubishi-corporation-extend-partnership-in-german-offshore-grid-connections.html

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Recommendations for tests of power transmission DC cables up to 800kV, Elektra 189, CIGRE, 2000

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HVDC power transmission cables with extruded insulation and their accessories for rated voltages up to 320kV for land applications – test methods and requirements, IEC 62895, 2014

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HVDC-OLPD – On-line High Voltage Direct Current Cable Monitor, HVPD, available online at http://www.hvpd.co.uk/industries/renewables/hvdc-olpd/

Author Profile

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Othmane has expertise in power cables, condition monitoring systems and the detection and location of faults in HV environments, having worked in this field in both academia and industry over the past five years. Othmane is also ORE Catapult's technical representative on a number of collaborative projects.

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