After-laying Testing and Diagnosis of Off-Shore Wind Farms Inter-Array- and Export-Power Cable Systems
About us

onsite hv solutions, headquartered in Switzerland, is an international organization with a team of highly qualified specialists, providing support in testing and maintenance of inter-array and export power cable systems in offshore wind farms.

onsite hv solutions possesses extensive scientific knowledge combined with years of field experience, long and close cooperation with world renowned universities and leading manufacturers around the world.

In addition, onsite hv solutions is actively working in organizations like CIGRE, IEEE and IEC, which allows us to understand the needs of electric power utilities, and to develop and offer effective asset management and asset optimization solutions accordingly.

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Overview of Goods and Services

Our Competences

Submarine cables play a vital role in bringing generated power to offshore substations and to shore. Our offshore trained test engineers are vital in supporting customers with their installation testing, service life maintenance and cable asset management.

- Cable system tests - types, scope of tests, test procedures, criteria for evaluation of measurement results with e.g. mechanical-, electrical- and non-electrical tests such as:
  - Pre-qualification tests of the cable system consisting of: offshore- and onshore- cables, factory joint offshore joint, transition joint, land joint and cable terminations
  - Cable system type and routine tests
  - Inspection and acceptance tests (FAT)
  - Tests before laying the cable (verifying that the cable has not been damaged during loading onto a vessel or transport)
  - Inter-operational tests (connections subsequent cable sections, after other works)
  - Acceptance tests after building the cable line (SAT)
  - Maintenance test during cable line operation lifetime
  - Test in case of a failure during operation

In the field of on- and offshore power cable networks, our expert team is able to support the process of determining the requirements for designing, installation testing and service life management of export- and inter-array cable systems. For on- and off-shore power cable connections onsite hv solutions provides the following core competences:

Technical competences

- OTDR of fibre optic cable testing
- TDR test on cable cores
- Insulation resistance test
- Damped AC after-installation- and diagnostic testing including partial discharge and dissipation factor estimation of inter-array cable strings (up to 66 kV) and export cable circuits (up to 230 kV)

Man-power competences

- Highly qualified specialists with over 10 years of field-testing experiences
- Offshore trained test engineers with GWO certificate (Sea Survival, First Aid, Working at Heights, Manual Handling, Fire Awareness) and HUET with CAEBS

Expertise competences

- Measurement data evaluation and analysis
- Measurement results interpretation
- Data reporting including recommendation
- Data storage and evaluation for condition-based maintenance

Follow-up competences

- Risk impact estimation incl. future action recommendation
- Export and Inter-array cables condition data management
Knowledge Support and Cooperation

Based on our long term experiences in the field of power cables we can support our customers with:

- Full commission services of newly installed cables
- Training & Knowledge support
- Data evaluation of PD measurements
- Supervision and expertise support
- Condition assessment of cables in service
- Condition based maintenance (CBM) recommendations

HV testing possibilities using Dual Power and Dual Side:

- Inter-array cables strings up to 33 kV by DAC MV60os
- Inter-array cables strings up to 66 kV by DAC HV110os
- Export cable circuits up to 230 kV by DAC HV300
- Export cable circuits up to 400 kV by DAC HV400 (project based)

Cooperation parties

In the past years we have worked successfully world-wide together with the different parties in the field of OWF installation and operation:

- Cable manufacturers of onshore- and offshore cables
- Engineering, procurement, and construction (EPC) contractors
- Supervising- and research institutes
- Consultants
- Offshore wind farm owners and operators
Offshore Wind Farms Power Cables Reliability

The increasing demand for renewable energy worldwide has contributed to the fast development in the quantity and size of installed offshore wind farms (OWF).

For this type of generation, the submarine power cables are of great importance for the power transmission from the wind turbines to the offshore- and to the onshore substations. The experience from the last 20 years shows that:

- The power cables are the largest contributor to the failures of the power supply from the offshore plants.
- Repairs of such a critical infrastructure are extremely challenging and costly.
- Several aspects of the design, transportation, installation, quality testing and maintenance of power cables at offshore wind farms require special attention.

Failures of offshore power cables

Based on the experiences from the last twenty years of OWF operation, the offshore cable failures are responsible for up to 80% of the total financial losses and insurance claims. This situation is much more remarkable and worrisome because, when considering the total costs of a windfarm, the offshore cables account for less than 10% of the total capital costs.

In the last 7 years, about 90 offshore cable failures have been reported with over € 350 million in insurance claims.

Depending on the size of the OWF and the location of the failed turbine the financial impact of a single inter-array cable failure can range between € 200 thousand up to € 3 million per case.

In the next ten years the expected worldwide annual growth of 19% in the installed OWF facilities will result in about 177 GW capacity by 2030.

The following major problems are often resulting in OWF power cables failures:

- The pressure to reduce levelized cost of electricity, triggers questionable decisions on developers- and contractors sides.
- The offshore industry is focused on strongly driving down the costs with less room for motivating the development and innovations.
- The technical solutions are constantly being under the development to target specific problems that occur during installation and operation.
- There is combination of insufficient risk identification, the (project specific) subsea cable design and the shortcomings in how specific quality testing procedures are implemented.
- Faults in the open sea, caused by dragging fishing nets, anchor strikes and erosion.

Field examples of mechanical damage on the armour of an inter-array cable
Quality Control of Submarine Power Cable Systems

Export cables up to 230 kV might be of very long length connections up to several tens of kilometers and the quality of installation is extremely important for OWF power delivery from the offshore substation (OSS) to the shore.

Inter-array cables up to 66 kV are connected through single turbines to a string up to more than 10 km lengths and the quality of installation is extremely important for power delivery from strings with up to 10 wind turbine generators.

Depending on the OWF size and configuration in case of a cable failure an off-shore repair of any damages of such critical cabling infrastructure is challenging and very costly. As a result considering responsible operation and asset management of export and inter-array power cables several aspects have to be considered.

The developments of IEEE standards in last 10 years which are made in cooperation between power companies, manufacturers and service companies, and are referring to selected IEC measurement documents, describe the best state-of-the-art of modern non-destructive methods for both after-installation and maintenance testing and diagnosis, see also page 10.

Basic asset management aspects determining a safe and reliable grid operation for OWF power cables. The “finger-print” approach means a cable system quality determination over the overall life-time by evaluation of diagnostic parameters e.g. partial discharges monitored voltage testing, dissipation factor (tan δ), etc.
On-site testing and diagnosis of export- and inter-array cable systems

Considering the risks, the offshore industry needs to setup own reliable specifications for submarine cable testing and condition assessment. In general an effective after-lying testing technology has to be dedicated:

- for off-shore testing,
- to provide the adequate information like voltage testing and condition finger printing (e.g., PD, tan δ) during whole installation and operation process,
- to ensure a reliable operation of export and inter-array cables,
- to provide contractors the basis for lowering the risks during the warranty period,
- to enable service providers during operation sound basis for condition based maintenance (CBM).

Testing considerations

As present international recommendations for off-shore are mainly made based on-shore grid application, present off-shore procedures are recommending only basic testing. This situation shows certain deficiency regarding reliable testing of submarine cables and for sure it is not considering optimal reduction of the risks of possible failures and very high costs of repairs.

Therefore testing procedures during manufacturing, transportation, installation and operation are needed to exclude or at least to reduce possible risks of a damage during transportation respectively installation and consecutively in a failure during operation.

Higher efficiency rating of OSW installations and optimal quality control will provide protection:

- of the investments of OSW farm owners,
- against the warranty risks for contractors and subcontractors,
- in the interests of insurers,
- against unexpected operational failures and high repair and maintenance costs,

The use of damped AC (DAC) technology provides since 20 years in on-shore and since 5 years in off-shore approved testing after-installation and condition assessment protocol.

Dedicated partial discharge- and tan δ- monitored voltage testing is the most modern way for sensitive and non-destructive testing and diagnosis of export- and inter-array cables.

Possible scenarios in case of a cable failure

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After-laying Testing and Diagnosis of Off-Shore Wind Farm Inter-Array- and Export- Power Cable Systems
On-site testing of export and inter-array power cables by damped AC technology

Various damped AC (DAC) system solutions are available for testing of OWF inter-array and export power cable systems with lengths up to 100 km.

Damped AC Testing and Diagnosis

Is for more than 20 years in use and it is in accordance with relevant testing parameters from international standards and recommendations (IEEE, IEC, CIGRE).

Due to its extremely low input power demand very compact damped AC (DAC) technology makes easy energizing of very long lengths of power cables.

Applicable for on-site after-laying/commissioning, and diagnostic testing of all types of AC and HVDC on- and off-shore power cables up to 400 kV.

Provides standardized PD detection and dissipation factor estimation during voltage withstand test and partial discharge test according to IEC 60270.

Off-shore side

On-shore side

Export cable up to 230 kV

Damped AC 300 kV (Dual Side and Dual Power) for testing export cables up to 230 kV

Damped AC 60 kV* off-shore version for cables up to 33 kV

Damped AC 110 kV* off-shore version for cables up to 66 kV

* Dual Side and Dual Power configuration available

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After-laying Testing and Diagnosis of Off-Shore Wind Farm Inter-Array- and Export- Power Cable Systems
Partial Discharge Testing and Diagnosis

Considering the complexity of the installation process in an off-shore environment, as well as all risks coming from the manufacturing and transportation, a dedicated testing of the installed cables is crucial for verification of the complete cable system integrity and to exclude defects e.g.:

- voids and cuts in polymeric materials,
- delamination and
- contaminations of interfaces,
- protrusions or wrong use of shield materials,
- missing or wrongly applied components or connections or incorrect dimensions,
- misalignment of accessories.

All that potentially might lead to an increase of the local stress and can eventually lead to early failure or during operation a higher aging rate.

A safe and reliable OWF cable grid operation starts already at the moment of commissioning a newly installed cable circuit followed by an adequate condition based maintenance.

As on- and off-shore HV cable links are getting longer and longer, it has to be taken into account that:

- destructive over-voltage testing only is not technically optimal and sufficient for the detection of all possible installation defects,
- For long length dedicated PD diagnosis is more sensitive to detect all defects.

Sensitive PD-monitored withstand test can be more effective in the identification of faults originating from poor installation and to providing the so-called “0”-fingerprint for further condition evaluation of a cable circuit, e.g. to be compared just before the end of the warranty period.

**Dual Side PD measurement**

- DAC technology provides the possibility to energize high capacitances, i.e. very long lengths of power cables, with a low input power demand combined with a sensitive PD detection and localization.
- Detection and localization of PD in cable systems with long length can be improved by performing PD measurements at both sides of the cable circuit.
- On both sides of the cable system, PD detectors are installed.
- The detectors have to be synchronized to correlate the measurement data of both sides.
- In this particular configuration the PD pulses are directly measured and there is no need to take reflections as is the case with the single sided TDR evaluation.
- As both units are synchronized, the difference in the arrival times of the pulses at both sides together with the pulse velocity obtained from the calibration provides the location of the discharging defect.
Relevant International Standards & Guidelines

General
- IEC 60060-3: High Voltage Test Techniques Part 3: Definitions and Requirements for On-site Testing

On-site testing
- IEEE 400: Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above
- IEEE 400.4: Guide for Field-Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current Voltage (DAC)
- IEC 63026: Submarine power cables with extruded insulation and their accessories for rated voltages from 6 kV (Um = 7,2 kV) up to 60 kV (Um = 72,5 kV) - Test methods and requirements
- HD 620 S2 (CENELEC): Distribution Cables with Extruded Insulation for Rated Voltages from 6 kV up to 36 kV
- IEC 60840: Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 30kV up to 150kV – Test Methods and Requirements
- IEC 62067: Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 150 kV up to 500 kV – Test Methods and Requirements
- HD 632 S2 (CENELEC): Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 36kV up to 150kV
- Cigré TB 496: Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV

Standardized PD detection
- IEEE 400.3: Guide for PD Testing of Shielded Power Cable Systems in a Field Environment
- IEC 60270: Partial discharges measurements
- IEC 60885-3: Test Methods for Partial Discharges Measurements on Lengths of Extruded Power Cable
- Cigré TB 502: High-Voltage On-Site Testing with Partial Discharge Measurement
- IEC 62478: High voltage Test Techniques - Measurement of Partial Discharges by Electromagnetic and Acoustic Methods
- Cigré TB 444: Guidelines for Unconventional Partial Discharge Measurements
- Cigré TB 662: Guidelines for Partial Discharge Detection Using Conventional (IEC 60270) and Unconventional Methods

Dissipation factor measurement
- IEC 60141: Tests on Oil-Filled and Gas-Pressure Cables and Their Accessories
- IEC 60141: Tests on Oil-Filled and Gas-Pressure Cables and Their Accessories
- Cigré TB 627: Condition Assessment for Fluid-Filled Insulation in AC Cables
Inter-array Cable Strings Testing and Diagnosis

Example of criteria for the risk management for the contractor (e.g. 5 year warranty) system operators, insurers have to be related to the quality control e.g.:

- **Soak test** = due to lack of information about operational reliability = **No warranty**
- **Voltage test only** = due to showing extreme defects only = **Limited warranty**
- **DAC voltage test** = including sensitive (PD- and Tan δ) fingerprinting = **Full warranty**

![Partial Discharge pattern](image1)

![Dissipation factor (tan δ)](image2)

![DAC fingerprint of OWF power cable string](image3)

![Layout of a string](image4)

![DAC PD measurement and PD mapping of a complete string performed from the OSS](image5)
Export Cable Testing and Diagnosis

The OWF export cable circuits are characterized by:

- High capacitance which requires extremely high power demand for conventional AC test systems.
- Due to very long factory lengths large number of (factory) joints are installed.
- There is a need to test the complete cable drum in the factory before shipping and on-site after installation.
- Accessibility and space constraints regarding off-shore access to the cable.
- No possibility for distributed partial discharge measurements on individual joints of a subsea cable.
- In the case of HVAC or HVDC cables, any possible defects due to installation and transportation can only be detected and located with damped AC voltage testing including partial discharge detection.

DAC testing of long lengths export power circuits

- Due to its low input power demand damped AC technology makes it possible to energize very long lengths (tens of kilometers) of HVAC and HVDC power cable with a high capacitance.
- Applicable for all types HVAC and HVDC HV and EHV power cables.
- Applicable for on-site after-laying / commissioning, maintenance and diagnostic tests.
- Approved testing methodology, in accordance with test parameters from relevant international standards and recommendations (IEEE, IEC, CIGRE).
- DAC technology meets the IEEE and IEC test parameters specification of an on-site testing system.
- Possibility of dual sided partial discharge detection on very long lengths (tens of kilometers) of power cables.
Dual Side PD measurement on long lengths export power cable circuits

- Dual Side PD testing and diagnosis is dedicated for long transmission cable circuits
- Localization along the complete cable circuit of all types of insulation defects
- Improvement of over-all PD measurement performance up to 200%
- High sensitive PD measurement with automatic real-time PD localization
- Fully integrated advanced PD diagnosis for a complete cable condition picture
- Simple setup with intelligent inter-communication and synchronization

Example of recent testing projects of long cable lengths with damped AC technology

<table>
<thead>
<tr>
<th>Cable length</th>
<th>Voltage</th>
<th>Cable type</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>62 km, 50 km and 25 km</td>
<td>132 kV</td>
<td>XLPE</td>
<td>Poland</td>
</tr>
<tr>
<td>27.5 and 26.1 km</td>
<td>230 kV</td>
<td>Oil-filled</td>
<td>Singapore</td>
</tr>
<tr>
<td>38 km, 36 km, 34 km, 30 km, 27.5 km, 18 km, 16 km</td>
<td>110 kV</td>
<td>XLPE</td>
<td>Poland</td>
</tr>
<tr>
<td>31 km, 30.9 km, 27 km and 21 km</td>
<td>110 kV</td>
<td>XLPE</td>
<td>Ireland</td>
</tr>
<tr>
<td>22.2 km and 17.5 km</td>
<td>50 kV</td>
<td>XLPE</td>
<td>Netherlands</td>
</tr>
<tr>
<td>27 km and 18 km</td>
<td>35 kV</td>
<td>XLPE</td>
<td>Lithuania</td>
</tr>
<tr>
<td>25 km and 26 km</td>
<td>30 kV</td>
<td>XLPE</td>
<td>Poland</td>
</tr>
<tr>
<td>14.0 km</td>
<td>25 kV</td>
<td>XLPE (sea)</td>
<td>Netherlands</td>
</tr>
<tr>
<td>13.3 km</td>
<td>220 kV</td>
<td>XLPE (land/sea)</td>
<td>Russia</td>
</tr>
<tr>
<td>17.4 km</td>
<td>150 kV</td>
<td>XLPE</td>
<td>Netherlands</td>
</tr>
<tr>
<td>26 km</td>
<td>15 kV</td>
<td>XLPE</td>
<td>Poland</td>
</tr>
</tbody>
</table>

DAC PD patterns before/ at the moment insulation breakdown during after-lying test of a 13.3 km long land-to-submarine 220 kV cable
HVDC Cable Testing and Diagnosis

Typical challenges of submarine HVDC power cable circuits

- Installing a submarine HVDC cable is a costly and challenging activity. The lifetime of a submarine cable might be tens of years and the technical interventions for its repairing in case of faults are also costly and difficult.
- Cigré TB 496 states for the routine test testing with AC voltage could be considered, but that long manufacturing lengths and high voltage levels may render AC testing impractical. This can be overcome by testing with DAC.
- Cigré TB 496 recommends for the after-installations test a DC voltage of 1.45 Uo (for 1 hour), where a negative polarity shall be used regardless of the polarity of the pole. It is obvious that it is not providing the desired optimal selection criteria to obtain an overall cable condition assessment. Additionally, an HV DAC test combined with a partial discharge test could be performed on the complete installed lengths.
- DC over-voltage test is not sufficient to demonstrate the presence of insulation defects in cable insulation and in the accessories and only AC stresses can demonstrate these defects.
- Due to high capacitance of HVDC cables which requires extremely high power demand for conventional AC test systems the application of damped AC is most obvious to check the quality of a large number of (factory) joints installed and the complete cable insulation.

Recommended after-laying testing of HVDC power cables

- On-site after-laying test has the goal to verify the quality of the complete cable system. It is a field test performed after the complete cable system installation, including terminations and joints, before the cable system is put into normal service operation.
- The after-laying test has to be performed with a PD monitored damped AC withstand test.
- This test consists of a high voltage test with a predetermined magnitude (IEC conform) and the monitoring of partial discharges improves the evaluation and determination of the overall cable condition.
- The combination of a voltage withstand test with PD detection and dissipation factor (tan δ) provides information of an insulation weak spot and insulation degradation prior to breakdown.
- Regarding the complete installed HVDC cable length any possible defects as introduced in the factory or after the installation and transportation, can only be detected and located by means of AC electric stresses e.g. by damped AC (DAC) voltage testing including single- or dual-side partial discharge detection at the cable terminations.

Damped AC test with PD measurements of a 320 kV HVDC cable
CBM of Offshore Inter-array Cable Strings

Using a dedicated method like DAC technology better quality control of newly installed offshore power cable circuits and approaches to preserve power cable quality (CAPEX) over the OWF operation time will be possible, resulting in a higher reliability and consequently lower costs of outages (OPEX).

Based on non-destructive advanced DAC diagnosis of service aged inter-array cable strings actual insulation condition can be determined and used for condition based maintenance (CBM).

By using cable condition knowledge rules the asset management decisions of OWF cable networks can be supported.

<table>
<thead>
<tr>
<th>Cable circuit</th>
<th>Actual condition</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>String 1:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSS to WTG 1_8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>String 2:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSS to WTG 2_8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>String 3:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSS to WTG 3_8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>String 4:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSS to WTG 4_8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>String 5:</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| OSS to WTG 5_8     | Internal PD found at:  
1. Location WTG 5_6, phase L1  
2. Location WTG 5_1, phases L1, L3 and L3  
3. Location WTG 5_6, phase L3 | Investigate/repair the indicated location. The next maintenance tests should be done within a period of approximately 3 years if no repair action will be performed to verify the PD development. |

* recommendations are based on the results of the DAC condition assessment done in two years inspection interval.