Figure 1: Setup of Resonant Test System (RTS) at Offshore substation (OSS)

Next generation offshore cable testing: resonant technology and TruePD in action

HIGHVOLT's offshore RTS system sets a new standard for 66 kV cable testing. Designed for harsh offshore conditions, it ensures fast mobilization, safe operation and reliable PD detection. Built on decades of expertise and full offshore compliance, it secures grid stability from installation through long-term operation.

The design, installation and commissioning of offshore wind farms face several challenges for the inter-array grid. The continuously increasing power ratings of the individual wind turbines lead to increasing operating voltages (U_m) from 36 kV to 72.5 kV for the inter-array cables to reduce operating currents and therefore thermal losses.

As these cables are designed as high voltage cables and not as medium voltage, the after-installation cables should be tested by resonant test systems (RTS) as defined in IEC 63026:2019 and CIGRE TB 841. Options for measuring partial discharges are also in focus now to keep grids stable for as long as possible.

As the market leader, HIGHVOLT has installed and successfully operated more than 260 RTS systems worldwide. Building on this experience, the company has developed a completely new RTS system specifically designed for offshore operations. Offshore conditions differ significantly from those of conventional onshore testing, requiring the system to be specially adapted for transportation and operation at sea.

In close consultation with stakeholders, including platform operators and test service providers, HIGHVOLT established basic conformity with offshore standards, specifically ensuring compliance with DNVGL-ST-E 273. Further discussions highlighted the growing importance of specific procedures for the transport, installation, and operation of high-voltage test systems on offshore substations (OSS). They also emphasized the need for enhanced methods to ensure the reliability and availability of long cable runs, such as through improved partial discharge measurement techniques.

Cable testing methods

Established cable manufacturing methods guarantee a high standard on the cable itself and factory testing minimizes the risk of failures in the cable insulation close to zero. Failures in the field are most likely related to two sources: external impact on the cables (anchor) and installation issues through process deviations. Deviations in installation routines are likely to be directly correlated to premature termination failures, resulting in outage and potential loss of revenue. Anticipating that the typical 66 kV array cable system's premature failures might be concentrated on these end terminations, robust testing of the cable system, as installed, is important to ensure reliable, continuous operation over the design life.

The highest risk of failure arises from improper handling of the termination components, particularly regarding the field grading along the dielectric interface between the cable insulation and the termination insulation. The accidental inclusion of air bubbles, dust or uneven surfaces, combined with the use of either too little or too much installation grease, can create imperfections. These imperfections may initiate partial discharges (PD) when an electric field is applied.

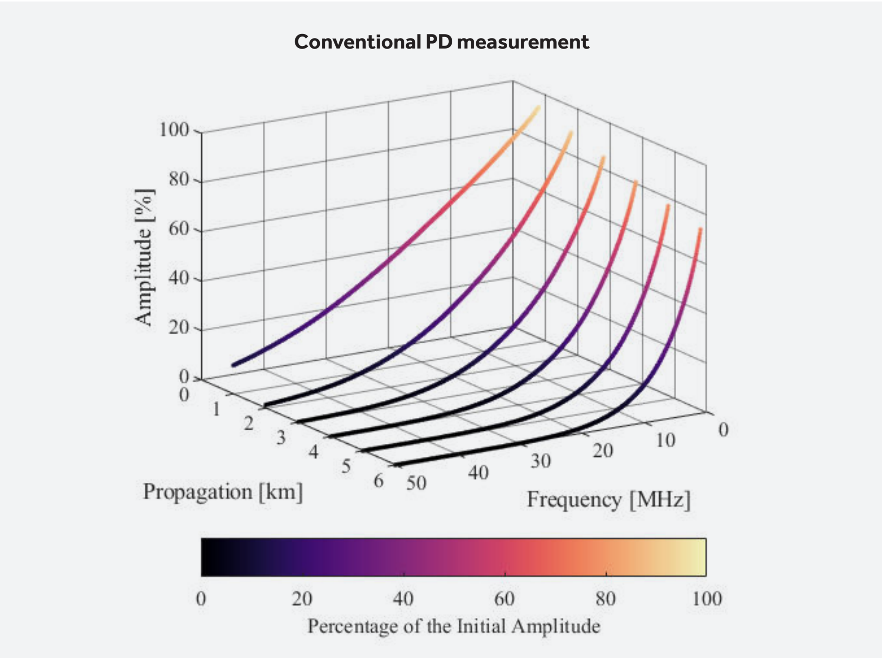

Figure 2: Signal attenuation in a cable as the function of frequency

Due to the stochastic physical process and the related boundary conditions, the number of polarity reversals is directly correlated to the probability of initiating a partial discharge at the incriminated cable termination. Therefore, RTS is advantageous to other test methods like very low frequency (VLF) and damped AC (DAC) for the detection of installation failures. It is noted that IEC 63026:2019 does not recommend VLF testing of this voltage class, nor permit the use of DAC. For medium voltage cables with Um < 36 kV, DAC and VLF have their merits for diagnostic measurements.

The principle of the RTS (Figure 1) is that of a frequency-tuned resonant circuit in which the cable capacitance is energised by the feeding source. Combining it with a resonant reactor forms an oscillating circuit providing a large output voltage when exiting at the resonant frequency. Here, only the ohmic losses of the circuit must be compensated by the power source, meaning long cables can easily be energised. It is very important to note that the oscillating circuit is always forming a sinusoidal voltage of very low harmonic distortion, independent of the frequency or shape of the voltage of the feeding source.

PD evaluation during cable testing

A major drawback of the conventional PD measurement technology with capacitive coupled signals is the specific damping characteristic of the cable in connection with a π-filter. Here, the PD signals can only be measured for less than 1000 m. To cover a longer cable or a combination of cable segments of longer length, several PD sensors need to be installed at accessible cable joints or switchgears. As this might be a prohibitive effort, alternative solutions are requested.

Nonconventional PD measurement TruePD

As shown in Figure 2, the frequency dependency of the attenuation of a high-frequency signal in a cable is the most critical physical effect. To overcome this effect, shifting the analyzed frequency of a PD to lower frequencies and applying new signal processing approaches and algorithms enables new insights. The generic concept is given below.

Generic concept of TruePD

Based on an inductive coupler, a specially designed high frequency current transformer (HFCT), the detection of signals within a bandwidth of 100 kHz to 10 MHz allows a systematic analysis of PD signals. It must be stated that the chosen frequency range also covers a lot of exterior noise. Therefore, the signal processing needs to find the PD signals within that noise. This is done by slicing a signal stream and applying algorithms like linear predictive coding (LPC). This includes feature extraction, which allows a clustering of the critical measurements and events. Practical measurements have shown a limitation of today's measuring systems to a suitable cable length of 12 km.

The evaluation is based on the transfer function of the test circuit and the clustered data. For each data cluster, a set of preferential features can be identified. Combining that with the transfer function of the test circuit enables the recombination of the effective charge at the location of the discharge.

Figure 3 shows the principle of evaluating the transfer function. By injecting a known reference impulse and measuring the receiving signal at the far end of the test object, the distortion of the impulse equals the transfer function. With a double-sided measurement, a high-resolution location of the signal becomes possible.

Injecting a reference PD signal and measuring at both ends of a multi-segment cable of nearly 14 km total length was proving the concept. By automated evaluation of the data, e.g., in a wave propagation diagram, the location of the PD can be estimated (Figure 4). The evaluation of the results for 50 pC reference PD gives an error of 0.14% of the total string length. An interesting fact for further analysis is the effect that an increased injected PD level seems to lead to a higher error value, nevertheless, always in the range below 0.25%.

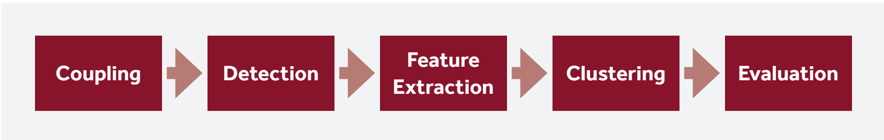

Figure 3: Generic concept of True-PD

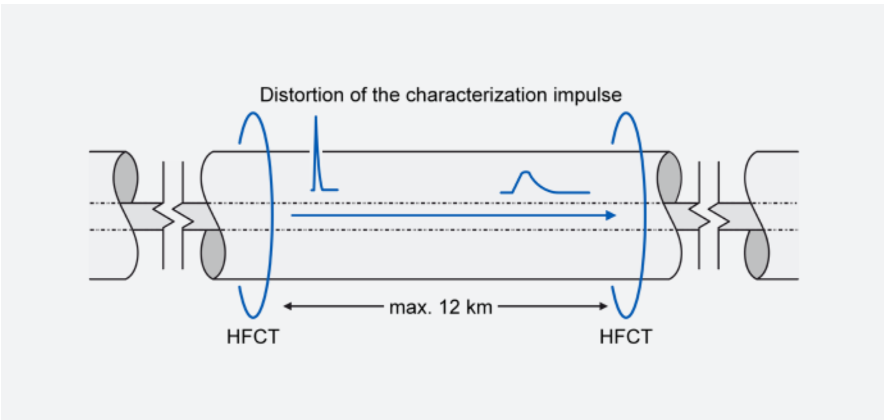

Figure 4: Principle of evaluating the transfer function of the test object

Anticipating customer requirements

One of the greatest challenges during the development process was the necessary shift in mindset. Traditionally, our focus has been on designing highly sophisticated and complex test systems that can meet today's demands and anticipate future requirements in a controlled laboratory environment.

However, the offshore solution was not driven by the features and functionalities of the test source itself but rather by the need to comply with the specific requirements of the various operational processes. These included onshore mobilization, transportation to and positioning on the offshore substation (OSS), installation and operation of the test circuit and managing interferences with other activities on the OSS.

The primary focus shifted to mobilization, demobilization and remobilization processes. We needed to address how quickly the test system could be mobilized, what demobilization activities would be required including cleaning, performance checks and replacement of consumable materials and how rapidly the system could be remobilized after a test campaign.

Transportation and handling also became critical considerations. It was essential to ensure a smooth transfer from road to marine transport at the harbor and to design a modular system that could be easily transported over open water. Given the wide variety of working conditions on offshore substations, we also had to ensure a flexible footprint for all components. Furthermore, efficient storage of all components and parts had to be planned to optimize both the setup and demobilization of the test system.

Solution delivered

The offshore RTS complies fully to IEC 63026 and CIGRE TB 841 [1, 2] and DNVGL E273 [3]. Figure 6 shows part of the system at the roof deck on duty on the OSS.

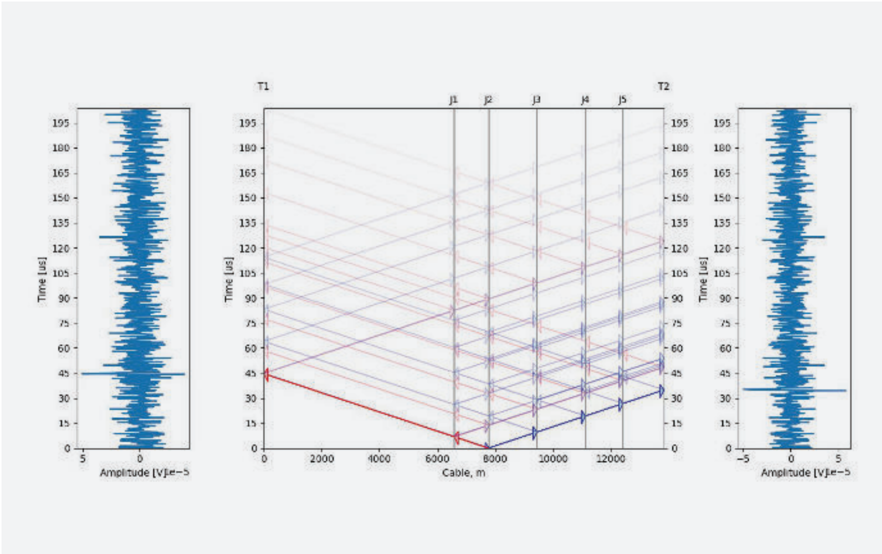

Figure 5: Wave propagation diagram

The technical parameters of this specific test system with two reactors can be found in the table below.

It has to be stated that a conventional setup can be extended up to four reactors in parallel, covering a load capacitance of 11.2 µF at maximum test voltage. Assuming a typical 66 kV array cable, testing a maximum string length up to 35 km becomes possible.

Operational experience

During the test campaign, the test system demonstrated very good performance. However, the specific agreed requirements and the actual operational conditions revealed certain areas for improvement. As this was understood by all stakeholders, HIGHVOLT offered to revise the test system following the conclusion of the campaign.

Parameter	Value	Unit	Remark
Rated Voltage	80	kV	
Rated Current	37.5	A	
Rated Power	5000	kVA	Equivalent Power @50 Hz
Weight	3.7	t	Max. weight per unit
Load capacitance per reactor	5.6	µF	@20 Hz

Key features for the success of the product

Touch-proof design of high voltage test source: The electrically isolated design of all components of the HV test source enabled parallel working of other processes beside electrical testing, high degree of operational freedom at minimal space requirements.

Weather independent operation of test system: As all power and control connections were made by offshore capable cable connections the complete system could be operated independent from the weather conditions. Offshore proven coatings on all metallic structures allow safe, permanent operation even during heavy rain, storms, and ice.

Modularity as an enabler of agility and flexibility: The modular design allows the installation and operation of the test system with a minimal mobilization of workforce. This means two qualified service technicians, including non-planned change requests.

Modularity for safe transportation over open water: Predefined transportation units comply with DNV-ST-E273 standards, making the handling of HV test equipment comparable to typical service equipment. Sticking to the weight limit of 3.7 t allows a hassle-free transportation over open water without additional approvals and paperwork.

Independent voltage measurement at the cable under test conditions: Integrating an additional voltage divider at the connection point enables a safe operation at the cable independent from the HV source at the roof deck.

Integrated partial discharge (PD) measurement: PD measurements are key for a qualitative evaluation of the cable. The system includes optional PD measurement directly at the connection to the cable under test (CUT). With specialized HFCT sensors, PD measurements at the far end of wind turbines are also possible.

For primary distribution cables rated at or above 36 kV, the relevant standards recommend resonant testing as the preferred method.

Figure 6: Setup of RTS at OSS

Conclusion

The successful development of the first offshore-capable RTS system for 66 kV inter-array cables was primarily driven by the long-term collaboration between all stakeholders, particularly the OSS operator, the test service provider and the test system manufacturer. From the outset, the requirements of the relevant standards served as a crucial foundation for the development. Another key factor was the deep understanding of the operational requirements for mobilizing the test equipment, conducting operations on the OSS and carrying out demobilization.

The test campaign itself was carried out jointly by the test service provider and the manufacturer. This cooperation allowed all technical assumptions to be verified under real field service conditions. The joint execution of the test campaign proved vital for both parties, helping to build a stronger appreciation for the importance of seemingly minor technical details. These insights led to a number of optimizations, all aimed at reducing handling complexity, increasing safety and improving both operational efficiency and technical capability.

The growing use of cables in primary distribution grids, along with their increasing role in ensuring grid reliability and availability, is driving new requirements such as onsite testing. For primary distribution cables rated at or above 36 kV, the relevant standards recommend resonant testing as the preferred method. In response, modular test systems have been developed and tailored to meet the specific needs of local markets, such as Southeast Asia and North America.

Partial discharge (PD) measurements are essential for providing detailed analysis of failure root causes and early indications of potential failures. As conventional PD measurement technologies struggle to fully monitor longer cables, TruePD offers an effective alternative.

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