ON-SITE TESTING OF 66 KV SUBSEA ARRAY CABLES FOR OFF-SHORE WINDFARMS

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ABSTRACT

Off-shore windfarms with extruded XLPE inter array cables with ratings up to 66 kV will be more and more common. IEC is anticipating the situation with a new standard IEC 63026 (under development) to guide manufacturers, test service providers and operators is under development. This paper discusses the kind of application of this standard and the practical implication in the field. A test system to cover the requirements is proposed and the test methodology analyzed and discussed in depth.

INTRODUCTION

Off-shore windfarms are moving towards higher generation power per wind turbine. To connect the wind turbines in the most efficient way, the voltage level of the connecting array cables is more and more moved to 66 kV, with reference to $U_m = 72.5$ kV. Regarding cable technology, it can be stated that extruded XLPE cables are state of the art and a cost-efficient solution. This allows the increase of the power capacitance, leading to an increase of the number of connected wind turbines and therefore the maximum length of the string. Utilizing 66 kV cables off-shore, the experience regarding failures and failure mechanisms during installation and operation is limited. To guide manufacturers, test service providers and operators, a new standard is under development: IEC 63026. As the standard is not published yet, there is no doubt that a dielectric on-site test for commissioning will be recommended.

For the practical application two different set of requirements can be defined: The installation of an individual wind turbine and its connection to the wind farm and the connection of a complete string of wind turbines to the collector platform for full operation. To ensure the quality of the cable system, it is important to apply a test voltage in such a way, that potential partial discharges (PD) and therefore potential failures can be detected safely.

In a first step the physical background how PD in a cable system can be initiated and measured will be discussed. Based on that background the different methods to generate a suitable test voltage to ensure the dielectric integrity of the cable as well as the sufficient amount of energy to initiate PDs in wrongly mounted cable joints and terminations are compared.

As a solution a resonant test circuit shows the preferred performance to detect PD in cables and cable accessories. The structure of such a test system is explained, especially the necessary adaptations for offshore applications for cable systems with rated voltages up to 66 kV. These adaptations are covering the test circuit as such and also the infrastructure for the transportation, installation and application of the resonant test system. The integration of the PD measurement is one of the key discussion points.

TESTING OF CABLES

Cable systems with U_r above 36 kV should be tested to evaluate their technical integrity and performance. Whereas the cable as such has passed the factory test, the cable systems includes joints and terminations. There assembly takes place on-site and deviations and failures cannot be excluded (Figure 1; [1]). For the typical length of array cables, joints will be not expected or only for a few special layouts. Nevertheless, terminations are mounted at each connection on the collector platform and at all wind turbines.

To test the integrity of terminations, the cable should be applied with a test voltage and partial discharges (PD) should be measured at each termination. To increase the probability to find the failures, the dielectric stress - based on electric field as well as shape and distribution of test voltages - should be as similar as possible to the operational stresses. A preferred solution to generate an applicable test voltage is a resonant test circuit.
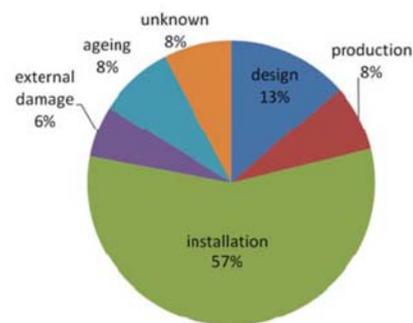

Figure 1: Statistic of failure cause of cable accessories [1]

Resonant Test Circuit

Resonant test systems use the resonance effect to generate a high AC test voltage [2]. The capacitance C of the test object (cable system) and the inductance L of a reactor (part of the test system) form an oscillating circuit. The reactive energy oscillates between these two elements and does not have to feed from the power source again in each period. While energy in a capacitor is stored in the electrical field between its electrodes, energy in an inductor is stored in its magnetic field. If an oscillating circuit is excited, energy swings between the two elements L and C.

For the generation of a constant AC voltage an additional feeding source has to deliver active power only to compensate the unavoidable losses inside the test circuit. The required feeding power is in a range of typically 0.5 … 3 % of the total test power, depending on the design of the resonant test system and the losses in the test object.

An oscillating circuit is mainly characterized by two parameters, its natural frequency f_0 (1) and the quality factor Q (2). At the natural frequency (1) the reactance of the capacitance C is equal to the reactance of the inductance L.

$$f_0 = \frac{1}{2\pi\sqrt{L \cdot C}} \qquad (1)$$

$$Q = \frac{S_{test}}{P} \qquad (2)$$

The quality factor Q describes the ratio between the apparent test power S_{test} and the active loss power P. The lower the losses, the higher the quality factor and the lower the required feeding power.

Resonance occurs if an oscillating circuit is excited at its natural frequency f_0. In that case the AC feeding source delivers pure active power which compensates exactly the circuit losses. By this a sinusoidal AC voltage with a constant amplitude is generated. The losses in test system and test object are considered by the resistor R in the equivalent diagram (Figure 2). Depending on the placement of this feeding source one may differentiate between series resonant circuits and parallel resonant circuits.
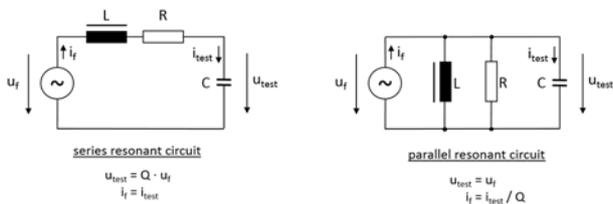

Figure 2: Voltages and current in series and parallel resonant circuit

In a series resonant test system, the quality factor describes also the ratio between test voltage and feeding voltage. Assuming a quality factor of 100, a feeding voltage of 0.6 kV only is required to generate a test voltage of 60 kV.

There are two technical solutions to achieve resonance: One can adjust the inductance of the HV reactor until the natural frequency f_0 becomes identical to the feeding frequency f_f (inductance-tuned resonant circuit: ACRL) or one can feed the circuit at its natural frequency (frequency-tuned resonant circuit: ACRF). [2]

All further discussions are based on ACRF (Figure 3). The reactor of an ACRF system has a fixed inductance. It contains typically an iron core with several gaps of a fixed width or a bar core. The use of multiple small gaps reduces the losses caused by the stray flux and the connected eddy currents in metallic parts including the copper windings. Due to the lower losses, the quality factor Q of a reactor

with a fixed inductance is significantly higher than that of an adjustable rector and is typically in the range of Q = 100 … 200 for the complete HV test circuit including a low loss cable load. This corresponds to losses respectively a necessary feeding power in a range of 0.5 … 1 % of the apparent test power.
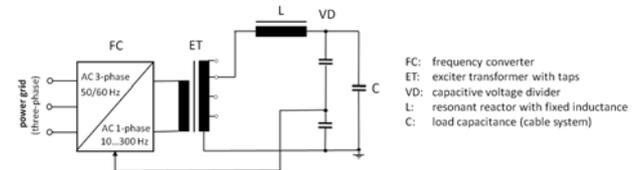

Figure 3: Schematic diagram of an ACRF test system

The natural frequency f_0 of the HV circuit decreases with an increasing load capacitance. To operate in resonance, the frequency of the feeding source has to be tuned to the natural frequency of the HV circuit. The range of the load capacitance is given by:

$$\frac{C_{max}}{C_{min}} = \left(\frac{f_{min}}{f_{max}}\right)^2 \qquad (3)$$

Assuming a frequency range of 10...300 Hz the load capacitance can vary in a range 900:1 for the same reactor without additional taps. If the capacitance of the test object is too small to operate in the allowed frequency range, an additional basic load capacitor may be applied. Especially for long cable systems the frequency dependence is an advantage. A lower test frequency reduces the apparent test power and the required feeding power.

As variable-frequency feeding source frequency converters are used. Depending on the control system, the tuning can be done automatically or manually. High power frequency converters deliver a single-phase output voltage in a frequency range typically 10...300 Hz.

For series resonant test systems, the wave shape of the feeding voltage has no influence to the wave shape of the test voltage, which is pure sinusoidal. This allows the application of frequency converters with both, rectangular or sinusoidal output voltage as feeding source in series resonant systems.

Converters with insulated gate bipolar transistors (IGBT) work in a switching mode at high efficiency and deliver a square-wave output voltage. The test voltage level is controlled by the duty or the amplitude of the output voltage.

In general, the switching of power transistors leads to noise pulses which effect additional PD measurements. In case of a square-wave output voltage only four high noise pulses are generated per period which may be effectively suppressed by a so-called gating of the PD measurement.

Cable Failure Mechanisms and Relevant Test Methods

Consistently various technical solutions with different voltage waveforms were developed over decades. Available are: ACRF at resonant frequency (10 Hz – 300 Hz), VLF (Very Low Frequency at 0.1 Hz), DAC (Damped Alternating Voltage) and DC (Direct Current) [3]. All these techniques are used quite successfully in testing and diagnosis of cables. Their operational conditions and test voltage properties (especially for HV cables) are defined in various standards, like IEC 60840 [4], IEC 61442 [5], IEC 62067 [6] and CIGRE recommendation No. 490 [2].

The 66 kV level falls in between the classic MV cables and the HV cables. Referring to typical design parameters like critical electrical field, geometries for accessories, the 66 kV off-shore array cables tend towards HV cables.

One has to keep in mind that applying test techniques on medium (MV) and high voltage (HV) cable systems might lead to different results, as average electrical field strength and radial distribution increases with rated voltage. This is also one major reason why test voltage of HV AC cables must have different test voltages when performing after laying tests: Up to 3 U_0 for VLF and 2 U_0 for AC (10 – 300 Hz) [4],[5].

It is important to state that the design and used materials of MV and HV cables are different. This has a strong influence on behaviour of defects and possible build-up of space charges in extruded cables. For AC cables the main difference is the average electric field strength. In MV cable it lies typically in the range of 3 … 5 kV/mm and in HV cables within 13 … 17 kV/mm, the 66 kV cables might be in-between. This emphasizes that PD behaviour like inception voltage and delay time to PD inception will depend significantly on defect type, defect position within the cable, applied test voltage, test frequency and test duration.

Before shipment extruded cables are routine tested in the factory. The cable will pass this test if no breakdown occurs and no PD activity up to a given level was detected. That means possible new defects produced within the cable or cable junctions and terminations due to assembly and external stress during transport and laying process, have "seen" no high voltage stress or electrical field and therefore have not experienced any PD activity. Depending on the defect, the delay time to start partial discharge activity after voltage application plays an additional important role, like for voids. This is verified in various publications [7], [8]. For voids with a diameter below about 1 mm, delay time will lay in the range of several minutes.

If a test voltage is applied on site, two factors to start a PD activity must be fulfilled: The local electrical field E_d must be above the critical field E_{crit} for this defect type and a so called "start electron" must be available during the time when $E_d > E_{crit}$. If a start electron is not available but $E_d > E_{crit}$ is fulfilled, the discharge will only start if an electron after a certain time period will be available. This leads

to the observed delay time, especially for a void or a delamination. The start electron might be produced by different sources: Cosmic rays, radioactivity of by field emission from metallic components, if the electric field is high enough.

Considering a defect like a void in the XLPE insulation of a 150 kV AC cable (Figure 4), the PD inception voltage U_{inc} of the void is 130 kV (1.3xU_0), which would be less than the proposed test voltage 1.7xU_0 (Figure 5). Igniting a PD in this void, the condition for the instantaneous applied test voltage U(t) is U(t) > U_{inc}. The number of times it happens, depends upon the nature of the test wave, voltage magnitude and its frequency. [9]
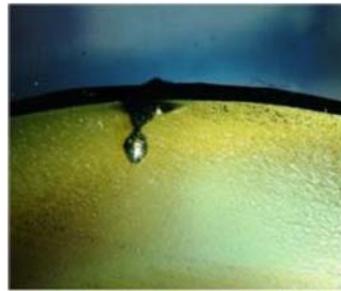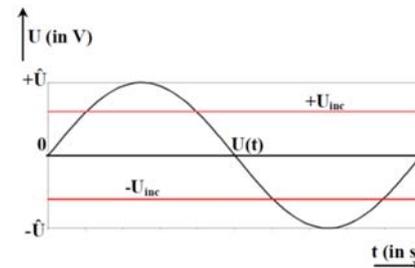

Figure 4: Example of void in a XLPE insulation

Figure 5: Illustration of PD inception voltage (U_{inc}) over applied test voltage

Integrating the applied test voltage exceeding the inception voltage over the testing time gives the voltage stress experienced by the defect in a definite period of time. This determines the probability to ignite the partial discharge in the void. The equation to calculate the area is given by (4).

$$\int_0^t \left(U_{AC}(t) - U_{inc} \right) \cdot dt \qquad (4)$$
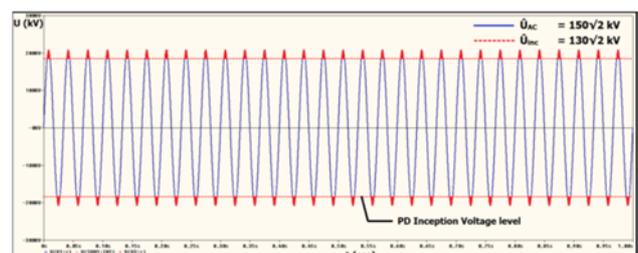

Figure 6: Voltage stress above PD inception voltage for ACR test at 30 Hz

Figure 6 explicitly shows the voltage stress experienced in the void over the inception voltage for AC. It can be finally stated, that for the evaluation of cable accessories the voltage form should be chosen such, that the field distribution inside the accessories are equivalent to the distribution during service. Therefore, a continuous full sinusoidal test voltage close to the operating frequency or higher is to be preferred to overcome the issue of PD inception delay and give therefore very high probability to identify critical failures in cable systems after laying and for diagnosis during lifetime.
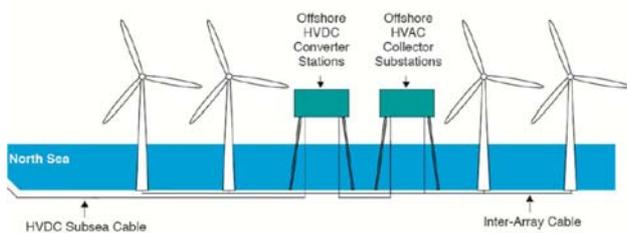
OFF-SHORE ON-SITE TEST SYSTEM

Figure 7: Schematic sketch of general layout of off-shore wind park [10]

The inter-array cables to connect wind turbines and the collector station. These cables are MV cables up to 66 kV. The inter-array cables form a complex radial MV-grid around the collector platform. To test these cables, a suitable test system must be available at the collector platform (Figure 8).

Figure 8: Converter platform in Trianel Wind Farm, Borkum. Photo: Trianel

The test system can be installed either at cable deck or the roof deck and needed to be connected to the substation deck. The distance between the location of the test system and the connection point to the test object can be as long as 80 … 100 m. The installation can be permanent or temporarily. The test system as such must be off-shore qualified, as the environmental conditions at the roof deck are clearly off-shore outdoor, this is also valid for an installation at the cable deck, as here wet and salty air cannot be excluded. Another limitation is given by the structure of the platform and the working and safety procedures. Moving of equipment will be limited by a maximum weight and size.

Referring to the ongoing technical discussions during the development of the future standard IEC 63026 three different kind of test procedures are anticipated for electrical tests after installation:

a) Test for 30 min with $U_0 / U_r = 1.0 … 1.4$, with a frequency between 10 Hz to 500 Hz shall be applied between the conductor and the metal screen/sheath
b) Test for 24 h with the rated voltage U_0 of the system
c) Test for 15 min with the RMS rated voltage value of $3 U_0$ at a frequency of 0.1 Hz applied between the conductor and the metal screen/sheath.

Based on the discussions above, a modular resonant test system was developed.

Resonant Test System (ACRF)

The schematic of the ACRF is shown in Figure 9, the protection impedance is needed to save the reactor in case of a breakdown in the test object.
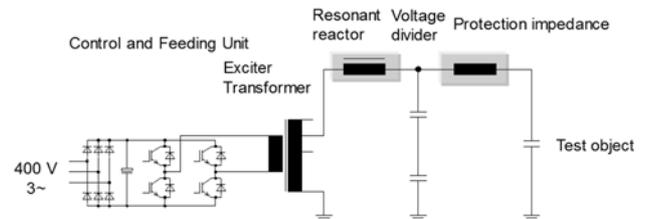

Figure 9: Schematics of test system

For practical reasons, the test frequency is recommended to be limited to 200 or 300 Hz. One of the reasons is, that in case of the utilization of accessories with a refractive field control, the losses will increase with frequency. For critical refractive designs, frequencies higher than 300 Hz might lead to a thermal stress of the refractive material what can lead to premature ageing or even to a thermo-electric breakdown.

Table 1: Overview of cable and test system parameters

Condition		Unit	Variants		
			A	B	C
Cable	Voltage Rating U_m	kV	>7.2 until 72.5		
	Capacitance	µF/km	0,25		
Test Requirements	Test Voltage	kV	80		
	Test Capacitance	µF	2.5	7	11
	Tested Cable Length	km	10 *	28 *	44 *
	Test Frequency	Hz	10 - 300		

** without anticipation of additional capacitances in test circiut

Regarding the test voltage, it is anticipated that for a rated voltage of 60 kV a test voltage of 62.3 kV should be applied for 30 min. As the rating and duration is always open to individual agreement between manufacturer and customer, the test system is designed for 80 kV test voltage and minimum test duration of 30 min (Table 1).
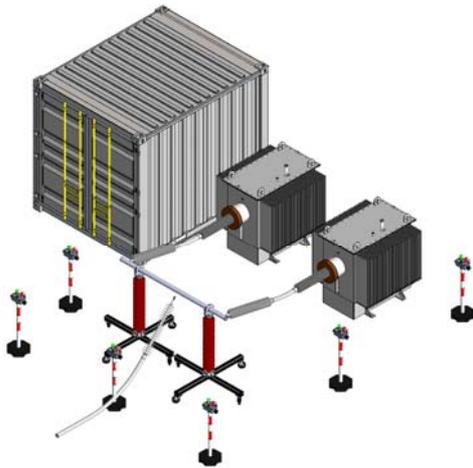
Figure 10: Layout of test source with feeding unit and exciter (container), reactors and collection point

Figure 10 shows the practical layout of the test source. Here the container hosts the power source and exciter transformer to feed and control the test circuit. Close to the source the reactors are positioned and connected in parallel. With a connecting cable the test source will be connected to the so-called connection point (Figure 11). Here the voltage divider is installed to control the test circuit. For correct PD measurement a blocking impedance and coupling capacitor should be installed here as well.
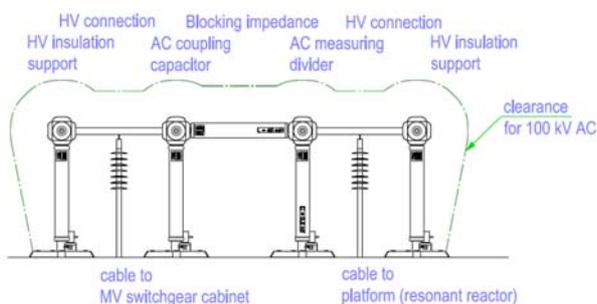

Figure 11: Connection point to test object including voltage divider, blocking impedance and coupling capacitor
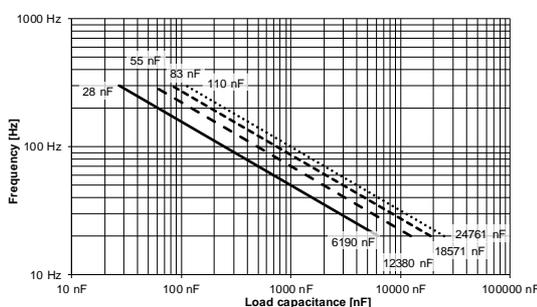

Figure 12: Load range for frequency over capacitance and different reactor designs

As the system design is modular, several reactors were designed to fit with requirements of maximum allowed loads and cable capacitances, which are varying between different projects. The load range for these reactors can be found in Figure 12.

CONCLUSION

Critical and complex infrastructure like off-shore wind parks should be undergone an intense on-site test program. For array cables up to 66 kV, it is crucial to qualify the cable system after laying to detect potential failure risks in the accessories like termination. Here a sensitive PD measurement is key. To generate a test situation comparable to the stresses in service, ACRF test sources are preferential. The newly developed ACRF test system covers all requirements in space, weight and especially performance to execute tests on cables with a maximum capacitance of 11 µF, a calculated cables length of 25 to 40 km dependent on the cable design. As the test system is modular for the feeding source as well as for the reactors, a high extensibility and flexibility can be achieved by paralleling the reactors as well as operating several feeding sources in Master-Slave-Mode to increase the feeding power if needed.

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