Accelerating the transition to 132 kV systems for offshore wind farms:

CARBON TRUST

132 kV array cable requirements and the need for improved testing standards

Summary report of Work Package 9 of the High Voltage Array Systems Project

March 2023

EnBW · equinor · OW Ocean Winds · Ørsted · RWE · ScottishPower Renewables · Shell · SSE Renewables · TotalEnergies · Vattenfall

INTRODUCTION

The Offshore Wind Accelerator

The Offshore Wind Accelerator (OWA) is the Carbon Trust's flagship collaborative research, development and demonstration programme. The joint initiative, which has been running since 2008, is a collaboration between the Carbon Trust and nine offshore wind developers. Its aim is to reduce the cost of offshore wind to be competitive with conventional energy generation, to accelerate the deployment of offshore wind globally, and to drive industry standards and best practice.

The High Voltage Array Systems project

The High Voltage Array Systems (Hi-VAS) project is a joint industry project set up within the OWA with the aim of developing industry-wide consensus on the optimal next array voltage level (above the current standard, 66 kV) and how the transition to the next voltage level can be best made. The project is driven and funded by ten international offshore wind farm developers: EnBW, Equinor, Ørsted, Ocean Winds, RWE, ScottishPower Renewables, Shell, SSE Renewables, TotalEnergies and Vattenfall. The project follows on from a previous study the OWA conducted in 2010 that reviewed the technical and economic benefits of increasing array cable voltages to greater than 33 kV, in response to an increase in Wind Turbine Generator (WTG) capacities. The 2010 study set 66 kV as the global standard array voltage, and this remains the standard today. In 2022, the Hi-VAS project identified 132 kV to be the next array operating voltage, and highlighted the urgency in making the transition.

Acknowledgments

This report provides an executive summary of Work Package 9 of the Hi-VAS project delivered by RINA. RINA worked closely with the Carbon Trust and the Hi-VAS project partners over the course of the Work Package. RINA also engaged numerous cable and cable material manufacturers. We will not list all those manufacturers who provided input for confidentiality purposes; however, we would like to thank all those who provided input.

Contents

Abbreviations

Al	Aluminium
Cu	Copper
DAS	Distributed acoustic sensing
DTS	Distributed temperature sensing
Hi-VAS	High voltage array system
OEM	Original equipment manufacturer
OWA	Offshore wind accelerator
OWF	Offshore wind farm
TP	Transition piece
TR-XLPE	Tree retardant crosslinked polyethylene
VLF	Very low frequency
WP	Work package
WTG	Wind turbine generator
XLPE	Crosslinked polyethylene

1. Introduction

As identified by the Offshore Wind Accelerator High Voltage Array System (Hi-VAS) project, the offshore wind industry will be moving to 132 kV array systems. Doing so will enable large wind turbine generators (WTGs) with power capacity greater than 14 MW to be connected in a cost effective manner

Although no showstoppers for the transition to 132 kV were identified, challenges still remain to transition from 66 kV to 132 kV.

132 kV array cable was identified as a critical area where further technical development and higher consensus across the industry are required. To mitigate the risks associated with the next-generation 132 kV array cable and to accelerate the transition to 132 kV, further engagement across the offshore wind farm (OWF) developers and the supply chain is essential.

Work package 9 (WP9) of the Hi-VAS project was devised to understand the 132 kV array cable requirements, build industry-wide consensus on these requirements, and to scope further work for the Hi-VAS project to address any remaining uncertainties regarding 132 kV array cable.

This report summarises the findings of WP9.

2. Methodology

RINA worked closely with the Carbon Trust to conduct an impartial investigation on the 132 kV array cable requirements across the cable supply chain and OWF developers through questionnaires, one-to-one discussions and meetings, and with the wider industry through a stakeholder workshop. Two questionnaires were designed to understand the 132 kV array cable requirements from the perspectives of OWF developers (10 stakeholders engaged) and the cable supply chain (11 stakeholders engaged) to identify the level of consensus and any differences in views that need to be addressed. One-to-one discussions were carried out with each stakeholder to further understand the details of these requirements. Two internal developer-only project meetings were held to provide the 10 developer project partners with updates on initial 132 kV array cable requirements and collect feedback. One external stakeholder workshop was held to present and discuss the initial version of 132 kV array cable requirements across the wider industry.

Representatives on the CIGRÉ Task Force working on the testing and qualification of wet cable designs with a rated voltage above 72.5 kV have been informed of the progress and outputs of WP9. A full CIGRÉ Working Group is expected to be set up in September 2023, to build upon the work of the Task Force.

This summary report presents 132 kV array cable requirements collated from the information gathered through comprehensive engagement with the industry. This report discusses technical design requirements, applicability of existing testing standards and new tests that need to be considered in future standards for 132 kV array cables, especially for wet designs and dynamic cables, as well as other requirements for cable installation, condition monitoring and maintenance. The report also sets out the further work the Hi-VAS project will conduct to close areas of uncertainty in 132 kV array cables.

3. Qualification standards for 132 kV array cable and gaps in the standards

3.1. Overview of existing testing standards relevant to 132 kV array cable qualification

One of the major concerns recognised by the industry is the lack of specific testing standards for qualifying 132 kV array cable including accessories. This is particularly the case for wet designs, which OWF developers have strong interest in being brought to market.

A comprehensive review has been conducted on the existing IEC testing standards and CIGRÉ recommendations that are relevant to 132 kV array cable qualification (Table A1.1). Generally, the routine, sample, pre-qualification, and post-installation tests recommended in IEC 60840, IEC 63026, CIGRÉ TB 490 and CIGRÉ TB 841 are universally applicable for all design types (dry-static, wet-static, dry-dynamic, wet-dynamic) of 132 kV array cable. However, type test variations exist between wet/dry designs and between static/dynamic installations of 132 kV array cable, and improvements are required.

It should be noted that IEC 63026 covers the testing of subsea cable with a rated voltage between 6 and 60 kV, and therefore, it should not be directly applied to 132 kV inter array cable. However, it can be used when combined with IEC 60840. CIGRÉ TB 722 is also only applicable to subsea cables with a rated voltage level of 6 to 60 kV and cannot be directly used for 132 kV array cable. Further investigations are needed to verify the applicability of the existing testing procedures and acceptance criteria presented in CIGRÉ TB 722 for use at the 132 kV voltage level.

3.2. Gaps in testing standards and proposed new tests for dry-static designs

Overall, the combination of IEC 60840, IEC 63026, CIGRÉ TB 490, CIGRÉ TB 623, CIGRÉ TB 722 and CIGRÉ TB 446 provides good guidance on 132 kV dry-static design qualification. Dry designs with laminated/welded metallic sheaths shall pass the water barrier qualification tests in CIGRÉ TB 722 and CIGRÉ TB 446 to meet the requirements. In some circumstances, static cable is also subjected to cyclical mechanical stresses (e.g., cable entering a monopile) and fatigue testing on such cable should be considered. Fatigue testing on metallic components described in CIGRÉ TB 862 for dynamic cables could be referred to when defining the fatigue test for static cable experiencing dynamic movements, depending on the environment and project requirements. This is not exclusive to 132 kV array cables and could also apply to array cables at other voltage levels such as 33 and 66 kV.

A number of shortcomings within the relevant combined standards have been identified. The following new tests or improved methods are proposed for an updated testing procedure for 132 kV dry-static designs:

- Long-term integrity of radial water barriers over the designed cable lifespan is not adequately addressed and extra fatigue tests should be included to demonstrate the reliability of the water barriers.

- Monitoring method, testing method and acceptance criteria on qualifying the continuity, integrity, and uniformity of welded/laminated metallic sheaths should be introduced.
- Metallic screen connection methods and testing methods after completing connection (also applies to wet designs) should be introduced as greater risks associated with higher circulating currents are expected for 132 kV array cable with large conductors. The report published by CIRED WG 2017-1 can serve as a reference at this stage.
- The effect of water pressure could compromise the cable's water barrier properties which should be considered during testing.
- Explicit guidance on when a successful qualification using aluminium conductor cables is applicable to copper conductor cables without further testing, should be provided (also applicable for wet and dynamic designs).
- The effects of changes in physical parameters on qualification testing are not considered.

3.3. Gaps in testing standards and proposed new tests for wet-static designs

IEC 63026, CIGRÉ TB 490 and CIGRÉ TB 722 could serve as the basis for testing and qualifying wet-static designs of 132 kV array cable. Accelerated wet ageing testing and residual dielectric strength testing are required in CIGRÉ TB 722 as a mandatory acceptance test for wet designs of submarine cable up to 60 kV. Over the years, several shortcomings have been identified in the existing testing procedures. In addition, the existing testing procedures only cover the design voltage level of 6 to 60 kV. To extend the testing procedures in CIGRÉ TB 722 to the 132 kV voltage level, the test requirements need to be thoroughly reviewed and evaluated.

The following suggestions have been proposed for an updated testing procedure for 132 kV wet-static designs:

- The expected lifespan of 20-25 years in CIGRÉ TB 722 needs to be reconsidered because of the extended lifespan for wind farm infrastructure from 25 to 40 years. The existing test result acceptance criteria may need to be revised to be able to project cable performance over a longer lifespan.
- Existing wet ageing test procedures do not fully reflect the operational conditions. The impact of water pressure, ion diffusion rate of saltwater, higher electrical stress, higher operational temperature and conductor corrosion effect over long-term operation shall be taken into consideration:
  - Buckling of the cable due to hyperbaric conditions in deep water during installation. Such environmental conditions should be considered during qualification test to assess its impact.
  - Ion diffusion rate in sea water is lower than in fresh water and the pre-conditioning procedures might need to be reconsidered to reflect this difference.
  - Higher electrical stress and operational temperature might affect water tree initiation and growth rate.
- Testing method on anticorrosion properties of metal conductors especially Al alloy should be considered and developed.

- One stakeholder suggested that switching is more common for array cables due to the wind profile, and that the impact of switching transients needs to be assessed, especially for wet designs. However, it is noted that not all stakeholders considered the impact of switching to be more common for array cables.
- Diffusion characteristics of polymer sheathing should be measured because ageing of the wet insulation can be delayed with the appropriate design of sheath.
- Higher consistency is required for the assumptions made by cable OEMs to interpret Weibull results and generate more consistent projections on safe working stresses.

3.4. Gaps in testing standards and proposed new tests for dynamic designs

Dynamic cables require extra testing to evaluate the impact of constant flexing and fatigue on their long-term reliability. CIGRÉ TB 623, CIGRÉ TB 722 and CIGRÉ TB 862 provide good testing guidelines for dynamic cable qualification and the tests listed in these documents should be applicable to 132 kV dynamic array cable. A comprehensive fatigue and mechanical testing plan, in line with a project's technical requirements, is needed. The fatigue testing would need to be informed by the outputs of the global analysis package.

Based on these CIGRÉ recommendations, the following additional tests are proposed for dynamic cables. Note that these suggestions may be generally applicable to submarine dynamic array cables and not specifically to the 132 kV voltage level.

- Electrical testing should be performed after fatigue testing to prove that the impact of mechanical stress on dielectric performance is limited and validate that the retained insulation properties are sufficient for the design type.
- Fatigue tests should be performed, and S-N curves should be generated for the insulation as well as the metallic components listed in CIGRÉ TB 862.

4. Summary of 132 kV array cable requirements, consensus level, and gaps

A key aim of this work was to build industry consensus on the functional requirements for 132 kV array cables. Overall, a relatively high level of consensus on 132 kV array cable requirements has been built across the OWF developers and supply chain. Generally, long-term technical performance reliability is the priority when OWF developers make decisions on the design type of 132 kV array cable. Similar principles also apply to the selections of insulation, conductor and sheath materials when there are several available options. The decision will be made based on specific project requirements and site conditions, provided the design is fully qualified according to relevant standards. Apart from the design and qualification requirements, requirements on installation, post-installation testing, condition monitoring, maintenance and repair were also discussed with the industry. The main findings are presented in Table 3.1.

Table 3.1: Summary of 132 kV array cable requirements

132 kV array cable requirements		Consensus level across industry	Further investigations and improvement required
Technical design and performance			
Design type	Qualified dry-static, wet-static, dry-dynamic, wet-dynamic with reliable performance over its designed lifespan. Anticipated commercialisation timescale (i.e., available to order) from cable supply chain: Dry-static (lead free): 0-3 years Wet-static: 2-5 years Dry-dynamic (lead free): 0-3 years Wet-dynamic: 2-5 years Cable accessories: 1-2 years	High	
Wet insulation material	Qualified materials such as TR-XLPE, super clean XLPE, XLPE, etc.	High	
Conductor material	Qualified Cu/Al alloy for both static and dynamic cable.	High	More research and development work on Al alloy with improved mechanical and anticorrosion properties are required.
Sheath material for dry designs	Mainly Cu/Al alloy (some stakeholders indicate that lead will continue to be used in some circumstances at least during the initial transition period, e.g., before alternative metallic sheaths are available for dry designs and before 132 kV wet designs are qualified).	High	Further optimisation on Cu/Al alloy sheaths: • Anticorrosion properties; • Improve continuous production length and reduce the number of cable joints; • Improve testing method for qualifying continuity, uniformity, integrity of welded/laminated metallic sheath (CIGRÉ TB 446 and TB 722).
Use of lead sheath	Likely to reduce in the long-term.	High	
Expected life span	Dry-static: > 35 years	High	
	Wet-static: scattered results ranging from 20 to 35 years as well as longer than 35 years associated with wet insulation performance. 25-30 years was the common life expectancy voted for by both OWF developers and supply chain.	Medium	
	Dry-dynamic: > 35 years	High	
	Wet-dynamic: longer desired lifespan (>30 years) by developers compared to the proposed achievable lifespan by most of the cable OEMs (20-30 years).	Low	Combined effects of fatigue, corrosion, and water tree needs to be considered.

132 kV array cable requirements		Consensus level across industry	Further investigations and improvement required
Testing standards			
Dry-static design	IEC 60840, IEC 63026, CIGRÉ TB 490, CIGRÉ TB 623, CIGRÉ TB 446, CIGRÉ TB 722 provide good guidelines except for a few shortcomings.	High	As presented in 3.2.
Wet-static design	IEC 63026, CIGRÉ TB 490, and CIGRÉ TB 722 serve as a basis but significant works and improvements are required to extend to 132 kV array cable.	High	As presented in 3.3.
Dynamic cable	CIGRÉ TB 623, CIGRÉ TB 722 and CIGRÉ TB 862 serve as a basis and more tests should be considered.	High	As presented in 3.4.
Other requirements			
Installation	- WTG OEMs and TP OEMs shall be involved and informed about cable design changes so the new WTGs and TPs can be designed to accommodate these changes. - Installation approach and additional aids could be applied depending on project requirement and site conditions. - Better jointer qualification strategy and checking system need to be developed to ensure high quality termination jointing works.	High	A separate project within the Carbon Trust's Offshore Wind Accelerator programme, 'Quality and quantity of qualified termination specialists', will be seeking to improve the jointer qualification standard and number of jointer personnel in 2023.
Post-installation testing	- Power frequency resonance testing is considered as the primary testing method with VLF test and 24-hour soak test as alternative options. - Power frequency resonance testing is a proven method at 132 kV while VLF test is yet to be proven at 132 kV. - Post-installation test on termination needs to be developed.	Medium	Possibility and effectiveness of VLF testing at 132 kV needs confirmation. Different opinions across both OWF developers and cable OEMs needs resolution.
Condition monitoring	- DAS and DTS will be employed as basic technique. - Special consideration need to be given to termination monitoring. Techniques such as thermal imaging, screen circulating current measurement, partial discharge monitoring, and non-reversible temperature stickers could be employed.	Not applicable	Condition monitoring design for the dynamic installation environment requires development and testing to avoid fibre movement within the overall fibre package within the cable.
Maintenance and repair	- Visual inspection is recommended on an annual/biannual basis and cost is likely to be similar with 66 kV array cable. - Overall repair cost of 132 kV array cable is likely to increase slightly compared with 66 kV array cable.	High	
Fundamental research	More fundamental research works on cable materials (e.g., insulation, semi-conducting screen, Al alloys) are needed.	High	Top 3 voted research topics by the industry: • Combined effect of temperature variation, mechanical fatigue, electrical

132 kV array cable requirements		Consensus level across industry	Further investigations and improvement required
			stress, and water tree development on the insulating properties. • Maximum allowable operating electric field of wet designs. • Effect of mechanical fatigue on insulating properties for cable installed in dynamic environment.

5. Next Steps – Hi-VAS Phase 2

In 2023, the Hi-VAS project will move onto its next Phase (Phase 2). The fundamental aim of Phase 2 will be to continue to accelerate and de-risk the transition from 66 kV to 132 kV array systems.

As context for Phase 2, to date the Hi-VAS project has found:

- From an OWF developer perspective, the development of 132 kV cables is the key to unlocking the transition to 132 kV.
- Generally, there is suitable industry experience and standards for dry 132 kV array cables.
- However, OWF developers have a strong desire to see 132 kV wet cables brought to market.
- The appropriate qualification tests for 132 kV wet cables are unknown, due to lack of formal standards covering this, lack of experience and lack of industry consensus (see section 3.3).

Phase 2 will therefore focus on building understanding and industry consensus on the qualification tests for 132 kV wet array cables. This is the key to enable OWF developers to safely procure 132 kV wet cables, and to provide the supply chain clarity on what requirements their future cable products must meet.

Phase 2 will achieve this by continuing with the large, developer-led consortium. One or more testing houses and cable suppliers will be procured via tender. The testing house(s) and cable supplier(s) will be tasked with conducting a series of experiments that will help to determine suitable testing procedures.

Phase 2 will also include a large supply chain-wide advisory panel who will follow and review the work as it progresses, and to whom the results will be disseminated. The intention will be to make results available to representatives of standards bodies to enable development of optimal future formal standards.

More information will be published on this in the coming months. However, if you are interested (as an OWF developer or member of the supply chain) to participate in the project, please contact the Carbon Trust (Robert.keast@carbontrust.com and Bethany.white@carbontrust.com).

APPENDIX

Appendix 1: Testing standards relevant to 132 kV array cable

Table A1.1: Overview of main existing testing standards relevant to 132 kV array cable

<table>
<tr><th colspan="2" rowspan="2">Test</th><th rowspan="2">Test object</th><th colspan="4">Standards</th></tr>
<tr><th>Dry-static</th><th>Dry-dynamic</th><th>Wet-static</th><th>Wet-dynamic</th></tr>
<tr><td colspan="2">Routine test</td><td>- Cable with manufactured lengths
- Cable with delivery lengths
- Factory joint,
- Repair join
- Termination</td><td colspan="4">IEC 60840, IEC 63026*, CIGRÉ TB 490</td></tr>
<tr><td colspan="2">Sample test</td><td>- Cable cores
- Complete cable
- Factory joint (if not type tested)</td><td colspan="4">IEC 60840, IEC 63026*, CIGRÉ TB 490</td></tr>
<tr><td rowspan="9">Type test</td><td>Mechanical test</td><td>- Complete cable system</td><td colspan="4">IEC 63026*, CIGRÉ TB 490, CIGRÉ TB 623, CIGRÉ TB 862</td></tr>
<tr><td>Electrical test</td><td>- Complete cable system</td><td colspan="4">IEC 60840, IEC 63026*, CIGRÉ TB 490, CIGRÉ TB 446</td></tr>
<tr><td>Longitudinal /radial water penetration (LWP, RWP) test</td><td>- Complete cable system</td><td colspan="4">IEC 63026*, CIGRÉ TB 490</td></tr>
<tr><td>Non-electrical tests</td><td>- Cable components
- Complete cable</td><td colspan="4">IEC 60840, IEC 63026*, CIGRÉ TB 490, CIGRÉ TB 623</td></tr>
<tr><td>Qualification of water barrier</td><td>- Cable and accessory</td><td colspan="2">CIGRÉ TB 722*, CIGRÉ TB 446</td><td colspan="2">Not applicable</td></tr>
<tr><td>Qualification of wet dielectrics</td><td>- Cable</td><td colspan="2">Not applicable</td><td colspan="2">CIGRÉ TB 722*</td></tr>
<tr><td>Characterisation test of dynamic cable (for information only)</td><td>- Cable</td><td>Not applicable</td><td>CIGRÉ TB 862</td><td>Not applicable</td><td>CIGRÉ TB 862</td></tr>
<tr><td>Component test of dynamic cable</td><td>- Cable components</td><td>Not applicable</td><td>CIGRÉ TB 862</td><td>Not applicable</td><td>CIGRÉ TB 862</td></tr>
</table>

Test		Test object	Standards			
			Dry-static	Dry-dynamic	Wet-static	Wet-dynamic
	Other tests	- Complete cable system	Not applicable	CIGRÉ TB 862	Not applicable	CIGRÉ TB 862
Pre-qualification test		- Complete cable system	IEC 60840, CIGRÉ TB 490			
Post installation electrical test		- Complete cable system	IEC 60840, IEC 63026*, CIGRÉ TB 490, CIGRÉ TB 841			

* Note: IEC 63026 and CIGRÉ TB 722 only cover the testing of subsea cable with a rated voltage between 6 and 60 kV.

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Published in the UK: 2023