

FLOATING OFFSHORE WIND  
CENTRE OF EXCELLENCE

Delivered by  
**CATAPULT**  
Offshore Renewable Energy

FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

# DYNAMIC CABLE TECHNOLOGY QUALIFICATION FRAMEWORK AND CASE STUDIES



Photo courtesy of Principle  
Power. Artist: DOCK90

Author: 2H Offshore  
(edited by ORE Catapult)

Date: 29/09/2022

Reference:PN000486-RPT-013

Status: Public

In partnership with:

**2H**  
offshore

## DISCLAIMER

---

Whilst the information contained in this report has been prepared and collated in good faith, ORE Catapult makes no representation or warranty (express or implied) as to the accuracy or completeness of the information contained herein nor shall we be liable for any loss or damage resultant from reliance on same.

## DOCUMENT HISTORY

---

Revision	Date	Prepared by	Checked by	Approved by	Revision History
Rev 1	29/09/2022	L Ferreira (2H, lead author) & W Brindley (OREC, editor)	B Jenkins & C Twaddle	M Hamilton	Issued as final

## PREFACE

---

Floating offshore wind (FOW) technology is developing rapidly. Offshore wind is expected to be a major contributor to the UK's clean energy mix as we move towards net zero emissions. The North Sea region is set to become the world's first floating offshore wind market of scale, propelling the UK's net zero ambitions by 2050. The first round of ScotWind lease awards is for up to 28GW of offshore wind capacity from 20 sites around the coast of Scotland. Commercial-scale floating wind projects are set to make up 65% of this total [5][6].

A significant part of the technology proposed for deployment in floating offshore wind projects is not novel. It is adapted or has evolved from other applications, mostly fixed bottom wind and the oil and gas industry. Whilst the principles of these technologies remain the same, the specification, operating conditions, scale and volume for deployment in floating offshore wind may differ.

Dynamic cabling and its ancillary equipment are already an area of deep knowledge and strength for the UK supply chain. This ORE Catapult project, Floating Offshore Wind Dynamic Cabling Systems – Technology Development and Qualification Programme, aims to stimulate the development and validation of relevant technologies, and to grow the capacity to deliver cabling systems for large scale floating offshore wind cost-effectively.

This project itself is split into three (3) separate phases:

- **Phase 1** focuses on the development of a dynamic cable system technology qualification framework, based on the assessment of technology risk and failure modes specific to its application in floating offshore wind.
- **Phase 2** of the project seeks to support the development and qualification of relevant technologies using the framework developed in phase 1. Both by providing direct support for such activities in the FOW Centre of Excellence (CoE) programme, and by coordinating support in other programmes.
- **Phase 3** is a parallel programme of enabling research to fill knowledge gaps required to qualify technology.

Phases 2 and 3 are being carried out by ORE Catapult from mid 2022 onwards. Phase 1 is the scope of this report. This document has been developed to fulfil the following objectives:

- Development of a framework for qualification of FOW dynamic cable components and systems, setting out clear stages of development, methods of assessing the stage of development of a technology, and methods of progressing through the stages;
- Technology qualification mapping case studies;
  - Selection of 2 FOW dynamic cable components to be used as case studies: a 66kV AC dynamic power cable, and a bend stiffener connector have been selected.
  - Use of technology qualification framework to develop a technology qualification plan for each case study component, including addressing any identified technology qualification gaps

The above work has been supported by a FMECA study covering the major dynamic cable reliability concerns, and a study mapping the existing qualification codes and standards.

# CONTENTS

---

- 1 SUMMARY ..... 11**
  - 1.1 Recommendations ..... 13
- 2 INTRODUCTION ..... 17**
- 3 CASE STUDY SELECTION OVERVIEW ..... 20**
  - 3.1 Power Cable ..... 20
  - 3.2 Bend Stiffener Connector (Latching Mechanism) ..... 21
- 4 PROPOSED QUALIFICATION FRAMEWORK ..... 22**
- 5 APPLICATION TO POWER CABLE CASE STUDY ..... 26**
  - 5.1 Qualification Basis ..... 26
  - 5.2 Technology Assessment ..... 30
  - 5.3 Threat Assessment ..... 35
  - 5.4 Qualification Plan ..... 37
  - 5.5 Qualification Plan - Feasibility Stage (TRL 2) ..... 39
  - 5.6 Qualification Plan - Concept Validation (TRL 4) ..... 41
  - 5.7 Qualification Plan - Prototype Validation (TRL 6) ..... 45
  - 5.8 Qualification Plan - System Integration (TRL 8) ..... 54
  - 5.9 Qualification Plan - Operational (TRL 9) ..... 57
  - 5.10 Execution of the Plan ..... 59
  - 5.11 Performance Assessment ..... 59
  - 5.12 Discussion ..... 60
- 6 APPLICATION TO BEND STIFFENER CONNECTOR CASE STUDY ..... 63**
  - 6.1 Qualification Basis ..... 63
  - 6.2 Technology Assessment ..... 66
  - 6.3 Threat Assessment ..... 70
  - 6.4 Qualification Plan ..... 71
  - 6.5 Qualification Plan - Feasibility Stage (TRL 2) ..... 72
  - 6.6 Qualification Plan - Concept Validation (TRL 4) ..... 72

- 6.7 Qualification Plan - Prototype Validation (TRL 6)..... 74
- 6.8 Qualification Plan - System Integration (TRL 8) ..... 77
- 6.9 Qualification Plan - Operational (TRL 9)..... 79
- 6.10 Execution of the Plan ..... 80
- 6.11 Performance Assessment..... 80
- 6.12 Discussion..... 80
- 7 REFERENCES.....82**
- Appendix 1 QUALIFICATION FRAMEWORK DETAILS.....85**
- A1.1 Qualification Basis ..... 85
- A1.2 Technology Assessment ..... 85
- A1.3 Threat Assessment ..... 89
- A1.4 Technology Qualification Plan..... 89
- A1.5 Execution of the Plan..... 92
- A1.6 Performance Assessment..... 92
- Appendix 2 TRL STAGE DETERMINATION QUESTIONNAIRE .....93**
- A2.1 Feasibility Stage (TRL 2) Questionnaire ..... 93
- A2.2 Concept Verification Stage (TRL 4) Questionnaire ..... 94
- A2.3 Prototype Validation Stage (TRL 6) Questionnaire..... 95
- A2.4 System Integration Stage (TRL 8) Questionnaire ..... 96
- A2.5 Operational Stage (TRL 9) Questionnaire..... 97
- Appendix 3 GLOBAL AND LOCAL ANALYSIS GUIDANCE .....98**
- A3.1 Feasibility Stage (TRL 2)..... 98
- A3.2 Concept Validation (TRL 4) ..... 100
- A3.3 Prototype Validation (TRL 6) ..... 103
- A3.4 System Integration (TRL 8) ..... 103
- A3.5 Operational Stage (TRL 9)..... 104
- Appendix 4 CHARACTERISATION TYPE TESTS.....105**
- A4.1 Bending Stiffness Test ..... 105

A4.2 Tensile Characterisation Test ..... 105

A4.3 Friction Coefficient Test ..... 105

**Appendix 5 MECHANICAL TYPE TESTS .....106**

A5.1 Coiling testing..... 106

A5.2 Tensile Bending Test..... 106

A5.3 Tensile Test..... 107

A5.4 Combined Axial Compression and Bending Test & Axial Compression Test..... 108

**Appendix 6 ELECTRICAL TYPE TESTS .....109**

A6.1 Partial Discharge (PD) Test ..... 109

A6.2 Tan  $\delta$  Measurement Test..... 109

A6.3 Heating cycle voltage test ..... 109

A6.4 Lightning Impulse Voltage Test Followed by a Power Frequency Voltage Test..... 110

**Appendix 7 PROJECT SPECIFIC TESTS .....112**

A7.1 Bending Test Without Tension ..... 112

A7.2 Crush Test..... 112

A7.3 Crush Test for Long Term Stacking..... 112

A7.4 Sidewall Force Test..... 112

A7.5 Impact Test..... 112

A7.6 Pulling Stocking Test..... 112

A7.7 Cable soil Interaction Test ..... 112

A7.8 Marine Growth Measurement ..... 113

**Appendix 8 OTHER TESTS FROM CIGRE TB 862 .....114**

A8.1 Clamp Squeeze Test ..... 114

A8.2 Clamp Slippage Test ..... 114

**Appendix 9 CABLE CHARACTERISTICS FOR PROTOTYPE TESTS.....115**

**LIST OF FIGURES**

Figure 1 – Schematic Representation of Power cable in Lazy Wave Configuration..... 18

Figure 2 – 66kv Dynamic Cable (Image 1, ORE Catapult render) ..... 20

Figure 3 – Bend Stiffener Connector (Image Sources from left to right: First Subsea, Balltec [20], and S3N Ventus) ..... 21

Figure 4 – Steps in the Qualification Process ..... 25

Figure 5 – Generic 66kV Dynamic Power Cable Cross-Section [39] ..... 28

Figure 6 - 3 Core Inter-Array Power Cable for Floating Offshore Wind System Hierarchy ..... 31

Figure 7 – Risk Matrix for the FMECA [2] ..... 37

Figure 8 – Steps in the Qualification Process for the Power Cable Case Study..... 39

Figure 9 – Example of global analysis (left, using OrcaFlex) and local analysis (right, using UFLEX) for an example dynamic cable ..... 40

Figure 10 – Flow Chart of the Test Sequence of Mechanical and Electrical Tests on Dynamic Cable (Modified from [39]) ..... 48

Figure 11 - Fatigue Testing Rig at OREC Facility ..... 54

Figure 12 - Analysis Refinement Example ..... 57

Figure 13 – Case Study versus Framework Relationship..... 60

Figure 14 – Bend Stiffener Connector for Floating Offshore Wind System Hierarchy..... 67

Figure 15 – Steps in the Qualification Process for the BS Connector Case Study ..... 72

Figure 16 – Prototype Validation Tests ..... 74

Figure 17 – New Technology System Hierarchy from ABS [24]..... 86

Figure 18 – Qualification Plan & TRL ..... 91

Figure 19 - Analysis Workflow for Feasibility Stage of Dynamic Power Cable Applications ..... 98

Figure 20 – Power Cable Example Configurations ..... 99

Figure 21 - Analysis Workflow for Concept Validation of Dynamic Power Cable Applications..... 101

Figure 22 – Workflow for Characterisation Tests and Analysis..... 103

Figure 23 - Example of coiling test arrangement [48]..... 106

Figure 24 - Example of Cable Laying Vessel [17] ..... 107

Figure 25 - Schematic Representation of Bending Test Over Sheave [40]..... 107

Figure 26 – Schematic of a Standard Impulse Voltage Shape [13]..... 110

# LIST OF TABLES

Table 1 – Summary of Tasks per Stage of the Qualification Plan for the Power Cable Case Study ..... 12

Table 2 – Summary of Tasks per Stage of the Qualification Plan for the BS Connector Qualification.. 13

Table 3 – Components of the Power Cable System and Ancillaries..... 18

Table 4 – TRL Levels used in the case studies from ORE Catapult [19] ..... 24

Table 5 – Summary of Tasks per Stage of the Qualification Plan ..... 24

Table 6 – Main Codes and Standards Identified for Qualification of Inter Array Dynamic Power Cables [7] ..... 29

Table 7 – Components of the Cross Section of the Power Cable ..... 31

Table 8 – Technology Characterisation according with DNV [43] ..... 32

Table 9 – Systematic Screening Table for Inter Array Dynamic Power Cables..... 34

Table 10 – Power Cable System Threat Assessment Summary [2] ..... 36

Table 11 – Summary of Tasks per Stage of the Qualification Plan for the Power Cable Qualification . 38

Table 12 - Recommendations for when design changes can be verified through Individual Component Fatigue Test [39]..... 43

Table 13 – Qualification of Wet Dielectrics from CIGRE TB 722 ..... 44

Table 14 – Dynamic Power Cable Qualification – Characterisation Tests..... 46

Table 15 – Dynamic Power Cable Qualification – Mechanical Type Tests ..... 47

Table 16 – Dynamic Power Cable Qualification – Electrical Type Tests ..... 49

Table 17 – Dynamic Power Cable Qualification – Non-Electrical Type Tests on Cable Components and on Complete Cable ..... 50

Table 18 – Dynamic Power Cable Qualification – Longitudinal/ Radial Water Penetration Tests..... 51

Table 19 – Fatigue Tests ..... 52

Table 20 – Post Fatigue Test [48] ..... 52

Table 21 – Modification where Full-Scale Fatigue Test is recommended [39] ..... 53

Table 22 – Dynamic Power Cable Qualification – Project Specific and Special Tests ..... 56

Table 23 – Other Applicable Test from CIGRE TB 862 [39] ..... 56

Table 24 – Project Stages ..... 61

Table 25 – Main Codes and Standards Identified for Qualification of Bend Stiffener Connectors..... 65

Table 26 – Components of the Bend Stiffener Connector of the Case Study ..... 67

Table 27 – Systematic Screening Table for Bend Stiffener Connector..... 69

Table 28 – BS Connector Threat Assessment Summary [2] ..... 70

Table 29 – Summary of Tasks per Stage of the Qualification Plan for the BS Connector Qualification 71

Table 30 Bend Stiffener Connector Qualification – Project Specific Tests..... 78

Table 31 – Technology Characterisation according with DNV [43]..... 87

Table 32 – TRL Levels from ORE Catapult [19] ..... 88

Table 33 – Summary of Tasks per Stage of the Qualification Plan..... 91

Table 34 – Feasibility Stage (TRL 2) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector ..... 93

Table 35 – Concept Verification Stage (TRL 4) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector ..... 94

Table 36 – Prototype Validation Stage (TRL 6) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector ..... 95

Table 37 – System Integration Stage (TRL 8) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector ..... 96

Table 38 – Operational Stage (TRL 9) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector..... 97

## NOMENCLATURE

---

AC Alternating Current

---

Al Aluminium

---

ASTM American Society for Testing and Materials

---

BS Bend stiffener

---

CoE Centre of Excellence

---

CIGRE International Council on Large Electric Systems

---

Cu Copper

---

DLC Design Load Case

---

EHV Extra High Voltage

---

eN eN curves describe the relation between total strain and the number of cycles

---

FAT Factory Acceptance Testing

---

FEA Finite Element Analysis

---

FMEA Failure Modes and Effects Analysis

---

FMECA Failure Mode, Effects & Criticality Analysis

---

FOW Floating Offshore Wind

---

GW Giga Watt

---

IEC International Electrotechnical Commission

---

IMP Integrity Management Plan

---

ISO International Organization for Standardization

---

kW Kilo Watt

---

MBR Minimum Bend Radius

---

OBR	Operating Bend Radius
ORE	Offshore Renewable Energy
OTDR	Optical Time Domain Reflectometer
PD	Partial Discharge
QP	Qualification Plan
RAM	Reliability, Availability and Maintainability
RAO	Response Amplitude Operator
ROV	Remotely Operated Vehicle
SN	S-N curve relates stress (S) to number of cycles to failure (N)
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level

# 1 SUMMARY

---

This document details the output from Offshore Renewable Energy (ORE) Catapult's Floating Offshore Wind Dynamic Cabling Systems – Technology Development and Qualification Programme [1]. The aim of this document is to set out a process tailored to the qualification of dynamic cable system components, with practical examples, that can be used to plan and document the path from early feasibility to a well proven operational system.

The first part of this report proposes a qualification framework for dynamic power cable and ancillary equipment for floating offshore wind (FOW) applications. The framework is summarised at a high level in Section 4, with further details provided in Appendix 1. The qualification approach is based mainly on DNV "Technology Qualification", DNV-RP-A203, [43], and ABS "Guidance Notes on Qualifying New Technologies", [24], as summarised in Figure 4. Although these two guidance documents are used as reference, other qualification framework codes (e.g. Lloyd's Register (LR), etc) could be adopted within the framework with small adjustments. The framework aims to set out clear stages of development, methods of assessing the stage of development of a technology, and methods of progressing through the stages of qualification and TRL levels for any power cable and ancillary equipment.

Dynamic cables are complex systems, with significant variation in the scope, scale, function and complexity of the different system components and technologies. Furthermore, each component has different applicable standards and industry good practice. As such we have presented two case studies (Sections 5 and 6) as the focus of the report to describe how the more detailed elements of the qualification framework works in practice:

- 66kV AC dynamic power cable for typical UK - North Sea conditions
- Bend stiffener connector for typical UK - North Sea conditions.

For the power cable case study, a 3 core 66kV power cable in a lazy wave configuration is assumed. The case study represents a typical qualification program for a generic cross-section at TRL 1-2 (analytic proof of concept stage). No analysis is carried out or specific acceptance criteria are provided. Rather a workflow is discussed on how the power cable qualification progresses from lower TRL levels up to operationally qualified (TRL 9). The summary of the activities for each stage of qualification for the power cable is given in Table 1.

The case study of the power cable demonstrated how the proposed framework, which is quite generic, can be applied with specifics for the power cable when the activities for qualification are assigned to each stage of the process. It is found that TRL levels can be subjective, therefore the importance of having clear criteria and documented evidence to support the fulfilment of those criteria is needed. As a consequence, to progress across the qualification levels it is necessary to demonstrate the criteria are fulfilled at all previous TRL stages. It is also found that there remain gaps in the qualification standards, for example around the integration of thermal-electrical analysis and axial compression testing. Further to support the schedule of the process, some testing, for example the test for Wet Designs [38], could be started at an earlier TRL level.

The case study for the bend stiffener connector demonstrated the connector without the latching mechanism for multiple cycles is already at TRL 6 for floating wind applications, since the connector size and loading are within what is currently considered fully qualified for oil and gas umbilical applications. However, considering the implementation of the latching mechanism for multiple latch and unlatch cycles, the bend stiffener connector of the case study is at design stage (TRL 4). Some suppliers from oil and gas have the capability of performing multiple latch/ unlatch cycles and so the

TRL level has to be assessed in a case-by-case basis. The case study also included the option to qualify "weak-links", which are used for accidental cable disconnection systems, intended to only be activated during accidental events. The summary of the activities for each stage of qualification for the bend stiffener connector is given in Table 2

Overall the case studies show that the qualification framework can be used to plan and document the path from early feasibility to a well proven and reliable system. The more generic qualification framework presented in Section 4 and Appendix 1 can be used as the basis for any dynamic cable system component. The framework can be adjusted and optimised to the particular situation, accounting for the variability that occurs in supplier experience, cross-section designs, and the design details of the component.

Table 1 – Summary of Tasks per Stage of the Qualification Plan for the Power Cable Case Study

Requirement	Feasibility (TRL 2) <sup>(4)</sup>	Concept Validation (TRL 4) <sup>(4)</sup>	Prototype Validation (TRL 6) <sup>(4)</sup>	System Integration Stage (TRL 8) <sup>(4)</sup>	Operational Stage (TRL 9) <sup>(4)</sup>
Global/ Local Structural Analysis	X	X	X	X	X
Thermal-Electrical Analysis	X	X	X	X	X
Component Tests		X			
Individual Component Fatigue Tests		X			
Tests for Wet Designs (CIGRE TB 722)		X			
Characterisation Tests			X		
Type Tests <sup>(1)</sup>			X		
Full-Scale Fatigue Test <sup>(2)</sup>			X		
Project Specific Tests				X	
Other Tests (CIGRE TB 862)				X	
Monitoring		X <sup>(3)</sup>		X	X
Commissioning Tests					X

1\ Includes mechanical type tests, electrical type tests, non-electrical type tests and longitudinal/ radial water penetration test.

2\ As per CIGRE TB 862 [39], fatigue test is a part of the type tests.

3\ Monitoring required to be integrated into the cross section (e.g. fibre optics) must be addressed at TRL 4.

4\ TRL 1, 3 and 5 are not shown but each TRL level shown means requirements from previous levels are fulfilled. For example, to reach TRL 6 the technology has to have fulfilled all requirements from TRL 6, TRL 5, TRL 4, TRL3, TRL 2 and TRL 1

Table 2 – Summary of Tasks per Stage of the Qualification Plan for the BS Connector Qualification

Requirement	Feasibility (TRL 2)	Concept Validation (TRL 4)	Prototype Validation (TRL 6)	System Integration Stage (TRL 8)	Operational Stage (TRL 9)
Local Structural Analysis	X	X	X	X	X
Material Tests		X			
Emergency Release Extended Material Test		X			
Emergency Release Small Scale <sup>(1)</sup> Test to Failure		X			
Latch/ Unlatch Test			X		
Full-Scale <sup>(2)</sup> Strength Test			X		
Full- Scale <sup>(2)</sup> Fatigue Test			X		
Emergency Release Full-Scale <sup>(2)</sup> Fatigue Test				X	
Project Specific Tests				X	
Monitoring		X <sup>(3)</sup>		X	X
Commissioning Tests					X
Notes:					
1\ Small Scale means non-complete assembly					
2\ Full-Scale means complete assembly					
3\ Monitoring integrated with the bend stiffener connector must be addressed at TRL 4.					

## 1.1 Recommendations

Some key recommendations for qualification of the power cable and bend stiffener connector for floating wind applications are:

### General

- In order to move through all TRL stages, it is recommended that the requirements of each preceding TRL level are demonstrated to have been met.
- Previous qualification experience within floating wind or other similar application areas should be considered to replace some re-testing activities with suitably validated engineering design tools.
- The order of the testing should be carefully considered to capture the interacting electrical, mechanical, thermal and electromagnetic effects. The order recommended by the test standards should be respected where specified. In some cases there are gaps in combined effect testing requirements in the standards; in which case additional testing should be considered.
- Until TRL 6 (Prototype Validation), it is recommended that the vendor should aim to qualify for a wide range of applications.

- In the Operational stage (TRL 9), before installing a comprehensive range of monitoring devices on the technology being qualified, it is recommended to have a clear plan of how often the measured data will be collected (if not online) and how each measurement will be used to add value to the project in terms of reliability and life extension.
- Regardless of the component being qualified for floating offshore wind (power cable or ancillaries), some qualification requirements are design outputs which can be variable (e.g. fatigue life, interface loads). When possible, it is easier to adjust and optimise the power cable configuration ensuring the system remains within the existing qualification than to modify the cable cross section requiring requalification.
- There are a large number of qualification tests required within the codes of varying complexity, duration and cost to qualify components. Where possible it is recommended that the most complex, long and costly qualification tests (e.g. full-scale fatigue test) should be minimised in number through careful planning and execution of the qualification programme. It is also recommended, through industry collaboration and code guidance development, that methods and tools to minimise the requirement for repeating full-scale qualification tests in the event of design changes are established. This could for example include increased acceptance of the use of validated engineering tools in the qualification process.
- In line with the above, it is recommended that code guidance be more specific about what does and does not meet the requirements of qualification evidence (e.g. test requirements, certification, operational experience details) in order to standardise the qualification basis.
- It is also recommended that the industry investigate and define more clearly how to widen the applicability of the qualification.

### Power Cable

- Although CIGRE TB 862[39] has been released to close a gap and discuss the importance of structural analysis of submarine cables for dynamic applications, no similar guidance is available to discuss thermal-electrical analysis of the power cable and should be developed by the industry.
- All handling of the cable and ancillaries (e.g. clamping, spooling, tensioner compression, strain, controlled and free bending, etc) could affect how the cable will behave globally and subsequently could possibly change the internal mechanical and electrical stresses within the cable. This is recommended to be an area for industry collaboration aiming to define what level of damage or deviation from nominal design is allowed whilst maintaining system qualification.
- The Tests for Wet Designs from CIGRE TB 722 [38] take at least 2 years to complete and, in addition to the requirements of standard IEC 63026 [48], are mandatory for cables classified as “wet”. This framework recommends they start at the Concept Validation (TRL 4) stage but suggests they can be finished at the Prototype Stage (TRL 6), when all other type tests from IEC are carried out.
- If a qualified power cable only has minor changes in an individual component of the cross section, it is recommended that where possible, the modifications are verified through component testing and the full-scale fatigue test does not have to be carried out in the Prototype Validation (TRL 6).
  - Guidance about what can be considered minor changes is given in CIGRE TB 862 [39] (Table 12 and Table 21) and it is recommended engineering analysis is used to justify.
- The mechanical type tests defined in IEC 63026 [48] do not include the Combined Axial Compression and Bending Test and the Axial Compression Test as mechanical type tests. However,

to address the high risk identified in the FMECA [2] these tests have been incorporated to the qualification plan as illustrated in Figure 10 and are recommended.

- The requirements for compression testing should be considered carefully. Static tests with short samples are readily achievable, however longer length dynamic testing is difficult to achieve, expensive and not well defined.
- The Longitudinal / Radial Water Penetration Test is a type of test defined in IEC 63026 [48]. However, a dynamic cable section, as for the case study, will generally not be subject to a field repair and will normally be removed and replaced in its entirety, potentially negating the need for these tests as given in CIGRE TB 862 [37]. It should be noted that if the water blocking design changes, the influence on the overall cable behaviour and validity of past tests needs to be assessed.
- Although not mentioned by CIGRE TB 862 [39], the floater offset is dependent on both power cable and mooring requirements. Therefore, it is recommended that as the power cable configuration enters the detailed design in the System Integration Stage (TRL 8) the analysis shall be more refined and consider a fully coupled analysis model, with mooring lines and power cable.
- It is recommended that tests are performed to understand the “Cable soil Interaction” (e.g. soil friction coefficients, trenching, characteristics and vertical stiffness) as part of qualification of dynamic floating wind power cables. Codes are available from oil and gas (DNV-RP-F114), but may not be directly applicable to dynamic inter array cables (e.g. new geotechnical conditions).
- No specific guidance is provided on marine growth in CIGRE TB 862 [39]. Code guidance from oil and gas is available, but may not be directly applicable to dynamic inter array cables (e.g. temperature influence, new areas). It is recommended that to support the qualification of dynamic power cables for floating wind a guidance on marine growth is developed.
- The design and limitations of the monitoring concepts based on the fibre optic within the cable are recommended to be investigated in advance of TRL 9 (i.e. accuracy and fibre unit redundancy). For relatively new concepts adapted to a floating wind farm, such as DSS, it is recommended to start investigations at the Concept Validation Stage (TRL 4).
- The monitoring devices installed externally to the cable can be proposed at the System Integration Stage (TRL 8).

### **Bend Stiffener Connector**

- Most technology is not novel and comes from the Oil and Gas sector and limited floating wind demonstration projects, however, it is recommended that this previous experience is utilised carefully based on the different application and requirements of this technology applied to floating wind.
- A bend stiffener connector without emergency release from a supplier with oil and gas experience is expected to be at TRL 4 for floating wind.
- The latching/unlatching mechanism is not new but the requirement for multiple cycles of latch/unlatch is typically increased for floating wind. It is recommended this is addressed through qualification of the component for the expected number of latch/unlatch cycles for floating wind applications and account for aging effects, marine growth and loading. To reach TRL 6 it is recommended that the qualification plan includes latch-unlatch tests.

- Full scale fatigue tests are recommended to reach TRL 6, but could be potentially avoided based on validated engineering tools.
- Wet storage of the system once unlatched can also be an issue due interaction with the environment, such as potential for marine growth and material ageing (corrosion, embrittlement, etc).
- A bend stiffener connector with emergency release from a supplier with oil and gas experience is expected to be at TRL 2 for floating wind. To reach TRL 4 the Qualification Plan is recommended to include Emergency Release qualification tests e.g. extended material test and small scale fatigue test.
- It is recommended that the emergency release full-scale strength test to failure shall be performed with the cores powered with nominal high voltage, to replicate typical accidental scenario in service conditions.
  - If the high voltage remains in the cable/ connector during emergency release, the effects of this are recommended to be addressed in the tests.

## 2 INTRODUCTION

---

To support the growing offshore wind industry, the need for developing reliable, high voltage inter array cable technologies is critical. Submarine power cables have been in use for the offshore wind industry for well over two decades, but almost all of them have been for static application for fixed wind projects or export of power to shore. As floating wind farms are becoming a reality, the focus of new development in power cables is for dynamic inter-array HV power cables. A typical arrangement of a dynamic power cable and the components within it are shown in Figure 1. Standards and guidelines for dynamic power cables have been developed [7], but due to the nascent stage of floating wind energy, the guidelines are not comprehensive and do not provide a qualification framework over the entire life cycle of the power cables.

This document provides a qualification framework for high voltage dynamic power cable and ancillary equipment for floating offshore wind (FOW) applications based on a review of the range of framework codes [3].

The definition of low (LV), medium (MV), and high (HV) voltage can vary, but in this report LV cables are up to 3.6kV and MV up to 36kV.

The framework provides standard guidance to be followed by all suppliers of high voltage power cables and ancillary equipment who want to qualify their product for floating wind applications. This includes new entrants or well established businesses that want to transition from static or land applications to a dynamic offshore scenario as well as umbilical suppliers who want to transition from lower voltage umbilicals in Oil and Gas to medium and high power voltage cables. The framework presented in this document is also meant for developers of wind farms as it provides a standard approach to be followed by all suppliers resulting in well qualified technologies according to the codes and standards available. The framework can be utilised for any component in the system or for the complete assembly as appropriate.

To test the proposed qualification framework, two case studies are developed for a typical North Sea field condition. The selection of the case studies is based on findings from the FMECA [2], discussion with ORE Catapult and stakeholder engagement [3], which indicated that these are particular areas of interest for the industry due to gaps in technology qualification and need for pushing the boundaries through innovation.

The first case study outlines the qualification process for a generic 66kV dynamic inter-array power cable cross-section, as shown in Figure 2 and given in Section 3.1. The second case study outlines the qualification framework for the bend stiffener connector (Figure 3), as described in Section 3.2.

Figure 1 – Schematic Representation of Power cable in Lazy Wave Configuration

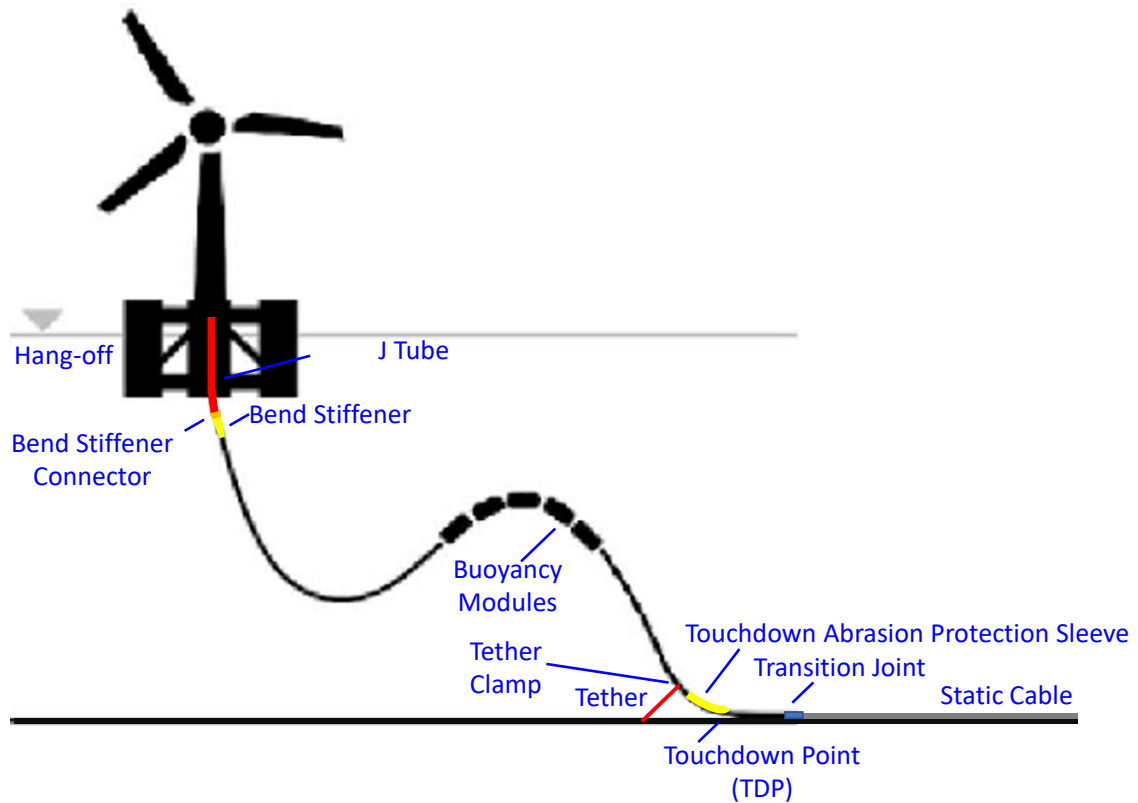


Table 3 – Components of the Power Cable System and Ancillaries

Component	Description
Power Cable	3-core power cable used to collect the power from the individual offshore turbines or connect the turbines with an offshore HVAC substation[41].
Hang off/ termination	Assembly that transfers cable loads to the platform structure. This is achieved by termination of load bearing elements (armour wires) in a strain termination (bounding epoxy mould, welded termination or clamping of armour wires). The loads are transferred from this anchor block to the platform structure via a split flange.
Bend Stiffener	Usually at the top of the cable to limit bending stresses and curvature to acceptable levels by adding a local stiffness to the cable at the point of connection [9].
Bend Stiffener Connector (Latching Mechanism)	A structure or mechanism that connects a bend stiffener to a supporting structure allowing the bending moment to be transferred from the bend stiffener to the supporting structure [28].
I/J Tube	Tube formed as an “I” or “J” attached to a platform or foundation to facilitate, support and protect cable entry to the platform/generator [41].

Component	Description
Buoyancy Modules	Discrete component, consisting of a buoyancy element, an internal clamp and any necessary fasteners to secure these components in position, used to provide net uplift to power cables by attaching a series of such components along a length of pipe [28].
Ballast Modules	Negatively buoyant component of which a number are used at discrete points over a length of power cable to provide added weight [28].
Tether	Chain or rope used to connect a cable to a tether base, including connecting hardware necessary at each end termination [28].
Tether Clamp	Clamp used to connect the tether to the cable.  The clamp to connect the tether to the cable can be a high-risk location.
Touchdown Abrasion Protective Sleeve	Specially designed protection sleeves around the cable's touchdown point to protect the outer layer of the cable [9].
Transition Joint	Transition from the dynamic section to the static cable. The transition joint could be a factory joint or a rigid joint. The transition joint is not exposed to dynamic loading during service [39].

## 3 CASE STUDY SELECTION OVERVIEW

---

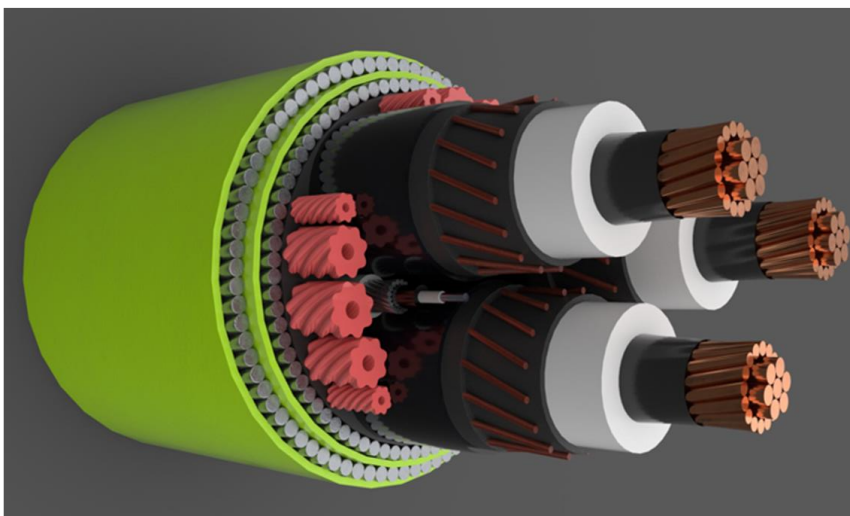
### 3.1 Power Cable

Although the qualification of each component separately is relevant, the qualification of the cable as a complete unit is important to confirm the technology readiness for operations. For example, some components of the power cable may have been used before in other applications and therefore be already “qualified”, however it is known that when there is a combination of high voltage, heat, water depth, dynamic motions and therefore complex interaction between the components, these same components may not function as expected in the final assembled power cable.

Additional reasons for selecting the power cable as one of the case studies are:

- Key part of the cable system, with high consequences from failure
- Used in all Floating Offshore Wind Farms
- New designs will all need qualification
- Technological development will be required for floating wind (higher voltages)
- Armour sections are identified as qualification gap since they have different requirements from static power cable designs for offshore wind, although armour and sheath layers are similar to dynamic oil and gas cable and umbilical designs
- Qualification of the water barrier in case of dry design (although a wet design is considered in the case study in Section 5)
- Gaps are identified in qualification testing, for example enhanced compression testing
- Interest to understand the outer sheath materials (e.g. PU or PE) strength and sturdiness against dynamic motion.
- Effect of thermal and electromagnetic loading on materials.

Figure 2 – 66kv Dynamic Cable (Image 1, ORE Catapult render)



### 3.2 Bend Stiffener Connector (Latching Mechanism)

The bend stiffener connector (latching mechanism) is expected to be needed on almost all systems in Floating Wind in the UK (since bellmouths have to date been typically considered more suitable for spars in deep waters). It has been identified as a high-risk area during stakeholder engagement due to reliability issues to date, believed to be partly due to lack of qualification testing. Additionally, there are opportunities for design optimisation and improved reliability, resulting in reduced OPEX.

Therefore, the bend stiffener connector is selected of one of the case studies. It will also consider the growing demand for diver-less connection and emergency release mechanisms of power cables which are ideally suited for offshore wind farm operations and maintenance.

Note that API 17 L1 [28] refers to bend stiffener connectors as a “load transfer device”.

Figure 3 – Bend Stiffener Connector (Image Sources from left to right: First Subsea, Balltec [20], and S3N Ventus)



## 4 PROPOSED QUALIFICATION FRAMEWORK

---

There are many recommended practices available to provide the industry with structured approaches to qualify new technologies, and ensure they function within specified design criteria. The various classification agency technology qualification codes and standards differ with respect to terminologies, approval stages and document reviews; however, the overall process and format is similar, as summarised below:

- **Scope** – Applies to qualification of technologies (new material, component or system) that are not covered by existing industry codes and standards.
- **Functional Specification or Qualification Basis** – A functional specification and technology qualification basis is developed for the technology to be qualified. This identifies the functional requirements, environment, loads, temperatures, conditions, etc. that apply to the new technology.
- **Technology Assessment** – Technology is screened for novel elements against existing technology and field use to identify which aspects of the technology have the most uncertainty. These items with uncertainty will be the focus of the technology qualification programme. The Technology Assessment usually includes assessing the technology readiness level (TRL) of the current state of the technology being qualified. Different industries and companies have their own TRLs and definitions including the following: ORE Catapult [19], API Recommended Practice 17N [29], and United States Department of Defence (US DoD) [44].
- **Threat Assessment** – Novel aspects of the technology undergo a risk based (FMECA, HAZID, HAZOP, etc.) analysis of the potential failure modes and threats to the feasibility of the technology.
- **Technology Qualification Plan** – A technology qualification plan is developed with a focus on the higher rated risks using the functional specification or qualification basis to set the acceptance criteria.
- **Execution of the Technology Qualification Plan and Assessing Performance** – A technology qualification plan is executed, and the results analysed against the criteria established by the functional specification or technology qualification basis.
- Classification agencies give the option to obtain a type approval certificate or similar for the qualified technology.

In the framework proposed in this report, DNV-RP-A203 [43] and ABS “Guidance Notes on Qualifying New Technologies”, [11], are used as reference with inputs from other codes such as “Risk Based Qualification of New Technology – Methodological Guidelines” from BV NI 525, [23].

The framework proposed in this report may be applied for qualification of new material, component or system technologies for cabling systems of floating offshore wind, including ancillary equipment. It covers any of the four categories defined by ABS [24]:

- i) Existing design, process or procedures challenging the present boundaries and envelope of technology in current offshore or marine applications
- ii) Existing technologies in new or novel applications
- iii) New or novel technologies in existing applications

iv) New or novel technologies in new or novel applications

Although the framework proposed in this report focuses on the qualification of new technologies, it could also be used to qualify existing ones.

A summary of the framework proposed is shown in Figure 4. It includes TRL levels (Table 4) to define milestones in the technology qualification programme in order to measure progress and clearly define when one stage is complete, and the technology can move to the next one.

The Qualification Plan depends on the level of maturity of the technology, which has been identified in the Technology Assessment. The Qualification Plan also takes into consideration the Threat Assessment, since the qualification programme for the technology shall address, as a minimum, all novel/low TRL elements identified as high-risk failure modes. The qualification plan will define the specific qualification activities, the sequence of these activities, and the qualification criteria required to progress to the next level of technology readiness. A high level breakdown of tasks for each stage of the qualification plan is shown in Table 5.

Once the Qualification Plan has been executed and the Performance Assessment has indicated that the technology has met the qualification criteria from a specific stage, the Qualification Basis, Technology Assessment and Threat Assessment are revised to incorporate additional requirements concerning the next stage. For example, once a technology has been qualified as TRL 6 (“Technology Qualified”), the requirements will include aspects particular to the end user (project specific) so it can be qualified as TRL 8 (“Technology Integrated”).

Once all stages have been completed, the technology reaches TRL 9 and is classified as “Operationally Qualified”.

Dynamic cables are complex systems, with significant variation in the different system components and technologies. Each component has different applicable standards and industry good practice. As such we have presented two case studies as the focus of the report to describe how the more detailed elements of the qualification framework works in practice:

- 66kV AC dynamic power cable for typical UK - North Sea conditions (Section 5)
- Bend stiffener connector for typical UK - North Sea conditions (Section 6).

More detail on each of the stages of the more generic Qualification Framework is given in Appendix 1, which can be used as the basis for any dynamic cable system component. The case studies should be treated as examples only; the framework should always be adjusted and optimised to the particular situation, accounting for the variability that occurs in supplier experience, cross-section designs, and the design details of the component.

Table 4 – TRL Levels used in the case studies from ORE Catapult [19]

Level	Explanation
TRL 2	Technology concept formulated. Invention begins: Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
TRL 4	Technology validated in lab. Basic technological components are integrated: Basic technological components are integrated to establish that the pieces will work together.
TRL 6	Technology demonstrated in relevant environment. Model/prototype is tested in relevant environment: Represents a major step up in a technology’s demonstrated readiness, which is well beyond that of TRL 5. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
TRL 8	System complete and qualified. Technology is proven to work: Actual technology completed and qualified through test and demonstration.
TRL 9	Actual system proven in operational environment. Actual application of technology is in its final form: Technology proven through successful operations. Includes competitive manufacturing in the case of key enabling technologies.

Note: TRL 1, 3, 5 and 7 are not shown but each TRL level shown means requirements from previous levels are fulfilled. For example, to reach TRL 6 the technology has to have fulfilled all requirements from TRL 6, TRL 5, TRL 4, TRL3, TRL 2 and TRL 1

Table 5 – Summary of Tasks per Stage of the Qualification Plan

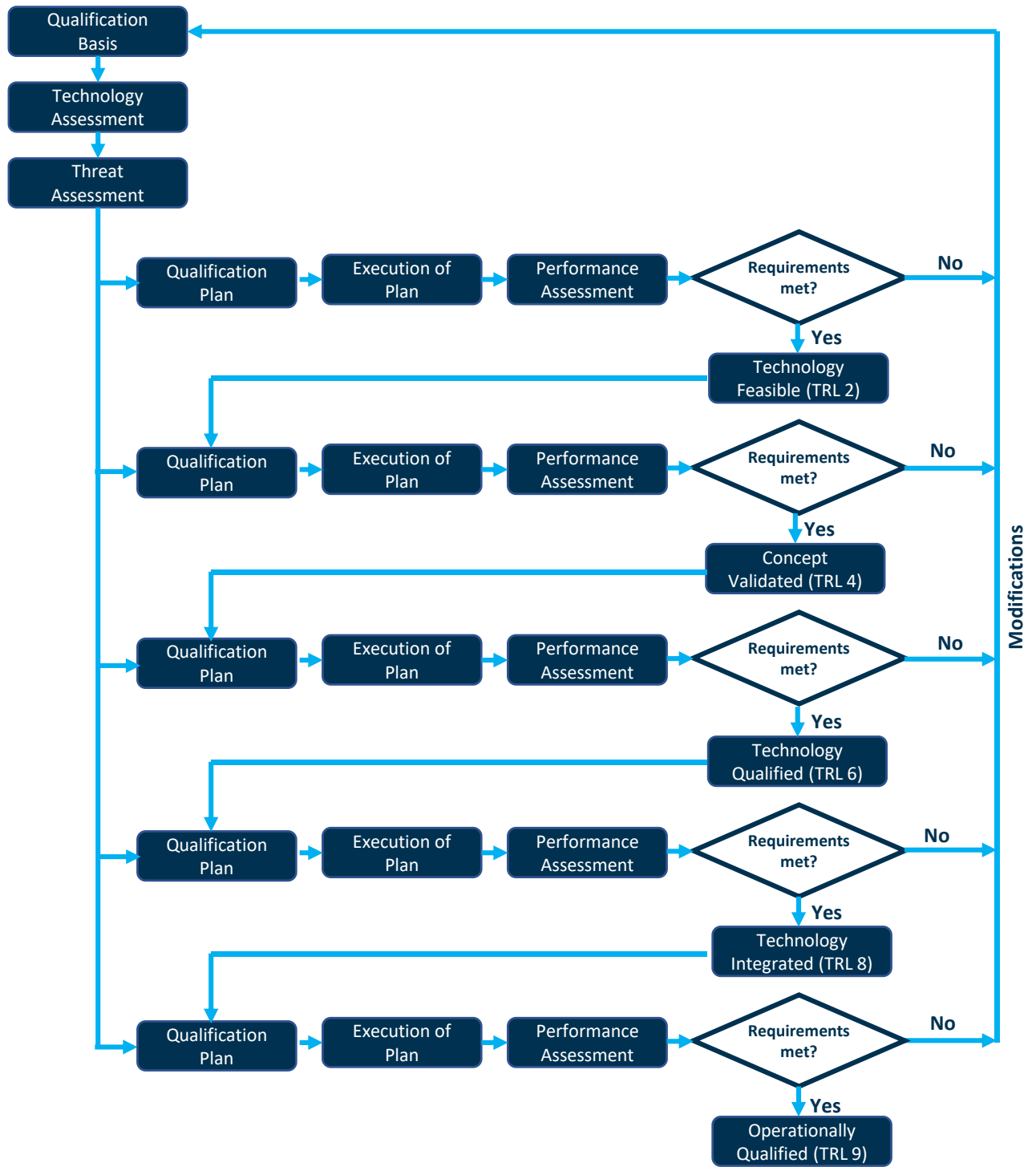
Requirement	Feasibility (TRL 2)	Concept Validation (TRL 4)	Prototype Validation (TRL 6)	System Integration Stage (TRL 8)	Operational Stage (TRL 9)
Analysis	X	X	X	X	X
Component Tests		X			
Individual Component Fatigue Tests		X			
Characterisation Tests			X		
Type Tests			X		
Full-Scale Fatigue Test <sup>(1)</sup>			X		
Project Specific Tests				X	
Monitoring		X <sup>(2)</sup>		X	X
Commissioning Tests					X

1\ As per CIGRE TB 862 [39], fatigue test is part of the type tests.

2\ Monitoring integrated with the component must be addressed at TRL 4.

3\ TRL 1, 3, 5 and 7 are not shown but each TRL level shown means requirements from previous levels are fulfilled. For example, to reach TRL 6 the technology has to have fulfilled all requirements from TRL 6, TRL 5, TRL 4, TRL 3, TRL 2 and TRL 1.

Figure 4 – Steps in the Qualification Process



## 5 APPLICATION TO POWER CABLE CASE STUDY

---

Although the qualification of each component separately is relevant, the qualification of the cable as a complete unit is the most important. The TRL level will depend on the maturity of the technology as a system. For example, some components of the power cable might have been used before in other applications and therefore be already “qualified” (as shown in 5.2.2) but when there is a combination of high voltage, friction between components, heat, water and dynamic motions, the same component might not function as expected. Therefore, based on findings from the FMECA performed as part of the project [2], discussion with ORE Catapult and stakeholder engagement [3], the power cable has been selected as one of the case studies to test the framework detailed in Section 4.

To test the qualification framework fully across all the TRL stages, a power cable design without any prior qualification or track record in floating wind is assumed. It is assumed the power cable under qualification is TRL 1, from a new entrant supplier to the market with the following experience:

- No track record in floating wind application
- No track record in fixed wind application
- No experience with MV/HV subsea power cables
- Some limited track record in Oil and Gas dynamic low voltage umbilicals.

### 5.1 Qualification Basis

In floating offshore wind projects, tethered lazy wave configurations are commonly used as they can better accommodate the large motions from the floater.

In the case study presented in this report, a typical lazy wave configuration of the power cable is considered as shown in Figure 1 and described in Table 3.

The cable is assumed to be part of a wider array-level (more than 30 turbines) and connected in a daisy chain to the next turbine type configuration, in line with small scale demonstration projects (such as Kincardine or Hywind). Other configurations are possible, but this is chosen for the case study for simplicity.

The voltage of the cable is 66kV (U).

#### 5.1.1 Design System Requirements

Some system requirements are detailed below. Every time a new stage of the qualification plan is executed, the Qualification Basis is reassessed and updated with additional information. For technologies categorised with lower TRL, there are several uncertainties and assumptions, therefore the amount of known information will be less. However, as the TRL increases, the level of detail available increases and the system requirements become more well defined.

For the case study, the power cable under consideration is assumed to be at a low TRL level and therefore limited information is available, as given below.

#### Design Life

The power cable and ancillary equipment design life is assumed as 25 years.

## Environmental Data

Environmental conditions similar to the metocean data considered in “Floating Offshore Wind Dynamic Cable – Design Requirements” [14], from FOW CoE project PR5 – Dynamic Cable Systems, are utilised to represent typical North Sea conditions.

In this case study, a water depth of 100m is considered.

## Cable Cross-section

For this case study, a generic 66kV dynamic power cable cross-section is used as shown in Figure 5. It is based on the following characteristics:

- 3 x Power Cores
- 1 x Fibre Optic
- Extruded PE outer and inner sheath
- 2 layers of steel armour
- Wet design
- EPR or XLPE insulation
- Copper Conductor (cross section area assumed 800mm<sup>2</sup>)

A wet design is selected for the case study based on the following rationale. In accordance with the radial water barrier used in the submarine cable, the design of the power cables is divided into dry and wet. To be considered as dry, the cable has to pass the tests defined in CIGRE TB 722 [38]. Dry design with corrugated Cu/Al sheath is a proven design for high voltage applications, they can be used for dynamic cables but are expensive and lead to a complex solution.

A more popular approach for dynamic cables is to go for wet designs where the XLPE or similar materials used for insulation are added with water tree retardants which will mitigate the water tree phenomenon that leads to degradation of insulation.

For dynamic high voltage cables, which are limited by the use of wet solutions, the influence of water treeing and the associated accelerated electrical aging is of concern. However, it has been shown that high relative humidity is necessary for water tree inception [10]. By delaying the water ingress with sheaths and swelling tapes, the time to reach critical humidity levels in the material can be increased significantly. A wet design with suitable additives for insulation surrounded by an oversheath is therefore considered the basis for the case study.

Dynamic power cables are subjected to fatigue loading from wave, current and movement of the floating platform, therefore, the cable structure must be electrically and mechanically fit-for-purpose throughout the design life. Copper cores generally have greater fatigue resistance being able to withstand larger strain amplitudes over longer durations than aluminium without cracking or breaking. However, it should be noted that aluminium alloys (for example Aluminium 6201) can offer superior mechanical fatigue and creep performance compared to copper [22]. Additionally, the higher conductivity of the copper results in relatively smaller conductor sizes [9], while there are schools of thought that the weight reduction of Aluminium is key for dynamic applications. Therefore, the choice between copper and Aluminium is open to discussion, with some cable suppliers preferring one over

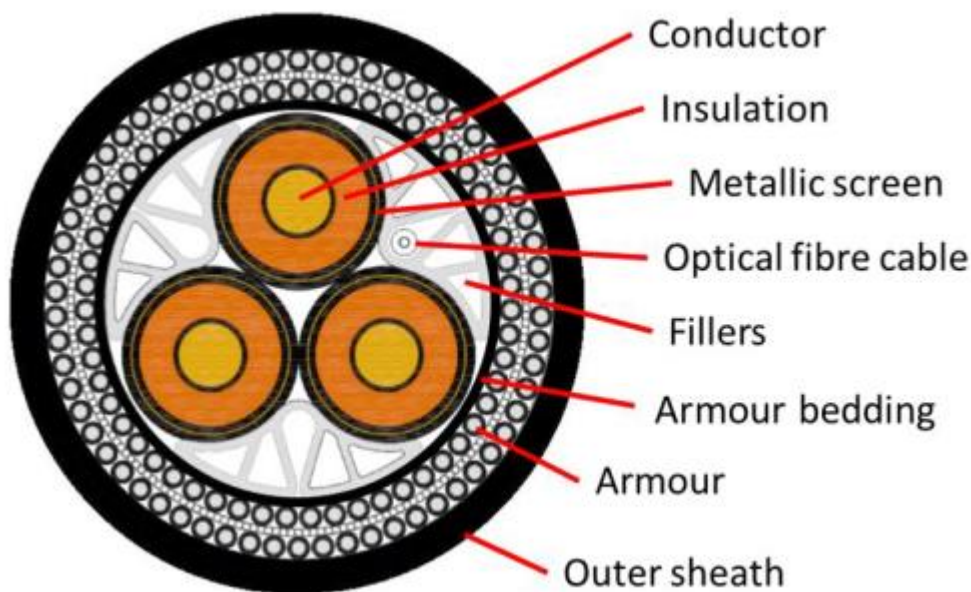
the other. For the purpose of this case study, copper cross-sectional area of 800mm<sup>2</sup> [14] is selected and used as the basis of the case study.

A key change to the dynamic cable compared to a static application is the use of a more robust outer protective sheath (PE, Nylon or similar solid extruded cover) instead of light protective rovings (helically wrapped strings of polypropylene rope coated in bitumen) used in static cables. Another key difference in dynamic cables is the extra layer or more of armouring to protect the cable from mechanical damage and provide torque balance.

For this case study, it is assumed that no rigid joints are required, and a transition joint can be present between the dynamic and static section. Therefore, the qualification of rigid joints is not included in this case study. For simplicity it is also assumed that no factory joints and splices of the power cores are included in the dynamic cable section.

For the purpose of this case study, tests involved during the manufacturing of each core of the cable are not outlined, rather the focus is on the 3 core power cable design to ensure that the cable is fit for purpose over the design life of the field. Each core of the cable is assumed to have passed the FAT tests and routine test during manufacturing IEC 63026 [48].

Figure 5 – Generic 66kV Dynamic Power Cable Cross-Section [39]



### 5.1.2 Standards, Codes & Industry Practices

Due to the maturity status of power cable technology for offshore wind dynamic service, no standardised qualification basis exists, however, relevant codes applicable to the qualification of power cables have been identified [7] and are summarised in Table 6.

Table 6 – Main Codes and Standards Identified for Qualification of Inter Array Dynamic Power Cables [7]

Code	Title
CIGRE TB 490	Recommendations for Testing Long AC Submarine Cables with Extruded Insulation for System Voltage Above 30 to 500 kV
CIGRE TB 623	Recommendations for Mechanical Testing of Submarine Cables.
CIGRE TB 722	Recommendations for Additional Testing for Submarine Cables.
CIGRE TB 862	Recommendations for Mechanical Testing of Submarine Cables for Dynamic Application
IEC 63026	Submarine Power Cables with Extruded Insulation and Their Accessories for Rated Voltages from 6 kV ( $U_m = 7.2$ kV) up to 60 kV ( $U_m = 72.5$ kV) –Test Methods and Requirements.
DNV-RP-F401	Electrical Power Cables in Subsea Applications
ISO 13628-5	Subsea Umbilicals
API Spec 17E	Specification for Subsea Umbilicals

### 5.1.3 Areas of Expertise

The qualification of power cables for dynamic applications includes electrical and mechanical type tests. Therefore, the main areas of expertise are:

- **Mechanical Engineering:** Most of the expertise in terms of the dynamic response of the high voltage dynamic inter array cables for floating offshore wind comes from other similar systems in Oil and Gas with lower voltage umbilicals or no voltage flexible pipes. Expertise in the following areas apply:
  - global response of the system (stress and fatigue response)
  - structural response to global loads (for example radial compression)
  - local analysis of the component interaction (stress, fatigue, thermal and electromagnetic response)
- **Engineering of Material:** Experience with materials (polymers, metallurgy etc.) can come from oil and gas, renewables or other areas.
- **Electrical Engineering:** Experience with high voltage systems come from static submarine applications for fixed wind. Experience with medium voltage dynamic cables (up to 36kV) from oil and gas is also applicable.

#### 5.1.4 Operational, maintenance, and inspection strategies

The description of the technology typically includes operational, maintenance, and inspection strategies, organised in an integrity management plan (IMP). It includes activities such as:

- Periodic visual inspection to identify damage to the exterior and build-up of marine growth
- Period cleaning of marine growth when it exceeds the design allowable thickness and coverage
- Monitoring of platform motions and environmental loads to ensure loads on the cable are within design envelope
- Condition monitoring of the internal cross section based on fibre optic distributed temperature sensing (DTS) and on distributed strain sensing (DSS)
- Tests carried out periodically (e.g. tan delta)
- Partial Discharge (PD) monitoring (in development)

#### 5.1.5 Lessons Learned from Similar Technologies

The description of the technology can include lessons learned from similar technologies to prevent the same issues from happening. Some lessons learned from qualification of pilot floating wind cable designs, and umbilicals and flexible pipes from oil and gas that can be applied to the qualification of FOW power cables are:

- Global configuration design and process utilising global and local cross section analysis
- Local analysis versus full-scale mechanical response to calibrate structural properties such as friction coefficients, SN fatigue curves, etc.
- Full scale fatigue testing approach to best simulate and represent in-service load conditions
- In terms of the mechanical design (e.g. sheath and armouring), the oil and gas industry has vast previous experience with material selection for dynamic applications (metallic and polymer).

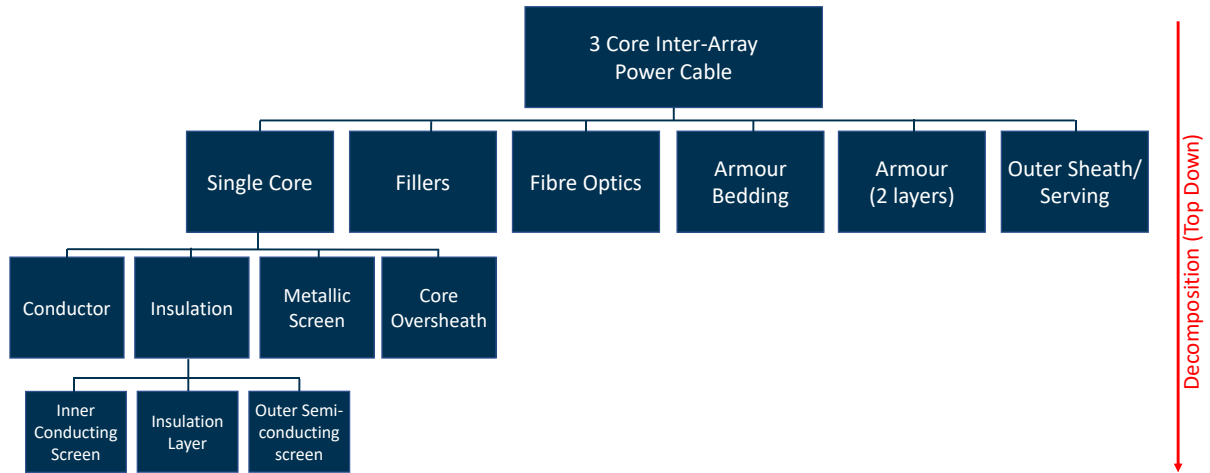
## 5.2 Technology Assessment

### 5.2.1 Technology Decomposition Analysis

The Technology Assessment includes a decomposition where the system (power cable) is divided into subsystems, which can be further broken down into components.

For the power cable of the case study, the system (3 core cable) includes subsystems with different functions, such as mechanical protection (armour layers and outer serving) and electrical transmission (conductor), as given in Figure 6 and described in Table 7. Note Figure 6 does not give a full decomposition as this is not necessary for the case study, however, further decomposition (for example the fibre optics) is possible.

Figure 6 - 3 Core Inter-Array Power Cable for Floating Offshore Wind System Hierarchy



- Notes:
- 1\ Fibre Optics decomposition not shown (fibres, carrier tube, armours, oversheath)
  - 2\ End fittings not considered in case study

Table 7 – Components of the Cross Section of the Power Cable

Component	Description
Armour	Covering consisting of a metal tape(s) or wires, generally used to protect the cable from external mechanical effects [46]. The armour is the primary load bearing part of the cable structure.  Alternatively, there are some non-metallic amour packages available from specific vendors.
Armour Bedding (Inner Sheath)	Referred to as “bedding layer” and consists of a continuously extruded thermoplastic material applied over the core of the cable which includes the three electrical cores and any additional elements (e.g. fibre optic cables) laid up together and filled with appropriate fillers to achieve a circular cable cross-section.  Not all cable designs have an extruded inner sheath, with some suppliers opting for rovings/servings.
Core	Assembly comprising a conductor with its own insulation (and screens if any) [47].
Conductor	Part of a cable core designed for transmission of electric current, typically made of copper or aluminium [46].
Fillers	Item wholly or partially filling the voids between the functional components of the cable with the purpose(s) of maintaining the relative location of the components, maintaining the shape of the cross-section, influencing the weight-to-diameter ratio, separating components for wear considerations, or providing a certain radial stiffness [30].
Fibre Optics	Most submarine cable systems for offshore power generation are equipped with fibre optics for data transmission, temperature measurement and fault localisation [41].

Component	Description
Insulation	<p>The insulation system consists of an inner conducting screen, an insulation layer and an outer semiconducting screen.</p> <p>The extruded insulation system consists predominantly of cross linked polyethylene (XLPE), although ethylene propylene rubber (EPR) is often an option.</p>
Metallic Screen	<p>Component with several functionalities. It acts in normal conditions as a return path for capacitive and induced currents, and to carry fault currents. For wet designs, the screen is normally made from either helically applied copper wires, tape, or braid. A layer of polymeric material is extruded over the metallic screen to protect it during manufacturing and transportation before assembly, but also to reduce internal abrasion during cable bending [39].</p>
Outer Sheath/ Serving	<p>Outer covering of cable, over the armour layer. Typically made as a continuous tubular polyethylene sheath [46]. Similar to oil and gas (flexibles and umbilicals) other polymers are available and may be selected based on temperature and strain limits.</p> <p>Contrary to the inner sheath where there is debate about extrusion, the industry agrees that the outer sheath should be extruded (for dynamic applications).</p>

### 5.2.2 Technology Characterisation

Uncertainty is associated mainly with the novel elements in the technology (e.g. novel components or a new application). In order to understand where uncertainty is greatest the methodology from DNV [43] is adopted in this framework to assess the level of effort involved in qualification of the technology. As shown in Table 8, the technology is characterised considering its application area (known, limited knowledge and new) and the degree of novelty of the technology (proven, limited field history and new or unproved).

Table 8 – Technology Characterisation according with DNV [43]

Application Area	Degree of Novelty of Technology		
	Proven	Limited Field History	New or Unproved
Known	A	B	C
Limited Knowledge	B	C	D
New	C	D	D

Note: DNV uses numbers 1 to 4, but letters are used here instead to avoid confusion with TRL levels:

- A)** No new technical uncertainties (i.e. proven technology by supplier).
- B)** New technical uncertainties.
- C)** New technology in existing applications (new technical challenges).
- D)** New technology in new applications.

Inter-array dynamic cables for floating wind have evolved from static export submarine cables and dynamic umbilical cables from Oil and Gas. Based on the components identified in the Technology Decomposition Analysis (Section 5.2.1), a systematic screening table for the dynamic power cable is shown in Table 9.

Category A technology elements are proven with no new technical uncertainties, where proven methods for verification, tests, calculations and analysis can be used to provide the required qualification evidence. It is important not to overlook the proven elements, as they may be critical for the overall performance of the technology, therefore these elements should be handled through the regular design process, ensuring compliance with an applicable standard or industry practice.

Elements in category B to D require technology qualification and have an increasing degree of technical uncertainty. The defined categorisation makes it possible to distinguish between the novelties of the technology itself (proven, limited field history and new or unproved) and its application areas (known, limited knowledge and new).

The technology categories assessed for this case study are shown in Table 9. Power cable fillers and fibre optics are classified as “C”, which means “new technical challenges” [43]. Fibre optics and fillers have been used in umbilicals for Oil and Gas dynamic applications for many years, however, inter array dynamic cables for floating wind characterises a new application, in particular due to the HV aspect.

Approximately half of the components are ranked as “D”, “Demanding new technical challenges”, since the application area (floating offshore wind) is new, and the use of that component has limited field history or is unproven in this field.

Based on the relatively low maturity ranking in Table 9, qualification of the power cable of the case study is needed at a system (3-core cable) level as well as individual component level.

Experienced power cable vendors might be able to apply lower characterisation based on their experience with HV submarine cables for static applications, or umbilicals for the oil and gas sector. However this case study is for a power cable from a new entrant supplier to the market with no experience in floating wind or MV/HV subsea power cables.

Table 9 – Systematic Screening Table for Inter Array Dynamic Power Cables

Item	Description	Similar Technology Exists	Relevant Rules, Guides or Industry Standards	New Technology (Yes/No)	Technology Category <sup>(1)(2)</sup>	Notes
1	Conductor	Static power cables	IEC 63026	No	D	New application area & Limited field history
2	Insulation	Static power cables	IEC 63026	No	D	New application area & New or Unproven
3	Metallic Screen	Static power cables	IEC 63026	No	D	New application area & New or Unproven
4	Core Oversheath	Static power cables	IEC 63026	No	D	New application area & Limited field history
5	Fillers	Static power cables, Umbilicals	IEC 63026	No	C	New application area & Technology proven
6	Fibre Optics	Static power cables, Umbilicals	IEC 63026	No	C	New application area & Technology proven
7	Armour Bedding	Flexible pipes and Umbilicals	IEC 63026, API 17E, ISO 13628-5	No	C	New application area & Technology proven
8	Armour Layer	Flexible pipes and Umbilicals	IEC 63026, API 17E	No	C	New application area & Technology proven
9	Outer Sheath/ Serving	Flexible pipes and Umbilicals	IEC 63026, API 17E, API 17L1/L2, ISO 13628-5	No	C	New application area & Technology proven

Notes:

1\ From [24], where: “A” No new technical uncertainties (proven technology), “B” New technical uncertainties, “C” New technical challenges, “D” Demanding new technical challenges.

2\ Based on the case study premise of a supplier with limited experience. Some of the current vendors are likely to be in a higher technology category.

### 5.2.3 Technology Stage Assessment (TRL)

Following the results from the technology characterisation in Section 5.2.2, a detailed analysis of the maturity level of the technology is carried out to determine which stage of the qualification plan is most suitable for the power cable. In this case study, it is assumed the power cable is at TRL 1 and has to complete all stages of the Qualification Plan to reach TRL 9. The standard questions given by ABS [24] are used as a basis for the specific questions suggested in Appendix 2 for qualification of the power cable of the case study.

At the beginning of the Qualification Programme, the answers for all the questions in Appendix 2 are “No” as the activities to support evidence of any qualification have not been carried out yet. As qualification for a certain TRL stage starts it is expected that all activities from prior stages have been completed satisfactorily, therefore answers shall be “yes” for the prior stage and evidence provided. Although the answers to these questions are not presented in the case study, the questions are adjusted based on the learnings from the case study when considering the standard questions and gaps in these questions. For example, the use of global and local FE analysis to support the process. It is assumed that the activities performed at each step of the qualification process sufficiently answer the questions to progress to the next TRL level at each stage.

The more mature power cable design from an experienced vendor could already have evidence to support many of the requirements from early stages of the qualification framework and therefore skip some activities of the qualification plan proposed. The process is refined to capture this, in that in order to progress from one TRL stage to the next, the technology assessment should justify that the previous TRL stage questions are all evidenced fully and documented.

## 5.3 Threat Assessment

For the dynamic power cable system, ORE Catapult has conducted a failure mode, effects & criticality analysis (FMECA), which includes the power cable as well as the ancillary system components. The results of this activity are used in this case study to exemplify failure mechanisms for the power cable and associated risk levels (Figure 7), as shown in Table 10. The reference example FMECA may be used as a basis for defining the qualification programme, but it should be noted this investigates one failure mode at a time and critical combinations of failures should also be identified.

Note, the reference FMECA example does not consider installation of floating wind cables, and a qualification programme shall consider installation. This is important since all handling of the cable and ancillaries can have an impact upon how the cable will react globally and subsequently could affect the internal mechanical and electrical stresses within the cable. There are tests for the qualification of the power cable that are carried out specifically for installation loads, such as the Crush Test described in CIGRE TB 623 [37]. A Threat Assessment including installation is of key importance for the System Integration Stage (Section 5.8), when the power cable reaches TRL 8 and has been integrated to the final operating system and operating environment.

The reference FMECA example also does not consider risks associated with interference of the power cable with adjacent structures, such as other cables and mooring lines. The impact loads can result in cable deformation, resulting in higher electrical stresses, overheating and premature failure. This scenario is relevant to be assessed by the qualification framework, specifically in the System Integration Stage (Section 5.8), when the power cable is integrated to the final operating system.

The qualification programme for the power cable addresses, as a minimum, all novel/low TRL elements identified in Section 5.2.2 and all high-risk failure modes, identified through the threat assessment in this section.

The activities from the qualification plan that address the “very-high”, “high” and “medium” risks for the power cable and outer sheath are shown in Table 10. For example, for the “very-high” risk of exceedance of compressive capacity, buckle of armour wires or internal cable cores, the tests for Combined Axial Compression and Bending Test and Axial Compression Test are part of the qualification plan from the Prototype Validation Stage, as described in Section 4.7.3.

Table 10 – Power Cable System Threat Assessment Summary [2]

Item/ Component	Failure Mechanism [2]	Risk <sup>(1)</sup> [2]	Addressed by Activity of Qualification Framework Stage
Power cable	Exceedance of compressive capacity, buckle of armour wires or internal cable cores	Very High	Combined Axial Compression and Bending Test and Axial Compression Test are part of the qualification plan from the Prototype Validation Stage, as described in Section 5.7.4.
	Exceedance of tensile/bending limit	High	Tensile Bending Test and Tensile Test are part of the qualification plan from the Prototype Validation Stage, as described in Section 5.7.4
	Material Fatigue	High	Component fatigue testing is carried out at Concept Validation Stage, as given in Section 5.6.4. Also addressed by the Full-Scale Fatigue Test in the Prototype Stage as per Section 5.7.8.
	Exceedance of bending tension capacity in static region	Medium	Tensile Bending Test and Tensile Test are part of the qualification plan from the Prototype Validation Stage, as described in Section 5.7.4
Outer Sheath/ Serving	Abrasion, cuts, crushing, kinking	Medium	Material tests are part of the Component Tests carried out at the Concept Validation Stage as given in 5.6.3
	Fatigue	Medium	Component fatigue testing is carried out at Concept Validation Stage, as given in Section 5.6.4. Also addressed by the Full-Scale Fatigue Test in the Prototype Stage as per Section 5.7.8.
	Creep	Medium	Material tests are part of the Component Tests carried out at the Concept Validation Stage as given in 5.6.3

Note: 1\ Risk matrix defined in Figure 7

Figure 7 – Risk Matrix for the FMECA [2]

		Consequence severity				
		Negligible	Noticeable	Significant	Major	Catastrophic
Likelihood	Frequent	0	0	0	0	0
	Probable	1	0	0	0	0
	Occasional	8	1	1	3	1
	Remote	0	3	6	14	4
	Very Unlikely	1	9	8	20	10
Risk Criticality		Very Low	Low	Medium	High	Very High

### 5.4 Qualification Plan

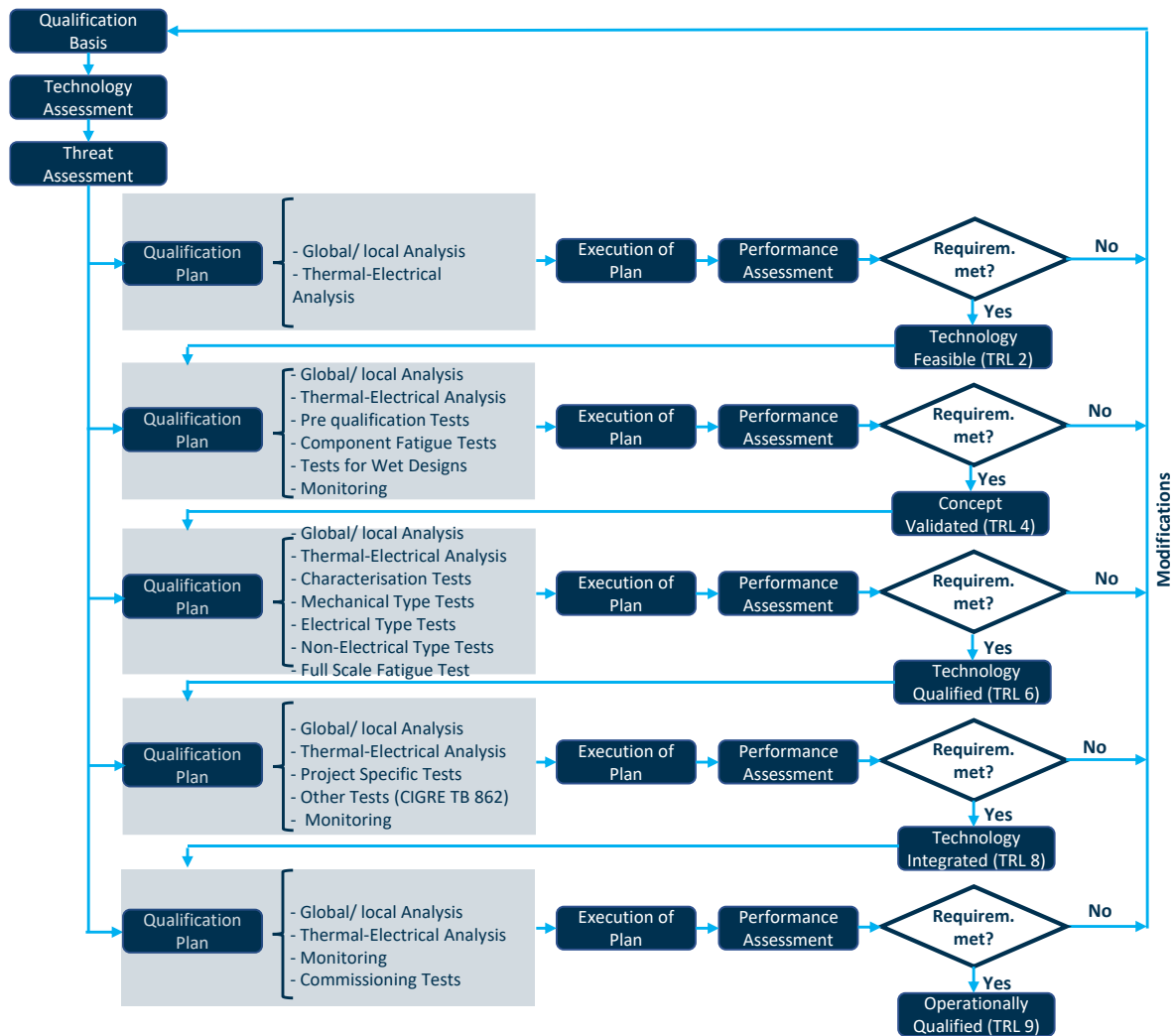
The qualification plan depends on the results from the Threat Assessment in Section 5.3 and Technology Stage Assessment in Section 5.2.3. Each stage of the qualification plan for the power cable is summarised in Table 11 and shown in Figure 8.

As the power cable of the case study is assumed to have TRL 1, all activities for each stage of the qualification plan are detailed in Sections 5.5 to 5.9.

Table 11 – Summary of Tasks per Stage of the Qualification Plan for the Power Cable Qualification

Requirement	Feasibility (TRL 2)	Concept Validation (TRL 4)	Prototype Validation (TRL 6)	System Integration Stage (TRL 8)	Operational Stage (TRL 9)
Global/ Local Structural Analysis	X	X	X	X	X
Thermal-Electrical Analysis	X	X	X	X	X
Component Tests		X			
Individual Component Fatigue Tests		X			
Tests for Wet Designs (CIGRE TB 722)		X			
Characterisation Tests			X		
Mechanical Type Tests			X		
Electrical Type Tests			X		
Non-Electrical Type Tests			X		
Full-Scale Fatigue Test <sup>(1)</sup>			X		
Project Specific Tests				X	
Other Tests (CIGRE TB 862)				X	
Monitoring		X <sup>(2)</sup>		X	X
Commissioning Tests					X
1\ As per CIGRE TB 862 [39], fatigue test is a part of the type tests.					
2\ Monitoring required to be integrated into the cross section (e.g. fibre optics) must be addressed at TRL 4.					
3\ TRL 1, 3, 5 and 7 are not shown but each TRL level shown means requirements from previous levels are fulfilled. For example, to reach TRL 6 the technology has to have fulfilled all requirements from TRL 6, TRL 5, TRL 4, TRL3, TRL 2 and TRL 1.					

Figure 8 – Steps in the Qualification Process for the Power Cable Case Study



### 5.5 Qualification Plan - Feasibility Stage (TRL 2)

The power cable of the case study under qualification has new features as identified in the technology characterisation in Section 5.2.2. Based on the technology assessment Section 5.2 it is identified that no proof or detailed analysis to support the design is available in the proposed application. Furthermore, at this stage no application specific qualification testing is performed and so assumptions may exist on the behaviour of materials and components. Indeed, the local or global design may also have a range of initial assumptions.

Therefore, in line with the TRL guidance followed in this framework, the inputs for this stage are the design premise and the outputs are a feasible configuration, basic cross-section design and estimates of the loads anticipated considering the new features. The qualification plan is therefore entirely about undertaking preliminary analysis and design to get to the output, for example to undertake basic cross-section sizing, global configuration and electrical analysis.

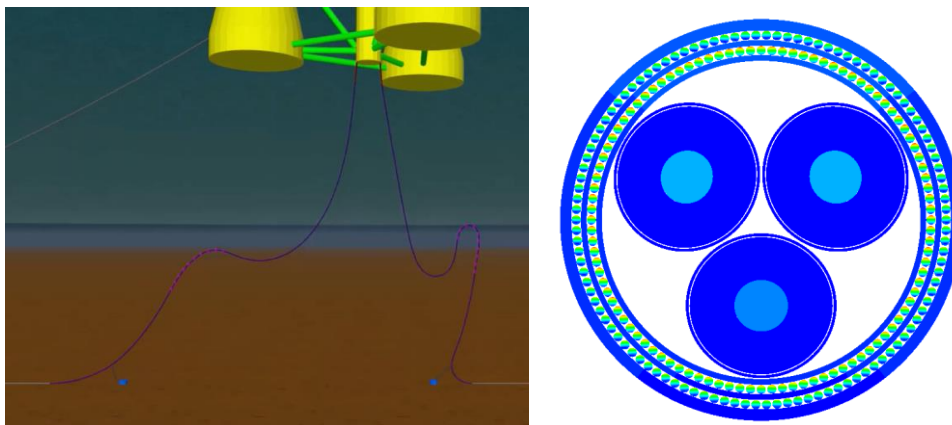
An outline of the cross-section design and Global Analysis required is detailed in Section 5.5.1.

### 5.5.1 Global and Local Cable Analysis

Inter array dynamic power cables are exposed to significant motions from the floating foundations that are hosting the tower and turbine arrangement. These cables are also exposed directly to extreme wave and current fluid loads. Numerical analysis can be used to determine the static and dynamic behaviour of the power cable when exposed to these conditions. Such analysis are normally defined as:

- **Global analysis:** includes the whole cable from platform connection to seabed interface, including buoyancy modules, bend stiffener and tethers (if present). OrcaFlex [15] is a commonly used global analysis tool. The cable is treated as a uniform structure, which can be checked against allowable tension, compression, and curvature limits.
- **Local analysis:** focusses on the cable cross section level, including all the cable subcomponents (sheaths, armour wire, conductor wires etc.). UFLEX [16] is an example of a local cable analysis software. Local analysis is used to extract the cable mechanical properties for input to the global analysis, and to check component stress and strain against design limits. It should be noted that the validity of UFLEX (or equivalent software) has to be underpinned by the component level qualification testing; otherwise, it is likely subject to error.

Figure 9 – Example of global analysis (left, using OrcaFlex) and local analysis (right, using UFLEX) for an example dynamic cable



Global analysis is usually the focus at the feasibility stage to perform a high-level design analysis to verify the concept. The assessment criteria of this stage only addresses some of the highest risk items identified in the Threat Assessment (Section 5.3), such as exceedance of tensile or bending limit. At this stage local analysis is not a requirement but might be carried out for preliminary input to the global analysis checks.

At the feasibility stage it might be that not all requirements are fully satisfied, but the analysis results indicate areas for improvement on the next stage, the Concept Validation given in Section 5.6.

More details on the global and local analysis methodology to be performed at each technology qualification stage is provided in Appendix 3 .

### 5.5.2 Thermal-Electrical Analysis

High level thermal-electrical analysis considering a simplified cross section of the cable is carried out at this stage to establish the cross section preliminary design. The outcome of the thermal analysis will significantly influence the mechanical analysis. For example, metallic materials are weakened at higher temperatures, fatigue strength is affected, polymers become less stiff, etc, which will all influence the

global response of the structure. Due to the low TRL level (TRL 1) it is expected that at this stage the same standard thermal-electrical analysis carried out for other high voltage static cables is applicable for the power cable of the case study.

The details of the thermal-electrical analysis are not within the scope of this document and are therefore not covered in as much detail as the mechanical aspects.

## 5.6 Qualification Plan - Concept Validation (TRL 4)

Once the power cable of the case study has met the requirements from the Feasibility Stage (Section 5.5), it starts the process to be qualified as “Concept Validated” (TRL 4), which means being validated in the lab. This includes analytical studies and laboratory studies to physically validate analytical predictions of the separate elements of the technology as well as integration of these components to establish that they will work together.

The overall system requirements defined at the Feasibility Stage (Section 5.5) are reviewed to confirm continued relevance. In addition, a preliminary manufacturing plan is developed.

The functional testing also considers and addresses some of the critical failure modes identified during the risk assessments (Section 5.3). For example, the FMECA [2] considered in this case study had identified catastrophic failure of the power cable due to material fatigue as high risk and this is addressed by the Individual Component Fatigue Tests proposed in Section 5.6.4.

For the new materials or those that can have a significant effect on the performance of the system, component tests (destructive or non-destructive) are used to identify the relevant failure modes and mechanisms or to explore the critical parameters and their effects, as described in Section 5.6.3.

For the dynamic power cable, activities in the qualification plan to validate the concept include testing of the subcomponents of the cable, such as the material used for the outer sheath or insulation.

The global analysis conducted at the Feasibility Stage is refined with outputs from the component tests and the individual component fatigue tests. Additional analysis is carried out, such as fatigue and interference analysis.

### 5.6.1 Global and Local Analysis

A more refined global analysis model is developed, based on more detailed information on operating conditions, and component test data.

The global loads from the analysis are provided to the suppliers of the ancillary equipment such as the bend stiffeners and bend stiffener connectors.

Fatigue assessment of metallic components (e.g. conductor wires, screen and armour) is usually performed at this stage. Interference analysis between the cable and other structures (e.g. floating platform hull, moorings, other cables) is also carried out. More details on the detailed aspects of global and local analysis is provided in Appendix 3 .

### 5.6.2 Thermal-Electrical Analysis

The same principles followed by the Global and Local Analysis apply to the thermal electrical analysis so that it is refined in comparison to the analysis carried out at the Feasibility stage (Section 5.5.2).

Although the power cables for floating wind are dynamic, the approach to thermal and electrical analysis at this stage is no different to static high voltage cables as applied in other similar applications

(e.g. fixed wind). Therefore, no detail is provided in this case study. However, it is key to consider in the thermal-electrical assessment the effect of the different cross-sections, environmental conditions, thermal conditions, interfaces, etc on the analysis outcomes. It should be noted that some of these inputs may be dependent on the dynamic loading output from the global/local assessments. Another consideration to be made is that specifically for power cables operating at their upper power limit, the operating temperature will affect the material properties of the cable.

Where there are specific aspects of the power cable that are novel (e.g. new materials) this needs careful attention so that the input properties to the thermal-electrical analysis are well understood, which in turn may define requirements for testing to establish these properties and calibrate the analysis.

Although the assumption of this case study is for 25 years of service life, for future potential lifetimes of approximately 50 years the thermal-electrical effects will affect the material properties further as ageing will become longer than the current 25-30 year requirement in oil and gas. For projects with extended field life the thermal-electrical aspects will be a key consideration, particularly for the highly dynamic environments.

The details of the thermal-electrical analysis are not within the scope of this document and therefore are not covered in as much detail as the mechanical aspects.

### 5.6.3 Component Tests

The power cable industry is rapidly growing and requires development of new cable designs to meet the challenging requirements, especially for the shallow water and harsh environment as per this case study. It is envisaged that this may require an introduction of new material, new cable cross-section or the extension of existing cable types to new sizes or ratings. To be qualified, the power cable may therefore require comprehensive testing of new materials, components, and production processes. Many of the new materials and concepts have been developed for underground cables before they were employed for submarine cables.

New polymers need to be evaluated under the specific conditions of dynamic power cables. Tests of dielectric strength, loss angle, leakage current, and dielectric response test, are used to characterize and screen insulation materials. These tests can often be performed on samples. Polymeric sheath materials used for insulation and outer sheath and cables are sometimes tested for their water vapour permeability, stability in salt water, abrasion resistance, carbon-black content, etc. However, in most cases, manufacturers use their well-proven sheath materials without the need for change.

For example, in dynamic cable applications, outer sheath/servings commonly made of polyethylene are extruded over the metallic armour wires to provide abrasion strength and mitigate corrosion. Introduction of any new material for outer sheath would need to satisfy the abrasion requirement from the following codes:

- ISO 9352 - Plastics — Determination of resistance to wear by abrasive wheels [54]
- ASTM D4060 – Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abrader [32]
- ASTM G176 – Standard Test Method for Ranking Resistance of Plastics to Sliding Wear Using Block-on-Ring Wear Test – Cumulative Wear Method [33]

In addition to abrasion, other factors such as thermal stability and strain limits shall be taken into account and satisfy the requirements of applicable standard requirements (e.g. IEC 60811).

In addition, the tests and recommendations from the codes above are used to address the medium risks identified for the outer sheath/serving in the FMECA [2] and shown in Table 10:

For the power cable of this case study the components technologically characterised as “4” in the Technology Characterisation in Section 5.2.2 shall be component tested or evidence that they have already been component tested shall be provided.

#### 5.6.4 Individual Component Fatigue Testing

To be able to estimate the fatigue life of the subcomponents of the cable, their specific S-N curves are required. Methods to develop a complete S-N curve are described in DNV-RP-F401 [47]. Testing shall be carried out at a minimum of three different stress/strain range levels. For the lowest stress/strain range it shall be aimed at obtaining fatigue lives of at least of the order of  $2 \times 10^6$  load cycles. For the highest stress/strain range it shall be aimed at obtaining fatigue lives of the order of  $10^4$  load cycles. A minimum of 5 valid test results shall be obtained for each stress/strain range level.

The test shall consider the range of temperature in service since temperature influences on the properties.

Another important area of focus described in DNV-RP-F401 [47] should be the friction factors to be applied between components.

More detailed guidance is given in DNV-RP-F401 [47].

If not known from previous projects or applications, the S-N curves for the following components of the power cable shall be estimated through individual component fatigue test in lab:

- Conductor
- Screen, helical applied copper wires or tapes
- Metallic screen
- Polymeric layers and tapers
- Armour layers (ASTM E739 [35] is relevant for this component)
- Fibre optics

If a qualified power cable only has minor changes in an individual component of the cross section, such as the described in Table 12, the modifications can be verified through component testing and the full-scale fatigue test does not have to be carried out in the Prototype Validation (Section 5.7.8).

For the case study, however, no previous qualification is available, therefore the individual component fatigue test shall be carried out at this stage and the full-scale fatigue test carried out at the Prototype Validation 5.7.8.

Table 12 - Recommendations for when design changes can be verified through Individual Component Fatigue Test [39]

Component	Modifications verified through component testing recommended by CIGRE TB 862
Conductor	Changes in conductor design such as compacting process, lay angles of strands or water blocking solution can typically be verified through component testing.

Screen, helical applied copper wires or tapes	Changes in manufacturing process or material that affect the component S-N curve can typically be verified through component fatigue testing. The behavior of a helically applied screen during cable bending is to a large extent affected by the external contact pressure onto the cores inside the cable. This makes it difficult to verify more substantial changes in the screen design through component testing.
Metallic sheath (water barrier)	Changes in manufacturing process that affect the component S-N curve can typically be verified through component fatigue testing.
Polymeric layers and tapes	Changes in dimensions, manufacturing process or material of polymeric sheaths and tapes can typically be verified through component testing with regards to friction coefficients and abrasion properties.
Armour layer / strength members	Changes in dimensions, material grade or manufacturing process that affect the S-N curve can typically be verified through component fatigue testing.
Fiber optic cable	Changes in dimensions, material grade or manufacturing process that affect the S-N curve can typically be verified through component fatigue testing.

### 5.6.5 Tests for Wet Designs (CIGRE TB 722)

For wet cable designs, CIGRE TB 722 [38] describes additional mandatory tests, which are not recommended by other CIGRE or IEC codes. These tests can either fail, requiring a redesign of the wet type dielectric, or pass, leading to a qualified cable design for wet applications. The mandatory tests in IEC 63026 [48] can be performed before, after or in parallel with the qualification tests given in Table 13. The case study presented in this document recommends the tests for wet designs from CIGRE TB 722 [38] are at least initiated at the Concept Validation, since they take around 2 years to complete.

As described in CIGRE TB 722 [38] users shall choose the ageing protocol (Regime A, B or C) according to their region and preference. However, CIGRE TB 722 [38] states that most widely accepted wet ageing protocols are at 50 Hz or 60 Hz and up to 2 years duration (Regimes A & C) and that in some countries a shorter duration testing protocol at 500 Hz frequency (Regime B) has been used. There is published literature indicating that some power cable vendors have experience with both 500Hz and 50Hz testing of 66kV HV [23], with good equivalence, especially when compared in terms of average electrical stress at breakdown.

Findings from Regime A for a 66kV power cable with aluminium core can be seen in [18], from FLOATANT, and the same Regime A is proposed for the power cable of this case study.

Compliance with the tests in Table 13 is required to demonstrate that the dielectric (insulation materials), when saturated, retains sufficient dielectric strength to allow the insulation material to operate at the intended design dielectric stress,  $E_{design}$ , of the cable when continuously immersed in sea water throughout its service life.  $E_{design}$  stands for the intended operating dielectric stress at the conductor screen.

The power cable of the case study is a wet design and therefore must pass the tests given in Table 13.

Table 13 – Qualification of Wet Dielectrics from CIGRE TB 722

Test Category	Test	Reference for Test Procedure	Relevant Sections
Qualification of Wet Dielectrics	Accelerated Ageing of Dielectric	CIGRE TB 722	Section 3.6.3
	Residual Dielectric Strength	CIGRE TB 722	Section 3.6.4

### 5.6.6 Monitoring

At this stage any monitoring concept based on the fibre optics within the cross section of the cable is designed and tested.

Note that fibre optic design and testing are not within the scope of this document and are therefore not covered in detail.

## 5.7 Qualification Plan - Prototype Validation (TRL 6)

Following the Concept Validation stage (Section 5.6), if all requirements are met, the power cable of the case study starts the activities to reach TRL 6. At the end of the Prototype Validation stage all engineering studies and design risk assessments are completed and the cross section is refined to the detailed design. This stage of the qualification is the last which involves only the vendor of the power cable. To qualify with TRL higher than 6 the end user of the power cable has to actively participate in the process and the qualification becomes project specific.

A prototype or full-scale power cable unit is manufactured and all necessary qualification testing is carried out. The activities of the qualification plan for Prototype Validation involve a series of type tests and to complete these following IEC 63026 [48], the characteristics of the cables given in Appendix 9 shall be known.

The only very high risk identified in the FMECA [2] considered in this case study is the catastrophic failure of the cable due to exceedance of compressive capacity, buckle of armour wires or internal cable cores and this is addressed by the mechanical type tests proposed in Section 5.7.4. This framework includes the Combined Axial Compression and Bending Test and Axial Compression Test proposed by CIGRE TB 862 [39] to verify compression on the power cable. These tests are very recent recommendations from CIGRE since TB 862 was released in January 2022.

The qualification plan of this stage also includes full-scale fatigue testing (Section 5.7.8).

### 5.7.1 Global and Local Analysis

At this stage the power cable cross section is at the detailed design phase. Uncertainties on the inputs of the power cable are minimised due to the tests carried out such as the characterisation tests in Section 5.7.3.

### 5.7.2 Thermal-Electrical Analysis

The same principles followed by the Global and Local Analysis apply to the Thermal-electrical analysis which is further refined in comparison to the analysis carried out at the Concept Validation stage (Section 5.6.2). The outputs from the analysis are used to support the electrical type tests described in Section 5.7.5.

The details of the thermal-electrical analysis are not within the scope of this document and are therefore not covered in as much detail as the mechanical aspects. However, it is worth highlighting some key points to be considered in relation to the interaction between the mechanical and the thermal-electrical properties:

#### Bend Stiffener

During operation the bend stiffener insulates and therefore increases the temperature of both the enclosed cable as well as the bend stiffener itself. This is made worse by the fact that the bend stiffener

is typically attached to a J-tube (or I-tube) where the ability of the seawater to act as a heat exchanger is limited.

The band stiffener and J-tube can often limit the current carrying capacity of the conductor, and therefore the power capacity of the cable system as a whole. There is a drive to push the cable temperature as high as possible to increase the power capacity. If the temperature goes above limits, the risk of accelerated degradation or outright failure of the bend stiffener and cable components is increased

Thermal finite element analysis is used to predict bend stiffener and cable core temperatures; however, the analysis is sensitive to a wide range of modelling uncertainties. Therefore, the analysis margins are slim and the need for physical test validation of the thermal analysis is critical for dynamic cables.

### Hysteretic Bend Moment-Curvature Relationship

The moment-curvature relationship is affected by temperature, therefore outputs from the thermal-electrical analysis shall be taken into consideration in the Characterisation Tests (described in Section 5.7.3).

#### 5.7.3 Characterisation Tests

Characterisation tests are performed to measure key parameters of the dynamic power cables so that uncertainties related to input data can be minimised in the global and local analysis. The characterisation tests given in CIGRE TB 623 [37] and CIGRE TB 862[39] are given in Table 14.

The outputs from the characterisations are used in the global and local analysis, as described in Section 5.7.1.

Further information about each test is given in Appendix 4 .

Table 14 – Dynamic Power Cable Qualification – Characterisation Tests

Test Category	Test	Reference for Test Procedure	Relevant Sections
Characterisation Tests	Bending Stiffness Test	CIGRE TB 862	Section 6.4.2
	Tensile Characterisation Test	CIGRE TB 623	Section 6.10
	Friction Coefficient Test	CIGRE TB 623	Section 6.11

#### 5.7.4 Mechanical Type Tests

Something particular about the power cable, which shall be considered in the execution of the qualification plan, is that the order of the tests is of key importance to capture both the mechanical and electrical requirements of the power cable. Power cable mechanical testing while subject to high voltage and/or wet conditions at the same time is usually not possible and is currently not a code requirement, therefore, one shall be followed by the other to capture both, as shown in the schematic of Figure 10.

A dynamic cable installed in shallow water depths as in the North Sea is likely to be subjected to axial compression, i.e. negative tension, due to dynamic motion of the cable and of the platform. Therefore the Combined Axial Compression and Bending Test and the Axial Compression Test suggested in CIGRE TB 862 [39] (but not part of the type tests given in IEC 63026 [48]) are recommended and included in this framework. It is proposed that both tests from CIGRE TB 862 are carried out as part of the mechanical type tests, as shown in Figure 10. These tests address the high risk identified in the FMECA [2] (Section 5.3) of exceedance of compressive capacity, buckle of armour wires or internal cable cores.

As known from oil and gas experience and explained in CIGRE TB 862 [39], when a cable is exposed to axial compression, a negative tension is created in the load bearing components, primarily the armour wires and conductors. Negative tension on the armour wires will create a radial force outward which potentially could lead to failure of the outer sheath (e.g. bird-caging). If the outer covering is sufficiently strong, negative tension could instead lead to local buckling. Compressive loads in combination with cyclic bending of the cable has been found to be a mechanism that can trigger lateral buckling of the armour wires. Buckling of the armour wires is not acceptable for a dynamic cable since it will affect the stiffness, load carrying capacity, fatigue, and torsional stability of the cable.

The requirements for compression testing should be considered carefully. Static tests with short samples are readily achievable, however longer length dynamic testing is difficult to achieve, expensive and not well defined.

The case study is based on a power cable without previous experience or validation; therefore, the compression tests are proposed at the Prototype Validation Stage. For experienced vendors, the compression tests could be treated as a characterisation test (Section 5.8.2) and only be repeated if requirements from a specific project are pushing the current boundaries in terms of compression.

The mechanical type testing summarised in Table 15 is carried out with sample 1, which will be subsequently subjected to the electrical type tests described in 5.7.5.

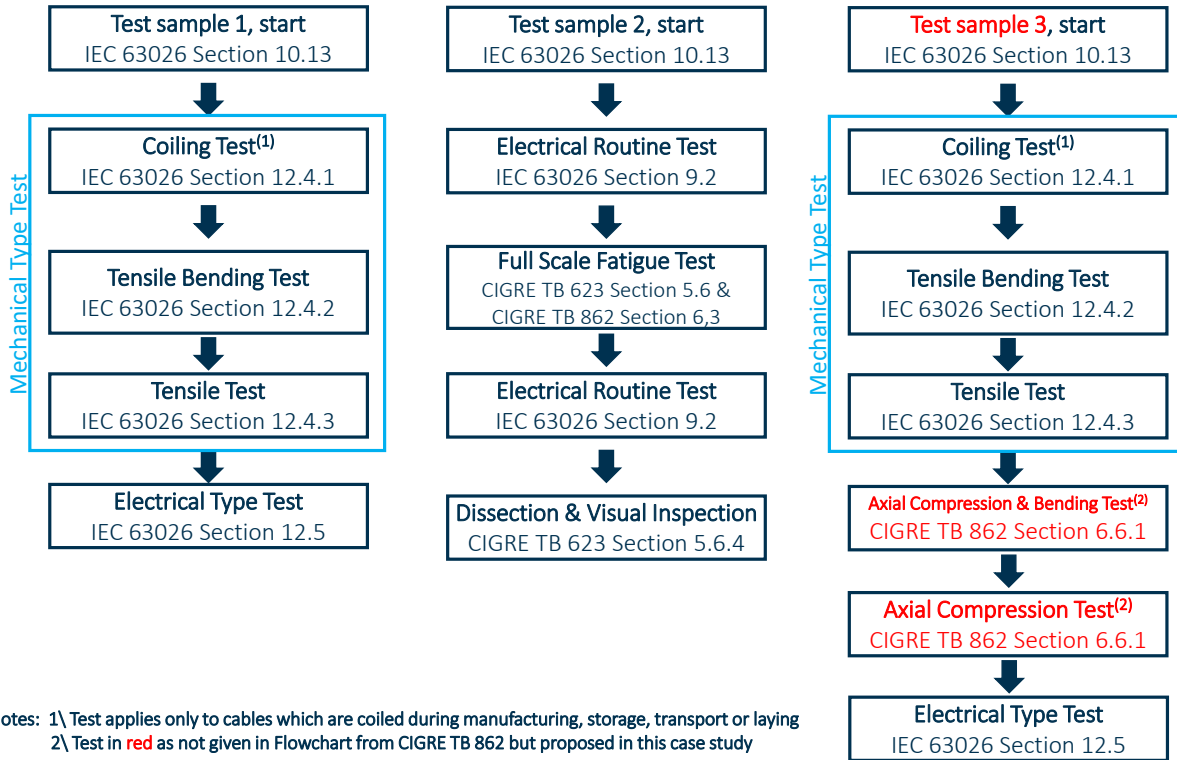
Further information about each test is given in Appendix 5 .

Table 15 – Dynamic Power Cable Qualification – Mechanical Type Tests

Test Category	Test	Reference for Test Procedure	Relevant sections
Mechanical Test	Coiling Test <sup>(1)</sup>	IEC 63026	Section 12.4.1
		CIGRE TB 623	Section 5.1
	Tensile Bending Test	IEC 63026	Section 12.4.2
		CIGRE TB 623	Section 5.2
	Tensile Test	IEC 63026	Section 12.4.3
		CIGRE TB 623	Section 5.5
	Combined Axial Compression and Bending Test <sup>(2)</sup>	CIGRE TB 862	Section 6.6.1.3
	Axial Compression Test <sup>(2)</sup>	CIGRE TB 862	Section 6.6.1.4
Notes:			

- 1\ Applies only to cables which are coiled during manufacturing, storage, transport or installation.
- 2\ Given in CIGRE TB 862 as “Other Tests”

Figure 10 – Flow Chart of the Test Sequence of Mechanical and Electrical Tests on Dynamic Cable (Modified from [39])



Notes: 1\ Test applies only to cables which are coiled during manufacturing, storage, transport or laying  
 2\ Test in red as not given in Flowchart from CIGRE TB 862 but proposed in this case study

### 5.7.5 Electrical Type Test

The electrical type tests for the dynamic power cable qualification are summarised in Table 16. Samples for the electrical tests shall be taken from the cable subjected to the previous mechanical type tests given in 5.7.4.

Prior to the electrical type tests the insulation thickness is measured following the method given in IEC 60811-201.

Further information about each test is given in Appendix 6 .

Table 16 – Dynamic Power Cable Qualification – Electrical Type Tests

Test Category	Test	Reference for Test Procedure	Relevant Sections
Electrical Type Test	Partial Discharge Test	IEC 63026	Section 12.5.3
		CIGRE TB 490	Section 8.8a & Section 8.8d
	Tan $\delta$ Measurement Test	IEC 63026	Section 12.5.4
		CIGRE TB 490	Section 8.8b
	Heating Cycle Voltage Test	IEC 63026	Section 12.5.5
		CIGRE TB 490	Section 8.8c
	Lightning Impulse Voltage Test	IEC 63026	Section 12.5.6
		CIGRE TB 490	Section 8.8f
	Resistivity of Semi-Conductive Screens Test	IEC 63026	Section 12.5.8
		CIGRE TB 490	Section 8.8j

### 5.7.6 Non-Electrical Type Test on Cable Components and on Complete Cable

Non-electrical type tests are an integral part of the cable fabrication to ensure that necessary standards and qualification plans are followed and manufactured as per required standards. The list of non-electrical type tests that may be performed as part of this case study are shown in Table 17. The tests shall be carried out on all cores.

According to IEC 63026 [48] the non-electrical type tests on cable components only need to be carried out on samples from cables of different voltage ratings and/or conductor cross sectional areas if different materials and/or different manufacturing processes are used to produce them. However, repetition of the ageing tests on pieces of complete cable to check compatibility of materials may be required if the combination of materials applied over the screened core is different from that of the cable which type tests have been carried out previously (Sections 5.7.4 and 5.7.5).

As a minimum the test which is affected by the design change (water penetration test) shall be repeated.

For the case study, since it is a new power cable design, all non electrical type tests in Table 17 shall be carried out.

Table 17 – Dynamic Power Cable Qualification – Non-Electrical Type Tests on Cable Components and on Complete Cable

Test Category	Test	Reference for Test Procedure	Relevant sections
Non-Electrical Test on Cable Components and on Complete Cable	Check of Cable Construction	IEC 63026	Section 12.7.2
		CIGRE TB 490	Section 8.9.1
	Mechanical Properties of Insulation (Before and After Ageing)	IEC 63026	Section 12.7.3
		CIGRE TB 490	Section 8.9.2
	Mechanical Properties of Over-sheaths (Before and After Ageing)	IEC 63026	Section 12.7.4
		CIGRE TB 490	Section 8.9.3
	Compatibility of Materials	IEC 63026	Section 12.7.5
		CIGRE TB 490	Section 8.9.4
	Pressure Test at High Temperature for ST7 Over-sheaths	IEC 63026	Section 12.7.6
		CIGRE TB 490	Section 8.9.6
	Ozone Resistance Test for EPR and HEPR Insulations	IEC 63026	Section 12.7.7
		CIGRE TB 490	Section 8.9.9
	Hot Set Test for EPR, HEPR and XLPE Insulations	IEC 63026	Section 12.7.8
	Measurement of Carbon Black Content for Black PE Outer Sheaths	IEC 63026	Section 12.7.9
	Tests on Components of Cables With a Longitudinally Applied Metal Tape or Foil, Bonded to the Oversheath	IEC 63026	Section 12.7.10
	Water Absorption Test for Insulation	IEC 63026	Section 12.7.11
	Shrinkage Test for XLPE Insulation	IEC 63026	Section 12.7.12
	Determination of Hardness for HEPR Insulation	IEC 63026	Section 12.7.13
Determination of Elastic Modulus for HEPR Insulation	IEC 63026	Section 12.7.14	
Shrinkage Test for PE Oversheath	IEC 63026	Section 12.7.15	

**5.7.7 Longitudinal / Radial Water Penetration Test**

The longitudinal/radial water penetration tests are summarised in Table 18. Samples for these tests shall be taken from the cable subjected to previous mechanical type tests. The test object shall be

preconditioned by at least three heating cycles, ensuring the cable has experienced the proper thermal expansion [36].

As highlighted by CIGRE TB 862 [40], the conductor and metal screen water penetration tests are longitudinal water penetration tests relevant for a scenario where a cable has been damaged and must be repaired. The tests seek to verify that the length of cable that must be cut out and replaced due to longitudinal water penetration is within acceptable limits. A dynamic cable section, as for the case study, will generally not be subject to a field repair and will normally be removed and replaced in its entirety, potentially negating the need for these tests.

Table 18 – Dynamic Power Cable Qualification – Longitudinal/ Radial Water Penetration Tests

Test Category	Test	Reference for Test Procedure	Relevant sections
Longitudinal / Radial Water Penetration Tests <sup>(1)</sup>	Conductor	IEC 63026	Section 12.6.2
		CIGRE TB 490	Section 8.7.2
	Metal Screen	IEC 63026	Section 12.6.2
		CIGRE TB 490	Section 8.7.2
Note 1: tests not needed for the power cable of the case study since generally not subjected to a field repair.			

### 5.7.8 Full-Scale Fatigue Test

The fatigue tests are summarised in Table 19. Samples for the fatigue test shall be taken from a cable subjected to electrical routine tests defined in IEC 63026 [48] Section 9.2 (PD Test and Voltage Test), as shown in Figure 10.

Guidance about how global/local analysis supports the fatigue tests is detailed in Section 5.7.1. The main purpose of the dynamic fatigue test is to evaluate the structural fatigue performance of a power cable.

A fatigue test can be used to achieve one or more of the following objectives:

- qualify a power cable for dynamic service,
- verify manufacturer stated fatigue performance, and
- validate service life design methodology and tools.

Because the full-scale fatigue test is complex, expensive and time consuming, there are some changes to the individual components of the cable that can be assessed through individual component fatigue testing, avoiding the full-scale, as described in the Individual Component Fatigue Testing Section 5.6.4, Table 12. However more substantial design changes require the fatigue test to be repeated, such as those that affect geometry (e.g. OD, angles), contact pressures onto the components and how the components interact [39]. These may be caused by changes to the cable construction, or how the cores are assembled (manufacturing process, lay angles, etc). Generally, if a change in an individual component does not significantly affect the interaction with other components, then full-scale fatigue testing does not need to be repeated and individual component testing can be carried out to provide

the necessary qualification. Modifications to the power cable that result in need for a full-scale fatigue test are given in Table 21.

For the case study scenario, full-scale fatigue testing is carried out to qualify a power cable for dynamic service. Fatigue is a significant driver for the cable performance, and therefore qualification testing is a key part to confirming the cable cross-sections resistance to fatigue loads and/or that the cross-section fatigue design tools are accurate.

For example, the test facility available at OREC (see Figure 11) is able to simulate the required fatigue cycles at a set load to replicate the power cable behaviour in the field conditions. Full scale testing shall be performed according to the minimum requirements provided in [37]. A safety factor shall be agreed between the purchaser and the manufacture [39], but typical values vary from 3 to 10.

As per CIGRE TB 623 [37] the number of cycles within each block (representing different bending radius and number of cycles) is adjusted to achieve total accumulated fatigue damage equal or greater than the expected fatigue damage during service life. Therefore the fatigue test conditions shall represent the worst case expected loading. Based on this, failure is not expected therefore demonstrating the cable is fit for the fatigue conditions and no gross design or manufacturing errors are present.

After the full-scale fatigue test, an electrical routine check and a full visual inspection of the cable shall be carried out to identify non-conformance and damages. The integrity of the optical fibre shall be verified through a continuity check. The list of tests that need to be performed post fatigue test to ensure the integrity of the cable is given in Table 20.

Table 19 – Fatigue Tests

Test Category	Test	Reference for Test Procedure	Relevant sections
Fatigue Test	Full-Scale Fatigue Test	CIGRE TB 623	Section 5.6
		CIGRE TB 862	Section 6.3

Table 20 – Post Fatigue Test [48]

Test Category	Test	Reference for Test Procedure	Relevant Sections
Electrical Routine Test (Post Fatigue Test)	Partial Discharge	IEC 63026	Section 9.2.1
	Voltage Test	IEC 63026	Section 9.2.2
	Shrinkage test for PE outer Sheath	IEC 63026	Section 12.7.15
Visual Inspection	Visual Inspection	CIGRE TB 623	Section 5.6.4

Table 21 – Modification where Full-Scale Fatigue Test is recommended [39]

Component	Modifications where Full-Scale Fatigue Test is recommended by CIGRE TB 862
Conductor	Larger conductor cross section. Change of conductor type from compacted to keystone or vice versa. Change of conductor material (copper to aluminium for example).
Screen, helical applied copper wires or tapes	Change from tape to wire or vice versa. Larger outer diameter of screen layer. Larger distance from cable centre point to outside of screen wire. Substantial modification of lay angles, wire diameter or distance between wires. Substantial changes of tape application or overlap.
Metallic sheath (water barrier)	Larger outer diameter of sheath. Larger distance from cable centre point to outside of sheath. Change of sheath material. Introduction or removal of adhesive bonds. Substantial change in thickness of sheath. Substantial change of adhesive bond properties. Change from corrugated sheath to smooth or vice versa.
Fillers	Change of rope to shaped filler or vice versa. Change of filler design or material that substantially changes the contact force distribution onto the cores or fibre optical cable.
Polymeric layers and tapes <sup>(1)</sup>	Removal of existing layer. Substantial change in layer thickness, friction coefficient or modulus.
Armour layer / strength members	Change of armour wire geometry, from round to flat or vice versa. Change in number of armour layers. Change of armour material (metal to composite or vice versa or affecting modulus by more than 10%). Adding or removing bitumen on armour layer. Change in lay angles, dimensions or number of wires that substantially increases the contact force onto the layers beneath.
Fiber optic cable	Substantial change in fibre optical cable design or position in cable.
Note: 1\ This table is taken from CIGRE TB 862 [39]. This framework recommends that changes to the insulation be treated as polymeric layers and tapes.	

Figure 11 - Fatigue Testing Rig at OREC Facility



## 5.8 Qualification Plan - System Integration (TRL 8)

Considering the power cable of the case study has completed all previous stages and has reached TRL 6, it can start the System Integration stage.

When the power cable of the case study gets to this stage, it means it has passed all type tests from IEC 63026 [48] and the full-scale fatigue test. It is, therefore, qualified and can be installed in a floating offshore wind farm. The same power cable from this case study, which has reached TRL 6, could be used in different projects as far as the requirements from the activities proposed in this System Integration Stage of the qualification framework are met.

Global analysis is carried out to verify the loads from the specific project are within the envelope that the power cable was previously qualified for.

The qualification plan of this stage includes tests that are specific to the end user, therefore project specific, as described in Section 5.8.2. It also includes the tests to verify the interaction between the power cable and ancillary equipment given in Section 5.8.3.

At the end of this the power cable is qualified as TRL 8 and has been installed within the final operating system and operating environment.

### 5.8.1 Global and Local Analysis

At this stage the global analysis is repeated considering the final design of the ancillary equipment (bend stiffeners, tethers, etc.). Full consideration of the combined floating foundation, tower, turbine and mooring line response is considered to reduce conservatism and uncertainty.

Additional project specific tests are proposed in Section 5.8.2 to support inputs for the global analysis and reduce uncertainties: cable soil interaction and marine growth measurement. It is recommended that project specific data for marine growth is used in the System Integration stage.

Installation analysis is carried out considering the installation vessel selected for the project.

### 5.8.2 Project Specific Tests

Type tests are sufficient to verify the design of the cable and ancillary equipment. However, some tests depend on project specific requirements, as described in CIGRE TB 623 [37], and listed in Table 22.

If a dynamic inter array power cable has already been qualified to TRL 8, examples of specific situations that may require to be considered with project specific tests are [37]:

- Deeper water depth or different environments like seabed conditions
- New type of cable storages, roller ways, pulling or breaking devices or other equipment
- New type of laying, installation, protection or repair method or configuration

The power cable of the case study is a new cross section to be installed in a new site therefore all tests from Table 22 shall be carried out.

One additional test that has been included in this framework is the Cable soil Interaction Test. This test is not currently covered by any codes but is relevant to correctly model the soil friction coefficients and trenching characteristics. These parameters can be important to accurately calculate the fatigue damage at the touchdown zone region of the cable. Generic assumptions of the soil friction coefficients from oil and gas codes (e.g. DNV-RP-F114) can lead to inaccurate results, since geotechnical and material characteristics may be different. In current floating offshore wind projects, a stable TDP has been achieved using clamps. However, as floating projects increase in scale (> 50 WTGs), the reduction in complexity of the power cable by avoiding clamps can reduce installation time and costs.

Regarding marine growth, CIGRE TB 862 states that codes from oil and gas may not be directly applicable to sites where floating wind farms are intended to be installed. Another factor that may affect the marine growth profile in HV dynamic inter array cables is the temperature influence. Therefore another test that is proposed in this case study is the marine growth measurement. This shall be included in the Metocean report specific for the site of the project and the cross section of the power cable.

Defining the methodology for performing the cable soil interaction test and the measurement of marine growth is not within the scope of this report, however from oil and gas experience it is known that there are feasible tests available to determine soil interaction parameters.

A test commonly carried out in oil & gas which is also applicable for dynamic inter array power cables is a tensioner trial, as outlined in API 17E [30]. This is often of particular interest in deep water, therefore not included in this case study, but should be considered for qualification of power cables for areas of deeper water depth.

Further information about each test is given in Appendix 7 .

Table 22 – Dynamic Power Cable Qualification – Project Specific and Special Tests

Test Category	Test	Reference for Test Procedure	Relevant Sections
Project Specific Tests and Special Test	Bending Test Without Tension	CIGRE TB 623	Section 6.2
	Crush Test	CIGRE TB 623	Section 6.3
	Crush Test for Long Term Stacking	CIGRE TB 623	Section 6.4
	Sidewall Force Test	CIGRE TB 623	Section 6.5
	Impact Test	CIGRE TB 623	Section 6.6
	Pulling Stocking Test <sup>(1)</sup>	CIGRE TB 623	Section 6.7
	Cable soil Interaction Test	Proposed by 2H	NA
	Marine Growth	Proposed by 2H	NA

Notes: 1\ not carried out for the case study

### 5.8.3 Other Tests from CIGRE TB 862 (Interface with Ancillary Equipment)

Relevant tests, applicable to the case study, that are not part of the type tests given in IEC 63026 [48] and CIGRE TB 623 [37] have been included in CIGRE TB 862 [39] and are summarised in Table 23.

These are additional mechanical tests related to the loading conditions resulting from dynamic applications and interaction with ancillary equipment, and are therefore recommended to be carried out for the power cable of this case study.

Table 23 – Other Applicable Test from CIGRE TB 862 [39]

Test Category	Test	Reference for Test Procedure	Relevant sections
Other Applicable Tests	Clamp Squeeze Test	CIGRE TB 862	Section 6.6.2
	Clamp Slippage Test	CIGRE TB 862	Section 6.6.3

### 5.8.4 Monitoring

At this stage the case study assumption is that the monitoring concept is installed externally to the cable (e.g. motion and position sensors strapped to the sheath or buoyancy module) and is designed for the specific project application. However, it is noted that monitoring embedded in the power cable may be present and fulfil the requirements.

## 5.9 Qualification Plan - Operational (TRL 9)

Considering the power cable of the case study has completed all previous stages and has reached TRL 8, it can start the last stage of the cable framework qualification process, which is the Operational Stage. At the end of this stage the cable reaches TRL 9 and is qualified as “Operationally Qualified”.

To be qualified as TRL 9 means the cable has been integrated into the final system and has been operating successfully in service in the relevant operational environment for at least 3 years.

The activities of the Operational Stage are as follows [24]:

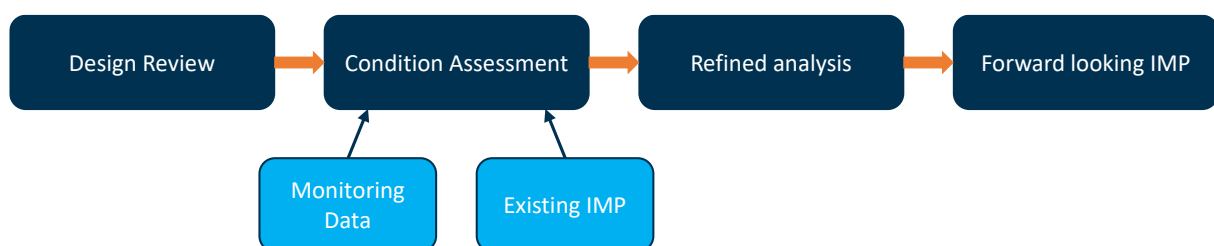
- Implementation of in-service survey, inspection and monitoring plans
- Collection and analysis of operational performance data
- Comparison of operational data above with previously specified performance requirements, goals and criteria
- Performance of root cause analyses for any observed failure and using feedback to introduce modifications for improvement
- Comparison of observed parameters with any critical assumptions made during the previous qualification stages and updating calculations as necessary

The qualification plan for the Operational Stage includes monitoring activities (Section 5.9.2) and global and local analysis (Section 5.9.1) to use the measured data to verify and confirm the performance of the system.

### 5.9.1 Global and Local Analysis

The global model is calibrated with measurements from the monitoring campaign and rerun to confirm results from previous stages remain valid. Based on the results, the integrity management plan (IMP) is updated to ensure long term reliability. The quality of a risk-based inspection plan is dependent on knowledge of the system.

Figure 12 - Analysis Refinement Example



### 5.9.2 Monitoring

With the cable in service, it is possible to validate prior assumptions and predictions through monitoring.

Monitoring campaigns are carried out to measure the dynamics of the cable and correlate with the expected operational envelope. Electrical measurements are also carried out to confirm that the losses and heat are within the design conditions.

The following is recommended to be monitored:

**Environmental Data:**

- Wind Speed (velocity and speed)
- Wave Data (significant wave height, wave peak period, and direction)
- Current speed and direction

**Structural:**

- Strain (fibre optic or external)
  - Inclination as an alternative
- 6 DOFS at key locations (accelerometers)
- Visual Inspection
- Marine growth thickness and density as a function of depth and versus time

**Electrical:**

- Offline monitoring: periodic offline monitoring of insulation resistance (IR) and partial discharge (in the end of the 2<sup>nd</sup> year) [2]
- Power

**Thermal**

- Temperature

In addition to the above, the digital twin is proposed for structural monitoring of the power cable of this case study. With the help of sensor data and machine learning, digital twin technology can be an efficient and economical method of monitoring and inspecting a large number of power cables in offshore wind platforms, which is the context of the power cable of this case study. Digital twins have been proven to work well in the oil and gas industry and have been used for integrity management of riser systems. Benefits include monitoring mooring lines, power cables and platform structures in real-time, minimising the cost of instrumentation, tracking and forecasting extreme events and fatigue, and ultimately preventing costly failures and unplanned shutdowns.

There are common condition monitoring technologies methods available, many of which have been proven for bottom-fixed wind and theoretically will work for dynamic cables but are yet to be widely demonstrated or tuned to floating applications. Examples are as follows:

- Distributed temperature sensing (DTS) utilises fibre optic cable that is already integrated into the cable, and monitors the cable temperature along its length
- Distributed acoustic sensing (DAS) utilises fibre optic cable that is already integrated into the cable, and can detect cable obstructions e.g. due to dropped objects.
- Partial discharge (PD) monitoring, which requires additional hardware. When carried out continuously (online) early warning of insulation damages caused from partial discharge can be detected, as well as increasing the understanding of cable response to loads and temperatures

- Line impedance resonance analysis (LIRA) can detect cable degradation due to a range of reasons (e.g. impact, moisture ingress, temperature damage). This is currently performed offline but in-situ; online LIRA monitoring has been demonstrated on onshore sites but not yet demonstrated offshore at 33 kV or higher
- Power quality (PQ) monitoring requires additional hardware and can monitor voltage drops and other aspects of the power quality such as flicker and oscillations. This could be performed at the substation or at each turbine
- Visual inspection via ROV to monitor cable position
- Direct measurement of cable position or movement using inclinometers on the cable or bend stiffener to measure cable angle and elevation at the platform interface. Alternatively, accelerometers or curvature sensors could be used
- Inferred cable motion monitoring via platform position and angle monitoring using Global Positioning Systems (GPS) or Motion Reference Units (MRUs), or by using hydrophones or sonar to record distance between cable and platform.

Where the monitoring technology is embedded in the cross-section, it is necessary that the monitoring technology itself is subject to sufficient qualification and that the complete cable cross section is also qualified with the embedded technology.

### 5.9.3 Commissioning Tests

As per IEC 63026 [48] the following tests are carried out when the installation of the cable system has been completed:

- DC Voltage test of the oversheath
- AC voltage test of the insulation
- DC voltage test of the insulation
- Time Domain Reflectometry (TDR)

## 5.10 Execution of the Plan

The technology qualification plans described from Section 5.5 to 5.9 are executed. The mechanical and electrical type tests are executed at relevant test houses and by teams with suitable capability. It is important that all tests are well documented for verification by the certification body. At the end of each stage, the qualification plan of the next stage is reviewed to make any relevant adjustments.

## 5.11 Performance Assessment

The success of the technology qualification plan is measured by comparing the results against the acceptance criteria established from the Qualification Basis. The technology is considered qualified when both risk and uncertainty have been reduced to acceptable levels. It is assumed at each TRL level that this process is successfully completed.

## 5.12 Discussion

At the beginning of this project, the objective was to prepare a framework and test it in the form of a case study. Attempting to do as proposed initially proved inefficient; a framework separated from the specifics of the case study would be a repetition of what is already available from DNV [43], ABS [24] and other certification bodies. The alternative approach developed in this report was to build the framework and case study together, with one feeding back to the other, as shown in Figure 13.

From the code mapping exercise, which is reported in a separate Technology Qualification Review and Mapping report [3], it has been understood that the analysis and tests to be carried out to qualify a dynamic inter array HV power cable are not clearly defined in a single code, but are a combination of many documents with guidance and recommendations. IEC 63026 [48] is the base for the qualification of dynamic power cables however based on engagement with the industry (power cable vendors and testing facilities) it became evident that additional tests from CIGRE are also recommended to increase the knowledge of the behaviour of the cable and improve its reliability through life.

The case study of the power cable demonstrated how the proposed framework, which is quite generic, becomes very specific for the power cable when the activities for qualification are assigned to each stage of the process. TRL levels can be subjective, therefore the importance of having well documented evidence to support the fulfilment of the criteria for each TRL stage is highlighted.

Figure 13 – Case Study versus Framework Relationship



Some lessons learned from the exercise of testing the framework with a generic high voltage dynamic inter array cable are the following:

### General:

- While there are currently industry codes and standards for performing qualification work (e.g. ABS, DNV, BV, etc), the qualification of power cables is very complex due to all the individual components of the system. Therefore, the case study was a very useful exercise to map the activities required for qualification of each specific stage of the qualification plan and also to understand how to move from one TRL level to the next. It shows that in order to move through all TRL stages, it must be demonstrated that the requirements of each preceding TRL level has been met. However, previous experience within floating wind or other similar areas may be used to demonstrate that some of the requirements are already achieved with prior qualification testing, or can be achieved with a reduced amount of testing.
- Although the framework is tested on a generic case-study, selection of the case study and the assumptions that underly are found to influence the outcome heavily. As such, although it is possible to define a standard framework for approaching the qualification of power cables, how this is implemented into a qualification plan will vary greatly between the specific vendors and developers. This variation will be based on vendor's/developer's previous similar qualification and/or field experience, the maturity and calibration of the design tools, the specific cross-section designs and many other factors. Therefore each qualification plan must be developed based on the outcome of the qualification framework process and no standardised qualification plan is possible.

- There are potentially a large number of different tests that are required to qualify the HV dynamic inter array power cable, each being of varying complexity, duration and cost. It is recommended that the qualification plan carefully considers how the most complex, long term and costly tests (e.g. full-scale tests) can be planned and executed in order to both minimise the number of these tests for a specific cable design, but also to allow the qualification to be extended in the event of design changes (e.g. different loading regimes, different cross-sections) without the need for repeating all the tests. This is an area for further industry collaboration.
- The case study follows the qualification framework and only becomes project specific at the System Integration Stage. Until TRL 6 (Prototype Validation) it is carried out by the vendor alone. However, if a power cable is to be qualified for a specific project from the beginning of the process some activities in terms of analysis could be optimised and save cost and time. The global analysis can be carried out in 3 stages: Feasibility, FEED and detailed design, as shown in Table 24, while currently the framework proposes analysis in 4 stages.
- Conversely, the vendors should ensure that when qualifying a cable up to TRL 6 that they develop the qualification for a wide range of applicability (e.g. loading etc) to assist in making the qualification process efficient at the project specific stage.
- On the basis of the above, if vendor and end user work together on the qualification framework of the power cable from the beginning, they can discuss and define together what modifications to make to the system if any requirement is not met along the process. It depends on experience to define whether the cable cross section or the wider global cable configuration, or even the mooring line design, shall be adjusted to reach a working solution. Many times, the configuration can be optimised through analysis to meet the requirements (MBR, tension, compression, etc), but due to the lack of track record in floating wind, it might be the case that the review of the cross section is the most cost efficient solution, especially if this change is done before the type tests and full-scale fatigue test.

Table 24 – Project Stages

	Feasibility (TRL 2)	Concept Validation (TRL 4)	Prototype Validation (TRL 6)	System Integration Stage (TRL 8)	Operational Stage (TRL 9)
Cable Cross Section	Feasibility	FEED	Detailed Design		
Cable Configuration	Feasibility		FEED	Detailed Design	

**Feasibility Stage (TRL 2):**

- Although CIGRE TB 862[39] has been released to close a gap and discuss the importance of structural analysis of submarine cables for dynamic applications, no similar guidance is available to discuss thermal-electrical analysis of the power cable. Similarly to the structural aspects, the thermal-electrical properties of the power cable also have to pass some type of initial feasibility assessment. The case study for the power cable, therefore, includes thermal-electrical analysis as one of the activities of the qualification plan. The thermal-electrical analysis starts at the Feasibility Stage (Section 5.5) and continues until the Prototype Validation Stage, when the cross section gets to the detailed design.

**Concept Validation Stage (TRL 4):**

- The Tests for Wet Designs from CIGRE TB 722 [38] take at least to 2 years to complete and, in addition to the requirements of standard IEC 63026 [48], are mandatory for cables classified as “wet”. This framework recommends they start at the Concept Validation stage but suggests they can be finished at the prototype stage, when all other type tests from IEC are carried out.
- If a qualified power cable only has minor changes in an individual component of the cross section, it may be possible that the modifications can be verified through component testing and the full-scale fatigue test does not have to be carried out in the Prototype Validation.

**Prototype Validation Stage (TRL 6):**

- Something particular about the power cable, which shall be considered in the execution of the qualification plan, is that the order of the tests is of key importance to capture both the mechanical and electrical requirements of the power cable.
- The mechanical type tests defined in IEC 63026 [48] do not include Combined Axial Compression and Bending Test and the Axial Compression Test as mechanical type tests, however to address the high risk identified in the FMECA [2] these tests have been incorporated into the qualification plan as illustrated in Figure 10.
- Since the order of the tests for the qualification of power cables is important to capture the effects of both mechanical and electrical aspects, the tests above are proposed to be carried out before the electrical type tests.
- The Longitudinal / Radial Water Penetration Test is a type test defined in IEC 63026 [48]. However, a dynamic cable section, as for the case study, will generally not be subject to a field repair and will normally be removed and replaced in its entirety, potentially negating the need for these tests.

**System Integration Stage (TRL 8)**

- Although not mentioned by CIGRE TB 862 [39] the floater offset is dependent on both power cable and mooring requirements. Therefore, as the power cable configuration enters the detailed design the analysis shall be more refined and consider a fully coupled analysis model, with mooring lines and power cable.
- The test for “Cable soil Interaction” has been included in the case study of the power cable. Interaction with the seabed is not covered by IEC or CIGRE. Soil friction coefficients, trenching characteristics, abrasion characteristics and vertical stiffness should be known to capture realistic loads at the touchdown zone of the power cables when performing analysis.
- The measurement of marine growth has been included in the case study of the power cable as an input to the global model in order to accurately capture the effects on the power cable and ancillary equipment.

**Operational Stage (TRL 9)**

- Before installing a comprehensive range of monitoring devices on the power cable, it is key to have a clear plan of how often the measured data will be collected (if not online) and how each measurement will be used to add value to the project in terms of reliability and life extension.

## 6 APPLICATION TO BEND STIFFENER CONNECTOR CASE STUDY

The bend stiffener latching mechanism (load transfer device) has been flagged as a high-risk area during discussion with ORE Catapult and stakeholder engagement. There are reliability issues to date, believed partly to do with lack of qualification testing considering the specific requirements for renewables applications which differ from oil and gas, such as the ability for multiple latch and unlatch cycles throughout the connector field life.

Bend stiffener connectors used for flexible risers and deep water umbilicals are typically more heavily loaded than those for floating offshore applications. However, there are some differences between bend stiffener connectors for oil and gas and offshore wind applications that shall be taken into consideration, such as the fatigue loading regime. There has also been experience in oil and gas that when decommissioning occurs, reversal of the connectors is difficult due to extended duration subsea, and so caution is recommended on utilising oil and gas experience as a basis for qualification.

For the case study it is considered that the bend stiffener connector size and loading proposed for offshore wind are within the specification currently fully qualified for oil and gas. The bend stiffener connector without the latching mechanism for multiple cycles is therefore already at TRL 6 for floating wind applications. However, considering the implementation of the latching mechanism for multiple latch and unlatch cycles, the bend stiffener connector of the case study is considered to be at design stage (TRL 4).

To test the qualification framework, a bend stiffener connector from a vendor with previous oil and gas experience but a new entrant to the floating wind market is considered, therefore at TRL 4.

Some experienced bend stiffener connector vendors from oil and gas may be able to provide evidence of the latch/ unlatch capability of their product (TRL 6). In this case the number of tests to qualify their product for floating offshore wind shall be reviewed and reduced accordingly.

Another area of interest but still under development is the so called "weak-links" or Emergency Release System, which are accidental cable disconnection systems, intended to only be activated during accidental events. The Emergency Release System is included in the case study as an optional program.

### 6.1 Qualification Basis

In the case study presented in this report, the bend stiffener connector is used in a power cable in typical lazy wave configuration as shown in Figure 1.

#### 6.1.1 Design System Requirements

For the case study, the bend stiffener connector under consideration is assumed to be at TRL 4 level. The case study is based on the following premise:

- Bend stiffener connector for the power cable described in Section 5, for the North Sea, in shallow water depth of around 100m.
- In general, and as assumed in this case study, the bend stiffener connector size and loading are considered to be enveloped by what is currently considered fully qualified for oil and gas umbilical applications. Therefore, engineering judgement shall be exercised to allow previous test data, analysis or field equipment track record to be used in lieu of performing the tests specified in the Qualification Plan (Section 6.4).

- The bend stiffener connector is a diver-less design that may or may not require disconnect via Remotely Operated Vehicle (ROV) intervention.
- A key difference between bend stiffener connectors currently qualified for oil and gas umbilical applications and HV dynamic power cables for FOW applications is the cable detachment and reattachment. This requirement may be driven by the following two situations.
  - Planned disconnect: A planned disconnect situation may arise due to the need to perform maintenance on the floating structure. For this scenario, the HV power cable will either be laid on the seabed or hung-off an adjacent floating structure. To facilitate this planned disconnect, the bend stiffener connector is required to be designed and qualified for multiple latch and unlatch cycles. This differs from oil and gas umbilical applications in which the bend stiffener connector is latched once and typically disconnected once upon decommissioning of the asset.
  - Unplanned disconnect (Emergency Release): An unplanned disconnect situation may arise due to an accidental event such as floating structure drift off due to a mooring line failure. In this scenario, the bend stiffener connector may be designed to release via an emergency release mechanism when a certain load is achieved; however, should be designed to remain intact for extreme event load cases. Depending on the design of the bend stiffener connector, the emergency release mechanism may require disconnect at the following locations:
    1. Bottom of I-tube
    2. Top of I-tube
    3. Core electrical connectors at the floating structure junction box or termination

Currently it is not clear whose responsibility is regarding the hardware to disconnect the above.

- As the requirement for a bend stiffener connector emergency release mechanism has not been implemented into HV power cable FOW applications, it is included in the case study as an optional program.
- It is assumed in this case study that the emergency release is designed to protect the floating platform, not the cable.
- The Emergency Release Mechanism at the top of the I-tube (hang-off location) should activate at a predetermined load, e.g. machined bolt that fails in tension at a predetermined load, but note that other options exist.

### 6.1.2 Standards, Codes & Industry Practices

Relevant codes applicable to the qualification of bend stiffener connectors are summarised in Table 25.

Table 25 – Main Codes and Standards Identified for Qualification of Bend Stiffener Connectors

Code	Title
API RP 17L2,	Recommended Practice for Ancillary Equipment for Flexible Pipes and Subsea Umbilicals
API RP 17A	Design and Operation of Subsea Production Systems – General Requirements and Recommendations
ISO 13628-5	Petroleum and Natural Gas Industries – Design and Operation of Subsea Production Systems – Part 5: Subsea Umbilicals
ISO 13628-7	Petroleum and Natural Gas Industries – Design and Operation of Subsea Production Systems – Part 7: Completion/Workover Riser Systems
API-STD-2RD	Dynamic Risers for Floating Production Systems
DNV-RP-C203	Fatigue Design of Offshore Steel Structures
API Spec 17L1	Specification for Ancillary Equipment for Flexible Pipes and Subsea Umbilicals
ASTM D3623-78 <sup>a</sup>	Standard Test Method for Testing Antifouling Panels in Shallow Submergence
NACE TM0169	Standard Guide for Laboratory Immersion Corrosion Testing of Metals
NACE TM0174	Laboratory Methods for the Evaluation of Protective Coatings and Lining Materials on Metallic Substrates in Immersion Service

### 6.1.3 Areas of Expertise

The qualification of bend stiffener connectors includes mainly mechanical type tests. Therefore, the main areas of expertise are:

- **Mechanical Engineering:** Most of the expertise in terms of the connection of the high voltage dynamic inter array cables for floating offshore wind comes from other similar systems in Oil and Gas with lower voltage umbilicals or no voltage flexible pipes.
- **Material Engineering:** Most of the expertise in terms of the emergency release mechanism comes from similar applications in oil and gas.
- **Electrical Engineering:** the experience with high voltage systems come from HV system applications and is needed for the emergency release mechanism. Experience also comes from MV system applications in oil and gas.

### 6.1.4 Operational, maintenance, and inspection strategies

The description of the technology typically includes activities such as the following in the integrity management plan (IMP):

- Periodic visual inspection to identify damage to the connector exterior and build up of marine growth

- Periodic cleaning of marine growth when it exceeds design allowable thickness and coverage
  - This is particularly important for the latching mechanism since marine growth can hinder the ability to latch and unlatch the connector.
- Monitoring of platform motions and environmental loads to ensure loads on cable are within design envelope

### 6.1.5 Lessons Learned from Similar Technologies

Some lessons learned from qualification of pilot floating wind cable designs, umbilicals and flexible pipes from oil and gas that can be applied to the qualification of bend stiffener connectors are:

- Some bend stiffener connector designs incorporate mechanisms that break unintentionally during unlatching and require re-building in the field before re-latching;
- Another problem seen in the field is that the accumulation of marine growth may prevent unlatching of the bend stiffener connector, or, conversely, marine growth has contributed to unplanned de-latching of a connector;
- From oil and gas experience, when decommissioning occurs, reversal of some system designs is often difficult, resulting from the extended duration subsea;
- Oil and gas has experienced difficulty making the connection between the bend stiffener and platform during construction many times. Given the volume of connectors needed for a wind farm development, this aspect of repeatability becomes a critical component of the design;
- Fatigue failure of bend stiffener connector have been observed;
- Lessons from installation of bend stiffener connectors for fixed offshore wind shall be taken into consideration.

## 6.2 Technology Assessment

### 6.2.1 Technology Decomposition Analysis

The bend stiffener connector of the case study includes the sub-systems and components given in Figure 14 and described in Table 26. The component breakdown and descriptions given are general and proprietary bend stiffener connector designs may differ from what is described below. Further breakdown into sub-components is possible, but isn't addressed further for the purposes of the case study.

Figure 14 – Bend Stiffener Connector for Floating Offshore Wind System Hierarchy

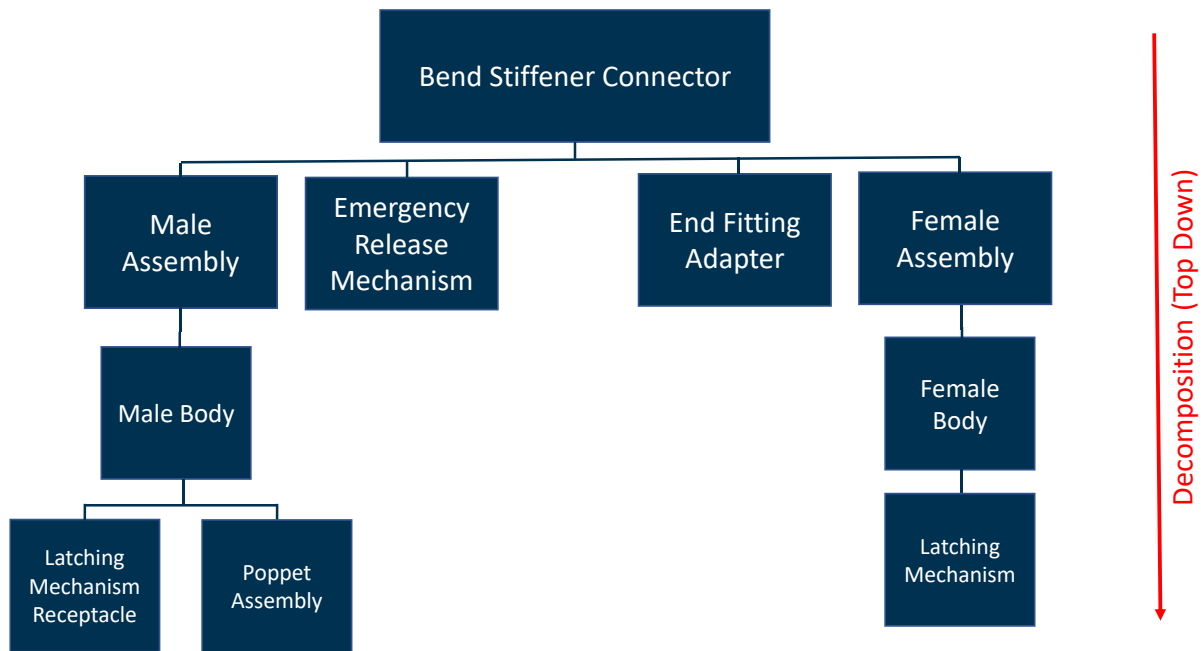


Table 26 – Components of the Bend Stiffener Connector of the Case Study

Component	Description
Male Body	Forged body containing a flange on the bottom to interface to the bend stiffener and a latching mechanism receptacle on the top.
Latching Mechanism Receptacle	The male body incorporates a latching mechanism receptacle on the top which is a profile that the latching mechanism on the female assembly latches to.
Poppet Assembly	The poppet assembly disengages the end fitting adapter and allows it to be disconnected from the male assembly.  Note that different vendors might have different designs and/or terminology.
Female Body	Forged body containing a bell mouth on the bottom to allow alignment of the male assembly when stabbing to the I/J-tube and a flange on the top to bolt to the bottom of the /J-tube. The female body also incorporates a latching mechanism.
Latching Mechanism	The latching mechanism on the female body interfaces to the latching mechanism receptacle in the male body to take the tensile load of the dynamic power cable during installation until the dynamic power cable is hung-off on the top of the I/J-tube.  The latching mechanism fulfils the requirement for latching and unlatching multiple times.  Note that some suppliers have the latching mechanism mounted upon the male assembly
End Fitting Adapter	The end fitting adapter is incorporated into the dynamic power cable end fitting and sits inside the male assembly during installation until disengaged by the poppet assembly.

Component	Description
	<p>Once the end fitting adapter is disengaged from the male assembly the dynamic power cable is winched and hung-off on the top of the I/T-tube.</p> <p>Note that different vendors might have different nomenclature for their cable termination release hardware.</p>
Emergency Release Mechanism	<p>The emergency release mechanism allows for the dynamic power cable to disconnect from the host facility in the event of a failed event scenario, e.g. drift off due to failed mooring, to prevent damage to the host facility.</p>

### 6.2.2 Technology Characterisation

Bend stiffener connectors for floating wind have evolved from dynamic flexible pipes from Oil and Gas. Based on the components identified in the Technology Decomposition Analysis (Section 6.2.1), a systematic screening table for the dynamic power cable is shown in Table 27.

Generally, the bend stiffener and connector technology is well established and within existing loading limitations (strength / fatigue) of oil and gas umbilicals, i.e., technology category “A”. However, the unlatching and emergency release mechanisms are not a functional requirement for oil and gas umbilicals and therefore considered new technology with demanding new technical challenges, i.e., technology category “D”.

Based on the high maturity ranking in Table 27, qualification of the bend stiffener connector of the case study focuses on the latching mechanism (technology category “C”) and the emergency release mechanism (technology category “D”).

Experienced bend stiffener connector power cable vendors might be able to apply lower characterisation based on their experience with dynamic applications for the oil and gas sector.

Table 27 – Systematic Screening Table for Bend Stiffener Connector

Item	Description	Similar Technology Exists	Relevant Rules, Guides or Industry Standards	New Technology (Yes/No)	Technology Category <sup>(1)(2)</sup>	Notes
1	Male Body	Static power cables, Umbilicals	API Spec. 17L1, API RP 17L2, API RP 17A, ISO 13628-7, API STD 2RD, DNVGL-RP-C203, ISO 13628-5	No	A	Known application area & Technology proven (oil & gas umbilicals)
2	Latching Mechanism Receptacle	Static power cables, Umbilicals		No	A	Known application area & Technology proven (oil & gas umbilicals)
3	Poppet Assembly	Static power cables, Umbilicals		No	A	Known application area & Technology proven (oil & gas umbilicals)
4	Female Body	Static power cables, Umbilicals		No	A	Known application area & Technology proven (oil & gas umbilicals)
5	Latching Mechanism	Static power cables, Umbilicals		No	C	Limited knowledge application area & Technology with limited field history
6	End Fitting Adapter	Static power cables, Umbilicals		No	A	Known application area & Technology proven (oil & gas umbilicals)
7	Emergency Release Mechanism	None		Yes	D	Limited knowledge application area & New technology

Notes:

1\ from [24], where: “A” No new technical uncertainties (proven technology), “B” New technical uncertainties, “C” New technical challenges, “D” Demanding new technical challenges.

2\ Based on the case study premise of a supplier with limited experience. Some of the current vendors are likely to be in a higher technology category.

### 6.2.3 Technology Stage Assessment (TRL)

Following the results from the technology characterisation in Section 6.2.2, a detailed analysis of the maturity level of the technology is carried out to determine which stage of the qualification plan is most suitable for the bend stiffener connector. The questionnaire in Appendix 2 can be used to determine the TRL level, based on answers of “yes” to all prior stages, with evidence provided.

In this case study, it is assumed the bend stiffener connector without the emergency release is at TRL 4. If the emergency release is included some additional tests at the component level are needed for the bend stiffener connector to reach TRL 4. The remaining components are at TRL 6.

### 6.3 Threat Assessment

For the dynamic power cable system, ORE Catapult has conducted a failure mode, effects & criticality analysis (FMECA), which includes the power cable as well as the ancillary system components. The results of this activity are used in this case study to exemplify failure mechanisms for the Bend Stiffener (BS) connector and associated risk levels (Figure 7), as shown in Table 28.

The qualification programme for the Bend Stiffener connector addresses, as a minimum, all novel/low TRL elements identified in Section 6.2.2 and all high-risk failure modes, identified through the threat assessment in this Section [2].

The activities from the qualification plan that address the “high” and “medium” risks for the BS connector are shown in Table 28. For example, for the “high” risk of Latching Failure is addressed by the latch/ unlatch test in the Prototype Validation Stage (Section 6.7.1).

Table 28 – BS Connector Threat Assessment Summary [2]

Item/ Component	Failure Mechanism [2]	Risk <sup>(1)</sup> [2]	Addressed by Activity of Qualification Framework Stage
Bend Stiffener Connector	Latching Failure	High	Latch/ Unlatch Test is part of the qualification plan from the Prototype Validation Stage (see Section 6.7.1)
	Deformation of bend stiffener due to overload	Medium	Full-Scale Strength Test is part of the qualification plan from the Prototype Validation Stage (see Section 6.7.2).
	Deformation of bend stiffener due to overheating	Medium	Full-Scale Strength Test is part of the qualification plan from the Prototype Validation Stage (see Section 6.7.2).
	Crack propagation, fatigue	Medium	Material Test is part of the qualification plan from the Concept Validation Stage (see Section 6.6.1).
	Plastic embrittlement	Medium	Material Test is part of the qualification plan from the Concept Validation Stage (see Section 6.6.1).
	Material fatigue	Medium	Full-Scale Fatigue Test is part of the qualification plan from the Prototype Validation Stage (see Section 6.7.3)

Note: 1\ Risk matrix defined in Figure 7

## 6.4 Qualification Plan

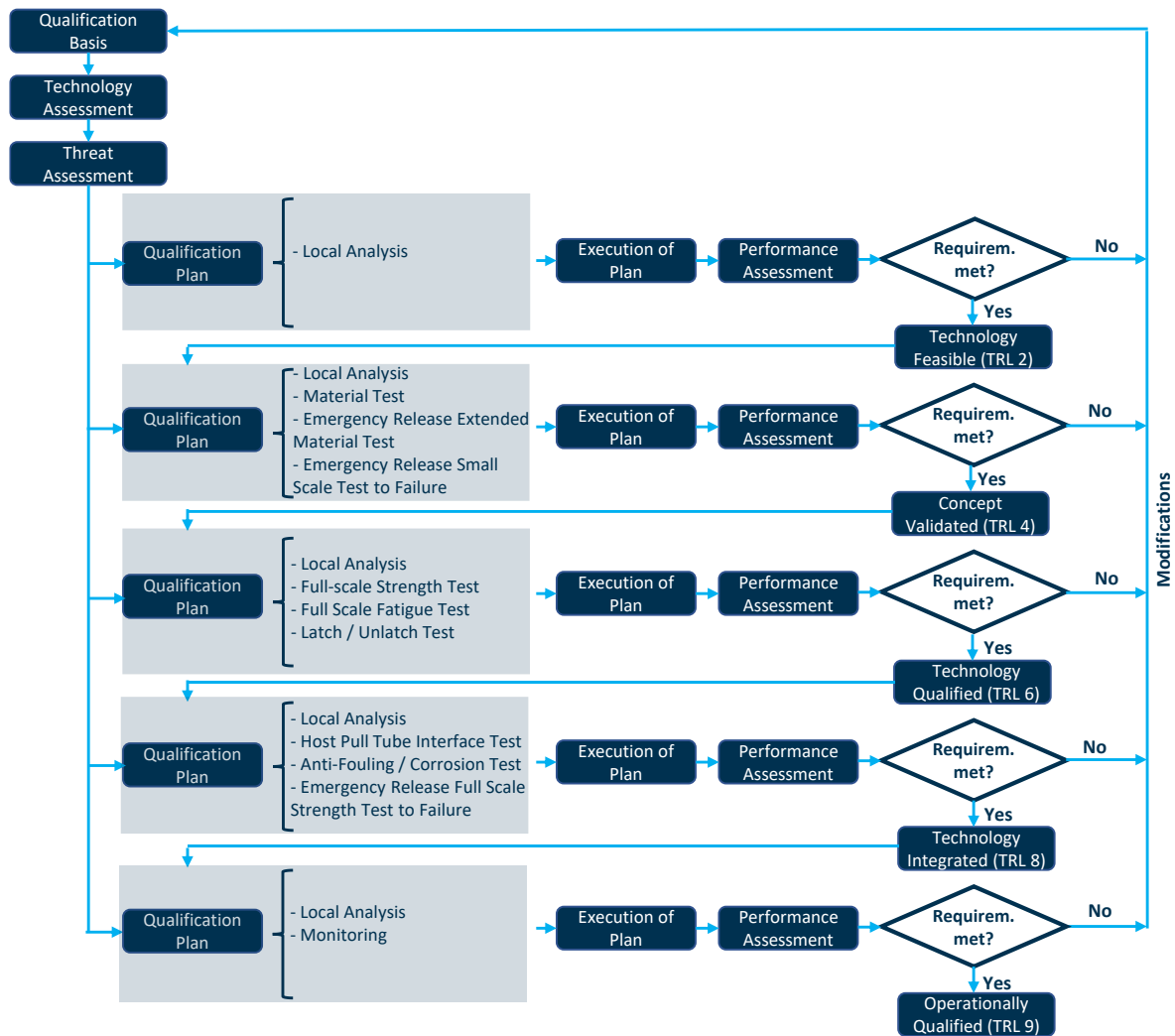
The qualification plan depends on the results from the Threat Assessment in Section 6.3 and Technology Stage Assessment in Section 6.2.3. Each stage of the qualification plan for the BS Connector is summarised in Table 29 and shown in Figure 8.

All activities for each stage of the qualification plan are detailed in Sections 6.5 to 6.9.

Table 29 – Summary of Tasks per Stage of the Qualification Plan for the BS Connector Qualification

Requirement	Feasibility (TRL 2)	Concept Validation (TRL 4)	Prototype Validation (TRL 6)	System Integration Stage (TRL 8)	Operational Stage (TRL 9)
Local Structural Analysis	X	X	X	X	X
Material Tests		X			
Emergency Release Extended Material Test		X			
Emergency Release Small Scale Test to Failure		X			
Latching Mechanism Small Scale Tests		X			
Latch/ Unlatch Test			X		
Full-Scale Strength Test			X		
Full-Scale Fatigue Test			X		
Host Pull Tube (Bend-Stiffener Latch) Interface Test				X	
Anti-fouling / Corrosion Coating Qualification Test				X	
Emergency Release Full-Scale Strength Test				X	
Monitoring				X	X
Commissioning Tests					X

Figure 15 – Steps in the Qualification Process for the BS Connector Case Study



### 6.5 Qualification Plan - Feasibility Stage (TRL 2)

In line with the TRL guidance followed in this framework, the inputs for this stage are the design premise and the outputs are a basic design of the bend stiffener connector based on the load envelope anticipated during operations.

It is assumed that most technology of the bend stiffener connector of the case study is not novel and that sufficient evidence supports that it has already fulfilled the requirements from the Feasibility Stage (TRL 2), such as preliminary local analysis.

### 6.6 Qualification Plan - Concept Validation (TRL 4)

To be qualified as “Concept Validated” (TRL 4), the bend stiffener connector has been validated in lab.

As the bend stiffener connector of the case study includes an emergency release mechanism, laboratory studies to physically validate analytical predictions of separate elements of the technology are proposed. Component pre-qualification tests that are destructive or non-destructive are used to identify the relevant failure modes and mechanisms or to explore the critical parameters and their effects, such as the tests described in Section 6.6.2 and 6.6.3

### 6.6.1 Material Test

Material testing is used to qualify the bend stiffener connector base materials. This test addresses the medium risks of crack propagation and plastic embrittlement identified in the FMECA (Section 6.3).

According to API RP 17L2, [25] (but other codes may be applicable) these tests are commonly used for quality control during the manufacturing process.

- Chemical composition, 1 test per heat
- Tensile test, 1 specimen per heat
  - Yield strength
  - Ultimate strength
  - Elongation
- Impact strength, 3 specimens per heat

In addition to the above tests, the following tests are also recommended:

- Hardness, 1 test per heat
- Fatigue (S-N) test
  - The fatigue S-N test may be omitted provided the base material S-N curve in an industry code or standard, e.g. DNVGL-RP-C203 [43] can be used.

The acceptance criteria for the material tests shall be in accordance with the manufacturer's design specification.

### 6.6.2 Emergency Release Extended Material Test

If the emergency release is part of the purchase specification, extended material tests based on ASTM A370 [34] shall be conducted to gain additional information on the emergency release failure mechanism mechanical properties. One way of fulfilling this requirement is to conduct multiple tension tests on each heat treatment lot (batch of materials that is heat treated together) of emergency release materials to understand the variance in the yield and tensile strength and to obtain a full stress-strain curve if needed for design purposes.

The extended material tests will be used to determine the emergency release geometry typically through an elastic-plastic analysis of the connector such that it fails at a pre-determined level, typically corresponding to the accidental load the bend stiffener connector will experience during a mooring failure load case.

These tests should be repeated for each heat treatment lot of emergency release base materials.

Note this test is based on the assumption that the emergency release mechanism is a machined bolt that fails in tension at a predetermined load. For other mechanisms other tests may apply.

### 6.6.3 Emergency Release Small Scale Test to Failure

The purpose of the emergency release small scale test to failure is to validate the load the emergency release is expected to fail via testing on the sub-component level, e.g. bolt. Small scale tests to failure

based on guidance from DNV-RP-C203 [44] are conducted as a pure tension test of the emergency release.

The acceptance criteria for the emergency release small scale test to failure is per the manufacturer’s design specification.

These tests should be repeated for each heat or heat treatment lot of emergency release base materials.

**6.6.4 Latching Mechanism Small Scale Tests**

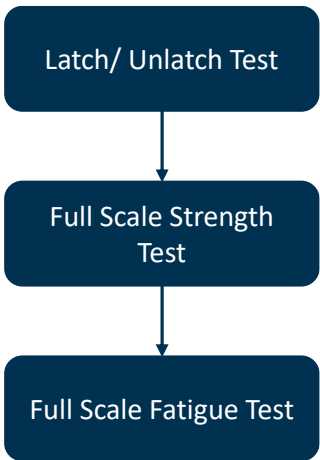
Note that although the bend stiffener connector are typically reversible, the latching and unlatching mechanism may have previously not been developed for multiple latching and unlatching cycles. As such, additional tests might be required for the latch/ unlatch mechanism at the concept validation stage prior to the prototype testing stage. For example, this could include component wear tests or small scale tests to demonstrate the proposed functionality of components within the latching/unlatching mechanism. However, this is not explored further in the case study as no specific design is considered for this mechanism, and the design and approach may lead to differing levels of concept validation testing.

**6.7 Qualification Plan - Prototype Validation (TRL 6)**

Following the Concept Validation stage (Section 6.6), if all requirements are met, the bend stiffener connector of the case study starts the activities to reach TRL 6. At the end of the Prototype Validation stage all engineering studies and design risk assessments are completed and the bend stiffener connector is refined to the detailed design. This stage of the qualification is the last which involves only the vendor of the bend stiffener connector. To qualify with TRL higher than 6 the end user of the connector has to actively participate in the process and the qualification becomes project specific.

A prototype or full-scale bend stiffener connector is manufactured and all necessary qualification testing is carried out. The activities of the qualification plan for Prototype Validation involve full-scale strength and fatigue tests and Latch/ Unlatch test, following the proposed order in Figure 16.

Figure 16 – Prototype Validation Tests



### 6.7.1 Latch/ Unlatch Test

The latch/ unlatch test is to confirm the bend stiffener connector can be latched/ unlatched repeatedly. There are no floating wind industry codes and standards that address latch/ unlatch of bend stiffener connectors. ISO 13628-7, [53] is an oil and gas industry code that addresses connector latch/ unlatch testing and therefore the following recommendations are provided. API Spec 17L1 provides some recommendations for pull-in tests and can be used as a guideline for crafting a latch/ unlatch program.

- The bend stiffener connector shall be not require intervention (no ROV/diver) to latch and only potentially need ROV for disconnection.
- Bend stiffener connector shall be latched/ unlatched to the cycles included in the purchase specification. If the number of latch/ unlatch cycles are not specified in the purchase specification, then it is recommended to conduct a minimum of 10.
- During each latch/ unlatch cycle, the bend stiffener connector shall be fully removed and reinserted into the female receptacle.
- Different typical nominal tension load or angle (or curvature) combinations can be applied to demonstrate reliability of disconnect for unlatch/ latching within the required specification of the connector.

Typically, a total of 10 cycles is required for the expected stab in angle. In the test program it is recommended that the latch/ unlatch test be combined with the strength test (Section 6.7.1). In this case 9 out 10 cycles of latch/ unlatch cycles would be performed, then the strength load test would be conducted followed by 1 additional latch/ unlatch cycle.

The following acceptance criteria are offered for the latch/ unlatch test.

- The bend stiffener connector shall be inspected after testing for wear and galling. If wear and galling are observed, it shall be demonstrated that it is within the acceptable limits per the manufacturer's design criteria.
- At each reattachment the bend stiffener connector shall self-align on latch.

The latch/ unlatch test shall be repeated for the following changes.

- Change in nominal connector size
- Change in latching mechanism design

As the latch/ unlatch will be carried out during planned maintenance operations, it is assumed the power cable will be shut down and have no power. Therefore, this test is carried out considering the strength aspects of the connector only. However, after each re-latching operations it is recommended that electrical continuity is checked before re-energising the cable.

The recommendation to adopt requirements from ISO-13628-7 [53] for qualification of bend stiffener connectors will require more work from the supply chain than what is currently done. Although more onerous, this will help decrease the high risk of latching failure in offshore wind projects identified in the FMECA (Section 6.3).

### 6.7.2 Full-scale Strength Test

The full-scale strength test is performed to address the medium risk identified in the FMECA (Section 6.3) of deformation of the bend stiffener due to overheating. The failure causes associated with this risk may be thermal loads from electrical cores greater than anticipated, insulation from stiffener or J-tube greater than expected or insufficient material stiffness or strength at elevated temperatures.

A full-scale strength test is conducted to validate strength FEA results. Floating wind industry codes and standards do not provide recommendations on executing a bend stiffener connector full-scale strength test programme. API RP 17L2, [25] refers to API RP 17A, [26] for prototype testing of connectors; however, API RP 17A, [26] lacks details on executing a bend stiffener connector full-scale strength test programme. Therefore, the following recommendations are provided for executing a bend stiffener connector full-scale strength test programme based on guidance in 13628-7, [53].

- Testing to be conducted on at least 1 full-scale specimen inclusive of male connector and female receptacle
- Specimen to be strain gauged to correlate strains experienced during testing to those predicted by FEA
- Specimen to be tested to its extreme load capacity under combined loading (tension and bending)
- Specimen to be disassembled and visually inspected for damage
- Dimensional inspection
- One latch/ unlatch cycle shall be conducted after testing to the extreme load capacity, refer to Section 6.7.1 for additional test details and acceptance criteria.

The acceptance criteria for the full-scale strength test shall be as follows.

- The specimen shall not exhibit any failure of the latching mechanism or deformations which will inhibit its functionality
- If bend stiffener connector design incorporates an I/J-tube seal, deformations at the seal shall not cause water ingress into the I/J-tube
- Measured strains shall match to those predicted by FEA or be within a reasonable tolerance justified by engineering practice, sensitivity to manufacturing tolerances / friction coefficients, FEA, etc.
- Loads applied correctly and test procedure followed.

The following recommendations are provided for acceptance of previous qualification test data.

- Qualification on a different size of bend stiffener connector is valid on other sizes provided the bend stiffener connector predicted strength failure mechanism is unchanged
- Qualification of a different size bend stiffener enables validated engineering tools to be utilised to establish suitable design with reduced testing requirements
- Change to the bend stiffener connector latching mechanism design (i.e. dogs, balls) requires requalification

### 6.7.3 Full-scale Fatigue Test

A full-scale fatigue test is conducted to validate the fatigue performance. This test addresses the medium risk identified in the FMECA [2] (Section 6.3) of material fatigue. Assuming a bend stiffener connector with emergency release system for the case study, the full-scale fatigue test for the bend stiffener connector includes the emergency release system.

As with the full-scale strength test, there are limited industry codes and standards that provide guidance on full-scale fatigue testing; therefore, the following recommendations are provided from 13628-7, [53].

- Testing to be conducted on at least one (1) full-scale specimen inclusive of male connector and female receptacle
- Specimen to be strain gauged to correlate actual recorded strains from testing and number of cycles
- The strain range shall correlate to a mean number of cycles to failure on the order of  $10^6$

The acceptance criteria for the full-scale fatigue test shall be as follows.

- Specimen shall achieve the target number of cycles before failure as determined in accordance with the recommendations in DNVGL-RP-C203, [4] for a 95% confidence level. The 95% confidence level is typical for fatigue testing of girth welds in offshore oil and gas riser applications as specified in API STD 2RD, [27].
- Specimen failure mechanism shall be the same as predicted by FEA
- Testing may be stopped at a predetermined runout number of cycles, typically 1.3 to 1.5 times the target number of cycles, before failure.

The following recommendations are provided for acceptance of previous qualification test data.

- Qualification on a different size of bend stiffener connector is valid on other sizes provided the bend stiffener connector predicted fatigue failure mechanism is unchanged
- Change to the bend stiffener connector latching mechanism design (i.e. dogs, balls) requires requalification

## 6.8 Qualification Plan - System Integration (TRL 8)

Considering the bend stiffener connector of the case study has completed all previous stages and has reached TRL 6, it can start the System Integration stage.

The qualification plan of this stage includes tests that are specific to the end user, therefore project specific. It also includes the tests to verify the interface between the bend stiffener connector and ancillary equipment given in Section 6.8.1. It is assumed that the tests at the Prototype Stage remain valid as the project specific requirements are within the connector specification already qualified to TRL 6 level.

At the end of this the bend stiffener connector is qualified as TRL 8 and has been installed with the final operating system and operating environment.

Table 30 Bend Stiffener Connector Qualification – Project Specific Tests

Test Category	Test	Reference for Test Procedure	Relevant Sections
Project Specific Tests	Host Pull Tube (Bend-Stiffener Latch) Interface Test	ISO 13628-5	Section 6.8.1
	Anti-Fouling / Corrosion Coating Qualification Test	ASTM D3623-78A; NACE TM0169, NACE TM0174, NORSOK M501	Section 6.8.2
	Emergency Release Full-Scale Strength Test to Failure	Proposed by 2H	Section 6.8.3

### 6.8.1 Host Pull Tube (Bend-Stiffener Latch) Interface Test

The host pull tube (bend-stiffener latch) interface test is to confirm fitment between the male bend stiffener connector and female receptacle as described within ISO 13628-5, [52]. The following should be checked during the host pull tube (bend-stiffener latch) interface test.

- Fitment between the bend stiffener connector latching mechanism and profile on the female receptacle
- Visually verify latch/ unlatch indicator markings
- The bend stiffener connector shall be functioned using ROV/diver interfaces and tooling to latch/ unlatch the connector with the applicable installation back tension and misalignment angle

It is recommended that the host pull tube (bend-stiffener latch) interface test be checked during FAT on every bend stiffener connector manufactured.

### 6.8.2 Anti-fouling / Corrosion Coating Qualification Test

An anti-fouling / corrosion coating qualification test is conducted to qualify the coating's ability to inhibit marine growth or corrosion. Specifically, coatings may be applied to the bend stiffener connector latching mechanism to mitigate marine growth/corrosion that may prevent the functionality of the latching mechanism.

Immersion tests are recommended to qualify anti-fouling coatings in accordance with industry codes and standards, e.g. ASTM D3623-78A, [6] and NORSOK M501 [58].

Immersion tests are recommended to qualify corrosion coatings in accordance with industry codes and standards, e.g. NACE TM0169, [9] and NACE TM0174, [10].

Other parameters which shall be considered in this test due to the specific requirements for latching and unlatching multiple times are:

- Temperature conditions at the latching mechanism
- Impact of several cycles of clearing any marine growth that accumulated to demonstrate the coating can withstand the periodic cleaning mentioned above.

### 6.8.3 Emergency Release Full-scale Strength Test to Failure

The purpose of the emergency release full-scale test to failure is to validate the load the emergency release is expected to fail via full-scale testing on the bend stiffener connector. The connector shall be loaded to the tension the connector is expected to experience during the accidental load case until failure. Tension load should be applied in incremental steps and held constant for at least 1 minute before increasing to the next load step.

The acceptance criteria for the emergency release full-scale strength test to failure is per the manufacturer's design specification, typically corresponding to the accidental load the bend stiffener hang-off will experience during a mooring failure load case.

These tests should be repeated for each change in the emergency release accidental load case, i.e. bending, tension, top angle and temperature therefore are project specific.

Depending on the design of the bend stiffener connector, the emergency release mechanism may require disconnect at the following locations:

1. Bottom of I-tube
2. Top of I-tube
3. Core electrical connectors at the floating structure junction box or termination

Currently it is not clear whose responsibility is regarding the hardware to disconnect the above. Once defined, the emergency release full-scale strength to failure shall account for the locations above, as applicable.

If the specification is that in an accidental situation there will be no time to shut down the power transmission before disconnecting the electrical cores, then it is key that the abrupt disconnection of the core electrical connectors is tested with high voltage, similar to a typical accidental scenario. On the other hand, if the specification is that that power is switched off before triggering the weak-link set of devices, then the test shall be carried out in this scenario.

## 6.9 Qualification Plan - Operational (TRL 9)

Considering the bend stiffener connector of the case study has completed all previous stages and has reached TRL 8, it can start the last stage of the cable framework qualification process, which is the Operational Stage. At the end of this stage the cable reaches TRL 9 and is qualified as "Operationally Qualified".

To be qualified as TRL 9 means the connector has been integrated into the final system and has been operating successfully in service in the relevant operational environment for at least 3 years.

The qualification plan for the Operational Stage includes monitoring activities (same measurements from the power cable Section 5.9.2) and local analysis to use the measured data to verify and confirm the performance of the system.

## 6.10 Execution of the Plan

The technology qualification plans described from Section 6.5 to 6.10 are executed.

The material and mechanical tests are executed at relevant test houses and by teams with suitable capability. It is important that all tests are well documented for verification of the certification body. At the end of each stage, the qualification plan of the next stage is reviewed to make any relevant adjustments.

## 6.11 Performance Assessment

The success of the technology Qualification Plan is measured by comparing the results against the acceptance criteria established from the Qualification Basis. The technology is considered qualified when both risk and uncertainty have been reduced to acceptable levels. It is assumed at each TRL level that this process is successfully completed.

## 6.12 Discussion

Some lessons learned from the exercise of testing the framework with a generic bend stiffener connector for 66kV inter array cable are the following:

- Most technology is not novel in the case study (e.g. same as oil and gas application)
- The latching/unlatching mechanism is not new but the requirement for multiple cycles of latch/unlatch is specific to floating wind applications
  - In oil and gas, the connector is typically latched during installation and usually unlatched for decommissioning; therefore damage can occur during unlatching and storage. Specific additional tests may be needed depending on the design of the mechanism.
  - Some designs from oil and gas already have the capability for multiple cycles of latch/unlatch. In this case the tests which are needed for qualification shall be revised on a case-by case basis.
- The fatigue loading regime is different from oil and gas since a floating turbine has specific dynamic behaviour
- A bend stiffener connector without emergency release from oil and gas is typically at TRL 4 for floating wind
  - To reach TRL 6 the qualification plan is to complete the latch-unlatch tests and fatigue tests (different fatigue loading regime)
  - Additional tests from the Prototype Validation Stage (TRL 6) are not required for a bend stiffener connector without emergency release from oil and gas to reach TRL 6 as these are already addressed through oil and gas qualification
- A bend stiffener connector with emergency release is typically at TRL 2 for floating wind regardless of whether the bend stiffener connector has track record in oil and gas

- To reach TRL 4 the Qualification Plan is to complete the Emergency Release tests, e.g. extended material test and small scale fatigue test
- The emergency release is project specific since disconnection shall occur at very particular load limits, therefore the qualification of the emergency release skips the Prototype Stage (TRL 6)
- The emergency release qualification goes from the component level (TRL 4) to the project specific level (TRL 8)
- The emergency release full-scale strength test to failure shall be performed with the cores powered with nominal high voltage, to replicate typical accidental scenario in service conditions.
  - If the assumption is that power is switched off before triggering the weak-link set of devices, then the test shall be carried out in this scenario.
- The case study demonstrates that the proposed framework approach can be applied to a component within the overall system.

## 7 REFERENCES

---

- [1] ORE Catapult – “Floating Offshore Wind Dynamic Cabling Systems – Technology Development and Qualification Programme, ORE/21/072, Invitation to Tender”, 23rd August 2021.
- [2] Astrimar / ORE Catapult – “FOW Dynamic Cable Risk and Reliability Results”, PN000486-RPT-004, Rev. 1.
- [3] 2H Offshore/ ORE Catapult – “Dynamic Cable Technology Qualification Review and Mapping Report”; Report No PN000486-RPT-009; Draft; 11<sup>th</sup> March 2022.
- [4] Website, [https://www.great.gov.uk/international/content/investment/sectors/offshore-wind/?utm\\_source=google&utm\\_medium=paidsearch&utm\\_campaign=ditinvestmentatlashpopaidsearch&utm\\_content=DSA&gclid=Cj0KCQjwz7uRBhDRARIsAFqjullLJTpTosO\\_vBXmsBoldE7cH-o02nj93NNYNTKnVViGwhtTmmnLBPwaAtXwEALw\\_wcB](https://www.great.gov.uk/international/content/investment/sectors/offshore-wind/?utm_source=google&utm_medium=paidsearch&utm_campaign=ditinvestmentatlashpopaidsearch&utm_content=DSA&gclid=Cj0KCQjwz7uRBhDRARIsAFqjullLJTpTosO_vBXmsBoldE7cH-o02nj93NNYNTKnVViGwhtTmmnLBPwaAtXwEALw_wcB), accessed on 15<sup>th</sup> March 2022.
- [5] Website, <https://www.crownstatescotland.com/news/scotwind-offshore-wind-leasing-delivers-major-boost-to-scotlands-net-zero-aspirations>, Accessed on 29 September 2022.
- [6] Website, <https://www.crownstatescotland.com/news/three-shetland-scotwind-projects-announced>, Accessed on 29 September 2022.
- [7] 2H Offshore/ ORE Catapult – “Dynamic Cable Technology Qualification Review and Mapping Report”; Report No PN000486-RPT-009; Draft; 11<sup>th</sup> March 2022.
- [8] European Wind Energy Association – “Deep Water – The Next Step for Offshore Wind Energy”; Report; July 2013.
- [9] COREWIND – “D3.1 Review of the state of the art of dynamic cable system design”, INNOSEA / JDR / RAMBOLL / IREC / COBRA / UL DEWI / WINDEUROPE, February 2020.
- [10] B. Sonerud, F. Eggertsen, S. Nilsson, K. M. Furuheim and G. Evenset, "Material considerations for submarine high voltage XLPE cables for dynamic applications"; 2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena; 2012, doi: 10.1109/CEIDP.2012.6378924.
- [11] 2H Offshore/ ORE Catapult – “Dynamic Cable Technology Qualification Framework and Guidance Report”; Report No PN000486-RPT-010; Draft 1; 1<sup>st</sup> April 2022.
- [12] Statoil – “Hywind Buchan Deep Metocean Design Basis”; RE2014-002, 13th May 2013.
- [13] Website, ” <https://electrical-engineering-portal.com/impulse-withstand-voltage-test-performed-on-assemblies>”, Accessed on 15<sup>th</sup> March 2022.
- [14] Peritus/ ORE Catapult – “Floating Offshore Wind Dynamic Cables – Design Requirements”, PN000412-RPT-002, Rev. 1, 8<sup>th</sup> October 2021.
- [15] Orcina – “OrcaFlex Reference Manual”; Version 11.0c.
- [16] SINTEF – “UFLEX2D Version 2.8.8 User Manual” - 11 April 2018.
- [17] Website: <https://www.vanoord.com/en/equipment/cable-laying-equipment/>, accessed on 20<sup>th</sup> April 2022.
- [18] FLOATANT – “D.3.3 – Cable Core Conductor Innovations”, 200220\_FLT\_WP3\_D3.3\_V0.1, 28<sup>th</sup> February 2020.

- [19] Email from ORE Catapult to 2H, "RE: FOW CoE PR27 - PN000486-RPT-011 - Draft 1 - Dynamic Cable Technology Qualification - Case Studies", 22<sup>nd</sup> April 2022. Attachment: "TRL Guide.docx".
- [20] Website: <https://www.balltec.com/solutions/balltec-surf-solutions-tools/8-bendlok/>, accessed 15<sup>th</sup> June 2022.
- [21] ORE Catapult – "Dynamic Cables and Ancillary Systems – Market Projections", PN000412-RPT-003, Rev-1.
- [22] S. Frazer, S. Luther, M. Socariceanu, "The Effect of Elevated Temperature Upon Power Cable Umbilical Technology", Deep Offshore Technology International 2013.
- [23] J. Featherstone, A. Neumann, J Wan, L Harris, "Full Scale Wet Age Testing of XLPE Insulated Power Cables in Salt Water", October 2019.

#### ABS

- [24] ABS - "Guidance Notes on Qualifying New Technologies", April 2017.

#### API

- [25] API - "Recommended Practice for Ancillary Equipment for Flexible Pipes and Subsea Umbilicals", API RP 17L2, 2nd Edition, June 2021.
- [26] API - "Design and Operation of Subsea Production Systems – General Requirements and Recommendations", API RP 17A, 5th Edition, May 2017.
- [27] API - "Dynamic Risers for Floating Production Systems", API STD 2RD, 2nd Edition, September 2013.
- [28] API - "Specification for Ancillary Equipment for Flexible Pipes and Subsea Umbilicals", API Spec 17L1, 2nd Edition, June 2021.
- [29] API – "Recommended Practice for Subsea Production System Reliability and Technical Risk Management", API RP 17N, 2009.
- [30] API - "Specification for Subsea Umbilicals", API Specification 17E, 5th Edition, July 2017.

#### ASTM

- [31] ASTM- "Standard Test Method for Testing Antifouling Panels in Shall Submergence", ASTM D3623-78A, 2020.
- [32] ASTM – "Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser", ASTM D4060, 2019.
- [33] ASTM – "Standard Test Method for Ranking Resistance of Plastics to Sliding Wear Using Block-on-Ring Wear Test – Cumulative Wear Method", ASTM G176, 2003.
- [34] ASTM – "Standard Test Methods and Definitions for Mechanical Testing of Steel Products", ASTM A370, 2021.
- [35] ASTM – "Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life ( $\epsilon$ -N) Fatigue Data", ASTM E739-10, 2015.

#### CIGRE

- [36] CIGRE – "Recommendations for testing long AC submarine cables with extruded insulation for system voltage above 30 to 500 kV", TB 490, Working Group B1.27, February 2012.
- [37] CIGRE – "Recommendations for mechanical testing of submarine cables", TB 623, 2015.
- [38] CIGRE – "Recommendations for additional testing for submarine cables", TB 722, Working Group B1.55, April 2018.
- [39] CIGRE – "Recommendations for mechanical testing of submarine cables for dynamic applications", TB 862, 2022.
- [40] CIGRE – "Recommendations for mechanical tests on submarine cables", Electra 171, 1997.
- [41] CIGRE – "Offshore Generation Cable Connections", TB 610, Working Group B1.40, February 2015.

[42] CIGRE – “Advanced Design of Metal Laminated Coverings: Recommendation for Tests, Guide to Use, Operational Feed Back”, TB 446, Working Group B1.25, February 2011.

## **DNV**

[43] DNV - “Technology Qualification”, DNV-RP-A203, June 2017.

[44] DNV - “Fatigue Design of Offshore Steel Structures”, DNV-RP-C203, September 2019.

[45] DNV - “Loads and site conditions for wind turbines”, DNV-ST-0437, November 2016.

[46] DNV – “Subsea power cables in shallow water”, DNV-RP-360, March 2016.

[47] DNV - “Electrical power cables in subsea applications”, DNV-RP-F401, June 2017.

## **IEC**

[48] IEC – “Submarine power cables with extruded insulation and their accessories for rated voltages from 6 kV ( $U_m = 7,2$  kV) up to 60 kV ( $U_m = 72,5$  kV) - Test methods and requirements”, IEC-63026, 2019.

[49] IEC – “High-voltage test techniques - Partial discharge measurements”, IEC 60270, 2000.

[50] IEC – “Power cables with extruded insulation and their accessories for rated voltages above 30 kV ( $U_m = 36$  kV) up to 150 kV ( $U_m = 170$  kV) – Test methods and requirements”, IEC 60840, May 2020.

[51] IEC/IEEE – “Subsea Equipment: Part 1: Power connectors, penetrators and jumper assemblies with rated voltage from 3 kV ( $U_{max} = 3,6$  kV) to 30 kV ( $U_{max} = 36$  kV)”, BS IEC/IEEE 61886-1:2021, Edition 1.0, April 2021.

## **ISO**

[52] ISO - “Petroleum and Natural Gas Industries – Design and Operation of Subsea Production Systems – Part 5: Subsea Umbilicals”, 13628-5, 2009.

[53] ISO - “Petroleum and Natural Gas Industries – Design and Operation of Subsea Production Systems – Part 7: Completion/Workover Riser Systems”, 13628-7, 2005.

[54] ISO – “Plastics — Determination of resistance to wear by abrasive wheels”, 9352, 2012.

## **NACE**

[55] NACE - “Standard Guide for Laboratory Immersion Corrosion Testing of Metals”, NACE TM0169, 2021.

[56] NACE - “Laboratory Methods for the Evaluation of Protective Coatings and Lining Materials on Metallic Substrates in Immersion Service”, NACE TM0174, 2002.

## **NORSOK**

[57] NORSOK - “Action and Action Effects”. N-003, Revision 3, January 2017.

[58] NORSOK - “Surface preparation and protective coating”. M-501, Edition 6, February 2012.

## APPENDIX 1 QUALIFICATION FRAMEWORK DETAILS

---

The qualification process is outlined below:

1. **Qualification Basis**
2. **Technology Assessment**
3. **Threat Assessment**
4. **Technology Qualification Plan**
5. **Execution of the Technology Qualification Plan**
6. **Assessing Performance**

### A1.1 Qualification Basis

The first stage of the qualification framework is the Qualification Basis, which has the purpose to provide a set of criteria against which all power cable and ancillaries qualification activities and decisions are assessed. The technology qualification basis describes the technology, how it will be used, the environment in which it will be used and the performance and technical acceptance criteria [43]. The technology qualification basis is used in the qualification framework to assess the state of the technology and develop the acceptance criteria for the technology qualification plan.

The qualification basis includes the following as a minimum:

- Design System Requirements
- Standards, Codes and Industry Practices
- Areas of Expertise
- Operational, maintenance and inspection
- Lessons learned from similar technologies

The documentation regarding this step of the qualification process can be a single report or a package which compiles all relevant information. It is understood that some requirements definition and supporting description documentation is developed throughout the qualification process, therefore the submittal only needs to include the information available based on the design maturity of the new technology.

### A1.2 Technology Assessment

Once the Qualification Basis is complete, the next stage is to perform the Technology Assessment to determine which elements require technology qualification and identify their key challenges and uncertainties. The Technology Assessment is executed using a top-down methodology in which the system-level functions are decomposed into elements including interfaces.

The Technology Assessment includes the following:

- Technology Decomposition Analysis
- Technology Characterisation
- Technology Stage Assessment (TRL)

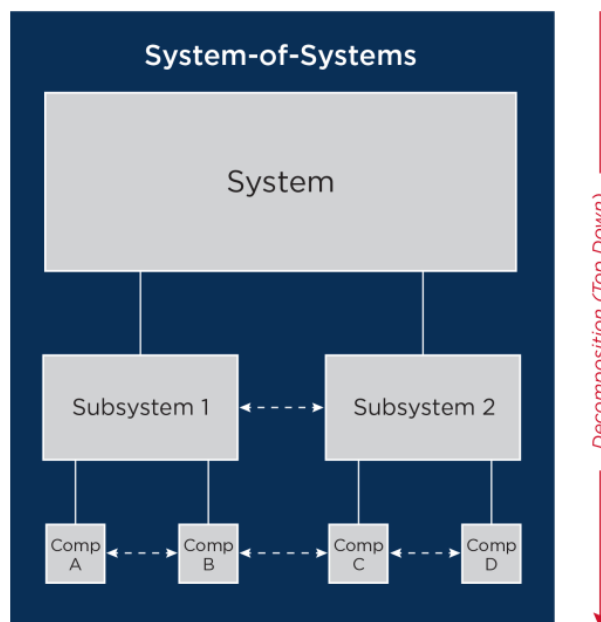
### Technology Decomposition Analysis

The Technology Assessment includes a decomposition where the system is divided into subsystems, which can be further broken down into components. This is done in order to fully understand the novel elements of compound technology and provide a means of communication between people with different disciplines, if applicable.

The decomposition process as shown in Figure 17 is used to achieve the following, as described by ABS [24]:

- Mapping functional requirements of the system to item(s) (e.g., subsystems or components) identifying ownership of a specific functional requirement,
- Mapping functional requirements to specific performance requirements,
- Confirming that all defined functional requirements can be addressed by configurable items,
- Identifying new technology items prior to determining if qualification is needed and what interactions between items need to be considered.

Figure 17 – New Technology System Hierarchy from ABS [24]



### Technology Characterisation

Uncertainty is associated mainly with the novel elements in the technology (e.g. novel components, known components combined/manufactured in a novel way, or known components in a new application). In order to understand where uncertainty is greatest the methodology from DNV [43] is

adopted in this framework to assess the level of effort involved in qualification of the technology. As shown in Table 31 the technology is characterised considering its application area (known, limited knowledge and new) and the degree of novelty of the technology (proven, limited field history and new or unproved). The characterisation increases from categories A) through D), where:

- A) No new technical uncertainties (i.e. proven technology by supplier).
- B) New technical uncertainties.
- C) New technology in existing applications (new technical challenges).
- D) New technology in new applications.

Table 31 – Technology Characterisation according with DNV [43]

Application Area	Degree of Novelty of Technology		
	Proven	Limited Field History	New or Unproved
Known	A	B	C
Limited Knowledge	B	C	D
New	C	D	D

Note: DNV uses numbers 1 to 4, but letters are used here instead to avoid confusion with TRL levels.

The objective of the categorisation is to identify and isolate novel elements of the system and subsystems identified in the Technology Decomposition Analysis to direct the qualification efforts.

Category A technology elements are proven with no new technical uncertainties, where proven methods for verification, tests, calculations and analysis can be used to provide the required qualification evidence. As given in [43], category A includes proven technology in a known application area. It is important not to overlook the proven elements, as they may be critical for the overall performance of the technology, therefore these elements should be handled through the regular design process, ensuring compliance with an applicable standard or industry practice.

Elements in category B to D require technology qualification and have an increasing degree of technical uncertainty. The defined categorization makes it possible to distinguish between the novelties of the technology itself (proven, limited field history and new or unproved) and its application areas (known, limited knowledge and new).

The Technology Characterisation looks into each individual component of the technology to give the basis to assess the TRL level in the next step of the Technology Assessment, which is the TRL Stage Assessment. The TRL level definition will depend on the maturity of technology as a system.

### Technology Stage Assessment (TRL)

Following the results from the Technology Characterisation in a detailed analysis of the maturity level of the technology is carried out to determine which stage of the qualification plan is most suitable for the technology:

- Feasibility (TRL 2)
- Concept Verification (TRL 4)

- Prototype Validation (TRL 6)
- System Integration (TRL 8)
- Operational (TRL 9)

A more mature design could result in the ability to start a later qualification stage, therefore reducing the amount of time and cost to complete the qualification framework.

Table 32 – TRL Levels from ORE Catapult [19]

Level	Explanation
TRL 1	Basic principles observed. Scientific research begins translation to applied R&D: Lowest level of technology readiness. Examples might include paper studies of a technology's basic properties.
TRL 2	Technology concept formulated. Invention begins: Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
TRL 3	Experimental proof of concept. Active R&D is initiated: This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
TRL 4	Technology validated in lab. Basic technological components are integrated: Basic technological components are integrated to establish that the pieces will work together.
TRL 5	Technology validated in relevant environment. Fidelity of technology improves significantly: The basic components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
TRL 6	Technology demonstrated in relevant environment. Model/prototype is tested in relevant environment: Represents a major step up in a technology's demonstrated readiness, which is well beyond that of TRL 5. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
TRL 7	System prototype demonstration in operational environment. Prototype near or at planned operational system: Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment.
TRL 8	System complete and qualified. Technology is proven to work: Actual technology completed and qualified through test and demonstration.
TRL 9	Actual system proven in operational environment. Actual application of technology is in its final form: Technology proven through successful operations. Includes competitive manufacturing in the case of key enabling technologies.

The questions proposed by ABS in [24] are adopted for the framework as a starting point but can be adjusted in accordance with the technology under qualification. For any specific stage, if all questions are answered as “yes” and evidence to support the answers is provided, the supplier’s technology can be considered at that TRL level and progress to the next one.

Due to differences in supplier’s experiences and the subjective nature of the TRL Assessment and the Technology Characterisation, it must be carefully evaluated if and how previous supplier experience with similar technology is applicable to these steps. Therefore, it is key that all suppliers follow the standard framework proposed through all TRL level steps to ensure that similar technologies when applied to dynamic floating wind cable applications will have the same level of qualification and safety at the end of the qualification programme. The time and consequently cost for an experienced supplier of similar technologies to progress from one TRL to the next in a floating wind dynamic cable application will be optimised. To do this, an experienced supplier must demonstrate that the experience from similar technologies is relevant within the qualification process and to define the qualification approach considering the gaps in the existing qualification.

### **A1.3 Threat Assessment**

The objective of the threat assessment is to identify relevant failure mechanisms for the novel technology elements, identified in the technology assessment, and assess their associated risks. The threat assessment for qualification shall include installation and operational phases.

For a thorough Threat Assessment, it is good practice to consider risks regarding all elements of the system including those which have been characterised as having no new technical uncertainties (proven technology). This approach will guarantee that any design changes made to a particular individual element of the system which may impact other elements is captured in the Threat Assessment and addressed during the qualification programme (e.g., via interfaces, or any change to system operational limits).

The higher risk failure modes identified in the Threat Assessment will be carried forward and form the basis for the technology qualification plan. As given in ABS and DNV, there are several threat or failure mode identification techniques in common use e.g. FMECA, HAZOP, FTA, SWIFT, OPERA, etc [24][43].

An FMEA is a reasoning approach best suited to reviews of mechanical and electrical hardware systems. The FMEA technique (1) considers how the failure modes of each system component can result in system performance problems and (2) makes sure the proper safeguards are in place. A quantitative version of FMEA is known as failure modes, effects and criticality analysis (FMECA), which is a systematic technique and simple to apply. However, it investigates one failure mode at a time and may not identify critical combinations of failures.

### **A1.4 Technology Qualification Plan**

The Qualification Plan depends on the results from the Technology Stage Assessment and shall include activities that mitigate the risks found in the Threat Assessment.

The Qualification Plan will include specific activities so that the technology can progress from the current TRL level to the next level. A more mature technology from an experienced provider of similar products could result in the ability to start at a later qualification stage, therefore reducing the amount

of time and cost to complete the qualification framework. However, it should still be evidenced that the technology has achieved each of the TRL levels. The Qualification Plan, therefore, depends on what has been already done in terms of qualification for a new technology and on what is the objective of the current qualification stage. For a technology to reach TRL 9, each stage of the qualification plan has to be completed or evidence provided based on the applicability of previous qualification to skip any earlier TRL step.

The requirements for each step of the Qualification Plan are shown in Table 1 but the activities are very specific to the technology being qualified. The judgment regarding when and how much requalification of the technology as a system or individual components is needed if only some aspects are changed or are novel shall be addressed on a case by case basis. The changes can be regarding the application of the technology (high loads, different water depth or temperature, etc) or the individual components of the technology (parts of the system such as new materials). The level of qualification required in the plan may also be dependent on the magnitude of this change.

The TRL levels that are not explicitly given in the qualification plan in Table 33 (e.g. TRL 1, TRL 3, TRL 5 and TRL 7) are to be fulfilled in the qualification plan of the subsequent level. For example, the activities of the System Integration Stage (TRL 8) include all the requirements from TRL 7 and TRL 8.

The qualification plan must also consider that the order of tests is important to capture both the mechanical and electrical aspects as these are typically not possible to capture in the same tests. Therefore one test may need to follow the other test to capture both aspects. For electrical tests, the sequence of electrical tests is also important (e.g. lightning impulse test is carried out after the heating cycle voltage test and not before).

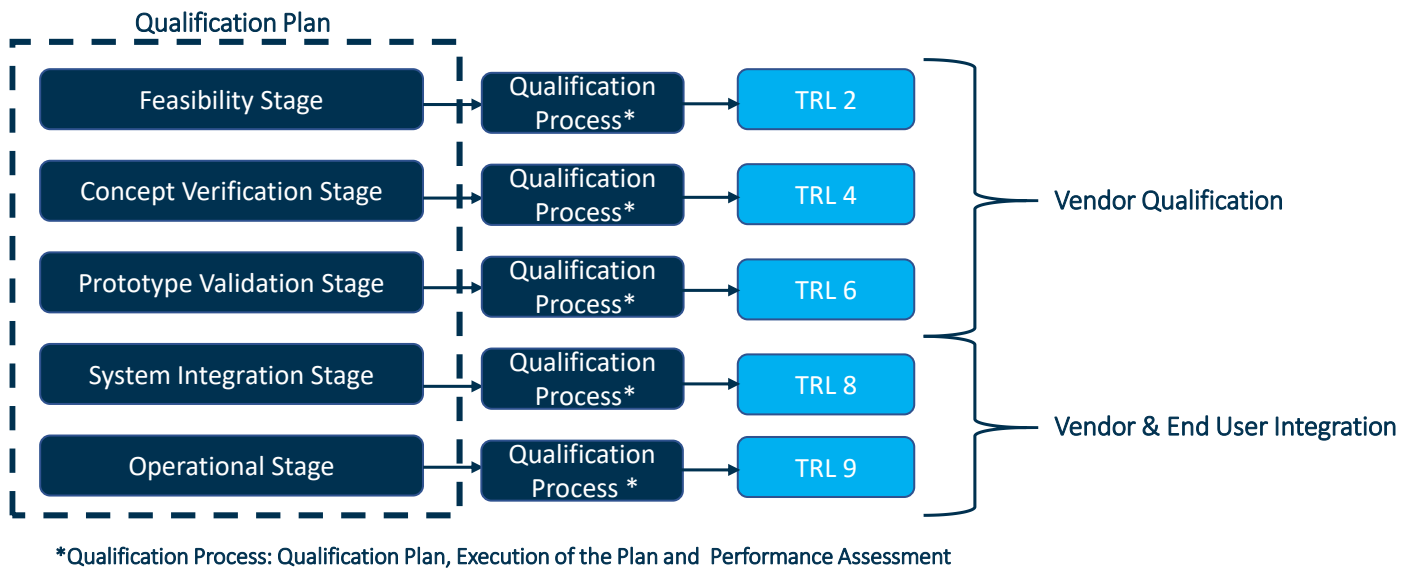
The qualification plans presented in the case studies for the power cable and the bend stiffener connector (Section 5 and Section 6, respectively) are examples based on specific assumptions, and are therefore only indicative of what a qualification plan may look like.

Table 33 – Summary of Tasks per Stage of the Qualification Plan

Requirement	Feasibility (TRL 2)	Concept Validation (TRL 4)	Prototype Validation (TRL 6)	System Integration Stage (TRL 8)	Operational Stage (TRL 9)
Analysis	X	X	X	X	X
Component Tests		X			
Individual Component Fatigue Tests		X			
Characterisation Tests			X		
Type Tests			X		
Full-Scale Fatigue Test <sup>(1)</sup>			X		
Project Specific Tests				X	
Monitoring		X <sup>(2)</sup>		X	X
Commissioning Tests					X

1\ As per CIGRE TB 862 [39], fatigue testing is part of the type tests.  
 2\ Monitoring integrated with the component must be addressed at TRL 4.  
 3\ TRL 1, 3 and 5 are not shown but each TRL level shown means requirements from previous levels are fulfilled. For example, to reach TRL 6 the technology has to have fulfilled all requirements from TRL 6, TRL 5, TRL 4, TRL 3, TRL 2 and TRL 1.

Figure 18 – Qualification Plan & TRL



## A1.5 Execution of the Plan

The technology qualification plans described in should be executed to confirm the margins for the failure modes of concern.

The execution of the technology qualification plans consists of the following key steps [43]:

- Performing the activities in the technology qualification plan
- Collecting and documenting test data generated by each qualification activity
- Ensuring test data and reporting is traceable
- Determining the performance margin for each failure mode

In the event the physical testing does not achieve the analytical model predictions, then the analytical model should be adjusted and additional testing conducted, if necessary.

If physical testing determines an unexpected failure mode, then the additional failure mode should be considered and included in the technology qualification process. Any new or unexpected failure modes should also be assessed in relation to the original threat assessment to confirm any knock on impacts of the behaviour identified in the new failure mode.

The execution of the technology qualification plan represents the main cost in the technology qualification process compared to the previous steps. It is therefore important that the qualification activities are well planned to efficiently minimise time and resources.

## A1.6 Performance Assessment

The objective of the performance assessment is to measure success of the technology qualification plan by comparing the results against the acceptance criteria established from the Qualification Basis. The technology is considered qualified when both risk and uncertainty have been reduced to acceptable levels.

Per [43], the key steps of the performance assessment are to:

- Review and interpret evidence supplied to substantiate the qualification of the technology
- Confirm that all qualification activities have been executed and that acceptance criteria have been met
- Perform a gap analysis between the evidence supplied and the potential failure modes / mechanisms identified in the TA
- Assess the margins between the limitations of the technology, e.g. ultimate failure load and the allowable design limitation, e.g. allowable design load. Margins may be dictated by industry codes and standards or be based on reliability, risk or probabilistic methods.

## APPENDIX 2 TRL STAGE DETERMINATION QUESTIONNAIRE

### A2.1 Feasibility Stage (TRL 2) Questionnaire

Table 34 – Feasibility Stage (TRL 2) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector

Item	Question	Yes/No	Evidence to Support
1 <sup>(1)</sup>	Has what is specifically new and/or unique about the component been clearly identified?		
2	Has what specifically needs qualification been defined?		
3 <sup>(1)</sup>	Have potential applications of the component been identified?		
4 <sup>(1)</sup>	Have fundamental objectives and requirements for the component been identified?		
5 <sup>(1)</sup>	Have basic functionality and durability of the individual sub-components and assembly as a whole been analysed?		
6 <sup>(1)</sup>	Have basic principles been observed and reported?		
7 <sup>(1)</sup>	Have lessons learned from similar technologies been reviewed and documented? (e.g. flexible pipes, umbilicals, static high voltage cables, wave or tidal energy systems)		
8 <sup>(1)</sup>	Have basic design calculations been performed and reported?		
9	Have conceptual research and development been completed and reported?		
10	Has a preliminary list of reliability drivers been prepared?		
11	Can engineering drawings (basic configurations, interfaces, and/or PFD's or flow charts) and calculations be submitted for review?		
12	Have any early stage risk assessment and mitigation studies been performed and documented?		
13 <sup>(2)</sup>	Has global analysis been performed in FEA software such as OrcaFlex and to show the feasibility of the component?		
Notes:			
1\ Adjusted by 2H for the Power Cable Case Study			
2\ Added by 2H for the Power Cable Case Study			

## A2.2 Concept Verification Stage (TRL 4) Questionnaire

Table 35 – Concept Verification Stage (TRL 4) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector

Item	Question	Yes/No	Evidence to Support
1 <sup>(2)</sup>	Are all requirements to achieve TRL2 met?		
2	Has the concept functionality been demonstrated by physical models or "mock-ups"?		
2 <sup>(1)</sup>	Has laboratory scale material testing been performed? (e.g. outer sheath material, metallic component fatigue)		
3 <sup>(1)</sup>	Have laboratory degradation mechanisms been performed? (e.g. Accelerated Ageing of Dielectric and Residual Dielectric Strength from CIGRE TB 722 [38] for the power cable)		
4	Have all conceptual design engineering studies been completed and reported? (e.g. global and local analysis)		
5	Have preliminary function/performance/reliability engineering studies been completed? (e.g. global and local analysis)		
6	Has durability been confirmed by testing or calculation? (e.g. fatigue analysis)		
7	Has a viable manufacturing or fabrication scheme been documented?		
8	Has preliminary qualitative design risk analysis (e.g., FMECA) been documented?		
9	Have the initial risk assessments been reviewed/updated to identify any additional technical risks?		
10 <sup>(3)</sup>	Has the emergency release passed the extended material test?		
11 <sup>(3)</sup>	Has the emergency release passed the small scale test to failure?		
Notes:			
1\ adjusted by 2H for the Power Cable Case Study			
2\ Added by 2H for the Power Cable Case Study			
3\ Added by 2H (applicable to bend stiffener connectors only)			

### A2.3 Prototype Validation Stage (TRL 6) Questionnaire

Table 36 – Prototype Validation Stage (TRL 6) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector

Item	Question	Yes/No	Evidence to Support
1 <sup>(2)</sup>	Are all requirements to achieve TRL4 met?		
2 <sup>(1)</sup>	Have all items in the manufacturing of the power cable been specified?		
3	Has the manufacturing and assembly process been accepted?		
4	Has a prototype or full-scale production unit been manufactured?		
5 <sup>(1)</sup>	Has the power cable passed basic functionality testing of prototype (physical or virtual) or full-scale product to demonstrate fitness and function capability in a simulated or actual operating environment? (e.g. type tests)		
6	Has a performance data collection system been established and properly documented?		
7 <sup>(1)</sup>	Has the power cable passed performance, durability, and accelerated life tests? (e.g. full-scale fatigue test)		
8	Is the degradation of function/performance within expected acceptable limits?		
9 <sup>(1)</sup>	Has the power cable passed system reliability analyses?		
10 <sup>(1)</sup>	Have the operating/destroy limits been established or confirmed? (e.g. using global and local analysis)		
11	Have the degradation limits and rates been established or confirmed?		
12	Has the required in-service monitoring needs and means been identified?		
13	Has a process risk assessment (e.g., process FMECA) been performed and documented?		
14	Has the final design risk assessment (e.g., FMECA) been completed for all life cycle modes (including assembly, transit, storage, installation, hook-up, commissioning, operation, decommissioning) for all interface permutations and properly documented?		
15	Have the residual risk and uncertainty been estimated and properly documented?		
16	Has the reliability study been updated and properly documented?		
17 <sup>(3)</sup>	Has the bend stiffener connector passed the Latch/ Unlatch test?		
Notes:			
1\ adjusted by 2H for the Power Cable Case Study			
2\ Added by 2H for the Power Cable Case Study			
3\ Added by 2H (applicable to bend stiffener connectors only)			

## A2.4 System Integration Stage (TRL 8) Questionnaire

Table 37 – System Integration Stage (TRL 8) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector

Item	Question	Yes/No	Evidence to Support
1	Are all requirements to achieve TRL6 met?		
2	Has the design risk assessment (e.g., FMECA) considering full system interfaces been updated and properly documented?		
3	Have all other technical risks been identified/addressed and properly documented?		
4	Has the component been deployed into a full prototype and fully integrated with the intended systems?		
5	Has the function/performance when connected/integrated into a wider system been fully tested?		
6 <sup>(1)</sup>	Have all mechanical and, electrical interfaces been fully addressed and documented?		
7	Have all system integration requirements been confirmed?		
8	Has installation/hook-up/testing/commissioning with a wider system been completed as per specifications? (e.g. project specific tests from CIGRE TB 623 [37] for the power cable)		
9	Is there a data collection system in place to document performance and reliability?		
10	Has a detailed in-service inspection/monitoring/sampling plan been defined and properly documented?		
11	Can inspection/monitoring/sampling functionality be validated?		
12 <sup>(3)</sup>	Has the project specific pull-in load been tested recreating the exact lines of tension?		
Notes:			
1\ adjusted by 2H for the Power Cable Case Study			
2\ Added by 2H for the Power Cable Case Study			
3\ Added by 2H (applicable to bend stiffener connectors only)			

## A2.5 Operational Stage (TRL 9) Questionnaire

Table 38 – Operational Stage (TRL 9) Questionnaire adapted from ABS [24] for the Power Cable & Bend Stiffener Connector

Item	Question	Yes/No	Evidence to Support
1	Are all requirements to achieve TRL8 met?		
2	Has the component demonstrated acceptable reliability and availability in the targeted operating environment?		
3	Has the in-field service monitoring, sampling, and inspection plan been successfully implemented?		
4	Has reliability and integrity performance data been properly collected, analysed, and documented?		
5	Have any underperforming components of the technology been identified?		
6	If so, then has there been any reliability improvements for failed or underperforming components?		
7	Has there been any performance feedback from projects or suppliers?		
8	Have any unexpected aspects (e.g., interdependencies or influences on performance) or safety concerns been observed?		
9	Has the technology been reliable for at least one survey (or maintenance or planned replacement) cycle or agreed upon time period as indicated in the in-service inspection plan (ISIP)?		
10	Has the design risk assessment (e.g., FMECA) been updated with in service performance data?		
11	Has the system reliability assessment been updated and properly documented?		
12 <sup>(2)</sup>	Has the component had operating service experience of at least 3 years?		
Notes:			
1\ adjusted by 2H for the Power Cable Case Study			
2\ Added by 2H for the Power Cable Case Study			

## APPENDIX 3 GLOBAL AND LOCAL ANALYSIS GUIDANCE

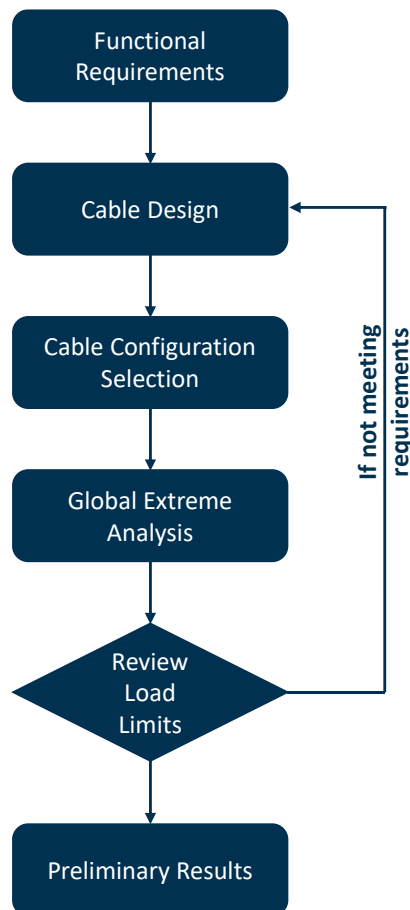
Guidance on applying numerical global and local analysis to power cables is defined for each TRL stage below. A high-level explanation of global and local analysis is provided in Section 5.5.1.

### A3.1 Feasibility Stage (TRL 2)

In finite element analysis (FEA), the cable is divided into a series of straight line segments with a node at each end. Properties of the power cable are defined to reproduce mass per unit length, axial, bending and torsional stiffness. A finite element package such as OrcaFlex [15] can be used to model the global behaviour of the power cable. At this stage usually a simplified approach is adopted, and a reduced load case matrix is assessed to test the feasibility of the power cable and identify areas for improvement. Further optimisation is carried out at the Concept Validation Stage 5.6.1.

A high-level analysis workflow to show how global analysis is carried at the Feasibility Stage is shown in flowchart format in Figure 19.

Figure 19 - Analysis Workflow for Feasibility Stage of Dynamic Power Cable Applications



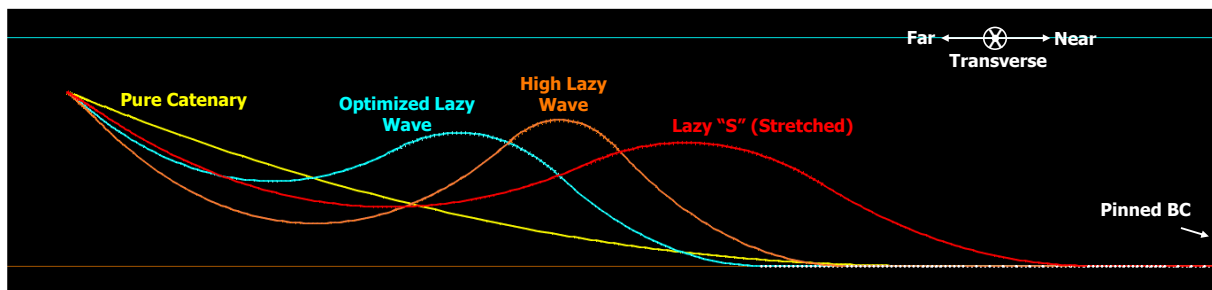
#### Configuration Selection

There are many possible configurations in which the dynamic power cable can be attached to the floating foundation, as shown in Figure 20. The pure catenary configuration is the simplest as it does not require ancillary equipment such as buoyancy modules. However, in the shallow water depths of

the North Sea (~100m), they are usually not feasible due to the large offsets experienced by the floater, resulting in MBR and compression issues.

A lazy wave configuration is commonly used in situations where environmental conditions are moderately harsh, including regions of the North Sea. The solution consists of distributed buoyancy elements attached on a long section along the cable. The resulting configuration has a sag bend and a hog bend and this prevents most of the wave-induced loads from the floating foundation from transferring to the part of the cable on the seabed. Lazy wave configuration is widely used for dynamic cable configurations operating in the relatively shallow water depth of 100m – 300m seen in North Sea. The aim of the global analysis is to ensure that the selected configuration is a feasible concept. Typical configuration for the case study is shown in Figure 1.

Figure 20 – Power Cable Example Configurations



### Global Extreme Strength Analysis

Extreme strength assessment for power cable configuration is performed next considering extreme metocean conditions. This usually considers 50-year return period waves and associated currents and wind at the site location, as specified in the design load cases (DLC) from DNV-ST-0437, [45]. In this type of analysis parameters such as maximum and minimum tension, maximum curvature (minimum bend radius - MBR), maximum absolute twist, and maximum lateral movement are calculated along the cable length to ensure all the parameters are within the allowable limits based on the cable cross-section. Special attention is given to the top, sag, hog and touchdown zone of the cable, which are usually the critical sections in terms of the parameters aforementioned.

The assessment criteria of this stage only address some of the risk failures identified in the Threat Assessment (Section 5.3), FMECA [2], such as exceedance of tensile or bending limit due to over excursion of the cable and incorrect design. At this stage not all threats are addressed (i.e. no fatigue analysis is run) because the objective is just to perform a high-level design analysis to verify the concept.

Therefore the configuration is deemed feasible if the results from the extreme results show that:

- Bend radius above Operating Bend Radius (OBR)
- Tensions within allowable limits
- Compressions within the allowable limits
- Reduced lateral movement at touch down zone

If the results exceed the allowable limits and the configuration does not work for the specified conditions, other configurations (such as tethered lazy wave are explored or a cable re-design is considered.

### **Local Cable Cross Section Analysis**

At this stage local analysis is not a requirement but might be carried out for preliminary input to the global analysis checks.

## **A3.2 Concept Validation (TRL 4)**

### **Extreme Storm Analysis**

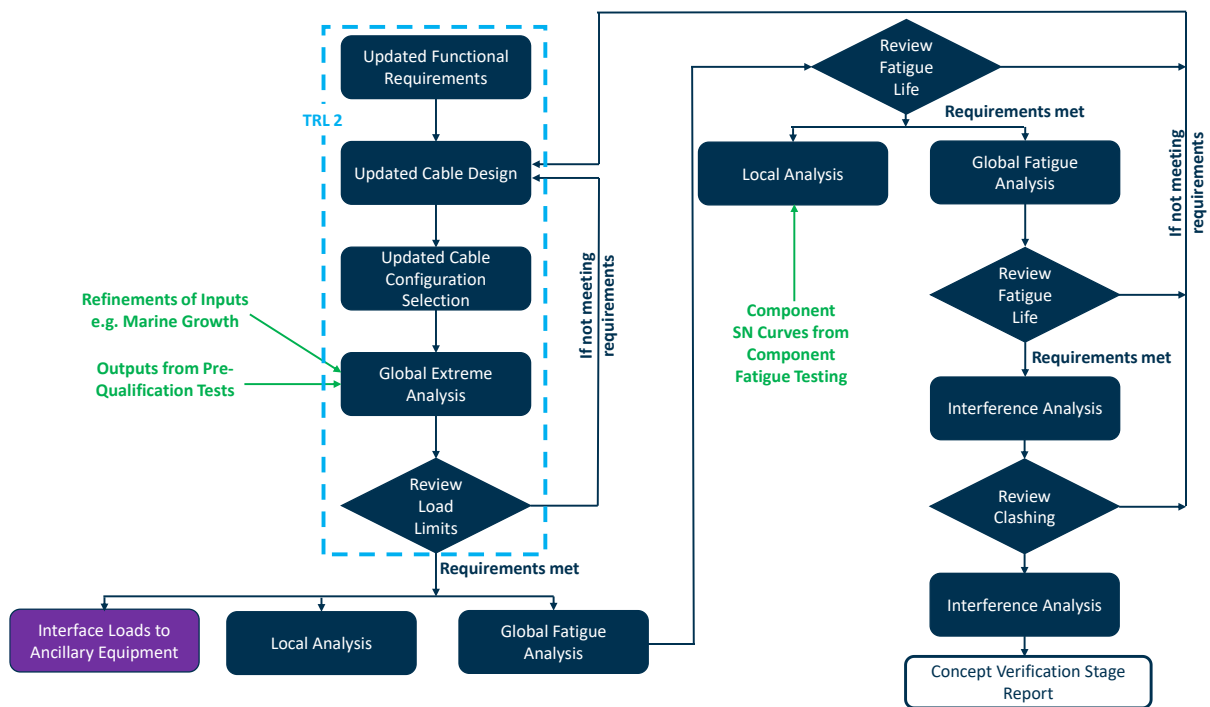
The operating conditions and the relevant environment are further refined, for example marine growth, in comparison to the analysis carried out at the Feasibility stage (Section 5.5.1), therefore the extreme storm analysis is revised. The outputs from the Component Tests in Section 5.6.3 are used to further refine the model.

As identified in the FMECA [2] considered for the Threat Assessment (Section 5.3), marine growth needs to be considered in the power cable and ancillary equipment since it greatly impacts the results of the dynamic analyses. It leads to an increase in the cross-sectional dimensions of the cable and ancillary equipment, affects the drag coefficients and increases the weight. Marine growth can have an especially large impact when the project's characteristics include shallow water, light cable and if the configuration is not tensioned from the seabed (i.e. catenary, lazy wave, etc.) [39], which is the scenario of this case study. The standards available for oil and gas may not be directly applicable to sites where floating offshore wind farms are intended to be installed, e.g. the North Sea. However, due to lack of more appropriate data, the marine growth profile from NORSOK K-N003 [57] is used at this stage in this case study.

The global loads from the analysis are supplied to the providers of the ancillary equipment. For example tension versus angle curves are extracted at the top of the cable and provided to the bend stiffener supplier.

Fatigue and interference analysis are also carried out at this stage, as shown in Figure 21.

Figure 21 - Analysis Workflow for Concept Validation of Dynamic Power Cable Applications



### Global Fatigue Analysis

As identified in the threat assessment (Section 5.3), one of the main design issues for power cables in marine applications is fatigue strength. Dynamic power cables have a range of potential failure modes, however, the fatigue damage of the copper conductor, screen and armour wires is one of the most common problems affecting the longevity of their service life. With the increasing utilisation of dynamic power cables for current and future field developments, compounded by the recurrent need for field life extension, it is essential to understand the accumulated fatigue damage over the operational life.

To calculate the fatigue life, a good understanding of the operating conditions over the expected field life is essential; especially the metocean conditions and the floating structure motions. This case study, in line with recommendations from the FMECA [2], assumes the buoyancy lines EOL values for OD with marine growth to estimate the drag in the fatigue analysis.

Fatigue life is defined as the number of cycles of stress or strain a structure or structural element can sustain before failure of the material occurs. In practice fatigue life often refers to the number of years for which safe operational conditions are ensured. CIGRE TB 862 [39] provides a good framework to evaluate the expected loads and motions of the power cables and design a full-scale fatigue test to validate the structural integrity for the expected operational life.

To ensure a fatigue life larger than the desired service life, the industry accepted fatigue analysis methodology shall be used [39]. This is a two-step procedure. First dynamic global analysis is performed to extract power cable motions (usually tension and curvature) for a set of metocean conditions. The fatigue critical locations along the cable length (often at the bend stiffener region, near the buoyant section, and at the touchdown location) is detected for further analysis. In the second step, the stresses are assessed at the critical locations evaluated in step one, using a local analysis software such as UFLEX. The full range of stress cycles (or sometimes strain cycles) predicted over the

component lifetime are then used to predict the accumulated fatigue damage using S-N (or e-N) curves, including appropriate fatigue safety factors. It is important that the S-N fatigue curves are appropriate for the specific material and component being considered, and ideally derived from physical fatigue testing at the component level.

The fatigue assessment is performed as follows:

- Hysteresis curve (i.e. pipe bending moment versus curvature) is added to the global analysis models
  - At this stage usually a generic representative curve is used
  - Alternatively, local analysis using power cable cross-section is conducted in software such as UFLEX [16] to determine the hysteretic curve
- Global fatigue dynamic simulations are performed for the prescribed loading conditions
- The global loads output from the fatigue assessment are utilised as inputs to the ancillary equipment design (e.g. bend stiffener) and iterations are done to confirm the design of all the systems.

Upon completion of the fatigue analysis, if the results indicate acceptable fatigue life, interference analysis is carried out. It is assumed for the case study that all requirements are satisfied.

### Local Fatigue Analysis

One of the requirements for a technology to meet TRL 4 is that separate elements of the technology are validated analytically and in lab. At this stage specific SN curves or eN curves are developed in lab as described in Section 5.6.4 and subsequently used to calculate fatigue at the subcomponents.

Also, from the FMECA [2] it can be seen that material fatigue of the armour layers, outer serving and electric cores are medium risk and shall be addressed by this qualification plan.

From the global fatigue analysis tension and curvature time traces are extracted at the critical locations, usually along the bend stiffener, hog and sag bends, and touch zone. The extracted time traces are input to the local analysis model developed allowing stress time traces to be calculated for subcomponents of the power cable (core, metallic screen and armour wires) using software such as UFLEX [16].

### Interference Analysis

As described in the Threat Assessment (Section 5.3), although the risk of interference of the power cable with adjacent structures has not been captured in the FMECA [2], it is a recognised risk (CIGRE TB 862 [39]) and shall be addressed by the activities of the qualification plan.

The aim of the interference assessment is to identify potential clashing between the power cable and any adjacent structure, for example, mooring lines or other power cable systems. If more than one power cable is hooked to the floating foundation then clashing between the adjacent power cables shall also be assessed. A limiting criteria of 'no clashing' is used for this assessment, therefore a system response of clearance greater than zero between the mooring-cable or cable-cable pair is deemed acceptable. If clashing is observed for the selected configurations, the location and magnitude of maximum impact energy is assessed to ensure that it is within the cable capacity. If the clashing is not acceptable or the impact energy exceeds the allowable limits, then cable re-design

shall be considered, e.g. power cable hang-off angle/azimuth, mooring arrangement, floating structure spacing, etc.

### A3.3 Prototype Validation (TRL 6)

At this stage the power cable cross section is at the detailed design phase. Uncertainties on the inputs of the power cable are minimised due to the tests carried out such as the characterisation tests in 5.7.3, as shown in Figure 22.

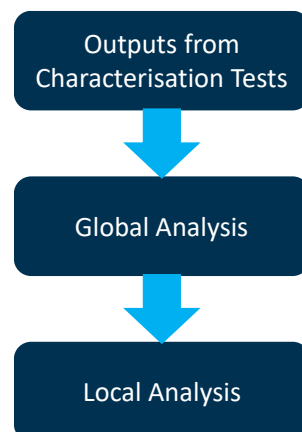
The hysteretic stiffness from the test is modelled in the global analysis to reduce conservatism. This increases the computational time compared to a linear stiffness and also requires that a detailed description of the moment-curvature relationship has been established through testing considering the full range of operating temperatures.

The analyses carried out are:

- Global and Local Extreme Analysis
- Global and Local Fatigue First Order Analysis
- Interference Analysis
- Installation Analysis

Note there are still uncertainties about the power cable final lazy wave configuration which is project specific. Therefore, the cable configuration with ancillary equipment will be at detailed design in the System Integration Stage 5.8.

Figure 22 – Workflow for Characterisation Tests and Analysis



### A3.4 System Integration (TRL 8)

At this stage the global analysis is repeated considering the final design of the ancillary equipment. A finite element package such as OrcaFlex [15] is used to model the global behaviour of the power cable coupled to the floating foundation, tower, turbine and mooring lines and thus analyse a more optimised configuration to ensure cable integrity is maintained over the design life. At this stage

project specific data is used, such as mooring lines (properties and configuration) and ancillary equipment. In addition to the project specific data the cable is modelled incorporating data from all the tests carried out in previous stages of the qualification framework, resulting in a very accurate model.

Although not mentioned by CIGRE TB 862 [39] the floater offset is dependent on both power cable and mooring requirements. Therefore the analysis at this stage shall consider a fully coupled analysis model to optimise the power cable based on the full system response.

Additional project specific tests are proposed in Section 5.8.2 to support inputs for the global analysis and reduce uncertainties: cable soil interaction and marine growth measurement. It is recommended that project specific data for marine growth is used in the System Integration stage.

It is expected that only minor adjustments to the lazy wave configuration from the Prototype Validation stage (Section 5.7.1) are needed to achieve the design requirements of the cable integrated with the ancillary equipment. An area of high fatigue damage is the top of the cable and this can be improved with the addition of a well designed bend stiffener. At this stage it is key to have a good interface with the providers of ancillary equipment in case they also need minor adjustments to improve the system response.

The global analysis flowchart is similar to the presented for the Concept Validation, but all design load cases (DLC) from DNV-ST-0437, [45] are assessed. At this stage, in addition to wave induced fatigue, VIV analysis is also carried out.

Installation analysis is carried out considering the installation vessel selected for the project.

In summary the analyses carried out with project specific data are:

- Global and Local Extreme Analysis
- Global and Local Fatigue First Order Analysis
- Global VIV Fatigue Analysis
- Interference Analysis
- Installation Analysis

### **A3.5 Operational Stage (TRL 9)**

The global model is calibrated with measurements from the monitoring campaign and rerun to confirm results from previous stages remain valid. Based on the results, the integrity management plan (IMP) is updated to ensure long term reliability. The quality of a risk-based inspection plan is dependent on knowledge of the system.

## APPENDIX 4 CHARACTERISATION TYPE TESTS

---

### A4.1 Bending Stiffness Test

The bending stiffness of the power cable is nonlinear and can be affected by factors like temperature. The use of accurate bending stiffness on the analysis model influences the dynamic loading of the cable.

As explained in CIGRE TB 862 [39], the moment-curvature relationship of a dynamic cable is complex and affected by several parameters. It is therefore common to simplify the bend stiffness in the global analysis by applying a conservative lower bound constant bend stiffness, but this will result in a conservative assessment of the curvature response, i.e. overpredicting the curvature range for both extreme and fatigue loads. It should be noted that a lower bound stiffness will not be conservative when assessing bend moment at interfaces, such as the bend stiffener. Therefore, the bending stiffness estimated from test shall be used to capture the correct dynamic response of the cable and provide accurate loads to the suppliers of ancillary equipment.

CIGRE TB 862 [39] cites CIGRE TB 669 where three common test principles are proposed: the three-point bend method (also termed single-point load method), four-point bend method (termed two-point load method) or moment method. Common for all test methods is that the test is performed without tension in the cable.

The four-point bend method described in CIGRE TB 862 is suggested as part of this case study as for this method the load is distributed along a wider area in comparison to the three-point bend method, avoiding premature failure.

### A4.2 Tensile Characterisation Test

This test is performed to establish axial stiffness, torsional balance, and rotational characteristics of the cable. As an output the test confirms that the cable is torsionally stable and that the local model predicts these characteristics accurately. The output of this test can also provide input to the global analysis of the cable in this qualification stage in order to reduce uncertainties and capture more accurately the dynamic motions and loads of the cable. The test is described in CIGRE TB 623 [37].

### A4.3 Friction Coefficient Test

The test to estimate the friction coefficient of the power cable of this case study is relevant for installation analysis and for the interface between the power cable and ancillary equipment such as the buoyancy modules. As explained in CIGRE TB 623 [37] the areas where friction plays some role are:

- Cable sliding against a sheave, chute, caterpillar contact surfaces, capstan wheel or other laying equipment on a cable laying vessel
- Cable sliding in pulling grips (Pulling Stockings) or in clamps/ropes and in buoyancy units
- Cable sliding against a wall of a straight or curved pipe, hole or cable support during installation
- Cable sliding in cable clamps during cable operation

In addition, depending on the cable design, the slip plane may not be the outer serving to some external interface and slippage may occur internally. This becomes of particular importance in deeper water installation. Tests from API 17E[30] can be used to address this.

## APPENDIX 5 MECHANICAL TYPE TESTS

### A5.1 Coiling testing

This test applies only to cables which are coiled during manufacturing, storage, transport or installation and do not apply to cables that are wound on drums or turntables. For the power cable of this case study, the coiling test is likely to be applicable since the in the North Sea cables are usually coiled during installation as opposed to using drums/turntables.

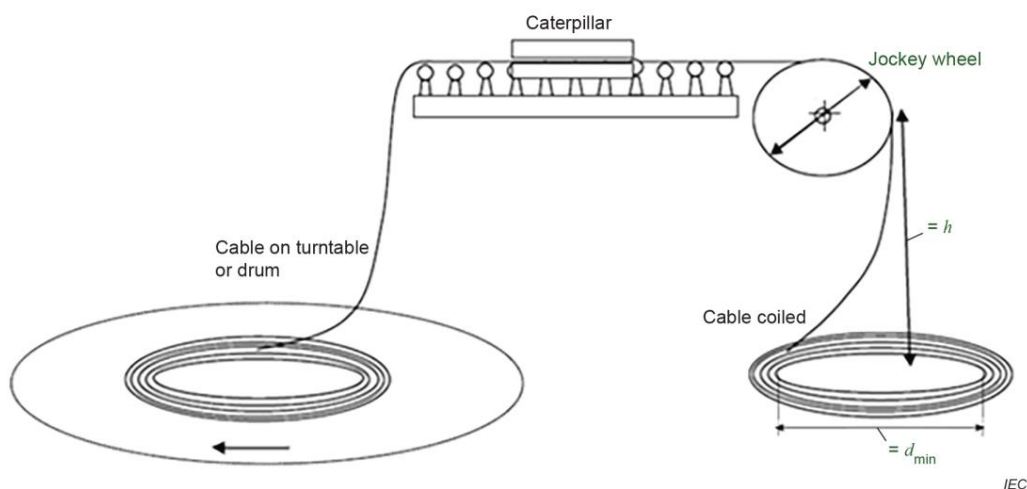
When performed, this test is a pre-condition for the electric type tests described in Section 5.7.5, therefore the same sample subjected to the coiling test shall be subsequently used for the electric type tests.

The coiling test confirms the suitability of the cable for coiling according to the parameters encountered in cable handling. An example of arrangement is shown in Figure 23.

After the coiling test, the test cable and all joints shall be inspected visually for deformation of the outer layer. A complete visual inspection shall be performed as described in IEC 63026 [48] Section 12.5.7 and CIGRE TB 623[37] Section 5.1.4.

Further details for the coiling test are available in Section 12.4.1 of [48] and Section 5.1 of [37].

Figure 23 - Example of coiling test arrangement [48]



### A5.2 Tensile Bending Test

This test is a pre-condition for the electric type tests described in Section 5.7.5, therefore the same sample subjected to tensile bending test shall be subsequently used for the electric type tests.

This test is designed to consider the forces that apply to cables during laying and normal recovering. The tensile bending test is applicable for cables which are intended to be installed, recovered or repaired with a method that comprises simultaneous bending under tension, e.g. laying over lay wheels, lay chutes or around capstan wheels [37]. For dynamic applications such as the power cable of this case study, in addition to during installation, bending under tension can occur in extreme loading scenarios.

The test cable is laid halfway around a large sheave, which represents the laying wheel of the cable-laying vessel. An example of a cable-laying vessel is shown in Figure 24. For the test a pulling force is applied to the cable ends as shown in Figure 25 while they are moved three times back and forth around the sheave.

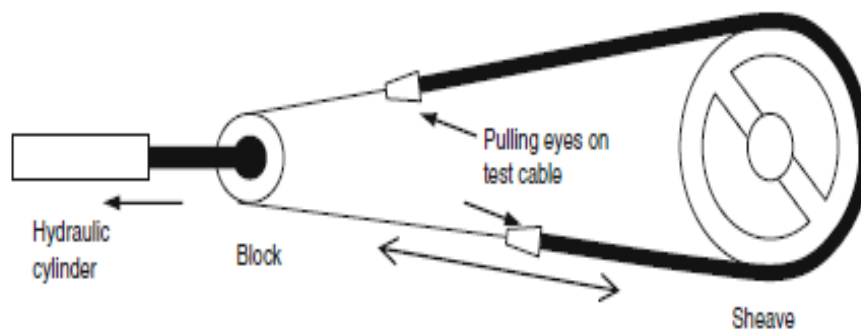
After the tensile bending test, a complete visual inspection shall be performed as described in IEC 63026 [48] Section 12.5.7 and CIGRE TB 623[37] Section 5.1.4 and the integrity of the optical fibre shall be verified through a continuity check.

Further details for the tensile bending test are available in [48] and Section 5.2 of [37].

Figure 24 - Example of Cable Laying Vessel [17]



Figure 25 - Schematic Representation of Bending Test Over Sheave [40]



### A5.3 Tensile Test

The purpose of this test is to verify the performance of the cable when exposed to an axial tensile force without bending. The tensile test shall be performed if the expected axial tensile forces during the cable installation and/or service life are larger than the test tension used in the tensile bending test. This could for instance be during a pull-in operation, if a vertical laying spread is used or during the operation of a dynamic cable.

For the power cable of the case study, axial tensile forces during the cable installation are not expected to be high due to the shallow water. However higher loads can be seen in extreme loading scenarios and results from the global analysis (Section 5.7.1) are used to evaluate if the tensile test is needed.

If a tensile bending test has been performed, then the tensile test may be performed on the same sample.

After the tensile test, a complete visual inspection shall be performed as described in IEC 63026 [48] Section 12.5.7 and CIGRE TB 623[37] Section 5.1.4 and the integrity of the optical fibre shall be verified through a continuity check.

Further details for the tensile test are available in [48] and Section 5.5 of [37].

#### **A5.4 Combined Axial Compression and Bending Test & Axial Compression Test**

The dynamic inter array power cable of the case study will likely be subjected to some level of axial compression at the touchdown zone and sag/hog bend sections due to the dynamic movement of the cable and large excursions of the floater platform in the same direction as the touchdown zone (near direction). Negative tension on the armour wires can lead to bird caging or trigger lateral buckling, as identified by the Threat Assessment FMECA [2] summarised in Section 5.3.

The previous IEC and CIGRE codes for power cables did not include any tests or recommendations for axial compression, only radial. CIGRE TB 862[39] released in January 2022 recommends tests for combined compression and bending and axial compression only to address this scenario. For the case study, this is of particular relevance due to the shallow water depth and harsh environmental conditions in the North Sea.

Following the test, the acceptance criteria include dissection and visual inspection, as well as an integrity check of the optical fibre.

Further details for the compressive tests are available in Section 6.6.1 of [39].

## APPENDIX 6 ELECTRICAL TYPE TESTS

---

### A6.1 Partial Discharge (PD) Test

PD is an electrical discharge that occurs across a localised area of the insulation between two conducting electrodes, without completely bridging the gap (IEC 60270 [49]). The purpose of the PD test is to verify that the cable insulation is free from partial discharges above a specified magnitude at a specified voltage. The PD is therefore used to assess the health of electrical insulation. In the context of this case study, this test will verify the suitability of new materials used for insulation or the suitability of the insulation for higher voltages in new cable designs.

The test voltage shall be raised gradually to and held at  $2 U_0$  for 10s and then slowly reduced to  $1.7 U_0$ . For the case study  $U_0=36kV$ .

The test can be carried out at an ambient temperature and at high temperature.

The partial discharge test shall be carried out after the final cycle of the heating cycle voltage test or, alternatively, after the lightning impulse voltage test [36].

Further details for the partial discharge test are available in Section 12.5.3 of [48] and Section 8.8 [36].

### A6.2 Tan $\delta$ Measurement Test

Tan delta, also referred to sometimes as the dissipation factor, is a diagnostic method of testing cables to determine the quality of the cable insulation. This is done to try to predict the remaining life expectancy and in order to prioritize scheduled maintenance, replacement, or rejuvenation of the cable system under test.

Similar to the PD test, the Tan  $\delta$  measurement test will verify the suitability of new materials used for insulation or the suitability of the insulation for higher voltages in new cable designs.

Further details for the tan  $\delta$  measurement test is available in Section 12.5.4 of [48] and Section 8.8 [36].

### A6.3 Heating cycle voltage test

The heat cycles test set is performed by feeding current periodically into the cable under testing. In on-cycle, the test set heats up the cable for at least 8 hours. The conductor temperature shall be maintained within  $90^{\circ}C$  for at least 2 hours of each heating period. In the off-cycle, the cable cools down for at least 16 hours until its conductor temperature is less than or equal to  $30^{\circ}C$  or within 10K of ambient temperature, whichever is higher. The cycle of heating and cooling shall be carried out 20 times.

During the whole of the test period, a voltage of  $2U_0$  shall be applied to the test assembly. For the case study  $U_0=36kV$ .

The purpose of this test is to verify that the HV power cable of the case study has been designed to comply with system operating requirements and to confirm that it will provide the expected reliability under normal and overload operating conditions.

In IEC 63026 [48] there are no requirements to measure the temperature at the other subcomponents of the cable during the test. In this case study it is recommended that the temperature at the outer sheath (serving) is measured. [

Further details for the heating cycle voltage test are available in Section 12.5.5 of [48] and Section 8.8 [36].

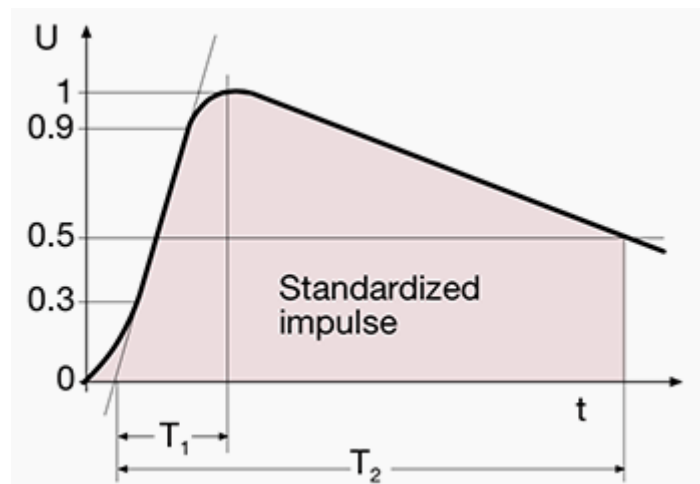
#### A6.4 Lightning Impulse Voltage Test Followed by a Power Frequency Voltage Test

The capability to withstand lightning transients is a mandatory requirement for any medium / high voltage power cable system. As a type test, this test is carried out on the cable system of about 20m to 25m length of cable mounted with all accessories and at the applicable Basic Impulse Level voltage (BIL) of that system.

After the lightning impulse test, the test assembly shall be subject to a power frequency voltage test at the routine test voltage for 15min.

Further details for the lightning impulse voltage test are available in Section 12.5.6 of [48] and Section 8.8 [36].

Figure 26 – Schematic of a Standard Impulse Voltage Shape [13]



#### Resistivity of Semi-Conductive Screens

Semi-conductive screens are part of the insulation system. The semiconducting inner and outer screens contain carbon black as an active conducting filler. The performance of the semiconducting screen compounds and their extrusion is important for MV, HV and EHV cables [41]. The semiconducting screens have to be securely bonded to the insulation, thus assuring the consistent bond required at the important stress interface.

The resistivity of extruded semiconducting screens applied over the conductor and over the insulation shall be determined by measurements on test pieces taken from the core of a sample of cable as

manufactured and a sample of cable which has been subjected to the ageing treatment to test the compatibility of component materials. The test shall be conducted as per IEC 63026 [48] section 12.5.8.

For the case study, following IEC 63026[48], the resistivity of the semi-conducting screens both before and after ageing shall not exceed  $1000\Omega\cdot\text{m}$  and  $500\Omega\cdot\text{m}$  at the conductor and insulation screens, respectively.

Further details for the measurement of the resistivity of semi conductive screens are available in Section 12.5.8 of [48] and Section 8.8 [36].

## APPENDIX 7 PROJECT SPECIFIC TESTS

---

### A7.1 Bending Test Without Tension

This test is recommended to be performed when the relative bending radius during handling of the cable is smaller compared to what has previously been verified with a similar cable design. The number of bending repetitions and the bending radius should reflect the expected conditions during cable handling.

### A7.2 Crush Test

The crush test is carried out to verify if the cable can withstand the expected crush loads during installation or repair.

### A7.3 Crush Test for Long Term Stacking

This test is performed to check if the cable can withstand long term crush loads representative for stacking during storage, transportation or operation.

### A7.4 Sidewall Force Test

The purpose of the test is to verify that the cable can withstand the sidewall forces that the cable will be exposed to during installation or operation. Sidewall forces are radial forces that arise when a cable is in tension simultaneously as it is bent against another object. For the case study this may occur when pulling the cable over a fixed metallic curve like J-tube.

### A7.5 Impact Test

The test is primarily performed for information to establish the impact capacity of the cable and to give an indication of the effect of a typical impact. Impact damage may for example result from accidentally dropped objects. In fixed wind rock placement may be used as a protection method where the rock size is chosen to be small enough to avoid cable damage and large enough to give suitable long-term protection. However in floating wind, as is the scenario of this case study, the cable is free hanging therefore this test shall be carried out to assess the effect of a typical impact.

### A7.6 Pulling Stocking Test

During laying, jointing and lifting operations, the cable may be attached to the vessel by a pulling stocking (sometimes referred to as a Chinese finger). This is not applicable to the power cable of this case study.

### A7.7 Cable soil Interaction Test

A test to measure the cable soil interaction and estimate site specific soil coefficients is recommended to be carried out at the project site prior to the commencement of the global analysis of the project so that accurate cable soil interaction is modelled.

## **A7.8 Marine Growth Measurement**

Marine growth thickness and density measurement as a function of depth and versus time is recommended to be carried out at the project site prior to the commencement of the project so that accurate marine growth properties can be used in the analysis.

## APPENDIX 8 OTHER TESTS FROM CIGRE TB 862

---

### A8.1 Clamp Squeeze Test

The power cable interfaces with the seabed and other ancillaries such as bend restrictors, buoyancy modules and potentially tethers or other touch down point restraints. The purpose of the clamp squeeze test is to verify that the cable can withstand the design clamping pressure and to characterize the cable's short and long-term behaviour with regard to clamping loads.

After completion of the clamping test, the clamp is uninstalled, and the cable shall undergo dissection and visual inspection. There should be no cracks nor holes in the outer sheath and particular attention should also be paid to harmful indentations in the cable cores.

For the case study, buoyancy modules are used therefore this test shall be carried out as part of the qualification process.

Further details for the clamp squeeze test are available in Section 6.6.2 of [39].

### A8.2 Clamp Slippage Test

This test verifies that the clamp will not slip when exposed to the expected maximum tensile load occurring during installation and operation. The temperature during the test should take the expected operating temperature of the clamp into consideration.

After completion of the clamp slippage test the clamp is uninstalled, and the cable shall undergo dissection and visual inspection. There should be no cracks nor holes in the outer sheath and particular attention should also be paid to harmful indentations in the cable cores.

For the case study, buoyancy modules are used therefore this test shall be carried out as part of the qualification process.

Further details for the clamp slippage test are available in Section 6.6.3 of [39].

## APPENDIX 9 CABLE CHARACTERISTICS FOR PROTOTYPE TESTS

---

To carry out the cable system tests described in Section 5.7 the following characteristics of the cable shall be known [48]:

- a. Name of manufacturer, designation and manufacturing date (date of last production phase) or date code;
- b. Rated voltage: values shall be given for  $U_0$ ,  $U$ ,  $U_m$
- c. Maximum laying depth in water;
- d. Type of conductor, its material and nominal cross section area, in square millimetres; conductor construction;
- e. Material and nominal thickness of insulation ( $t_n$ )
- f. Type of manufacturing process for the insulation system;
- g. Nature of watertightness measures in the screening area;
- h. Material and construction of metal screen, for example number of wires; the DC resistance of the metal screen; material construction and nominal thickness of metal sheath, or longitudinal applied metal tape or foil bonded to the oversheath, if any;
- i. Material and nominal thickness of the core oversheath, if any;
- j. Material type, number of layers, direction of lay and diameter of the wire in each layer of the wire armour; material type and thickness of the additional layer of metal tapes, if any;
- k. Material type and thickness of the outer serving, if any;
- l. Nominal diameter of the conductor ( $d$ );
- m. Nominal overall diameter of the cable ( $D$ );
- n. Nominal inner diameter ( $d_i$ ) and calculated nominal outer diameter ( $D_{i0}$ ) of the insulation;
- o. Nominal capacitance, corrected to 1km length, between conductor and screen;
- p. Calculated nominal electrical stress, in kV/mm, at conductor screen ( $E_i$ ) and at insulation screen ( $E_0$ ).