Guidelines for Open-Water Testing of Wave Energy Converters

Prepared for the Northwest National Marine Renewable Energy Center

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Preface

This document aims to provide a comprehensive set of wave energy system testing guidelines to assist in developing test plans that help reduce risk and maximize safety for successful open-water testing. The protocols describe practical testing methods which can be followed to systematically identify design deficiencies at the earliest stage possible when it is least expensive to repair and to ultimately prove device performance in real sea conditions. Technical standards and industry best practices serve as the basis for these guidelines and where standards and other protocols are available; this effort will reference them. When no standard is available with detailed performance measurement methods, this document will go into greater detail to fill in the gap. In this way, it will act as an over-arching structure, utilizing both existing standards and newly developed protocols to create a comprehensive resource.

Abbreviations and Acronyms

MHK	Marine and Hydrokinetic
NNMREC	Northwest National Marine Renewable Energy Center
PTO	Power Take Off
R&D	Research and Development
RD&D	Research, Development, and Demonstration
SOP	Safe Operating Plan
STD	Standard Deviation
TRL	Technology Readiness Level
WEC	Wave Energy Converter

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1 General Information

1.1 Purpose

Experience from the Navy and the offshore oil and gas industries, as well as from conventional wind, demonstrate that a systematic and incremental testing regime is a necessary component of research, development and demonstration (RD&D) to mitigate technical, environmental, and fiscal risk in technologies prior to full-scale commercial rollout. Unlike aerospace and many other mature industries that can leverage decades of experience and knowledge to rapidly advance and even skip testing stages, the wave energy industry is still in the early stages of development. Thus, an incremental, rigorous, and cautious testing approach is warranted to move technologies from scaled bench tests and laboratory testing to open-water testing. The procedures and approach within this document will therefore be needed until a comprehensive knowledge base is developed from extensive field deployments and operational experience [1].

> *It should be stated that following a staged, systematic development plan is not a guarantee for successes, but not following one is probably a pathway to disappointment, lost time and wasted resources. [2]*

This set of recommended protocols and practices was created from experience and input and guidance from industry, scientists, and government officials to establish a practical and comprehensive guide to open-water testing of Wave Energy Converter (WEC) technologies.

1.2 Scope

This set of guidelines defines the recommended testing protocols and practices for testing WECs at NNMREC and are applicable, but not limited to point absorbers, attenuators, terminators, oscillating water columns, and surge devices that drive electrical, hydraulic and Pneumatic PTOs. These guidelines cover both pre-deployment testing and readiness verification and open-water testing

1.3 Overview

In-water testing is a critical step in technology development of WEC systems, but it should only occur after laboratory testing has been successful and the technology has advanced as far as possible. Laboratory testing provides the necessary risk reduction that can reduce the cost and duration of in-water testing and greatly increase the chances of success.

In-water testing is used to evaluate the performance of large scale models, or full scale prototypes in the natural environment, under naturally generated environmental conditions. Because in-water testing utilizes the natural environment, testing can be used to monitor and evaluate environmental and ecological interactions, and then test mitigation technologies and strategies prior to commercial roll-out.

When a technology is ready for in-water testing, at TRLs 5-9, it is typically a large, fully functioning complex electro-mechanical machine. The complexity and associated cost of technology, necessitates a cautious step-wise approach to rigorously evaluate and refine the technology to reduce risk to acceptable levels prior to deployment in open-water. As such, these protocols and practices are developed to reflect a multi-step testing strategy. Therefore, two stages are identified for a fully assembled device: 1) Pre-Deployment Testing and Readiness Verification which includes dry dock and dockside testing and 2) Open-Water Testing which includes device deployment, operation and recovery. These protocols are developed around the following objectives of open-water testing:

- Field evaluation and characterization of technology, including verification of system function, integrity, reliability and ultimately viability
- Technology proving and demonstration
- Establish power matrices
- Gaining installation, operational, maintenance and recovery experience
- Quantifying costs
- Characterizing and understanding of the environmental interactions and effects
- Collect data for numerical model calibration and validation
- Device Qualification/Commissioning and Certification
- Determining the skills, equipment, vessels, and procedures needed at all life-cycle stages
- Development and evaluation of control strategies

1.3.1 Pre-Deployment Testing and Readiness Verification.

Technologies that first enter the water have an elevated risk of failure because even a small design, fabrication, or assembly oversight, such as a damaged O-ring, can lead to the rapid loss of a system. Once problems are identified, the cost and time associated with repair and modification is much less at dry dock than after deployment in the open-water testing site Therefore, immediate deployment of a technology after fabrication or modification into an open-water environment is not recommended. It is essential to identify technical issues as early as possible. Comprehensive dry dock/on dock tests followed by wet dockside tests are important to verifying system readiness prior to early sea trials and open-ocean testing are also needed to help to identify performance, safety, and survivability issues that could be catastrophic once a WEC is in the open-ocean.

> One hour (dollar) to install or repair in a shore/land facility will take three hours (dollars) in a dry dock and at least eight hours (dollars) in the field – much more if the system has to be recovered and brought to shore for repair

The pre-deployment testing and readiness verification stages are shown in Figure 3. These steps include:

1. **Dry sub-assembly testing**. As components arrive to the staging and assembly area, they should be individually tested for function prior to being installed into the assembly. This step is necessary to not only reduce the time and cost of removing defective parts, but also because it is often very difficult to identify which part has failed once the WEC is fully assembled and interactions between components can be complex. Ideally, components such as the PTO will have been tested on a dynamometer.

2. **Dry system testing**. Once the system is fully assembled and prior to placing the system in the water, a set of comprehensive tests should be conducted to verify the system is ready to get wet. This includes test to verify seal integrity, safety functions, electronics and sensor operation among others. Caught early, issues such as seal damage and open ports can save the system from significant damage by water ingress.

3. **Dockside wet system testing.** Upon successful dry dock testing, a short duration wet test is recommended, where the device is placed in the water to further verify seal integrity, stability, safety system function, and overall sensor and electronic operation. Facilities to support this test can either be a shore side facility or a test tank with sufficient depth. In subsequent tests, further functionality can be tested by powering the technology, if possible, to have the system move and mimic operation. Ballasting systems can also be tested while the WEC is attached to a lift. Ideally, testing areas should be sheltered with little, if any, waves and currents that can make these initial tests more difficult.

4. **Test readiness review and verification.** The final step before proceeding to open-water testing is a test readiness review and verification. This is a review by **all** stakeholders to ensure that the WEC is ready for open-water testing. This should include are review of previous testing results, acceptance of the open-water testing plan and safe operating procedures (SOPs), conformity to established procedures, compliance with permits allowing operation and verification that all previous deficiencies have been corrected.

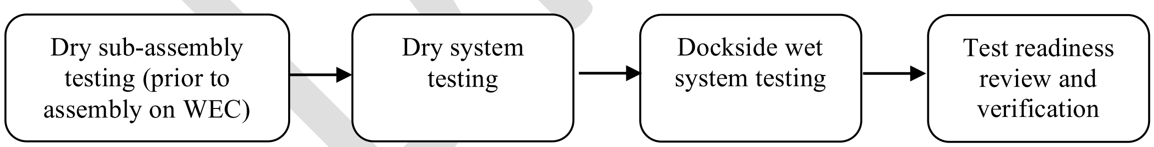

Figure 1. Recommended steps in for pre-deployment testing and readiness verification

1.3.2 Open-Water Testing

Open water testing in a real environment is the most expensive, challenging, and risky stage of WEC technology development. Loss of a device in open-water can occur rapidly and subsequent recovery is very costly. Ideally, a system will have proceeded through initial pre-deployment testing and readiness verification testing before being exposed in open-water. The goal of open-water testing is to move from the controlled laboratory environment and to full or near to full scale open ocean conditions in order to move from a technology development platform to a commercial demonstrator. Comprehensive long term tests are required to verify and validate system functionality, operation, performance, survivability, and environmental and ecological impacts. In addition, the function of the device is tuned and deployment, operation, and recovery techniques are developed. Open water testing also is the only time when the ecological interactions can be fully characterized and, if necessary, mitigation techniques developed. Finally, open water testing is ideal to showcase their technology.

While a WEC may have been successfully passed through comprehensive dockside dry and wet testing, moving directly to long duration full open-ocean testing is not recommended. Many parts of the WEC still remain untested and unproven for long deployments. Therefore incremental testing is also recommended verify proper operation and to reduce risk of damage and system loss.

1. **Initial sea trials.** Building upon the initial wet dockside tests and prior to deployment in open-water for long term operation, deployment in a benign environment (very calm conditions) is essential to shake down the device, verify system functionality, and prove seaworthiness prior to connecting to long term fixings, such as moorings. These initial sea trials help to identify performance, safety, and survivability issues that could be difficult to fix once the WEC is installed.

2. **Short duration testing.** After vetting through sea trials, the WEC should be tested for a short duration (days to weeks) before it is inspected either on station at sea or back dockside to catch any wear, fatigue, fouling and corrosion issues before they require costly repairs or result in system failure.

3. **Long duration testing in regular seas.** After the WEC is fully operational and has passed initial inspections (all issues corrected), it should be closely monitored for long term operation (weeks to months) in regular seas. Judicious choice of deployment dates is necessary to minimize the risk that the WEC is exposed to storm conditions before it has been proven through regular seas. Inspections should be done at regular intervals thereafter.

4. **Testing in extreme conditions.** Once confidence is gained for the overall system, long term testing of months and in extreme sea conditions should be pursued in all expected sea conditions.

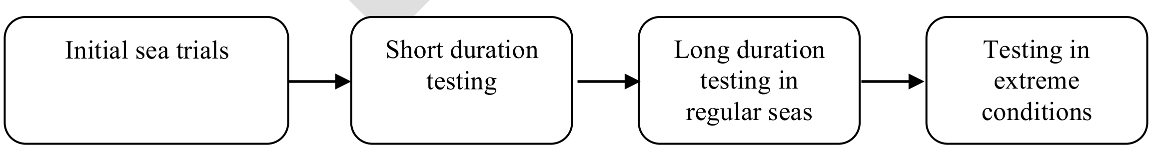

Figure 2. Recommended steps for open-water testing

1.3.3 Pre-Deployment and Open Water Wave Energy Device Testing

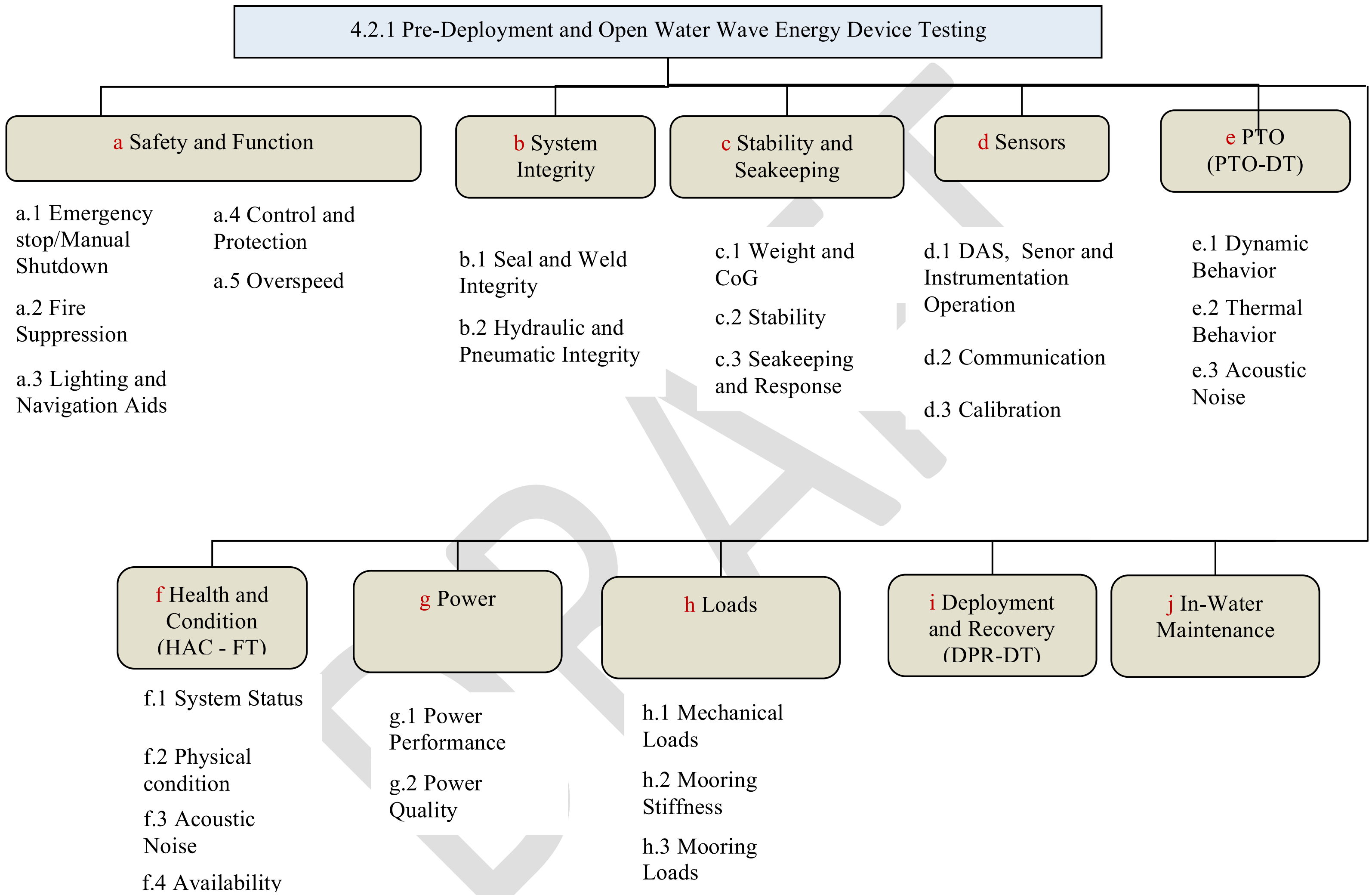

Figure 3. Breakdown of the various tests for pre-deployment and open water current energy device testing

1.4 References

API RP 2MOP / ISO 19901-6, Marine Operations, Petroleum and natural gas industries specific requirements for offshore structures-Part 6: Marine Operations

API Bull 2INT-MET, Interim Guidance on Hurricane Conditions in the Gulf of Mexico

BSH 2007, Design of Offshore Wind Turbine

IEC 61400-3, Wind turbines - Part 3: Design requirements for offshore wind turbines

IEC 61400-22, Wind turbines - Part 22: Conformity testing and certification

ISO 19901-6, Marine operations

ISO 19901-1, Metocean design and operating considerations

ABS, 29 Offshore Installations

ABS 167, Environmental Protection Notation for Offshore Units, Floating Installations, and Liftboats

AWEA RP, Recommended Practice for Design, Deployment, and Operation of Offshore Wind Turbines in the United States

BV NI525 Risk based qualification of new technology - methodological guidelines

BV NI567 Risk based verification of floating offshore units

BV NI572 Classification and certification of floating offshore wind turbines

BV NI589 Wind farms service ships

DNV-OS-H101 Marine Operations, General

DNV-DSS-904 Type Certification of Wind Turbines

DNV-OSS-304 Risk Based Verification of Offshore Structures

DNV-OSS-901 Project Certification of Offshore Wind Farms

DNV-RP-A205 Offshore Classification Projects - Testing and Commissioning

DNV-RP-C205 Environmental Conditions and Environmental Loads

DNV-RP-F205 Global Performance Analysis of Deepwater Floating Structures

GL 1 Guideline for the Certification of Wind Turbines, Edition 2010

GL 2 Guideline for the Certification of Offshore Wind Turbines, Edition 2005, reprint 2007

Protocols for the Equitable Assessment of Marine Energy Converters, EquiMar, 2011

Driscoll, R. U.S. Marine and Hydrokinetic Testing Capabilities and Needs Assessment: Identification of Existing and Needed Testing Capabilities and Infrastructure. NREL Internal Report. Dec 6 2010

Overview and Bibliography of MHK Testing Guidelines and Relevant Standards, Working Draft v0.3, September, 2012.

2 Test Planning and Test Considerations

A test plan should clearly define and detail the testing to be conducted. It should outline the testing objectives and requirements, define the testing methodology, identify resources such as equipment and personnel, and provide a detailed schedule of events. The reasons for developing a test plan are:

To communicate the testing to participants and stakeholders

Facilitate review that will help to ensure all aspects (risk, safety, testing needs) have been properly considered

To provide a systematic guide to setting up, executing and decommission an experiment

To support any regulatory or legal review and approval

In many instances, such as when testing to a standard or

In many instances, such as when testing to a standard or when a test is sufficiently different or independent of other tests, independent test plans are recommended.

2.1 Testing Process

Understanding the testing process is essential to developing an effective test plan that will yield the highest probability of success, safety and delivering appropriate data. The following flow chart provides a high level summary of the testing process

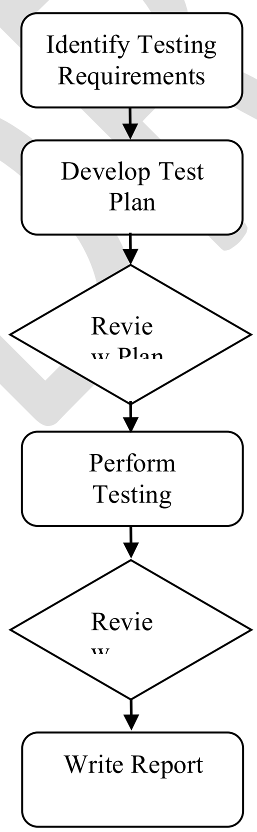

Figure 4. Diagram showing the test plan development steps

2.2 Components of a Test Plan

The following list provides an overview of the various sections of a test plan.

1. Introduction and Background

Basic background information for the test and equipment under test. Specific subsections should include

- Test scope and objectives
- Test duration
- Roles and responsibilities of all parties and participants
- List of reference documents (DAS and instrumentation design and engineering drawings, WEC engineering documents and drawings, support equipment manuals, interface documents, etc.)

2. Description of Test Articles

Detailed descriptions of the test article, along with renderings or other drawings that help familiarize readers with the WEC and support equipment. Information should include the dimensions and weights, mooring configuration, WEC specifications, etc.

3. Description of Testing Site and Test Set-up

Overview of the staging site, test area, and deployment configurations. Information should include bathymetric map of the site and deployment coordinates of each article to be deployed, mooring configurations for each article, watch circles, historic site metocean conditions, and any information on site calibration and valid measurement sectors that will govern data acceptance/rejection.

4. Test Methodology and Methodology

A high level overview of the testing methodology and type of tests/monitoring that will be conducted. This section should also include a detailed Gantt chart of testing activities.

5. Test Descriptions

The goals of each test, along with step-by-step testing procedures, pass/fail criteria and capture matrices. The capture matrices are a critical component of the test plan as they define how much data is needed for each test.

Other documents that should be included in the test plan for quick reference are:

Appendix 1: Safety Compliance and Safe Operating Plans

Appendix 2: Risk Assessment and Mitigation

Appendix 3: Test Instrumentation and Hardware Specifications Sheets

Appendix 4: Data/Channel List

Appendix 5: Electrical and Mechanical Drawings

2.2.1.1 References

National Renewable Energy Laboratory internal Test Plans

3 Safety Considerations and Risk Assessment

WECs are multifaceted electro-mechanical machines that are deployed in energetic environments to directly produce electricity or other forms of usable work and energy. The combination of moving components, electrical and hydraulic power, sea conditions, people and sea life; among many other factors, make WECs a potential hazard to people, property and the environment. As well, costs to build, deploy and test typically constitute a significant portion of project costs. Therefore, a thorough risk assessment and development of risk mitigation plans prior to deployment will help to maximize the potential for success and minimize potential personnel, environmental and fiscal harm. A brief overview of a risk assessment and consequence analysis is provided herein, along with an outline for a risk mitigation plan. As safety paramount, general safety targets need to be set and all hazardous operations need to have approved Safe Operating Plans (SOPs). This summary leverages the work done by the American Petroleum Institute.

3.1 Risk Assessment and Consequence Analysis

Hazardous events can arise at any time during the use of a WEC (during mobilization, installation, operation, repair and recover) that may result in injury or fatality, damage to the environment and damage to property. Risk assessments are therefore recommended to help identify and mitigate risk that may occur over the life of a test – from mobilization through deployment and system recovery/decommissioning. The following methodology summarizes procedures commonly used in the offshore oil and gas and land based wind for risk assessment. The goal is, by understanding the risks, appropriate mitigation measures and plans can be developed to maintain risk within acceptable levels. Knowledge provided by risk assessments help to inform decisions about how to deal with those risks. The steps outlined in this section provide a brief guide to evaluate and categorize risk based on probability and severity. References are provided at the end of this section that provide more detail and guidance on performing risk assessments and consequence analysis.

3.1.1 Hazard Identification (HAZID)

Hazard Identification (HAZID) studies are used to identify the project risks that impact person, property or the environment. These can be a result of a failure, an operation or intervention, unintended action, or external event (such as a collision with a vessel) that have a direct impact or can initiate a chain of events. These hazards can be identified from past history of the device under test or similar devices, brain storming what-if scenarios, Failure Modes and Effects Analysis (FMEA), among many other techniques. The references provided at the end of this section provide much more detail.

3.1.2 Probability Assessment

This aims to determine the probability of an event or a sequence of events will occur leading to hazard. Quantitative estimates can be obtained by using data bases of historic failure rates (provided by manufacturer for example), fault tree analysis (FTA) and other methods for reliability analysis. When historic numbers are not available, fatigue analyses can be used and best judgment is also acceptable when no other alternative is available. As part of this analysis, site specific data should be considered, such as the occurrence and size of storms.

3.1.3 Consequence Assessment

Consequence assessment quantifies the range of possible outcomes that may result from the hazard event. Consequences are typically evaluated from a financial loss, injury and loss of life, and environmental and property damage perspectives. This can be done from both qualitative and quantitative standpoints. Damages can often extend beyond the incident itself and affect the whole industry, consider the BP Deepwater horizon and the impact to the offshore oil and gas industry.

3.1.4 Risk Evaluation

The overall Risk of a hazard is typically evaluated with a Risk matrix that plots the frequency of the Hazard against the severity of the consequence. As part of this analysis, levels of risk must be defined as acceptable and unacceptable or via a rating scale. Typically, the higher the risk, the more mitigation effort is required. The highest risks often require redesign while moderate risks can be handled through pragmatic measures.

3.2 Safety Targets and Considerations

As part of the risk analysis, safety targets must be set that define the acceptable level of risk and exposure to hazards. These will feed into the risk evaluation and mitigation plans and define what acceptable risk is and what is not. As well, the exposure of people must be considered. The ISO has defined three life-safely categories, of which, the following 2 are applicable: 1) S2 – manned evacuated has personnel onboard but is evacuated during extreme weather events and S3 – unmanned which only has personnel onboard for occasional inspection and maintenance. Each of these require evacuation plans and equipment, with S2 likely requiring permanent equipment aboard.

3.2.1 Elements of a Safe Operating Plan

Safe operating plans (SOPs) are essential elements that reduce the risk of injury and death when operating in potentially hazardous environments. SOPs define accepted procedures and equipment needed to safely complete frequently occurring tasks. SOPs need to contain a description of the activity, the location, general requirements, required training, acceptable conditions and restrictions, considerations, the working methodology and a rescue plan or emergency response plan. SOPs should be developed by a team to provide a breadth of insight. SOPs should have a review and approval process that has at least one level of independent review. These should be reviewed at least once a year and refined as knowledge and experience are gained through application.

For infrequent or one time tasks, safe working permits provide a more streamlined method of establishing a safe working practice. While less burdensome than SOPs, work permits still required definition of the task, the safe working methods, safety equipment and a rescue/emergency response plan. Approval is usually by a safety officer.

3.2.2 References:

- Guidelines on design and operation of wave energy converters, Carbon Trust, May 2005

- API RP 2FPS, Recommended practices for planning, designing, and constructing floating production systems, March 2001
- Protocol for the Equitable Assessment of Marine Energy Converters, First edition, 2011
- National Renewable Energy Laboratory internal Safe Operating Procedures
- BV NI525 Risk based qualification of new technology - methodological guidelines

4 Data Acquisition, Instruments, Sensors and Data

4.1 Rational for Investment in a comprehensive quality data acquisition and instrumentation system

Data Acquisition systems (DAS) and Instrumentation are the backbone of testing and they are often the element between success and failure – quality and comprehensive data are the key to a successful test. A quality, comprehensive and robust measurement system will provide the data needed to:

- characterize device performance, loads and Seakeeping, including feeding certification efforts and substantiating developers claims
- inform environmental studies, reviews and mitigation efforts
- feed future design iterations
- forensically analyze failures
- optimize device performance and cost

Too often DASs are overlooked or are considered a much lower priority than the task of deployment and operation resulting in insufficient data to feed analysis and future design. This often results in re-testing or proceeding with develop but at a higher risk.

4.2 Considerations for making measurements in the ocean

Following are a list of some practical considerations for instrumentation in the ocean. Much of this is detailed in the report of the first instrumentation workshop sponsored by the Department of Energy and hosted by NREL.

Power and communication to a WEC can be disrupted for a number of reasons. Thus, data acquisition systems software should be designed to autonomously start up and recorded data when restarted. They should also be designed to record data internally with sufficient memory for the duration of testing.

Careful sensor selection is also crucial to ensure that measurements are of sufficient quality to meet requirements, but also to ensure long term survivability. Just because a sensor is labeled “water-proof” or has water ingress protection through IP68 (International Protection Rating interpreted as Ingress Protection Rating), does not mean it will survive in the marine environment.

Because the ocean is a harsh environment, sensor failure is common. Thus, when possible, have redundant sensors, especially for critical measurements. As well, when a sensor fails, it does not necessarily stop sending data, therefore data QA is essential.

Stainless steel and other materials often considered corrosion resistant/proof in air many not be in the marine environment or in the presence of other materials and electrical fields. Careful attention must be give to material selection and measures taken to inhibit corrosion.

Grounding devices to seawater is a common but not necessarily a good practice for long term installations. Seawater grounds may offer cost savings, but they will create electric dipoles and create an electromagnetic field (EMF). Corrosion also accelerates leading to increased replacement of cathodic corrosion protection anodes.

4.3 Data Link to Shore

The data link to shore is a critical element that allows near real time monitoring and controlling of the WEC. This link should therefore be designed with an adequate level of redundancy to accommodate partial and complete failure in the primary link. Failure could result from any number of reasons that may temporarily interrupt or terminate the primary link. A secondary channel does not necessary need the bandwidth of the primary channel to transmit all data collected, but should be sufficient to monitor the DAS, provide updates of WEC health, provide summaries of data collected and to interact with the DAS. If a cable is being used as the primary link, the secondary link should be a radio link (cellular, VHF, UHF, RF, satellite, etc). The duplication needs to include power components, backup batteries, telemetry hardware, and software that automatically switch between the primary and secondary data link. If two radio links are used, then they should be of different form.

4.4 Location and Deployment Considerations for Various Instruments

4.4.1 Wave Measurement Instruments

Care shall be taken in locating the Wave Measurement Instruments, WMIs. Each WMI should be located sufficiently far from the WEC to reduce or eliminate the potential for of mooring entanglement (wave buoy) and acoustic interference (acoustic profilers). Also, the WMIs should not be located too far from the WEC, since the correlation between the wave climate at the measurement location and at the WEC mooring site will be reduced. The WMI location should also be chosen to be aligned with the WEC in the direction of predominant wave propagation where wave disturbance from external factors in minimal. See Section 5.2 for more information on the definition of measurement sectors and the impact of choosing the CWMI location.

Note: Waves are often multi-directional, their speed of propagation of the various wave constituents is frequency defendant and their properties can change based on external factors (wind, current, bathymetry, obstructions, etc). It is therefore often of little value to measure time series of the waves at any distance from the WEC. Wave measurements very near the WEC will likely be affected by reflection and diffraction from the WEC.

4.5 Calibration

Calibration is an essential quality assurance step that is essential to not only provide credibility, but more importantly to help ensure the success of a test. Calibration lead to accurate data – bad data can have disastrous consequences if not identified and they are used to feed future design iterations. It is very important that calibrations are done correctly and regularly to gain and maintain confidence in measurements. Regular calibration is critical because sensor attributes can change with time. So, for example calibration at the beginning and end of a test will help identify changes in the sensor and evaluate the quality of the data and feed uncertainty analysis.

Note: it is critical to follow established and proven practices and methods, use only sensors and measures for comparison that have already been certified against standard measures, that the calibrations are carried out by competent people and that the calibration is well documented.

Calibration should be done for a sensor or instrument:

- when it is new
- when it has been used for a specified time or as required by the manufacturer
- at the beginning and end of a test
- when it has been modified or repaired
- when its accuracy comes into question via questionable measurements or disagreement with another sensor
- after an incident that may affect its operation such a being dropped, loaded beyond its working range, after transit where it is out of direct supervision, etc.

While it is beyond the scope of this document to detail the calibration procedures for all instruments, there are many organizations and standards produced the cover calibration. These range from general guidelines to procedures for specific tests. Many IEC testing standards have calibration requirements.

Relevant Standards and References

- National Institute of Standards and Technology, http://www.nist.gov/index.html
- IEC 62008, Performance characteristics and calibration methods for digital data acquisition systems and relevant software
- ISO/IEC 17025, General requirements for the competence of testing and calibration laboratories
- ISO 9000, Quality Management, http://www.iso.org/iso/iso_9000
- NDBC Technical Document 09-02. Handbook of Automated Data Quality Control Checks and Procedures, National Data Buoy Center, 2009

4.6 Uncertainty

Measurements are not exact and only represent an estimate of the true value of the measurand (the quantity being measured). A formal definition of uncertainty is: uncertainty is a parameter that characterizes the dispersion of values for a measurement that could occur for a specific value of the measurand (ISO Guide to the Expression of Uncertainty in Measurement). A simpler definition is: uncertainty is the range of values around a specific measurement for which the real value is likely to occur. For data sets to be credible, they must provide a quantitative measure of the data quality. The preciseness of a measurement can vary depending on many factors that may include the quality, accuracy and precision of an instrument, the dependence of the value being measured on other factors, the mounting of the instruments, etc. It is therefore necessary to provide a quantitative and traceable measure of the uncertainty for all measurements.

According to the ISO Guide to the Expression of Uncertainty in Measurement and as developed in IEC 61400-12-1, Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2005-12, uncertainty is grouped into two categories based on the method used to calculated there value:

Type A: Uncertainty that is determined from the data series using statistical methods – this is uncertainty associated with the measurements. The probability density function (PDF) is derived from the observations

Type B: Uncertainty that is calculated by other means, such as information provided by the manufacturer on their specifications sheet,

These standards define how Type A and B uncertainties are calculated and combine, as well as, they include examples for guidance.

Relevant Standards and References

- IS0 Guide to the expression of uncertainty in measurement, 1995, ISBN 92-67-10188-9
- IEC 61400-12-1, Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2005-12

5 Site Characterization and Calibration

The wave climate is affected (distorted) by many factors, including local bathymetry, refraction around headlands, other obstacles, currents and wind (among many other factors). Therefore, it is recommended that the site be assessed in order to quantify the site metocean conditions, including waves, currents and wind; as well as, to identify bathymetric and obstacles that may cause systematic differences between the location of the metocean sensors and the buoy(s) under test.

The goals of the site characterization are to 1) choose the best location for the wave measurement system relative to the WEC, 2) determine the valid measurement sector(s), 3) to characterize any change is wave field between the measurement location(s) and the WEC mooring location to a table of wave field correction factors for all valid wave directions and 4) determine of the uncertainty in the correction factors.

5.1 Site Characterization

The bathymetry and obstructions at the test site must be well characterized. For sites with rapid changes in water depths, a grid resolution of 1 m x 1 m is recommended. For sites with more gently slowing bottoms, the grid resolution can be relaxed. A side scan sonar survey is recommended to identify bottom clutter and obstacles. Any large objects should be visually surveyed. The side scan imaging can also be used to determine cable routing and locations to place anchors and instruments.

Prior to deploying a WEC for testing, at least two wave measurement instruments, WMIs, are needed. One placed at the WEC deployment location and the other at the site proposed for the WMI. If more than one WMI is to be used for the WEC test, and this is recommended, each should be placed at their proposed locations. Simultaneously to the wave measurements, the current profile and meteorological conditions (wind speed and direction) should also be measured to characterize their influences on the wave climate. Since the wave field, currents and meteorological conditions can change significantly from month to month, it is therefore recommended that these measurements be made for one year. A minimum of 3 months is suggested (IEC 62600-100 TS Ed 1).

Note: the locations of the WMIs and WEC for the test need to be well established as any changes may invalidate the site characterization.

Relevant Standards and References

- IEC 61400-12-1, Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2005-12
- IEC 62600-100 TS Ed 1: Marine energy - Wave, tidal and other water current converters - Part 100: Electricity producing wave energy converters - Power performance assessment of electricity producing wave energy converters

Recommended measurements:

Based on IEC 61400-12-1 and IEC 62600-100 TS Ed 1, data shall be collected continuously with no change in the sampling configuration. It is critical that the measurement parameters of the different WMIs be identical and that all instruments are synchronized and use the same time convention.

Water depth via a pressure sensor or acoustic altimeter	made at least once an hour with the burst of sufficient duration to average out wave effects
Directional wave spectra via a wave buoy or an acoustic profiler.	Sample rates of at least 5 Hz with averaging period of between 20 and 30 minutes. The spectral frequency range should be at least from 0.033 to 0.5 Hz with the resolution not exceeding 0.015Hz.
Water current profiles via an acoustic current profiler	a bin resolution of between 1 and 4 meters with ensembles at least every 20 to 30 minutes. Each ensemble must have sufficient number of pings to obtain a measurement std of less than 2.5 cm/s and so wave effects are averaged out. The sampling period of each ensemble shall be at most 10 minutes. The range of measurements should be at least +/- 150% of the expected maximum current.
Wind Speed and Direction via a conventional cup or 3D sonic anemometer system. If possible, temperature and relative humidity are also useful measures to determine the air density.	A sample rate of at least 1Hz. Ideally this should be made at 10 m above the mean sea surface.

Data shall be rejected for the following reasons:

- Degradation or failure of the test equipment
- External interference that may affect measurements, such a large boat moored closeby

5.2 Determination of Measurement Sector

A measurement sector needs to be established that shall exclude measurements where the wave field, seen by the WEC and/or the measurement system, is significantly disturbed by obstacles such as other buoys, bathymetry, shorelines/headlines and other obstacles, including the WEC under test. In IEC 61400-12-1, it is recommended that measurement sectors be eliminated when wave filed corrections are more than 2% between adjacent sectors. To establish measurement sectors, data should be binned by direction with bins being no larger than 10° and no smaller than the directional uncertainty of the WMI. The valid measurement sector should be defined using degrees from true north and using the direction of travel of the wave.

Relevant Standards and References

- IEC 61400-12-1, Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2005-12
- IEC 62600-100 TS Ed 1: Marine energy - Wave, tidal and other water current converters - Part 100: Electricity producing wave energy converters - Power performance assessment of electricity producing wave energy converters

An example of a measurement sector is provided in Figure xxx for WEC 1. Sectors A, B and C are valid sectors where, when waves are propagating from these directions, should be kept. Sectors 1, 2 and three are invalid sectors where, when wave are propagating from these directions, data should be rejected. Sector 1 is invalid because the wave field reaching WEC 1 will have been disturbed by WEC 2. Sector 2 is invalid because the wave field reaching the wave buoy is disturbed by WEC 1. Sector 3 is invalid because the wave field reaching the wave buoy is disturbed by WEC 2. The wave buoy is assumed to have no impact on the wave field reaching WEC 1.

If one or more significant components of the direction wave spectra are not in the valid measurement sector, the data should be discarded.

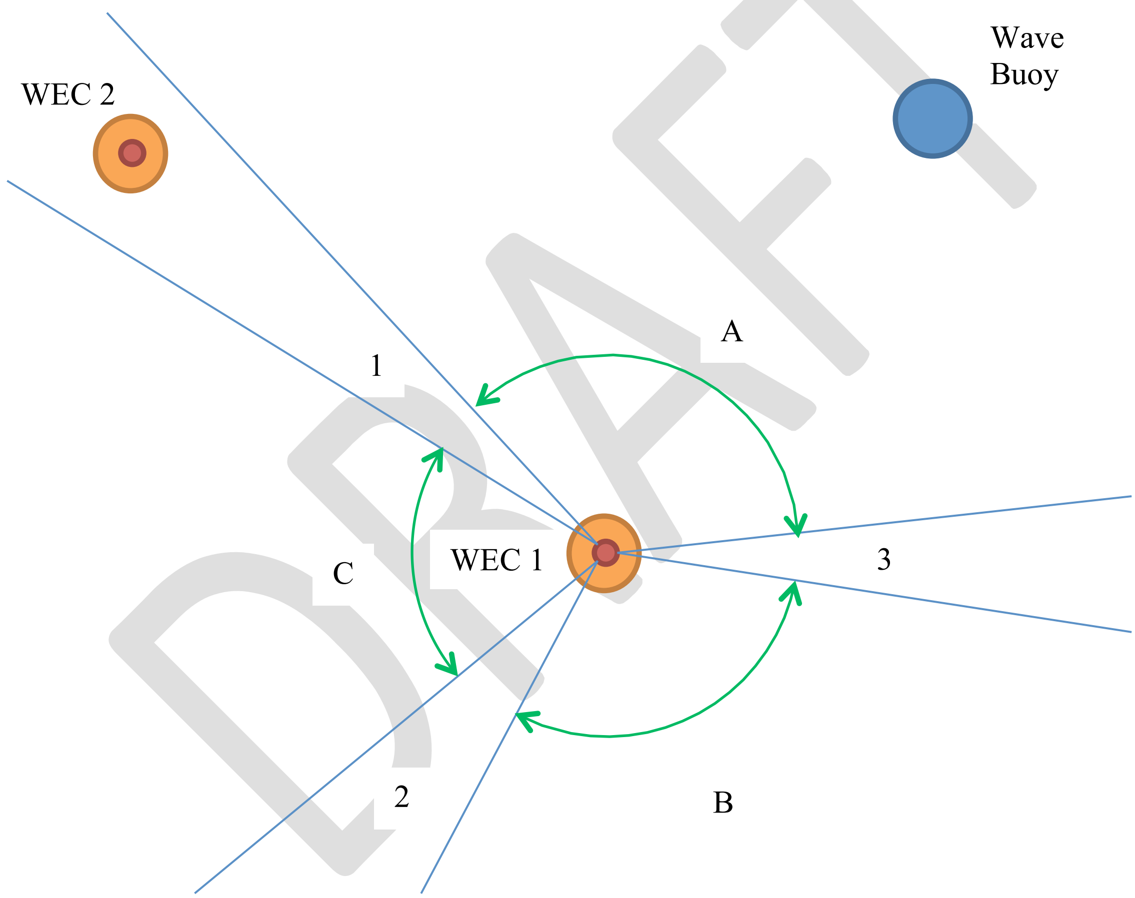

Figure 5. Diagram showing the valid and invalid measurement sectors for a hypothetical arrangement of two WECs and a WMI buoy.

6 Safety Function Testing

This section provides a brief overview of the safety equipment, relevant standards and testing that should be conducted prior to deployment and while at sea on all WEC systems to ensure a basic level safety for personnel, environmental, and property.

Wind has included many of the operating and emergency functions that wind turbines must perform under a general heading of safety and function testing. To be consistent with the DOE testing protocols outline, the safety and function are split into different testing categories in this document. This section focuses on safety functions of emergency stop, fire suppression, overspeed and navigation lights. Health monitoring tests the fault detection and alerting function. Control tests typical start up, stopping and other operations typical of the day-to-day WEC operation, along with, faults such as loss of grid.

6.1 General Considerations and Guidelines

- IEC 61400-1: Wind turbines – Part 1: Design requirements
- IEC 61400-2 : Wind turbines – Part 2: Design requirements for small wind turbines
- 29 Code of Federal Regulations(CFR) Part 1910, Occupational safety and health standards
- OSHA 3149.(n.d.)Construction Resource Manual. Washington, D.C.: Occupational Safety and Health Administration
- 33 CFR 140–147, Outer Continental Shelf activities (identification markings, means of escape, guard rails, life preservers, fire extinguishers, first aid kits, and so on)
- 30 CFR 585.810 to .811, Safety management systems
- 29 CFR 1926.605, Safety and health regulations for construction—Marine operations and equipment
- IMCA M 187, Guidelines for lifting operations (same as IMCASEL 019)
- IMCA M 202, Guidance on the transfer of personnel to and from offshore vessels
- IMCASEL 019, Guidelines for lifting operations
- IMCASEL 025, Guidance on the transfer of personnel to and from offshore vessels
- EMEC, Guidelines for Health & Safety in the Marine Energy Industry
- IEC 61400-1 Wind turbine generator systems – Part 1: Safety requirements
- IEC 1400-1 Wind turbine generator systems – Part 2: Safety of small wind turbines
- ANSI/ICEA S-93-639/NEMA WC 74, 5–46 kV Shielded power cable for use in the transmission and distribution of electric energy
- ANSI/ICEA S-94-649, Standard for concentric neutral cables rated 5–46 kV
- ANSI/ICEA S-97-682, Standard for utility shielded power cables rated 5–46 kV
- EMEC, Guidelines for Grid Connection of Marine Energy Conversion Systems

- DNV-OS-J201 Offshore Substations for Wind Farms
- DNV-OS-D201 Electrical Installations
- DNV-RP-F401 Electrical Power Cables in Subsea Applications
- TN 065 GL Wind Technical Note 065 (TN 065) Grid Code Compliance Certification procedure, Revision 7, Edition 2010
- TN 066 GL Wind Technical Note 066 (TN 066) Grid Code Compliance (GCC) Test procedure for Low Voltage Ride Through (LVRT), Revision 7, Edition 2010

6.2 Inspection of WEC markings, hazard warnings and personnel protection

Markings

The WEC should be inspected to verify that the following information is prominently and legibly displayed on a nameplate

- manufacturer and country of manufacture
- Model and serial number
- Production year
- Rated power
- Reference current speed
- Rated voltage at the terminals
- Frequency at the terminals
- Operating depth range
- Operating ambient temperature range

Hazard warnings, area demarcations and safety equipment

WECs have large moving components and high electrical power that represent hazards to personnel. Each non-go area and hazard should be clearly marked. The WEC should therefore be inspected to verify that all necessary warnings and hazardous area demarcations are in place and clearly visible. These include

- Identification of required PPE
- Safety instructions
- Fixing/tie-off points
- Fall protection system
- Warning labels for hazards
- Marking of hazardous areas
- Protection from moving or rotating parts

Personnel Protection

The WEC should be inspected to verify that all personnel protection systems are present and properly installed. These include such items as panel covers, conductor insulation, fall protection tie offs, lock-out tag-out systems, etc.

6.3 Emergency Stops

Purpose

An emergency stop shall provide operators with a quick, easily and safely accessible button(s) that overrides the WEC controls and causes all moving parts to stop in a safe position. As approaching or boarding a WEC to push the emergency stop can be hazardous, WECs should be equipped with a remote stopping feature that can be activated from a vessel operating near the device and from a shore station. Once activated, all power to components and output from the WEC should be terminate. The goal is to avert or reduce a hazardous event by rendering the machine safe. It is also recommended to have a redundant stop that can be activated even under a complete loss of power.

Relevant Standards and References

- NFPA 79: Electrical Standard for Industrial Machinery
- ISO 13850: Safety of machinery -- Emergency stop -- Principles for design
- OSHA 1910 Subpart S.
- IEC 61400-1: Wind turbines – Part 1: Design requirements
- IEC 61400-2 : Wind turbines – Part 2: Design requirements for small wind turbines

Considerations and Requirements

There are three categories of emergency stops; the appropriate one should be determined by a risk assessment:

- **Category 0:** Stopping by immediate removal of power to the machine actuators (i.e., uncontrolled)
- **Category 1:** A controlled stop with power to the machine actuators available to achieve the stop and then removal of the power when the stop is achieved
- **Category 2:** A controlled stop with power left available to the machine actuators

Standards state that an emergency stop should satisfy the following requirements:

- Shall override all other functions and operations in all modes
- Power to the machine actuators that can cause a hazardous condition shall be removed as quickly as possible without creating other hazards
- Reset shall not initiate a restart
- Actuators of emergency stop devices shall be colored RED and the background immediately around pushbuttons and disconnect switch actuators shall be colored YELLOW.

- The actuator of a pushbutton-operated device shall be of the palm or mushroom-head type.
- Emergency stop devices shall be located at each operator control station and at other locations where emergency stop is required and shall be positioned for easy access and for non-hazardous operation by the operator and others who may need to operate them.

Testing

Testing should be incremental and aim to credibly and quantitatively verify all functions of the emergency stops before the device is placed in the water and be done at all stages, including tests when the device is deployed and operating. On land, pre-deployment testing should include separate activation of each and every safety stop and direct verification that all mechanical and electrical actions have occurred. This needs to occur again when the device is placed in the water and once the WEC is on station operating. After activation of each safety stop, the device should be brought back up to full operation before the next stop is tried.

Emergency stops are also used to provide impulsive type loads for open-water structural testing.

6.4 Fire Suppression

Purpose

WECs include many systems and components that have the real potential to start a fire and therefore, all WECs should have mechanisms to detect and extinguish fires. Fires within a WEC can result in significant damage to internal components, structural damage and loss of seals with a real potential for a loss of device, release of toxic chemicals and human injury. These fires can be started via heat, electrical circuit, and chemical reaction and sustained by the combustibles.

Considerations and Requirements

All WECs should be equipped with sensors to monitor and detect internal temperature and smoke, an emergency notification system and an active fire suppression system. Passive fire protection should also be included to prevent fires. Also, while people are aboard the WEC, portable fire extinguishers should be readily available.

Relevant Standards and References:

- Guidance Notes on Fire-Fighting Systems, American Bureau of Shipping, May 2005.
- RP 14G Recommended Practice for Fire Prevention and Control on OpenType Offshore Production Platforms, American Petroleum Institute, March 2007
- Offshore Stnadard DNV-OS-D301, Fire Protection, DNV, October 2008
- GL Wind Technical Note Certification of Fire Protection Systems for Wind Turbines, Certification Procedures, Revision 2, Edition 2009
- http://www.uscg.mil/hq/cg5/cg5214/fesys.asp

Testing

Test as per manufacturer's specifications prior to deployment and routinely as needed. All portable extinguishers should be checked annually by a qualified inspector.

6.5 Lighting and Other Aids to Navigation.

Purpose

Coastal waterways are actively used by recreational boaters, fisherman, commercial vessels and the military. Vessels transit the coast in all weather conditions both day and night, at times, with extreme limited visibility. Therefore it is essential to ensure that all surface buoys used for a test are both highly visible via sight and radar in all conditions.

The U.S. Coast Guard requires that all buoys have navigational lighting with specific light colors, flash patterns and visibility range to allow other vessels to visually detect and identify the buoys. Passive and active radar reflectors and Automatic Identification Systems (AIS) are also recommenced to assist in the detection and avoidance of offshore buoys. AISs are used for identifying and locating vessels by electronically exchanging data with close by ships and base stations. The purpose of these tests is to verify the function of the navigation lighting and other navigational aids aboard the WEC.

Relevant Standards and References

- Federal Aviation Administration (FAA)AC70/7460-1K, Obstruction marking and lighting
- USCGCOMDTINST M16672.2D, Navigation rules, international-inland
- 33 CFR Part 67, Aids to navigation on artificial islands and fixed structures
- IALA Recommendation O-139, The marking of man-made offshore structures
- International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) document

Considerations and Requirements

Lighting and other aids to navigation must function continuously to ensure all surface buoys used in the test are visible to traffic. It is therefore recommended that cameras or other systems be installed to verify the operation of lighting and a shore based AIS receiver be used to verify AIS operation. If a collision does occur, the offending operating vessels often claim the aids to navigation were not working, so continuous monitoring and recordkeeping is essential.

Lighting

Prior to being installed on the WEC, all lights should be turned on to verify the correct color and flash pattern. It is often easier to fix the light prior to install if a defect is found. For lights that are solar powered, the lights should be placed in an area for which the sunlight is unobstructed for 8 - 12 hours – during daylight hours and charging verified. These lights should be left operating for 24 hours. If after 24 hours the light is no longer functioning, the test will be considered a failure. For lights that use a light sensor to switch on and off, the lights should be placed in a dark room to verify that the light automatically switches on and has the correct flash timing. Lights should also be submerged to a depth of 3 m and held there for 2 hours. If the light does not function or if any condensation or evidence of water ingress is evident, the test will be considered a failure.

Once the lights are installed, they should again be tested to verify operation and correct flash pattern before launch. Once on station and deployed, it is important to verify the operation of the navigation lights yet again. It is also recommended that the range of the lights be verified by transiting away from the test location at night and recording the distances that the lights can be viewed.

Automatic Identification System

AISs integrate VHF radio transceivers with a GPS for positioning (and other sensors for ships) and transmit a unique identification, position, course, and speed. The information and its transmission must be verified both prior to deployment and once on station. To do this, a second unit, typically a base station is recommended that simply captures all local AIS transmissions. For both tests, monitor the transmission from the buoy and verify the identification string and the location. Once deployed, the AIS should be continually monitored via the shore station to provide evidence of operation and to track the WEC within a watch circle.

Radar Reflector

Once on station and deployed, it is important to verify the radar signature of the WEC for numerous legal and permitting reasons. To do this, position a radar equipped vessel (preferably a smaller vessel with a radar mounted at a level common to recreational vessels) at the required distance of detection or the largest distance it is able to maintain a radar contact with the WEC. The vessel will then transit in a circle at of this distance for a swept angle of at least 90 degrees to verify radar return from the buoy. Ideally, this should be done at different distances to record the strength of return.

RACON

RACONs (Radar beaCON) may be used on the surface buoys to provide an active response to a radar pulse at the same frequency. This shows up on the radar display of the transmitting vessel. If this technology is used, it should also be verified on land and once the buoy is on station. Prior to deployment, the RACON antenna should be installed on a dock or at a point where a vessel mounted radar can be used to verify operation. Once deployed, the RACON should be tested in much the same way the radar reflector is tested to verify transmission and reception of the RACON signal

6.6 Control and Protection

Purpose

WEC control and protection systems govern operation and keep the overall system within its operating parameters. These systems also govern the response of the turbine in fault situations by driving the WEC into an appropriate safe state. The purpose of this test is to verify the operation of the WECs control and protection system.

Relevant Standards and References

- IEC 61400-1: Wind turbines – Part 1: Design requirements
- IEC 61400-2 : Wind turbines – Part 2: Design requirements for small wind turbines

Considerations and Requirements

The control and protection system should be tested to verify it is able to perform the following functions or control the following parameters:

- Start-up and shut down over all expected operating conditions (verification above rated current speed is needed)
- Shutdown at loss of the grid/load
- Disconnection from grid
- Grid fault ride-through
- Power output
- Alignment with the current (if an active alignment system is used)
- Excessive vibration protection
- Emergency shutdown under normal operation
- Battery over- and under-voltage protection.

6.7 Overspeed and Overextension Protection

Purpose

Overspeed and overextension are conditions in which the PTO velocity, either angular or linear exceeds its design limit or exceeds it travel limit. These can result from control failures, loss of the grid or load, extreme events, high resource among others. Overspeed and overextension protection systems take a physical action to limit the PTO velocity and stroke. For wind turbines, two types of brakes exist, mechanical (e.g. conventional disc brakes) and aerodynamics systems that have many forms: fixed pitch systems that are stall regulated, pitch machines that turn blades so they stall, furling/yawing that turns the axis of the turbine at an angle to the wind, and ailerons or tip brakes (similar to aircraft) that disrupt flow across the blades. Many internal combustion engines use mechanical governors to limit their speed. Loading the generator can also be used as a means to slow the wave capture mechanism. The purpose of this test is to verify that the overspeed protection system works at rated waves and above.

All WECs should be equipped with a minimum of two independent overspeed protection systems that each are able to slow moving parts to acceptable operating speed/translation and/or to completely brake the system and hold it locked in all expected operating conditions. Overspeed systems must automatically function and fail safe.

Relevant Standards and References

- IEC 61400-1: Wind turbines – Part 1: Design requirements
- IEC 61400-2 : Wind turbines – Part 2: Design requirements for small wind turbines

Considerations and Requirements

For an overspeed system to operate, it must automatically function even if the WEC loses electrical power or if hydraulic systems lose pressure.

The overspeed protection should be automatically activated once a threshold velocity/extension is reached and a prioritized braking scheme is often used. Testing should be done both dockside and at sea. Dockside, a synthetic velocity/extension signal should be input in the WEC SCADA to simulate and overspeed conditions. The brakes should be monitored for activation. This should be done for conditions that activate the primary brake and the secondary brake. Once deployed, the system should be tested again to verify activation of the overspeed protection. This should be done using a synthetic signal and by allowing the WEC to approach a true overspeed threshold. This actual overspeed condition with verify the ability of the brakes to stop the WEC under load.

7 System Integrity and Design

Ensuring that all components of the WEC system are watertight is essential to maximize survivability and reduce risk of damage to dry components and ultimately the loss of the device. This is particularly true for all submerged watertight compartments but also for above water components and compartments because it is likely that every component of a WEC will experience times of submergence either via a large wave during a storm event or during deployment and/or recovery. Because water can enter a water tight compartment through a scratch across a sealing surface, imperfections in welds, gaps created from differential expansion and contraction rates a interfaces of different material, improper installation of seals, manufacturing errors, contamination of a sealing surface, among many other factors. Leakage is accelerated when a pressure difference occurs caused by water pressure or heating and cooling of the WEC. Detecting these defects early on is critical because the cost of repair is an order of magnitude less on shore than when the WEC is deployed.

For devices that use hydraulic or pneumatic systems, it is also essential to test these systems because small leaks can rapidly render a WEC inoperable and the leaked fluids can damage internal components.

Relevant Standards and References

- U.S. Coast Guard for fabrication of steel ocean buoys, specification No. 464, Revision J
- API RP 2SIM, Structural integrity management of fixed offshore structures
- ISO 19900, Petroleum and natural gas industries—General requirements for offshore structures
- ISO 19901-4 Petroleum and natural gas industries—Specific requirements for offshore structures
- API RP 2SIM, Structural integrity management of fixed offshore structures
- API Bulletin 2HINS, Guidance for post-hurricane structural inspection of offshore structures
- API Bulletin 2INT-EX, Interim guidance for assessment of existing offshore structures for hurricane conditions
- AISC 335-89, Specification for structural steel buildings – Allowable stress design and plastic design
- API RP 2X, Ultrasonic and Magnetic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Technicians
- BV NI165 Ultrasonic testing of hull butt welds
- BV NI199 Cyclic fatigue of nodes and welded joints of offshore units
- BV NI409 Guidelines for corrosion protection of seawater ballast tanks and hold spaces

- BV NI422 Type approval of non destructive testing equipment dedicated to underwater inspection of offshore structures
- BV NI423 Corrosion protection of steel offshore units and installation
- DNV-OS-C301 Stability and Watertight Integrity
- DNV-OS-C401 Fabrication and Testing of Offshore Structures

7.1 Seal and Weld Integrity

Purpose

WECs are likely to contain on or more dry chambers that require no water ingress to protect internal components and to maintain positive buoyancy and stability. Typically welds are used at joints to fuse metal and seals are used at hatches and joints that are not welded. The follow tests should be used prior to placing the WEC in the water to verify all compartments are water tight.

Relevant Standards and References

- U.S. Coast Guard for fabrication of steel ocean buoys, specification No. 464, Revision J

Considerations and Requirements

Following is a description of an internal and external pressure tests that should be conducted after assembly and just prior to the WEC being placed in the water. If possible, the pressure tests should also be conducted after any maintenance or activities that require a hatch of a water tight compartment to be opened.

It should be noted that the testing apparatus to support the testing also needs to be air-tight. Any leaks in the testing apparatus could yield a false negative test. It is therefore recommended to test all testing apparatus and to purchase quality components rated for both vacuum and pressure testing. A digital sensor is recommended instead of a dial type pressure gauge.

Also, temperature difference of the WEC caused by internal or external heat sources (the sun for example) can cause pressure fluctuations. Therefore, it is recommended to perform the test is as static conditions as possible.

More rigorous weld inspections should be mandated at the time of manufacture and include visual inspection, measurement for conformance to plans and radiographic/ultrasound inspection by a certified welding inspector.

Testing

Internal Pressure Testing

Each and every separate chamber or housing of the WEC should be subjected to separate air tests at distinct times to verify water tightness according to the Air Test specified in section 4.5.2 of the specifications of the U.S. Coast Guard for fabrication of steel ocean buoys, specification No. 464, Revision J. To do this, each chamber will be pressured to 3 psi above ambient and the air source turned off. The pressure should remain constant for 10 minutes and pressure will be recorded every minute to a resolution of 0.25 psi, preferable to a higher resolution. A soap water solution will also simultaneously be applied to all welds and seals. Any drop in pressure or leaks detected with the soapy water (via manifestation of bubbles) will be considered a failure.

External Pressure Testing

Some seals, such as O-ring seals, are specifically designed for external pressure. These may be part of an underwater instrument or located on a subsurface component. To test these and seat all seals, each chamber will be vacuumed to at least 3 psi (preferably 5 – 10 to ensure seating of the O-ring)) below ambient and the air source turned off. The pressure should remain constant for 10 minutes and pressure will be recorded every minute to a resolution of at least 0.05 psi.

Monitoring at Sea

Because a seal failure or any leak for that matter can result in the loss of expensive equipment and/or sinking of the WEC, all water tight chambers should be continuously monitored for water ingress. Both humidity and water ingress sensors can be used and the associated data streams should be part of the critical data reported on system health. With warning, catastrophic failures may be avoided.

7.2 Hydraulic and Pneumatic Integrity

Purpose

Some WECs use hydraulic and/or pneumatic systems in PTOs, to drive brakes or for other means. These represent critical components and a small leak can result in an expensive repair if a system has to be recovered and taken to dry dock. Therefore all hydraulic components should be tested and monitored to verify system integrity – no leaks

Considerations and Requirements

Monitoring the temperatures, pressures, flow rates and reservoir levels can help to quickly identify any faults in hydraulic and pneumatic systems. These measurements should be continuously while the system is in operation, as well as, used to verify the systems integrity prior to deployment.

Testing

Static Pressure Testing

Each hydraulic and pneumatic system should have a port to allow the system to be pressurized. Pressurize as per specifications and every joint, seal and pipe inspected for leaks. Using the pressure measurements from the DAS, monitor the hydraulic/Pneumatic pressure for at least 10 minutes. If a pressure drop occurs, conduct the visual inspection again until the leak is found. For a pneumatic system, brush the soapy water on the locations of potential leakage. If the system contains a motor, it should be started up and a similar inspection and monitoring process conducted.

Dynamic Pressure Testing

In cases where a WEC uses hydraulics to transfer power within a PTO, the mechanism actuated by the waves should be manually driven through its full range of motion. While actuating the system, inspect all components, including the dynamic seals for leaks. Also, the DAS should be used to measure hydraulic pressures, flow rates and component positions/rotary angles at points that verify hydraulic cylinders, motors and other components are being driven as expected.

Monitoring at Sea

Monitoring the health of a hydraulic system is critical to detect system faults and take corrective action. As previously mentioned, the critical channels include fluid temperatures, pressures, flow rates and reservoir levels. In addition, the RPM, angles and linear position/velocity of actuators and motors should also be monitored.

8 Stability and Seakeeping

8.1 Weight and CoG

Purpose

To capture and track the weight and CoG of a WEC while it is assembled and deployed

Relevant Standards and References

- ISO 19901-5 / API RP 2MOP Weight control during engineering and construction

Considerations and Requirements

The location of weight and the overall CoG are often critical to the performance of a WEC. Slight changes between the design and as built system can affect the water line, orientation and seakeeping characteristics resulting in decreased system performance. Therefore it is essential to have a weight tracking/monitoring process in place during construction and assembly to track and compare the as built system with the engineering design. This is also important as instrumentation packages and other components are added that were not initially considered during design. As part of this, the device developer must first determine what the as built targets and acceptable margins are. These provide the basis for determination of success or failure. This testing assumes the various components have been fabricated and are ready for assembly at the mobilization site.

Establishing a consistent measurement scale (units) and coordinate system is essential to ensure conformity and minimize error. As well, a spread sheet should be developed to enter weight measurements for various components and calculates the offset from the design weight. This program should also calculate the net weight and CoG (based on the design location of the components).

A single person should also be designated as responsible for tracking the as built weight over the entire build and assembly process.

Monitoring

As sub-assemblies are delivered and offloaded at the mobilization/staging area, the net weight should be measured and recorded via a calibrated load cell in-line with the lift. It is often very difficult to directly measure the dry center of gravity without a complex lifting apparatus with multiple load cells via a lift – however, the wet CoG can be directly determined by an inclining test as overviewed in the stability test. Therefore dry component CoG can be estimated from 3D CAD models, provided that the component dimensions and weight are within predetermined acceptable margins.

As new components, cables, and other items are added, all of these need to be weighed, located and input into the net mass and dry CoG calculation.

Once the WEC is fully assembled, the complete system should be weighed prior to placement in the water and the measurement compared with the weight tracking calculations.

If possible, once the WEC is in the water, measure and compare the draft, pitch and list (roll) against calculations. Be aware that the density of the water will affect the displacement, therefore, if possible, a direct measure of the water temperature and salinity should be made to calculate the water density.

8.2 Stability

Purpose

To perform an inclining test to measure the GM and CoG of the WEC.

Relevant Standards and References

- Inclining test unified procedure, IACS, Jan 2004
- BV NI299 Guidelines on documents to be submitted for stability study

Considerations and Requirements

Stability is simply defined as the tendency of the WEC to return to its original upright position after it has been displaced. The metacentric height, GM, is used to quantify the initial static stability of floating bodies and it physically represents the distance between the wet CoG and the metacenter. Note: as ballast, mooring lines and other components are added at sea, the CoG will change. A larger GM results in a greater resistance to overturning but shorter roll and pitching periods.

An ideal inclining test should be performed during calm conditions with the WEC connected to its mooring and all moving parts locked down. Ideally, this would occur at a sheltered test berth that is protected from open ocean swells. The WEC should be ballasted to its working state and not list by more than 0.5 degrees.

Testing

An inclining test is done by moving weights of a known value horizontally from the center of the WEC outwards to induce a tilt by applying a known overturning moment. By knowing the WEC dimensions, restoring properties, tilt/list angle draft, and weight, the GM and CoG can be calculated

Instruments: CT sensors, 2 axis inclinometer and/or MRU, compass, GPS

A CT should be used to measure the water temperature and salinity to calculate the density. Ideal, measurements should be made throughout the test.

Measure the draft of the WEC, ideally with all weights aboard

Move the weights to a position to create a 1 degree list and record the position of the weights and the list angle of the WEC

Repeat step 2 for 1 degree list increments up to 4 or 5 degrees than back to the initial undisturbed state, and repeat all steps again to ensure repeatability

Repeat steps 2 and 3 at an angle of 90 degrees for buoys that are non-symmetric.

8.3 Seakeeping and Response

Purpose

Seakeeping is a measure of how well a buoy responds to sea conditions during operation and standby modes. The purpose is to characterize the response of the buoy to all (operating and extreme) sea conditions under all states of the buoy (operation, standby, control settings, etc).

Considerations and Requirements

The Seakeeping and response of a WEC to metocean conditions can affect its survivability and performance. Here, a pull (roll period) test and a motion monitoring program are suggested to provide data to quantify the response of the WEC. The pull test also provides a quick estimate of the roll and pitch period of the WEC and the motion/metocean monitoring program should provide a comprehensive data set to calculate Response Amplitude Operators and time series of all six degrees of freedom.

The pull test should be performed during calm conditions with the WEC connected to its mooring and all moving parts locked down. Ideally, this would occur at a sheltered test berth that is protected from open ocean swells. The WEC should be ballasted to its working state.

Testing – Pull Test

A pull test is done by using line, attached as high as possible, to pull the WEC and induce a tilt of between 5 and 15 degrees. The line is then rapidly released and the motion of the buoy is recorded. The righting period (either roll or pitch) can be calculated. This can also provide a rough estimate of the GM.

Instruments: 2 axis inclinometer and/or MRU, compass, GPS and a load cell

Measure the draft of the WEC

Apply load to the pull line until the WEC is at the desired tilt angle. The pull line is typically pulled by a winch aboard a moored vessel.

Rapidly release the load by parting the line; this can be done by a line release. Care should be taken to protect crew and equipment from the line whipping back.

Repeat steps 2 at least 2 more times so that 3 pull tests are done for roll and pitch.

Monitoring

The response of WECs to waves is non-linear and multivariate – it can change depending on the operating state of the WEC, wave bimodality, wind and current loading, among other factors. Therefore, it is essential to obtain long-term measurements over a wide range of metocean conditions to provide a sufficient breadth of data to calculate RAOs, validate models, etc. Motion and metocean measurements need to be tightly synchronized to ensure data sets from different DASs can be aligned.

Recommended measurements:

- 6 DOF Motion via at least one Motion Reference Unit, MRU, or equivalent (IMU, INS, etc) with data rates between 10 and 100 Hz connected with a GPS and compass/inclinometer to eliminate low frequency drift. The MRU should be placed as close to the CoG as possible to reduce rotation induced translation. Note: the motion measurement system needs to be carefully selected so channel bias/drift, temperature bias, sensor alignment, and internal processing will yield data of sufficient quality.
- Directional wave spectra via a wave buoy or an acoustic profiler. A measurement rate of at least 5 Hz and an averaging period of between 20 and 30 minutes are recommended. The spectral frequency range should be at least from 0.033 to 0.5 Hz with the resolution not exceeding 0.015Hz. It is critical that the measurement periods of the different WMIs be synchronized. The range of measurement should be sufficient to meet the 100 year site conditions.
- Water current profiles via an acoustic current profiler with a bin resolution of between 1 and 4 meters. Ensembles of currents should be provide at least every 20 to 30 minutes with sufficient number of pings in each ensemble to obtain a measurement std of less than 2.5 cm/s and so wave effects are averaged out. The sampling period of each ensemble shall be at most 10 minutes. The range of measurements should be at least +/- 150% of the expected maximum current. If the local currents are not well known, this range should be increased.
- Wind velocity should be measured by a conventional cup or 3D sonic anemometer system with a sample rate of at least 1Hz. Ideal this should be made at 10 m above the mean sea surface. If possible, temperature and relative humidity are also useful measures to determine the air density.
- Water depth via a pressure sensor or acoustic altimeter to capture tidal and storm driven changes in water depth. Burst measurements should be made at least once an hour with the burst of sufficient duration to average out wave effects.
- Buoy draft should be measured via a pressure sensor located on the body of the WEC. Burst measurements should be made at least once an hour with the burst of sufficient duration to average out wave and buoy motion effects.

9 Sensors

9.1 DAS, Sensors, and Instrumentation Operation

Purpose

Testing a DAS and the sensors/instruments requires review of the data, not just verification that data are being written to files. Therefore, it is useful to have a software module pre-written that can load, display, and (as needed) analyze data as it is recorded at the mobilization site and throughout the testing stages. Functions of the software module should be written to support specific tests – thereby allowing near real time evaluation of a test. This reduces the time needed access, import and evaluate the data if it is done via a command line or spread sheet, but more importantly, it increases the probability of identifying errors and oversights that would otherwise show up in post-processing. If not caught during a test, errors may result in test failure, requiring repetition of the test or, even worse, skipping of the test and proceeding with the insight that could have been provided.

Considerations

Testing a DAS and the sensors/instruments requires review of the data, not just verification that data are being written to files. Therefore, it is useful to have a software module pre-written that can load, display, and (as needed) analyze data as it is recorded at the mobilization site and throughout the testing stages. Functions of the software module should be written to support specific tests – thereby allowing near real time evaluation of a test. This reduces the time needed access, import and evaluate the data if it is done via a command line or spread sheet, but more importantly, it increases the probability of identifying errors and oversights that would otherwise show up in post-processing. If not caught during a test, errors may result in test failure, requiring repetition of the test or, even worse, skipping of the test and proceeding with the insight that could have been provided.

Testing – Base DAS

The following steps are recommended to verify that the DAS is operating and the base functions are working correctly. To minimize trouble shooting, this set of steps should be done early on in the WEC assembly with a minimum number of channels connected.

1. Turn on DAS, but don’t start the acquisition software. If possible, monitor current and voltage to identify any shorts or excessive power draws – the power load on the DAS should be characterized via bench testing and simply verified here

2. For each instrument that is connected at the time of this test, turn these on one at a time and if possible, monitor current and voltage to identify any shorts or excessive power draws

3. Start the DAS software and begin to collect data, if possible, monitor the CPU load and compare with values from bench testing

4. Verify the DAS time is correct. If an external source, such as a GPS is used for timing, be sure it is connected and turned on.

5. Verify that data files are being recorded with the correct naming scheme.

6. If the DAS connects to another DAS, controller, or other external system, verify the connection and data transfer, this includes transfer of data for remote storage.

Testing – Individual Channels

It is recommended that an incremental approach to channel testing be used where tests are performed on individual channels or groups of channels as they are added. If channel testing is done after all sensors/instruments are connected, then it can be difficult to track down issues, especially if more than one occurs or if the error is contained within a large grouping of channels. So, for each channel or group of channels, the following testing sequence is recommended:

1. Turn the sensor/instrument on and if possible, monitor current and voltage to identify any shorts or excessive power draws

2. Start the DAS software and begin to collect data, if possible, monitor the CPU load and compare with values from bench testing

3. Verify that data is being written to the correct file and that, if metadata is saved, those metadata are correct

4. For each channel, verify that data is being collected and that those data are correct in value, sample rate, time stamp, etc. For serial channels that are not parsed and converted into floating point or equivalent representations, check the strings to make sure they are properly populated and the timing between strings is correct

Monitoring

Once the WEC is deployed, the CPU load, power usage and data from the individual channels should be monitored to detect any problems in the DAS or instrument/sensor operation. Automatic routines should be created to detect anomalous values and send out alerts. Redundant sensors are also useful to detect failures by straight forward comparison between the channels.

- NDBC Technical Document 09-02. Handbook of Automated Data Quality Control Checks and Procedures, National Data Buoy Center, 2009

9.2 WEC-Shore Communications

Purpose

As previously mentioned, the data links to shore are critical elements that enable monitoring of the WEC during autonomous operation and can provide direct control or override capabilities when needed. These links also provide channels to send alerts to faults and other conditions that may need a quick response. Therefore, the performances of these channels absolutely need to be verified to guarantee communication with the WEC. To do this, an incremental approach is recommended to help catch any issues before a WEC is moored and recovery can be costly. The following testing sequence is recommended

- Test the communication signal strength, connections, transmission and commands (reboot, hardware reset, etc.) prior to buoy deployment. This can be done from a boat using a laptop or portable DAS that mimics the communication system and protocols
- If communications are to be relayed through a second buoy, such as the Wave Sentinel, this communication needs to be verified before deployment. Ideally, the WEC and second buoy should be connected ashore using the same umbilical(s) that will be used at sea. All functions should be verified.
- If initial sea trials are planned, this is another opportunity to test the communication system and repeat connection, transmission and command testing. This is the ideal test to push the communication channel to test all capabilities because it is in the closest to its operating state without being connected to the moorings. If it fails here, the buoy can be readily recovered and fixed ashore.

Once deployed and prior to the WEC being left to operate autonomously, it is again critical to verify that the buoy can be controlled remotely, that all safety commands are functional and that the buoy's status is broadcast.

10 PTO

Testing of PTOs is done to characterize efficiency, loads transfer, dynamic and thermal behavior, wear and failure characteristics and generation of acoustic noise. PTO testing is best performed on a dynamometer in a controlled environment. Using a dynamometer, a PTO is able to be thoroughly tested under a wide range of conditions that may be difficult to achieve at sea. Using off-axis non-torque loading devices, extreme environmental temperatures and unsteady loading, adverse conditions can also be simulated. At sea, the environmental conditions loading the WEC cannot be controlled and measured to the same level as in a dynamometer; therefore, dynamometer testing is highly recommended before proceeding to field testing. This is common in the wind industry where extensive field experience has demonstrated the need to perform comprehensive component testing. With that said, it is still useful to monitor PTO performance and health during open-ocean testing.

10.1 Dynamic Behavior

Purpose

While operating in the ocean, it is important to monitor the structural response and loads within the PTO, between the input shaft (or like component) and the generator, to quantify fatigue and observe PTO health. Monitoring the PTO health can understand changes in performance and identify wear of the PTO that can inform operation and repair. If a failure in the PTO occurs, these data may in instrumental to determine cause.

Recommended measurements

- Torque on the input shaft (or similar component) and output shaft (generator end)
- Vibration
- Lubricating oil condition
- Acoustic emissions
- PTO temperature

10.2 Thermal Behavior

Purpose

Unlike wind and other land based turbines where generators can be cooled by air flow, underwater WEC systems are often sealed and cooling is dependent on thermal conduction through the structure to the sea water and air. In place and at certain time of year, the seawater can exceed 20 - 30 °C in the summer, potentially leading to a poor heat sink and higher PTO operating temperatures. It is therefore important to monitor the PTO temperature to ensure that it is within specifications.

10.3 Acoustic Noise

Purpose

While acoustic noise may be measured as part of monitoring the dynamic behavior, it is also worth monitoring to characterize the noise being generated within the PTO and generator housing. This can be compared with above and below water noise being transmitted to the far field; thereby helping to understand transmission and quantify WEC noise insulation.

11 Health and Condition Monitoring

11.1 System Status

Purpose

To monitor and track the status of the WEC under test to inform operators of its current condition and alert if intervention is needed, as well as, to provides a track history of the state of the device.

Relevant Standards and References

- Wind turbine availability, Danish Standard Availability Working group for Wind turbines, 19 august 2005
- IEC TS 61400-26-1:2011, Wind turbines - Part 26-1: Time-based availability for wind turbine generating systems
- IEC TS 61400-26-2: Wind turbines - Part 26-2: Production based availability for wind turbines

Considerations and Requirements

Real time monitoring of the status of a WEC under test is critical because it alerts operators to conditions that require rapid intervention, such as flooding of a compartment. It can also provide information that can help inform a maintenance plan, trace faults and tune operation. Therefore, the system status should consider the complete WEC system, from generator to grid connection.

Keeping a comprehensive historical record is essential because it is used to help inform analyses such as power performance where knowledge of system status is used to determine valid and in-valid data sets. For example, if a device is not operating due to a fault, the power performance data is invalid and can be justifiably rejected. Comprehensive records of faults and repairs can help build credibility.

Note: it is important to have the ability to add notes to the record of system status to provide additional information, such as, the direct cause of a shutdown, reasons why the WEC might be producing less power, etc.

System Status Categories

Table 1 presents a list of system status categories that are suggested to be considered when determining the state of a WEC. This list covers a large range of states and is intended as a starting reference, but is by no means complete. *The references for this section provide a much more detailed listing of the categories that would be applicable to a commercial system under test.* Therefore, this list should be customized for specific WEC devices and expanded or reduced to provide the level of detail necessary for a given test . For example, utilities could ask large WECs or arrays of WECs to curtail production.

Table 1. Status categories for a WEC

Operating – Waiting for Waves	Wave field is too small for generation, however, WEC is fully operational and connected to the grid

Operating – Normal Generation/Full Performance	WEC is operational, connected to the grid and producing power as per specifications/normal operations
Operating – Reduced Generation/Partial Performance	WEC is operational, connected to the grid and producing power, but the power production is reduced from specification for some reason
Operating – Start up	WEC is transitioning between waiting for waves and generating
Shutdown – Extreme Waves	WEC is in a protective state because the wave field is too large to produce power
Shutdown – Extreme Environment	WEC is in a protective state because of other environmental conditions that may damage the turbine (icing, extreme temperature, high winds, etc)
Shutdown - Nuisance	WEC is shutdown for nuisance reduction (avoid mammal harassment, etc)
Shut Down – Planned Maintenance	WEC is shutdown for routine and planned maintenance
Shutdown – Unplanned Maintenance	WEC is shutdown for unplanned maintenance
Shutdown – Utility	WEC is shutdown by order of the utility
Shutdown – Test Facility	WEC is shutdown by the test facility
Shutdown – Owner	WEC is shutdown by owner
Shutdown – Utility Forced Outage	WEC is shutdown due to grid faults or other conditions caused by the utility
Shutdown – Test Facility Forced Outage	WEC is shutdown due to faults caused by the test facility
Shutdown – WEC Forced Outage	WEC is shutdown due to internal faults
Shutdown – Force Majeure Outage	WEC is shutdown due to a third party or due to acts of God (collisions with ships, vandalism, earthquakes, etc)

11.2 Physical Condition

Purpose

To verify first hand that the WEC is in good operating condition

Considerations and Requirements

As mentioned previously, WECs are multifaceted machine that are composed of different materials and protection systems. For systems that are being put into the ocean for the first time, it is important to monitor the wear, corrosion, fouling and other physical conditions that can affect performance and survivability.

Recommended measurements:

While not specifically measurements, the following list of activates is recommended:

- Regular above and below water general visual inspections of the hull, mooring lines and external equipment/sensors
- Scour at anchors and piles

- Hatch seals
- Corrosion of connector contacts

11.3 Acoustic Noise

Purpose

To measure the complex acoustic emissions from WEC generator systems

Relevant Standards and References

- IEC 61400 – 11, IEC 60804: Integrating-averaging sound level meter
- EC 61400-11 2002-12 Wind Turbine Generator Systems – Part 11: Acoustic Noise Measurement Techniques 2.1 Edition
- IEC 61400-11 ed3.0 Wind turbines - Part 11: Acoustic noise measurement techniques

Considerations and Requirements

Unlike wind turbines, WEC systems transmit sound underwater and, depending on the design, may also have above water sound transmission as well. Considering this, the methodology presented herein, based on wind turbines, should only be considered a guide and may require modification for underwater application.

Recommended measurements

Sound level (above water): 1/3 octave bands: 45 to 11,200 Hz (IEC 61260 Narrow band spectra: 20 – 11,200 Hz (IEC 60651 At least 30 measurements, at least 1 minute in duration, with at least 3 measurements within 0.5 m/s of integer wind speeds, for both operation and non-operation (background). Note: these may need to be modified for the specific WEC under test.

Current and wind speed and direction at WEC depth: synchronous with sound measurements.

Water temperature and pressure: synchronous with sound measurements

Distance and direction from the WEC to the microphone

For wind, the following measurements are typical:

A-weighted sound pressure level: At least 30 measurements, at least 1 minute in duration, with at least 3 measurements within 0.5 m/s of each integer wind speed. This must be done for both operation and non-operation (background)

One-third octave band measurements: Energy average of at least three spectra (based on a least 1 min data record) at each integer wind speed. One third octave bands shall be used with center frequencies from 50 to 10,000 Hz.

Narrow band measurements: 2 minutes of A-weighted measurements (operation and background) for each integer wind speed.

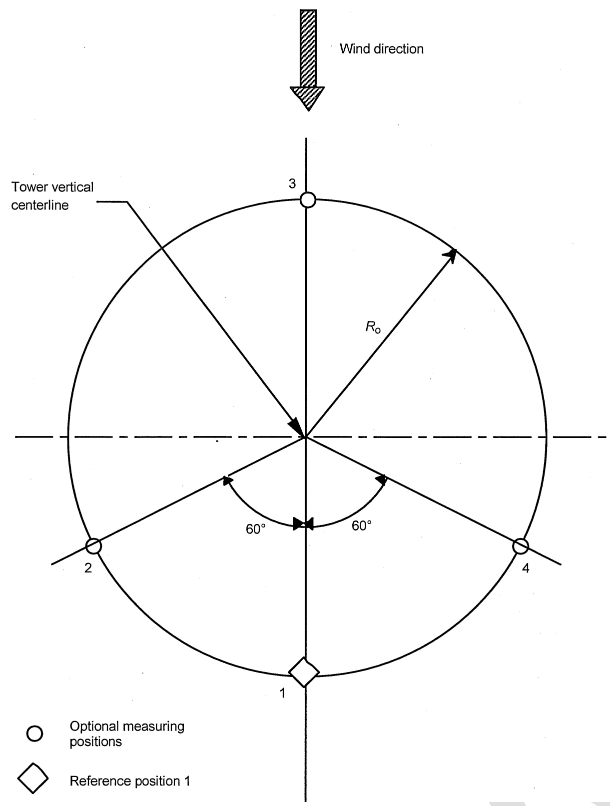

Figure 6. Diagram from the IEC standard that shows where sound measurements are made for wind turbines

11.4 Availability

Purpose

To quantify the fractions of time a WEC is capable of producing power while accounting for environmental conditions.

Relevant Standards and References

- Wind turbine availability, Danish Standard Availability Working group for Wind turbines, 19 august 2005
- IEC TS 61400-26-1:2011, Wind turbines - Part 26-1: Time-based availability for wind turbine generating systems
- IEC TS 61400-26-2: Wind turbines - Part 26-2: Production based availability for wind turbines

Considerations and Requirements

Availability can be defined as time based or production based, both are presented herein. Availability differs from capacity factor. Time based availability is a direct measure of the ratio of available time to the total time. Production based availability is a direct measure of the ratio of actual production over potential production based on the actual wave resource. Capacity factor is the ratio of actual energy production to the maximum potential production if the WEC operated continuously at full nameplate capacity.

Please note that this list of conditions is simplified from the once presented in the references for this section. This is done to reflect the early stages of WEC technology and the references should be used for technologies ready for certification testing.

Determination of Availability

Following IEC TS 61400-26-1, system time based availability is calculated using:

$$Time\ based\ availability\ =\ 1 - \frac{Unavailable\ Time}{Available\ Tme + Unavailable\ Time}$$

were

$$Total\ Time\ =\ Available\ Time + Unavailable\ Time$$

The only time considered as available according to the standard is Operating – Normal and Operating – Reduced. All other categories are considered unavailable.

Following IEC TS 61400-26-2, system production based availability is calculated using:

$$Production\ based\ availability\ =\ 1 - \frac{Lost\ Production}{Actual\ Production + Lost\ Production}$$

where

$$Lost\ Production\ =\ Potential\ Production - Actual\ Production$$

The following table can be used to help define and categorize the measures of availability

Table 2. Measures of availability used to calculate production based availability

Condition	Actual Production	Potential Production	Lost Production
Operating – Waiting for Waves	0	P_{P_OW}	P_{P_OW}
Operating – Normal Generation/Full Performance	P_{A_ON}	P_{P_ON}	$P_{P\_ON} - P_{A\_ON}$
Operating – Reduced Generation/Partial Performance	P_{A_OR}	P_{P_OR}	$P_{P\_OR} - P_{A\_OR}$
Operating – Start up	P_{A_OS}	P_{P_OS}	$P_{P\_OS} - P_{A\_OS}$
Shutdown – Extreme Waves	0	P_{P_SEW}	P_{P_SEW}
Shutdown – Extreme Environment	0	P_{P_SEE}	P_{P_SEE}
Shutdown - Nuisance	0	P_{P_SN}	P_{P_SN}
Shut Down – Planned Maintenance	0	P_{P_SPM}	P_{P_SPM}
Shutdown – Unplanned Maintenance	0	P_{P_SUM}	P_{P_SUM}

Shutdown – Utility	0	P_{P_SU}	P_{P_SU}
Shutdown – Test Facility	0	P_{P_ST}	P_{P_ST}
Shutdown – Owner	0	P_{P_SO}	P_{P_SO}
Shutdown – Utility Forced Outage	0	P_{P_SUF}	P_{P_SUF}
Shutdown – Test Facility Forced Outage	0	P_{P_STF}	P_{P_STF}
Shutdown – WEC Forced Outage	0	P_{P_SWF}	P_{P_SWF}
Shutdown – Force Majeure Outage	0	P_{P_SFM}	P_{P_SFM}

12 Power

12.1 Power Performance

Purpose

To measure the WEC's power performance (measure of the capability of a WEC to produce electric power and energy for specific wave characteristics) in the open-ocean to provide data to calculate the power matrix and estimate annual energy production. This section provides an overview of the recommended practices and procedures, along with practical considerations for gathering data for standard analyses.

Considerations and Requirements

The power performance of a WEC is one of the most important parameters to characterize via field testing, yet remains one of the most contested measurements because of the wide range of capture methods, technologies and methods of calculation. However, as a WEC advance toward commercialization, the power performance should be accurately known to help advance the design and provide credible data to help attract investment. The IEC has developed a Technical Specification that is useful to guide analysis and is reference herein. Several other reference are provide that can provide addition information on testing and what standard in the wind industry.

Relevant Standards and References

- Performance Assessment for Wave Energy Conversion Systems in Open Sea Test Facilities, European Marine Energy Center,
- Protocols for the Equitable Assessment of Marine Energy Converters, David Ingram et al., EquiMar, 2011
- IEC 61400-12-1, Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2005-12
- IEC 62600-100 TS Ed 1: Marine energy - Wave, tidal and other water current converters - Part 100: Electricity producing wave energy converters - Power performance assessment of electricity producing wave energy converters, 2012.
- IEC 60044-1 :I 996, Instrument transformers - Part *I:* Current transformers
- IEC 60688:1992, Electrical measuring transducers for converting a.c. electrical quantifies to analogue or digital signals
- IEC 62008, Performance characteristics and calibration methods for digital data acquisition systems and relevant software

Recommended measurements:

- Water depth via a pressure sensor or acoustic altimeter to capture tidal and storm driven changes in water depth made at least once an hour with the burst of sufficient duration to average out wave effects.
- Directional wave spectra via a wave buoy or an acoustic profiler. A measurement rate of at least 5 Hz and an averaging period of between 20 and 30 minutes are

recommended. The spectral frequency range should be at least from 0.033 to 0.5 Hz with the resolution not exceeding 0.015Hz. It is critical that the measurement periods of the different WMIs be synchronized. The range of measurement should be sufficient to meet the 100 year site conditions.

- Water current profiles via an acoustic current profiler with a bin resolution of between 1 and 4 meters. Ensembles of currents should be provide at least every 20 to 30 minutes with sufficient number of pings in each ensemble to obtain a measurement std of less than 2.5 cm/s and so wave effects are averaged out. The sampling period of each ensemble shall be at most 10 minutes. The range of measurements should be at least +/- 150% of the expected maximum current. If the local currents are not well known, this range should be increased.
- Wind velocity should be measured by a conventional cup or 3D sonic anemometer system with a sample rate of at least 1Hz. Ideal this should be made at 10 m above the mean sea surface. If possible, temperature and relative humidity are also useful measures to determine the air density.

Power Performance Monitoring

The power matrix should be determined by simultaneous measurements of the wave climate, the power output from the WEC at the test site and external factors such as wind, current, water depth and mooring line tensions (if applicable). Based on IEC 62600-100 TS Ed 1, WEC power should be reported via a normalized power matrix that is constructed using the "method of bins." The specifications are:

- significant wave height with a maximum bin width of 0.5 meters
- energy period with a maximum width of 1.0 seconds.

With power measurements being divided into a 2 dimensional array of bins, the measurement period for each combination of bins must be sufficiently long to establish a statistically significant database over the desired ranges of significant wave height and energy period. For wind, IEC 61400-12-1 recommends that at least 30 min of data be collected for each bin which should include at least three independent and valid data sets to allow a basic level of statical analysis. According to IEC 62600-100 TS Ed 1, if the WEC is connected to the grid, the grid needs to be monitored for export capacity that might constrain the WEC output capacity.

Recommended measurements:

The net electric power of the WEC shall be measured using a power measurement device (e.g. power transducer) and be based on measurements of current and voltage on each phase.

- Net electric power based on measurements of current and voltage on each phase. Sample rates should be at least 2 Hz and full-scale range of the power measurement device should be set to -50 % to +200 % of WEC rated power. For certification purposes, transducers must meet the requirements of the following standards and should be class 0.5 or better – specific details are given in 62600-100 TS Ed 1 and IEC 61400-12-1.

- Power transducers IEC 60688
- Current transformers IEC 60044-1
- Voltage transformers IEC 60044-2
- Ideally, the power transducers need to be places as close to the generator as possible to limit line loss. If measurements are made some distance away, the line loss must be accounted for.
- Directional wave spectra via a wave buoy or an acoustic profiler. A measurement rate of at least 5 Hz and an averaging period of between 20 and 30 minutes are recommended. The spectral frequency range should be at least from 0.033 to 0.5 Hz with the resolution not exceeding 0.015Hz. It is critical that the measurement periods of the different WMIs be synchronized. The range of measurement should be sufficient to meet the 100 year site conditions.
- Water current profiles via an acoustic current profiler with a bin resolution of between 1 and 4 meters. Ensembles of currents should be provide at least every 20 to 30 minutes with sufficient number of pings in each ensemble to obtain a measurement std of less than 2.5 cm/s and so wave effects are averaged out. The sampling period of each ensemble shall be at most 10 minutes. The range of measurements should be at least +/- 150% of the expected maximum current. If the local currents are not well known, this range should be increased.
- Wind velocity should be measured by a conventional cup or 3D sonic anemometer system with a sample rate of at least 1Hz. Ideal this should be made at 10 m above the mean sea surface. If possible, temperature and relative humidity are also useful measures to determine the air density.
- Water depth via a pressure sensor or acoustic altimeter to capture tidal and storm driven changes in water depth made at least once an hour with the burst of sufficient duration to average out wave effects.
- Buoy draft should be measured via a pressure sensor located on the body of the WEC. Burst measurements should be made at least once an hour with the burst of sufficient duration to average out wave and buoy motion effects.
- WEC control system status should be monitored to determine the state of the WEC and reject data for the following reasons:
- WEC is not operating because of a fault or because it is shut down
- Wave climate is outside of WEC operating range
- WEC is not properly oriented toward the incoming waves
- Wave direction is outside the range of site calibration
- WEC load (if not grid connected) should be recorded in the case of a variable load bank.

12.2 Power Quality

Purpose

To measure the power quality characteristics in the open-ocean of WECs connected to the grid or grid emulators. As per IEC 61400-21, the power quality characteristics here include voltage quality (emissions of flicker and harmonics), voltage drop response, power control (control of active and reactive power), grid protection and reconnection time.

Relevant Standards and References

- IEC 61400-21, Wind turbines - Part 21:Measurement and assessment of power quality characteristics of grid connected wind turbines
- IEC 60044-1: Instrument transformers - Part *I:* Current Transformers
- IEC 60044-2: Instrument transformers - Part 2*: Inductive Voltage Transformers*
- IEC 61000-4-7:2002, Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto
- IEC 61000-4-15, Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 15: Flickermeter – Functional and design specifications
- IEC 61400-12-1, Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2005-12
- IEC 62008, Performance characteristics and calibration methods for digital data acquisition systems and relevant software

Considerations and Requirements

Characterization of power quality is important at higher TRLs when a WEC developer is developing specifications or aiming to certify that their technology meets specific power quality requirements. High quality measurement is essential to convince certification authorities and regulators of electrical grids. Unfortunately, no standards have been established for WECs, but a working group under the IEC has been established, PT 62600-30 Electrical power quality requirements for wave, tidal and other water current energy converters. Therefore, standards and practices for wind turbines will be leveraged. It should be highlighted that the new work item proposal, 114/79/NP**,** that established PT 62600-30 notes the following considerations for MHK systems:

- Land-based harmonic standards are designed for the low frequency band (for audio interference), whereas higher frequency (2-150 kHz) harmonics may deserve attention for marine power systems.
- Higher frequency components arising from power electronic converters may impact marine habitat and life, and cause interfere with underwater communication networks.
- Use of power electronic conversion equipment and subsea cables may create possible resonance conditions amplifying voltage problems at various locations.
- Tidal current devices exhibit periodic output variations and go through start/stop cycles that can potentially cause flicker. Also, oscillating power output from vertical

turbines and torque ripples due to tower shadow may deteriorate the flicker performance.

- Ocean wave devices containing internal energy storage (power take-off) schemes may provide power smoothing characteristics, reducing the output fluctuations.
- A wide range of machines from classical induction generators to more novel outer-rotor rim-type direct-drive generators are currently being considered for marine power devices.
- Proliferation of power electronics converters within single-machine/single-device or multimachine/single-device can potentially cause harmonic emission and dc-injection issues.
- Details for testing and calculating the various measures of power quality can be found in IEC 61400-21, Wind turbines - Part 21:Measurement and assessment of power quality characteristics of grid connected wind turbines and the other standards and references below.

Power Quality Monitoring

Power Quality Monitoring is one of the most demanding for DASs and different components, such as current harmonics/inharmonics, voltage fluctuations, active power, etc often have different measurement requirements.

Based on IEC 61400-21, specific monitoring should be sufficient to support the following calculations and analyses:

- Voltage fluctuations, Clause 7.3
- Flicker coefficient for continuous operation
- Fluctuations for WEC start up and switching operations for different wave conditions
- Current harmonics, interharmoics and higher frequency components during continuous operation, Clause 7.4
- individual harmonic components so that they can be grouped at values for frequencies of up to 50 times the fundamental grid frequency
- interharmonic components so that they can be specified as subgrouped values for frequencies up to 2 kHz
- higher frequency components so that they can be grouped at values for frequencies of between 2 kHz and 9 kHz
- Voltage drops, Clause 7.5
- Active power, Clause 7.6
- Maximum measured power with 0.2, 60 and 600 second averages
- Ramp rate showing available and measured active power when ramped at 10% of rated power per minute over 10 minutes

- Set-point control showing available and measured active power at set points decreasing from 100% to 20% of rated power in steps of 20%.
- Reactive power, both maximum inductive and capacitive reactive powers specified for 1 min averages for 0 – 100% of the rated power in steps of 10%
- Reactive Power, Clause 7.7
- Grid protection, the voltage and frequency levels that cause the WEC to disconnect from the grid and disconnection time, Clause 7.8
- Reconnection time, the time it takes the WEC to reconnect to the grid, Clause 7.9.

Acceptable test conditions based on those in IEC 61400-21 are as follows:

- The WEC should be connected to the grid/grid simulator through a standard transformer with a rate apparent power that is at least that of the WEC
- Total harmonic distortion (including all harmonics up to 50 times the grid frequency) should be less that 5% (based on 10 min averages at the WEC terminals) while the WEC is not generating
- Grid frequency should meet the following conditions, based on 0.2 s averages:
    - should be within ± 1% of the nominal frequency
    - rate of change should be less that 0.2%
    - if it does not meet the aforementioned conditions, the grid frequency should be monitored during testing
- Grid voltage should meet the following conditions, based on 10 min averages
    - Be within ± 10% of the nominal value
    - Unbalanced factor should be less than 2%, as determined in IEC 61800-3:2004, Clause B.3.

Recommended measurements:

Ideally, measurements should be made at the WEC side terminals if a built-in transformer is used.

In IEC 61400-21, the following requirements for measurement are specified

Equipment	Required accuracy	Applicable Standard
Voltage transformers	Class 1.0	IEC 60044-2
Current transformers	Class 1.0	IEC 60044-1
Filter + A/D converter + DAS	1% of full scale	IEC 62008

The instantaneous line currents and phase-to-neutral voltages should be measured for each phase at the WEC terminals.

Measurements should be taken for at least fifteen 10 minute time series for conditions corresponding to each bin in the power matrix.

For switching operations, the measurement periods should be long enough so that transients have died out.

Based on experience in wind, sample rates should be at least 50 kHz for all current and voltage channels, but if the TC114 PT 62600-30 working group's consideration is relevant for specific tests, sample rates could exceed 300 kHz.

13 Loads, Response, wear, and fatigue

13.1 Mechanical Loads

Purpose

To measure and characterize the mechanical loads at key locations in order to accurately quantify loads, verify adherence to codes, validate models and load estimates for design load cases (DLCs), reduce uncertainties, determine load paths, and fatigue analysis

Considerations and Requirements

Many different WEC designs exist and while it is not possible to provide definitive guidance for mechanical load monitoring for all variants, this section intends to provide a general overview applicable to WECs.

As suggested in IEC TS 61400-13, when developing a loads measurement campaign, it is important to consider the design DLCs these are what need to be verified through measurements. This requires mapping the DLCs to the measurement load cases (MLCs). For a WEC, it is also important to develop a testing matrix that maps the primary forcing, the significant wave height and period to the loads. This is analogous to the power performance matrix. It also must consider the effects of load variations due to WEC control/load state, marine currents and meteorological conditions. The goal is to collect sufficient time series and statistics to characterize the loads in each of the bins. If data requirements are known a priori, then once sufficient data are collected for a bin, there would be no need to process additional data for that bin.

Testing should consider all possible operating scenarios, including

- steady state operation for normal power production over the full range of operation
- extreme weather events with appropriate WEC state, such as system lockdown
- normal start-up and shut down
- emergency shut-down, grid failure and other fault conditions

Placement of load measuring devices, such as strain gauges should be done judiciously so that the sensor location, based on IEC TS 61400-13, has a high but linear strain to load relationship with as uniform stress distribution over the area that the strain gauges are applied. The location should also have sufficient area to install and have material of uniform properties to which the gauges can be applied.

For underwater applications, fiber optic strain gauges are recommended because they do not corrode or degrade in water, although they are sensitive to water pressure. If foil type strain gauges are used, purchase ones designed for underwater applications. When mounting, take time to prepare the mounting surface and make sure to use a water proof barrier that bonds firmly to that surface. Applying a thin layer of wax to the strain gauge will help keep it separate from the water proof barrier. If possible, use a solid core wire or connector near the sensors that will prevent water from wicking up the wire to the strain gauge. Underwater strain gauges typically have a much higher failure rate than those on the surface, so redundant sensors are recommended.

Calibration of strain gauge sensors is important to determine the sensor sensitivity after installation. Because the sensor and measurement system (DAS, bridge excitation, filters and amplifiers) are serial, it is important to characterize the measurement system separately using a simulated strain gauge. Prior to applying the calibration loads, apply a few preloads to eliminate any residual stresses. Then apply several calibration loads to generate strain in the intended direction of sensitivity and out of plane loads to determine cross sensitivity. Ideally, apply a sufficient number of loads so that the sensitivity and non-linearity can be mapped of the range of expected loads.

Relevant Standards and References

- IEC TS 61400-13, Wind turbine generator systems – Part 13: Measurement of mechanical loads
- IEC 61400 – 1, Wind turbines – Part 1: Design requirements
- TC 114/PT 62600-2, draft sections for Design requirements for marine energy systems
- ISO 19904-1, Floating offshore structures - monohulls, semi-submersibles and spars
- ISO 19904-2, Floating offshore structures - tension leg platforms
- ABS 115, Fatigue Assessment of Offshore Structures
- ABS 120, Surveys Using Risk-Based Inspection for the Offshore Industry
- DNV-OS-C101 Design of Offshore Steel Structures, General (LRFD Method)

Recommended measurements:

- strain gauge bridges that are sampled at rate such that they cut-off frequency is at least three times higher than the highest frequency in the measurement.
- load cells in guy lines and other axial loaded members that are sampled at rate such that they cut-off frequency is at least three times higher than the highest frequency in the measurement.
- accelerometers to capture mode shapes and structural vibrations that are sampled at rate such that they cut-off frequency is at least three times higher than the highest frequency in the measurement.
- WEC control system status should be monitored to determine the state of the WEC
- Directional wave spectra via a wave buoy or an acoustic profiler. A measurement rate of at least 5 Hz and an averaging period of between 20 and 30 minutes are recommended. The spectral frequency range should be at least from 0.033 to 0.5 Hz with the resolution not exceeding 0.015Hz. It is critical that the measurement periods of the different WMIs be synchronized. The range of measurement should be sufficient to meet the 100 year site conditions.

- Water current profiles via an acoustic current profiler with a bin resolution of between 1 and 4 meters. Ensembles of currents should be provide at least every 20 to 30 minutes with sufficient number of pings in each ensemble to obtain a measurement std of less than 2.5 cm/s and so wave effects are averaged out. The sampling period of each ensemble shall be at most 10 minutes. The range of measurements should be at least +/- 150% of the expected maximum current. If the local currents are not well known, this range should be increased.
- Wind velocity should be measured by a conventional cup or 3D sonic anemometer system with a sample rate of at least 1Hz. Ideal this should be made at 10 m above the mean sea surface. If possible, temperature and relative humidity are also useful measures to determine the air density.

13.2 Mooring Stiffness

Purpose

The goal of this test is to measure the mooring stiffness of the WEC by displacing the buoy and measuring the mooring tension and buoy orientation and position.

Considerations and Requirements

The mooring system often has a substantial effect on the seakeeping and response of a WEC. It is often difficult to achieve the exact mooring configuration used in design because of errors in anchor placement, differences in mooring hardware, variations in mooring line length, among many factors. It is therefore useful to measure the “as deployed” mooring stiffness, which is defined as the relationship between a horizontal force applied to the WEC and the corresponding WEC displacement. The mooring stiffness is often asymmetric and will depend on the direction of pull. The mooring stiffness is typically non-linear as well.

The mooring stiffness test should be performed during calm conditions with and all moving parts locked down. The WEC should be ballasted to its working state.

Prior to the test, the mooring configuration needs to be analyzed to determine the minimum combination of the range of pull loads and pull directions needed to fully characterize the mooring stiffness. For example, if a mooring system is symmetric across one plane, displacements only need to occur in two quadrants

If a mooring line is used that has a high degree of creep, the mooring stiffness test should be performed periodically for longer duration tests.

Testing

Before the test starts, the static, unloaded position of the WEC must be known. This location can be measured during times of minimal metocean conditions (no current, wind and waves).

If the pull vessel is to be anchored, anchor the vessel sufficiently far from the WEC so that the WEC – vessel – anchor line will be in the desired direction of pull. If the anchor winch is to be used to tension the mooring, be sure so that there is sufficient distance between the anchor and WEC so that all line pull loads can be achieved.

Attach the pull line at a hardpoint on the WEC, ideally one that aligns with the direction of pull so that the mooring configuration is not distorted from the static configuration.

If the vessel is at anchor, using either the anchor winch to pull the vessel and tension the pull line or use a winch/capstan or other method to tension the pull line. If the vessel is not at anchor, slowly increase the engine RPM until the desired pull line tension is reached.

Record the position of the WEC, pull vessel, and corresponding line tension.

Repeat steps 3 and 4 for each pull line tension increment

Repeat steps 1 -5 for each direction of pull

Recommended measurements:

- Buoy position via a GPS with data rates of at least 1 Hz with a resolution of less than a meter.
- Vessel position via a GPS with data rates of at least 1 Hz with a resolution of less than a meter.
- Pull in tension via an in-line load cell. The load cell should have a range of at least 3 times the expected maximum line tension and a sample rate of at least 10 Hz.

13.3 Mooring Loads

Purpose

The goal of this test is to monitor and characterize the mooring loads of the WEC under normal and extreme metocean conditions.

Relevant Standards and References

- API RP 2I, In-service Inspection of Mooring Hardware for Floating Structures
- API RP 2SK, Design and Analysis of Station-keeping Systems for Floating Structures
- API RP 2SM, Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring
- API RP 2T, Recommended Practice for Planning, Designing and Constructing Tension Leg Platforms
- API Spec 2F, Mooring Chain
- ABS, 8 Single Point Moorings
- ABS, 39 Certification of Offshore Mooring Chain
- ABS, 90 Application of Fiber Rope for Offshore Mooring
- BV NI432 Certification of fibre ropes for deepwater offshore services
- DNV-OS-E301 Position Mooring
- DNV-OS-E302 Offshore Mooring Chain

- DNV-OS-E303 Offshore Mooring Fiber Ropes
- DNV-OS-E304 Offshore Mooring Steel Wire Ropes
- DNV-RP-E304 Damage Assessment of Fiber Ropes for Offshore Mooring

Considerations and Requirements

It is recommended that each mooring line have a load cell to monitor mooring line loads. If possible, the inclusion of inclinometers in the load cells is helpful to determine the angle of the mooring line. These measurements provide a direct assessment of the mooring line health and provide data to quantify loads during extreme events and identification of adverse conditions such as snap loads.

Monitoring

For floating WECs, the mooring systems is the station keeping component of the design and any failures due to mooring line parting, anchor drag or shackle/chain fatigue can dramatically affect the device performance, cause instabilities and even the loss of the device. Therefore, it is helpful to monitor the health of mooring system to reduce risk. Because moorings are critical components, they are often built with a large safety factor. Therefore, quantifying the real mooring loads can help reduce costs by potentially reducing these factors.

Recommended measurements:

- Mooring line tension via an inline load cell that is located near the buoy. Ideally the load cell should include an inclinometer to measure the rise angle of the line. Data rates between 10 and 100 Hz to capture the dynamic loads. A load cell must be selected very carefully to ensure it has the required range and resolution, the needed factor of safety, it is made of the correct material that will be compatible with the res of the mooring system, the connector is rated for the application and is at the correct orientation, and probably most importantly, that it is designed to survive being submerged and subject to the motion and loading typically seen in mooring lines. Cheap load cells have a history of rapid failure.
- Buoy position via a GPS with data rates of at least 1 Hz with a resolution of less than a meter. While the accuracy of a GPS measurement is likely less, the repeatability from measurement to measurement is high, so a good resolution is warranted.
- Water depth via a pressure sensor or acoustic altimeter to capture tidal and storm driven changes in water depth which can directly affect the lay of the mooring lines. Burst measurements should be made at least once an hour with the burst of sufficient duration to average out wave effects.
- Buoy draft should be measured via a pressure sensor or altimeter located on the body of the WEC. Burst measurements should be made at least once an hour with the burst of sufficient duration to average out wave and buoy motion effects.
- 6 DOF Motion via at a Motion Reference Unit, MRU, or equivalent (IMU, INS, etc). While the motion measurement is not critical, it is recommended because WEC motion is affect by and affects the mooring line tensions. Data rates should be

between 10 and 100 Hz connected with a GPS and compass/inclinometer to eliminate low frequency drift.

- Directional wave spectra via a wave buoy or an acoustic profiler. A measurement rate of at least 5 Hz and an averaging period of between 20 and 30 minutes are recommended. The spectral frequency range should be at least from 0.033 to 0.5 Hz with the resolution not exceeding 0.015Hz. It is critical that the measurement periods of the different WMIs be synchronized. The range of measurement should be sufficient to meet the 100 year site conditions.
- Water current profiles via an acoustic current profiler with a bin resolution of between 1 and 4 meters. Ensembles of currents should be provide at least every 20 to 30 minutes with sufficient number of pings in each ensemble to obtain a measurement std of less than 2.5 cm/s and so wave effects are averaged out. The sampling period of each ensemble shall be at most 10 minutes. The range of measurements should be at least +/- 150% of the expected maximum current. If the local currents are not well known, this range should be increased.
- Wind velocity should be measured by a conventional cup or 3D sonic anemometer system with a sample rate of at least 1Hz. Ideal this should be made at 10 m above the mean sea surface. If possible, temperature and relative humidity are also useful measures to determine the air density.

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