Open Sea Operating Experience to Reduce Wave Energy Costs

# Deliverable D5.2

## Recommendations to TC114 from real-case applications of wave energy technical specifications


| | |
|---|---|
| Lead Beneficiary | UCC |
| Delivery date | 2019-07-12 |
| Dissemination level | Public |
| Status | Approved |
| Version | 1.0 |
| Keywords | Wave energy, International IEC specifications, performance, power quality, moorings, wave resource |



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654444

**Disclaimer**

This Deliverable reflects only the author's views and the Agency is not responsible for any use that may be made of the information contained therein

**Document Information**

| | |
|---|---|
| **Grant Agreement Number** | 654444 |
| **Project Acronym** | OPERA |
| **Work Package** | WP 5 |
| **Task(s)** | T5.2 |
| **Deliverable** | D5.2 |
| **Title** | Recommendations to TC114 from real-case applications of wave energy technical specifications |
| **Author(s)** | Florent Thiebaut (UCC), James Kelly (UCC), Lars Johanning (UNEXE), David Crook (UEDIN), Joannès Berque (TECNALIA), Pablo Ruiz Minguela (TECNALIA) |
| **File Name** | OPERA_D5.2_Recommendations to TC114 from real-case applications of TS_UCC_v1.0.docx |

**Change Record**

| Revision | Date | Description | Reviewer |
|---|---|---|---|
| 0.1 | 11/12/2018 | Initial outline | WP5 partners |
| 0.2 | 06/06/2019 | Partial draft with power performance and power quality application | UEDIN, UNEXE |
| 0.5 | 26/06/2019 | Full version for quality review | TECNALIA |
| 0.9 | 02/07/2019 | Integrate review comments | UCC |
| 1.0 | 12/07/2019 | Final version for the EC | EC |

# EXECUTIVE SUMMARY

This document represents deliverable 5.2 (D5.2) of OPERA Work Package 5 (WP5).

OPERA is a European Commission funded project that ultimately aims to reduce the time to market and costs of wave energy. OPERA WP5, entitled, "Applicability and Extension of IEC Technical Specifications using Open Sea Data" is dedicated to providing the first documented application of the ongoing normative process for the wave energy sector, the International Electrotechnical Commission (IEC) Technical Specifications (TS) for marine energy, reduce the uncertainties in their application and provide recommendations to the relevant marine technical committee of the IEC (TC114) that will accelerate the establishment of standards based on these technical specifications.

An initial review of all IEC TS used in the OPERA project was carried out and reported in Deliverable D5.1, which highlighted all parts of the IEC TS to be applied in the OPERA project. Following this review, all experimental work carried out in the OPERA project aimed at applying as close as possible relevant IEC TS.

Deliverable D5.2 is the documented application of the following TS:

- 62600-10 Part 10: Assessment of mooring system for marine energy converters.
- 62600-30 Ed. 1.0 Part 30: Electrical power quality requirements for wave, tidal and other water current energy converters.
- 62600-100 Ed. 1.0 Part 100: Electricity producing wave energy converters -Power performance assessment.

Note: D5.2 description in OPERA Grant Agreement also mentions the IEC 6200-102. D5.2 was written in accordance with T5.2 description and the documented application of IEC 6200-102 was reported in D5.3.

For each TS, D5.2 contains a description of work carried out, results and uncertainties in relation to wave measurement, WEC power and WEC power performance assessment, electrical power quality and assessment of mooring systems. Besides, D5.2 reports on the experience gained within the project and challenges associated with the experimental work and with the application of the TS. Finally, D5.2 provides recommendations for possible improvements on each TS. This should be available to TC 114 technical committees for the preparation of the next TS version.

# TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ADCP | Acoustic Doppler Current Profiler |
| BiMEP | Biscay Marine Energy Platform |
| CL | Capture Length |
| CMS | Condition Monitoring Systems |
| DP | Deployment Phase |
| FFT | Fast Fourier Transform |
| FMEA | Failure Mode and Effect Analysis |
| Hs | Significant wave height |
| HV | High Voltage |
| IEC | International Electrotechnical Commission |
| IMU | Inertial Measurement Unit |
| LV | Low Voltage |
| MV | Medium Voltage |
| MAEP | Mean Annual Energy Production |
| MEC | Marine Energy Converter |
| MWPP | Mutriku Wave Power Plant |
| NOTF | Notional Ocean Test Facility |
| NI | National Instrument |
| PWM | Pulse Width Modulation |
| RPN | Risk Priority Numbers |
| Te | Energy Period |
| TS | Technical Specification |
| VFD | Variable Frequency Drive |
| WEC | Wave Energy Converter |
| WMI | Wave Measuring Instrument |
| WP | Work Package |

# 1. INTRODUCTION

This document aims at providing feedback to the IEC Technical Committee based on real application of the following IEC Technical Specifications:

- 62600-10 Part 10: Assessment of mooring system for marine energy converters.
- 62600-30 Ed. 1.0 Part 30: Electrical power quality requirements for wave, tidal and other water current energy converters.
- 62600-100 Ed. 1.0 Part 100: Electricity producing wave energy converters -Power performance assessment.

This document was written during the final stage of OPERA project and is based on D5.1 where a review of the standards and a list of requirements was set for the project. The results and recommendations are based on work carried out in all project Work Packages where IEC specifications were applied. Testing carried out in OPERA includes:

- Two test locations, on-shore at Mutriku and off-shore at the BiMEP test site.
- Deployment of a wave measurement buoy and ADCP.
- Installation of a full-scale floating Wave Energy Converter (WEC).
- Installation of two types of mooring systems, one for single WEC and one shared mooring system for WEC clusters.
- The testing of two turbines, conventional Wells turbine and a new bi-radial turbine.

Final recommendations will be sent to TC114 relevant Technical Committee to help and accelerate improvements of next editions of the corresponding IEC Specifications.

# 2. IEC TS62600-100 ELECTRICITY PRODUCING WAVE ENERGY CONVERTERS - POWER PERFORMANCE ASSESSMENT

## 2.1 OVERVIEW OF TS100 METHODOLOGY AND APPLICATION IN BIMEP AND MUTRIKU

IEC/TS 62600-100 (hereafter TS100) provides technical specifications for the power performance assessment of electricity producing Wave Energy Converters (WECs). The discussion that follows refers to Edition 1.0, 2012-08. TS100 specifies methods to measure wave and derive sea-state statistics, measurements of concurrent WEC power output, evaluation of a power matrix and reporting at-sea testing results. TS100 applies to moored, floating WECs. It excludes bottom-fixed and shoreline devices like the Mutriku plant. The discussion in this section thus focusses on experience acquired in OPERA at BiMEP. However, some of the experience gained at EVE's Mutriku shoreline plant will be referred when relevant to TS100.

The Biscay Marine Energy Platform (BiMEP) is an open sea test site with grid connection for demonstrating and validating wave energy collectors and floating wind platforms. The IDOM Oceantec Marmok floating WEC is deployed at BiMEP Berth 4 (Figure 1).

OPERA deliverable D5.1 provides a clause by clause overview of the application of TS100 and other technical specifications in BiMEP, with some indication of the applicability in Mutriku. The table in Section 4 therein should be referred to for further details. In this section we report on the experience gained in the implementation phase of open-sea testing. The application of clauses that are not mentioned in this section does not need feedback as it could be fully applied without difficulties as described in D5.1. The experience gained since D5.1 is summarized in the table provided in Section 2.1.3.

### 2.1.1 COMPLIANCE OF WAVE MEASUREMENTS

#### 2.1.1.1 COMPLIANCE WITH CLAUSE 5.2.1

- Requirements:

Clause 5.2.1 specifies the wave measurements for wave power necessary at a test site. Two wave measuring instruments are to be deployed, one at the proposed WEC deployment location, and one at the location where long-term wave measurements will be collected. The latter is required to obtain reliable estimates of mean annual energy production that are less sensitive to year-to-year variability in the wave climate.

- OPERA experience:

Wave measurements are available at BiMEP since 2012 upwave of the central Berth. In addition, a deepwater wave buoy is operated by Puertos del Estado some 25 km to the northwest, with a record that spans over 20 years with excellent coverage (Figure 2). The long term wave climate in the area is thus adequately characterized. However, intra-site variability in the wavefield is significant and another buoy was deployed about 170 m upwave (northwest) of the Oceantec WEC during the OPERA project. The latter is an Axys Technologies Triaxys buoy that provides directional spectra every 20 minutes. In addition, three wave buoys are now operated within BiMEP by Zunibal, a wave buoy manufacturer. The site’s wavefield is thus well characterised.

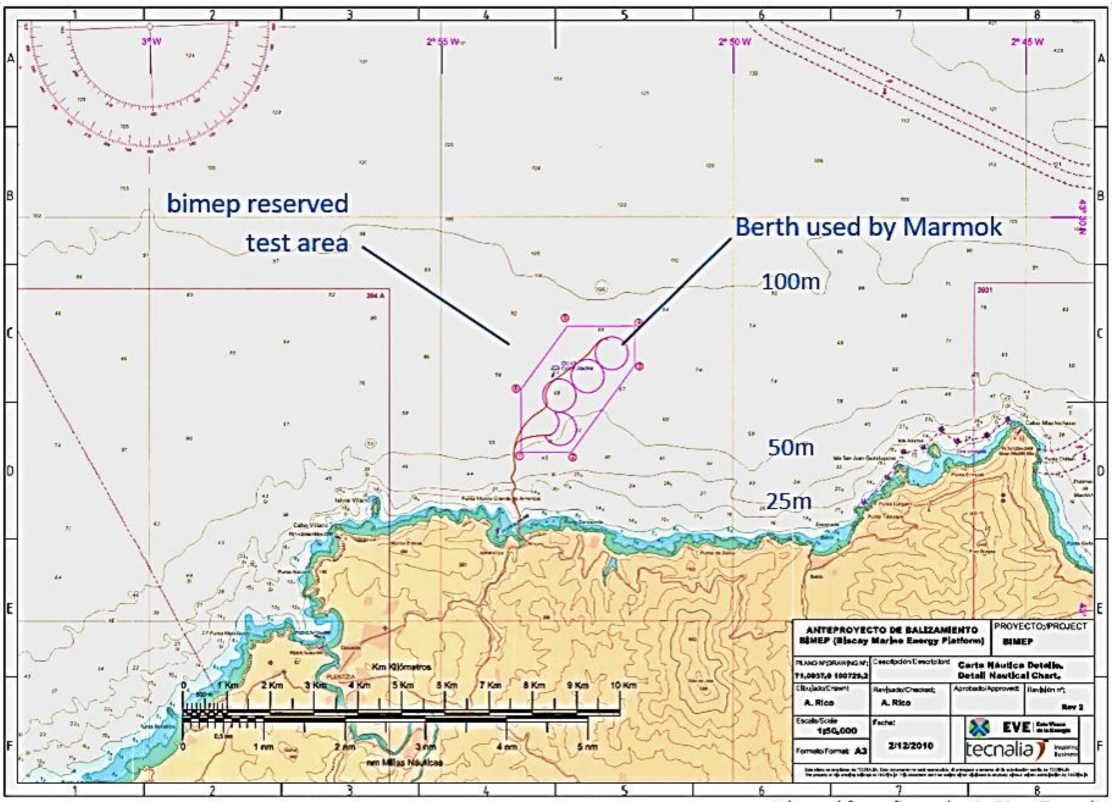


**FIGURE 1: BIMEP BATHYMETRY AND MARMOK BERTH OF DEPLOYMENT**

One requirement of Clause 5.2.1 that could not be entirely fulfilled in the OPERA project is the deployment of a Wave Measuring Instrument (WMI) *at* the WEC location, and at least 3 months *prior* to the WEC deployment. In OPERA, the Triaxys buoy was deployed 170 m upwave, to the NW. Considering the water depth of some 85 m at both WMI and OWC locations, and the highly consistent wave direction at BiMEP, it is expected that the change in the wavefield will be minimal between the buoy and the WEC.

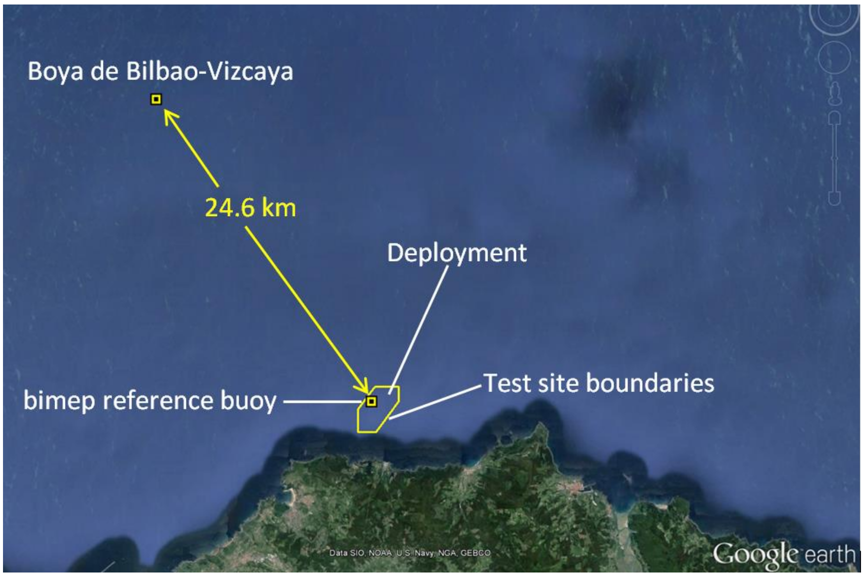


**FIGURE 2: LOCATION OF NEAREST DEEPWATER, LONG-TERM BUOY**

Although, the buoy was not deployed exactly at the WEC location, following clause 5.2.1, it is believed that the wave field at the WEC location is characterised with sufficient accuracy. Deploying the wave buoy at the exact WEC location meant significant increase in marine operations and cost. Understandably the developer needs to have the area clear of any wave buoy to facilitate the heavy marine operations involved in installing the WEC. Also an increase in the risk, if weather windows were to be rare, that marine operations for the WEC installation would be delayed in order to allow for the recuperation of the buoy. In this case, it simply was not a practical option.

It must be kept in mind that this type of particle following buoy has an excursion of the order of one water depth (here about 100 m). To this, margins of error in the positioning of the deploying ship (20 m) and in the inclination of the mooring line while deploying must be added. In this particular case, and this will often be the case in test sites, there are also electric cables on the bottom near the WEC that must not be damaged, so that deployment at the exact WEC location is best avoided. Some margins of error of the same order must be expected in positioning the WEC deployment. Its mooring system also will have an excursion. Therefore, a certain tolerance regarding the difference in the position of the wave measuring instrument and where the WEC will be deployed is necessary.

Another aspect in this requirement, that may require more attention, is the 3 months of observations *prior* to the WEC deployment. For the purpose of evaluating a spatial transfer model between a longer recording reference buoy and that at or near the WEC location, there are no reason this could not be during the WEC deployment, or after its decommissioning. There may be other reasons for these requirements but they are not explicit in TS100.

- Suggestions to IEC

This experience with OPERA therefore suggests that the following may merit attention regarding the practical application of Clause 5.2.1:

- Consider specifying a tolerance, or some conditions and criteria on the WMI location which in many cases cannot be deployed exactly at the WEC location due to the WMI mooring allowing excursions much larger than the WEC mooring system. For example, maximum distance allowed in terms of the dominant wavelength, water depth, and observed or calculated scale of spatial variability in the wavefield. If the tolerance can be increased sufficiently, consider the use of one WMI only near the WEC location.

- Explicit the reasons for the requirement of deployment of the WMI *prior* to WEC deployment and/or allow for deployment post-testing to calculate the wave transfer function from the reference buoy under certain conditions.

#### 2.1.1.2 COMPLIANCE WITH CLAUSE 6.2

Clause 6.2 specifies the sample duration and frequency to derive parameters describing the sea-state. The minimum sample duration is 20 minutes. This is complied with by the Triaxys buoy immediately upwave of the WEC. However, the record from the reference buoy of BiMEP, a Fugro Oceanor Wavescan, does not exactly comply.

Wavescan is a heave pitch and roll type of wave buoy, much heavier than the particle following Triaxys buoy, and appropriate for deepwater deployment. To save power and facilitate FFT calculations, the default sampling is set to 2048 measurements at 2 Hz, that is, a 17 min 4 s sample duration. This is standard in oceanography and is not reported to lead to bias in sea-state variable estimates. Sampling duration is a trade-off between reducing sampling variability, which benefits from longer sample, and adequately capturing changes form a stationary sea-state, which benefits from shorter sample. 17 minutes is usually considered an adequate trade-off, though for slowly varying wavefield a longer sampling duration is preferred, should battery power allow. The issue of sample duration is discussed in more detail in OPERA deliverable D5.3.

In summary, it appears a point worth considering regarding Clause 6.2, is whether the commonly used sample duration of 17 minutes 4 seconds is acceptable, instead of the clause’ s current requirement of 20 minutes.

#### 2.1.1.3 COMPLIANCE WITH CLAUSE 7.3.4

Clause 7.3.4 specifies the methods to correct for WEC interference with the wave measurements. A numerical model must be developed to estimate waves radiated and refracted from the WEC, which must have decayed at least 90% at the location of the wave measuring instrument.

This issue was not considered at BiMEP. It is convincingly argued that the dimensions of the WEC foreclose any possibility that its interaction with waves will influence the wavefield 170 m upwave, at the location of the Triaxys buoy.

It appears that criteria should be given to avoid the need for numerical modelling. For example, the distance between WMI and WEC location higher than a given number of WEC width or diameter.

Though TS100 does not include shoreline-fixed device in its scope, it is worth reporting here the experience with OPERA at EVE's Mutriku wave power plant. The stretch of the breakwater housing the turbines reflects waves coherently, as, unlike other parts of the breakwater, it is not protected by aggregate coastal defence structure like large rocks or tetrapods (Figure 3). The reflected wave is quite visible still 100 m offshore. The wave measuring instrument had to be located some 200 m upwave from the structure in order to reduce contamination of measurement of incoming waves. Accurately calculating the reflected wave and its decay would probably be quite complicated given the complex nearshore topography there. Should technical specifications be prepared in the future for shoreline devices, the issue of reflected waves requires a different type of clause than TS100/7.3.4.

**FIGURE 3: EVE'S MUTRIKU WAVE POWER PLANT**

#### 2.1.1.4 COMPLIANCE WITH CLAUSE 7.5

Clause 7.5 specifies the procedures for the calculations of derived parameters on the wavefield. This includes the derivation of the significant wave height, energy period and energy flux from the wave spectrum.

The Triaxys buoy has its own algorithms to derive wave spectra and sea-state parameters. The calculation is presumed to involve double integration of accelerometer data into velocities and then to surface elevation. It may be further presumed that one main issue is managing the growth of low frequency noise in the integrations. It has not been checked whether the algorithms used by Axys technologies comply with the requirements of Clause 7.5. Triaxys is one of three main buoys on the market for this type of deployment, and its performance and comparison with other wave measurements is documented in various publications.

Therefore, while Clause 7.5's intended application is probably different, it is worth mentioning here that for many of the commercially available buoys, it is difficult to verify whether spectral calculations and sea-state derivation procedures comply.

### 2.1.2 COMPLIANCE OF WEC POWER OUTPUT MEASUREMENTS

The application of TS100 specifications for WEC power output measurements is detailed in Section 2.3.

Power was measured at the output terminals of the Marmok WEC, as well as at the substation onshore. No particular difficulty is reported for the compliance of measurements at the output terminals comply with TS100's relevant clauses (Clause 8). Compliance is less straightforward for the onshore measurements, which were designed years prior to the WEC and more focused on billing exported power than for prototype testing.

The reader is referred to Section 2.3 for more details.

### 2.1.3 SUMMARY TABLE

The following table summarises the experience gained applying the TS100 clauses at BiMEP. A more detailed table of compliance can be found in OPERA deliverable D5.1. This table reports the additional experience gained from implementing TS100 in open-sea testing at BiMEP in the OPERA project.

**TABLE 1: SUMMARY OF EXPERIENCE APPLYING IEC-TS/62600-100 CLAUSES AT BIMEP**

| Clause number | Clause description | Specific requirement that was problematic in implementation | Suggested additional specifications to the clause |
|---|---|---|---|
| 5.2.1 | Wave measurement for wave power | Measuring *at* WEC location for at least 3 months *prior* to deployment | Specify or provide guidelines for acceptable distance from wave instrument and WEC; accept wave measurements during and after deployment to obtain the spatial transfer function |
| 6.2 | Sample duration and frequency for sea-state | Minimum of 20 minutes duration | Consider accepting the 17 min 4 s sample commonly used in oceanography; consider specifying conditions for using even shorter sample as per experience reported in OPERA/D5.3. |
| 7.4.3 | Correct for WEC interference in wave measurement | WEC radiated field must have decayed 90% at instrument location | Consider accounting for WEC dimensions in this clause and suggest criteria to when numerical modelling is not required |
| 7.5 | Derivation of sea-state parameters from spectral data | Ensemble of clause requirements | Consider accepting use of sea-state parameters provided by commercial buoys which may be calculated using proprietary undisclosed algorithms but have published documentation attesting the quality of their data. This may include external quality certification when available. |

## 2.2 LESSONS LEARNED ON WAVE DATA COLLECTION FOR OPEN-SEA POWER PERFORMANCE ASSESSMENT

This section provides information on the experience acquired in H2020 OPERA on the wave measurement for WEC applications. The focus is on the data collected at BiMEP for floating WEC application. Experience acquired at the Mutriku shoreline wave power plant is also mentioned where relevant.

WEC have wave data requirements that largely overlap with requirements for existing marine activities, such as offshore oil and gas, offshore wind, other marine or coastal structure and oceanographic studies. These requirements are useful for the definition of design parameters and the planning of marine operations. Design parameters include the long-term statistics of extreme events (storms) to dimensions marine structures for adequate strength, and mean regime statistics for fatigue design. Marine operations need both long-terms statistics for long-term planning, and operational forecasts ranging from weekly down to one-hour lead time for planning marine operations with adequate safety.

More specific to WEC projects is the need to define characteristics of the incoming wavefield to assess power performance of the WEC. Key statistics for wave energy conversion are the energy period and the spectral significant wave height. This section focusses on experience gained collecting these data within the OPERA project.

In addition, a highly specific requirement, that is an important part of the OPERA Project, is the predictive control of WECs. It requires real-time information on the incoming wavefield that is transmitted by the wave instrument to the WEC in quasi real time (generally less than one second latency) to be used in the WEC control system. This low latency requirement is new and not yet available from commercial wave buoys. As part of a research alliance with AXYS Technologies, the Triaxys buoy was equipped with an additional sensor that measured and transmitted heave motions in real time to the BiMEP office in Armintza. Data was received via a Yagi antenna deployed on the BiMEP watchtower overlooking the site from a hill at about 60 m above sea level. This setup provides useful information on waves in mean conditions, but less so in large waves and wind conditions. This experience is reported in OPERA/WP1 deliverables and is not described further here.

### 2.2.1 WAVE INSTRUMENT PURCHASE VS. CONTRACTING DATA PROVISION SERVICES

Assessing the power performance of a WEC requires accurate information on the wavefield impacting the WEC. As discussed in Section 2.1.1.1, this requirement is specified in Clause 5.2.1 of the IEC-TS/62600-100. Compliance with this clause requires the deployment of a wave measuring instrument at the WEC deployment location. At the OPERA project planning stage, the best approach was thought to be the acquisition of a new wave buoy that would be deployed in the immediate vicinity of the WEC.

From experience gained at the end of OPERA project, the deployment and operation of a WMI requires highly specialized work. Therefore, where a similar project is to be implemented, a data provision service should be contracted for the duration of the project, instead of the purchase of a wave buoy. In recent years, wave buoys suppliers offer these services and many of their clients have moved towards this type of agreement, rather than the traditional purchase of instruments. Wind farm developers, for example, increasingly find the data provision option more attractive because all the expertise to deploy, operate and maintain the buoy need not be developed in-house. The buoy supplier’s world-class specialists take care of all these, and any risk such as data gaps or instrument malfunction is externalized to the buoy supplier in the form of steep fine for any interruption in the data streams.

FIGURE 4: TRIAXYS BUOY MAINTENANCE, SEP. '17

If multi-billion euros projects such as offshore wind farms find it better to outsource wave buoy operation to specialists, this new type of arrangement will be, *a fortiori*, an interesting option for WEC prototype testing. The experience in OPERA strongly suggests that this option should be considered in future projects. Wave buoys are complex instruments and their safe commissioning requires experience. For a one-off deployment such as for prototype testing, the supplier's technicians or other specialists must be contracted. This is a cost in addition to the buoy sticker price that must be budgeted for.

Deployment and maintenance are also challenging and costly. In OPERA, reporting on the experience gained is a useful contribution to the wave energy sector. But the learning curve is steep, as shown in WP6 deliverables, with costs and times reduced very significantly after first-time operations. For one-off prototype testing, gaining this type of experience may not be the most valuable use of team time and resources.

In summary, for a wave energy project team, which must focus its expertise on wave energy conversion rather than on wave data collection, subcontracting the reliable provision of wave data to a specialist may be a better option. Wave buoy suppliers have started offering this type of services in recent years. IEC-TS/62600-100, particularly sections 5 and 7, would provide good guidance on defining adequate contractual agreements with a wave data supplier. Section 2.1.1 of this report may also be of some use. This may not apply to port authorities or oceanographic institutes, that purchase many WMI and have dedicated specialist technicians.

### 2.2.2 OTHER EXPERIENCE

Other experience of potential interest to WEC developers planning open-sea testing is reported hereafter in no particular order.

- Use of ADCPs: Acoustic Doppler Current Profiler (ADCP) suppliers' brochures may claim useful measurements of surface waves can be obtained from as far as 100 m below the surface. Experienced oceanographers however inform that this type of instrument's wave data is only useful up to depth of some 30 m. Although ADCP are a very accurate way to obtain unbiased directional spectra for wave energy, deployment any deeper is not feasible. Adding a fixed structure or mid-water floats with taut moorings to place the ADCP at 30m depth would be too costly and their motion would probably be a source of uncertainty especially in large waves.
- Budgeting for wave buoys: while not immediately visible in brochures, suppliers may inform post-delivery that a buoy's mooring system requires inspection every 6 months and yearly maintenance for fouling. Another significant add-on cost to consider when evaluating the option of externalizing the wave data provision service.
- As for any marine equipment, various things can and do go wrong with wave buoys, and more so with non-specialists in charge. Coverage cannot be assumed to be 100%. While this is fine for many oceanographic applications, for a WEC testing campaign any gap in data is catastrophic, considering the cost of each day operating at sea. Contracting clauses with data provision services should include adequate financial incentives for the supplier to ensure as complete a coverage as possible.
- It is difficult to measure incoming waves at a shoreline plant like that at Mutriku. Surface equipment is not only impacted by plunging breakers but by the risk of tampering from amateur or professional fishers in the area. Bottom measurement, in addition to wave forces, must be secured for impact of rocks being sloshed around in winter storms. Reflected waves off a breakwater of this type will contaminate measurements more than 100 m offshore. More generally nearshore wavefield in complex topography show such a high variability at short spatial scales that it is difficult to characterize it with a single point measurement. Finally, there may be bias towards longer energy periods when using bottom-fixed pressure sensor (more details are available in OPERA deliverable D5.3).

## 2.3 LESSONS LEARNED ON WEC POWER OUTPUT MEASUREMENTS

TS100 section 8 specifies what is required from the WEC power output measurements. This section compares the requirements set out in TS100 with what was achieved in practice during the OPERA project deployments.

Section 2.3.1 compares the requirements of TS100 with what was achieved by IDOM during the OEPRA project deployments. Sections 2.3.1.1 and 2.3.1.2 briefly comment on the repeatability and uncertainty of the measurements and how the recorded data was processed. Sections 2.3.2 and 2.3.3 reflect on the IDOM’s experience of reconciling what TS100 requires and what was practical during the OPERA deployments.

### 2.3.1 RECORDINGS OBTAINED DURING REAL SEA OPERATION

Table 2 compares a number of TS100’s requirements on the measurement of WEC power output with the experiences of IDOM gained during the OPERA deployments.

**TABLE 2: COMPARISON OF TS100 REQUIREMENTS WITH WHAT WHICH WAS ACHIEVED DURING OPERA DEPLOYMENTS.**

| Requirements set out in TS100 | Experience during OPERA deployments |
|---|---|
| For an AC grid-connected WEC, output power should be measured at its output terminals - the point at which AC power is output at the network frequency | During the real sea deployment, power magnitudes were recorded both on the WEC terminals and in the onshore substation (on the LV side where the cable landed) |
| The minimum sample frequency shall be 2 Hz. | Power measurements on the buoy were recorded at a rate of 4 Hz. Onshore measurements were recorded at a rate of 1 Hz. |
| Power measurement should be based on measurements of current and voltage on a minimum of two phases. | Power production measurements were based on the measurements of the following parameters:<br>• Current for three phases and total current,<br>• Phase-to-phase and phase-to-neutral voltage - voltage was measured directly,<br>• Active, reactive and apparent power per phase and total active, reactive and apparent power and<br>• Power factor per phase and total power factor.<br>In addition to the aforementioned parameters, the following parameters were measured:<br>• Frequency,<br>• Voltage and current phase angles,<br>• Active energy (import, export, net energy and total energy in kWh),<br>• Reactive energy (import, export, net energy and total energy in kVArh) related to quadrants Q1…Q4 and<br>• Apparent energy (in KVAh). |

| Requirements set out in TS100 | Experience during OPERA deployments |
|---|---|
| The electrical sensors and power measurement sensors should be, at a minimum, class 0.5 (0.5 % ratio, primary to secondary current, error) and calibrated to traceable standards. They shall meet the following standards:<br>• Power transducers: IEC 60688;<br>• Current transformers: IEC 60044-1[1]; and<br>• Voltage transformers: IEC 61869-3. | Measurements were recorded using two power analysers, namely:<br>• Bender PEM-575 with 100/5 current transformers (in the buoy). The PEM-575 has an active energy metering accuracy of class 0.2 S in compliance with ICE 62053-22:2003 (Bender, 2016) and<br>• Schneider PM5560 with 150/5 transformers (in the onshore substation). The PM5560 has an active energy metering accuracy of class 0.2 S in compliance with IEC 62053-22:2003 (Schneider Electric, 2019).<br><br>Based on reviewing the sensor's documentation and the scopes of the relevant standards, it is not clear that the sensors satisfy the requirements set out in the respective standards (IEC 60688, IEC 60044-1 and IEC 61869-3). This is discussed further in the paragraph following this table. |
| The power measurement device should have a capacity so as to enable the measurement of:<br>• Export power: 1 % to 200 % of rated power and<br>• Import power: -1 % to -50% of rated power | The nominal capacity of the sensors current transformers was set at 100 A. Considering the WECs voltage of 690 V, this resulted in a sensor capacity of ≈ 120 kW, which exceeds the capacity requirement of 200 % of the device's rates power. The input power range is also within this threshold. |
| For low power ranges within which the measurement device doesn't allow for class 0.5 measurements, power measurements should be set to 0. | Power output recorded below 1% of the rated capacity was not set to zero, as this condition can later be traced and excluded, if relevant, from power production analysis. |

Table 2 indicates that IDOM satisfied TS100's requirements in the majority of cases. Exceptions to this appear to be in the rate of measurement onshore (see section 2.3.3), power measurement sensor standards and in power measurement sensor calibration. The rate of power measurements on the buoy exceeded the requirements set out in TS100, therefore the

[1] BS EN 60044-1 has been withdrawn and superseded by BS EN 61869-2 and BS EN 61869-5.

issue of a slow rate of power measurement onshore is disregarded. It is assumed that the sensors were calibrated and not commented on, so this difference is disregarded. The power measurement sensor standards listed in the table are briefly described in the following paragraphs.

IEC 62053-22:2003 (Identical to BS EN 62053-22:2003+A1:2017 which was available) - Electrical metering equipment (a.c.) - Particular requirements, Part 22: Static meters for active energy (classes 0.2 S and 0.5 S) - “This part is a standard is for type testing electricity meters. It covers the particular requirements for meters, being used indoors. It does not deal with special implementations (such as metering-part and/or displays in separate housings,” [3]. IEC 62053-22:2003 sets out sensor mechanical requirements, climate conditions, electrical requirements and accuracy requirements.

IEC 60688 (Identical to BS EN 60688:2013 which was available) - Electrical measuring transducers for converting A.C. and D.C. electrical quantities to analogue or digital signals - “This International Standard is intended:

- To specify the terminology and definitions relating to transducers whose main application is in industry;
- To unify the test methods used in evaluating transducer performance;
- To specify accuracy limits and output values for transducers,” [4].

For power measurement sensors, IEC 60688 outlines factors such as class index, permissible limits of intrinsic error, auxiliary supply and reference conditions; requirements for inputs, outputs and accuracy; and establishes tests.

IEC 60044-1 - Instrument transformers - Part 1: Current transformers – Of relevance to this topic, this standard outlines requirements and tests... “necessary for current transformers for use with electrical measuring instruments,” [5]. For current transformers, IEC 60044-1 defines normal service conditions, current ratings, design requirements, required tests, required markings and additional requirements for different categories of current sensor.

IEC 61869-3 (Identical to BS EN 61869-3:2011 which was available) - Instrument transformers, Part 3: Additional requirements for inductive voltage transformers - “All transformers shall be suitable for measuring purposes, but, in addition, certain types may be suitable for protection purposes. Transformers for the dual purpose of measurement and protection shall comply with all the clauses of this standard,” [6]. For voltage transformers, IEC 61869-3 defines output, accuracy class, voltage ratings; design and construction requirements; and tests.

At a high level, these standards appear similar in terms of their content. A more detailed study and a comparison of applications is required to determine how they differ from one another. However, it is worth noting that the sensor manufacturers, both of whom are well established, have chosen IEC 62053-22:2003 as the standard against which to compare their meters. It could be concluded that this is a more established standard for power meters. It is not clear how the committee developing TS100 chose the standards for the different meters. However, it could also suggest that alternative meters should have been considered for use during the OPERA deployments.

It is recommended that WEC developers should use sensors that adhere to the standards that are most commonly used by sensor manufactures and the more mature marine industries. Further to this, it is recommended that at this stage of the industry's development that developers using TS100 should record the standards which their sensors adhere to and justify that instead of TS100 specifying standards.

In addition to the requirements listed in Table 2, TS100 also states that the following steps should be followed in the process of recording WEC power output:

- Measured power must be net power, including reductions due to the energising of power and ancillary systems.
- An assessment should be made of how the grid impacts on power output measurements. This is discussed to an extent in section 2.3.3. Periods during which the grid connection inhibits power output should be recorded and an external dump load should be considered.

Note, this additional list does not suggest that this information was not captured, but it was not commented on by IDOM in their reporting of their experience of undertaking power measurements.

#### 2.3.1.1 REPEATABILITY AND UNCERTAINTY OF MEASUREMENTS

No specific analysis of the repeatability of sensor measurements has been performed thus far. As is shown in section 2.4, numerous repeat measurements were recorded for similar sea states. However, section 2.4 also shows that there are large levels of variance in the measurements recorded due to sea state conditions never being exactly the same. This makes measurements of repeatability challenging. Repeatability of meter readings was most likely tested during calibration.

Uncertainty is reduced through evaluating repeat measurements and through knowledge of sensor characteristics. The following list outlines factors affecting the accuracy, and therefore a component of uncertainty, with which key parameters were measured:

- Phase voltage UL1-N, UL2-N, UL3-N ± 0.2 % of measured value.
- Current ± 0.2 % of measured value + 0.05 % of full-scale value.
- Neutral current I4 0.5 % of full-scale value.

- Frequency ± 0.01 Hz.
- Phase position ± 1 °.
- Active energy measurement according to IEC 62053-22.
- r.m.s. voltage measurement according to IEC 61557-12:2007 (Identical to BS EN 61557-12:2008 which was available), chapter 4.7.6 [7].
- r.m.s. phase current measurement according to DIN 61557-12, chapter 4.7.5.
- Frequency measurement according to DIN EN 61557-12, chapter 4.7.4.

Based on these figures, the order of measurement uncertainty of standard electrical magnitudes is at least an order of magnitude smaller than that of the WEC's primary energy captured.

#### 2.3.1.2 OUTLINE OF HOW RECORDED DATA AS PROCESSED

Recorded data was stored in cloud-based MYSQL databases, along with the other WEC data (environmental, device dynamics and operation conditions…). Direct analysis of power performance was achieved through two complementary approaches:

- Correlation of experimental data versus existing numerical models. Existing numerical models of primary capture, conversion from pneumatic to electric and power export were correlated piece-wise with experimental dataset.
- Analysis of experimental data, aiming to provide insights about trends and behaviour of the device and its measurements; measurement dispersion/uncertainty analysis

### 2.3.2 PRACTICALITIES OF RECORDING MEASUREMENTS AND DEVIATIONS FROM TS100

The challenge of measuring power output was overcome without the need for complex/expensive equipment, because a standard 690 Vac line voltage was used for the power export cable. This eliminated the need for voltage transformers, reducing measurement error. Further to this, the equipment used for the power measurement was commercially available off the shelf and operators did not require special training to use it.

Communication with the power measurement systems was independent of the plant controller system and thus does not depend on its operational state. High frequency sampling capability for waveform analysis (12.8 kHz) has not been utilised thus far. So far analysis has focused on averaged magnitudes, min/max values, standard deviations, total harmonic distortion etc.

The use of Modbus/TCP and fibre-optic communication directly with the power monitoring system allowed a sufficient 4 Hz rate to be implemented. However, it should be noted, a foreseeable effect of the power export cable on the electrical magnitudes was observed.

### 2.3.3 ADDITIONAL COMMENTS ON DEVELOPER EXPERIENCE

IDOM have highlighted the following from their application of TS100:

- It is important to note that the onshore system was designed and built without Oceantec/IDOM's participation, and thus the specific needs for wave energy were not taken into consideration. Limitations on the sampling frequency of the onshore power sensor may limit wave-to-wave power assessment - 1Hz rate may not be sufficient to analyse some features.
- It is also noteworthy to take into consideration the reactive power strategy that a WEC must adopt in order to deliver acceptable power quality to the electrical grid. When connected to a strong electrical grid, the voltage level can vary significantly on buoy terminal. This effect could be cancelled out, at least to some extent, by reactive power management on the regenerative drive. This could mean, for example, that the buoy may deliver a 0.98 power factor when producing 10 kW output power but may need to use a 0.95 power factor when producing 25kW. The absolute values may vary from site to site and have strong dependence not only in the electrical grid values, but also in the subsea cable and power export configuration used.

## 2.4 CHALLENGES ASSOCIATED WITH THE CHARACTERISATION OF RESOURCE AND POWER PERFORMANCE VARIABILITY

TS100 indicates that the primary metrics used to characterise sea states are Energy Period ($T_e$) and Significant Wave Height ($H_{m0}$). Recordings obtained in sea states which have $T_e$ and $H_{m0}$ values that lie within set ranges are 'binned' together and considered to have the same sea state inputs. The bins used have $T_e$ spans of 1 s and $H_{m0}$ spans of 0.5 m. This discretisation is due to the importance of $T_e$ and $H_{m0}$ in the wave energy flux, J calculation, equation (1).

$$J = \frac{\rho g^2}{64\pi} {H_{m0}}^2 T_e \quad (1)$$

$\rho$ in equation (1) is water density and g is acceleration due to gravity. See J is proportional to $T_e$ and $H_{m0}^2$.

Figure 5 is an occurrence matrix indicating the number of sea states, for specified $T_e$ and $H_{m0}$ ranges, that were observed to occur when IDOM's MARMOK-A-5 [8] Wave Energy Converter (WEC) was operational at BiMEP when operating under Control Algorithm 1 (CA 1). Figure 6 indicates normalised Capture Length (CL, ratio of absorbed wave power to wave resource [9]) coefficient of variation (a relative measure of the standard deviation and calculated as the standard deviation as a percentage of the mean) calculated for each of the sea state bins. Figure 6 highlights the variation in CL that can be calculated for apparently similar $T_e$ and $H_{m0}$ inputs.

| $H_{m0}$ (m) \ $T_e$ (s) | 0.5 | 1.5 | 2.5 | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.25 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 1 | 0 | 1 | 4 | 2 | 0 | 1 | 0 |
| 1.75 | 0 | 0 | 0 | 0 | 0 | 11 | 10 | 7 | 3 | 19 | 14 | 6 | 3 | 3 | 3 |
| 1.25 | 0 | 0 | 0 | 0 | 3 | 59 | 104 | 81 | 68 | 51 | 18 | 6 | 0 | 2 | 0 |
| 0.75 | 0 | 0 | 0 | 0 | 0 | 42 | 103 | 174 | 114 | 49 | 30 | 2 | 0 | 0 | 0 |
| 0.25 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**FIGURE 5: WEC (CA 1) NUMBER OF RECORDINGS.**

| $H_{m0}$ (m) \ $T_e$ (s) | 0.5 | 1.5 | 2.5 | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.75 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 3.25 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 2.75 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 2.25 | 0% | 0% | 0% | 0% | 0% | 20% | 0% | 0% | 0% | 0% | 11% | 6% | 0% | 0% | 0% |
| 1.75 | 0% | 0% | 0% | 0% | 0% | 46% | 20% | 13% | 15% | 19% | 20% | 25% | 8% | 7% | 9% |
| 1.25 | 0% | 0% | 0% | 0% | 83% | 63% | 46% | 40% | 37% | 51% | 52% | 88% | 0% | 4% | 0% |
| 0.75 | 0% | 0% | 0% | 0% | 0% | 71% | 41% | 40% | 43% | 44% | 37% | 49% | 0% | 0% | 0% |
| 0.25 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 48% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

**FIGURE 6: WEC (CA 1) COEFFICIENT OF VARIATION FOR EACH SEA STATE BIN.**

This indicates that either the $T_e$ and $H_{m0}$ ranges are too large or that additional sea state characteristics exist that aren't described by $T_e$ and $H_{m0}$. TS100 suggests additional parameters, such as spectral bandwidth and wave direction, that might be used to reduce variability in power performance assessment matrices (scatter diagrams and CL bins). The suitability of the metrics chosen to better characterise sea states will depend on the WEC and its operating principle. As the MARMOK-A-5 device is an axisymmetric spar buoy heaving point-absorber WEC, the *higher dimension* considered to reduce variability in OPERA is spectral bandwidth.

An extension of the analysis presented in this section features in OPERA D5.3 in the application and evaluation of IEC TS 62600-102 [10] (TS 102).

Four bandwidth parameters were investigated to determine if any correlation existed between them and the variability in power performance observed in the sea state bins. The bandwidth parameters are shown in equations (2a) to (2d).

$$\varepsilon_0 = \sqrt{\frac{m_0 m_{-2}}{{m_{-1}}^2} - 1} \tag{2a}$$

$$\varepsilon_1 = \sqrt{\frac{m_1 m_{-1}}{m_0^2} - 1} \tag{2b}$$

$$\varepsilon_2 = \sqrt{\frac{m_0 m_2}{m_1^2} - 1} \tag{2c}$$

$$\varepsilon_4 = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \tag{2d}$$

$m_n$ in equations (2a) to (2d) is the $n^{th}$ mode of the recorded sea states energy spectra.

The bandwidth parameters tested are as follows:

- Broadness parameter ($\varepsilon_0$) [11],
- Bandwidth parameter ($\varepsilon_1$) [12],
- Narrowness parameter ($\varepsilon_2$) [13] and
- Broadness factor ($\varepsilon_4$) [14]

The references listed alongside the parameters are believed to be the originators of the parameters. A number of studies and reports have compiled and reviewed these parameters and their effects on WEC performance, of particular note is [15].

Figure 7 is a plot of normalised CL against bandwidth for each of the recorded sea states that fell within the most populated bin of the WEC's power matrix when it was operating under CA1 at BiMEP; $H_{m0}$ ranging from 0.5 m to 1.0 m and $T_e$ ranging from 7 s to 8 s, see Figure 5. In total, 174 sea states that were recorded for the most populated bin. The coefficient of variation of normalised CL for the most populated bin is 40%, see Figure 6. Each of the bandwidth parameters considered are presented by different colours and shapes and their respective coefficients of variation are presented in the legend. Based on Figure 7, little clear relationship exists between normalised CL and bandwidth for the bandwidth parameters tested.

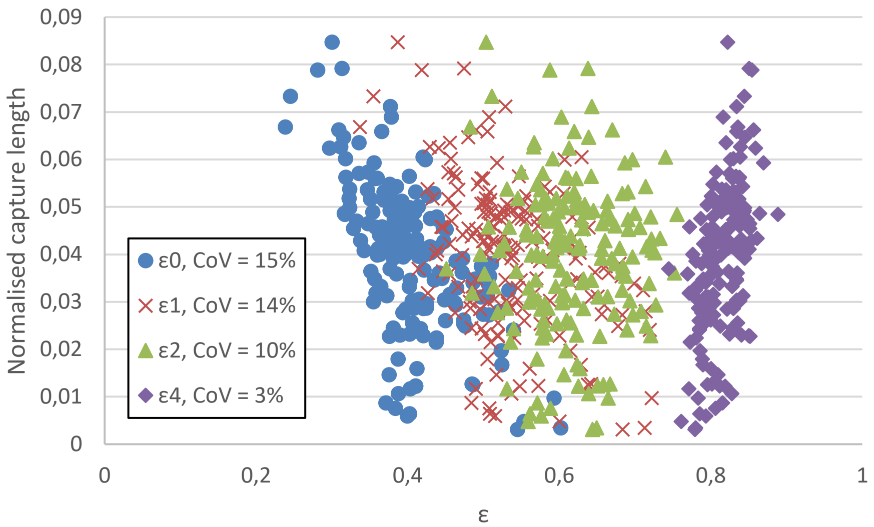


**FIGURE 7: NORMALISED CAPTURE LENGTH PLOTTED AGAINST EACH OF THE BANDWIDTH PARAMETER TESTED FOR FIXED HM0 (0.5 M TO 1.0 M) AND TE (7 S TO 8 S)**

However, of the bandwidth parameters tested, it is recommended that further investigation should be carried out determine what relationship exists between CL and the broadness parameter, $\varepsilon_0$. It varied the most out of the parameters tested and has the benefit of being calculated with lower order moments [16].

Figure 8 plots normalised CL against $\varepsilon_0$. The data is discretised by wave steepness, different marker colours and shapes. Wave steepness $(H_{m0}/\lambda(T_e))$ is a nondimensional parameter which is a function of both $H_{m0}$ and $T_e$ . Presenting it on Figure 8 enables a review of whether the variability of normalised CL within the bin is a result of higher resolution changes in $H_{m0}$ and $T_e$, i.e. greater resolution than the standard 0.5 m discretisation of $H_{m0}$ and 1 s discretisation of $T_e$. Figure 8 indicates that variability in normalised CL is not clearly related to higher resolution steps in $H_{m0}$ and $T_e$, i.e. it is not clear that the variability in normalised CL is related to changes wave steepness.

As a high level investigation into the relationship between normalised CL and $\varepsilon_0$, linear trend lines are presented on Figure 8 along with their equations and respective coefficients of determination. Five trend lines are presented, corresponding to the five wave steepnesses. A linear trend line was produced for the bin's full dataset which had a coefficient of determination ($R^2$) of 0.376. A perfect fit would have a coefficient of determination of 1. The coefficient of determination was only improved by 3% when increasing the complexity of the trendline to a second order polynomial.

o

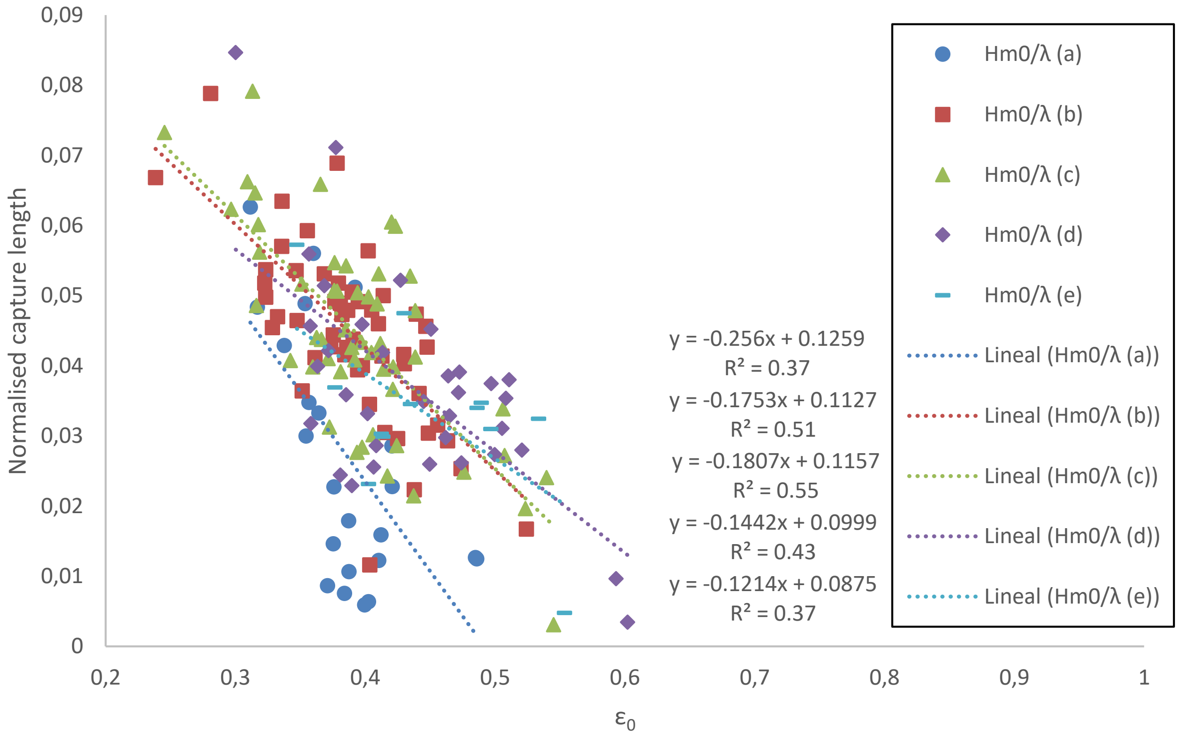


**FIGURE 8: NORMALISED CAPTURE LENGTH PLOTTED AGAINST E$_0$ FOR FIXED HM0 (0.5 M TO 1.0 M) AND TE (7 S TO 8 S)**

Although each of the trend lines for each of the steepness bins have low coefficients of determination (less than 0.55), the equations suggest that CL reduces with increasing $\varepsilon_0$.

Figure 9 depicts how the dimensionality of any of the matrices presented thus far can be increased; in this case the dimensionality of a mean normalised CL matrix. Each of the 'sheets' in Figure 9, along the $\varepsilon_x$ axis, present mean normalised CL matrices, discretised by $H_{m0}$ and $T_e$, for a range of bandwidth values. To observe how considering the additional bandwidth parameters impacts calculated Mean Annual Energy Production (MAEP) required the generation of similar higher dimension normalised CL and scatter diagrams.

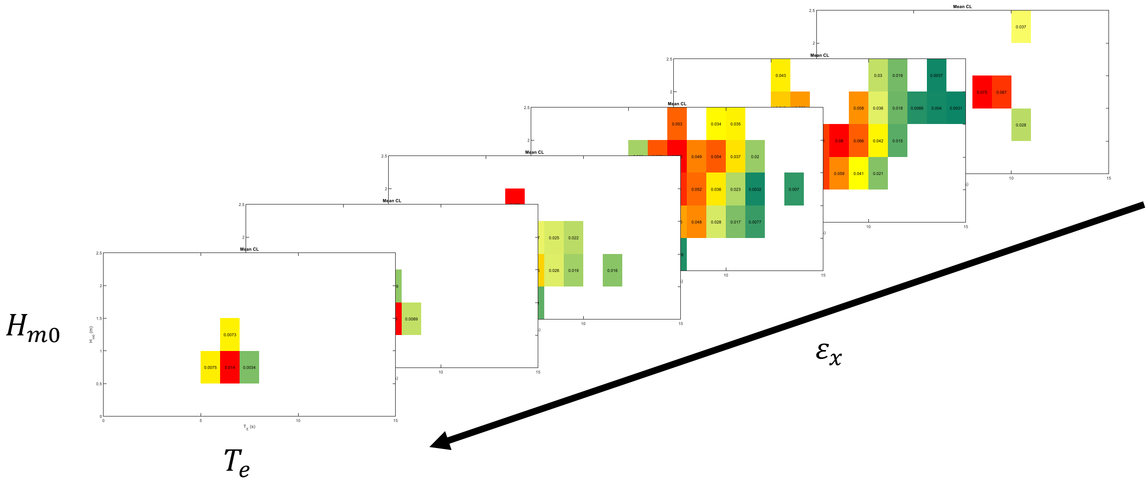


**FIGURE 9: DIAGRAM OF INCREASING DIMENSIONALITY OF CAPTURE LENGTH MATRIX**

Figure 10 shows the average normalised power performance contained in each bandwidth ranges, in the form of the percentage of overall power, for each of the bandwidth parameters tested. It also presents the number of sea states represented in each bandwidth range. Note, the results presented in Figure 10 are for the most populated bin of the matrix representing the WEC operating at BiMEP under CA1.

Figure 11 indicates the bandwidth ranges within which the all the sea states were recorded, for each of the bandwidth parameters tested.

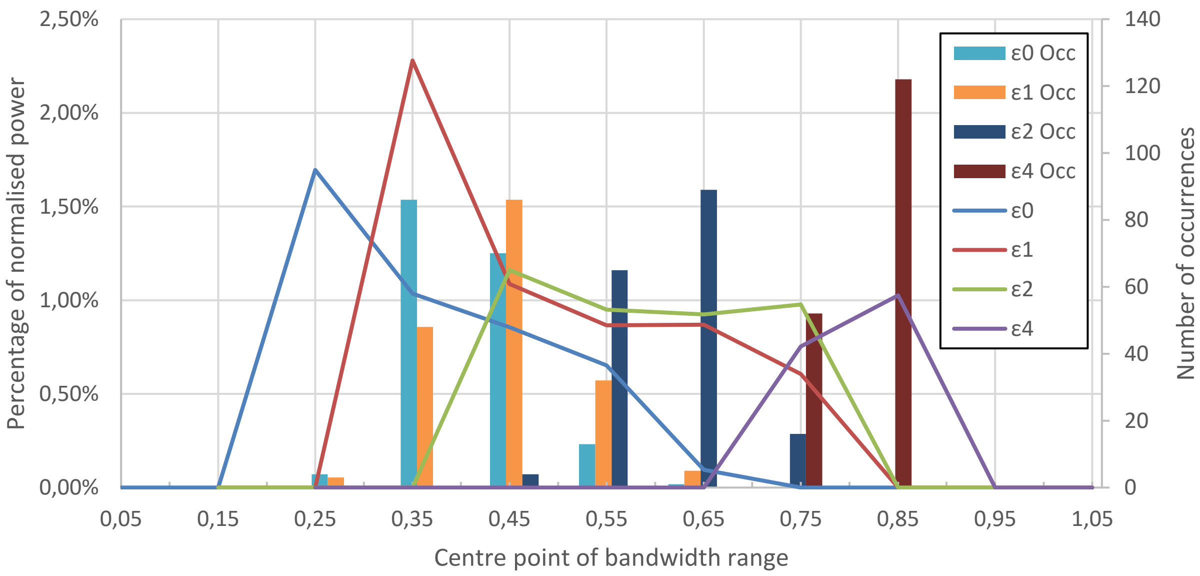


**FIGURE 10: PERCENTAGE OF NORMALISED POWER WITHIN THE BANDWIDTH RANGES FOR FIXED HM0 (0.5 M TO 1.0 M) AND TE (7 S TO 8 S) AND NUMBER OF SEA STATES REPRESENTED IN EACH BANDWIDTH RANGE**

| ε range | $\varepsilon_0$ | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_4$ |
|---|---|---|---|---|
| 0.0 - 0.1 | 0% | 0% | 0% | 0% |
| 0.1 - 0.2 | 1% | 0% | 0% | 0% |
| 0.2 - 0.3 | 25% | 2% | 0% | 0% |
| 0.3 - 0.4 | 47% | 21% | 2% | 0% |
| 0.4 - 0.5 | 23% | 44% | 26% | 0% |
| 0.5 - 0.6 | 4% | 23% | 33% | 0% |
| 0.6 - 0.7 | 0% | 9% | 28% | 1% |
| 0.7 - 0.8 | 0% | 1% | 9% | 35% |
| 0.8 - 0.9 | 0% | 0% | 3% | 58% |
| 0.9 - 1.0 | 0% | 0% | 0% | 7% |
| 1.0 - 1.1 | 0% | 0% | 0% | 0% |

**FIGURE 11: PERCENTAGE OF ALL SEA STATES RECORDED WITHIN PRESENTED BANDWIDTHS**

Figure 12 and Figure 13 present the percentage of overall energy content contained in each of the bandwidth bins, for each of the bandwidth parameters tested and both the control algorithms.

Figure 12 and Figure 13 indicate that, as the bandwidth parameters progress from $\varepsilon_0$ to $\varepsilon_4$, which roughly equates to using increasingly higher order moments to calculate the bandwidth parameters, the greater the bandwidth range containing the majority of sea states.

| | Pct of conventional MAEP | ε range 0.0 - 0.1 | 0.1 - 0.2 | 0.2 - 0.3 | 0.3 - 0.4 | 0.4 - 0.5 | 0.5 - 0.6 | 0.6 - 0.7 | 0.7 - 0.8 | 0.8 - 0.9 | 0.9 - 1.0 | 1.0 - 1.1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\varepsilon_0$ | 100% | 0% | 1% | 27% | 55% | 15% | 2% | 0% | 0% | 0% | 0% | 0% |
| $\varepsilon_1$ | 100% | 0% | 0% | 5% | 24% | 46% | 20% | 5% | 0% | 0% | 0% | 0% |
| $\varepsilon_2$ | 100% | 0% | 0% | 0% | 2% | 29% | 35% | 27% | 6% | 1% | 0% | 0% |
| $\varepsilon_4$ | 100% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 32% | 66% | 1% | 0% |

**FIGURE 12: BIMEP - CA1 – ANNUAL ENERGY CONTENT OF DIFFERENT BANDWIDTH RANGES AND COMPARISON OF MAEP CALCULATED WHEN CONSIDERING BANDWITH WITH CONVENTIONAL MAEP METHOD**

| ε range | | 0.0 - 0.1 | 0.1 - 0.2 | 0.2 - 0.3 | 0.3 - 0.4 | 0.4 - 0.5 | 0.5 - 0.6 | 0.6 - 0.7 | 0.7 - 0.8 | 0.8 - 0.9 | 0.9 - 1.0 | 1.0 - 1.1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\varepsilon_0$ | 100 % | 0% | 0% | 50% | 42% | 8% | 0% | 0% | 0% | 0% | 0% | 0% |
| $\varepsilon_1$ | 100 % | 0% | 0% | 1% | 41% | 50% | 7% | 1% | 0% | 0% | 0% | 0% |
| $\varepsilon_2$ | 100 % | 0% | 0% | 0% | 0% | 32% | 41% | 22% | 3% | 1% | 0% | 0% |
| $\varepsilon_4$ | 100 % | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 18% | 79% | 4% | 0% |

**FIGURE 13: BIMEP - CA2 – ANNUAL ENERGY CONTENT OF DIFFERENT BANDWIDTH RANGES AND COMPARISON OF MAEP CALCULATED WHEN CONSIDERING BANDWITH WITH CONVENTIONAL MAEP METHOD**

In general, the $\varepsilon_4$ parameter appears to compress the sea states to within a smaller range of bandwidths than the other parameters. This is also seen in Figure 7 and Figure 10.

## 2.5 RECOMMENDATIONS TO THE TC114 MAINTENANCE GROUP FOR TS100

Section 2.2 highlighted that the sensors used (developed by established sensor developers) adhered to different standards from those recommended in TS100. It is recommended that instead of specifying standards, TS100 should recommend that developers indicate the standards to which their sensors adhere to and justify the selection.

Section 2.3 also highlighted the limited control that an early stage developer might have on onshore infrastructure (the infrastructure used might be pre-existing). There may be limitations to what the developer can do to the landing point of the cable i.e. in the installation of dump load.

Section 2.4 highlighted the further work that needs to be done to identify the additional sea state characteristics that impact the performance of WECs. However, as these characteristics are WEC specific, this work should be led by developers and they should feedback to TC114.

# 3. IEC TS62600-30 ELECTRICAL POWER QUALITY REQUIREMENTS FOR WAVE, TIDAL AND OTHER WATER CURRENT ENEGY CONVERTERS

The International technical specification IEC 62600-30 focuses on power quality issues and parameters for single-phase and three-phase, grid-connected and off-grid marine energy converters (MEC), including wave, tidal, and other water current converter-based power systems. Poor electrical power quality negatively affects both power sources and loads, so this technical specification has been produced to establish measurement methods, application techniques, and result-interpretation guidelines to account for the electrical performance of MECs.

The measurement procedures specified in the IEC 62600-30 are valid for a single MEC unit with a three-phase grid or an off-grid connection. They are valid for any size of MEC, with varying specifications depending on the type of voltage connection, with three classes of connection, Low Voltage (LV), Medium Voltage (MV), and High Voltage (HV). The measurement procedures are designed for be as non-site-specific as possible.

In this section, the IEC 62600-30 guideline for measuring harmonic distortion and voltage variation are applied to the wave energy converter (WEC) of the Mutriku Wave Power Plant. For analytical purposes, the IEC 62600-30 breaks marine renewable energy resources into three classifications: Low, Medium, and High. For WECs, the resources can be classified through the sea summary statistics using either significant wave height ($H_s$) or energy period ($T_e$). The discretion is up to the developer, as is the parsing of the resource classification, though they should be based made site specific. The resource classifications presented here were based on $H_s$. Low energy seas are $H_s < 1.25$ m; medium energy seas are 1.25 m ≤ $H_s$ 2.5 m; high energy seas are $H_s \geq 2.5$ m. The IEC 62600-30 requires that at least 5 datasets under each resource classification are analysed. In this deliverable, 8 datasets for each resource classification were collected and analysed. Identifies the values of $H_s$ and $T_e$ for the 24 datasets and groups them by classification.

**TABLE 3: THE RESOURCE CLASSIFICATION OF THE 24 DATASETS PRESENTED IN SECTION 0.**

| Class | $H_s$ (m) | $T_e$ (s) | Class | $H_s$ (m) | $T_e$ (s) | Class | $H_s$ (m) | $T_e$ (s) |
|---|---|---|---|---|---|---|---|---|
| Low | 0.50 | 17.80 | Medium | 1.33 | 12.53 | High | 2.62 | 14.31 |
| | 0.54 | 8.06 | | 1.39 | 16.43 | | 2.64 | 13.65 |
| | 0.69 | 10.81 | | 1.58 | 15.51 | | 2.66 | 13.28 |
| | 0.74 | 9.98 | | 1.86 | 13.61 | | 2.74 | 15.54 |
| | 0.90 | 13.03 | | 1.93 | 15.05 | | 3.22 | 16.19 |
| | 0.94 | 13.34 | | 2.11 | 12.89 | | 3.35 | 15.65 |
| | 1.00 | 11.55 | | 2.23 | 14.33 | | 3.69 | 15.68 |
| | 1.09 | 10.12 | | 2.41 | 13.85 | | 4.14 | 16.81 |

## 3.1 OVERVIEW OF TS30 METHODOLOGY AND APPLICATION AT MUTRIKU PLANT

The international technical specification IEC 62600-30 (TS30) focuses on power quality issues and parameters for single-phase and three-phase, grid-connected and off-grid MECs. Poor electrical power quality negatively affects both power sources and loads, so this technical specification was produced to establish measurement methods, application techniques, and result-interpretation guidelines to account for the electrical performance of MECs.

The measurement procedures specified in TS30 are valid for a single MEC unit with a three-phase grid or an off-grid connection. They are designed to be as non-site-specific as possible. For analytical purposes, the TS30 divides marine renewable energy resources into three classifications: Low, Medium, and High. For WECs, the resources can be classified through the sea summary statistics using either significant wave height ($H_s$) or energy period ($T_e$). The decision of which statistic to use is made by the developer, as is the parsing of the resource classification, though the classifications should be based annual conditions of the deployment site. The procedures are valid for any size of MEC, with varying specifications depending on the type of voltage connection, which include three classes of connection, Low Voltage (LV), Medium Voltage (MV), and High Voltage (HV).

For this project, the TS30 specifications were applied to the Mutriku Wave Power Plant (MWPP). The MWPP is a fixed-type Oscillating Water Column (OWC) Wave Energy Converter (WEC) array. The OWC array consists of 16 chambers built into the breakwater protecting the harbour in Mutriku, Spain, which is located in the Basque Country along the Bay of Bisque. Each of the 16 OWC chambers has a two-stage Wells turbine and an 18 kW electrical generator that act as the Power Take-Off (PTO) system. The power generated by the wave energy plant is supplied to the local grid and accounts for approximately 400 MWh (confirm from source) of carbon free electricity annually [17].

Each OWC generator is controlled by an individual Variable Frequency Drive (VFD), which allows the turbines to operate efficiently over a wide range of sea state conditions. The VFDs feed into a DC-Bus, which is one of two within the plant. A single DC-bus accounts for 8 generators, and each DC-Bus supplies the grid though a 158 kW DC-AC converter that uses a variable frequency drive (VFD) to sync the AC out frequency with the local grid. The voltage and current outputs of a single DC-AC converter were monitored for the application of the IEC 62600-30 Standard.

### 3.1.1 MUTRIKU PLANT SCADA SYSTEM

The SCADA system used to apply the TS30 to the Mutriku plant was connected between one of the 158 kW converters used to supply the grid. Measurements were taken from between the DC-AC converter and the RFI filter that separated the grid from the converter. Voltage and current transducers installed within the plant's electrical system transformed the voltages and currents into signals that voltages that could be monitored by the SCADA system.

The main processing unit of the SCADA was a National Instruments (NI) cRIO-9082 operating NI Labview software. The cRIO-9082 is an 8-slot cRIO with a 1.33 GHz dual-core CPU, 2 GB of DRAM, 32 GB of ROM, and a Xilinx Spartan-6 LX150 FPGA. The cRIO was populated with NI-9239 analogue input modules with a voltage measuring range of -10 to 10 Volts. The NI-9239 has a sampling rate up to 50 kHz.

These specifications were vital for applying the TS30 Standards. To perform the harmonic and flicker analysis presented in this report, the TS30 required a 10-minute continuous dataset sampled at 20 kHz. The Xilinx Spartan-6 LX150 FPGA along with the NI-9239 analogue import cards allowed for high frequency sampling, but the sampling frequency was limited to 15 kHz, which is below the 20 kHz stipulated in the TS30. The limitation was because card was responsible for monitoring 3 signals, and number of signals handled by a single card effected the sampling rate. For 3 signals, the maximum sampling rate was 16.67 kHz. The high frequency harmonic analysis was limited to 7.5 kHz, rather than the 10 kHz because of the lower sampling frequency applied to the dataset. The sampling frequency and the 10-minute duration required of continuous required over 1 GB of memory per dataset. During deployment of the SCADA system, the 32 GB ROM had to be routinely cleared with each dataset being moved to the cloud-based data storage system developed in WP1.

As the NI-9239 analogue input cards had a voltage range of +/- 10 V, voltage and current transducers were installed as part of the SCADA system to convert the voltages and currents to signals that could be monitored by the analogue input cards. The same company, LEM, supplied the transducers for the voltage and current measurement to insure continuity in the datasets. The voltage transducers were LEM DVL 750, which provide bipolar and insulated measurement up to 1125 V. The output of the transducers is a milliamp current with a set mA/V ratio to represent the measured voltage. The current transducers were LEM LA 305-S, what are Hall Effect closed loop transducers, with a maximum range of +/- 500A. The output of the transducers is a milliamp current with a set mA/A ratio to represent the measured current. To produce signals that can be perceived by the cRIO, high tolerance resisters were placed in series with the current outputs of the transducers as specified by the LEM provided technical data sheets for both transducers. Figure 14 shows the voltages and current transducers installed at the Mutriku Wave Power Plant, at the time of the photos, the voltage signals had not yet been wired to the voltage transducers.

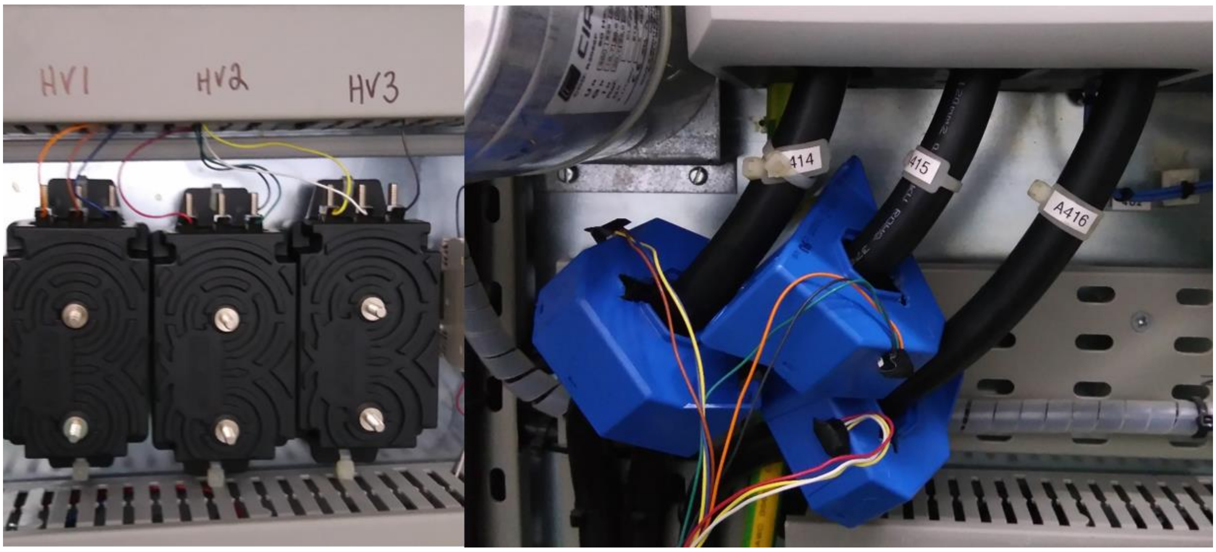


**FIGURE 14: VOLTAGE TRANSDUCERS (LEFT) AND CURRENT TRANSDUCERS (RIGHT) INSTALLED AT THE MUTRIKU WAVE POWER PLANT.**

The voltage and current transducers were retrofitted into the already operational MWPP, and there were difficulties with the physical placement of the current transducers due to space and wiring requirements. Ideally, the voltage and current measurements for the application of IEC 62600-30 should be taken after the RFI filter that is used to remove the high frequency signal generated by the VFD used in renewable energy generation systems. Unfortunately, the space and wiring requirements for the installation of the transducers between the RFI filter and the grid-side VFD. Figure 15 is a single-line diagram for an individual DC-Bus of the plant, which shows the ideal placement of the voltage and current transducers in green and the actual placement of the voltage and current transducers in red.

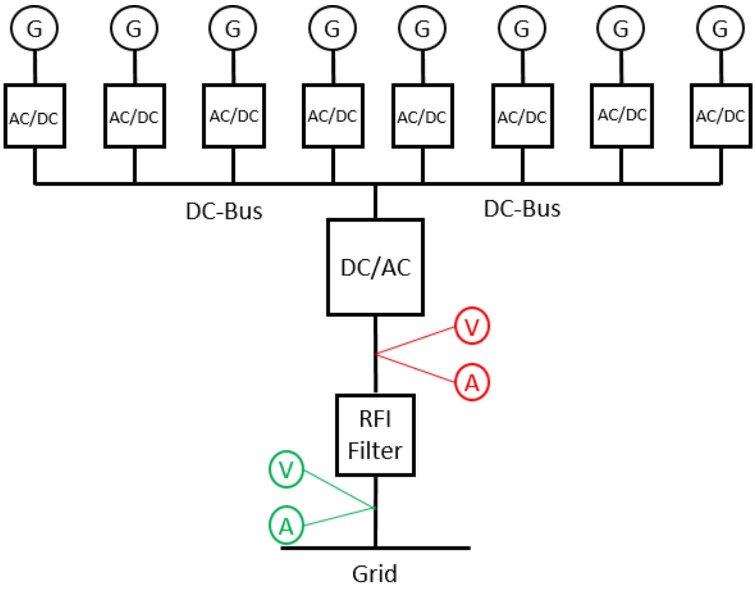


**FIGURE 15: MUTRIKU WAVE POWER PLANT SINGLE LINE DRAWING SHOWING HOW 8 GENERATORS ARE CONNECTED TO THE GRID VIA A SINGLE DC-BUS**

### 3.1.2 IMPACT OF TRANSDUCER PLACEMENT ON DATA MEASUREMENT

The forced placement of the transducers for data collection negatively affected the implementation of the TS30 standards. With the current and voltage transducers placed between the VFD and the RFI filter rather than on the grid side of the filter, the datasets were excessively influenced by the pulse-width modulation (PWM) switching of the VFD.

The principal issue manifested within the voltage signals. RFI filters for use in renewable energy systems are specifically designed to attenuate high frequency noise in voltage signals caused by the PWM switching VFDs use to generate a 50 Hz AC signal from a DC Bus. Figure 16 shows the voltage measurements taken from the MWPP SCADA system. For comparison, Figure 16 includes voltage measurements from the WEC emulator from the electrical laboratory at the Lir National Ocean Test Facility (NOTF) of University College Cork, where transducers were installed on the grid side of the RFI filter rather than the VFD side of the filter. The SCADA system at the Lir NOTF used the same NI and LEM equipment as was installed at the MWPP, however the voltage and current outputs of the laboratory equipment was lower than the MWPP. The laboratory measurements were taken as part of OPERA Task 5.5 and presented in Deliverable D5.4; for more details please refer to Deliverable D5.4.

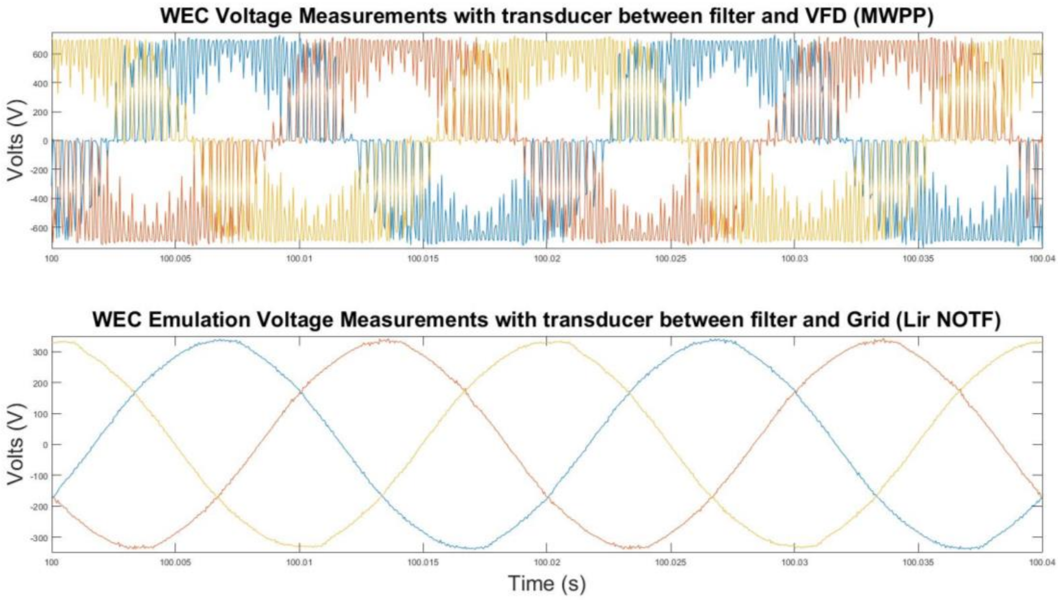


**FIGURE 16: VOLTAGE MEASUREMENTS FROM THE MWPP AND THE LIR NOTF ELECTRICAL LABORATORY THAT SHOW THE IMPACT OF TRANSDUCER PLACEMENT ON THE DATA.**

By comparing the voltage signals, the effect of the voltage transducer placement is glaringly obvious. The average value of the waveform in the upper plot of Figure 16 illustrates the 50 Hz sine wave, but the measured values are indicative of the PWM generated 3 kHz square wave. In contrast, the dry laboratory dataset lower plot of Figure 16 clearly shows the 50 Hz sine waveform, with very little to indicate the underlying 3 kHz PWM generated square waveform. This difference between the recorded waveforms are directly related to the placement of the voltage transducer in relation to the RFI filter, and have significant impact on the flicker identified for each dataset.

While the RFI filters are excellent at attenuating the high frequencies components in the voltage signals, they are less effective at attenuating the same high frequencies components in current signals, so the impact of the transducer placement was not as sever for current harmonic analysis. Figure 17 shows the current measurements taken from the MWPP SCADA system. For comparison, includes current measurements from the WEC emulator from the electrical laboratory at the Lir NOTF. While there is some difference between the two signals, it is much subtler than those seen in the measured voltage signals. The MWPP dataset has as more prevalent 3 kHz signal, but the 3 kHz signal is also prevalent in the Lir NOTF electrical laboratory generated dataset.

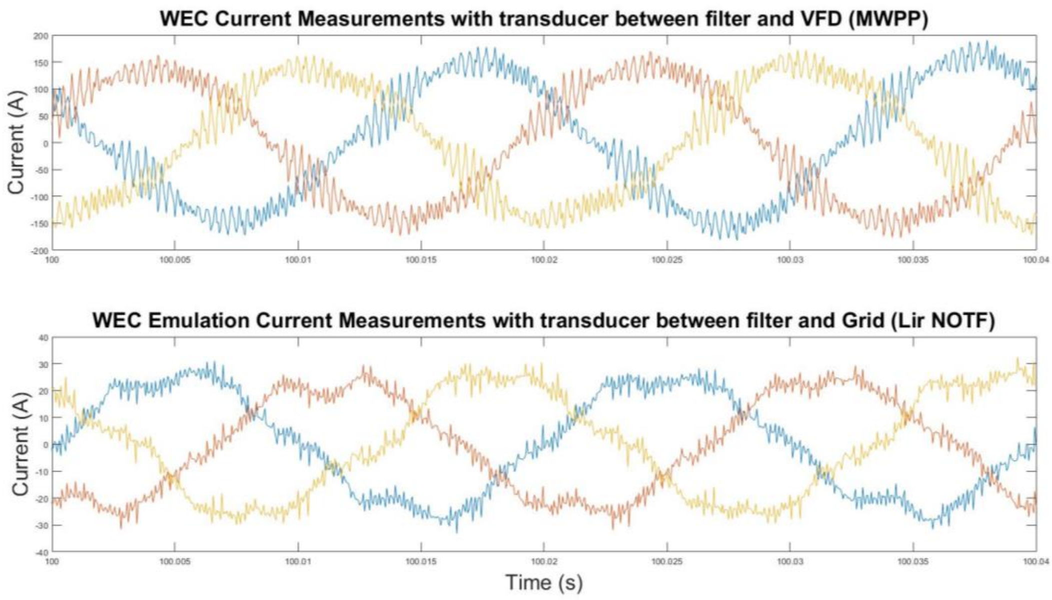


**FIGURE 17: CURRENT MEASUREMENTS FROM THE MWPP AND THE LIR NOTF ELECTRICAL LABORATORY THAT SHOW THE IMPACT OF TRANSDUCER PLACEMENT ON THE DATA.**

Based on the information provided in this section, two conclusions were reached that for the TS30 application:

1) the voltage flicker analysis performed for this report was largely compromised by the transducer placement,
2) confidence can be placed in the current harmonic distortion analysis results.

Even with these issues, there is value in completing the analysis for both the voltage flicker and current harmonic distortion for the datasets collected from the MWPP. Those results as well as recommendations for the IEC on the application of the IEC 62600-30 standards are presented below.

## 3.2 HARMONIC DISTORTION ANALYSIS AND OBSERVATIONS

The TS30 documentation stipulates that the emission of current harmonics need be measured and recorded. As recommended in the TS30, the harmonic distortion analysis is based on IEC 61000-4-7: General guide on harmonics and interharmonics measurements and instrumentation for power supply systems. The harmonic distortion analysis has three separate determinations, namely harmonic distortion, interharmonic distortion, and high frequency harmonic distortion. The analysis and observations are based on the Fast Fourier Transform (FFT) of the original signal, as outlined in the IEC 61000-4-7 documentation. The FFT of the original signals are performed using the ‘fft(x)’ function developed by The Mathworks, Inc. for their MATLAB software.

The harmonic distortion refers signals at frequencies which are an integer multiple of the fundamental frequency of the power system. The power system evaluated in this report has a fundamental frequency of 50 Hz, so the harmonics of the system are 100 Hz, 150 Hz, 200 Hz, etc, up to and including 2 kHz. Interharmonics refers to spectral components with frequencies between two consecutive harmonic frequencies. High frequency harmonics refer to those signals with frequencies above 2 kHz and below 50% of the sampling frequency, which was 15 kHz for the data collected and presented in this report, so the high frequency harmonics range is 2 kHz to 7.5 kHz.

### 3.2.1 Harmonic Distortion Below 2.5 kHz

Harmonic distortion below 2.5 kHz represents the harmonic orders from $h$ = 2 to $h$ = 50 for a 50 Hz signal, where $h$ is the integer ration of a harmonic frequency to the fundamental frequency, 50 Hz, of the power system.

For assessment of harmonics, the output of the FFT is grouped to the sum of the squared intermediate components between two adjacent harmonics as shown in equation (1). The FFT analysis assumes a stationery signal, but the magnitude of the power systems tends to fluctuate, spreading out the energy of the harmonic components to adjacent spectral-component frequencies. To account for the fluctuations in signal, the output components for each 5 Hz of the FFT are grouped using equation, as given in IEC 61000-4-7. The resulting harmonic subgroup of order $h$ has a magnitude of $I_{sg,h}$.

$$I_{sg,h}^2 = \sum_{k=-1}^{1} I_{C,(N\times h)+k}^2 \quad (1)$$

where $I_{C,(N\times h)+k}^2$ is the RMS value of the spectral component corresponding to an output bin of the FFT, $(N \times h) + k$ is the order of the spectral components, and $I_{sg,h}$ is the resulting RMS current value of the harmonic subgroup.

The resulting RMS of the amplitude of the current harmonic subgroups are used to determine the harmonic current distortion for each harmonic from $h$ = 2 to $h$ = 50. The TS30 states that harmonic currents below 0.1% of device rated current, $I_r$, for any of the harmonic orders need not be reported. Equation (2) is used to determine if the normalised currents of a given harmonic order need to be reported:

$$\left(\frac{I_{sg,h}}{I_r}\right)\% = \frac{\sqrt{\sum_{k=-1}^{1} I_{C,(N\times h)+k}^2}}{I_r\sqrt{2}} * 100 \quad (2)$$

where $I_r$ is the rated current of the wave energy converter.

Table 4 shows the average harmonic currents as a percentage of $I_r$, for the three resource classifications determined from the collected data based on equation (2). Figure 18 is a graphical representation of Table 4, including those harmonic currents below the 0.1% threshold.

**TABLE 4: AVERAGE REPORTABLE RATIOS OF HARMONIC CURRENT AMPLITUDE TO RATED CURRENT**

| Average Harmonic Current Amplitude/Rated Current ($I_h/I_r$ %) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *h* | Sea State | | | *h* | Sea State | | | *h* | Sea State | | |
| | Low | Medium | High | | Low | Medium | High | | Low | Medium | High |
| 2 | 0.337% | 0.374% | 0.390% | 13 | 0.336% | 0.296% | 0.273% | 22 | 0.132% | 0.138% | 0.132% |
| 3 | 2.713% | 2.691% | 2.819% | 14 | 0.169% | 0.161% | 0.171% | 23 | 0.111% | 0.100% | 0.098% |
| 4 | 0.266% | 0.281% | 0.301% | 15 | 0.469% | 0.505% | 0.601% | 24 | 0.107% | 0.112% | 0.111% |
| 5 | 1.581% | 1.727% | 2.044% | 16 | 0.241% | 0.240% | 0.253% | 33 | 0.120% | 0.115% | 0.120% |
| 6 | 0.201% | 0.202% | 0.200% | 17 | 0.338% | 0.298% | 0.312% | 39 | 0.221% | 0.238% | 0.232% |
| 7 | 0.401% | 0.420% | 0.457% | 18 | 0.134% | 0.132% | 0.130% | 41 | 0.218% | 0.235% | 0.228% |
| 9 | 0.106% | 0.097% | 0.108% | 19 | 0.223% | 0.192% | 0.193% | 46 | 0.098% | 0.093% | 0.102% |
| 11 | 0.305% | 0.366% | 0.339% | 20 | 0.148% | 0.152% | 0.146% | 50 | 0.277% | 0.247% | 0.267% |

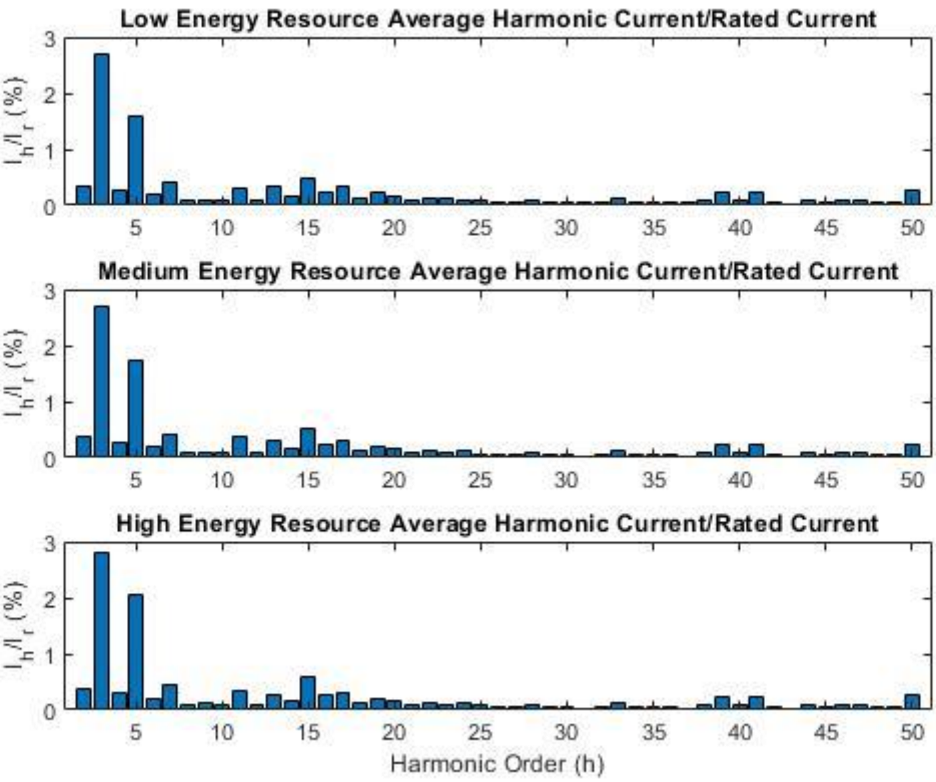


**FIGURE 18: AVERAGE NORMALISED HARMONIC CURRENTS VS. RATED CURRENT FOR EACH RESOURCE CLASSIFICATION.**

The most significant harmonic currents occur at the 3rd harmonic, 150 Hz, with additional notable harmonic currents occurring at the 5th harmonic, 250 Hz. The amplitudes of the remaining harmonic currents are below 1% of $I_r$ with a number of below 0.1%, which is below the reporting threshold set in IEC 62600-30. For verification purposes, other notable peaks, those above 0.3% of $I_r$, occur at harmonic orders 2nd, 7th, 11th, 13th, 15th, and 17th. At the higher order harmonics, the 39th, 41st, and 50th order harmonics reach the reporting threshold. There is little variation in the observed the harmonic currents across the three resource classifications, which small increases seen in the larger harmonic current amplitudes in the high energy classification.

Along with determining the RMS of the current amplitude at each individual harmonic, the Total Harmonic Current distortion (THC) was determined. The THC, as defined in IEC 62600-30, is found by applying equation (1) within equation (3).

$$THC = \frac{\sqrt{\sum_{sg,h=2}^{50} I_{sg,h}^2}}{I_r} * 100 \quad (3)$$

Where THC is a percentage, $I_{sg,h}$ is the RMS current value of the harmonic subgroup, and $I_r$ is the rated current of the WEC. Table 5 shows the total harmonic current distortion quantified for the 24 datasets presented in this report along with the $H_s$ and $T_e$ values for each dataset. While there is a clear increase in THC from the low energy sea classifications to the medium and high energy sea classifications, there is no measurable increase in THC from medium to high energy conditions. Here the increase in energy resource initially relates to an increase in total harmonic distortion, but the increase is only seen between the low and medium resource classifications, with no increase in the THC between the medium and high resource classifications.

**TABLE 5: TOTAL HARMONIC DISTORTION FOR ALL 24 DATASETS**

| Total Harmonic Distortion of Current | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Low | | | Medium | | | High | | |
| Hs (m) | Te (s) | THC | Hs (m) | Te (s) | THC | Hs (m) | Te (s) | THC |
| 0.50 | 17.80 | 0.06% | 1.33 | 12.53 | 0.13% | 2.62 | 14.31 | 0.17% |
| 0.54 | 8.06 | 0.07% | 1.39 | 16.43 | 0.09% | 2.64 | 13.65 | 0.18% |
| 0.69 | 10.81 | 0.08% | 1.58 | 15.51 | 0.12% | 2.66 | 13.28 | 0.17% |
| 0.74 | 9.98 | 0.13% | 1.86 | 13.61 | 0.14% | 2.74 | 15.54 | 0.05% |
| 0.90 | 13.03 | 0.08% | 1.93 | 15.05 | 0.17% | 3.22 | 16.19 | 0.19% |
| 0.94 | 13.34 | 0.10% | 2.11 | 12.89 | 0.16% | 3.35 | 15.65 | 0.12% |
| 1.00 | 11.55 | 0.10% | 2.23 | 14.33 | 0.19% | 3.69 | 15.68 | 0.16% |
| 1.09 | 10.12 | 0.12% | 2.41 | 13.85 | 0.19% | 4.14 | 16.81 | 0.08% |

### 3.2.2 Interharmonic Distortion Below 2.5 kHz

Interharmonics below 2.5 kHz represent the current RMS values of current components whose frequencies are not an integer of the fundamental, which appear as discrete frequencies of as a wide-band spectrum. A grouping of the spectral components in the interval between two consecutive harmonic components forms an interharmonic group.

Interharmonic components are caused primarily by two sources: variations of the amplitude and/or phase angle of the fundamental component and/or of the harmonic components, and power electronics circuits with switching frequencies no synchronized to the power supply frequency and power factors correctors. Potential effects include additional torques on motors and generators, disturbed zero crossing detectors, and additional noise in inductive coils.

Spectral components associated with interharmonics usually vary in both magnitude and frequency. Grouping them provides an overall value for the spectral components between two discrete harmonics, which includes the effects of fluctuations of the interharmonic components. To further reduce the effects of amplitude and phase angle fluctuations, components immediately adjacent to the to the harmonic frequencies that the interharmonics are between are excluded by using equation (3), that is given in Annex A of 61000-4-7:

$$I_{isg,h}^{2} = \sum_{k=2}^{N-21} I_{C,(N\times h)+k}^{2} \quad (3)$$

where $I_{C,(N\times h)+k}^{2}$ is the RMS value of the spectral component corresponding to the FFT that exceed the frequency of the harmonic order $h$, $I_{isg,h}^{2}$ is the r.m.s. value of the interharmonic current centred subgroup of order $h$, and $(N \times h) + k$ is the order of the spectral components.

The resulting RMS of the amplitude of the current interharmonic subgroups are used to determine the interharmonic current distortion between harmonics from $h$ = 2 to $h$ = 40. Equation (4) is used to determine if the normalised currents of a given harmonic order need to be reported.

$$\left(\frac{I_{isg,h}}{I_r}\right)\% = \frac{\sqrt{\sum_{k=2}^{N-2} I_{C,(N\times h)+k}^{2}}}{I_r\sqrt{2}} * 100 \quad (4)$$

Table 6 shows the average interharmonic currents as a percentage of $I_r$, for the three resource classifications determined from the collected data based on equation (3). Figure 19 is a graphical representation of Table 6.

**TABLE 6: AVERAGE REPORTED NORMALISED INTERHARMONIC CURRENTS VS. RATED CURRENT FOR EACH RESOURCE CLASSIFICATION.**

| Average Percentage Interharmonic Current Amplitude/Rated Current ($I_{ih}/I_r$ %) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *ih* | Sea State | | | *ih* | Sea State | | | *ih* | Sea State | | |
| | Low | Medium | High | | Low | Medium | High | | Low | Medium | High |
| 1 | 0.444% | 0.684% | 0.676% | 14 | 0.173% | 0.167% | 0.173% | 27 | 0.060% | 0.063% | 0.063% |
| 2 | 0.325% | 0.379% | 0.377% | 15 | 0.216% | 0.220% | 0.238% | 28 | 0.048% | 0.047% | 0.048% |
| 3 | 0.322% | 0.346% | 0.344% | 16 | 0.128% | 0.142% | 0.148% | 29 | 0.049% | 0.050% | 0.049% |
| 4 | 0.240% | 0.259% | 0.264% | 17 | 0.157% | 0.118% | 0.116% | 30 | 0.037% | 0.037% | 0.039% |
| 5 | 0.184% | 0.194% | 0.194% | 18 | 0.102% | 0.094% | 0.095% | 31 | 0.038% | 0.037% | 0.038% |
| 6 | 0.136% | 0.145% | 0.150% | 19 | 0.129% | 0.129% | 0.124% | 32 | 0.060% | 0.057% | 0.054% |
| 7 | 0.110% | 0.116% | 0.119% | 20 | 0.076% | 0.076% | 0.076% | 33 | 0.064% | 0.063% | 0.064% |
| 8 | 0.083% | 0.090% | 0.093% | 21 | 0.085% | 0.085% | 0.085% | 34 | 0.037% | 0.039% | 0.038% |
| 9 | 0.067% | 0.075% | 0.077% | 22 | 0.074% | 0.073% | 0.073% | 35 | 0.047% | 0.052% | 0.050% |
| 10 | 0.059% | 0.068% | 0.067% | 23 | 0.068% | 0.066% | 0.067% | 36 | 0.038% | 0.038% | 0.038% |
| 11 | 0.062% | 0.068% | 0.069% | 24 | 0.053% | 0.053% | 0.052% | 37 | 0.053% | 0.054% | 0.053% |
| 12 | 0.078% | 0.093% | 0.082% | 25 | 0.047% | 0.047% | 0.047% | 38 | 0.101% | 0.108% | 0.097% |
| 13 | 0.102% | 0.100% | 0.104% | 26 | 0.043% | 0.043% | 0.044% | 39 | 0.134% | 0.153% | 0.148% |

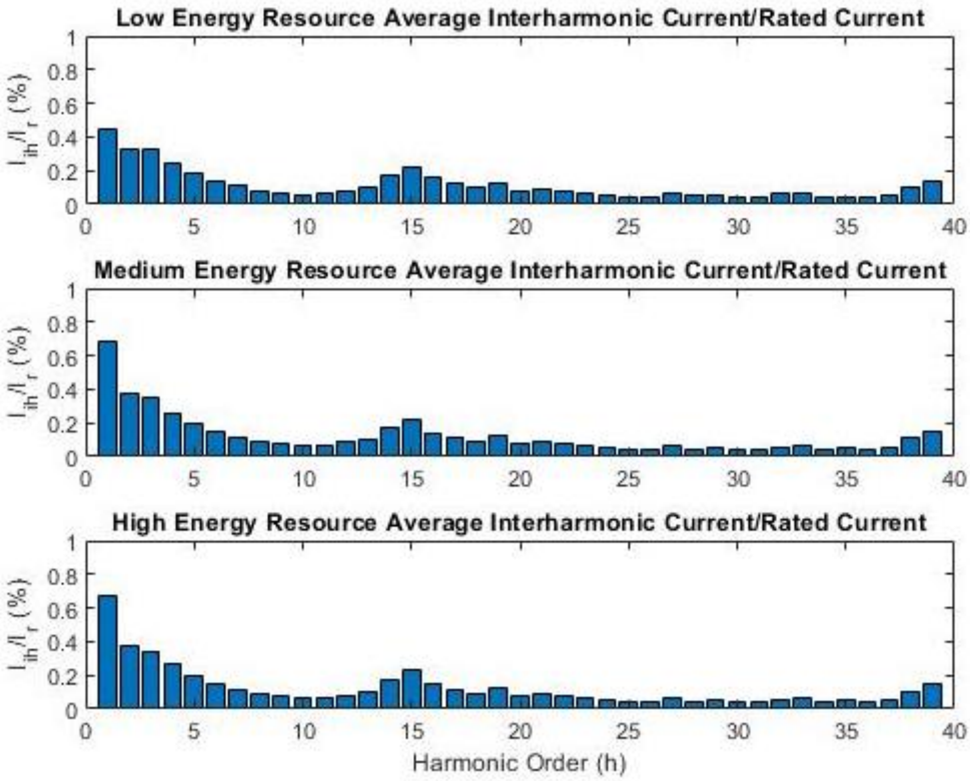


**FIGURE 19: AVERAGE NORMALISED INTERHARMONIC CURRENTS VS. RATED CURRENT FOR EACH RESOURCE CLASSIFICATION.**

For the interharmonics, the most significant harmonic currents occur at the 1st interharmonic, which represents the window around 75 Hz. With the exception of the 1st interharmonic current, there is no discernible change in the interharmonic currents across the three resource classifications. There is a clear distribution across the interharmonic orders with peak currents at the 1st order, reaching a minimum in the lower interharmonics at the 10th order, reaching a secondary maximum at the 15th order, and sitting an overall minimum until the 39th order interharmonic where there is a final small peak in current. There is a 50% increase in the 1st order interharmonic currents observed from the low energy to the medium and high energy classifications, with little change in the observed interharmonic currents beyond the 1st order.

### 3.2.3 High Frequency Harmonic Distortion

High frequency harmonics are components in signals with frequencies above the 40th harmonic, which is 2 kHz for a 50 Hz system. They can be caused by several phenomena, including PWM control of power supplies at the mains side connection, emissions like mains signalling, feed-through from load or generator side of power converters to the mains system side, and oscillations due to commutation notches. The measurement of these components are grouped into predefined frequency bands based on the signal energy of each band.

The FFT output is grouped into 200 Hz bands beginning at the first centre band above the harmonics range. For the analysis of 50 Hz signals, the first centre band frequency is 2100 Hz. The RMS of the amplitude of the high frequency current bands are used to determine the harmonic current distortion between harmonics from *f* = 2100 Hz to *f* = 7500. Equation (5) is used to determine if the normalised currents of a given harmonic order need to be reported:

$$I_{hfh,b} = \sqrt{\sum_{f=b-95}^{b+100} I_{C,f}^2} \quad (5)$$

where $I_{C,f}^2$ is the RMS value of the spectral component of the FFT of frequency *f*, *b* is the centre frequency of the 200 Hz band, and $I_{hfh,b}$ is the RMS value of the high frequency current centred around the frequency *b*.

The resulting RMS of the amplitude of the high frequency current bands are used to determine the harmonic current distortion between harmonics from *f* = 2100 Hz to *f* = 7500 Hz. Equation (6) is used to determine if the normalised currents of a given harmonic order need to be reported.

$$\left(\frac{I_{hfh,f}}{I_r}\right)\% = \frac{\sqrt{\sum_{f=b-95}^{b+100} I_{C,f}^2}}{I_r\sqrt{2}} * 100 \quad (6)$$

Table 7 shows the average high frequency harmonic currents as a percentage of $I_r$, for the three resource classifications determined from the collected data based on equation (5). Figure 20 is a graphical representation of Table 7.

**TABLE 7: AVERAGE REPORTED NORMALISED HIGH FREQUENCY HARMONIC CURRENT VS. RATED CURRENT FOR EACH RESOURCE CLASSIFICATION.**

| Average Percentage High Frequency Harmonic Current Amplitude/Rated Current ($I_{hfh}/I_r$ %) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| f (Hz) | Sea State | | | f (Hz) | Sea State | | | f (Hz) | Sea State | | |
| | Low | Medium | High | | Low | Medium | High | | Low | Medium | High |
| 2100 | 0.316% | 0.338% | 0.331% | 4100 | 0.273% | 0.295% | 0.283% | 6100 | 0.794% | 0.891% | 0.828% |
| 2300 | 0.211% | 0.214% | 0.222% | 4300 | 0.205% | 0.198% | 0.204% | 6300 | 0.672% | 0.648% | 0.657% |
| 2500 | 0.443% | 0.428% | 0.446% | 4500 | 0.137% | 0.138% | 0.135% | 6500 | 0.072% | 0.071% | 0.074% |
| 2700 | 2.195% | 2.083% | 2.225% | 4700 | 0.098% | 0.101% | 0.098% | 6700 | 0.111% | 0.106% | 0.108% |
| 2900 | 4.062% | 3.982% | 4.095% | 4900 | 0.176% | 0.191% | 0.178% | 6900 | 0.218% | 0.214% | 0.222% |
| 3100 | 4.003% | 3.848% | 3.959% | 5100 | 0.186% | 0.204% | 0.193% | 7100 | 0.189% | 0.182% | 0.187% |
| 3300 | 1.745% | 1.872% | 1.982% | 5300 | 0.099% | 0.101% | 0.099% | 7300 | 0.106% | 0.109% | 0.115% |
| 3500 | 0.377% | 0.386% | 0.398% | 5500 | 0.161% | 0.161% | 0.161% | 7500 | 0.084% | 0.083% | 0.085% |
| 3700 | 0.249% | 0.242% | 0.251% | 5700 | 0.748% | 0.718% | 0.734% | | | | |
| 3900 | 0.252% | 0.272% | 0.261% | 5900 | 0.974% | 1.071% | 1.011% | | | | |

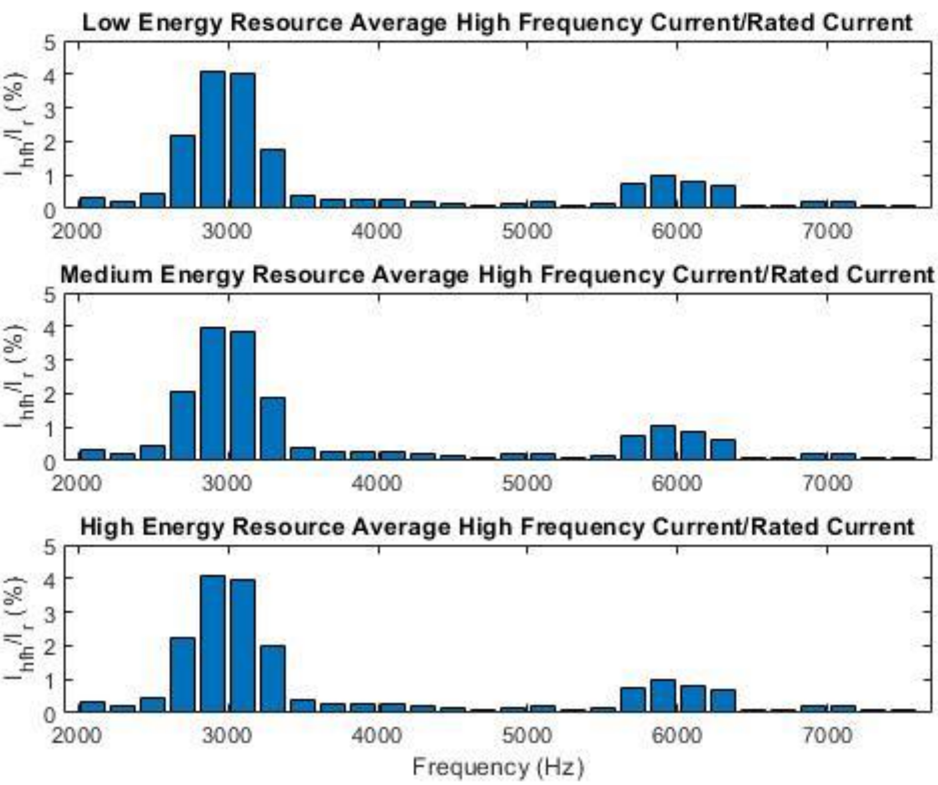


**FIGURE 20: AVERAGE NORMALISED HIGH FREQUENCY CURRENTS VS. RATED CURRENT FOR EACH RESOURCE CLASSIFICATION.**

The high frequency signals prevalent in the data collected from the sea-trials are directly related to the PWM switching of the grid side VFD used to create a 50 Hz sine wave to deliver power from the WEC to the grid, which has a switching frequency of 3 kHz. The largest currents are around the 3 kHz switching, with secondary currents at 6 kHz, which is the 2nd harmonic of 3 kHz. All other high frequency harmonics currents are well under 1% of $I_r$. The current amplitudes observed at 2900 Hz and 3100 Hz represent the largest occurring harmonic current amplitudes for the sea-trial datasets. This is largely influenced by the switching frequency of the VFD supplying power to the grid and the placement of the current transducers in relation to the RFI filter. There are no changes in the high frequency harmonic currents across the three resource classifications.

## 3.3 FLICKER ANALYSIS AND OBSERVATIONS

Flicker, which is described as voltage fluctuations during continuous operation by the TS30 documentation, refers to changes in the grid voltage. Flicker is caused by rapid changes to the voltage level of the electrical supply due to behaviour of devices connected to the electrical system. The voltage variations can result from fluctuating power consumed or generated by a load or a generator. In this case, the voltage fluctuations caused by the MWPP electrical generation are analysed.

The TS30 differentiates between Medium Voltage (MV) and Low Voltage (LV) flicker, with MV flicker analysis requires more depth analysis than LV flicker analysis. The grid connection between the Mutriku wave power plant and the local grid is a 460 V connection, which is categorized as a LV connection by IEC standards. For LV connected WEC units, a simplified measurement and direct reporting procedure is outlined in the TS30. Three phase instantaneous line currents and instantaneous phase-to-neutral voltages are to be measured at the WEC unit terminals or the point of common coupling as appropriate. However, within the Mutriku plant, there is no neutral available for monitoring, so for the tests performed for this project, the phase-to-phase voltage measured at the unit terminals instead. Additionally, the measurements were not taken from the point of common coupling, but rather then were taken from the output of the VFD prior to the RFI filter. It is suggested that at least fifteen 10-minute time series of instantaneous voltage and current measurements are collected. In this report, twenty-four 10-minute series are presented and evaluated, and they represent the same 24 data sets that were analysed in the Section 3.2.

For LV connections, the MEC unit short-term flicker disturbance factor during continuous operation, $P_{st}$, is stated as the 95th percentile for the measured condition. The limiting value $P_{st}$ is specified at 1.0 for a 10-minute observational period by IEC 61000-3-3. The limiting value corresponds to a level of lighting flicker in an incandescent 60W bulb that is visible and irritating to 50% of test subjects. The values of $P_{st}$ for all sea states fall between 2.5 and 5.5, which is significantly above the published limiting value.

As discussed in Section 3.1.2, the placement of the voltage and current transducers was suboptimal, and the analysis of the voltage flicker was compromised as a result. Despite this, there are beneficial observations to be made of the data analysis. The $P_{st}$ value determined by applying the IEC 61000-4-15 digital flickermeter, which is available within MATLAB® Simulink®. Each dataset was analysed using the MATLAB® Simulink® flickermeter, the resulting $P_{st}$ values are presented in tabular form in Table 8 following the example given in IEC 62600-30 Appendix A.

There appears to be little correlation between the energy period, $T_e$, or significant wave height, $H_s$, and the $P_{st}$ values. Figure 21 is a scatter plot of the data presented in Table 8 showing the $P_{st}$ values plotted against the measured significant wave height, $H_s$, while Figure 22 is a 3D scatter plot of the same data but including the values of energy periods, $T_e$, as well. These figures are used to illustrate the lack of correlation between the $P_{st}$ values and the sea state summary conditions, which the IEC 62600-30 uses to classify available wave energy.

**TABLE 8: FLICKER COEFFICIENT VALUES, $P_{ST}$, AS A FUNCTION OF RESOURCE CONDITIONS**

Scatter plot short-term flicker disturbance factor, $P_{st}$

| Significant Wave Height (m) \ Energy Period (s) | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 13.5 | 14 | 14.5 | 15 | 15.5 | 16 | 16.5 | 17 | 17.5 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.75 | | | | | | | | | | | | | | | | | | | 4.40 | | | |
| 3.5 | | | | | | | | | | | | | | | | | 4.35 | | | | | |
| 3.25 | | | | | | | | | | | | | | | | | 3.90 | | | | | |
| 3 | | | | | | | | | | | | | | | | | | 4.65 | | | | |
| 2.75 | | | | | | | | | | | | | | | | | 3.81 | | | | | |
| 2.5 | | | | | | | | | | | | 3.70 | 4.77 | 4.18 | | | | | | | | |
| 2.25 | | | | | | | | | | | | | 5.35 | | | | | | | | | |
| 2 | | | | | | | | | | | 4.94 | | | 4.28 | | | | | | | | |
| 1.75 | | | | | | | | | | | | | 4.55 | | | 4.57 | | | | | | |
| 1.5 | | | | | | | | | | | | | | | | | 4.11 | | | | | |
| 1.25 | | | | | | | | | | | 4.71 | | | | | | | 3.98 | | | | |
| 1 | | | | | | 4.55 | | | 4.75 | | | | | | | | | | | | | |
| 0.75 | | | | | 3.65 | | | | | | | 2.55 | | | | | | | | | | |
| 0.5 | | 3.31 | | | | | 3.47 | | | | | | | | | | | | | | 4.14 | |

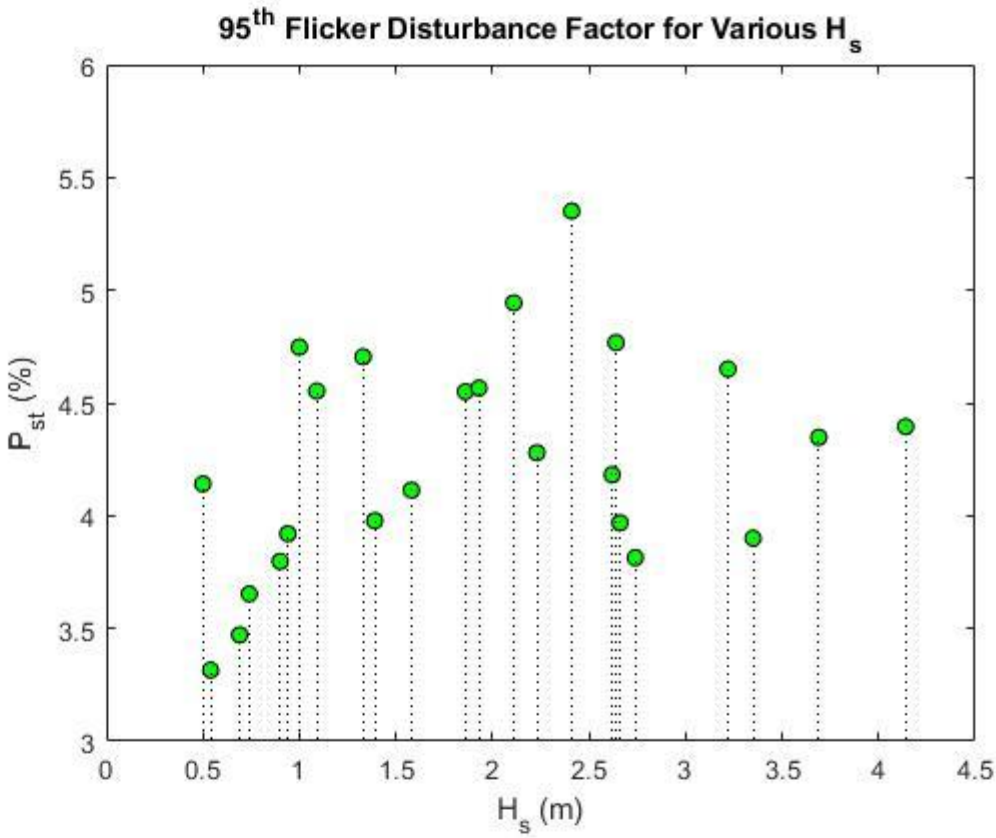


**FIGURE 21: SCATTER PLOT OF THE $P_{ST}$ VALUES BY SIGNIFICANT WAVE HEIGHT, $H_S$.**

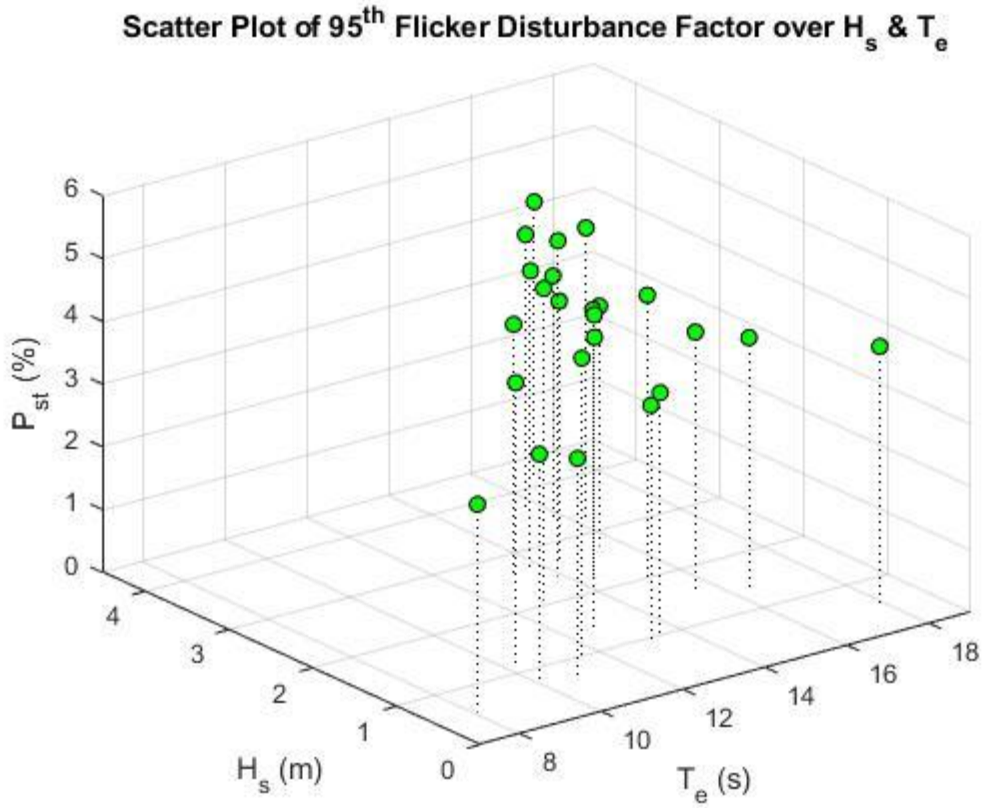


**FIGURE 22: 3D SCATTER PLOT OF THE $P_{ST}$ VALUE BY SIGNIFICANT WAVE HEIGHT, $H_S$ AND ENERGY PERIOD, $T_E$.**

In addition to the $P_{st}$ values, Figure 23 shows a 5-minute window of instantaneous flicker for each of the three resource classifications. Here the variations in voltage over time are clearer than through applying the $P_{st}$ value. The $P_{st}$ value for each of the three plots in Figure 23 are 4.55, 4.55, and 4.65 for the low, medium, and high resource classifications respectively.

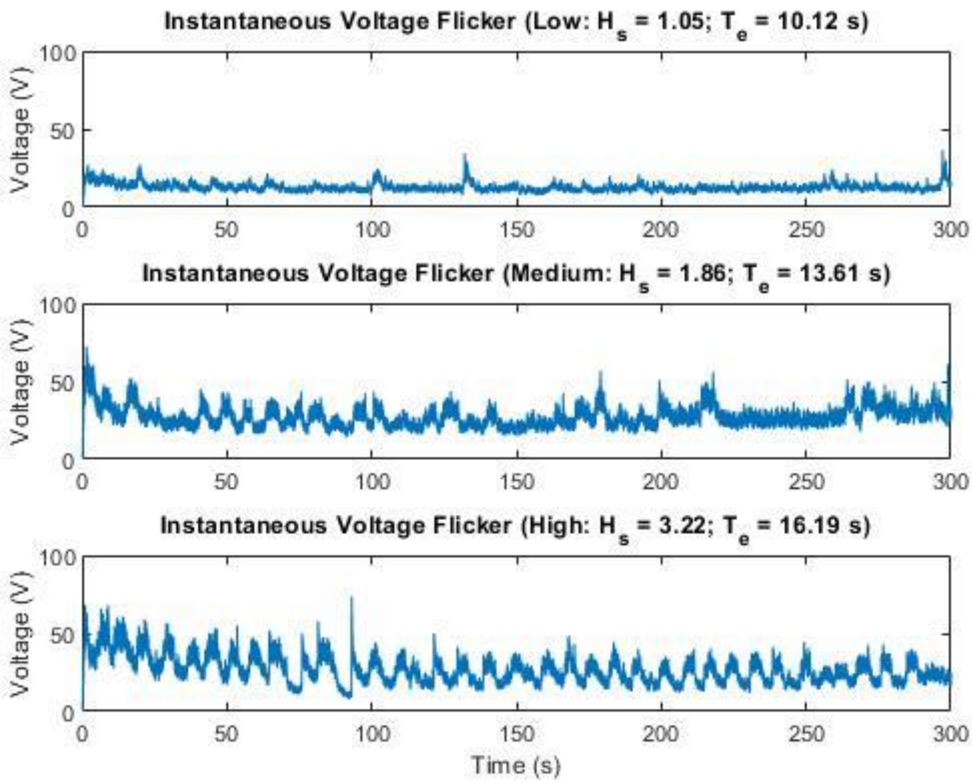


**FIGURE 23: INSTANTANEOUS VOLTAGE FLICKER FOR A SINGLE DATASET FROM EACH RESOURCE CLASSIFICATION.**

The low energy sea state resource created the smallest voltage fluctuations, while the fluctuations caused by the high energy resource has clear, consistent larger fluctuations. Under all conditions, the voltage fluctuations appear to be larger than desired. Compared to the $P_{st}$ values, the difference in the voltage fluctuation from each resource classification appears more clearly to the eye. This suggests that the available energy in the sea has an effect on the voltage flicker caused by a WEC.

## 3.4 RECOMMENDATIONS TO THE TC114 MAINTENANCE GROUP FOR TS30

- More clarity is required for the resource classification for wave energy devices. Currently, the resource classifications are to be set by the developer and can be based on either significant wave height, $H_s$ or energy period, $T_e$. This amount of variation makes it difficult to create comparable results across devices.
- The recommended number of datasets required for each resource classification should be increased from 5 to 10 or more for voltage variation testing. With 8 dataset per resource classification, there was not enough data to make any broad observations, as

there was no discernible pattern emerging from the datasets collected within the individual classifications or overall.

- Sample reporting in the Annex section of the TS30 focuses solely on the Flicker reporting. An expanded template which includes all aspects of the TS30 would be useful when generating results and reporting following data analysis.
- The TS30 was developed for a fully mature industry, while the marine renewable energy sector has not reached that stage of development. The costs associated with implementing the TS30 for the required IEC documents, equipment, data storage, and manpower may lead developers to look elsewhere during early stages development. If possible, guidance for lower cost power quality monitoring during prototype development should be included in TS30.
- The required accuracy for the voltage and current transformers for TS30 is Class 1.0. However, in the case of the TS100, the accuracy required for the voltage and current transformers is Class 0.5. These two documents should require the same accuracy, as the more accurate class will dictate transformer selection. It is recommended that TS30 required accuracy class be upgraded to Class 0.5.

# 4. IEC TS62600-10 ASSESSMENT OF MOORING SYSTEM FOR MARINE ENERGY CONVERTERS

Aiming to enhance knowledge, de-risk design processes and aid the cost reduction of the mooring system, reduction in uncertainties can be achieved through demonstration experience from realistic sea trials. Sea demonstrations in OPERA generate essential data and knowledge that is used to establish recommendations providing the basis for aiding in the standard development.

IEC TS62600-10 Ed. 1.0 (hereafter TS10) titled 'Assessment of mooring system for marine energy converters' focuses on the uncertainties and associated risks in mooring designs for marine energy converter, with a focus towards technical challenges as a result of highly coupled dynamic system, and application of novel mooring components and configurations.

OPERA provides the first documented application of TS10 to a real-case wave energy device. This is a crucial step in improving and ensuring the practical applicability of IEC/TS and towards the establishment of standards in the sector.

## 4.1 OVERVIEW OF TS10 METHODOLOGY AND APPLICATION IN THE KARRATU MOORING SYSTEM

TS10 combines expert knowledge from the marine energy and offshore engineering industries to formulate a guideline for mooring systems in a floating Marine Energy Converter (MEC) unit of any size or type deployed in open water conditions. It highlights the different requirements of MECs from existing and well-established mooring standards without duplicating existing processes and standards.

The aim of TS10 was to provide uniform methodologies for floating MEC mooring systems that can be applied at various stages including design, installation and condition monitoring. Similar to most standards, TS10 is not standalone and contains a list of normative references.

The application of TS10 for the scope of this project follows the general target set out in WP5, that is, the technical standard is first investigated in its current publication state. This is followed by the practical application of TS10 coupled with WP2 (more specifically Task 2.4 "Evaluation of shared mooring configurations"). This draws upon the latest state of the art standard developments including IEC, DNV and EMEC and the collected data from the OPERA open sea demonstrations to search for potential additional requirements which are not introduced in TS10.

At its outset, TS10 defines its scope followed by the description of mooring systems, design considerations, safety and risk conditions, analysis procedure and in-service inspection, monitoring testing and maintenance from Clause 7 – 11, respectively.

D5.1 identified that TS10 may not be comprehensive for application within OPERA as it mainly appears to adopt recommendations from ISO 19901-7:2013 and API RP 2SK and DNVGL standards are not included. Furthermore, it provides insufficient detail on the umbilical design and none on MEC PTO responses.

### 4.1.1 MOORING SYSTEM CONFIGURATION

With the aim of de-risking two mooring innovations, namely the Karratu shared mooring system and the Exeter Tether, two open sea trials are conducted under OPERA. Deployment Phase 1 (DP1) utilises the Karratu mooring system for station – keeping, whereas, Deployment Phase 2 (DP2) incorporates the Exeter tether in the Karratu mooring system.

The Karratu system reduces the number of mooring and anchoring components and is consequently expected to reduce costs and increase the reliability for arrays of MEC devices. The inherent load-extension characteristics of the innovative design of the elastomeric Exeter Tether are expected to permit significant reduction in peak and fatigue loads within the mooring system and at the hull connections, thus reducing the costs of these structures whilst improving reliability.

The Karratu mooring system is illustrated in Figure 24 displaying a wave energy array [2].

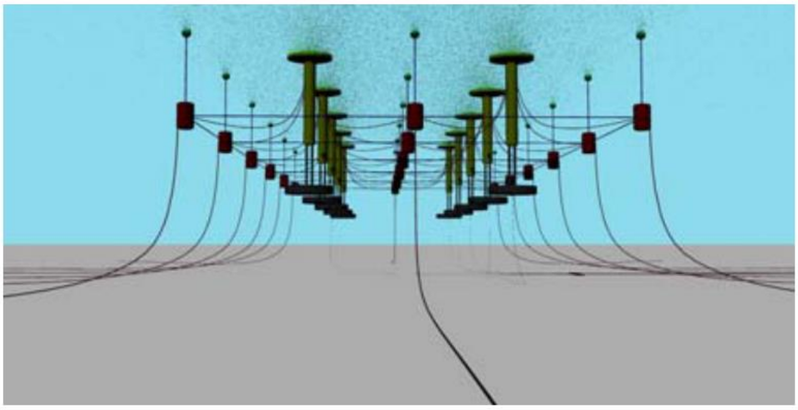

**FIGURE 24 DISPOSITION OF A WAVE ENERGY ARRAY EMPLOYING THE KARRATU SYSTEM FOR MOORINGS**

A schematic of the elastomeric Exeter Tether is illustrated in Figure 25.

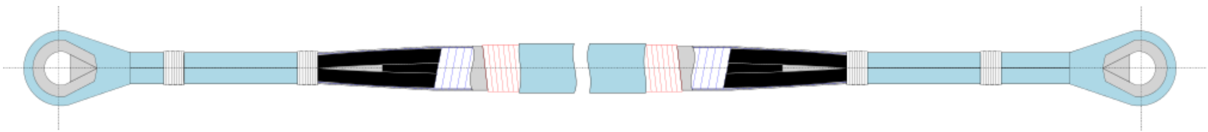

**FIGURE 25: SCHEMATIC OF THE EXETER TETHER SHOWING LOAD CARRIER (LIGHT BLUE), ELASTOMETER CORE (BLACK), ANTI-FRICTION LAYER (WHITE/BLUE) AND PARTICULATE FILTER LAYER (WHITE/RED).**

### 4.1.2 CONDITION MONITORING REGIME

Two mooring Condition Monitoring Systems (CMS) were designed and manufactured during the OPERA Project for the two deployment phases. This was the result of an extreme event at the end of DP1 resulting in the catastrophic failure of the CMS system. The loads exceeded the maximum CMS design loads, which were chosen on based on sacrificial design criteria in order to protect the MARMOK device for dangerous loads.

A motion response with Inertial Measurement Unit (IMU) and integrated GPS system located on the MARMOK records surge, sway, heave, roll, pitch and yaw. The GPS antenna and IMU are at known locations on the MARMOK device. Additionally, load shackles are selected as the preferred load monitoring hardware to facilitate simple substitution of components and to maintain the existing network mooring system architecture.

Unlike the first design, which had separate steel wire cables and a Tri-weight, the CMS designed for DP2 utilised the armouring strands of the cable to support the hanging catenary. Aramid cable grips are used to transfer loads from the armouring to the Node and MARMOK attachment points.

Both the CMS are illustrated and discussed in detail in Deliverable D2.1.

## 4.2 MOORING SYSTEM DESIGN AND MANUFACTURE

The environmental loading on the MEC and mooring system must be restrained by the mooring system. The mooring system for the MARMOK device is one square cell of the shared 'Karratu' system proposed with four catenary limbs comprising studlink chain and polyester rope for DP1. The latter is replaced by the Exeter Tether in DP2. Based on Clause 7.2 of TS10, this corresponds to a spread mooring system which is often used with axisymmetric floating structures and may be constructed using a combination of materials.

Clause 8.4 of TS10 recommends that the component strength and fatigue life be determined. Therefore, components of the innovative mooring systems underwent thorough lab-testing and de-risking prior to deployment in the open sea. The DMaC test facility was used to investigate performance and durability metrics of three different Exeter Tether scale prototypes (three samples of each size). Additional tests were carried out at rope manufacturer Lankhorst Euronete to determine the minimum break load of a full-scale tether sample.

Performance testing using harmonic displacement- and force-controlled tension-tension tests were used to quantify axial stiffness for three different Exeter Tether scale prototypes. The axial stiffness of the tether samples was observed to be highly dependent on previous loading, to a much greater degree than conventional synthetic ropes.

A Thousand Cycle Load Limit test was carried out on the smallest prototype size (estimated MBL = 222kN) and failure occurred after 1087 cycles (1000 cycles at 1-50%MBL and 87 cycles at 1-60%MBL). Inspection of the failed sample suggests that failure occurred in proximity to the end of the elastomeric cores. Minor design changes, including providing a chamfer on the end of the exposed cores and modification of the layer topology were then implemented to mitigate the risk of this occurring in service.

A full-scale (in terms of diameter) sample was pulled until failure and achieved a break load of 1597.5kN (or 162.9 Tonnes), which is almost 23% higher than the predicted failure load. This was encouraging for DP2 as it provided a suitable Factor of Safety based on numerical simulations of the MARMOK-A5 device and Karratu mooring system. Deconstruction of this failed sample highlighted several potential design improvements that were included in the final OPERA design.

## 4.3 DEVICE AND MOORING SYSTEM DATA COLLECTION DURING FIELD TRIALS

It was observed that the introduction of sacrificial CMS load design limits is essential to protect main station keeping system and WEC device; therefore, sacrificial CMS weak points should be applied. It was observed that peak load calculation for CMS requires fully dynamic cable simulation: using appropriate environmental parameters and informing design load cases for the condition monitoring system.

Full system specification of load monitoring equipment is essential to inform user and deployment contractor; including selected cable routes with support system, J-tube design and signal system. J-tube design needs to be carefully considered to avoid stress on cable system. Additionally, detailed deployment options are needed to be discussed ahead of deployment with the selected offshore operations contractor.

Load shackles were found the optimum choice, maintaining the load path of the existing mooring infrastructure and allowing a direct replacement without the need for a safety line. Specific consideration needs to be given to Load Shackle pin rotation to avoid measurement errors. Furthermore, load shackle location should be carefully considered and if possible to be chosen closest to the WEC device in order to avoid long distance monitoring cable designs.

The signal output from the load shackles and the data logging requirements for the system needs to be carefully considered Due to identified design conflicts, it was considered necessary to locate the load monitoring shackles at the mooring system nodes as opposed to the WEC hull; the associated cable route back to the DAQ from the nodes is challenging and various options are considered.

Corrosion and wear characteristics are undesirable criteria, contributing significantly to accuracy and reliable signal monitoring issues. Considerable marine growth was observed on the mooring system which is expected to have implications for the OrcaFlex numerical model set up for validation. As described in Clause 8.2.2 of TS10, the type and accumulation rate of marine growth at the site can affect mass and hydrodynamic properties of the mooring lines. This should be taken into consideration for mooring systems not subject to any regular marine growth removal or protection.

Figure 26 displays the wear and corrosion issues observed during the post-installation inspections in the load shackle and subsea connector.

a b c

**FIGURE 26: WEAR AND CORROSION ISSUES OBSERVED DURING DP1, A) MARINE FOULING ON LOAD SHACKLE, B) ROTATION PIN FAILURE ON LOAD SHACKLE, C) FOULING AND CORROSION ON SUBSEA CONNECTOR**

## 4.4 EVALUATION OF SHARED MOORING SYSTEM

The mooring design for the Oceantec Marmok device was based on the industry standard: DNVGL-OS-E301 which also provided an opportunity to verify the applicability of the TS10 standard. Clause 8.3 of TS10 recommends that wind and wave-induced actions on the mooring system be determined by relevant analytical or empirical methods or model testing, with appropriate consideration of water depth effects. It also recommends an investigation of the interaction between current and waves.

Convergence and robustness analyses were conducted on an OrcaFlex model of the device and described in Technical Standard 102. The investigation into simulation length indicated that the assumption of peak tension occurring with peak wave crest is not well founded. Varying the number of wavelets can produce larger crest events, thus, questioning the suitability of simulations based on 100 wavelets. Finally, no sensitivity to time step or element density was observed.

Validation and calibration of numerical simulations is an essential part in the assessment of the MARMOK device using Karratu mooring system. This facilitates the identification of the potential causes of discrepancies between the numerical model simulation results and field data as a result of environmental input constrains and analysis method.

The tension range was reduced for extreme, medium and low environmental condition during DP2 as seen in Figure 27. The tension was found to be reduced by ~50% during DP2, compared to tension measured at similar extreme environmental condition during DP1.

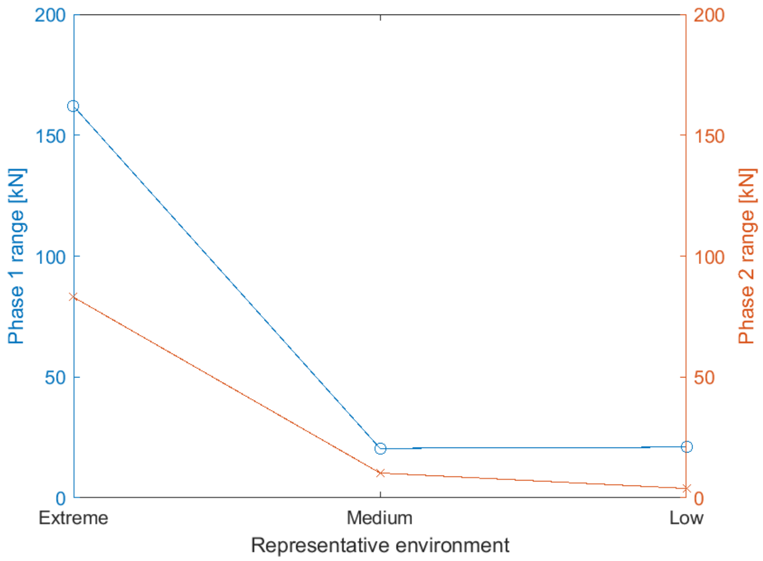


**FIGURE 27: COMPARISON OF THE RANGE OF TENSION FOR DP1 AND DP2 DEPLOYMENTS**

The horizontal motion in Northing and Easting was found to be reduced during DP2 relative to DP1. Similarly, the heave, roll and pitch were reduced for the extreme environment condition during DP2 and a limited effect was observed for low and medium environmental condition. These results are summarized in Figure 28 and discussed in D2.1.

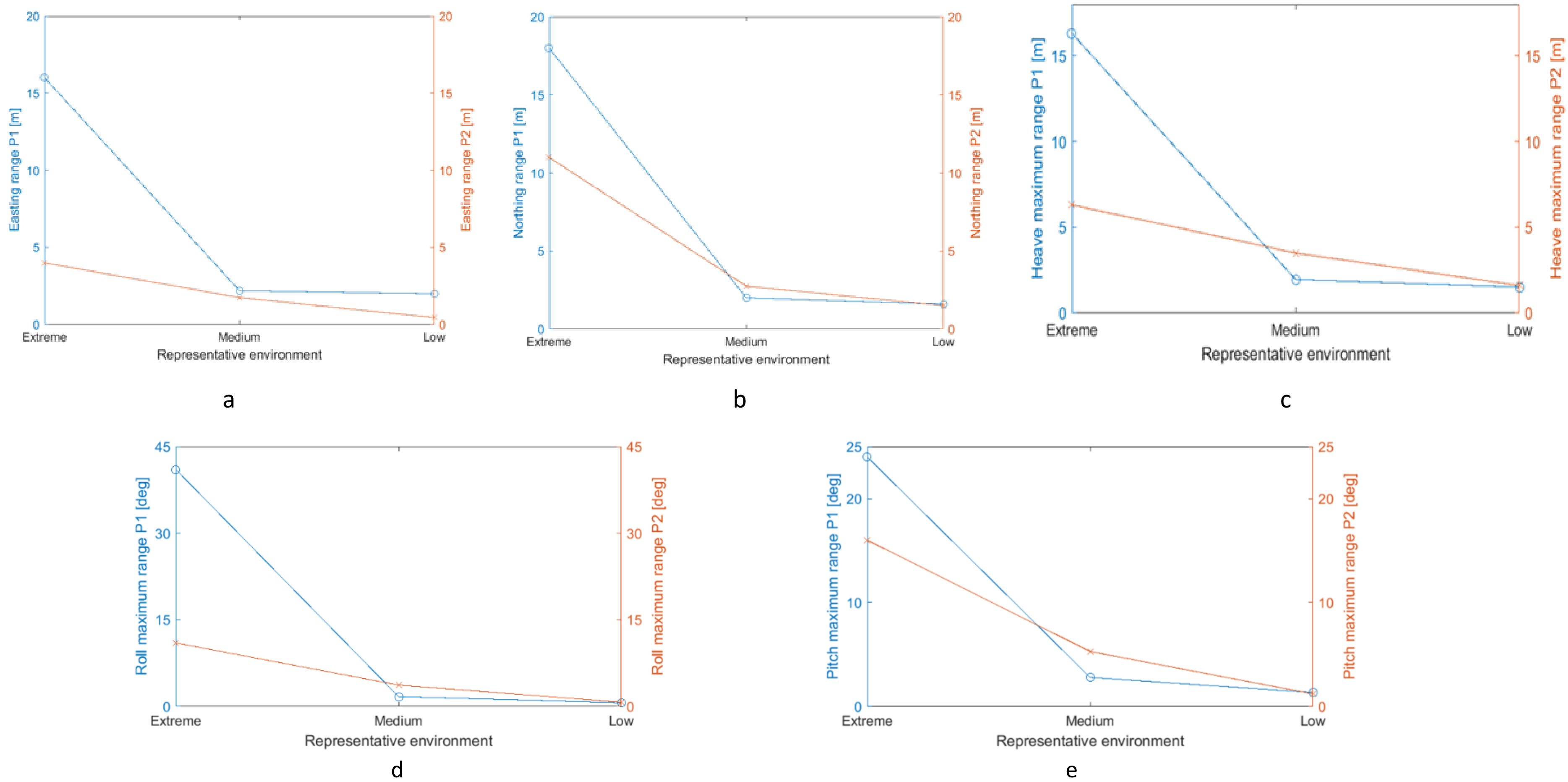


**FIGURE 28: COMPARISON BETWEEN MOTION BEHAVIOUR OF MARMOK IN EXTREME CONDITION BETWEEN DP1 AND DP2; A) HORIZONTAL MOTION (EASTING) B) HORIZONTAL MOTION (WESTING), C) HEAVE, D) ROLL , E) PITCH**

## 4.5 RECOMMENDATIONS TO THE TC114 MT 62600-10 MAINTENANCE GROUP FOR TS10

Lessons from the two deployment phases in OPERA have identified numerous gaps in knowledge and TS10 standard recommendations. Inclusion of the following could address these limitations:

- Introduction of novel (new) components requires inclusion of high safety factors to address higher risk element; standards should also enable the option to assess performance of novel components through a rigid certification process that could eliminate the requirement of higher safety factors;
- Uncertainties in unknown components requires performing a detailed component Failure Mode and Effect Analysis (FMEA) to deduce cumulative Risk Priority Numbers (RPN);
- Different safety factors should be considered based on risk criteria, where higher uncertainties should demand higher safety factors. Therefore, if novel mooring components and configurations are used, larger safety factor must be applied to ensure structural integrity due to increased risks;
- Fully dynamic simulations need to be performed to assess coupled behaviour between condition (mooring) monitoring system (CMS) and moored system during the design phase;
- For appropriate risk mitigation of novel components, it is recommended that numerous component and performance test campaigns must be run;
- CMS designs need to include enhancement of components to reduce loss of data due to corrosion and marine fouling;
- The CMS should at no time compromise the main mooring configuration and sacrificial weak points should be designed into the CMS;
- Fatigue factors must be assessed, and cable clashing and minimum bending radius identified for the CMS and auxiliary power for the DAQ.
- If possible, mooring loads should be monitored close to the floating device to avoid long cable routes through open water;
- Marine growth has a significant impact and it is recommended that this is appropriately incorporated in the modelling process particularly for long-term deployments for the longer term analysis.
- Simulation accuracy is sensitive to simulation length, occurring of peak wave crest, variation in number of wavelets, but not to time step or element density;
- An appropriate understanding of the response of the WEC, mooring line tension, number of elements, and simulation length is required before committing to a peak design tension.

# 5. CONCLUSIONS

This deliverable is the first documented real-case application of IEC 62600-100, 62600-10 and 62600-30 technical specifications. While most of the IEC TS requirements could be implemented throughout the OPERA project, this deliverable describes the experiment work and the list of discrepancies with corresponding IEC TS requirements. It then provides useful recommendations for the improvement of these IEC Technical Specifications

The most relevant findings and recommendations are summarised below:

- 62600-100: wave measurement
  - More specific information on the wave measurement requirements. Recommendation are difficult to fulfil and may not be justified.
  - Measurement duration does not match well established standards used with measurement buoys
  - Consider giving conditions for which a numerical model to correct on wave interference with measurement buoy is not required.
  - Consider accepting use data provided by commercial buoys which may be calculated using proprietary undisclosed algorithms but have published documentation attesting the quality of their data. This may include external quality certification when available.
  - Recommend limiting the use of Acoustic Doppler Current Profiler (ADCP) to location of 30m depth maximum. Manufacturers sometime increase this value to up to 100m. but experience shows that data quality is reducing.
- 62600-100: electrical power output measurement
  - WEC power output measurement does not present significant difficulties, however it is recommended to provide more information on the measurement of reactive power which has the potential to significantly influence the WEC impact on the grid.
  - Some sensors used adhered to different standards from those recommended in TS100. This should be discussed in the TS.
  - Some variations might be necessary for an early stage developer using pre-existing on onshore infrastructure. There may be limitations to what the developer can do to the landing point of the cable i.e. in the installation of dump load.
- 62600-100: sea state characterisation
  - Work carried out in OPERA to identify additional sea state characteristics that impact the performance of WECs did not lead into sufficient improvements. More work is required to develop TS100 but, as these characteristics are WEC specific, this work should be led by developers and they should feedback to TC114.

- 62600-TS 30: Power quality assessment
    - More clarity is required for the wave resource classification for wave energy devices, which was described more in detail in the TS 100 analysis.
    - Sample reporting in the Annex section of the TS30 focuses solely on the Flicker reporting. An expanded template which includes all aspects of the TS30 would be useful when generating results and reporting following data analysis.
    - The costs associated with implementing the TS30 for the required IEC documents, equipment, data storage, and manpower may not be suitable for early stage or prototype development lead by small companies. If possible, guidance for lower cost power quality monitoring during prototype development should be included in TS30.
- 62600-TS 10:
    - Different safety factors should be considered based on risk criteria, where higher uncertainties should demand higher safety factors. Therefore, if novel mooring components and configurations are used, larger safety factor must be applied to ensure structural integrity due to increased risks;
    - Fully dynamic simulations need to be performed to assess coupled behaviour between condition (mooring) monitoring system (CMS) and moored system during the design phase;
    - For appropriate risk mitigation of novel components, it is recommended that numerous component and performance test campaigns must be run;
    - CMS designs need to include enhancement of components to reduce loss of data due to corrosion and marine fouling;
    - The CMS should at no time compromise the main mooring configuration and sacrificial weak points should be designed into the CMS;
    - Fatigue factors must be assessed, and cable clashing and minimum bending radius identified for the CMS and auxiliary power for the DAQ.
    - Marine growth has a significant impact and it is recommended that this is appropriately incorporated in the modelling process particularly for long-term deployments for the longer-term analysis.
    - Simulation accuracy is sensitive to simulation length, occurring of peak wave crest, variation in number of wavelets, but not to time step or element density;
    - An appropriate understanding of the response of the WEC, mooring line tension, number of elements, and simulation length is required before committing to a peak design tension.

# 6. REFERENCES

[1] Bender, "PEM575 - Universal measuring device, Software version 2.00.xx," 2016.

[2] Schneider Electric, "PowerLogic™ PM550 series, User manual, HRB1684301-06," 2019.

[3] BSI, "BS EN 62053-22:2003+A1:2017, Electricity metering equipment (a.c.) - Particular requirements, Part 22: Static meters for active energy (classes 0,2 S and 0,5 S)," BSI Standards Publication, 2018.

[4] BSI, "BS EN 60688:2013, Electrical measuring transducers for converting A.C. and D.C. electrical quantities to analogue or digital signals," BSI Standards Publication, 2014.

[5] BSI, "BS EN 60044-1:1999, Instrument transformers - Part 1: Current transformers," British Standards Publication, 2003.

[6] BSI, "BS EN 61689-3:2011, Instrument transformers, Part 3: Additional requirements for inductive voltage transformers," British Standards Publication, 2012.

[7] BSI, "BS EN 61557-12:2008, Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1500 V d.c. -...," British Standards Publication, 2008.

[8] M. Ojanguren and J. L. Aguiriano, "MARMOK-A-5 Brief Description," Oceantec, 2016.

[9] A. Babarit, "A database of capture width ratio of wave energy converters," *Renewable Energy,* vol. 80, pp. 610-628, 2015.

[10] IEC, IEC-TS62600-102: Marine Energy - Wave, tidal and other water current converters - Part 102: Wave Energy converter power performance assessment at a second location using measured assessment data. Edition 1.0, 2016-08, 2016.

[11] D. Mollison, "Wave climate and the wave power resource," in *Hydrodynamics of Ocean-Wave Energy Utilization, Proceedings of the IUTAM Symposium*, Lisbon, Portugal, 1985.

[12] D. Woolf, "Sensitivity of power output to wave spectral distribution," Seapower Ltd., 2002.

[13] M. S. Longuet-Higgins, “The statistical analysis of a random moving surface.,” *Phil. Trans. R. Soc. Lond. A 249,* pp. 321-387, 1957.

[14] D. E. Cartwright and M. S. Longuet-Higgins, “The statistical distribution of the maxima of a random function,” *Phil. Trans. R. Soc. Lond. A 237,* pp. 212-232, 1956.

[15] J.-B. Saulnier, A. Clement, A. F. O. Falcao, T. Pontes, M. Prevosto and P. Ricci, “Wave groupiness and spectral bandwidth as relevant parameters for the performance assessment of wave energy converters,” *Ocean Engineering,* pp. 130-147, 2011.

[16] K. Doherty, “Temporal and Spectral Ocean Wave Characteristics and their Influence on WEC Performance (in Draft),” Kenneth Doherty Consultancy, 2015, 2015.

[17] I. O. L. d. A. J. M. Y. Torre-Enciso, “Mutriku wave power plant:From the thing out to the reality,” in *8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 2009.