Open Sea Operating Experience to Reduce Wave Energy Costs

Deliverable D1.2

Mutriku and BiMEP operating data collection experience

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EXECUTIVE SUMMARY

The main objective of WP1 is to ensure state of the art instrumentation is installed and operates as planned in the harsh open-sea environment, enhancing successful development of the technical work of other Work Packages.

This is articulated in the following specific objectives:

- Assessment of data requirements from other Work Packages and provision of robust and state-of-the-art instrumentation for the fulfilment of this requirements.
- Description of the existing research and operational infrastructure for the test to be completed in Mutriku Wave Power Plant and IDOM's WEC.
- Provision of a structured access for other Work package partners to the research data produced according to the Project Data Management Plan.
- Provision of a complete failure risk matrix and contingency plan for the systems comprising the instrumentation and monitoring system.

The present report aims to describe the operational experience and lessons learnt regarding data collection during the OPERA project, identifying the main challenges undergone for the completion of the testing campaigns in Mutriku and BiMEP.

Additionally, a failure record table is presented, following the templates and recommendations stablish in WP7, and gathering the main component failures raised during project lifetime.

Finally, an updated risk matrix has been completed including the operational and safety level risk assessment. This matrix expands the already existing risk matrix to incorporate new risks identified as consequence of preventive and corrective actions along the project.

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ABBREVIATIONS AND ACRONYMS

OPERA	Open Sea Operating Experience to Reduce Wave Energy Costs
WEC	Wave Energy Converter
BIMEP	Biscay Marine Energy Platform
GNSS	Global Navigation Satellite System
IMU	Inertial Movement Unit
HSSV	High Speed Switching Valve
SQL	Standard Query Language
WP	Work Package
TRL	Technology Readiness Level
LCOE	Levelized Cost of Energy
PTO	Power Take-Off
HART	Highway Addressable Remote Transducer
O&M	Operation and Maintenance
DOF	Degree of Freedom
UPS	Uninterruptible Power Supply
PWM	Pulse Width Modulation
EMI/EMC	Electro-Magnetic Interference/Electro-Magnetic Compatibility
RMS	Root Mean Square
CMS	Condition Monitoring System

1. INTRODUCTION

Despite important achievements have been accomplished so far, wave energy sector still requires open sea experience as it is essential to both reduce the cost of the technology, and to avoid repeating early engineering mistakes across the sector. OPERA project's main objective is to reduce the time to market of wave energy, by further advancing in 4 key innovations aiming to reduce up to 50% the Levelized Cost of Energy (LCOE) projections of a floating Oscillating Water Column (OWC) technology.

In the scope of OPERA, the objective of Work Package 1 (WP1) has been to ensure state of the art instrumentation is installed and operates as planned in open-sea environment, enhancing successful development of the technical work of other Work Packages in the OPERA project.

With the OPERA project reaching its end, open sea tests undergone have given valuable information in sense of equipment and instrumentation performance and reliability. A real-world experimentation has given valuable validation of the chosen sensors and instrumentation and equipment both in Mutriku and BiMEP. The tests carried out during this project have demonstrated the good expected behaviour of the chosen equipment. However, not all the instrumentation has completed the stablished initial operational requirements, causing and extra effort in keeping the system operational both for Mutriku and of the Wave Energy Converter (WEC).

The collected information regarding the subsystems comprising the WEC has brought valuable data for future wave energy converter deployments. This document describes the most noteworthy aspects of the deployed equipment, collected during both Mutriku and BiMEP test campaigns.

The purpose of this deliverable is to describe the performance and outcome of the different sensors and system during both, on-shore and open-sea experiments. All the lessons learnt during the tests are described, providing an important guide for new developments and seeking to reduce the repetition of the same mistakes in further designs.

Chapter 2 of this document makes a brief synthesis of the lessons learnt during the two testing campaigns in Mutriku Wave Power Plant and BiMEP. The learning obtained during these tests will be very useful for future developments in marine energy field. This section focuses on the faults and problems encountered in different equipment during the test months. Some of the problems are related to design mistakes, while others are related to accidental failures.

Chapter 3 summarises the most significant failures in instrumentation systems during the project, identifying failure mechanism, detection methods and impacts of the failures in system operation and safety, by making use of the failure record template provided by WP7. WP1 developed a failure risk matrix for the selected instrumentation, where a contingency plan detailed to mitigate a potential failure.

Chapter 4 examines the assessed matrix and compares it with the identified failures during the deployment. Based on the gained experience, the failure matrix has been updated to incorporate this operational feedback.

Chapter 5 draws some final general conclusions about the instrumentation and data collection experience and lessons learnt during the project.

Finally, a list of the instruments deployed for both Mutriku and BiMEP testing campaigns is included in the annex, and a simple performance rating is given, aiming to provide feedback to future wave energy projects.

2. DATA COLLECTION EXPERIENCE DURING MUTRIKU TEST CAMPAIGN

2.1 INTRODUCTION

Mutriku wave power plant is the first commercial plant in Europe to use wave energy to generate electricity. It has 16 turbines with a total capacity of 296 kW, harnessing air compressed by the action of the waves.

In the scope of the OPERA project, air chamber nº 9 from Mutriku was be equipped with a bi-radial turbine designed and developed in WP3, following Dry-lab tests that were carried out in order to validate the turbine performance. Additionally, a series of control strategies were tested for their real implementation controlling the bi-radial turbine with the aim of maximizing the power extraction from the waves.

Mutriku also intended to represent the first documented real-case application of existing IEC Technical Specifications. Tasks performed in WP5 include evaluation of uncertainty in power performance, power quality, yield and their reporting.

FIGURE 2-1: INTERIOR AND AERIAL VIEW OF MUTRIKU WAVE POWER PLANT.

The acquired data by the sensors during the real sea environment tests has granted valuable information for the OPERA project. Recorded data of power production, power quality, efficiency, mooring force data, and other areas certainly play a significant role in ocean energy technology development.

The performance of the deployed instrumentation and equipment have played a crucial role in the validation of the innovations proposed in the scope of the project, and the incorporation of lessons learnt to future developments will help the uncertainties and risk of the challenging and unpredictable environments.

With the objective of de-risking the Power Take-Off (PTO) -related innovations, i.e. the biradial turbine and the innovative control laws. A first test period was carried out in one of the air chambers of Mutriku wave power plant. The developed design has been tested during some months, where different control strategies were tested. The most relevant failures and lessons learnt identified during experiments are listed, and the solutions to these problems are detailed.

The same analyses have been accomplished for the test carried out in BiMEP, in the MARMOK-A-5 OWC buoy. Some of the sensors and equipment used in this second tests are same as those used in Mutriku, but in this case, due to the differences between two systems, new equipment and sensors are present.

Lessons were learned through the issues that arose during these real sea tests. These were a good indication of those that can arise during the implementation phase. Some of these issues come from designs that did not take into account operational or environmental aspects, but other faults can be classified as merely accidental. However, these lessons are very valuable to avoid these problems during the development of this technology.

Lessons learnt in Mutriku were helpful to prevent some important drawbacks that could occur in the buoy. Nevertheless, not all the elements installed in the buoy could be tested in Mutriku prior to the buoy tests. Furthermore, some elements already tested in Mutriku suffered faults during offshore test period.

2.2 CHALLENGES & LESSONS LEARNT

Mutriku wave power plant offers a relative controlled and accessible test site, and a fairly benign environment in which equipment and systems can be tested in close to BiMEP working conditions where eventualities can be overcome with more ease in opposite of BiMEP offshore deployment. Operation and Maintenance (O&M) of the plant is planned also considering weather windows, but no limitations apply other than attaining to reasonable levels of noise hazard inside the power plant, a factor that can otherwise be mitigated with adequate corrective environment. However, in very energetic sea states combined with high tides there is a real risk of waves overtopping the breakwater.

The Mutriku test campaign undergone brought important learning before the implementation of the turbine in the offshore location. The most relevant events are classified, dividing the system in most representative parts. Problems suffered with different equipment are detailed. In addition, the strengths of some of the chosen sensor and dispositive are also highlighted.

2.2.1 WAVE/AIR CHAMBER

The confined air chamber is the basis of the wave energy capture system for the fixed OWC converter. Two pressure sensors were also installed in the chamber, offering good performance during all the deployment, and giving chamber pressure measurements during the tests.

In addition to the pressure sensors, a Rosemount 5600 radar-based level meter was also incorporated to the air chamber. This sensor has worked well during all the testing period. However, to obtain accurate results the sensor needed some fine-tuning of the settings to compute the internal water surface. The exact functionality of all the configuration parameters is not readily available in the manuals and required some trial and error to produce smooth results across different sea states.

The level of the inner water is measured from the antenna at the top of the tank. The radar signal is reflected in the water and the echo is picked up by the antenna. As the signal is varying in frequency, the echo has a slightly different frequency compared to it. This difference is proportional to the distance from the water surface, so can be accurately calculated. This method is called FMCW (Frequency Modulated Continuous Wave).

The output reading is provided by means of a 4.20mA signals that incorporates a Highway Addressable Remote Transducer (HART) interface. This connection is used to configure the device making advantage of the software provided by the manufacturer.

Figure 2-4 show a typical echo curve of such types of sensor, with echo peaks intensity plotted against echo travel distance. The particularities of the chamber geometry, with a very flat and reflective bottom, produced a double bounce of the echo that must be filtered to have a good reading. Also, a hold-off distance had to be considered to avoid the perturbations produced by the signal traveling through the orifice hole of the chamber ceiling to reach the internal air chamber.

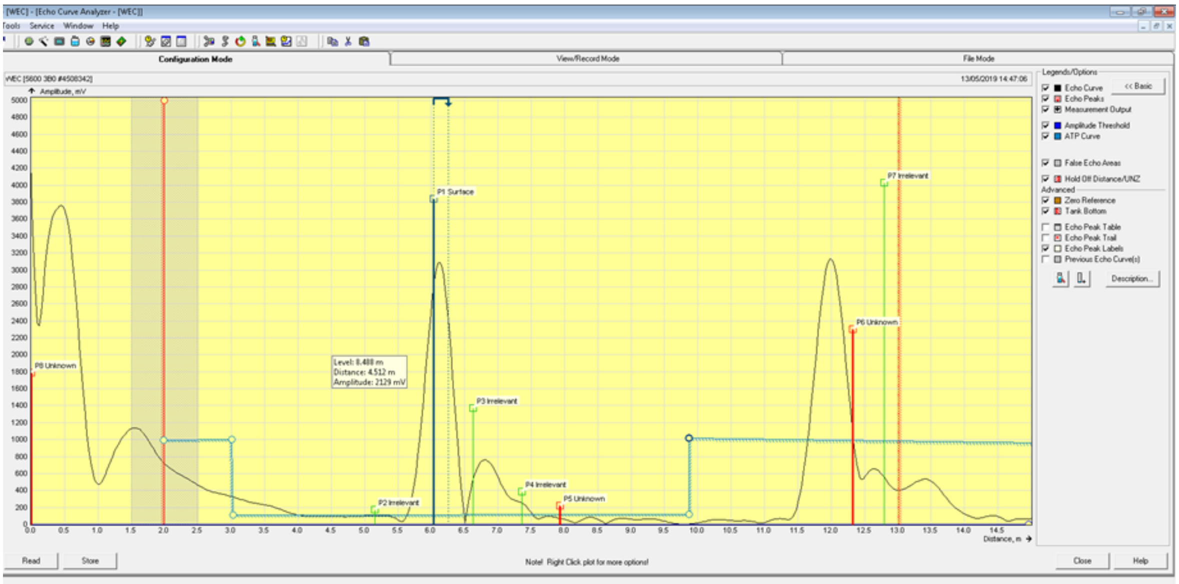

FIGURE 2-2: ECHO CURVES FOR RADAR LEVEL METER

In the MARMOK-A-5 device, the pressure sensors were located around the chamber in different 6 positions. Three of them in upper part of the chamber and three under the water, so the pressure all around the chamber could be monitored with a 120º position shift. All the sensors offered a good performance during all the test period.

Water level measurement sensor in BiMEP was the same as the one used in Mutriku, however, in this case the sensor had to be positioned in the border of the chamber due to the construction constraints for the biradial turbine, which ended up being too close to the chamber wall. The sensor provided a satisfactory outcome in general, but the mounting position caused some problems due to reflections of the electromagnetic echo in the internal chamber wall. This produced disturbances in the measurement, causing sometimes the sensor to enter in alarm mode and blocking sensor reading until the alarm was manually cleared.

2.2.2 MOORING LOAD SHACKLES

A novel mooring tether that combines the material properties of elastomeric and thermoplastic, has been implemented. The novel mooring allows the load-extension curve to exhibit a low stiffness response for normal operation conditions and a high stiffness response for extreme conditions.

FIGURE 2-3: F1 LINE WITH THE NEW ELASTOMERIC TETHER

To validate the effectiveness of the new mooring design, the force in the tethers has been monitored during this test period. For this purpose, four load shackles were installed in the node that connects the catenary and the conex. Unfortunately, the electrical cables of the load shackle broke about approximating one month after their installation.

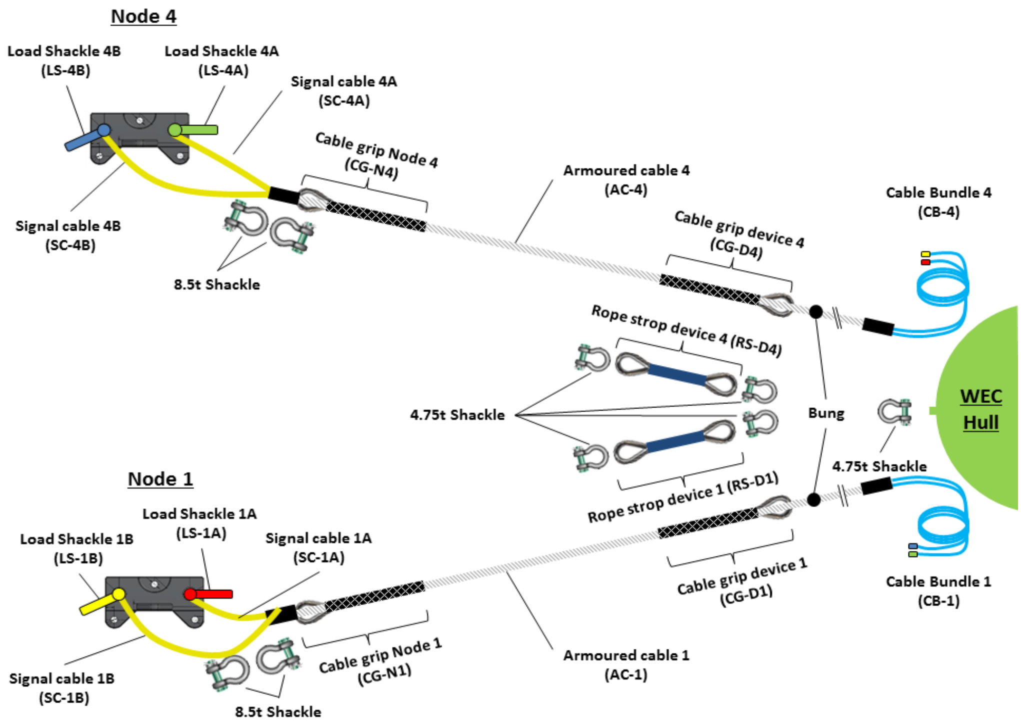

FIGURE 2-4: SCHEMATIC OF THE LSCS WHERE THE POSITION OF LOAD SHACKLES IS DETAILED

FIGURE 2-5: DETAIL OF THE LOAD SHACKLE ELECTRIC CABLE BRAKE

A more robust wiring should have been implemented in order to resist the force the waves imposed to the connectors. In a possible new implementation, the wirings should be protected more consciously.

2.2.3 BIRADIAL TURBINE

The novel biradial air turbine designed and developed by Kymaner within the OPERA project was initially tested in Mutriku in order to validate its performance before offshore test deployment. As the turbine is designed to fit the diameter of the chamber of the Marmok-A-5 buoy, an adapter was built with the purpose of coupling fitting the turbine structure to the series valve flange.

The turbine system is formed by different sensors and equipment:

- High Speed Switching Valve (HSSV);
- Air turbine (i.e., biradial rotor);
- Electrical Generator;
- Connectors; and
- A set of sensors, including 10 pressure sensors; 2 vibration sensor and temperature and humidity sensors.

2.2.3.1 HSSV VALVE

The High-Speed Series Valve (HSSV) is composed by four FESTO servo actuators that control the aperture of a circular annulus, responsible for cutting or allowing the circulation of the air flow coming from the chamber to the turbine. The actuators can open and close the valve in a short time (0.1 s), allowing the implementation of latching control.

FIGURE 2-6: HSSV VALVE ACTUATORS AND VALVE ANNULUS DURING CONSTRUCTION

The commissioning of the new turbine in Mutriku required an effort bigger than expected due to some problems in the valve control. The start-up procedure presented spurious failures. Because this situation was not adequately managed by the valve controller, the safety procedures where not adequately passed to the plant controller, leading to unsafe operation of the valve.

When the contractor, responsible for mounting and programming the valve, was contacted, they did not provide the required support, leading to a delay of the turbine commissioning. This highlights the advantage of choosing a qualified workshop to mount this type of sensitive components that will provide a good aftersales service.

During the last period of tests, some hardware failures were also detected, where some actuators would randomly raise errors and trip either during their homing process or during valve operation. Further investigation showed that hardware errors where caused by the faulty valve connectors. The connectors of the actuators are very fragile considering the harsh environment where they must operate, especially the encoder connectors. The connector plug-in process, even if carried out carefully, can result in damage in the actuators connectors. A more robust actuator should be chosen for this application in next designs.

FIGURE 2-7: CONNECTORS OF THE HSSV VALVE

Additionally, the software interface between de HSSV controller and the Control PLC had inconsistencies, and the HSSV control software required some reworking on site to ensure safe system operation.

Valuable information was obtained regarding the biradial turbine during the Mutriku test period. However, based in this experience, there was a substantial risk of a possible failure in the HSSV, leading to unsafe state where the valve would be stuck open with the consequence of putting to risk the whole turbine-generator set. This risk was identified during the last phase of the testing campaign in Mutriku, where some failures in the actuators eventually stopped the valve and prevented the system to open/close. Moreover, the system would halt wherever the error was raised, nullifying the safety close procedure and then leaving the air passage to the turbine wide-open.

Some measures were taken accordingly, following the Mutriku campaign, to mitigate this risk:

- First, a thorough refurbishment of the valve actuator was performed, and replacement of a motor was done, while the turbine was on the workshop and prior to its installation in the buoy.
- Second, a command signal was integrated in the PLC that would send a close order to the actuator in case of failure. Unfortunately, this would not avoid the HSSV to get stuck in an open position if an electric failure occurs. Mutriku chamber was equipped with a safety valve with a ballast that would close the air flow to the turbine if a failure occurred. However, the buoy is not equipped with such a protection system due to the strong dynamic effects the ballast would produce in the buoy.
- Last, the HSSV system was connected protected by the onboard Uninterruptible Power Supply, as originally defined in the Risk mitigation plan. This allows the HSSV to be operated even during eventual power shortages, as provides the system of a stable 230V volts output properly isolated from grid disturbances.

Furthermore, the software in the HSSV controller was revised by IDOM to identify critical points that would make the HSSV not reliable. The initialization process was extended to identify possible causes of valve obstruction. The error interface with the PLC was further extended to incorporate diagnosis information that may help identifying unsafe situation in the plant controller. It was also identified that the valve required the four actuators to be operation in order to adequately close the air flow. Nevertheless, the risk finally materialized when failure in valve initialization, and the HSSV commissioning delayed the start of the test campaign.

In March 2019, during some commissioning tests, an electrical failure caused the valve to stuck open with the turbine rotating freely. The attempt to take control on the generator was made, but an overcurrent in the HSSV cabinet tripped the U UPS system, leaving the buoy in blackout situation. This led to a loss with the buoy communication with the HSSV open, and the air flow spinning up the turbine. It was only due to the fact that the buoy was being operated from BIMEP's local offices that it was possible to make a fast trip to the buoy to manually stop the system, ensuring that the turbine didn't accelerate over the high-speed safety limit. Ultimately, decision to maintain the release valve open during the commissioning was also crucial, preventing all the air flow from going to the turbine and accelerating it to a speed where its integrity would have been compromised.

Further diagnosis determined that an electrical problem caused the actuator to fail and the HSSV to get stuck in open position. FIGURE 2-8 shows the state of the power connector and plug of the actuator. The probable cause of the electrical failure was identified a faulty connector that created a hot-spot in the connector, ultimately leading to its overheating.

FIGURE 2-8: POWER CONNECTOR AND PLUG OF HSSV ACTUATOR

Soon after the damaged actuator and power cable were replaced, some new problems appeared. These problems were related to the encoder connection of the actuators.

In-deep investigation revealed that the problem could come from either the Weidmuller connectors installed between the servo drives located inside the buoy or the actuators themselves located in the deck of the buoy.

This intermediate connection had to be installed in the power and encoder cables between the HSSV actuators and the drives of this actuators located inside the buoy. This connection was made using Weidmuller Rockstar connectors with the aim of facilitating the commissioning works of the turbine and its adaptation to the existing MARMOK-A-5 wiring systems. However, the harsh environment caused corrosion to build-up on these connectors. A bad connection due to rust could be probably the cause of the errors encountered.

FIGURE 2-9: HSSV ACTUATORS WEIDMULLER INTERMEDIATE CONNECTION

To solve the issue, a direct connection from the actuators and the drives was implemented, using 15-meter length cables, bypassing in the intermediate connection. The cables were passed through the connection box using cable glands. The Roxtec connectors were used to pass insert the cables inside the buoy. Additionally, EMI/EMC filters where installed in the servo drives, as this was recommended by the drives manufacturer to reduce possible noise interferences.

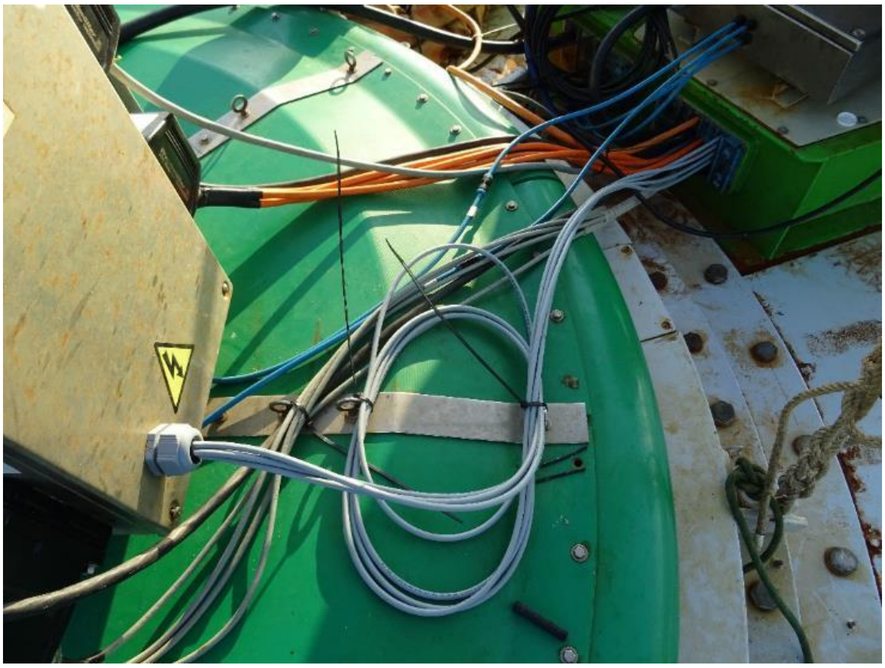

FIGURE 2-10: ENCODER CABLES DIRECT CONNECTION THROUGH CONNECTION BOX AND ROXTEC

These actions solved the encoder errors, however, soon after, new problems emerged in the HSSV valve.

During a heavy storm, and only two days after the encoder problem was solved, another actuator was damaged. Again, a shortcut error arose in the drive of the actuator number 1, and as had happened before, the actuator power connection was damaged, apparently due to an overcurrent.

With the testing campaign near its end, the decision was taken to bypass the terminal box again a route power cables directly from the drives to the actuators, using a direct connection, with 15-meter-long cables.

FIGURE 2-11: CABLE GLANDS IN CONNECTION BOX FOR ENCODER AND POWER CABLES

Finally, a decision was made to operate the valve at low speed (open/closing times around 1 second) and not using fast mode (open/close time of 0.1 second), as consequence that this imposed very tight control loops in the servo drives that produced following error trips in the drives when performing fast closes/openings.

This final modification paved the way for successful operation of the HSSV buoy for the rest of the test campaign, which totalled more than 900 hours of operation.

2.2.3.2 ELECTRICAL GENERATOR

The air turbine is directly attached to a generator with a flexible coupling to absorb the misalignments between parts. The generator is a commercial squirrel cage induction machine of SIEMENS with a rated power of 30kW.

A fault in the generator caused an early damage in the machine on September 2017 that ultimately led to stopping the test until the problem could be solved. The installed generator was not equipped with the correct degree of electrical insulation protection of the stator, which is typical of applications where the motor if fed by a Variable Frequency Drive.

The chosen generator was not appropriate for a Pulse Width Modulation (PWM) based inverter feeding as the power signal of FIGURE 2-12.

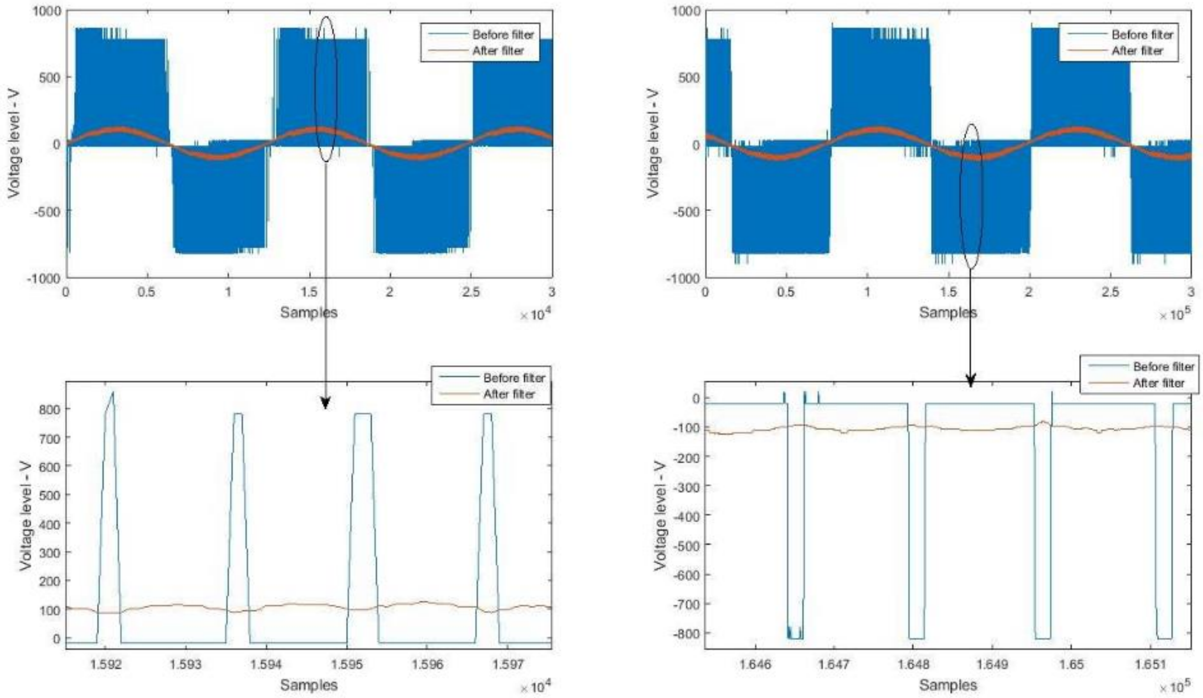

FIGURE 2-12: GENERATOR POWER VOLTAGE SIGNAL

The isolation of the stator could not cope with the chopped power input of the machine and a shortcut damaged completely the stator of the motor. Two actions were taken to deal with this problem:

- On one side, a new stator was reinstalled in the generator. This new stator incorporated a reinforced insulation to avoid possible new damages produced by the same cause. The procedure of extracting the generator from the turbine and reinstalling it in its position was a complex task, due to the tight fitting of the generator inside the HSSV supporting structure.

The procedure complicates furthermore if it was done in the MARMOK-A-5 buoy. A failure of this type offshore would mean a severe drawback that would have been extremely difficult to overcome while at sea.

- As an additional layer of protection, a sinus wave filter has been installed between the inverter and the generator. This filter smooths the power signal of the generator, avoiding high voltage values in the machine, protecting the stator and extending the life time of the generator, in order to pass the test in this harsh environment.

Unfortunately, this last action presented some drawbacks. The generator was previously controlled using a closed loop vector control with the control techniques power electronics. However, the use of the filter caused the control to be unstable due to the changes in the electrical parameters introduced by the new configuration. This issue has been detailed in deliverables D3.4 and D4.3.

This problem could be overcome if the control parameters of the vector control are recalibrated using the tuning tools offered by the power electronics. However, in order to perform these, some tests need to be carried out in the generator, without the turbine attached to it, and this was not possible because the generator was already installed in its position in the turbine before the filter was installed.

Due to the impossibility of implementing a closed loop control, a scalar open loop v/f control have been installed to control the generator in series with the filter. This kind of control reduced the performance compared to the closed loop FOC control. Nevertheless, the main objective of these tests is not only to validate performance of the turbine but also to compare different high-level control strategies programmed in the PLC. These tests could be carried out with this new deployment.

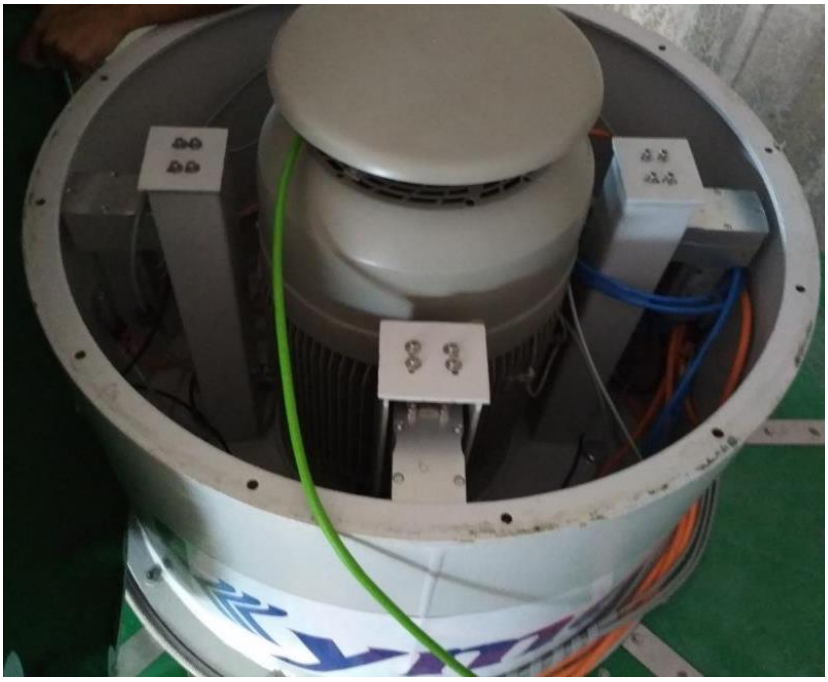

FIGURE 2-13: SIEMENS IM GENERATOR INSIDE THE TURBINE NACELLE

The integrity of the generator during the offshore test campaign raised some concerns, being a component that had already suffered a failure in Mutriku. The risk that the generator could suffer a second insulation failure persisted, as the sufficiency of the LC filter to prevent this from happening remained unclear.

However, the part of the generator that failed during the test period was the encoder of the generator. During a test stage, the encoder suddenly stopped working. Moreover, the encoder provided overcurrent error and consequently tripped power electronics, preventing the continuation of the tests campaign.

Even though the V/f control strategy does not need the speed feedback to work, it is still necessary to know the instantaneous rotational speed in order to test the controls developed in WP4. A replacement of the encoder was installed short after the failure, putting special attention on the robust mechanical fitting to the generator and avoiding once again the pass through the terminal boxes by means of a 15-meter cable that was routed directly to the variable frequency drive.

2.2.3.3 VIBRATION SENSORS

The vibration sensor equipped in the turbine during their dry-lab phase in Lisbon did not provide a meaningful reading. They provided acceleration RMS reading while rotary machine standards are generally expressed in mm/s. This led to the need to replace the sensors during the turbine commissioning in Mutriku.

The vibration values were measured in the turbine during normal operation and can be observed in FIGURE 2-14:

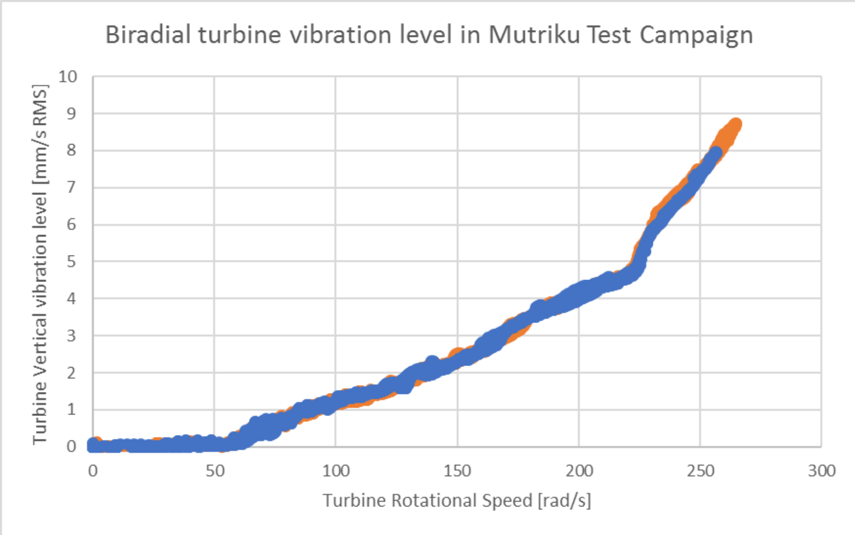

FIGURE 2-14: SIEMENS IM GENERATOR INSIDE THE TURBINE NACELLE

The mechanical coupling and the overall fitting of the generator to the turbine rotor was later revised prior to its installation in the MARMOK-A-5 and vibration levels were improved.

2.2.3.4 TURBINE CONNECTORS

The generator power cables and all the sensor cables of both turbine and the generator were connectorized using commercial Weidmuller Rockstar connectors. This was decided based on previous successful experience of IDOM with this approach applied to their Wells turbines. These connectors offered a very good performance during the MARMOK-A-5's first deployment campaign offshore.

However, the connection of the power cables required substantial work. The 35mm2 section cables used to feed the generator were complex to manipulate due to their low flexibility. The force produced due to the rigidity of the cables made them hard to introduce inside the connector holes and broke in some cases the eyelash that holds the connector pin in position.

FIGURE 2-15: WEIDMULLER ENCODER AND POWER CONNECTION

The installation of a more flexible cable would facilitate the setup for the power connector. A different kind of connector could also be chosen as the power cable was already installed in the test site.

The harsh environment where the turbine is installed led to rust appearing in the connectors. This effect is especially pronounced in Mutriku wave power plant as the air flow coming from the wave chambers is directly fed to the turbine galleria. This produces an ambient full of salty moist that affects to all equipment installed inside the plant.

During both Mutriku and BiMEP test campaigns some maintenance actions were taken, i.e. turbine terminal boxes and connector were inspected and cleaned to ensure correct operation.

2.2.4 POWER ELECTRONICS AND POWER MEASSUREMENT

The power electronics consist of two M700 series (Control-Techniques), connected back-to-back. The system is formed by a 132kw AC/DC regenerative dispositive and a DC/AC drive of 90kw. The regenerative is connected to the grid through an LCL filter and drive is directly connected to the generator. The power electronics in Mutriku are located in a room isolated from the area where the air chambers are located, so they are protected from exposure to moist and salty air to avoid corrosion. The electronics communicate with the PLC using TCP/IP protocol and different references are controlled through the PCL code.

FIGURE 2-16: POWER ELECTRONICS CABINET

The power electronics worked perfectly during the Mutriku test campaign. However, uncertainties in the power measurement resulted in significant extra effort in assessing the real electrical magnitudes coming from the generator mounted in the biradial turbine. The measurements by the Unidrive are not accurate, as they are only intended to represent approximate values, and incorporates significant errors depending on the load applied.

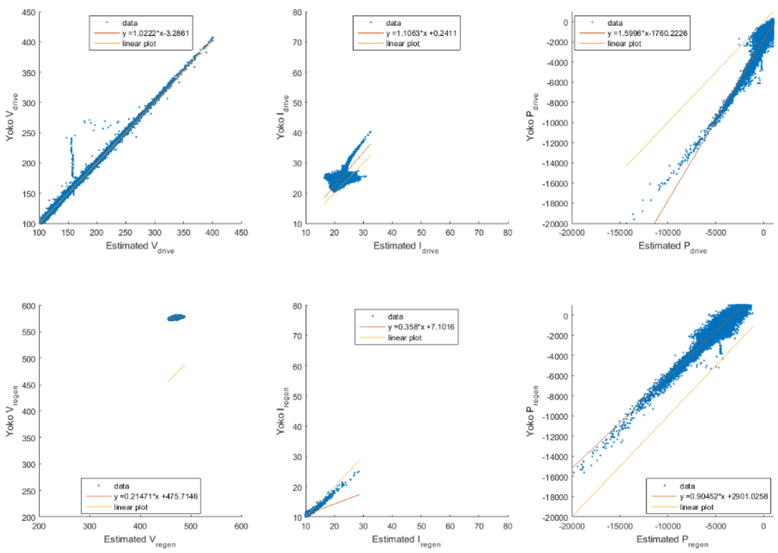

FIGURE 2-17: POWER ELECTRONICS POWER READING VS WATTMETER'S READINGS AS IN D4.2

This could be solved using a true RMS power measurement equipment, like a wattmeter, but the installation of this equipment for the duration of the complete test period was not feasible.

Fortunately, a Yokogawa wattmeter courtesy of Tecnalia was installed in the plant and registered power values for some days while Control Laws were being tested. In addition, some prior experiments in Tecnalia's dry lab were carried out under similar configuration to validate the data acquisition systems, enabling the most effective use of the time the equipment would be deployed in Mutriku.

The data of the test bench and the data registered with the wattmeter was then used to develop the corrections show in Deliverable D4.2. This compensation can be used to adjust the measures of the power electronics and obtain more accurate power results.

The power electronics installed in the buoy are the same as the one used in Mutriku. The main difference comes from the voltage level, 460V in Mutriku vs 690V in Marmok-A-5. The voltage level has been increased to the next 690V standard in order to reduce the current level circulating through the cable and reducing in this sense the losses. Furthermore, the cable section required for transmission of the same power level reduces. This turned to be a good solution, however, this produced some problems with the bus charge by the regen in the power electronics.

For proper operation of the rectifier, a minimum dc-link voltage is needed to obtain undistorted voltage waveforms. To have a full control of the rectifier, its six diodes of the IGBT semiconductors must be polarized negatively at all value of ac-voltage supply. To keep the diodes blocked, we need to ensure a dc-link voltage higher than the peak dc-voltage generated by the diodes alone.

The voltage generated by the rectification of the diodes, is the pre-charge bus voltage value.

$$V_c = \sqrt{2} \cdot V_{in} = \sqrt{2} \cdot 690 = 975V$$

As explained above, the bus voltage should be higher than this value. The LC filter installed to protect the generator has a maximum overvoltage limit of 1078V.

To fulfil these two requisites, a voltage bus of 1000V has been chosen. The bus voltage was set at 700V in Mutriku due to the grid power supply voltage was 400V. The effect of this voltage difference should be further studied.

2.2.5 POWER QUALITY MEASUREMENT

The acquisition system used to apply the IEC 62600-30 Standards to the MWPP 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 Radio-Frequency Interference (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 IEC 62600-30 Standards. To perform the harmonic analysis presented in this report, the IEC 62600-30 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 IEC 62600-30. The limitation was due to the card being responsible for monitoring 3 signals. The number of signals handled by a single card effects the sampling rate, and 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.

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. LEM supplied both 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, which 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 2-18 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.

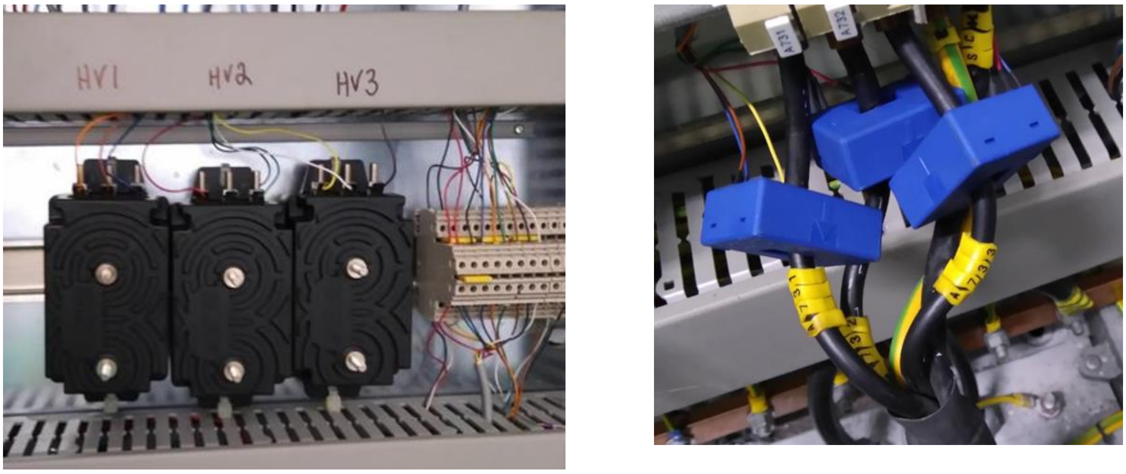

FIGURE 2-18: VOLTAGE (LEFT) AND CURRENT (RIGHT) SENSORS AS INSTALLED IN MUTRIKU

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 in renewable energy generation systems. Unfortunately, the space and wiring requirements forced the installation of the transducers between the RFI filter and the grid-side VFD, and this influenced the results of the testing. FIGURE 2-19 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.

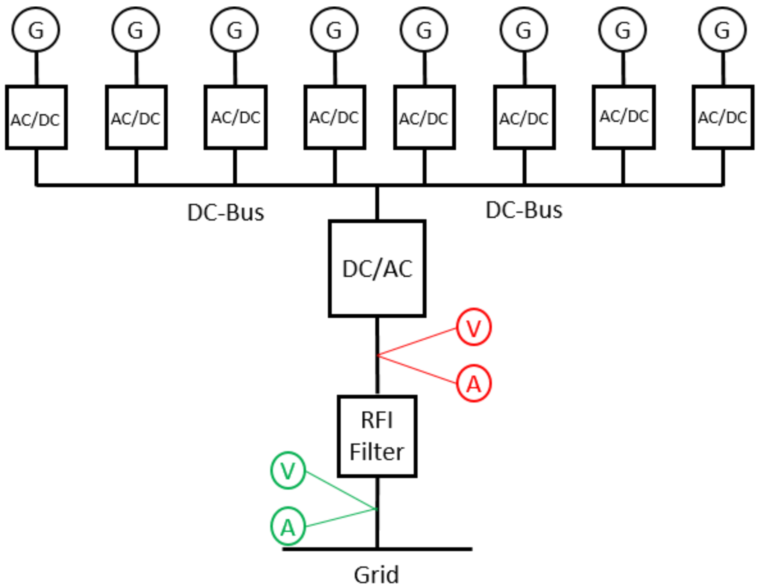

FIGURE 2-19: SINGLE LINE DIAGRAM OF USED MEASURING POINT (IN RED) AND THE MEASURING POINT RECOMMENDED BY TS (RED)

2.2.6 CONTROL SYSTEM

The control PLC installed was in charge of critical task for the correct operation of the complete PTO system:

- Acquire a process measurement values from field components (pressure, internal water level, temperature sensors.);
- Communicate with the Variable Frequency Drive in a fast a reliable way to correctly control the power extraction from the generator;
- Control the safety aspects of the power capture and trigger safety procedures if necessary (i.e. safely turn down the power electronics and close safety valve);
- Control the HSSV system to perform safety and control-level operations (i.e. latching/unlatching.; and
- Postprocess data to be presented to the SCADA system.

The selected PLC, a 600MHz CPU unit from Austrian manufacturer Bernecker & Rainer offered a very good performance without any major issue. Moreover, it showed excellent operability, and was a centrepiece across the 6 control laws testes in Mutriku.

IDOM had previously worked in the control software framework that implements the overarching state machine to control PTO operation, plant safety and acquisition system, in a way that only 48 hours were necessary to produce the first tests after turbine commissioning.

FIGURE 2-20: CONTROL CABINET PRIOR TO ITS INSTALLATION IN MUTRIKU

2.2.7 INERTIAL MOVEMENT UNIT SENSOR

Six Degrees of Freedom (DOF) of the buoy are monitored and stored online using an Inertial Movement UNIT (IMU) sensor and the help of a Global Navigation Satellite System (GNSS) antenna. During data analysis, uncertainties in the registered data concerning the yaw angle rose, detecting a non-constant drift in the yaw measurement.

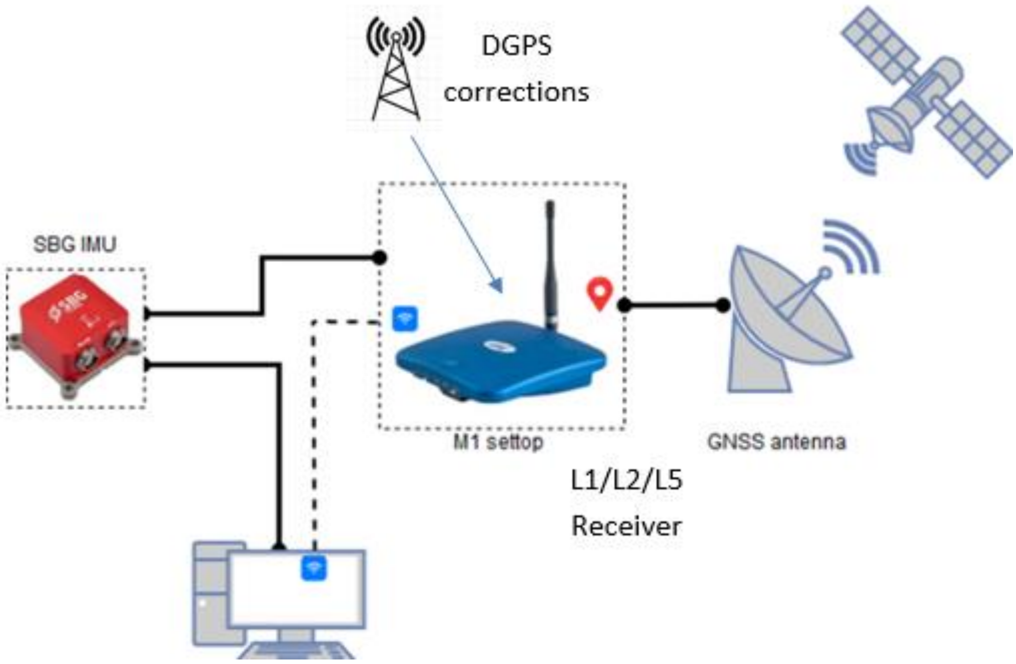

FIGURE 2-21: 6 DOF IMU SENSOR CONFIGURATION DURING DRY TESTS

A series of dry tests of the position monitoring system where performed in IDOM's offices to identify the possible source of the problem. The tests threw that the yaw value is measured using a gyroscope, which naturally measures angular rotation velocity, that needs to be integrated over time to obtain the angle value. This produces an intrinsic error that will be accumulated over time in the computed solution, producing a drift in the measured value.

However, a different response has been detected in this configuration for some time periods. Under certain conditions in the WEC, this drift is not present in the yaw value. This happens when an acceleration is detected by the sensor, where the Extended Kalman Filter of the IMU sensor can stabilize the heading angle, by detecting a significant acceleration of the buoy, where a device motion is supposed. Using this motion, the heading angle is estimated. Nonetheless, the buoy is fixed in the same location, so any motion caused by the waves should not be considered for yaw calculation.

The real position yaw position of the buoy should have been determined using two GPS antennas receiver. This solution would eliminate both the drift and the heading angle determination through the movement of the sensor, reducing considerably the uncertainties in the yaw result.

2.2.8 SCADA AND DATABASES

The SCADA and database system were deployed according to the plan detailed in D1.1, incorporating only small modifications. The acquisition rate was set to 4Hz as a good trade-off point between data being technically useful and the volume of the data and the acquisition rates to be feasible within project budget.

The databases were stored in a local MySQL server, and automatically replicated, on a real-time basis, to a cloud-based hosting platform (Amazon Web Services – Relational Database Service), to where the user queries are directed. This allow ensuring automated backups, high-availability (HA) of the data, and effective segregation of data writes (taking place in Mutriku server) and user data queries (coming from each project partner location).

Datasets produced during the Mutriku testing campaign so far include:

- 13 Months of plant operational data from Mutriku Wave Power Plant.
- 13 Months of biradial turbine operational data in Mutriku, including CL tests.
- 4 Months of Power Quality monitoring data from Mutriku.
- 4-5 days of continuous recording from wattmeter along with power electronics data.
- 4 Months of environmental data from Mutriku recorded and published in ZENODO repository

Access to database was given to project partners by two mechanism

- Providing direct access to the database: Specific allowed public internet addresses where given access to the virtual private cloud system. A username and password are required to be able to connect to the database system. Once setup, the user is able to fetch data my standard SQL commands or by means of a third-party software to access it (i.e. python code, Matlab Database Toolkit, etc.).
- Providing an online Data Query Tool, programmed in MS Excel, that already deals with database connection. The end user selects the columns to be fetched from a drop-down menu and can view/plot data by standard MS Excel procedures. This tool was developed with the aim of providing easy access to experimental data to both experts and non-experts, as the interface does not require any technical software nor special knowledge of data processing to be able to plot variables and perform simple analysis.

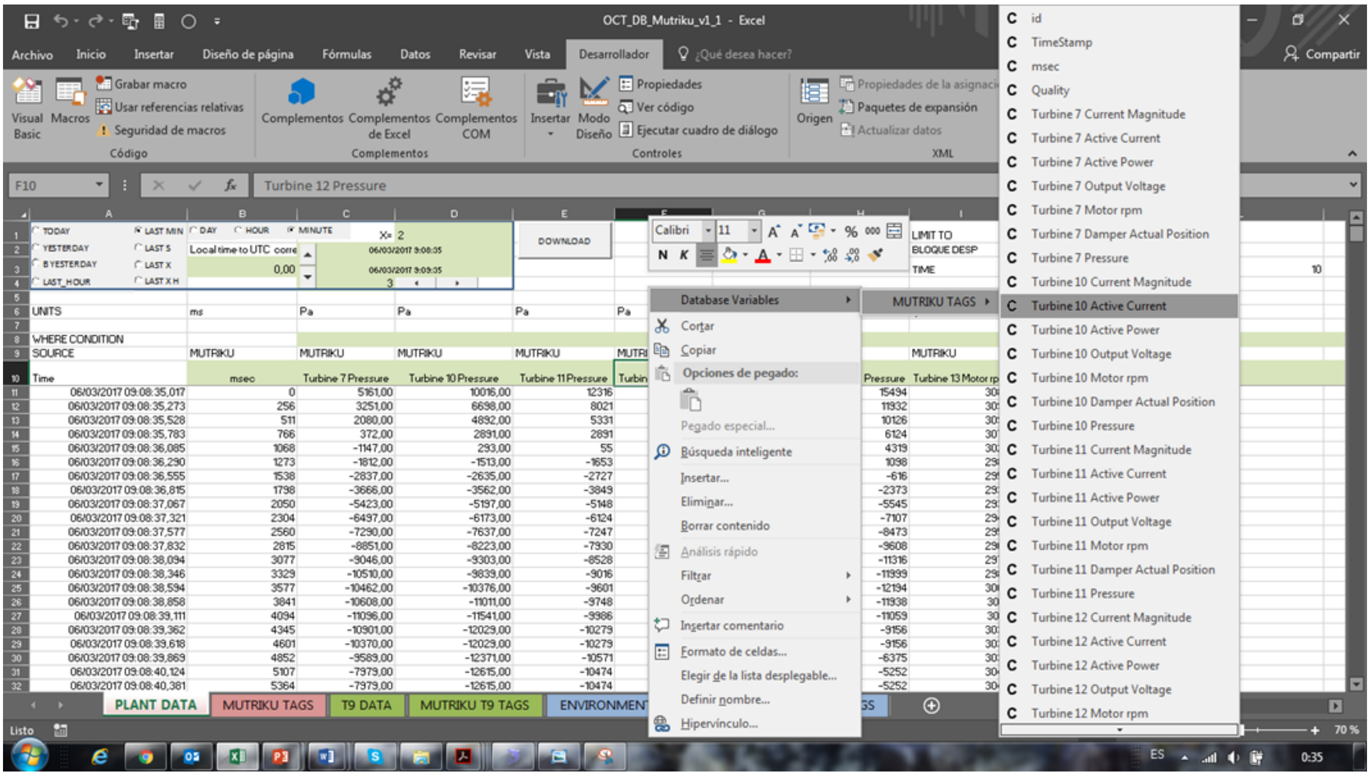

FIGURE 2-22: SCREENSHOT OF ONLY DATA QUERY TOOL

The approach used during the BiMEP test campaign was very similar, building on existing acquisition infrastructure already deployed by IDOM for this activity previous to OPERA project.

Datasets produced during the Mutriku testing campaign so far include:

- 2,250 tests, covering over +900 hours of operation since their beginning, for a rough 90% of system availability. This makes almost 6GB of operational data that has been the backbone of turbine and control law performance.

- 165 GB of data for the first testing campaign without the elastomeric tethers and 135 GB of data for the second testing campaign with the elastomeric tethers. This entails systematically storage of 800 million data rows of 20Hz of integrated mooring load and Wave Energy Converter movement information.

- 2.5 years of environmental statistical data from the tri-axys buoy and 4 months of real time wave elevation information.

For the acquisition of the environmental data, a separate laptop was prepared by Tecnalia, gathering all the information sent by the buoy both about 20-min statistical data and real-time wave elevation. This laptop was communicated by some scripts developed in PowerShell code to pass the information to the operational database holding all the rest of the data.

2.2.9 WAVE MEASUREMENT INTRUMENTATION

Underwater Pressure gauge with data logger:

With the objective of measuring the available wave resource in terms of wave height and period during the tests, a pressure sensor was installed at the bottom of the sea, at the wave plant entrance.

FIGURE 2-23: DIVERS INSTALLING THE UNDERWATER PRESSURE SENSOR

Installed in November 2016 (FIGURE 2-23), 200 m in front chamber #9, following the most frequent wave direction, in a depth of around 15 m. It was removed in May 2017, but a leakage in the battery happened in February leaving only three months of viable data.

After its repair, and due to the hard conditions of winter, it was not possible to reinstall it until late January 2018. In June 2018, it was removed again for data collection and reinstalled immediately. A total of 8 months of data was registered, out which 2.5 months covered the CL testing period in Mutriku.

Pressure gauge with real-time communication

The installation of an underwater pressure gauge with real-time reading capability was delayed due to the bad weather conditions happened during winter and local authorities' consent. It was finally installed in May 2018, 200 m offshore in a depth of around 15 m.

This sensor nevertheless served for execution of CL6.2 (predictive algorithms) tests in the late phase of the Mutriku test campaign.

Tri-axys buoy

In BiMEP, a tri-axys environmental buoy from the Canadian manufactures AXYS Technologies has been used to store the resource data in a database. The initial deployment of the buoy took place in December 2016 and it was de-commissioned on June 2019. The tri-axys buoy can measure statistical parameter of wave climate, provide wave spectra measurements and provide real-time elevation information to feed predictive control algorithms in the WEC.

FIGURE 2-24: TRIAXYS DEPLOYED AS CLOSE TO THE MARMOK-A-5

The buoy was installed 07/12/2016 in BiMEP (Armintza) with the support of multipurpose TUG boat (Hodeiertz) and a multipurpose work class speed boat, suited for shallow diving and quick interventions (UR-SUB). The operation was successful, and the buoy was in continuous operation till 29/09/2017 when a new operation was organized with the objective of extracting operational from the buoy and performing some cleaning and checking of the sacrificial anodes cathodic protection system.

This operation was completed with a multipurpose ship, using a crane to extract the buoy from the water. The operation was completed by divers. The buoy was cleaned and opened to extract the data, and unfortunately circuitry inside the environmental buoy was damaged during this operation.

FIGURE 2-25: RETRIEVAL OF TRI-AXYS BUOY FOR MAINTENANCE WORKS

The reparation of the damage required 2 months, with the buoy kept in a dry workshop, and in the beginning of 2018 the buoy was finally re-installed again and was in continuous operation until the end of 2018.

At this stage the batterie's performance started to deteriorate. The graph below shows the slow but steady decay of the battery voltage levels during Fall 2018. Unfortunately, this overlapped in time with the deployment and the commissioning of the wave energy converter.

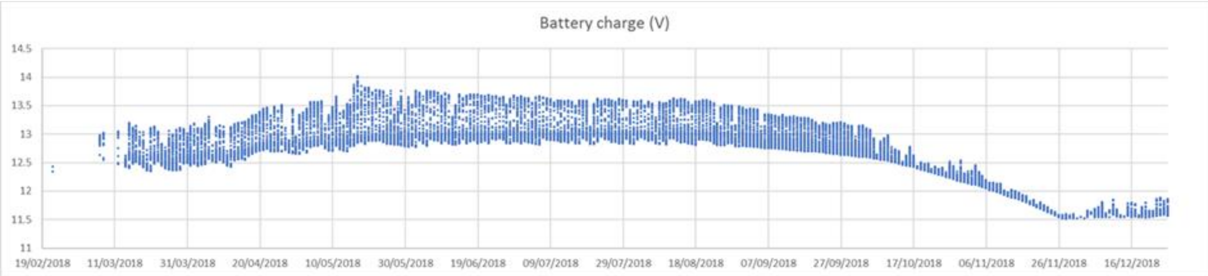

FIGURE 2-26: TRIAXYS BATTERY VOLTAGE ALONG 2018

With the aim of mitigating this lack of good quality environmental measurements, BiMEP's Fugro buoy was taken into consideration of a secondary source of wave climate measurement. This would cover with good quality data a period ranging from last three weeks of 2018 to the end of January, where a storm also damaged this buoy. The decision was taken to take out the Tri-axys buoy for battery replacement and to install a third measurement instruments while its reparation, this time from the Basque company Zunibal.

The Tri-axis buoy was again re-installed and started measuring again in February 2019 until the final decommissioning on June 2019. The last two operations where completed without divers with a small ship by personnel of Tecnalia due to the experience acquired in previous offshore operations.

TABLE 2-1: WAVE RESOURCE INFORMATION SUMMARYsummarises wave resource data availability and their source:

TABLE 2-1: WAVE RESOURCE INFORMATION SUMMARY

	2018						2019							
	W47	W48	W49	W50	W51	W52	W01	W02	W03	W04	W05	W06	[green]	Installed & Operational
TRIAXYS	[green]	[blue]	[blue]	[blue]	[blue]	[green]	[blue]	[blue]	[blue]	[blue]	[orange]	[red]	[blue]	Installed & Operational - low data quality
FUGRO	[red]	[red]	[red]	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[red]	[red]	[orange]	Installed & Not Operational
ANTEIA	[red]	[red]	[red]	[red]	[red]	[red]	[red]	[red]	[red]	[red]	[red]	[green]	[red]	Not Installed
				1 STORM						2 STORMS				

3. SENSOR FAILURE RECORD

3.1 INTRODUCTION

During the 42 months of project activity, and across two testing campaigns, a technical and project level risk register has been produced and maintained. The methodologies and templates for this assessment have been developed in WP7, and tables TABLE 3-1 and TABLE 3-2 synthesise the identified failure records produced according to these recommendations.

TABLE 3-1: LIST OF INSTRUMENTATION FAILURES IN MUTRIKU

Instrument	Failure Record	Description
Electrical Generator	F-Mutriku-01	Generator Failure due to inadequate electric insulation
High Speed Switching Valve	F-Mutriku-02	HSSV servomotor encoder failure
Underwater pressure sensor	F-Mutriku-03	Leakage of internal battery of underwater sensor

TABLE 3-2: LIST OF INSTRUMENTATION FAILURES IN BIMEP

Instrument	Failure Record	Description
Internal Water level sensor	F-Bimep-01	Failure in providing accurate readings due to unsuitable mounting position of the sensor
High Speed Switching Valve	F-Bimep-02	HSSV Encoder Failure
Electrical Generator	F-Bimep-03	Failure in electrical generator's encoder.
Mooring Load Shackles	F-Bimep-04	Failure of cables connecting the load shackles to the WEC.
Environmental buoy	F-Bimep-05	Depletion of internal battery of the wave measurement instrument

3.2 FAILURE RECORD IN MUTRIKU

TABLE 3-3, TABLE 3-4 and TABLE 3-5, provide the failure record in Mutriku, in relation to the electrical generator, high speed switching valve and underwater pressure sensor, respectively.

TABLE 3-3: GENERATOR FAILURE RECORD IN MUTRIKU

Category	Data to be recorded	Description
Identification	Failure record	F-Mut-01
	Equipment identification	S.03.01
Failure data	Failure date	2017/09/29
	Failure mode	Generator failure
	Failure impact on plant safety	Partial
	Failure impact on plant operations	Partial
	Failure impact on equipment function	Critical
	Failure mechanism	Physical, failure in dielectric isolation leading to winding short-circuit
	Failure cause	Inadequate stator dielectric insulation for used power supply
	Subunit failed	Electrical generator mounted into biradial turbine
	Component/Maintainable items failed	No maintenance is applicable, being component construction-level feature.
	Detection method	Fault detected by power electronics
	Operation condition failure	During system operation.
Remarks	Additional information	Failure caused by a bad selection and procurement of the generator, which was not equipped with proper insulation of the stator to be powered by a PWM signal.

TABLE 3-4: HSSV FAILURE RECORD IN MUTRIKU

Category	Data to be recorded	Description
Identification	Failure record	F-Mut-02
	Equipment identification	C.04.02
Failure data	Failure date	2018/08/08
	Failure mode	HSSV stops operation as remains blocked
	Failure impact on plant safety	Partial

	Failure impact on plant operations	Partial
	Failure impact on equipment function	Critical
	Failure mechanism	Physical
	Failure cause	Error in encoder signal received by Servo Drive.
	Subunit failed	HSSV actuators encoder
	Component/Maintainable items failed	Encoder
	Detection method	Fault detected by actuator driver
	Operation condition failure	Start-up
Remarks	Additional information	HSSV encoder of actuator 1 fault signal during start-up.

TABLE 3-5: UNDERWATER SENSOR FAILURE RECORD IN MUTRIKU

Category	Data to be recorded	Description
Identification	Failure record	F-Mut-03
	Equipment identification	W.09.01
Failure data	Failure date	2017/02
	Failure mode	Leakage in internal battery of underwater pressure sensor
	Failure impact on plant safety	None
	Failure impact on plant operations	None
	Failure impact on equipment function	None
	Failure mechanism	Electrical overcurrent/short-circuit
	Failure cause	Equipment design not robust enough
	Subunit failed	Sensor battery
	Component/Maintainable items failed	N/A
	Detection method	A Posteriori, after sensor retrieval and during data uploading process
	Operation condition failure	Operational
Remarks	Additional information	

3.3 FAILURE RECORD IN BIMEP

TABLE 3-6, TABLE 3-7, TABLE 3-8, TABLE 3-9 and TABLE 3-10 provide the failure record in BiMEP, in relation to the internal water level sensor, HSSV motor connection, generator encoder, load shackle cables and environmental buoy's battery failure, respectively.

TABLE 3-6: INTERNAL WATER LEVEL SENSOR FAILURE RECORD FOR BIMEP

Category	Data to be recorded	Description
Identification	Failure record	F-Bimep-01
	Equipment identification	D.02.01
Failure data	Failure date	2019/02/04
	Failure mode	Failure in providing accurate readings by the internal water level sensor
	Failure impact on plant safety	None
	Failure impact on plant operations	Partial
	Failure impact on equipment function	Partial
	Failure mechanism	Physical
	Failure cause	Unsuitable mounting position of the sensor
	Subunit failed	Internal water level sensor
	Component/Maintainable items failed	Measurement quality
	Detection method	Measure error / inconsistency
	Operation condition failure	Running
Remarks	Additional information	Manufacturer provides guidelines por sensor installation, that were not possible to follow due to space constraints.

TABLE 3-7: HSSV MOTOR CONNECTOR FAILURE RECORD FOR BIMEP

Category	Data to be recorded	Description
Identification	Failure record	F-Bimep-02
	Equipment identification	C.04.01

Failure data	Failure date	2019/03/01
	Failure mode	Motor connector burnt
	Failure impact on plant safety	Total
	Failure impact on plant operations	Total
	Failure impact on equipment function	Critical
	Failure mechanism	Physical
	Failure cause	Bad quality of electrical connection.
	Subunit failed	HSSV actuators
	Component/Maintainable items failed	Actuator power connector
	Detection method	Fault detected by actuator driver. Impossibility to operate valve.
	Operation condition failure	Operation
Remarks	Additional information	The whole actuator needed to be replaced while at sea.

TABLE 3-8: GENERATOR ENCODER FAILURE RECORD FOR BIMEP

Category	Data to be recorded	Description
Identification	Failure record	F-Bimep-03
	Equipment identification	S.03.01
Failure data	Failure date	2019/04/20
	Failure mode	Failure in electrical generator's encoder
	Failure impact on plant safety	None
	Failure impact on plant operations	Partial
	Failure impact on equipment function	Total
	Failure mechanism	Physical. Damage to encoder's optic disk.
	Failure cause	Bad quality of mechanical mounting of the encoder into generator shaft. Excessive Radial forces.
	Subunit failed	Generator rotary encoder

	Component/Maintainable items failed	Encoder mechanical fitting into generator frame
	Detection method	Fault detected by Frequency Converter Unit, not being able to read encoder feedback.
	Operation condition failure	Operation
Remarks	Additional information	

TABLE 3-9: LOAD SHACKLE CABLE FAILURE RECORD FOR BIMEP

Category	Data to be recorded	Description
Identification	Failure record	F-Bimep-04
	Equipment identification	C.04.01
Failure data	Failure date	2019/01/25
	Failure mode	Failure of cables connecting the load shackles to the WEC.
	Failure impact on plant safety	None
	Failure impact on plant operations	None
	Failure impact on equipment function	None
	Failure mechanism	Physical, brake of cable due to excessive load.
	Failure cause	Improper design
	Subunit failed	Cables connected to load shackles
	Component/Maintainable items failed	Cables in the connection point to the load shackles
	Detection method	Data loss
	Operation condition failure	Running
Remarks	Additional information	TRI-AXIS buoy data loss due to battery problems.

TABLE 3-10: ENVIRONMENTAL BUOY'S BATTERY FAILURE RECORD FOR BIMEP

Category	Data to be recorded	Description
Identification	Failure record	F-Bimep-05
	Equipment identification	S.12.01
Failure data	Failure date	2019/03/01
	Failure mode	Depletion of internal battery of the wave measurement instrument
	Failure impact on plant safety	None
	Failure impact on plant operations	Partial
	Failure impact on equipment function	Critical to itself None to the WEC
	Failure mechanism	Physical
	Failure cause	Battery deterioration, loss of incident solar power due to fouling
	Subunit failed	TRI-AXIS buoy
	Component/Maintainable items failed	Environmental buoy
	Detection method	Data loss
	Operation condition failure	Running
Remarks	Additional information	TRI-AXIS buoy data loss due to battery problems.

4. INTRUMENTATION FAILURE RISK MATRIX & CONTINGENCY PLAN

The updated risk matrix for the instrumentation system, presented in TABLE 4-1 and TABLE 4-2, provide the end-of-project evaluation of the main technical risk, incorporating all the lessons learnt. The evaluation is performed dividing the risk between those that potentially could impact in plant safety, and those risk that affect operational aspects of the buoy.

4.1 SAFETY RISK EVALUATION

TABLE 4-1: SAFETY LEVEL RISK EVALUATION AND CONTIGENCY PLAN FOR THE SYSTEMS IN THE WEC.

	Description Of Risk	Level of Risk			Proposed Mitigation/Maintenance
		P	I	R	
Air Chamber	Internal water surface hits turbine rotor in harsh sea	L	H	3	Establish safe operational limits taking into account internal water level excursion probabilities
Air Chamber	Pressure Signal wrong value involving an improper actuation of the valve.	L	M	3	Supervise pressure signal and ignore sensor until is fixed working in reduced performance. Introduce aperture valves and perform periodic inspection every 6 months.
Turbine Subsystem	Turbine-generator over-speed above safety limits.	L	H	3	Ensure safety run-down procedures when excessive input power.
Turbine Subsystem	HSSV blocked in unsafe position.	L	H	3	Take speed control of the generator reducing the speed to a safe value. Any possible source of obstruction should be kept away from air duct passage. Visually inspect the air ducts to identify potential sources of obstruction
Turbine Subsystem	HSSV thermal overload due to stress.	L	H	3	Ensure thermal monitoring of servo systems in performed on a real-time basis in order to avoid permanent damage.
Turbine Subsystem	Generator overheating.	L	H	3	Ensure thermal monitoring is performed on a real-time basis and stop tests until a safe temperature is reached.
Turbine Subsystem	Generator speed sensor failure.	L	H	3	Emergency stop of the system and close of the HSSV until the problem is solved.

					In FP-7 funded CORES project a redundancy of this sensor is recommended. The installation of another encoder is not viable in the WEC.
	Generator phase fault.	L	H	3	Ensure phase monitoring of servo systems in order to avoid permanent damage to the generator.
Control Subsystem	Communication with HSSV lost.	L	H	3	Safe Stop procedures must be implemented to guarantee no damage in the equipment: controlled run down of the turbine to 0 rpm. Implement redundant, fail-safe communication protocols where possible. This where not possible due to PLC restrictions in the HSSV controller.
	Communication with Power Electronics lost.	L	H	3	Safety procedures must be implemented in both sides. The Power electronics will trip and stop the generator, while the regenerative side will trip and stop. Implement redundant, fail-safe communication protocols where possible.
	Control cabinet over-temperature.	L	H	3	Safe stop of the whole system. Incorporate active/passive ventilation system in design phase. A basis thermal model of the buoy was performed during MARMOK-A-5 design. Passive ventilation system was incorporated to the buoy and active ventilation of electrical cabinets. PLC incorporates thermal monitoring of its on circuit boards. Select extended temperature ranged models for critical components
Power Electronics	Power electronics thermal overload.	L	H	3	Reduce air flow to generator. Check ventilation fans of the power electronics enclosure.

					A basis thermal model of the buoy was performed during MARMOK-A-5 design. Passive ventilation system was incorporated to the buoy and active ventilation of electrical cabinets.
	Power electronics equipment brake. Caused by semiconductor brake, bus brake or/and current sensor failure, etc.	L	H	3	Close valve and replace broken component.
	Phase fault/imbalance or earthing fault.	L	H	3	Safe disconnection of the power electronics to prevent further damage to personnel or equipment. Residual current monitoring is advised to detect earth leakage faults.

4.2 PERFORMANCE RISK EVALUATION

TABLE 4-2: PERFORMANCE LEVEL RISK EVALUATION AND CONTIGENCY PLAN FOR THE SYSTEMS IN THE WEC.

	Description Of Risk	Level of Risk			Proposed
		P	I	R	
Wave Instrument	Loss of wave forecasting measurement.	L	M	2	All control laws should contain an alternative control strategy in case this signal is not available. Such modes should remain operational and safe until wave forecasting information is restored.
Mooring	Mooring load sensor failure.	L	M	2	The replacement of this sensor is complex and expensive. In case of multiple line failure, replacement operations may be considered.
Buoy sensors	Inertial sensor failure	L	M	2	Plan Lab test before system deployment to ensure solution suitability. Plan system self-test and failure recovery mechanism for use when deployed. Incorporate diagnosis data to recorded dataset to check measurement quality on a real-time basis.
	GNSS system failure	L	M	2	Plan Lab test before system deployment to ensure solution suitability. Plan system self-test and failure recovery mechanism for use when deployed. Incorporate diagnosis data to recorded dataset to check measurement quality on a real-time basis.
Air Chamber	Pressure sensor failure.	L	M	2	Work only with the second installed sensor in reduced performance until it is fixed.

					Check operational data as early as possible to check data validity.
	Chamber temperature sensor failure.	L	L	1	Replacement of the sensor when possible.
	Chamber humidity sensor failure.	L	L	1	Replacement of the sensor when possible.
	Wave elevation signal outage/failure.	L	M	2	All control laws should contain an alternative control strategy in case this signal is not available.
Turbine Subsystem,	Existing systems not sufficient for system evaluation/ Turbine performance evaluation too complex.	L	L	1	Turbine performance evaluation tools should be specifically implemented. This could consist in excel spreadsheets or *MatLab* scripts for adequate performance evaluation using available sensors.
	Turbine presents excessive vibration levels.	L	L	1	Safety threshold should be defined in design stages. In excessive vibrations persist during turbine operation, level reduction mechanisms should be envisaged in advance.
	Generator temperature sensor failure.	L	M	2	Estimate generator temperature through remaining available sensors.
Control Subsystem	Control PLC does not have enough computational capacity for handling control laws.	M	M	2	Control laws should be adapted to the computational capacity of the PLCs. The upgrade of the PLC in Mutriku could also be evaluated. Early tests in Mutriku will help mitigate this risk in the WEC.
	Implementation of control strategies in PLC more complex than initially expected.	L	M	2	Early tests in Mutriku will help mitigate this risk in the WEC.
	Read/Write rates in the PLC to slow/not precise enough for correct control law implementation.	L	L	1	Task cycles in the PLC to be reduced to the minimum. Upgrade of the PLC or the I/O cards of the PLC may also be advisable. Early tests in Mutriku will help mitigate this risk in the WEC.

Power Electronics Subsystem,	Output power measurement from power electronics do not provide enough accuracy/resolution for evaluation purposes.	M	M	2	The need of specific electrical power measurements has to be evaluated.
	Communication between the PLC and the Power Electronics too slow/restricted for successful deployment/evaluation of control laws.	L	L	1	Communication rates can be pushed to achieve faster I/O refresh, but the feasibility and long-term stability of these changes may need evaluation.
Database Subsystem	Database system information loss.	L	H	3	Data buffering and daily backups should ensure data integrity across.
	Database data inconsistent.	L	M	2	Each WP partners is responsible of the validity of the data produced. In data in found to be invalid, problem should be traced downwards up to device level in order to assess the most suitable contingency action.
	Data rates to slow.	M	M	4	Check the adequacy of the rates specified by partners. If the solution can't guarantee correct evaluation of the successful completion of the technical work within the corresponding WP, the feasibility of the modification of these rated has to be evaluated by WP1 Leader and Project Leader.
	Database size grows too big.	M	M	4	Specific mechanism for size contention of the monitoring system should be implemented in the database design. Implement database level improvements to fasten access; partitioning, indexing… or eventually upscale server to allocate more computing resources (this is possible on-demand in AWS)

5. CONCLUSIONS

The ambitious instrumentation and data acquisition systems planned and deployed for field testing within the OPERA project has thrown very satisfactory results. This entailed:

- Defining a robust mooring condition monitoring system (CMS) with a 20Hz rate acquisition systems;
- Adequately instrumenting the biradial turbine;
- Providing high-quality environmental information data, including real-time wave elevation information both for Mutriku and BiMEP to feed predictive controls Laws;
- Deploying power quality metering system to meet IEC-TS-62000 power quality requirements; and
- Building and homogeneous acquisition system to incorporate all the operational data produced in the project and provide seamless access tools for every partner to access the data.

All the objectives listed above have been accomplished, clearing the path for successful innovation impact assessment.

The testing campaign in Mutriku offered a good opportunity to identify and mitigate risks. Problems encountered during onshore tests could be solved more easily and less costly than if the problem had emerged during the offshore tests. Events like the generator failure would be very hard to be overcome in the Marmok-A-5. This demonstrates the importance of the tests carried out in Mutriku wave plant before the offshore deployment and are strongly recommended for future demonstration projects. Even if the tests were carried out in an indoor test site, the same equipment configuration should be used during the experiments, providing the most realistic testing environment as possible.

The testing campaign in BiMEP presented many challenges, and the system commissioning took longer than expected. However, once the system was operational, an intense testing campaign was implemented, reaching the mark of 2,250 control law test runs that extended over more than 900 hours of tests.

6. REFERENCES

[1] Technical Note: “WP1-62600-30 Data Needs”. OPERA Project.

[2] Technical Note: “CORES sensor Recommendations”. OPERA Project.

[3] Technical Note: “Mooring condition monitoring signal requirements”. OPERA Project.

[4] Technical Note: “PTO Instrumentation”. OPERA Project.

[5] Technical Note: “Selection of a wave measuring instrument for *bimep*”. OPERA Project.

[6] Deliverable 7.1: “Initial risk and failure data collection protocol for H2020-OPERA project”

[7] Technical Note: “IMU and GNSS dry tests”.

[8] J.Kelly, E.Aldaiturriaga, P.Ruiz-Minguela : Marine Tidal and Wave Energy Converters: Technologies, Conversions, Grid Interface, Fault Detection, and Fault-Tolerant Control. [Paper Submmited, under revision]

7. ANNEX I: LIST OF AVAILABLE INSTRUMENTATION IN MUTRIKU AND BIMEP

Legend:

Column	Key
Function	R. Research O: Operational. B: Both
Interface	AI. Analog Interface D: Digital Interface C: Communications

Device Id Tag: **X.YY. ZZ**

X

X	measure code
T	Temperature
P	Pressure
L	Limit position
C	Displacement
H	Humidity
S	Rotational speed
A	Acceleration
V	Output voltage
I	Current
O	Various
W	Wave info

YY

Area Code

Code YY	Area
01	Air Chamber (MUTRIKU)
02	Air Chamber (WEC)
03	Turbine Nacelle
04	Turbine
05	Turbine Hall (Mutriku)
06	Power Electronics
07	MV Hall (Mutriku)
08	Machinery Room (WEC)
09	Wave Instrument (Mutriku)
10	Wave Instrument (*BiMEP*)
11	Other Chambers (Mutriku)
12	Mooring Lines

ZZ:

Sequential identification of device in each area per type

TABLE I-7-1: LIST OF EQUIPMENT AVAILABLE FOR MUTRIKU TEST CAMPAIGN.

Instr	Tag	Manufacturer	Description	Type	Model	IP	Signal type	Res/Acc	Interface	Range	Rating
Area 01: Air Chamber in Mutriku											
1	**D.01.01**	Rosemount	Internal Water Surface Level	Non-contacting Radar	5601	67	4..20 mA/HART	± 5mm	AI/C	Config.	Good
2	**P.01.01**	Druck Industrial	Air pressure inside chamber	Differential pressure transducer	GE PTX 7535	65	4 - 20 mA	0,10%	AI	-1.0 / +1.0	Good
3	**P.01.02**	Keller	Air pressure inside chamber (max)	Differential pressure transducer	PAA-21Y	65	0 - 5V	± 1%	AI	0.0 / +2.5	Good
4	**P.01.03**	Keller	Air pressure inside the adapter cone	Differential pressure transducer	PD 23	67	4-20 mA	0,005	AI	+/- 0.2	Good
5	**P.01.04**	Keller	Air pressure inside the adapter cone	Differential pressure transducer	PD 23	67	4-20 mA	0,005	AI	+/- 0.5	Good
Area 03: Generator Nacelle											
1	**T.03.01**	Analog Devices	Generator winding temperature	PT100	TMP 36GZ		V	0.5 ºC	AI	-40 +150 ºC	Good
2	**T.03.02**	Analog Devices	Generator winding temperature	PT100	TMP 36GZ		V	0.5 ºC	AI	-40 +150 ºC	Good
3	**T.03.03**	Analog Devices	Generator winding temperature	PT100	TMP 36GZ		V	0.5 ºC	AI	-40 +150 ºC	Good
4	**S.03.01**	Siemens	Generator shaft rotational speed	Encoder	1XP8012-10 HTL		ABZ	1024p/rev	DI	0 .. 9000rpm	Good
5	**T.03.04**	IFM	Temperature in the main bearing	PT100	TM4101	68/69K	V	0.15 ºC	AI	-40 +150 ºC	Not tested

6	**T.03.05**	IFM	Temperature in the main bearing	PT100	TM4101	68/69K	V	0.15 ºC	AI	-40 +150 ºC	Not tested
7	**A.03.01**	Hansford Sensors	Generator vibrations	Accelerometer	HS422	65	4 - 20 mA	< 5%	AI	5-2000	Good
Area 04: Turbine											
1	**H.04.01**	ROTRONIC	Relative humidity turbine duct (chamber side)	humidity sensor	HC2SM	66	0 - 1V	±0.8 %rh	AI	0-100	Not tested
2	**T.04.01**	ROTRONIC	Air temperature turbine duct (chamber side)	RTD or thermocouple		66	0 - 1V	+/- 0.1 ºK	AI	-50 / +100	Not tested
3	**P.04.01**	BD Sensors	Air pressure turbine duct (chamber side)	Differential pressure transducer	DMP331	65	0 - 10V 4 - 20 mA	± 0.5%	AI	-1.0 / +2.5	Not tested
4	**A.04.01**	Hansford Sensors	Turbine structure vibrations	Accelerometer	HS422	65	4 - 20 mA	< 5%	AI	5-2000	Not tested
5	**P.04.02**	Keller	Air pressure at the trailing edge of the guide vanes (A)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
6	**P.04.03**	Keller	Air pressure at the trailing edge of the guide vanes (B)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
7	**P.04.04**	Keller	Air pressure at the trailing edge of the guide vanes (A)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good
8	**P.04.05**	Keller	Air pressure at the trailing edge of the guide vanes (B)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good

9	**P.04.06**	Keller	Air pressure at the stator minimum radius (C)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
10	**P.04.07**	Keller	Air pressure at the stator minimum radius (D)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
11	**P.04.08**	Keller	Air pressure at the stator minimum radius (C)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good
12	**P.04.09**	Keller	Air pressure at the stator minimum radius (D)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good
13	**C.04.01**	FESTO	Safety /Latching valve	Driver x4	CMMP-AS-C2-3A-M0						Good
14	**C.04.02**	FESTO	Safety /Latching valve	Actuator x4	EMME-AS-60-S-LS-AM(B)	65					Some problems
15	**C.04.03**	FESTO	Safety /Latching valve	PLC							Good
16	**C.04.04**	B&R	Powerlink based I/O extension	PLC							Good
Area 05: Turbine Hall in Mutriku											
1	**S.05.01**	B&R	Control PLC	PLC			Modbus/TCP	-	C	-	Good
Area 06: Power Electronics											
1	**S.06.01**	Nidec	Power Electronics	VSI	M700 096-0104		Ethernet/IP	-	C	-	Good

Area 07: MV Hall in Mutriku											
1	**S.07.01**	Schneider	LV Network Analyser	Power Analyser	PM710		Modbus RTU	-	C	-	
2	**S.07.02**	Schneider	MV Network Analyser	Power Analyser	SEPAM S80		Modbus RTU	-	C	-	
Area 09: Wave Measurement Instrument											
1	**W.09.01**		Wave Measurement Instrument	Pressure Sensor	-	68			C		Late Implementation
Area 11: Other Chambers Mutriku											
1	**S.11.01**	Omron	Plant Data Gateway PLC	PLC	CJ1M		Modbus/TCP	-	C	-	Good

TABLE I-7-2: LIST OF EQUIPMENT AVAILABLE FOR *BIMEP* TEST CAMPAIGN

Instr	Tag	Manufacturer	Description	Type	Model	IP	Signal type	Res/Acc	Interface	Range	Rating
Area 02: Air Chamber in the WEC											
1	**D.02.01**	Rosemount	Internal Water Surface Level	Non-contacting Radar	5601	67	4..20 mA/HART	± 5mm	AI/C	Config.	Good
2	**P.02.01**	Omega	Air pressure inside chamber	Differential Pressure transducer	PXM459-350HCGI	65	4 - 20 mA	0,08%	AI	+/- 0.35	
3	**P.02.02**	Aplisens	Air pressure inside chamber (max)	Differential pressure transducer	PCE-28.SMART	65	4 - 20 mA/HART	± 0.1%	AI	-1.0 / +1.5	
4	**P.02.03**	Keller	Air pressure inside the adapter cone	Differential pressure transducer	PD 23	67	4-20 mA	0,005	AI	+/- 0.2	Good
5	**P.02.04**	Keller	Air pressure inside the adapter cone	Differential pressure transducer	PD 23	67	4-20 mA	0,005	AI	+/- 0.5	Good
6	**S.02.05**	Rotork	Release valve actuator	Actuator	IQT500 F10	68	Modbus RTU				Good
Area 03: Generator Nacelle											
1	**T.03.01**	Comet	Atmospheric air temperature	thermometer	T7411	65	Modbus RTU	+/- 2.5 %	C	-30...105	Good
2	**T.03.01**	Analog Devices	Generator winding temperature	PT100	TBD		Ω/uV	0.1 ºC	AI	-5 +150	Good
3	**T.03.02**	Analog Devices	Generator winding temperature	PT100	TBD		Ω/uV	0.1 ºC	AI	-5 +150	Good

4	**T.03.03**	Analog Devices	Generator winding temperature	PT100	TBD		Ω/uV	0.1 ºC	AI	-5 +150	Good
5	**S.03.01**	Siemens	Generator shaft rotational speed	Encoder	1XP8012-10 HTL		ABZ	1024p/rev	DI	0 .. 9000rpm	Good
6	**T.03.04**	IFM	Temperature in the main bearing	PT100	TM4101	68/69 K	V	0.15 ºC	AI	-40 +150 ºC	Not tested
7	**T.03.05**	IFM	Temperature in the main bearing	PT100	TM4101	68/69 K	V	0.15 ºC	AI	-40 +150 ºC	Not tested
Area 04: Turbine											
1	**H.04.01**	ROTRONIC	Relative humidity turbine duct (chamber side)	humidity sensor	HC2SM	66	0 - 1V	±0.8 %rh	AI	0-100	
2	**T.04.01**	ROTRONIC	Air temperature turbine duct (chamber side)	RTD or thermocouple		66	0 - 1V	+/- 0.1 ºK	AI	-50 / +100	
3	**P.04.01**	BD Sensors	Air pressure turbine duct (chamber side)	Differential pressure transducer	DMP331	65	0 - 5V	± 0.5%	AI	-1.0 / +2.5	
4	**A.04.01**	Hansford	Turbine structure vibrations	Accelerometer	HS423	65	4 - 20 mA	gh	AI	5-2000	
5	**P.04.02**	Keller	Air pressure at the trailing edge of the guide vanes (A)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
6	**P.04.03**	Keller	Air pressure at the trailing edge of the guide vanes (B)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
7	**P.04.04**	Keller	Air pressure at the trailing edge of the guide vanes (A)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good
8	**P.04.05**	Keller	Air pressure at the trailing edge of the guide vanes (B)	Differential Pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good

9	**P.04.06**	Keller	Air pressure at the stator minimum radius (C)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
10	**P.04.07**	Keller	Air pressure at the stator minimum radius (D)	Differential Pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.2	Good
11	**P.04.08**	Keller	Air pressure at the stator minimum radius (C)	Differential Pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good
12	**P.04.09**	Keller	Air pressure at the stator minimum radius (D)	Differential pressure transducer	PD 23	67	4-20 mA	0,5%	AI	+/- 0.5	Good
13	**C.04.01**	FESTO	Safety /Latching valve	Driver x4	CMMP-AS-C2-3A-M0						Good
14	**C.04.02**	FESTO	Safety /Latching valve	Actuator x4	EMME-AS-60-S-LS-AMD	65					Some problems
15	**C.04.03**	FESTO	Safety /Latching valve	PLC							Good
16	**C.04.04**	FESTO	Safety /Latching valve	Driver x4	CMMP-AS-C2-3A-M0						Good
Area 06: Power Electronics											
1	**S.06.01**		Power Electronics	VSI	M700		-	-	-	-	
Area 08: Machinery Room											
1	**S.08.01**	B&R	Control PLC	PLC	X20cCP1584		Modbus/TCP	-	C	-	Good
2	**S.08.01**	B&R	Powerlink I/O bus base	PLC	X20cBB80		Powerlink		C		Good

3	**S.08.02**	Schneider electric	Uninterruptable power system	UPS	Smart-UPS RT 2200 XL						CPU brake
4	**S.08.03**	SBG systems	GNSS based Inertial sensor	6-DoF	Ellipse2-E						Good
Area 10: Mooring Lines											
1	**F.10.01**		4 x Load shackle	2 Load shackles for each line 1 and 4	-		4..20 mA	-	AI		Problems in the connection electrical lines
Area 12: Wave Measurement											
1	**S.12.01**	Axys Technologies	Directional Wave Buoy	Precision measurement buoy	TRIAXYS				C		Overall good with some problems
Area 14: Mast											
1	**S.14.01**	Remberg	Wind speed measurement	Anemometer					C		Good
2	**S.14.02**	Vivotek	surveillance camera	CCTV					C		Not worked in second deployment

3	**S.14.03**	MOXA	3G connection antenna	3G	ANT-WCDMA-ANF-00						Good
4	**S.14.04**	SETTOP	GNSS antenna	RTK and GPS	Settop M1						Good. Difficult adjustment
5	**H.14.01**	Comet	Atmospheric air relative humidity	humidity sensor	T7411	65	Modbus RTU	+/- 0.4 ºC	C	0-100	Good
Area 16: Umbilical cable											
1	**S.16.01**		Umbilical cable	Power and communications					C		Brake due to mooring problems. Could be repaired.
2	**S.16.02**	Weidmuller	Connector between the cable and buoy						C		Good