Uppsala University

User Project: Real time simulations of a wave power system

Project Acronym: REWAP

Project Reference Number: 1586

Infrastructure Accessed UCC_MaREI_Ocean Emulator

Infrastructure
Access
Reports

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MaRINET2

ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and available of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

European
Commission

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Disclaimer

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1 Introduction & Background

1.1 Introduction

In this project, the direct-driven linear generator (LG) of the wave energy converter (WEC) designed at Uppsala University (UU) will be investigated. The purpose is to simulate the power output from single and several WECs and connect to a micro grid with the use of a real-time (RT) emulator at University College Cork (UCC), Ireland. The analysis will include considerations on WEC control strategies, energy storage and grid connection. Data of a number of WECs in a certain sea state, under different control strategies, will be provided from UU. This data will be injected into the micro grid. Both experimental data and data from a hydrodynamic model will be used for this. The results will illustrate the interaction between the WEC and the micro grid, which will be analyzed and presented scientifically. The proposed WEC has been studied since 2002, including offshore experiments at the research site in Lysekil, Sweden, see the homepage http://www.teknik.uu.se/elektricitetslara for more information. The deployment of the first the full-scale WEC in Lysekil was in 2006. The work on the UU WEC has resulted in publications in various scientific journals and the research covers a wide area of research (electric, environmental, mechanic, hydrodynamics etc.).

1.2 Development So Far

The wave power project started in 2002, and the first WEC prototype was deployed offshore in 2006 in the Islandsberg research test site, located nearby the town of Lysekil at the western coast of Sweden. Since then, 13 different WECs were deployed and tested there, including the first wave power park tested in 2009. The site is prepared for gird connection. However, they were not integrated to the grid, and a (micro) grid dynamics is of particular interest if the WEC is subject to different control strategies.

WEC hydrodynamic Simulink models as well as control of damping forces, energy storage (battery bank) and overall grid dynamics are tested. Moreover, different converter controls for grid integration and for energy storage have been investigated.

1.2.1 Stage Gate Progress

Previously completed: ✓

Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)	
• Finite monochromatic waves to include higher order effects (25 –100 waves)	
• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)	
• Restricted degrees of freedom (DofF) if required by the early mathematical models	
• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)	
• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable	
• Real seaway productivity (scaled duration at 20-30 minutes)	
• Initially 2-D (flume) test programme	
• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them	
• Evidence of the device seaworthiness	
• Initial indication of the full system load regimes	
Stage 2 – Design Validation	
• Accurately simulated PTO characteristics	
• Performance in real seaways (long and short crested)	

STAGE GATE CRITERIA	Status
• Survival loading and extreme motion behaviour.	
• Active damping control (may be deferred to Stage 3)	
• Device design changes and modifications	
• Mooring arrangements and effects on motion	
• Data for proposed PTO design and bench testing (Stage 3)	
• Engineering Design (Prototype), feasibility and costing	
• Site Review for Stage 3 and Stage 4 deployments	
• Over topping rates	
Stage 3 – Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	
• To employ a realistic/actual PTO and generating system & develop control strategies	
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	
• To validate electrical supply quality and power electronic requirements.	➲
• To quantify survival conditions, mooring behaviour and hull seaworthiness	
• Manufacturing, deployment, recovery and O&M (component reliability)	
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality (absorbed/pneumatic power-converted/electrical power)	➲
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	➲
• Device array interactions	
• Power supply interaction & quality	➲
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

1.2.2 Plan for This Access

The original test plan for this access was to investigate the (micro) grid dynamics when one, three and ten WECs were supplying power to the grid and to verify control strategies to maintain a grid code requirements under various load conditions, other disturbances in the grid. When a single WEC was operating, a measured wave data of different sea states was used as input. When wave power parks of three and ten devices were tested, the power data obtained in earlier offshore experiments with one WEC was used. The three phase voltages and currents from one WEC were replicated, respectively, three and ten times and superimposed in different ways. A number of different scenarios were replicated, covering the worst and the best case scenarios. For the worst case scenario, it was assumed that the power flowed from all WECs simultaneously. On contrary, in the best case scenario, the power was supplied more smoothly. Other cases were considered as well. These power series were converted to DC current signals and input as currents to the DC bus of a power converter at the MaREI facilities.

2 Outline of Work Carried Out

2.1 Setup

The setup used to test the different WECs and configuration is a microgrid of 400 VAC. The microgrid structure is configured with different controls to interface the distributed sources. The controller and power electronics system were electronically isolated from the local 400 VAC grid to allow for the system start up to be safely simulated.

2.2 Tests

The purpose of the investigation is to analyse the behaviour and control of the WEC(s) in a grid connected mode. Several tests are successfully conducted by considering three scenario, (i) a single-WEC, (ii) 3-WECs and (iii) 10-WECs, connected to the microgrid. All the tests are investigated for different phase-shifts of incoming ocean waves. The experimental data and the data from the hydrodynamic model is used during the investigations. We considered different cases for each scenarios mentioned above and reported in Table 2.1.

	Cases considered	**Structure of the microgrid**	**Tests conducted**
Scenario (i)	11	Load, grid, Diesel generator, Battery	24
Scenario (ii)	5	Load, grid, Diesel generator, Battery	34
Scenario (iii)	3	Load, grid, Diesel generator, Battery	29
Additional Tests	-	Load, grid, Diesel generator, Battery	04

Table 2.1 Test planning

Few tests were conducted with the power-factor variation to study the different controls and the behaviour of the WECs.

All the tests were conducted for 90 s only and the data were sampled at 10 kHz. The data were sampled on a real-time integrated monitoring system by using FPGAs on a National Instrument platform.

2.2.1 Test Plan

The test plan starts from the basic system check-up to ensure the system functioning and reliability with the connected WECs.

Scenario (i) - Single-WEC

1. Several tests are conducted for scenario (i), a Single-WEC, with different sea states.
2. The torque from the model is interfaced with the TRIPHASE-2 setup (rotatory rig) and tested for several cases.
3. The wave period ranging from 4.7 seconds to 7.5 seconds and the wave height from 0.8 m to 2.0 m in certain sea state.
4. The scenario (i) is tested with different structures of the microgrid, e.g. interfacing with the grid, load-bank, the battery-bank and the diesel generator.
5. A total of 24 sets of experimental tests are successfully recorded with different sea states and microgrid structure.

Scenario (ii) – 3-WECs

1. The data from the hydrodynamic model for different phase-shifts is used during the tests.
2. We considered five phase-shifts, (a) 0 s, (b) 5 s, (c) 10 s, (d) 15 s and (e) 20 s.

3. Three rectified outputs: 70 V, 60 V and 50 V of the WECs are used in the tests. Each output covers the five phase-shifts.
4. The rectified output of the 3-WECs is interfaced with the TRIPHASE-1 setup and tested for several cases.
5. The cases considered are with the different loads, grid, battery bank and with the diesel generator connected structures.
6. A total of 34 sets of experimental tests are recorded.

Scenario (iii) – 10-WECs

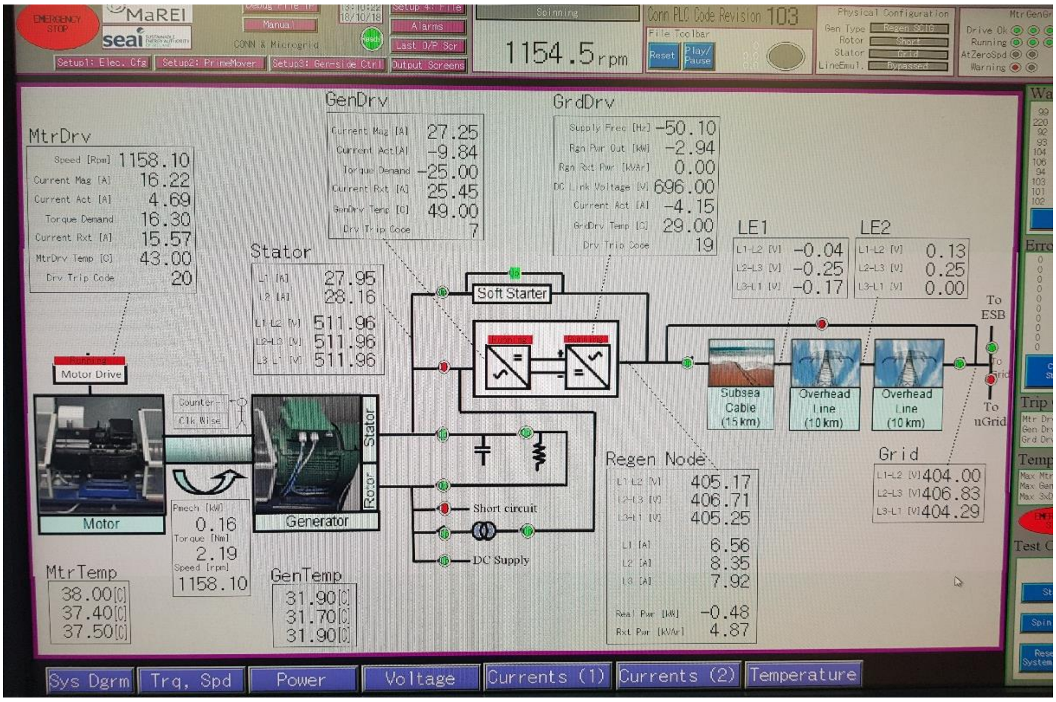
1. The data from the hydrodynamic model for different phase-shifts is used during the tests.
2. We considered three phase-shifts, (a) zero shift, (b) random shift, and (c) fixed shift.
3. Three rectified outputs: 70 V, 60 V and 50 V of the WECs are used in the tests. Each output covers the three phase-shifts.
4. The rectified output of the 10-WECs is interfaced with the TRIPHASE-1 setup and tested for several cases.
5. The cases considered are with the different loads, grid, battery bank and with the diesel generator connected structures.
6. A total of 29 sets of experimental tests are recorded.

2.3 Results

2.3.1 Results of Scenario (i)

A total 11 different sea states are used during the tests. The setup uses the TRIPHASE-2 unit from the control structure to interface the single WEC to the microgrid. The WEC is interfaced with microgrid in different topologies, e.g. grid, load, battery and the diesel generator.

Fig. 2.1 shows the block diagram of the connected setup in scenario (i). The code and the control from the Simulink model is interfaced with the TRIPHASE-2 unit by using a hardware-in-loop (HIL) setup. The reference torque from the model is used to control the motor speed, rev. per min (rpm), and hence the rotatory generator. The speed limits of the motor are between 400 rpm to 2300 rpm. The generator is a SCIG machine and its stator is connected with a back-to-back unit. This unit converts the AC to DC and further DC to AC to connect the AC loads or the AC-grid at the AC-bus of the microgrid. Fig. 2.2 shows the tests conducted in scenario (i).



1154.5 rpm

Gen Type: Regen SCIG
Rotor: Short
Stator: Grid
LineEmul.: Bypassed

MtrDrv
Speed [Rpm] 1158.10
Current Mag [A] 16.22
Current Act [A] 4.69
Torque Demand 16.30
Current Rxt [A] 15.57
MtrDrv Temp [C] 43.00
Drv Trip Code 20

GenDrv
Current Mag [A] 27.25
Current Act [A] -9.84
Torque Demand -25.00
Current Rxt [A] 25.45
GenDrv Temp [C] 49.00
Drv Trip Code 7

GrdDrv
Supply Freq [Hz] -50.10
Rgn Pwr Out [kW] -2.94
Rgn Rxt Pwr [kVAr] 0.00
DC Link Voltage [V] 696.00
Current Act [A] -4.15
GrdDrv Temp [C] 29.00
Drv Trip Code 19

Stator
L1 [A] 27.95
L2 [A] 28.16
L1-L2 [V] 511.96
L2-L3 [V] 511.96
L3-L1 [V] 511.96

LE1
L1-L2 [V] -0.04
L2-L3 [V] -0.25
L3-L1 [V] -0.17

LE2
L1-L2 [V] 0.13
L2-L3 [V] 0.25
L3-L1 [V] 0.00

Pmech [kW] 0.16
Torque [Nm] 2.19
Speed [rpm] 1158.10

MtrTemp
38.00 [C]
37.40 [C]
37.50 [C]

GenTemp
31.90 [C]
31.70 [C]
31.90 [C]

Regen Node
L1-L2 [V] 405.17
L2-L3 [V] 406.71
L3-L1 [V] 405.25
L1 [A] 6.56
L2 [A] 8.35
L3 [A] 7.92
Real Pwr [kW] -0.48
Rxt Pwr [kVAr] 4.87

Grid
L1-L2 [V] 404.00
L2-L3 [V] 406.83
L3-L1 [V] 404.29

Figure 2.1 Overview of the connected setup in Scenario (i)

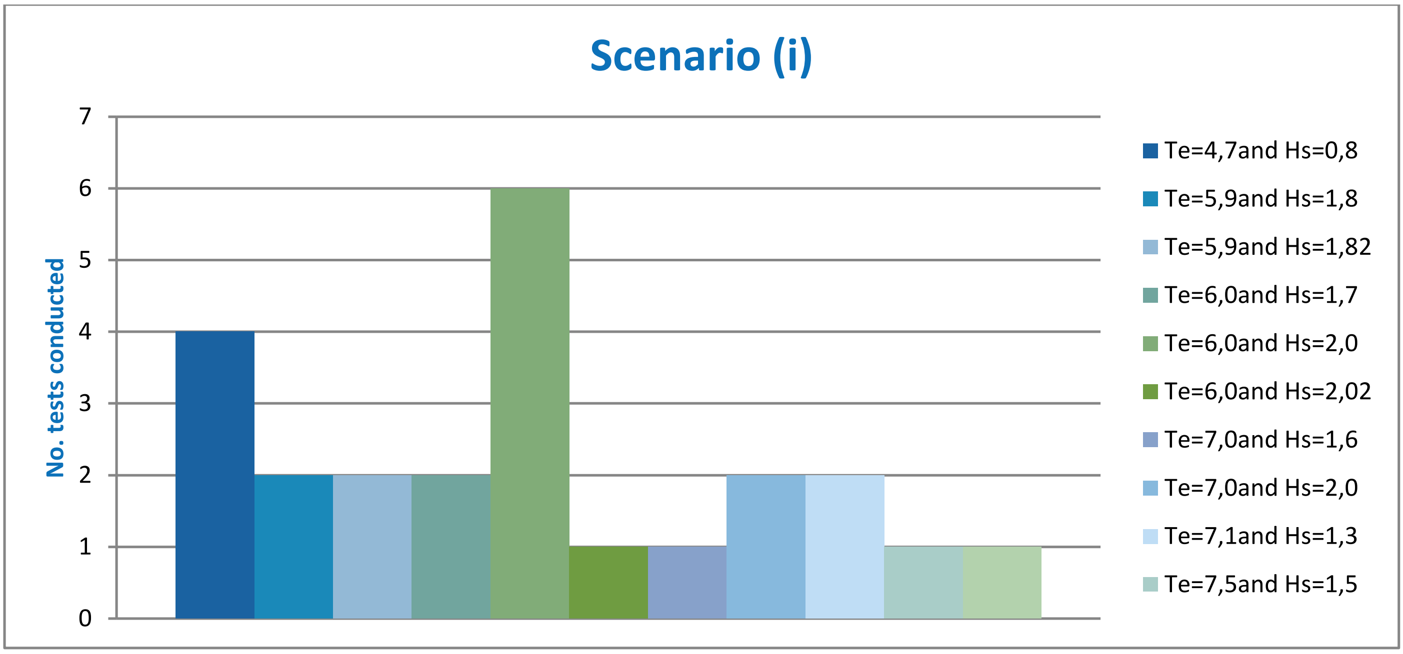


Figure 2.2 Tests conducted in Scenario (i)

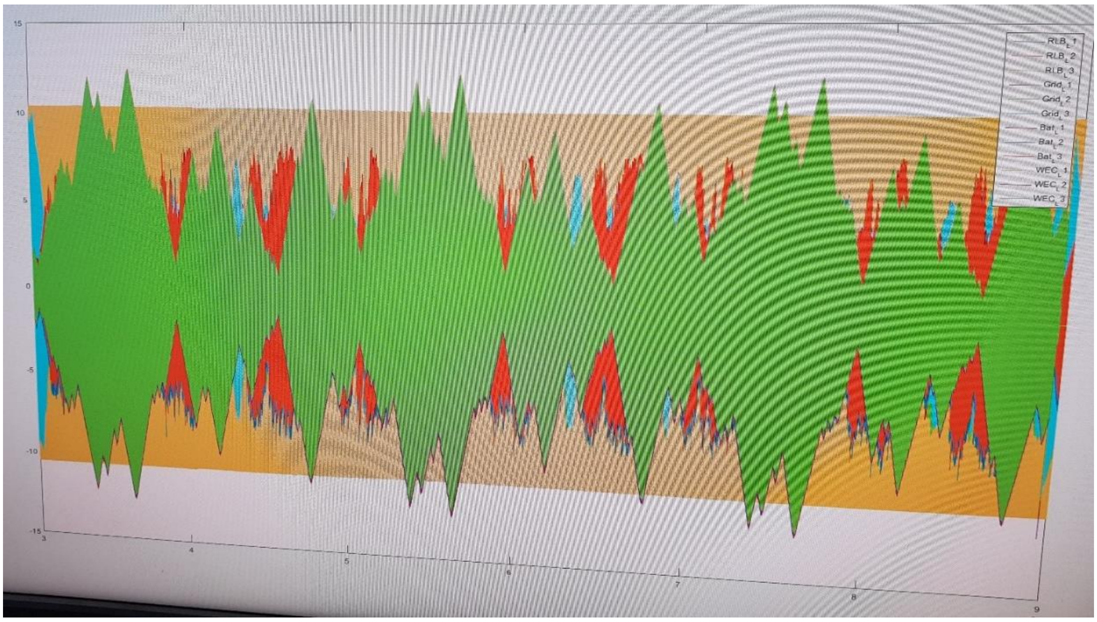


Figure 2.3 Recorded data in one of the sea states Scenario (i) - (Te= 6.0 s, Hs= 2.0 m).

Fig. 2.3 presents the data recorded during the test. The WEC current is shown in green curve, battery current are in blue, loads and grid currents are shown in yellow and the red, respectively. The figure depicts the operating conditions of the WEC and participation of the battery module to meet the power demand at the loads. When WEC delivers less amount of power, the green curve drops, battery module feeds the demand power to the loads, blue curve rises. A single WEC has much higher power fluctuations and this intermittency is reduced by the use of battery bank by smoothening the power to the loads.

2.3.2 Results of Scenario (ii)

Five different phase-shifts have been considered for this scenario. The setup uses the TRIPHASE-1 and TRIPHASE-2 units from the control structure to interface the 3-WECs to the microgrid. The WECs are interfaced with microgrid in different topologies, e.g. Grid, load, battery and the diesel generator.

Fig. 2.4 presents the tests conducted with different phase-shifts.

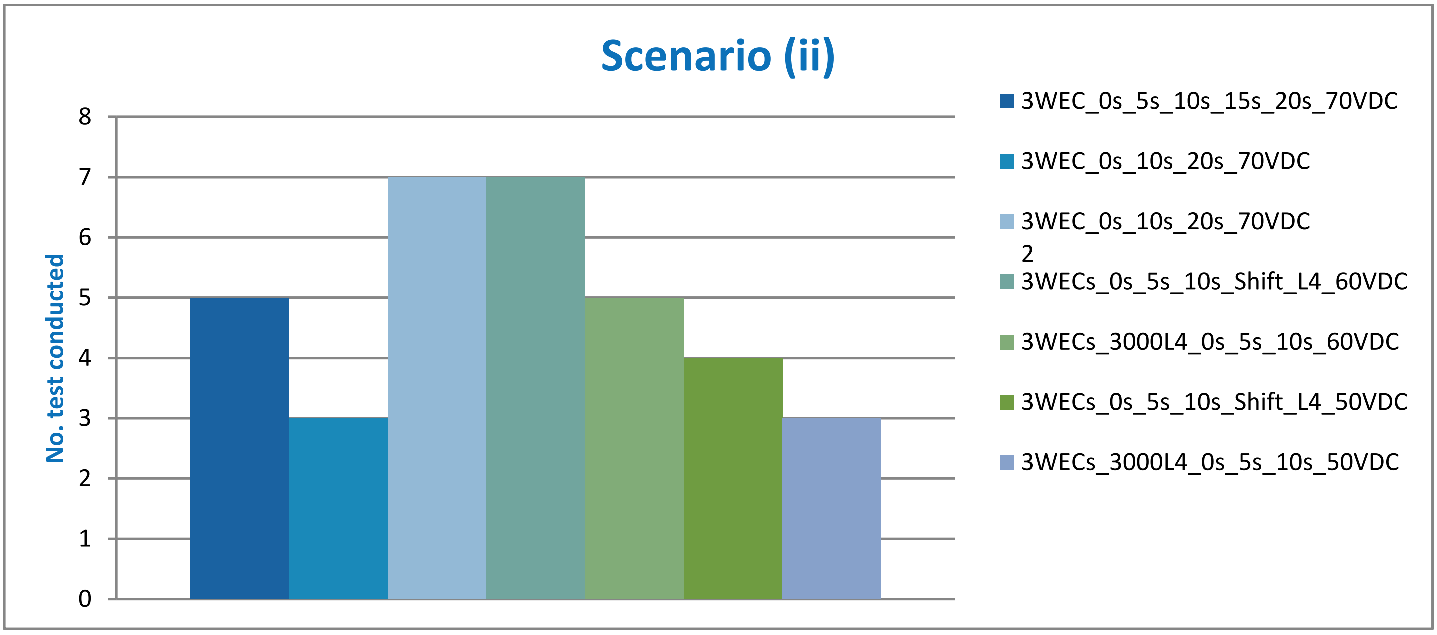


Figure 2.4 Tests conducted in Scenario (ii)

The currents recorded in one of the tests are shown in Fig. 2.5. Following the similar colour coding for the currents. For the first 30 seconds the WECs power is not interfaced to the system and therefore the battery module feeds the power demand at the loads. At the instant, when WECs are delivering power the power is smoothened and feeds the loads by reducing the stress of the batteries.

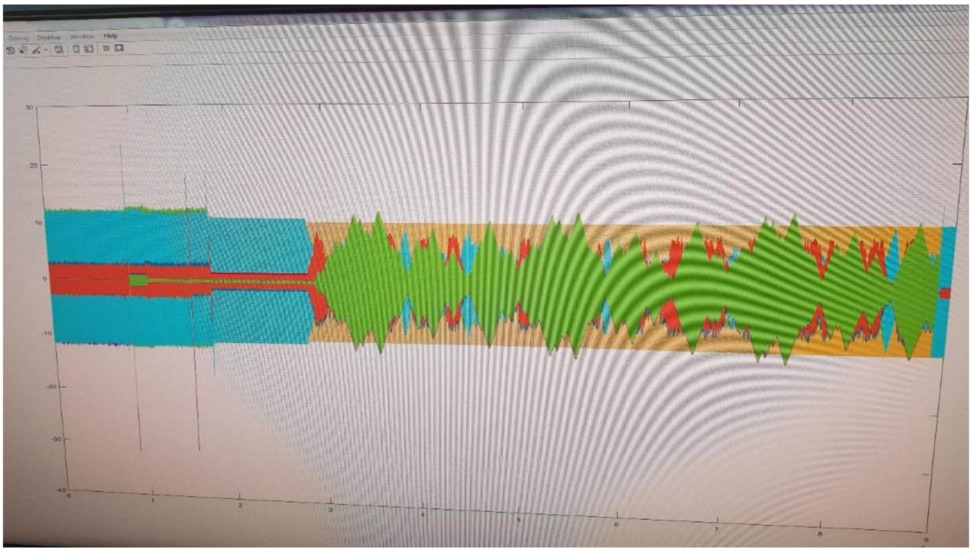


Figure 2.5 recorded data in one of the phase-shift Scenario (ii) - (70VDC_0s).

The behaviour of the WECs is presented with the diesel generator in Fig. 2.6. The purpose of the study is to emulate the WECs by utilizing the rectified power into the DC-link and feed a desalination plant as a big consumer. The DG emulates a sensitive load and feeds the harmonics in the microgrid. The study is carried-out to investigate the behaviour of the WECs in such condition along with the connected non-sensitive loads.

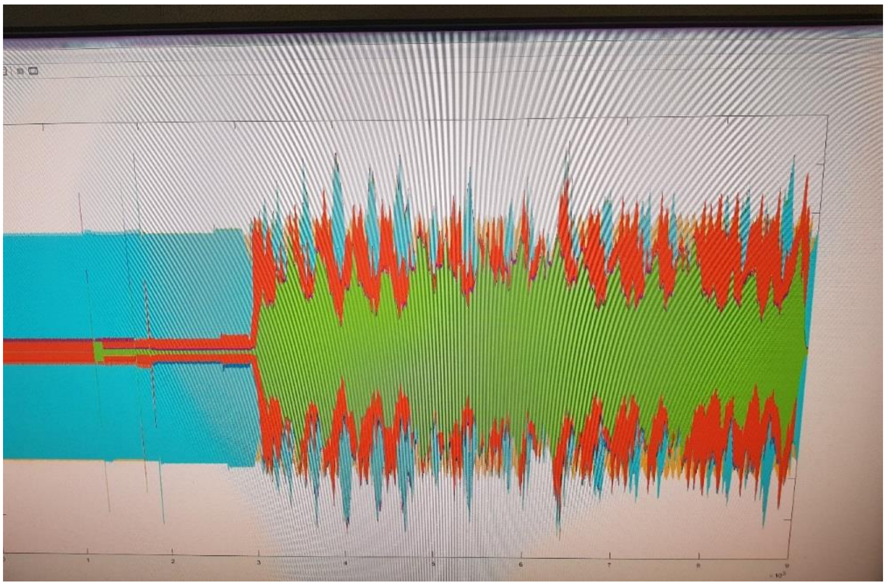


Figure 2.6 recorded data in one of the sea states Scenario (ii) - 70VDC_0s_with DG.

It is visible that the loads currents are having higher harmonics as compared to the previous case. This case is under investigation to improve the overall system power quality.

2.3.3 Results of Scenario (iii)

Three different phase-shifts have been considered for this scenario. The setup uses the TRIPHASE-1 and TRIPHASE-2 units from the control structure to interface the 10-WECs to the microgrid. The WECs are interfaced with microgrid in different topologies, e.g. Grid, load, battery and the diesel generator.

Fig. 2.7 presents the tests conducted with different phase-shifts under this scenario.

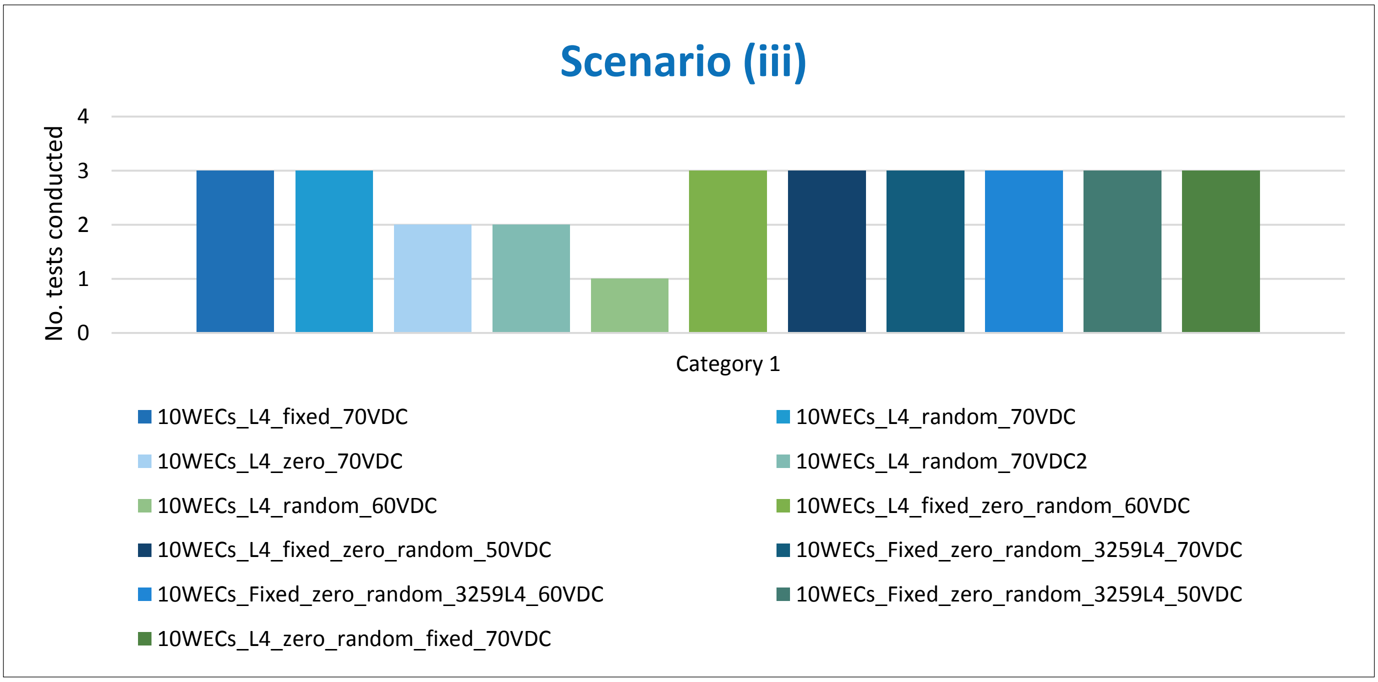


Figure 2.7 Tests conducted in Scenario (iii)

There different rectified voltage levels (70V, 60V and 50 V) are interfaced to the DC-link of the inverter connected to the microgrid. The WECs power is different in considered three phase-shifts (fixed, random and zero) from the model. Each voltage level is tested for all the three shifts and investigated on the behaviour of the microgrid connected with loads, battery, and the DG. Fig. 2.8 presents the recorded currents at different points of the microgrid.

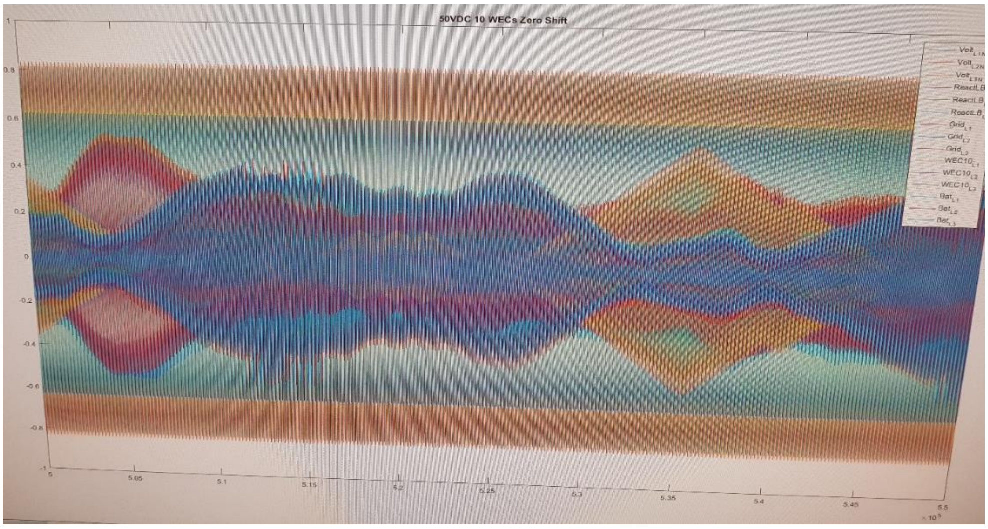


Figure 2.8 recorded data in one of the cases in Scenario (iii) - 50VDC_Zero_shift (zoomed view)

The WECs current is in yellow curve and having a varying nature, battery current is in blue curve and steady currents in yellow are from the load (in the background). It can be noted that the WECs power is compensated by the battery module to feel the load. When the WEC has less power delivery into the microgrid, the battery surplus the power to the microgrid and stores the excessive power from the WECs when its higher than the load demand.

In Fig. 2.9, a case of 50VDC_fixedshift is shown.

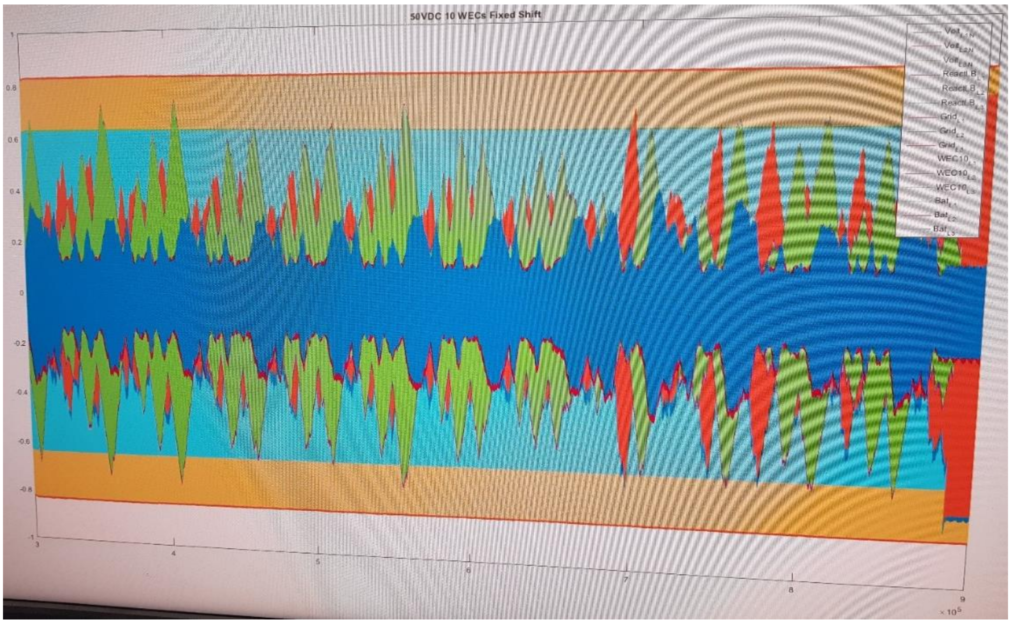


Figure 2.9 recorded data in the sea states in Scenario (iii) - 50VDC_Fixed_Shift

The WECs power has been improved in this case and less fluctuations are reported as compared to the previous case. The battery module has less stress but continuously participating to smoothen the WECs power to the load and the grid. Fig. 3.0 presents the case of 50V_randomshift.

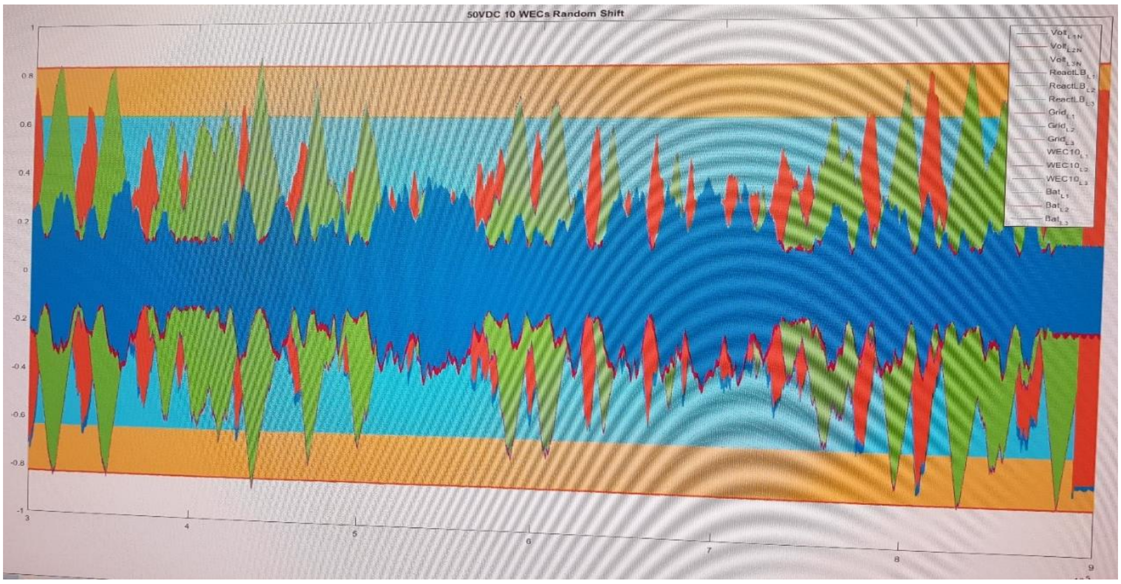


Figure 3.0 Recorded data in Scenario (iii) - 50VDC_Random_Shift

2.3.4 Additional Tests

Few other tests were conducted. One of the tests was conducted for maintain the terminal voltage and the frequency of the microgrid by utilizing the current synchronous detection (CSD) algorithm control for a virtual synchronous generator scheme.

The test is conducted in an islanded mode where the inverter and the battery bank are emulating the system inertia to maintain the voltage and the frequency to feed the loads. The unit templates and the quadrature templates are realized in the digital controller in the interfaced Simulink model to control the active and reactive power flow into the microgrid.

Other tests were carried out for a power factor measurement at different loads with the interfaced single WEC.

The results are under investigation and hopefully, we will be able to publish the investigated scenarios in quality journals and conferences.

2.4 Analysis & Conclusions

The analysis of the data will continue during this and next year.

3 Main Learning Outcomes

3.1 Progress Made

The main goal for this access was to verify control strategies, investigate grid interaction with one, three and ten WECs connected, ability of the control algorithms to control currents to the energy storage (battery bank), grid code compliance and ability of the control strategies to maintain it under different load conditions and harmonic emitting equipment.

A possibility to implement the hydrodynamic model of a point absorber with a linear generator power take off was also investigated. The output voltages and currents from a linear generator vary in both amplitude and frequency, and the major challenge here is to emulate similar behaviour with a rotational squirrel cage induction generator (SCIG). The other goal was to test different control strategies on the emulated linear generator but the challenge arose from the feedback from SCIG that should have been converted and fed to the hydrodynamic Simulink model.

3.1.1 Progress Made: For This User-Group or Technology

3.1.1.1 Next Steps for Research or Staged Development Plan – Exit/Change & Retest/Proceed?

Emulation hydrodynamic Simulink model needs to be further developed with a well-functioning control and tested for different wave series input. Interaction of such control strategies as reactive control and latching were not investigates due to limitations of the SCIG, but perhaps, input data could be prepared in the same manner as for the conducted wave power park tests and power/current signals can be emulated by means of a b2b power converter.

Control algorithms on active power factor control in a (micro) grid need to be tested. More test on the inverter control needs to be done, where it is shown how the inverter can be operated at different grid conditions. Furthermore and common control strategy for the inverter controlling the power from the wave power plant and the inverter controlling the power flow to the energy storage system could be tested. Different energy storage devises could also be tested.

3.1.2 Progress Made: For Marine Renewable Energy Industry

The importance of monitoring the power electronics in the marine renewable energy industry has been highlighted. Moreover, the study focuses on results in terms of electric power production and grid integration and can be useful for industries that consider to install their system to a microgrid or to a weak grid connection point.

3.2 Key Lessons Learned

- Prepare all the data of the required quality in advance
- Have a clear plan on what to test
- Make sure the models and the software versions are compatible

4 Further Information

4.1 Scientific Publications

List of any scientific publications made (already or planned) as a result of this work:

- 3 conference papers with preliminary titles:
  - “Power hardware-in-the-loop simulations of grid integration of a wave power park”, EWTEC 2019
  - “Smart Inverters for Power System Support”, EWTEC 2019
  - “Hardware in the Loop Testing of Hydrodynamic Model for a Wave Energy Converter with Linear Generator", ISOPE 2019
- 5 journal papers

4.2 Website & Social Media

Website: http://www.teknik.uu.se/elektricitetslara

YouTube Link(s):

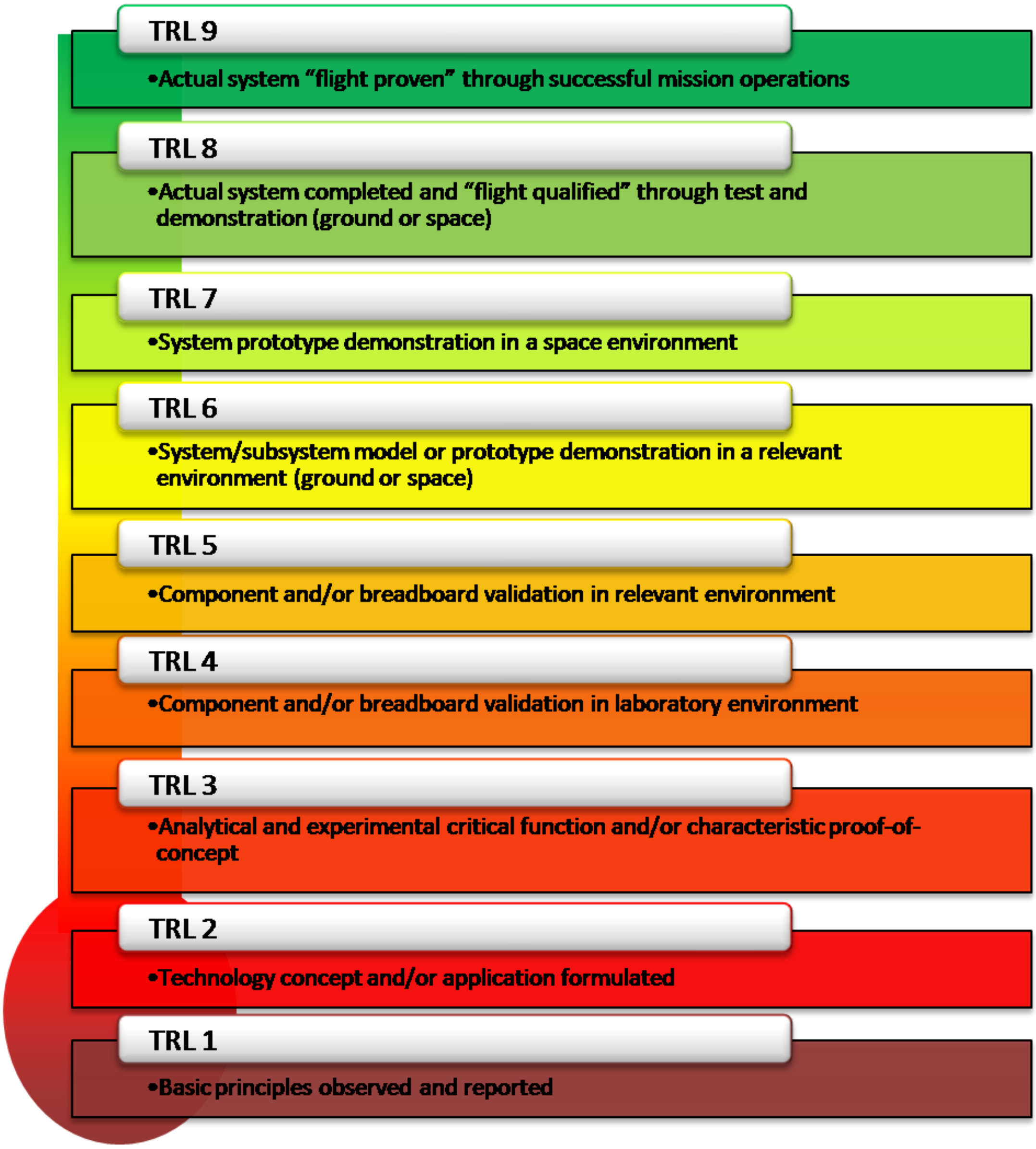
LinkedIn/Twitter/Facebook Links:

Online Photographs Link:

5 Appendices

5.1 Stage Development Summary Table

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.



NASA Technology Readiness Levels[1]

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[1] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

NASA TRL Definition Hardware Description Software Description Exit Criteria

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modelling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test Performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test Performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results

DEVELOPMENT PROTOCOL	***STAGE 1*** *CONCEPT VALIDATION*			***STAGE 2*** *DESIGN VALIDATION*	***STAGE 3*** *SYSTEMS VALIDATION*		***STAGE 4*** *DEVICE VALIDATION*		***STAGE 5*** *ECONOMICS VALIDATION*
	TRL 1: Confirmation of Operation	**TRL 2: Performance Convergence**	**TRL 3: Device Optimisation**	**TRL 4: Sub-Systems Assessment**	**TRL5: Sub-Assembly Bench Tests**	**TRL 6: Full System Sea Trials**	**TRL 7: Solo, Sheltered, Grid Emulator**	**TRL 8: Solo, Exposed, Grid Connected**	**TRL 9: Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power *v* Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_e = 1 : 5 - 10$)			$\lambda = 1 : 10 - 25$	$\lambda = 1 : 2 - 10$		$\lambda = 1 : 1 - 2$		$\lambda = 1{:}1$, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration *–inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production Pre-Commercial		Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δf) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed Power [kW]					▨	▨	▨	▨	▨
Converted	▨	▨	▨	▨					
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW