This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927.

Verification through Accelerated testing Leading to Improved wave energy Designs



Efficiencies and temperatures test register

2024-04-06

Lead participants: TECNALIA, IDOM

Dissemination level: Public

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Executive Summary

This dataset provides the inputs, measurements and calculus of the heating tests battery performed during **VALID Project** (funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927). The aim of the tests was to analyse the thermal behaviour and degradation process of an electrical generator under variable load conditions as in an oscillating water column (OWC) wave energy converter.

This dataset contains the information regarding power losses and temperature.

This dataset has been used in the analysis of the following reference:

Lopez Mendia, Joseba; Robles, Eider; Ceballos, Salvador; Ruiz-Minguela, Pablo and Rotger, Jacobo. (2024). Improving the OWC Wave Energy Converter Power Take-Off Efficiency throughout Experimental and Numerical Characterisation of an SCIG. Energies. 17. 1146. doi:10.3390/en17051146.

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Project partner names

RISE	RISE Research Institutes of Sweden AB
TECNALIA	Fundacion Tecnalia Research and Innovation
CORPOWER OCEAN	Corpower Ocean AB
RINA-C	RINA Consulting S.p.A.
BiMEP	Biscay Marine Energy Platform SA
IDOM	IDOM Consulting, Engineering, Architecture, S.A.U.
AAU	Aalborg University
AVL	AVL List GMBH
Wavepiston	Wavepiston AS
TU Delft	Delft University of Technology
Aquatera	Aquatera Sustainability Ireland LTD
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1 Summary of tests

Due to the physical limits and control restrictions in the test bench, all the tests have been run at a constant speed of 1.500 rpm (CF_{speed} =1). The torque has been the variable magnitude (variable CF_{torque}). The total Capacity Factor (CF) which will be CF_{power} is calculated as $CF=CF_{power}=CF_{torque}*CF_{speed}$.

The heating/degradation tests carried out on the generator are the following:

- Static tests with constant CF: CF 0.4-2
- Dynamic tests with variable CF: CF 0.8-1.8, with different peaks amplitude each

Table 1 shows the definition of the dynamic tests designed for the testing of the generator. Last column shows the number of tests of each kind carried out.

Table 1. Definition of Dynamic tests carried out on the generator

Test	RMS	Medium	High Peak	Low Peak	Amplitude	Class	Nº of tests
1_Peaks	0,5203	0,4375	0,9974	0,25	0,7474	low	1
2_Peaks	0,7663	0,6085	1,4969	0,25	1,2469	medium	0
3_Peaks	1,0434	1,0129	1,449	0,8	0,649	low	2
4_Peaks	1,1443	1,0265	1,9471	0,6	1,3471	medium	3
5_Peaks	1,2994	1,0201	2,4801	0,3	2,1801	high	1
6_Peaks	0,83	0,8	1,1	0,6	0,5	low	1
7_Peaks	0,9	0,82	1,5	0,5	1	medium	1
8_Peaks	1,04	0,8	2	0,25	1,75	high	1
9_Peaks	1,21	1,19	1,5	1	0,5	low	3
10_Peaks	1,25	1,19	1,9	0,9	1	medium	2
11_Peaks	1,37	1,2	2,35	0,6	1,75	high	2
12_Peaks	1,33	1,32	1,65	1,15	0,5	low	4
13_Peaks	1,37	1,32	2,05	1,05	1	medium	2
14_Peaks	1,45	1,31	2,5	0,75	1,75	high	3
15_Peaks	1,42	1,41	1,8	1,3	0,5	low	1
16_Peaks	1,45	1,4	2,1	1,1	1	medium	1
17_Peaks	1,56	1,42	2,6	0,85	1,75	high	2
18_Peaks	1,53	1,52	1,9	1,4	0,5	low	2
19_Peaks	1,55	1,51	2,2	1,2	1	medium	1
20_Peaks	1,65	1,52	2,7	0,95	1,75	high	3
21_Peaks	1,96	1,64	3,6	0,6	3	extreme	2
22_Peaks	1,61	1,6	1,96	1,46	0,5	low	1
23_Peaks	1,63	1,59	2,3	1,3	1	medium	1
24_Peaks	1,74	1,62	2,8	1,05	1,75	high	1
25_Peaks	1,81	1,8	2,15	1,65	0,5	low	1
26_Peaks	1,84	1,8	2,5	1,5	1	medium	6
27_Peaks	1,92	1,81	3	1,25	1,75	high	1

Information of the degradation tests (both static and dynamic) has been used for:

- Analysis of the generator power losses: a proper characterisation of the efficiency under static and dynamic load regimes for different CFs is necessary for the best sizing of the generator.
- Analysis of the thermal behaviour of the generator. The duration of the tests has been variable in order to let the stabilisation of the temperature.
- Analysis of the degradation of the generator.

In addition, Motor Current Signature Analysis (MCSA) tests were run between each degradation test in order to save all the possible data for post-processing and condition monitoring analysis.

The present dataset offers information about the generator power losses, characterisation of the efficiency and final temperature of the correctly registered tests. As the tests carried out have been extremely hard with the purpose of degrading the generator until breakage, many tests have been discarded from the dataset because one or more relevant variables had not been properly registered or the test had failed.

2 Methodology

Methodology on the segregation of losses represented in this dataset can be found in the following references:

Lopez Mendia, Joseba; Robles, Eider; Ceballos, Salvador; Ruiz-Minguela, Pablo and Rotger, Jacobo. (2024). Improving the OWC Wave Energy Converter Power Take-Off Efficiency throughout Experimental and Numerical Characterisation of an SCIG. Energies. 17. 1146. doi:10.3390/en17051146.

Deliverable 4.2 – Description of UC#2 hybrid testing platform. VALID project. December 2022.

3 Description of the test bench

The tests have been developed in the electrical PTO test rig available at Tecnalia [1], which was designed within the CORES FP7 [2] project. Since then, it has been used by many external research groups through MARINET [3] and MARINET2 [4] projects, and by internal groups for different applications.

The Electrical Power Take-Off Laboratory combines a controlled laboratory environment with harmonised procedures to reproduce open-sea operating conditions. When utilised it is believed to enable reduction of the development cost, risk and time of offshore renewable technologies such as wind, wave and tidal stream devices through its:

- Step-by-step control design, development and tuning.
- Comparison of different control laws in terms of efficiency, power quality and grid codes.
- Testing the reliability of hardware and software components.
- Right-sizing of electrical components.
- Detecting anomalies and critical operating conditions.
- After system deployment it also allows:
    - Replicating actual operating conditions (based on field measurements) which led to failures.
    - Validating the device models.

The test bench emulates a rotational-mechanical output of a wave energy converter, where throughout a numerical model of a primary energy conversion (hydrodynamic-mechanic, aerodynamic-mechanic) a final motor torque/speed reference is completed. Table 2 summarizes the different components of the test bench.

Table 2 Test bench components description

Component	Type	Specifications
Motor & Power converter	Leroy-Somer LSES 160 LUT	Squirrel-Cage Induction Motor Nominal values: 15 kW; 1,460 rpm; 97.77 Nm; 28.10 A Maximum values: 28 kW; 3,000 rpm
PLC	Beckhoff	Torque or speed commands updated every 10 ms
DAQ Board	NI-6221	Torque or speed commands updated every (100 ms freq) (Simulink-Matlab). Temperature measurement
Data logger	YOKOGAWA DL 750	Data acquisition recorder (used 1kHz freq) . Voltage, current, vibrations measurements
Control software	Matlab/Simulink environment and using an xPC configuration	Arbitrary torque or speed waveform references Programmable
Generator power converter	ABB	Bidirectional back-to-back converter Nominal values: 400 V; 50 Hz

The motor area is composed of a LSMV160LU-T 15kW motor, the LS UMV4301 frequency converter to control the motor and the motor control software (CT-soft). The aim of these components is to emulate the behaviour of the WEC (Wave/Wind Energy Converter) under any operational conditions. It is an emulation because the mathematical equations are programmed in the motor control software so that it behaves like the WEC.



Figure 1 General view of the test bench

The generator area includes a 3kW squirrel cage induction generator (SCIG) supplied by OBEKI [5], the frequency converter (ABB ACS-800 with window drive light software) to control the generator and a Beckhoff PLC with the generator and B2B control state machine. This part represents the real equipment that could be connected between the hydrodynamic-mechanic transformation and the grid. Figure 2 represents a general scheme of the test bench.

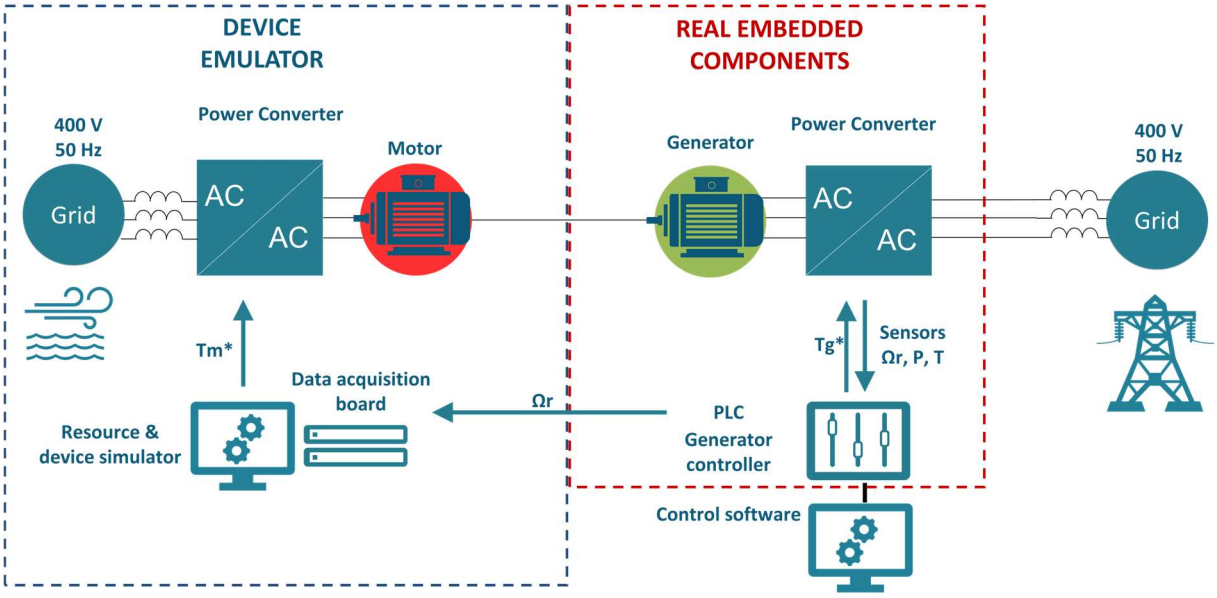


Figure 2 General scheme of the test bench

The motor and the generator are coupled by means of a shaft where a torque transducer is installed. The 3 kW generator rests in a table that lies on 6 brackets. Table 3 describes the main features of the electrical generator [5] tested:

Table 3. Main features of the electrical generator

Parameter	Unit	Value	Parameter	Unit	Value
Rated power	kW	3	Nº of phases	-	3
Voltage	V	230/400	Pole number	-	4
Frequency	Hz	50	Enclosure	-	IP 55
Rated torque	Nm	21	Isolation class	-	F
Speed	rpm	1565	Duty service	-	S1
Cos phi	-	0.78	Cooling		IC411
Efficiency	%	87.7	Connection	-	D/Y
Rated current	A	11/6.4	Weight	kg	38.5

3.1 Instrumentation and Sensors

Regarding the sensors available, Figure 3 represents a schematic of the different sensors and data acquisition systems:

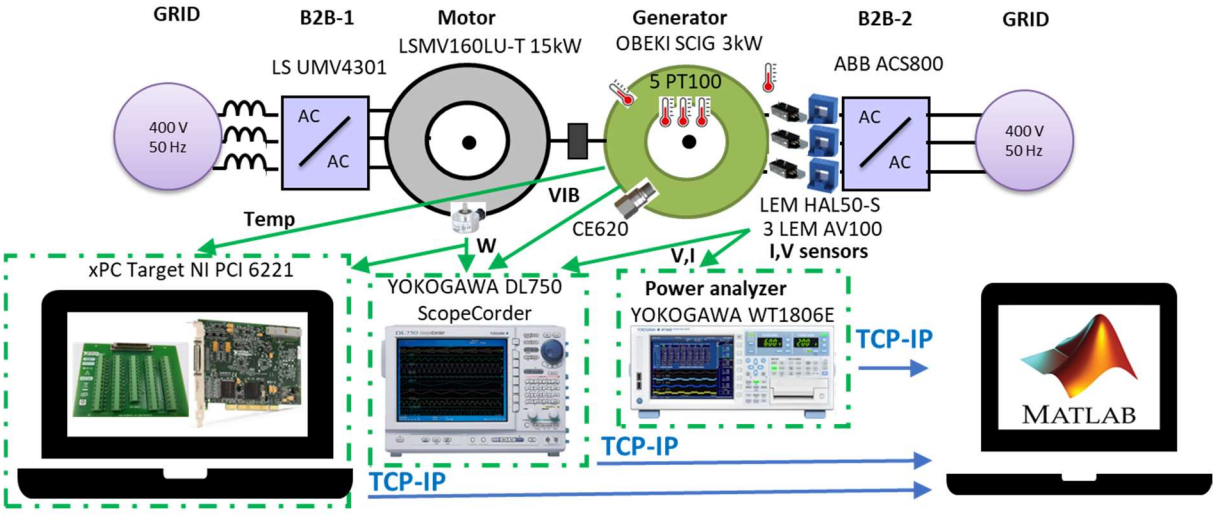


Figure 3 Test bench General scheme and data acquisition systems

As a summary, Table 4 describes the sensors used for the tests:

Table 4. Summary of sensors

Type	**Number**	**Detail**	**Position**	**Data acquisition system**
Current	3	Hal 50-S [6]	Sensor at each phase	DL 750 ScopeCorder
Voltage	3	LEM AV100 [7]	Sensor at each phase	DL 750 ScopeCorder

Vibration	2	Accelerometer CE 620 [8]	Generator case	DL 750 ScopeCorder
Temperature	5	PT100-3 wire [9] and temperature transmitter SEM206P [10]	One at each phase stator winding, one at case, one ambient	XPC target NI PCI 6221
Encoder	1	Encoder	Motor	XPC target NI PCI 6221

Apart from the measures from Table 4, several instrumentation and software has been used:

- Motor B2B control software: CT-soft.
- Generator B2B control software: Window drive light
- XPC Target NI PCI 6221 control Matlab-Simulink:
- Insulation measurement:
  - Partial discharge: Monesto 200
  - Leakage current: HIOKI CM4003
  - Megger: Quadtech Sentry 30 Plus AC/DC/IR Hipot Tester

A power analyser (Yokogawa WT1806E) has been used to analyse the power quality of the generator.

3.2 Summary of signals

Table 5 summarizes the signals obtained in the test bench, showing the sensor used, the acquisition equipment used, and its sampling rate.

Table 5. Summary of signals

Signal	Unit	Sensor	DAQ	Freq
Phase 1 current	A	Hal 50-S	DL 750 ScopeCorder	1kHz
Phase 2 current	A	Hal 50-S	DL 750 ScopeCorder	1kHz
Phase 3 current	A	Hal 50-S	DL 750 ScopeCorder	1kHz
Phase 1 voltage	V	LEM AV100	DL 750 ScopeCorder	1kHz
Phase 1 voltage	V	LEM AV100	DL 750 ScopeCorder	1kHz
Phase 1 voltage	V	LEM AV100	DL 750 ScopeCorder	1kHz
Vibration	dB	Accelerometer CE 620	DL 750 ScopeCorder	1kHz
Speed	rpm	Encoder	B2B software/ XPC target	10Hz
Active power	W	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Reactive power	Var	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Apparent power	Va	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 1 current	A	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 2 current	A	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz

Signal	Unit	Sensor	DAQ	Freq
Phase 3 current	A	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Current	A	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 1 Voltage	V	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 2 Voltage	V	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 3 Voltage	V	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Voltage		YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 1 Voltage freq.	Hz	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 2 Voltage freq.	Hz	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 3 Voltage freq.	Hz	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 1 current freq.	Hz	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 2 current freq.	Hz	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Phase 3 current freq.	Hz	YOKOGAWA WT1806E	YOKOGAWA WT1806E	10Hz
Stator Tº phase 1	ºC	PT100	XPC target NI PCI 6221	10Hz
Stator Tº phase 2	ºC	PT100	XPC target NI PCI 6221	10Hz
Stator Tº phase 3	ºC	PT100	XPC target NI PCI 6221	10Hz
Generator case Tº	ºC	PT100	XPC target NI PCI 6221	10Hz
Ambient Tº	ºC	PT100	XPC target NI PCI 6221	10Hz

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4 Generation of the time series

4.1 Pre-processing

A particular effort has been devoted to pre-processing data from a real sea state, in order to generate data that can be reproduced on a motor-generator testbench in lab environment.

For the current project, the "Wave to wire" model is used at the pre-processing stage, and specifically to generate of the power time series of the input that the electric generator receives. This model has been validated with the extensive real offshore deployment of the MARMOK A-5, paying special attention to significant magnitude power peaks.

4.1.1 Power time series

Different wave sites produce their wave resource data from decades of real sea environment. For instance, BiMEP, EMEC, PacWave North, PacWave South. These wave resource data could come in forms of time series or occurrence matrix among others. The occurrence matrix gives the probability of each sea state, defined by the significant wave height (H_s) and the peak period (T_p). For the elaboration of the characteristic time series BiMEP test site has been selected.

		SIGNIFICANT WAVE HEGHT HS (m)																	
		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9
PEAK PERIOD (s)	3	0.0%																	
	4	0.4%	0.2%																
	5	1.2%	0.7%	0.2%															
	6	0.8%	1.5%	0.8%	0.2%	0.0%													
	7	0.4%	1.1%	0.3%	0.3%	0.1%	0.0%												
	8	1.9%	5.5%	2.6%	0.8%	0.4%	0.2%	0.1%	0.0%										
	9	1.5%	3.9%	5.5%	1.9%	0.5%	0.2%	0.1%	0.1%	0.0%									
	10	1.3%	3.7%	5.2%	3.7%	1.0%	0.3%	0.2%	0.2%	0.1%	0.0%								
	11	1.5%	2.9%	3.7%	3.9%	3.6%	1.4%	0.5%	0.4%	0.2%	0.1%	0.0%	0.0%						
	12	0.9%	1.3%	2.8%	2.6%	3.2%	2.8%	1.6%	0.4%	0.3%	0.1%	0.1%	0.1%	0.0%					
	14	0.4%	0.6%	1.3%	1.3%	1.6%	1.7%	1.5%	1.0%	0.5%	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%			
	16	0.3%	0.4%	0.9%	0.5%	0.4%	0.6%	0.6%	0.5%	0.5%	0.4%	0.3%	0.3%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%
	18	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%		0.0%		0.0%	0.0%	0.0%				

Figure 4: BiMEP occurrence matrix

For the purpose of shortening computational time, the exiting sea states have been clustered in only 30 groups or "sea states". Each group has been conducted using adjacent sea states from the occurrence matrix, stablishing the energy of the group weighting the energy of each of the sea states.

Starting from the H_s and T_p of these 30 sea states, sequences of wave trains are generated with different seeds, and they are fed into the computational model of the MARMOK device.

4.1.2 Definition of peaks

The analysis conducted for the definitions of the tests to be performed in the VALID project focuses on the nature of the power that the generator endures. For this, two assumptions are made:

- The damage to the generator is produced only (or mainly) by high temperatures, and these are only produced by power peaks over the nominal power.
- Damage can be considered as cumulative.

These assumptions lead to the definition of power peak: Any electric power value over 0.8 time the nominal power of the generator.

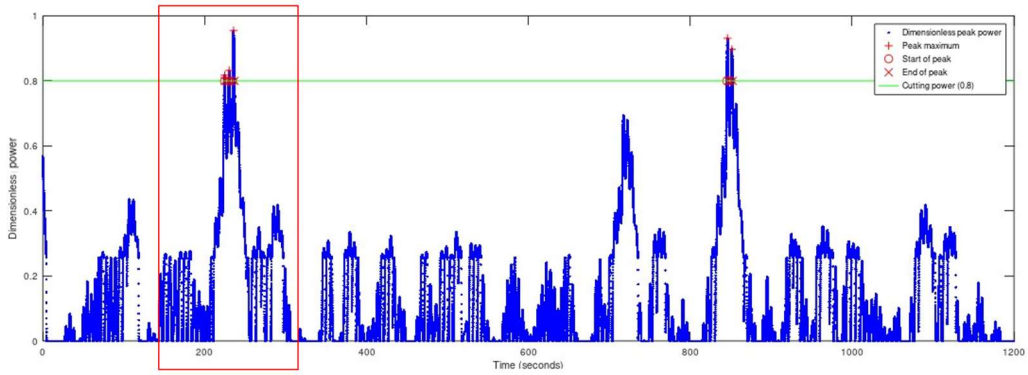


Figure 5: Cut-off at 0.8 times the nominal power

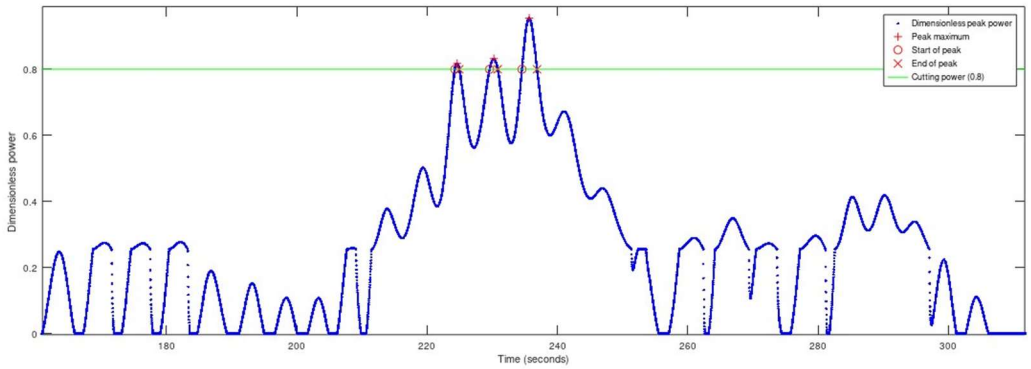


Figure 6: Detailed view of the peaks within the data frame above (marked in red)

For the characterization of the peaks the "Wave to wire" model has been run for the mentioned 30 sea states representing the environmental contour of BiMEP. This process for the 30 sea states has been repeated with 100 different seeds, applying the occurrence of each sea state for having an annual statistic of the power when weighting the results.

No correlation has been found between the different sea states and the type of peaks produced, other than that more energetic sea states produce a greater number of peaks of all powers. Therefore, the tests have focused on the response of the generator to peaks of different intensities and not to different sea states.

4.2 Implementation

Hybrid testing has been done at the generator-motor test bench in Tecnalia.

- The motor (15 kW) reproduces the time series of peaks.
- The motor shaft is coupled with the generator (3 kW) shaft.
- The generator (3 kW) will capture the peaks using a regenerative torque control law.

4.2.1 Peaks Trains

It has been observed when studying the time series that the peaks are not usually individual, but usually arrive in trains, in such a way that several peaks are repeated during various semi-periods of the waves and then there are no peaks for a certain time. No relationship has been found between the number of peaks in a train and the power of the peaks or the sea state that produced them. The same can be said for rest time between trains.

4.2.2 Power time series

When moving to the tests, a representative case of the analysis conducted to the peaks has been defined to be tested in the physical setup. Instead of a real wave train, bearing in mind the hypothesis that just the peaks introduce damage in the system, on a testing acceleration measure consecutive power peaks have been introduced.

The peaks introduced are a representation of the most probable peaks for the generator to face on a real application, introducing different peak magnitudes with their respective durations and time between them using the polynomial obtained for their representation. The tests will be conducted having 5 consecutive power peaks series inside which the peaks will be spaced half a wave period between each peak start. The duration of the peaks, and the time between peaks has been adjusted with the scale factor beetwen the real generator and the tested generators. The time between peaks has been adjusted to accelerate the tests without exceeding the target temperature.

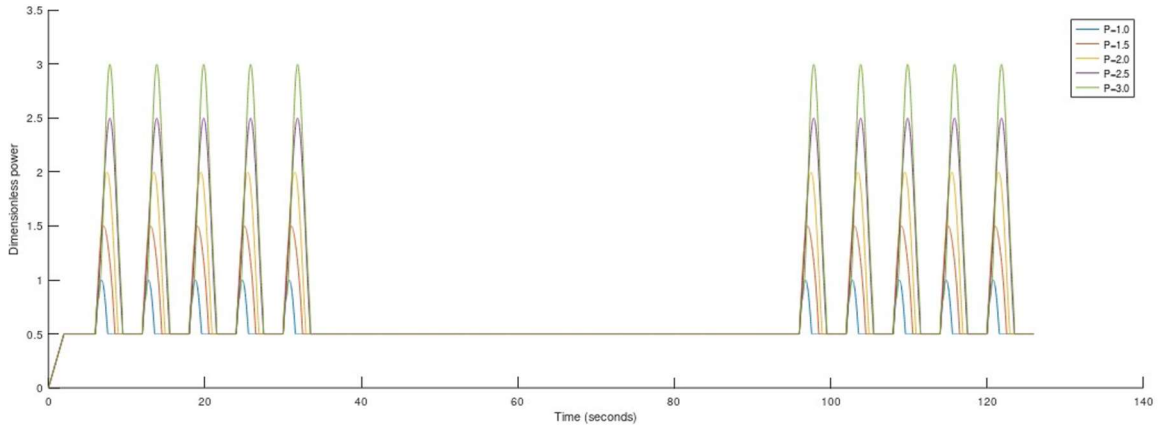


Figure 7: Time series generated for testing

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927.

5 Description of the dataset

Dataset is in the excel sheet "*VALID_generator_test_register_efficiencies.xlsx*".

First row provides information about the data of each column.

- **Blue**: input or informative data
- **Green**: measured data
- **Gray**: calculated data

Data in each column represents the following information:

- **Test code**: XX-YY-Z where XX means Torque (or Power, or total) Capacity Factor (CF),YY amplitude of the peaks and Z number of test for the same CF and amplitude.
- **Date**: Date when the test was carried out.
- **Duration**: Duration of the test in hours.
- **Input file**: Input file used for the torque/power. "Constant power" means that the test was performed at constant torque and power and there is no input file. Input files are also provided in the dataset as independent files.

  Example: TP_Pmed_0,8_(0,6-1,1).mat

  Torque Capacity Factor ≈0.8
  Lower peak amplitude = 0.6
  Higher peak amplitude = 1.1
  All the values are expressed in pu.

- **CF**: Indicates the capacity factor of the input torque (or input power) applied during the test. In pu.
- **Peaks ampl**.: When value is zero represents the test has been carried out at constant torque (and power). Otherwise, it represents the amplitude of the peaks.
- **Measured mean eff**.: Mean efficiency obtained from the input and output power measurements. [%]
- **Pcu1**: Calculated. Mean value of the stator cupper losses during the test. [W].
- **Pcu2**: Calculated. Mean value of the rotor cupper losses during the test. [W].
- **Pmec**: Calculated. Mean value of the mechanical losses during the test. [W].
- **Pfe**: Calculated. Mean value of the iron losses during the test. [W].
- **PLL**: Calculated. Additional load losses P_{LL}. According to IEC 60034-2-1, additional losses in a machine of a rated power between 1 kW and 10000 kW can be estimated as

  $$P_{LL} = P_{in}(0.025 - 0.005 \log_{10} P_N),$$

  where nominal power P_N is expressed in kW and P_{in} is the input power. [W].
- **Mean eff. calculated from losses**: Calculated. Mean efficiency of the generator during the test using the output power calculated by subtracting the losses from the input power. [%].
- **Eff**. **Error**: Calculated. Difference between the efficiency obtained from the measurements and the efficiency obtained from the estimated power losses. [%].
- **I1mean**: Measured phase current in the stator terminals. [A].
- **I2mean**: Calculated. Current of the rotor reduced (or referred) to the stator in the equivalent circuit of the electrical generator. [A].
- **Fmean**: Measured mean electrical frequency of the voltage in the stator terminals. Although the frequencies of the 3 phases have been registered, only one is represented. NOTE: Frequency was not saved in the initial tests. [Hz].

- **CosphiMean**: Measured cosphi in the output of the rotor terminals. [-].
- **Vmean**: Measured mean voltage in the rotor terminals. [V].
- **Total losses**: Calculated. Sum of the segregated losses. [W].
- **Pcu1(%):** Calculated percentage of the cupper losses in the stator. [%].
- **Pcu2(%):** Calculated percentage of the cupper losses in the rotor. [%].
- **Pmec(%):** Calculated percentage of the mechanical losses. [%].
- **Pfe(%):** Calculated percentage of the iron losses. [%].
- **PLL(%):** Calculated percentage of the additional losses. [%].
- **Temp. end**: Temperature in the stator windings at the end of each test. [ºC]. Temperature is registered in several PT100 sensors installed in the generator windings.

NOTES:

- Frequency was not saved during the initial tests. This is why some tests have no information about the segregation of losses as the frequency is needed for this calculation.
- During some tests, temperature was not correctly saved and that is why some tests have no information about temperature.

6 References

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