VALID

Verification through Accelerated testing
Leading to Improved wave energy Designs

Your new platform

VALID - WEC hybrid testing: Lessons learnt from the IDOM’s case study

2024-01-31

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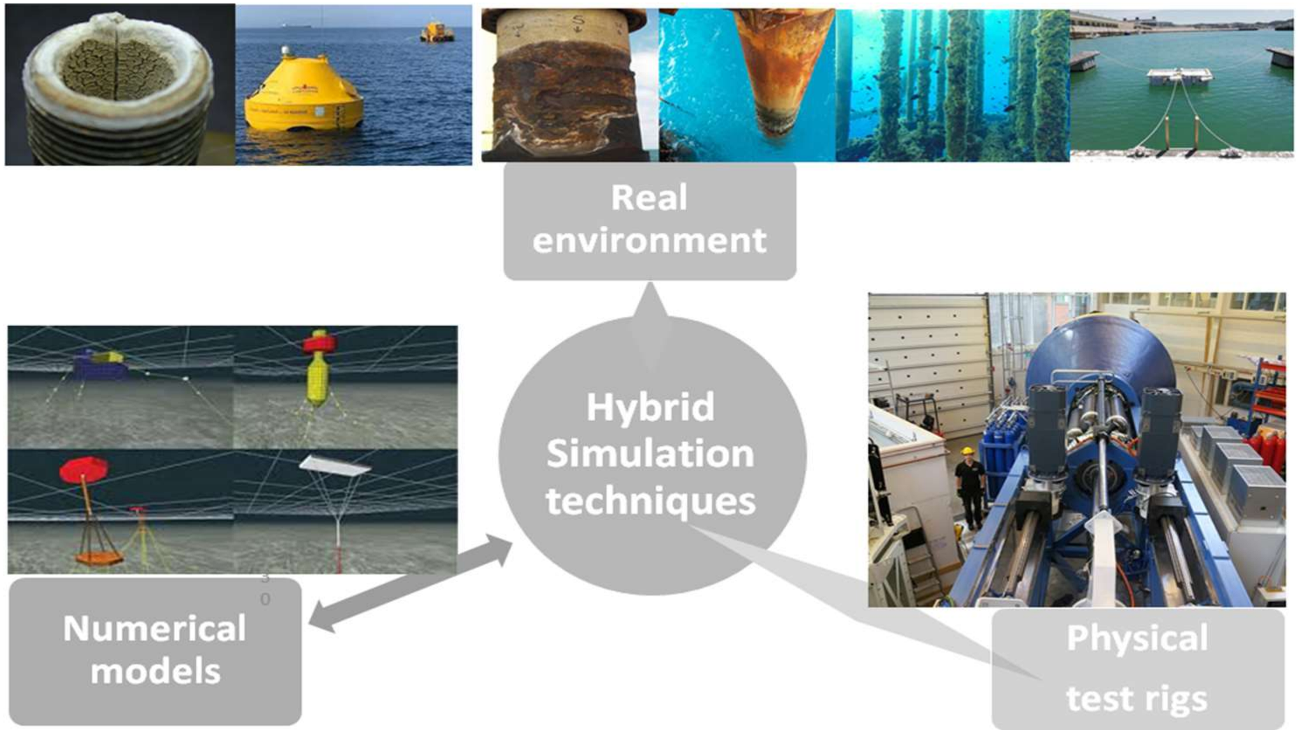
IDOM, TECNALIA

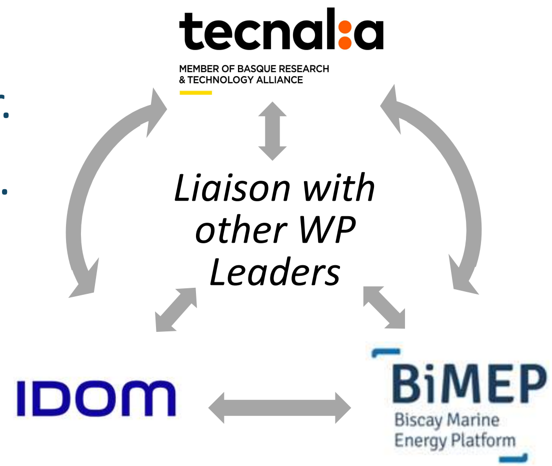
This project has received funding from the European Union’s Horizon 2020
research and innovation programme under grant agreement No 101006927.

What is Hybrid testing?



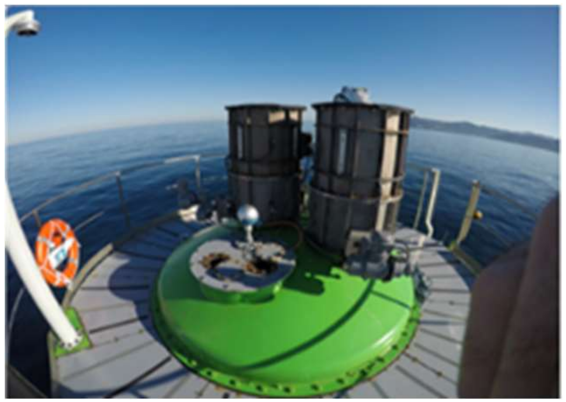
Electric generator failure

- Main aim: Produce a first-of-a-kind practical implementation of the novel testing methodology and hybrid platform on the electric generator.
- This failure mode will be exemplified on IDOM's OWC device (MARMOK).
- This technology has been extensively demonstrated at the Mutriku shoreline OWC plant (since 2011) and at the BiMEP open-sea testing site (2.5 years) within the H2020 OPERA project.



Mutriku Site

IDOM's MARMOK



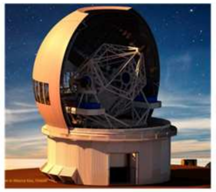
TECNALIA's testbench

WHO WE ARE

Bilbao Headquarters

We are an independent firm providing Consulting, Engineering and Architecture professional services, united in our way of doing things, shared objectives, the Service of our clients.

4300	65	920	125
Professionals	Years of experience	Partners	Countries



Science

Transport

Energy

Environmental

Industry

Telecom

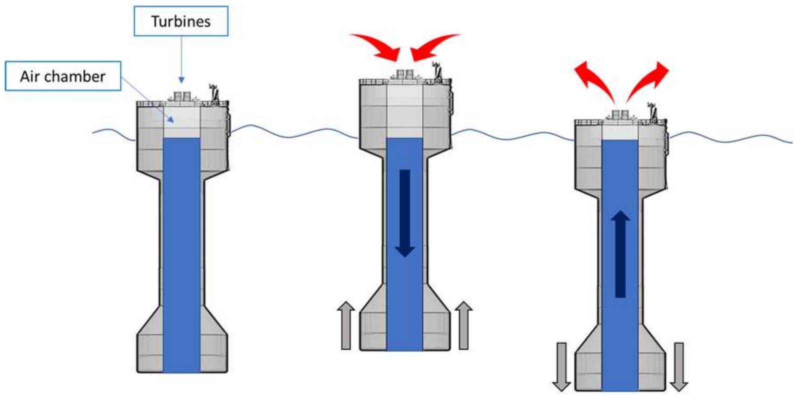
Building

Consulting

- Advanced Design & Analysis
- Energy
- Industry
- Architecture
- Consultancy
- Transport & Infrastructures
- Water & Environment

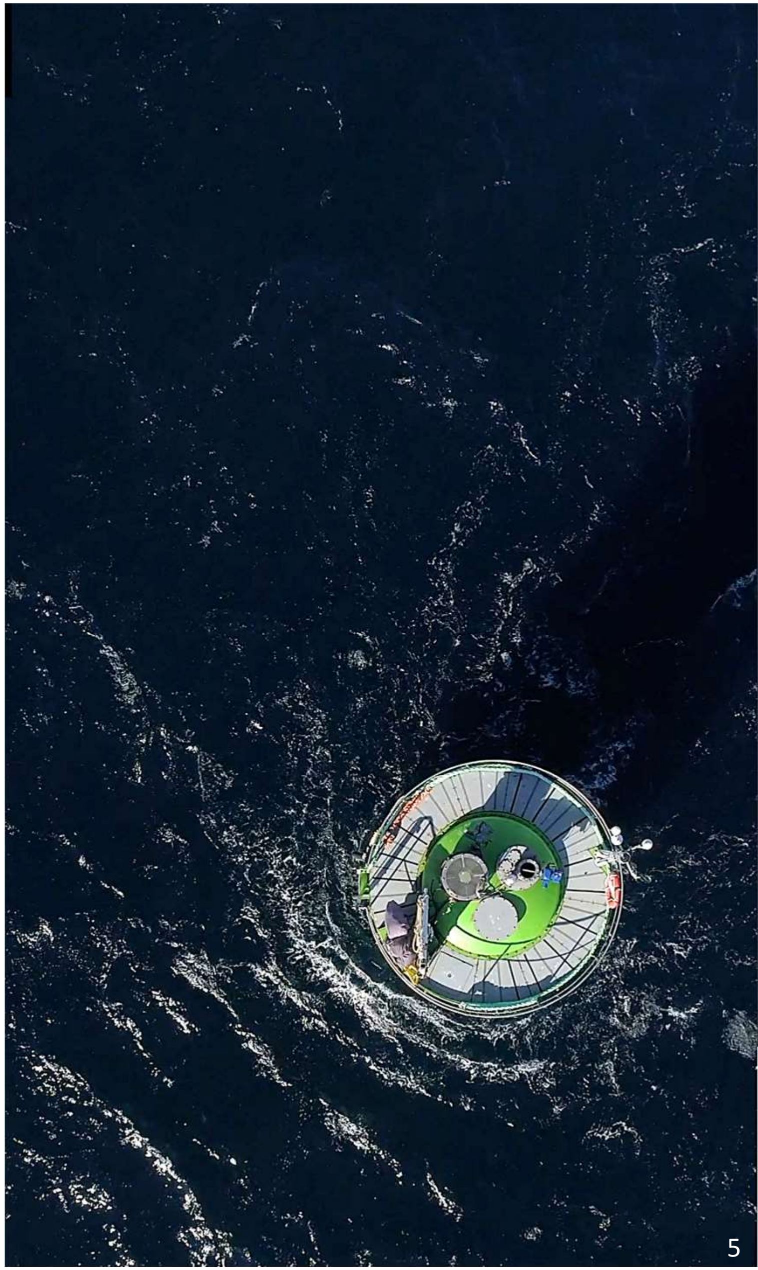
- Operating Globally
- 45 Offices Worldwide
- International activity >90%

The Technology



MARMOK's unique design provides the following advantages:

- *Simplicity:* formed by a single structural element, it avoids complex mechanisms exposed to offshore conditions. The only moving part is the turbine-generator set, which is placed on the deck and easily accessible.
- *Robustness:* 'spar buoy' configuration has been widely proved in the offshore industry to provide good performance and reliability.
- *Adaptability:* simple modifications permit the optimization of the device for a particular location and wide range of sea conditions.
- *Reduced maintenance:* due to the simplicity of the device and based on previous experience, minimum maintenance is required which supposes a substantial number of operating hours.
- *Potential to achieve a competitive LCOE*



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MARMOK WEC Technology

- Activities around marine renewables started 12 years ago with the development of a wave energy harvesting technology (Spar type OWC)
- Technology with outstanding simplicity, robustness and maintainability (a single moving part, not submerged)
- Viability of the technology demonstrated offshore during 2.5+ years (3 consecutive winters)

VALID

Mutriku Wave Power Plant

The Mutriku wave plant achieves cumulative electricity production of three million kilowatts per hour

11 ENE 2024

- The Mutriku plant is the first commercial plant in Europe to use wave energy to generate electricity, the longest-lived in the world and the one with the most hours of operation.
- It has reached 12 and a half years of continuous clean energy production, with an annual production of approximately 300,000 kWh.

The wave plant of Mutriku, the first worldwide commercial project associated with the wave power sector, has surpassed a new milestone in the field of wave energy by reaching cumulative electricity production of three million kilowatts per hour.

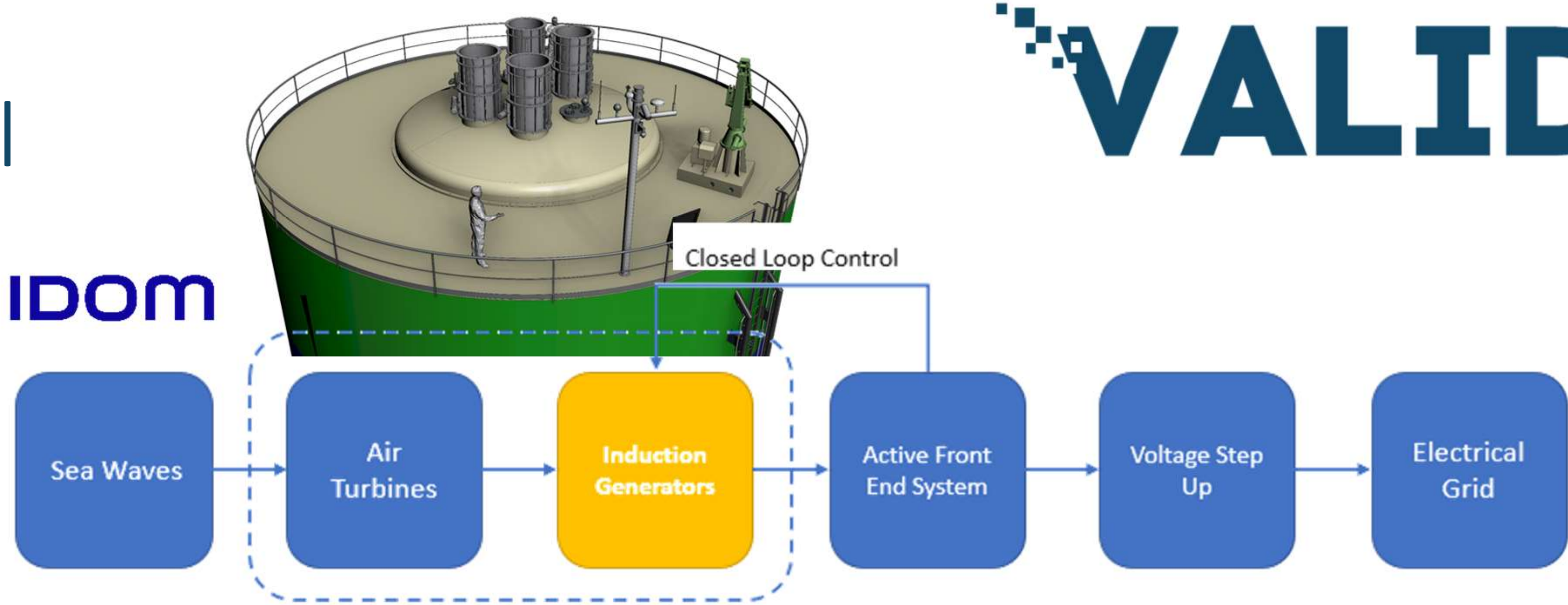
The Mutriku plant is the first European commercial plant that uses wave energy to generate electricity, the world's oldest and the one that accumulates more hours of operation. Since its launch in 2011, the Mutriku wave energy plant has been 12 and a half years old, generating clean energy continuously. It has passed several stages of development and has exceeded the production records achieved so far by a renewable

User Case II

VALID

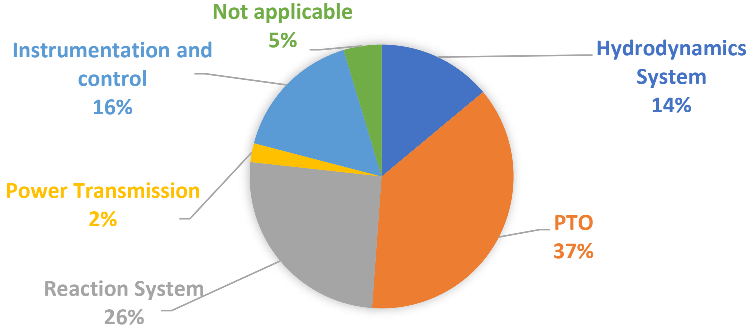
IDOM

The **electrical generator** is in the critical path of the Energy Conversion

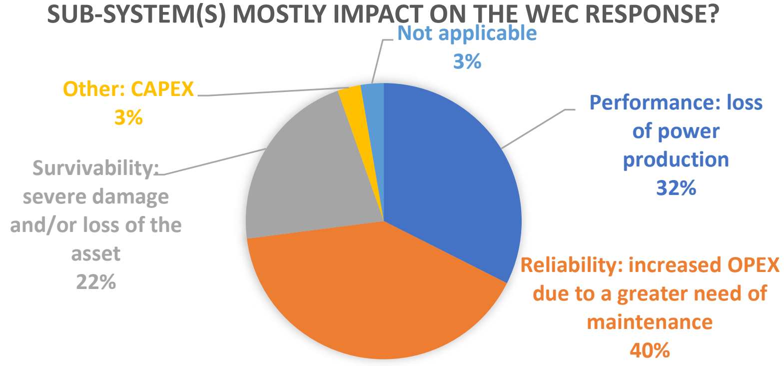


MARMOK PTO

IN YOUR OPINION/EXPERIENCE, WHICH OF THE MAIN SUB-SYSTEMS/COMPONENTS OF THE WEC IS THE MOST CRITICAL?

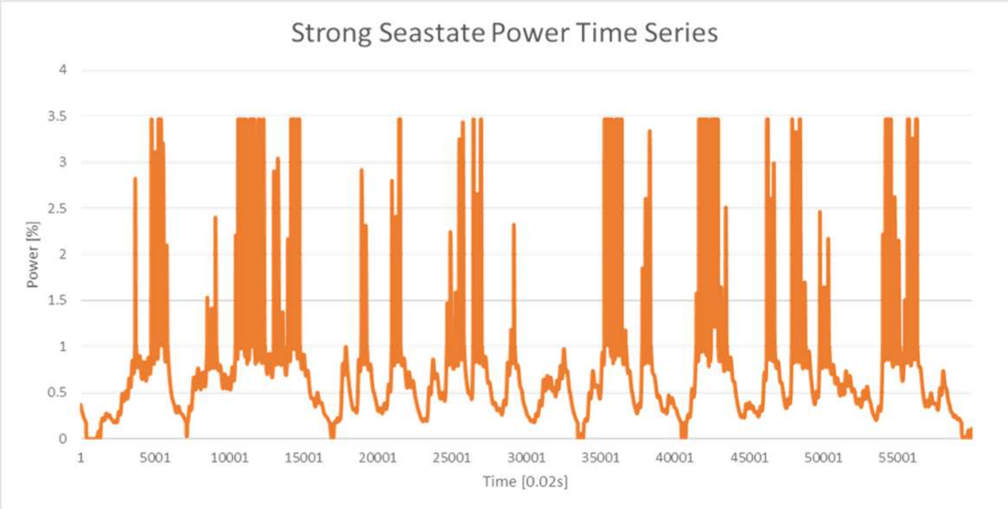


IN YOUR OPINION/EXPERIENCE, WHAT DOES THE CRITICAL SUB-SYSTEM(S) MOSTLY IMPACT ON THE WEC RESPONSE?



Generator Failure

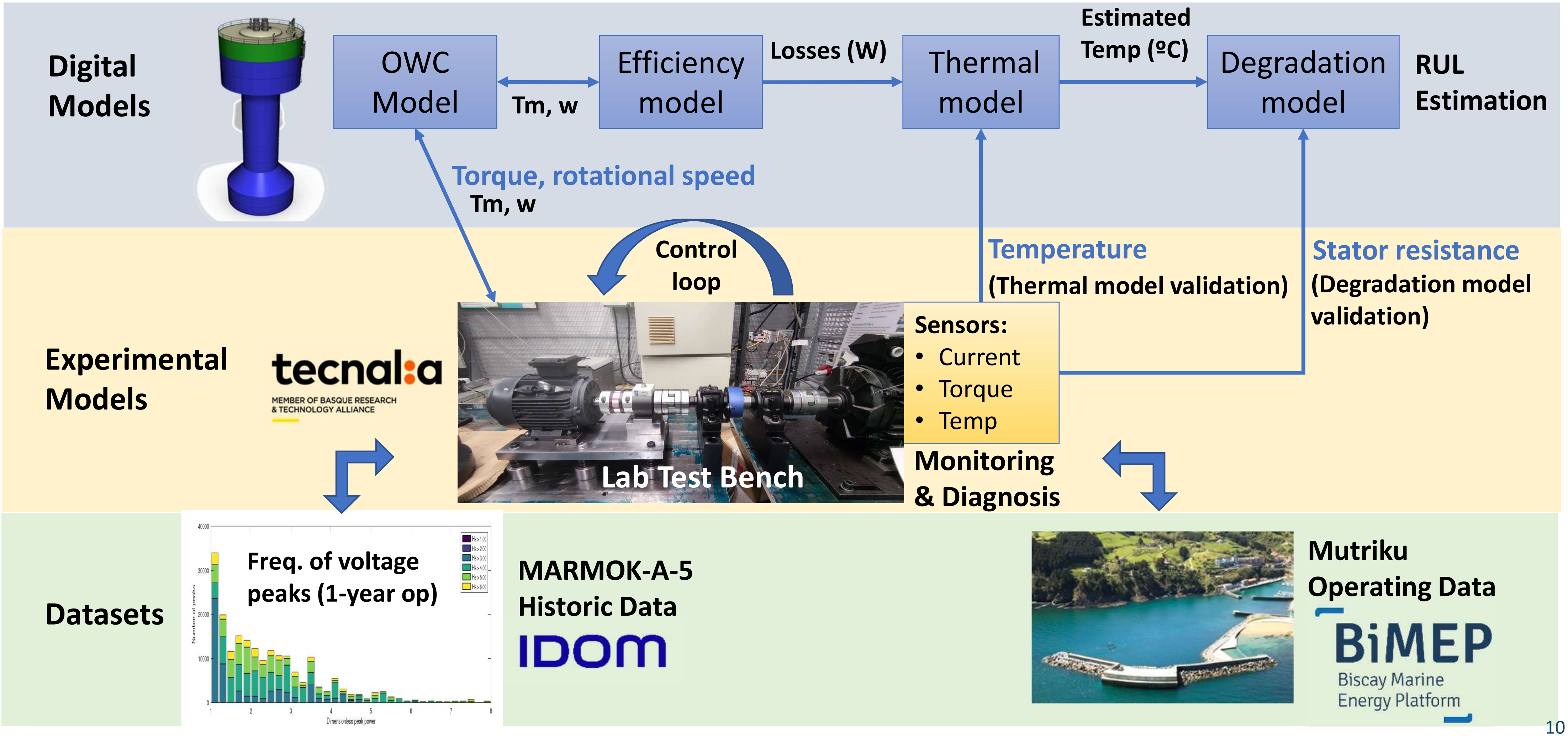
- **Stator winding** accounts for 65% of all failures.
- Stress factors:
  - Thermal degradation – **Temperature**
  - Electrical degradation – **Voltage**
  - External environment – **Humidity & salinity** → difficult to reproduce in the lab



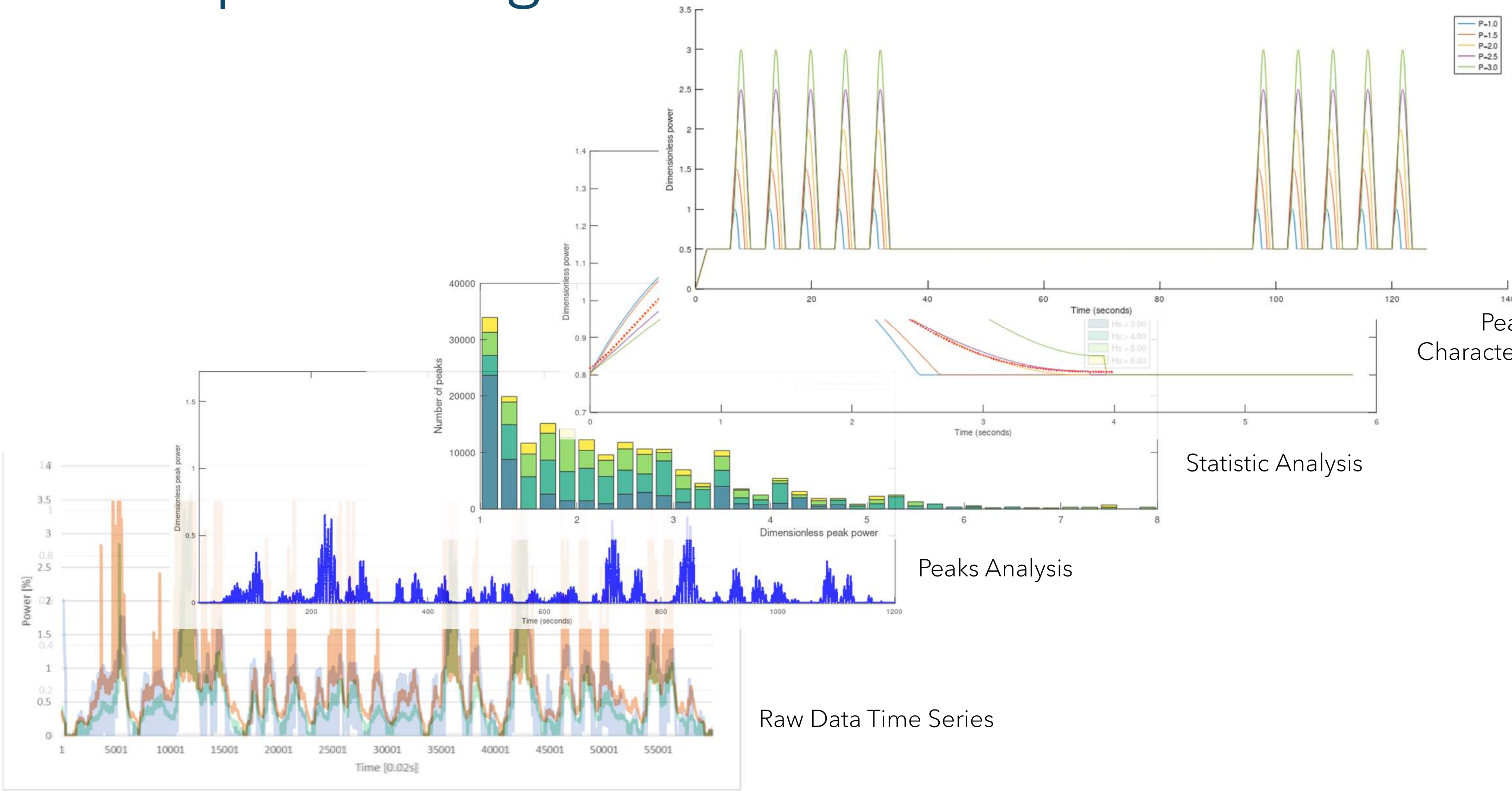
Generator Sizing

Generator	Performance	Survivability	Reliability
Sea State	Ave. to Rated Power	Peak to Rated Power	Overload Time
Mild	17%	1	> 1%
Medium	44%	3.5	6%
Strong	82%	3.5	15%

Hybrid Testing Set-Up



Preprocessing



Test Data

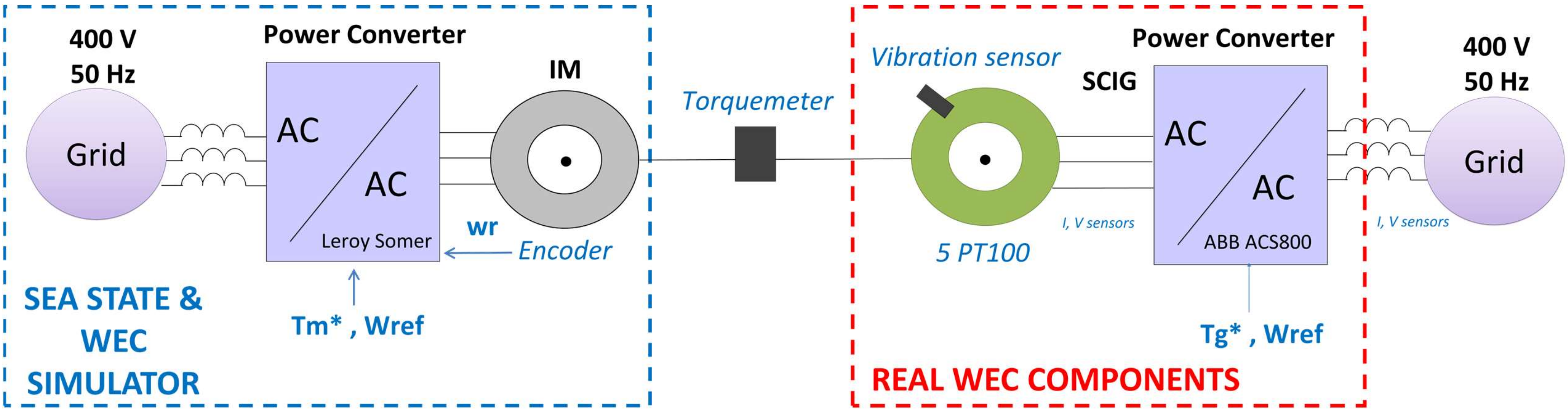
Peak Characterization

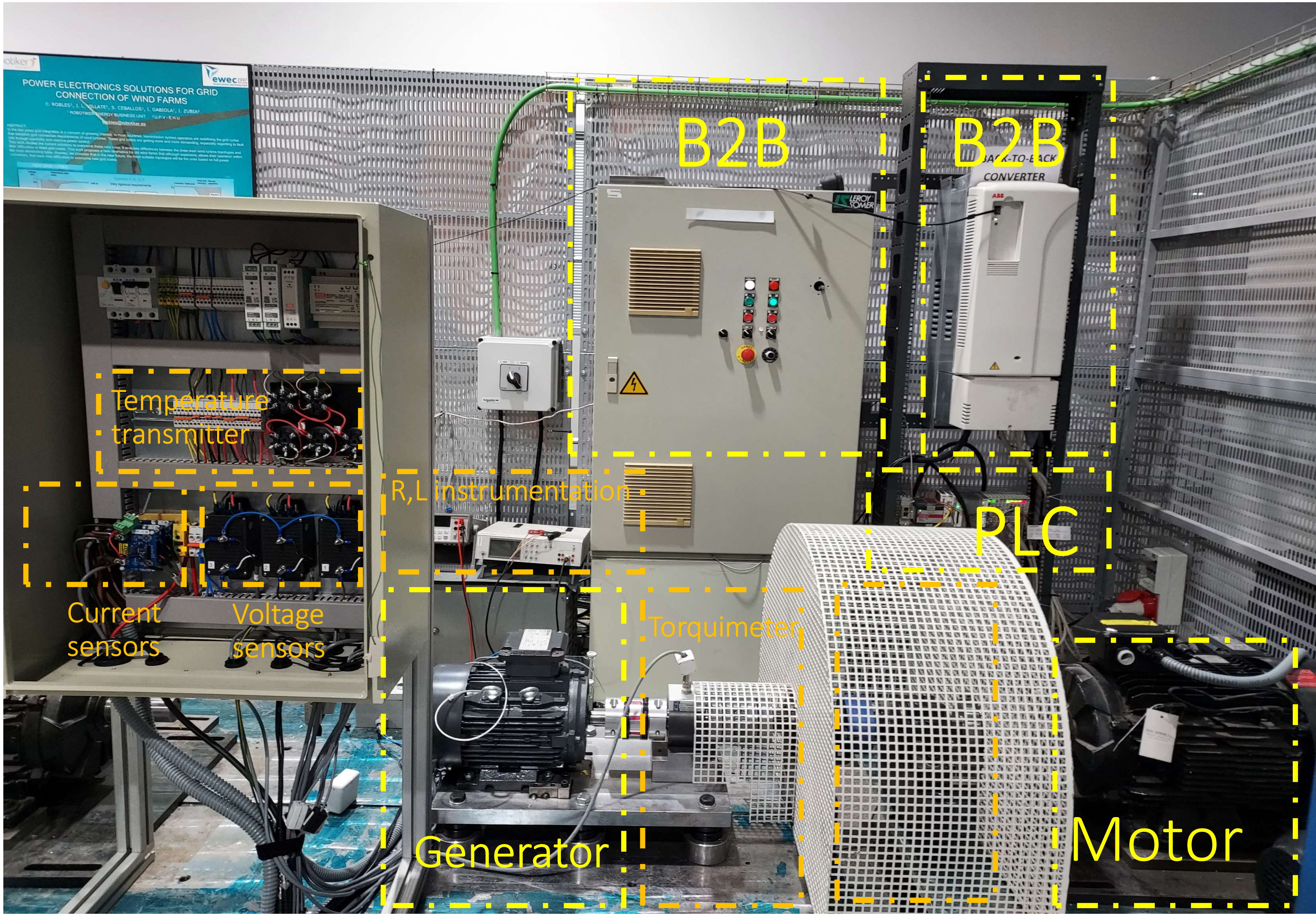
Statistic Analysis

Peaks Analysis

Raw Data Time Series

Test Bench description



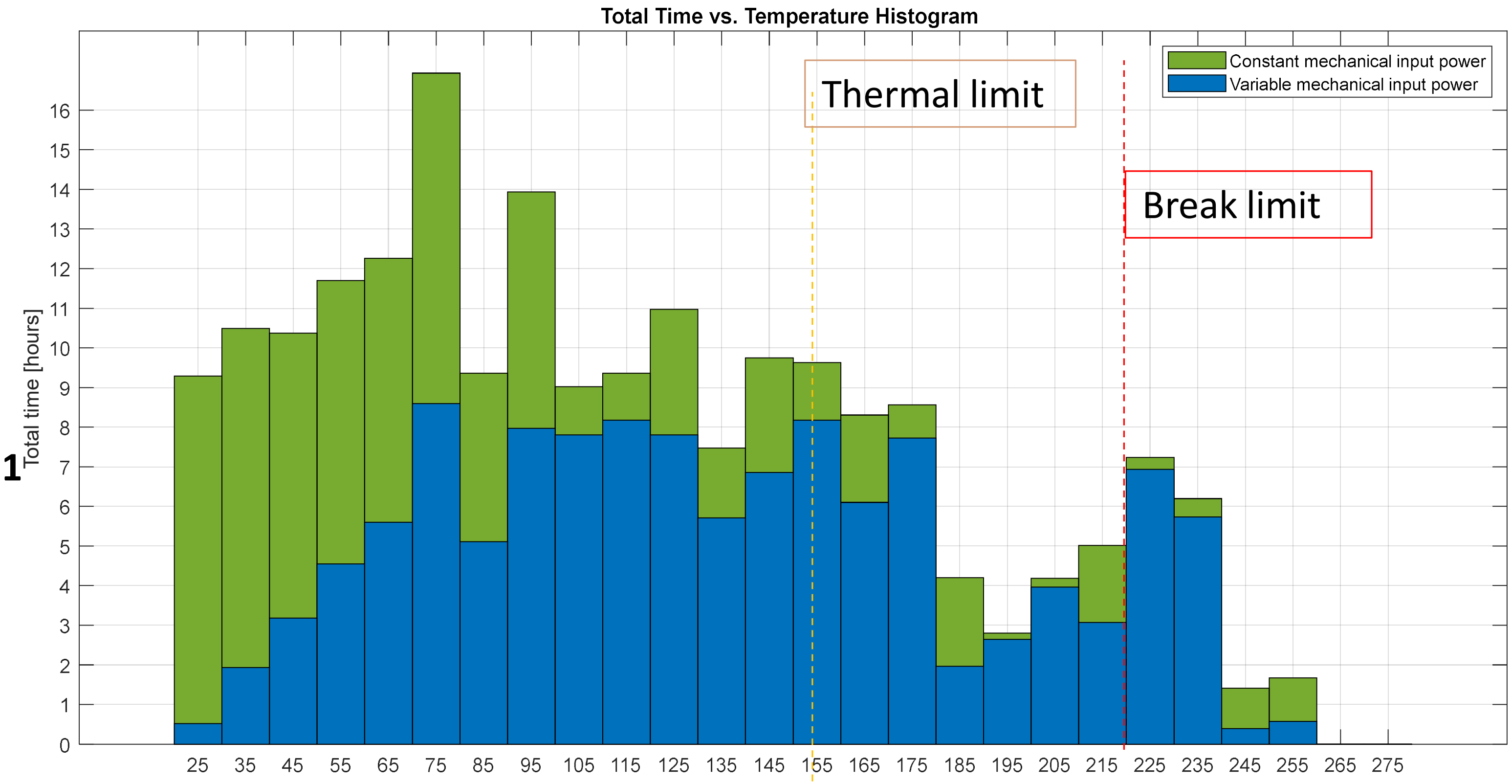

POWER ELECTRONICS SOLUTIONS FOR GRID CONNECTION OF WIND FARMS
B2B
B2B
BACK-TO-BACK CONVERTER
LEROY SOMER
Temperature transmitter
R,L instrumentation
Current sensors
Voltage sensors
Torquimeter
PLC
Generator
Motor

Generator 1: variable working conditions

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

Thermal fatigue testing of electric generator

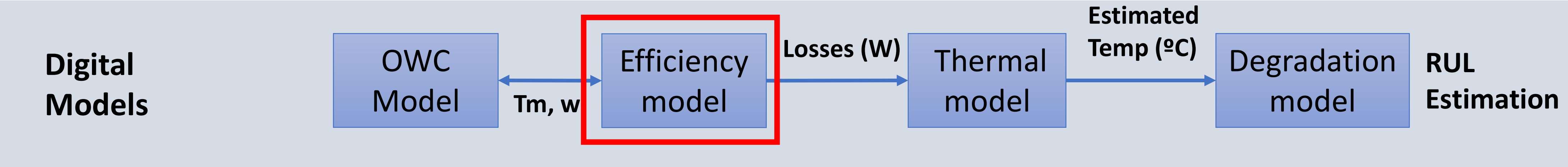
Generator 1

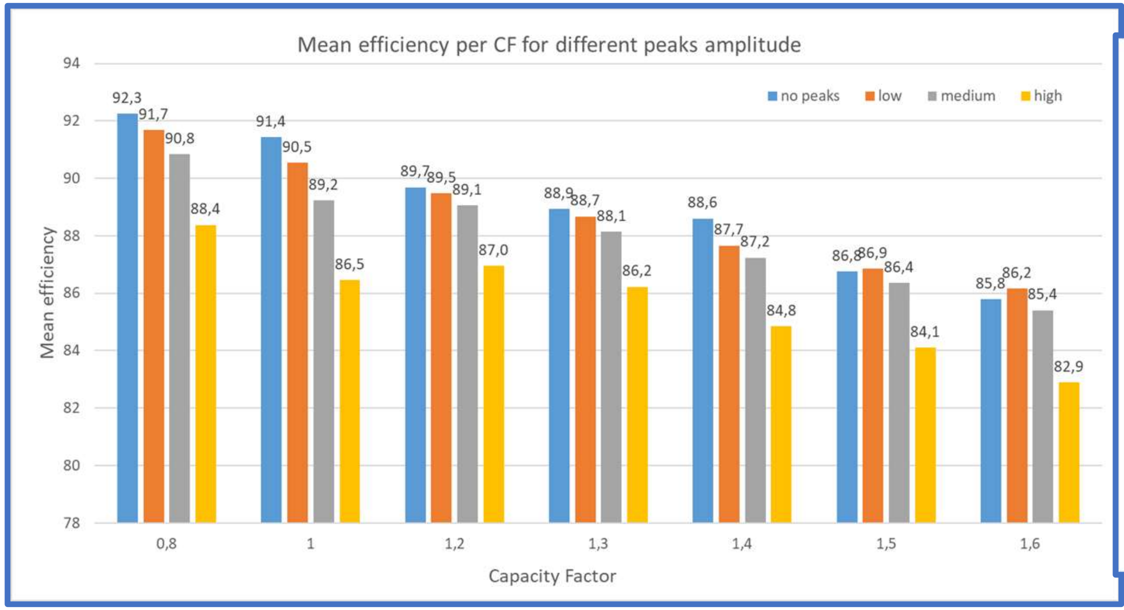


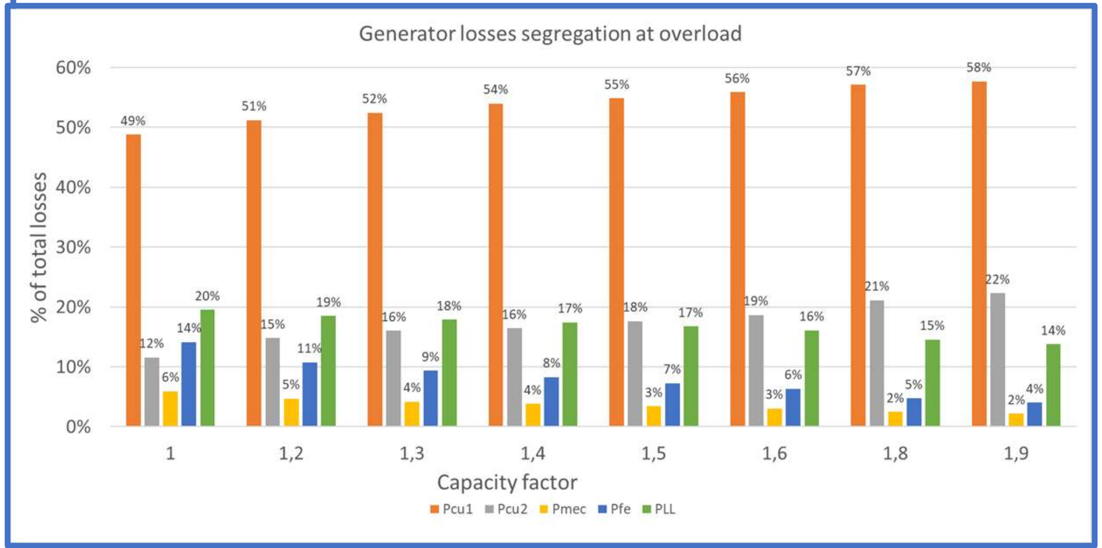
Test plan Generator 2 → no time, harder tests

Test	P rms	P media	P peak	P low	Amplitude	Period
32_Peaks	1,328	1,2	2,25	0,75	1,5	2
33_Peaks	1,414	1,3	2,36	0,86	1,5	2
34_Peaks	1,511	1,4	2,46	0,96	1,5	2
35_Peaks	1,612	1,5	2,54	1,04	1,5	2
36_Peaks	1,692	1,6	2,62	1,12	1,5	2
28_Peaks	1,705	1,7	2,05	1,55	0,5	2
29_Peaks	1,735	1,7	2,4	1,4	1	2
30_Peaks	1,792	1,7	2,72	1,22	1,5	2
31_Peaks	1,819	1,7	2,9	1,15	1,75	2

Models, validation and result analysis







*Capacity Factor CF = Torque CF * Speed CF*

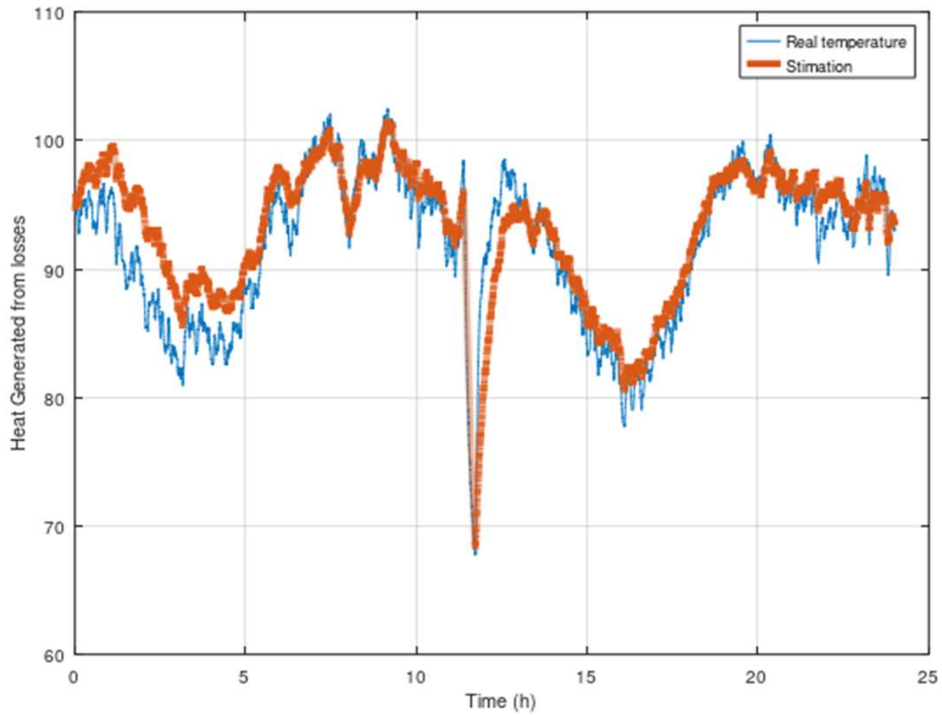
1st Order Thermal Model

$$\theta_{max} = \theta_{SF=1} * \left(\frac{I}{I_{nom}}\right)^2$$

$$\theta = \theta_{max} * \left(1 - e^{\frac{-t}{\tau}}\right) + \theta^{-1} * e^{\frac{-t}{\tau}} + \theta_{amb}$$

Where:

- θ – Actual winding temperature.
- θ_{amb} – Ambient temperature.
- τ_{max} – Maximum temperature increased due to actual stator current.
- θ^{-1}– Previous temperature increase.
- t – Sample time in seconds.
- τ– Heating time constant



2nd Order Thermal Model

$$\theta_{max\ case} = \theta_{SF=1\ case} * \left(\frac{I}{I_{nom}}\right)^2$$

$$\theta_{max\ copper} = \theta_{SF=1\ copper} * \left(\frac{I}{I_{nom}}\right)^2$$

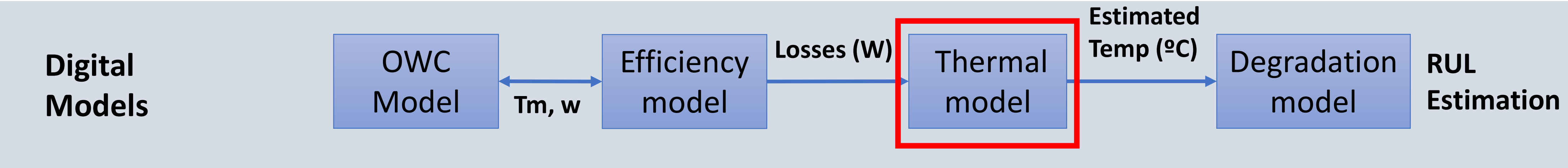
$$\theta_{case} = \theta_{max\ case} * \left(1 - e^{\frac{-t}{\tau_{case}}}\right) + \theta_{case}^{-1} * e^{\frac{-t}{\tau_{case}}}$$

$$\theta_{copper} = \theta_{max\ copper} * \left(1 - e^{\frac{-t}{\tau_{copper}}}\right) + \theta_{copper}^{-1} * e^{\frac{-t}{\tau_{copper}}}$$

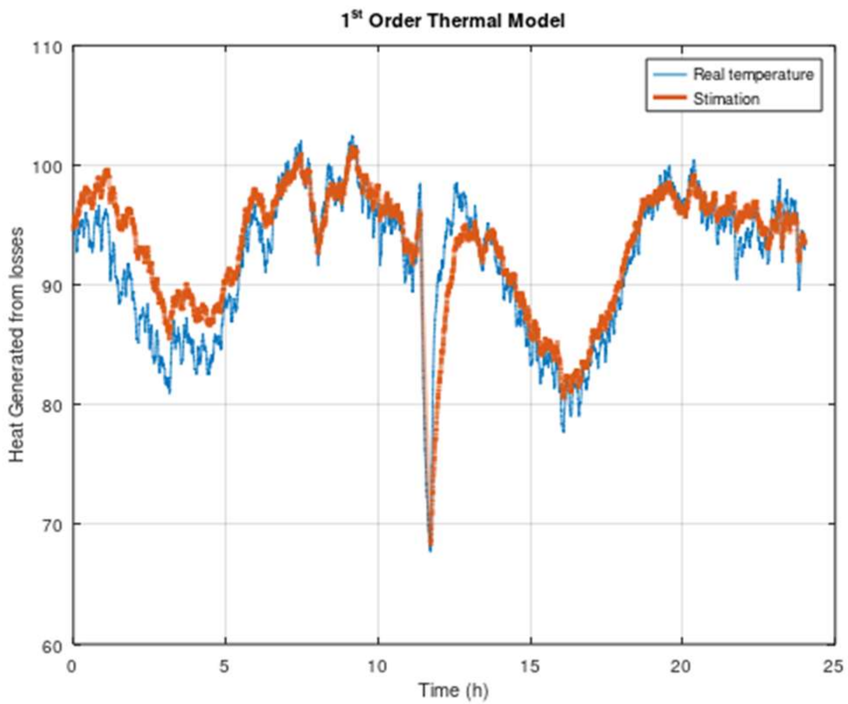
$$\theta = \theta_{copper} + \theta_{case} + \theta_{amb}$$

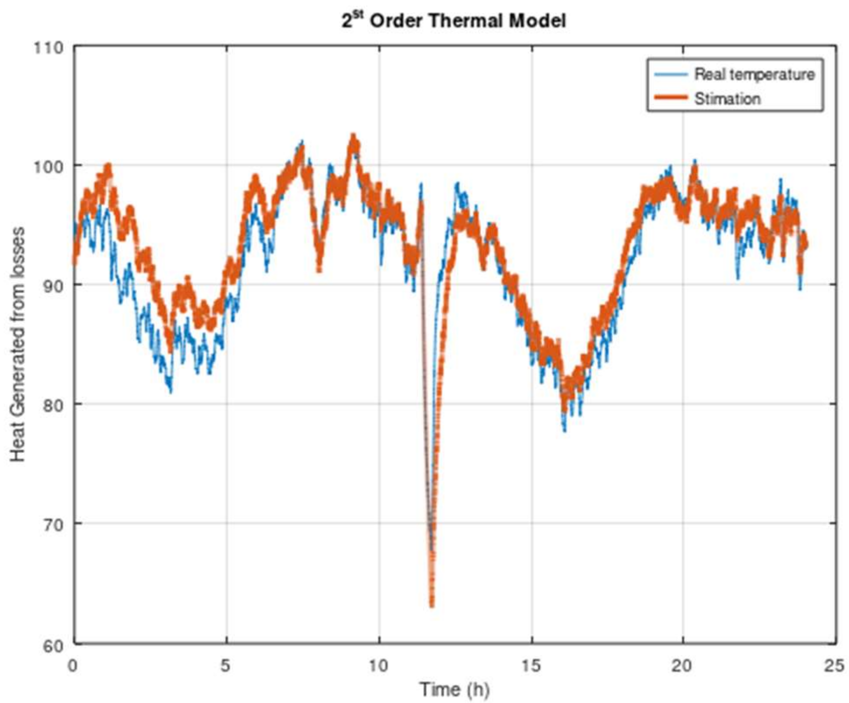
Where:

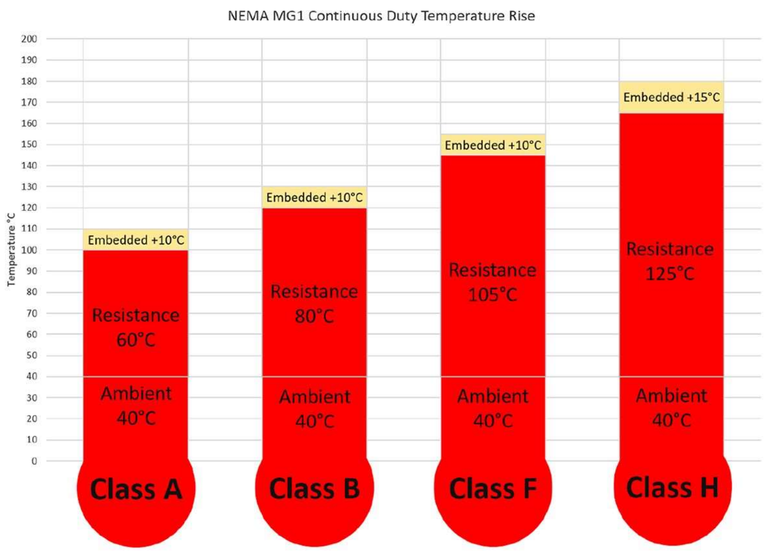
- θ – Actual winding temperature.
- θ_{amb} – Ambient temperature.
- $\theta_{max\ case}$ – Maximum temperature increased due to actual stator current in case.
- $\theta_{max\ copper}$ – Maximum temperature increased due to actual stator current in copper.
- θ_{case}^{-1} – Previous temperature increase in case.
- θ_{copper}^{-1} – Previous temperature increase in copper.
- t – Sample time in seconds.
- τ_{copper} – Heating time constant of copper / steel
- τ_{case} – Heating time constant of case



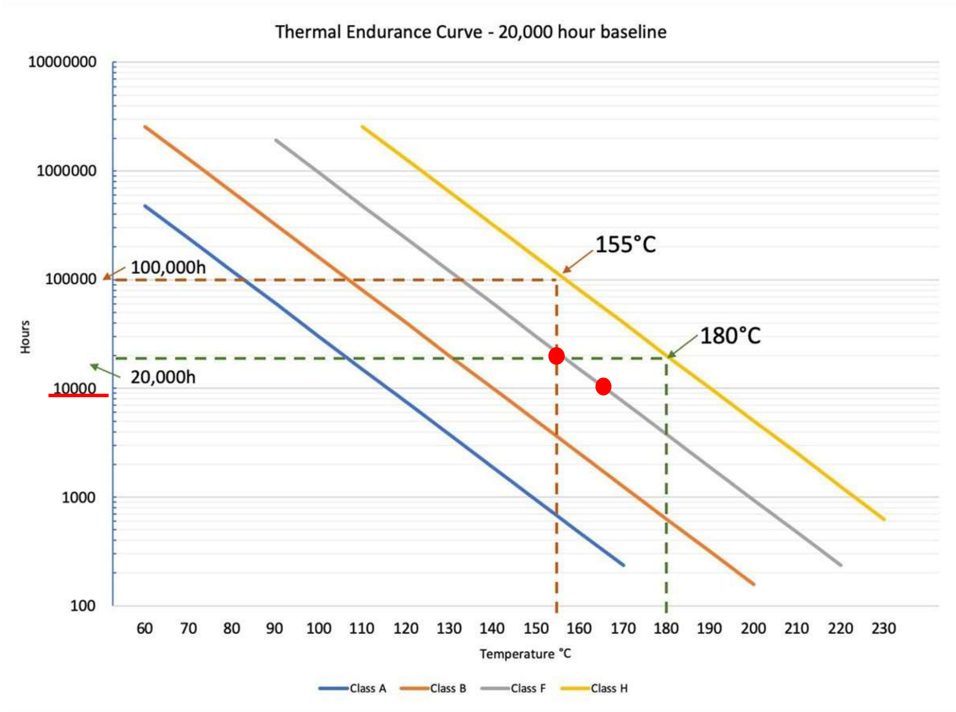
Comparation between models







Arrhenius



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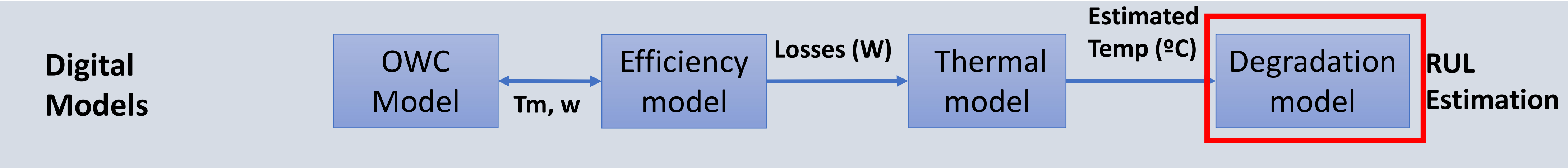
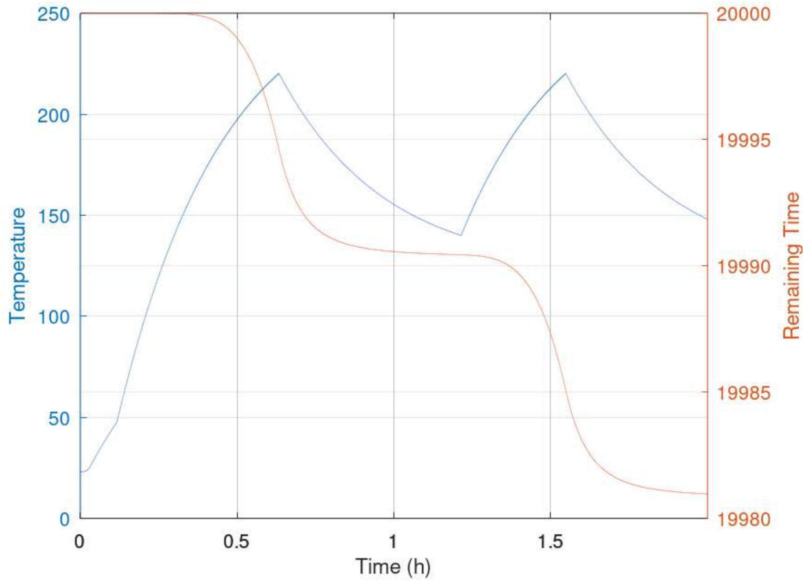


Modified Arrhenius model

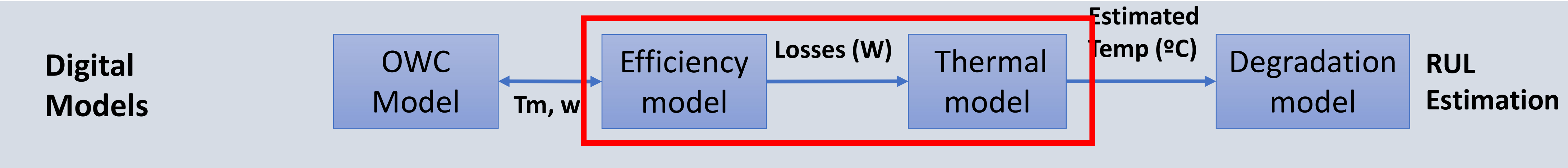
$$L = Ae^{B\left(\frac{1}{\theta_i} - \frac{1}{\theta_0}\right)} \longrightarrow log_e(t) = C_1 + \frac{C_2}{T}$$

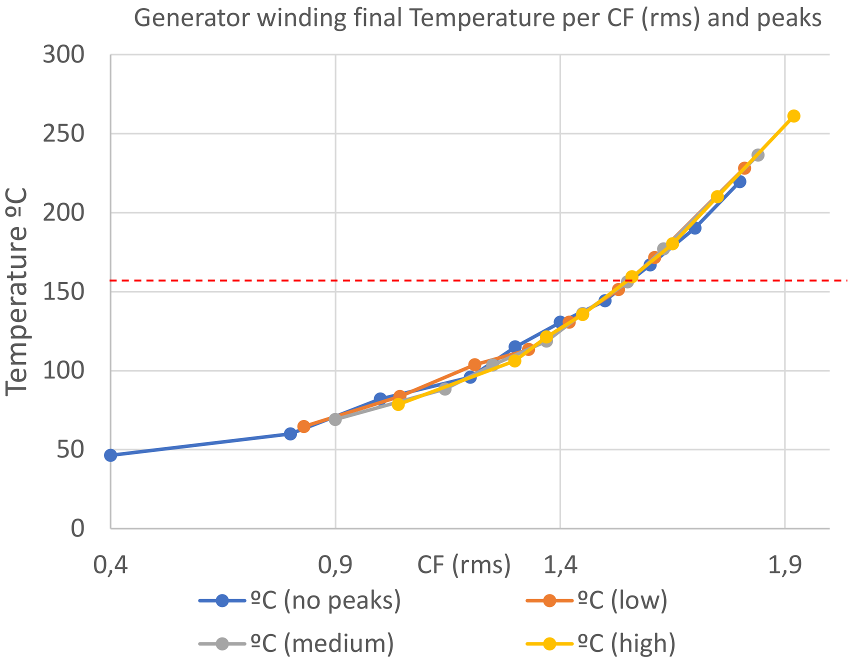


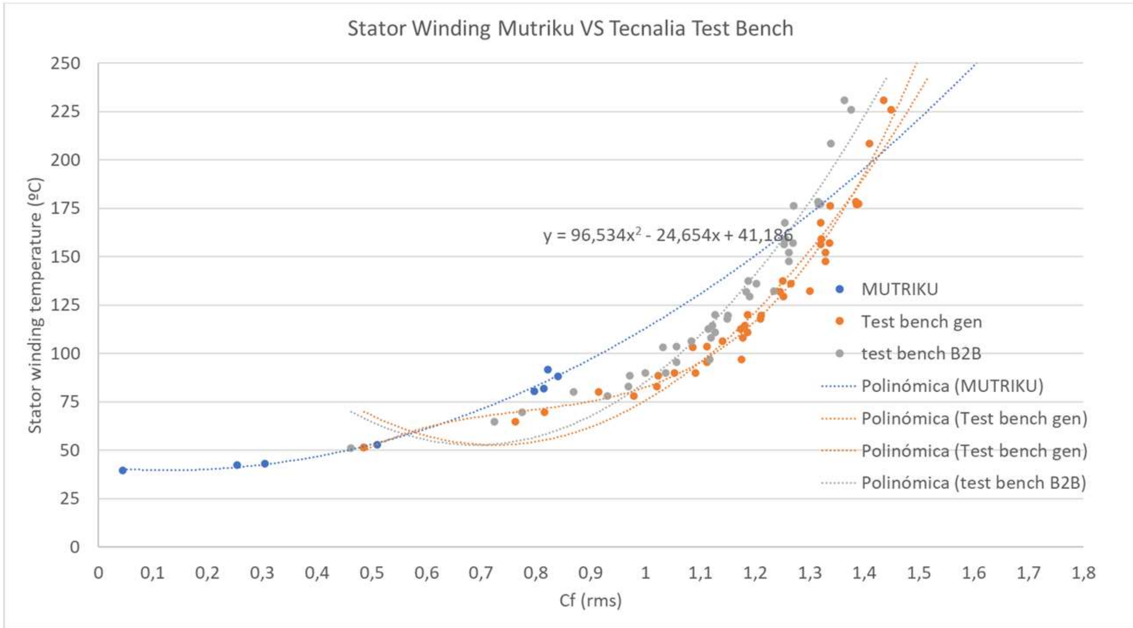
Rule-of-thumb (IEEE Std 117-2015)

Table 1—Temperature and exposure guide (estimated hot-spot temperature range)

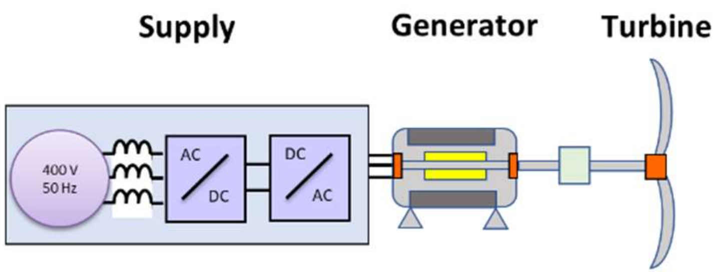
	Aging (temperature exposure) cycles (in days) for various insulation classifications in °C						
Exposure temperature	105 °C (days) (A)	130 °C (days) (B)	155 °C (days) (F)	180 °C (days) (H)	200 °C (days) (N)	220 °C (days) (R)	240 °C (days) (S)
310 °C							1
300 °C							2
290 °C						1	4
280 °C						2	8
270 °C					1	4	16
260 °C					2	8	32
250 °C				1	4	16	
240 °C				2	8	32	
230 °C				4	16		
220 °C			1	8	32		
210 °C			2	16			
200 °C		1	4	32			
190 °C		2	8				
180 °C	1	4	16				
170 °C	2	8	32				
160 °C	4	16					
150 °C	8	32					
140 °C	16						
130 °C	32						


Digital Models
OWC Model
Tm, w
Efficiency model
Losses (W)
Thermal model
Estimated Temp (ºC)
Degradation model
RUL Estimation


Generator winding final Temperature per CF (rms) and peaks
Temperature ºC
CF (rms)
0,4
0,9
1,4
1,9
0
50
100
150
200
250
300
ºC (no peaks)
ºC (low)
ºC (medium)
ºC (high)


Stator Winding Mutriku VS Tecnalia Test Bench
Stator winding temperature (ºC)
Cf (rms)
y = 96,534x² - 24,654x + 41,186
MUTRIKU
Test bench gen
test bench B2B
Polinómica (MUTRIKU)
Polinómica (Test bench gen)
Polinómica (Test bench gen)
Polinómica (test bench B2B)

Condition monitoring: Degradation estimation



Supply	Power quality	EPVA	
Mec. Imbalance or misalignment	MCSA	Vibration	EPVA
Insulation faults	Partial discharge	MCSA	EPVA
Stator electrical Imbalance	EPVA	MCSA	Power quality
Broken Bars	MCSA	EPVA / IPSA	
Bearing faults	Vibration	MCSA,EPVA, IPSA	
Coupling and Load Mechanical failures	Vibration	MCSA,EPVA, IPSA	

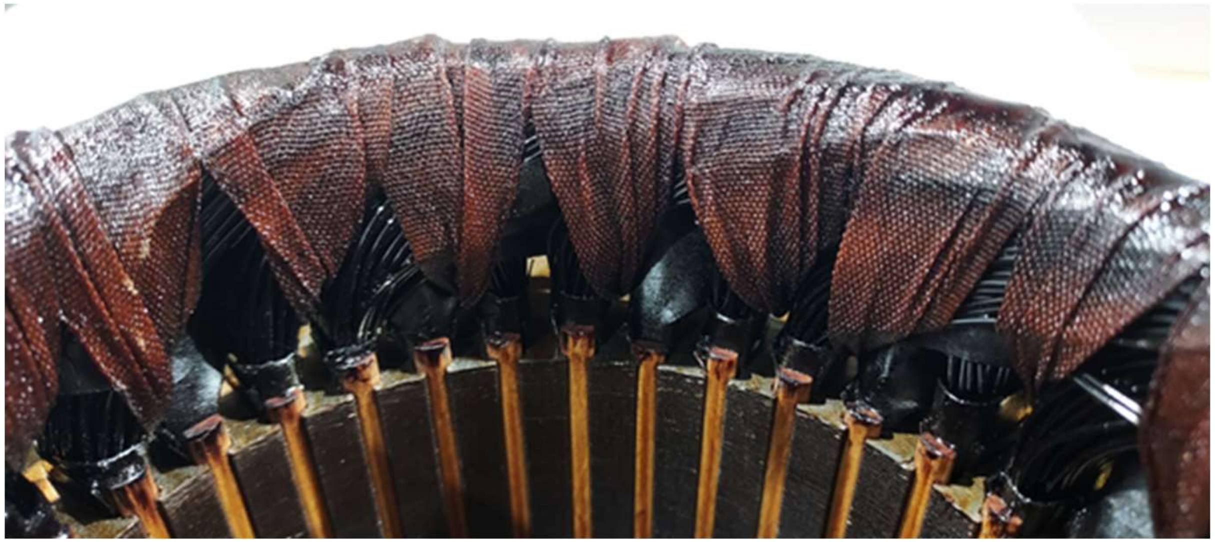
SIGNIFICANCE

- HIGH
- MEDIUM
- LOW

Failure detection

↓

burned stator winding



Base test(healthy) vs Final test (detected stator winding frequencies)

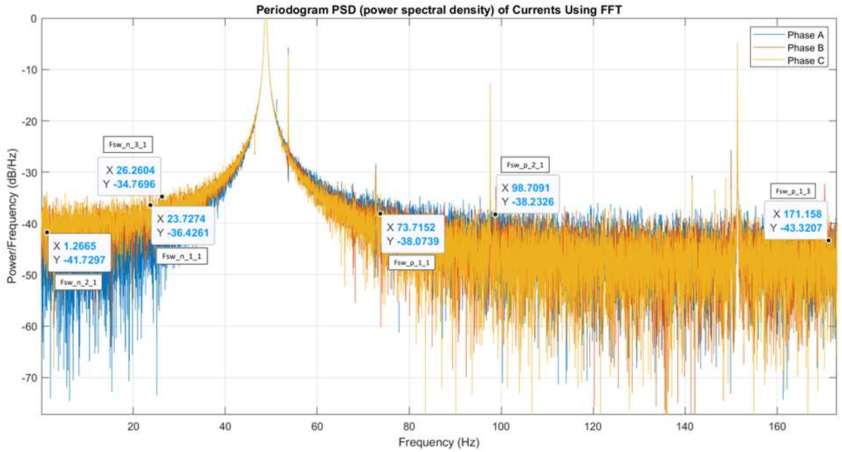
- Identification is made with the following expresión:

$$f_{SW} = f_s\left[k\left(\frac{1-s}{p}\right) \pm n\right]$$

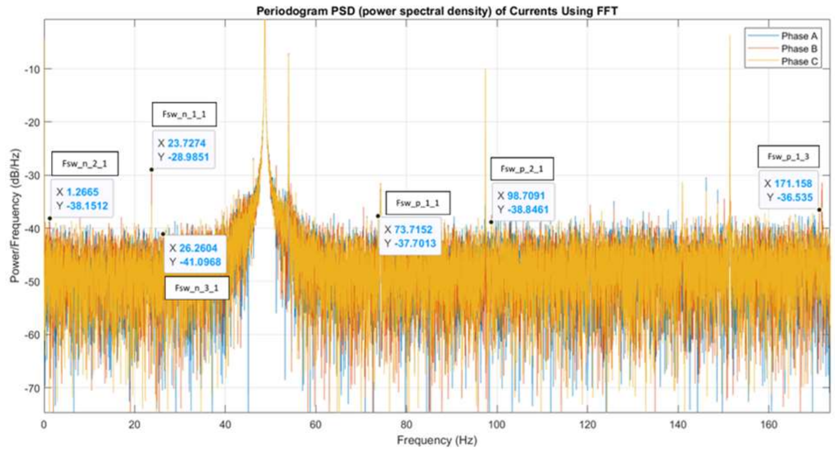
- fsw -> Stator winding failure freq.
- fs -> Supply frequency
- s -> Slip
- p -> pole pair
- k (k=1,2,3…) ->Stator winding constant.
- n (n=1,2,3…) -> Constant

Detected frequency	Final condition
Fsw	1.2665, 23.7274, 26.2604, 73.7152, 98.7091, 171.158

Base test



Final test



Main Challenges

- Uncertainties:
  - Correlation between instantaneous power peaks and corresponding sea states
  - Real doubt if these high temperatures will be achieved in the sea
  - Uncertainty in when the generator is going go break
- Thermal model:
  - Accurate thermal model for the whole operation range
  - Scalability
- Condition monitoring:
  - Difficulties in estimating progressive degradation until real breakage
- Amount of information:
  - Information of only 1 generator or maximum 2 generators. Not enough for conclusions

Programme

14:00-14:05 Welcome

Paula Garcia Rosa (IMPACT/SINTEF)

14:05-14:30 VALID session

WEC hybrid testing: Lessons learned from IDOM's case study

Iván Ruibal (IDOM)

Eider Robles Sestafe (Tecnalia)

14:30-14:55 IMPACT session

Experience from designing and executing tests on Carnegie Clean Energy's CETO 6 belt

Giacomo Alessandri (VGA)

Sam Neilson (Carnegie Clean Energy)

14:55-15:25 Panel discussion and Q&A session with the presenters

Moderator: Claudia Sans (VALID/Aquatera)

15:25-15:30 Close

Paula Garcia Rosa (IMPACT/SINTEF)