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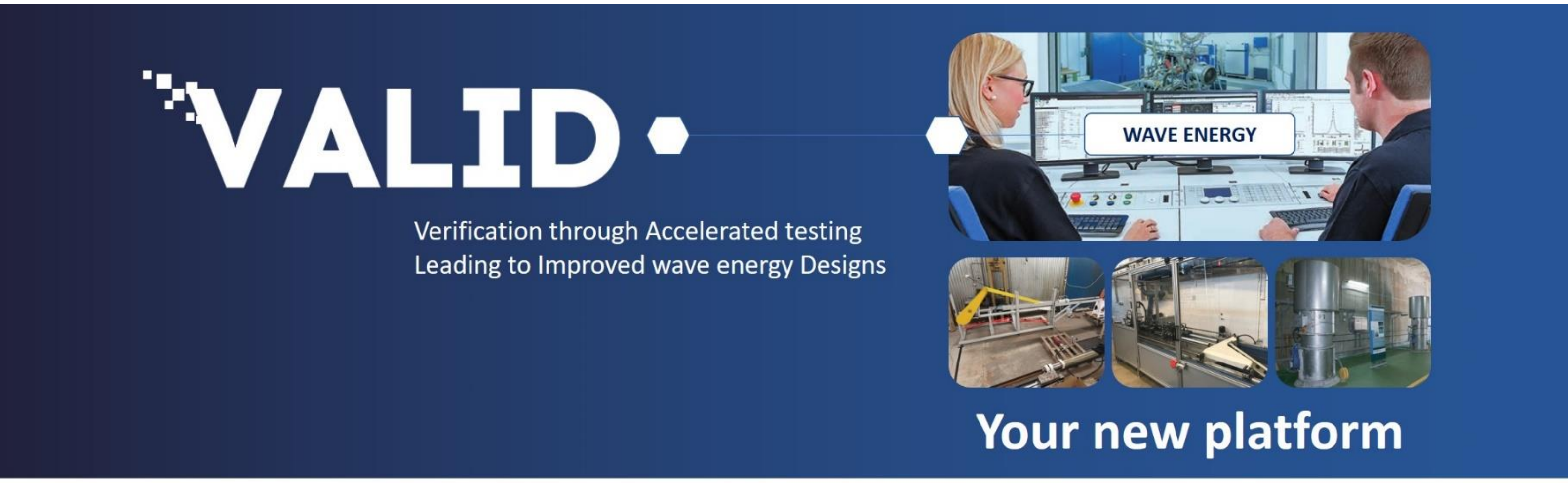
# Verification through Accelerated testing Leading to Improved wave energy Designs



Deliverable 4.1

Definition of Generator Thermal Fatigue Testing

Version 2.0

2022-01-20

**Lead participant: IDOM**

**Dissemination level: Public**

# DOCUMENT STATUS

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## Dissemination level

| Short | Type | |
|---|---|---|
| PU | Public | X |
| PP | Restricted to other programme participants (including the Commission Services) | |
| RE | Restricted to a group specified by the consortium (including the Commission Services) | |
| CO | Confidential, only for members of the consortium (including the Commission Services) | |

**EU PROJECT NO:** 101006927

# Executive Summary

Section 1 presents an overview of the user case, where besides a general description, a definition of target reliability, survivability requirements and a definition of environmental and operation conditions has been realized.

Section 2 gives a summary of critical failure modes of low voltage generators focusing on generator stator stresses which cause winding failure, such as thermal stress, which is one of the factors with greatest influence on insulation lifetime; and electrical degradation, which has been mainly associated over the years to high voltage electric machines. Finally, an introduction to multi-stress degradation, as the most usual case is to have more than one stress acting simultaneously and even interacting synergistically.

The aim of Section 3 is to extend standards and guidelines performed in Section 4.6 of D1.1 “Accelerated testing requirements” with particular application of the present user case. Starting from methodology for evaluating the environmental conditions, to successfully design an accelerated reliability test it is necessary to have a good knowledge of the intended use environment methodology for testing and scale effects. Regarding generators, a review of relevant standards that analyse different methodologies to be applied in rotating electrical machines has been completed. Thermal, electrical, mechanical, environmental and multifactor functional tests have been identified. Finally, methodology for scale effects: quantitative accelerated test methods, time compression, event compression, acceleration models and procedure for accelerated testing is defined.

Section 4 describes hybrid modelling to be developed for this user case at Tecnalia’s test bench with AVL capabilities. Based on actual test bench configuration and the functionalities of Model.CONNECT™ and Testbed.CONNECT™ hybrid testing arquitecture alternatives will be presented. Moreover, the model of Mutriku wave power plant divided in five numerical sub-models which facilitates the integration with model connect and the case study of MARMOK will be presented.

Section 5 describes testing specifications like the method for the definition of load cases which represents a challenge. The MCSA failure diagnosis method is presented for stator winding case. It is a non-invasive, online or offline monitoring technique for the diagnosis of problems in induction machines. Accelerated testing methodology has been developed based on Section 3.3. Peak concatenation and damaging sea state reproduction have been presented. Finally, a description of combined tests (Mutriku and Tecnalia’s test bench) is proposed.

Section 6 describes Mutriku site and TECNALIA’s test bench constraints and upgrade requirements for the user case, in which the generator, electrical and mechanical parameters are defined.

## Project partner names

- RISE Research Institutes of Sweden AB
- Fundacion Tecnalia Research and Innovation
- Corpower Ocean AB
- RINA Consulting S.p.A.
- Biscay Marine Energy Platform SA
- IDOM Consulting, Engineering, Architecture, S.A.U.
- Aalborg University
- AVL List GMBH
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- Technical University of Denmark

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# 1 Overview of User Case #2

This report - Deliverable 4.1 “Definition of Generator Thermal Fatigue Testing” - is a public document produced in the framework of the VALID project. The current document characterises the second User Case defined for the VALID project, which is related to the behaviour of the electric generator used by IDOM in their MARMOK Wave Energy Converter (WEC).

The aim of User Case #2 (UC) is the achievement of an understanding of the behaviour, limits, and consequences of the particular operation of an electric generator on IDOM’s MARMOK WEC technology. For a realistic and efficient study of these characteristics, a hybrid testing procedure is to be designed making use of an accelerated test process. The definition of the main features of the hybrid testing procedure in conjunction with the basis of the accelerated testing is presented in sections hereunder.

## 1.1 User case description

This UC is mainly focused on the Power Take-Off (PTO) system of IDOM’s MARMOK WEC. This technology utilizes the Oscillating Water Column (OWC) principle, extracting energy by means of air turbine-electric generator sets due to the compression and expansion of an air chamber confined between the two bodies that conform the system: a cylindrical structure and an oscillating water column, which is held by the former and acts as a piston to the air chamber. The PTO consists of 3 main elements: the air turbine, the electric generator and the control system. Several electric generator-air turbine sets are mounted on the top deck on their respective ducts, forcing the air to be inhaled and exhaled through them. The generators are connected to an active-front-end (AFE) system (specific configuration of the power electronics for power regeneration allowance). Part of the AFE system is to couple it with the grid, while the other controls the generators for variable speed/torque operations. IDOM has developed an in-house control strategy for the generators, which is implemented in the AFE system to gain control over dampening and optimizing power performance. Currently IDOM is engaged in designing a full-scale prototype of the MARMOK device for offshore testing.

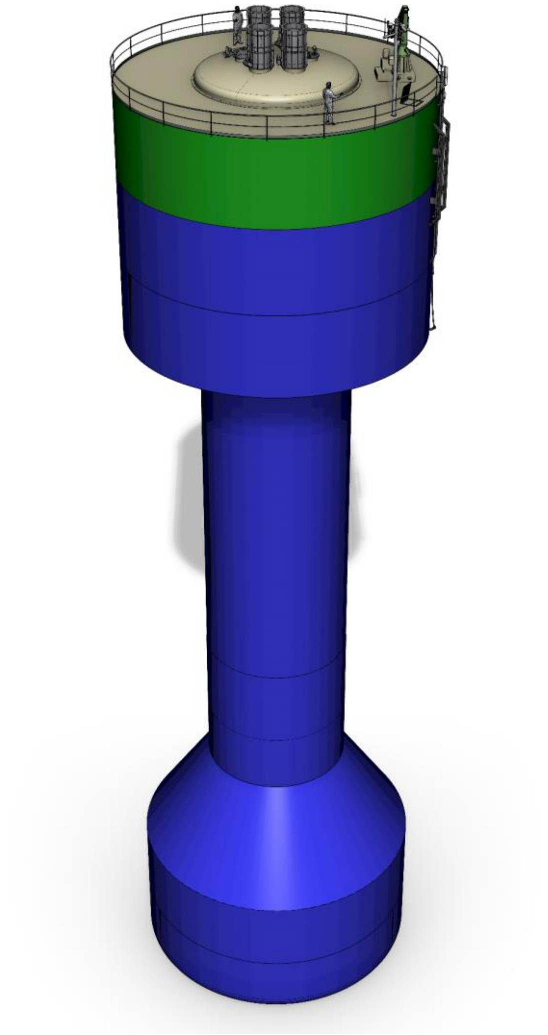


Figure 1: MARMOK A-15 External Structure Overview.

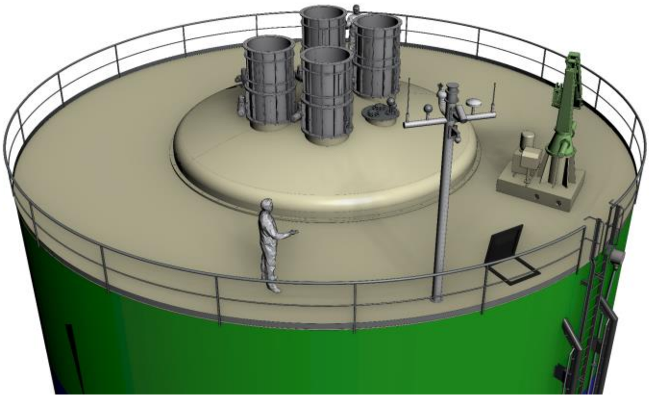


Figure 2: MARMOK A-15 Top Deck.

The target components to be tested for this UC are the electric generators. The electric generators bear the role of converting mechanical energy extracted by the air turbine into electrical power. Cage Induction machines are selected for the MARMOK PTO due to the robustness, ease of operation and low level of maintenance they present. Not to mention, the relative low cost and high availability of the machine around the global market. To be more precise, the MARMOK PTO system utilizes conventional cage induction motors and operates them as generators. This is achieved by running the motors above their rated synchronous speed creating negative slip. The active-front-end system takes cares of the control we need The rotation shafts of the motors are directly driven by the bi-directional air turbines with no gearboxes in between. Thus, the machines experience the full torque and speed of the air turbines. More on this will be further discussed in Section 1.3, in the context of certain sea-states data.

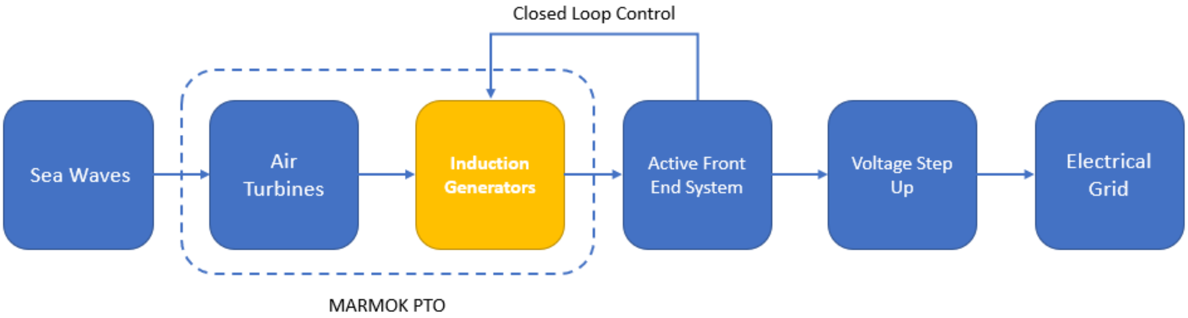


*Figure 3: MARMOK PTO Architecture.*

## 1.2 Definition of target reliability and survivability requirements

Since the installation is offshore, the maintenance activities could be challenged by short possible weather windows, in contrast to onshore applications. Therefore, the reliability and endurance of the generators are largely related to the frequency of marine maintenance activities. Based on past experiences with the small-scale prototype MARMOK A-5, the generators onboard have not suffered any major failure during almost 3 years of operation. However, a full power application is expected to be more demanding for the electric machine in terms of reliability since it will be designed for a ULS (Ultimate Limit Stress) of around 3 times its rated power. However, at the same time a generator failure is considered non catastrophic since remaining turbines will continue operating (ALS condition) hence WEC will continue genereating power. In addition to this WEC design has been adapted (crane onborar, modular design of turbines…) to allow an offshore reparison of a generator failure without the need of specialised vessels, and avoding the need of towing the device back to port, i.e. it is reparaible offshore. As a consequence, it can be considered acceptable a minimum Mean Time Between of around 2 years at the current state of development. With the knowledge gained during this project it is expected this MTBF may be increased up to 5 years. Through a deeper understanding of the failure modes of the generators, technology users are able to select and design better-suited machines to accommodate the high peak-to-average ratios for WECs with OWC technology. Besides, a condition monitoring procedure is also expected to be obtained from the current project, so the replacement of the generator can be previewed and the availability gets maximized.

## 1.3 Definition of environmental and operating conditions

The MARMOK's operation condition is the common offshore environment. This environment is well defined in certain international standards, for instance IEEE 45 – Recommended Practice for Electrical Installations on Shipboard. It is mainly defined by a moisture-laden and salt-laden atmosphere, demanding weather, sun, high wind velocities and ice. Roll and pitch of the structure up to 45 degrees. Vibration frequency range of 5 Hz to 50 Hz with velocity amplitude of 20 mm/s. This is a common environment for all WECs.

Sea waves are known to present high variability. Wave activities can vary significantly from time to time. Most of the waves captured by a WEC are surface waves created by wind. As wind varies between seasons and weather conditions, sea waves can be completely distinct at different times within a year at the same location. Graphics shown below are the 20-minute time series of 3 different representative sea-states of a typical offshore test site. These 3 sea-states show completely different behaviour of waves activities: mild, intermediate, and strong. Each contains waves of a different quantity of mechanical power.

Looking further into individual sea-states, for instance the intermediate and strong sea-state (Figure 5 and Figure 6) below. The variation of energy is significant as the energy generation can alter between 0 kW to peak 250 kW within one-minute timeframes. The rapid variation of power leads to a complicated limitation when designing electrical systems as the generation output to the system is constantly varying in a wide range. The ideal case is to size the electrical system close to the average power. In other words, intentionally downsizing the system to save space and cost. As mentioned, the electrical system will be overloaded for short periods of time to capture energy peaks. The extent of overloading or downsizing requires extensive investigation on the heat dissipation and the degradation of the insulation of each individual element in the electrical system.

Through analysing the 3 typical sea-states below, certain characteristics are extracted. Such as average power, peak power, peak to average, duty ratio, longest wave period etc. These are crucial datas directly related to electrical system design.

It should be noted that operating range in terms of $H_s$ and $T_e$ is determined during the design phase of the WEC when analysing the deployment site conditions so it may vary between different projects.

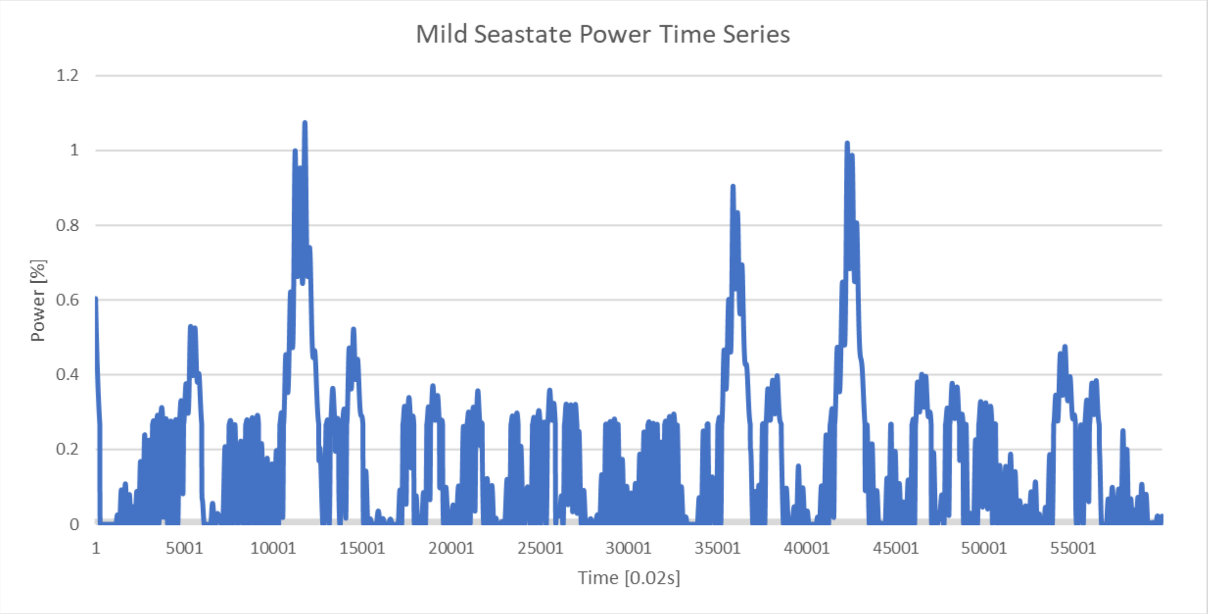


*Figure 4: Mild sea-state.*

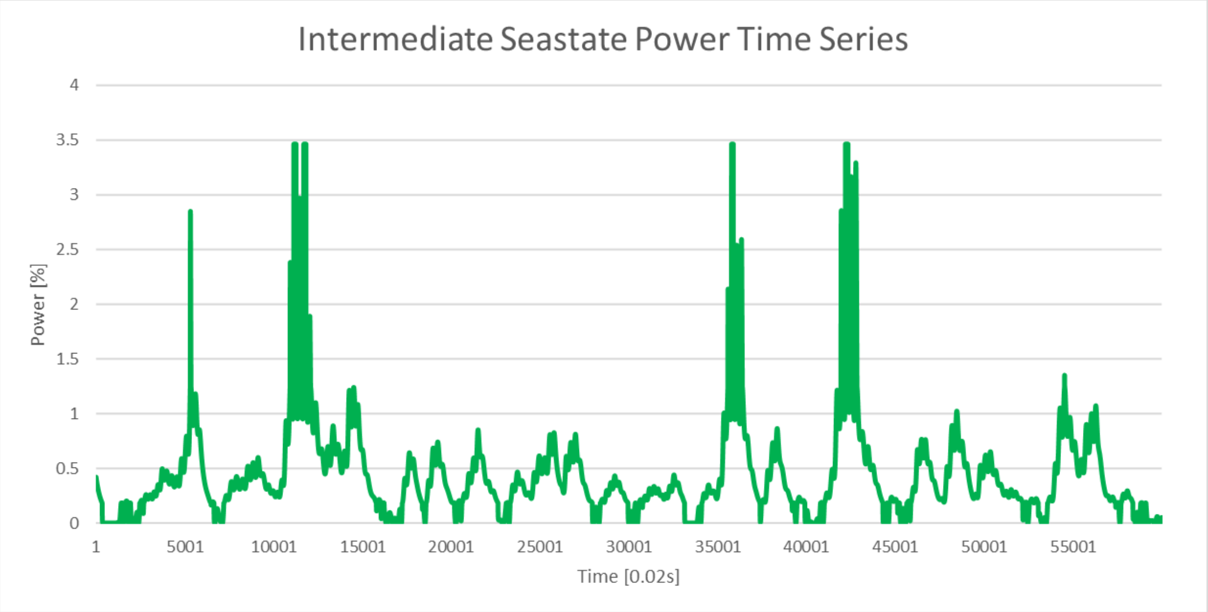


*Figure 5: Intermediate sea-state.*

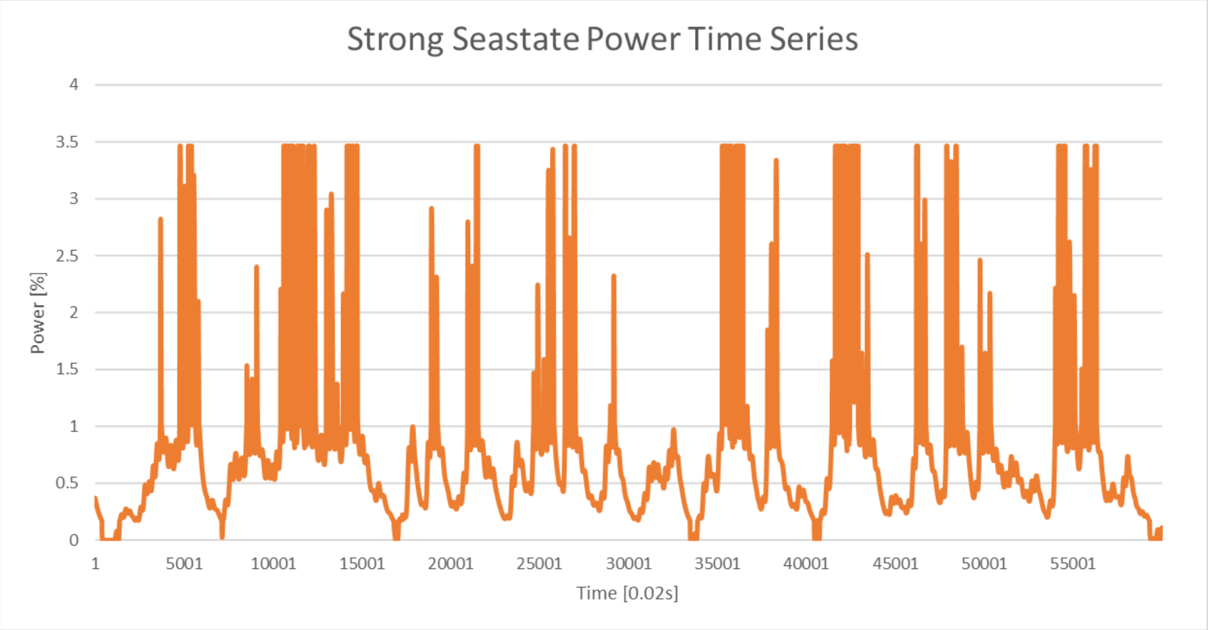


*Figure 6: Strong sea-state.*

Table 1: *Characteristics of different Seastates for a particular sea site*

| Sea-States | Mild | Intermediate | Strong |
|---|---|---|---|
| Non-dimentional Average Power (kW/ rated power) | 0.1699 | 0.4365 | 0.8229 |
| Non-dimentional Peak Power (kW/ rated power) | 1.07 | 3.464 | 3.464 |
| Peak to average ratio | 6.32 | 8.00 | 4.21 |

| | | | |
|---|---|---|---|
| Total Overload Time (s) | 1.96 | 76.44 | 176.36 |
| Duty Ratio (%) | 0.163% | 6.37% | 14.70% |
| Longest Overload Period (s) | 1.32 | 10.08 | 9.82 |

The duty ratio is defined as the percentage of time that a generator operates beyond its rated power level within the sea state. With IDOM's experience working with generators manufacturers, duty ratios of the overload operations and the occurring frequency of the peaks are usually requested for the selection of the insulation grade. This reveals the duration of excessive heat generation and available time for the generator to dissipate heat down to normal operating temperature in a wide perspective. The length of the energetic sea state also affects directly the heat generation and dissipation in a similar manner. Electric motors and generators usually have a 1.10 to 1.25 safety factor, which ensures that the machine can operate continuously beyond its rated power. During strong sea-states, extremely energetic waves push the torque and mechanical power rise high beyond the average value in such sea-state. The peak-to-average ratios in ranges from around 4 to 8 are expected, which represent a challenge for common generator design specifications. Therefore, in this UC a further understanding of the effect of sporadic overloading an electric generator and its consequences is pursued by means of accelerated tests.

## 1.4 User Case Testing

The user case 2 aims to produce a practical implementation of a novel testing methodology throughout a hybrid platform with the capabilities that AVL provides to the VALID project with Model.CONNECT$^{TM}$ and Testbed.CONNECT$^{TM}$ tools.

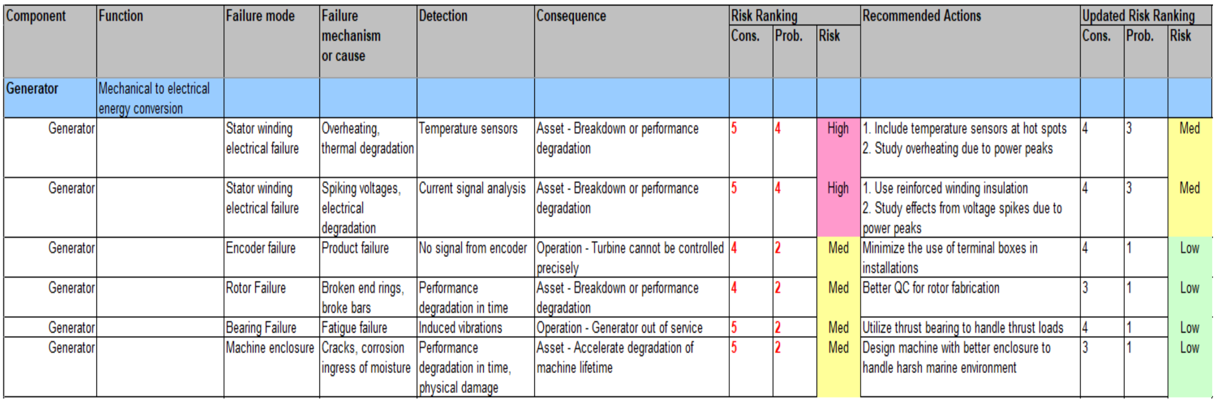
Since target component to be tested in this user case is the electric generator of the PTO, hybrid testing methodology will allow to emulate hydrodynamic to aerodynamic and aerodynamic to mechanic power transformations of IDOM's floating OWC converter, and focus the research on the physical part of the generator. For this issue, a controlled environment like Tecnalia's electrical test bench is convenient. Prior to performing any degradation tests, a diagnosis method will be studied to identify current status of the stator winding in order to predict future problems on it, analyzing the stator current, voltage and the temperature of the generator. Moreover, a detailed degradation model of stator winding will be analyzed, trying to obtain the benefit of Model.CONNECT$^{TM}$ software integration capabilities. Different options to perform accelerated tests over the generator insulation have been analized, concluding that directly applying the most damaging peaks, excluding from the tests low energetic states would be the most appropriate solution.

In pararell, Mutriku site will be sensorized to obtain real operation data to be used and compared with the data obtained from the testbench. Moreover, after the validation of the sensorization and diagnosis methods in the test bench, the possibility to develop the diagnosis method in Mutriku will be studied.

# 2 Electrical Generator Failure

## 2.1 Critical failure modes

The most common failure modes of low voltage electric generators are divided according to the construct of the machine itself, namely the shaft bearings, stator windings, rotor windings, and the machine enclosure. Mechanical failures of the shaft bearings have been regarded as one of the most common faults in an electrical machine for the current application. Combing with the electrical and mechanical faults of the stator winding, these cases account for almost 65% of all the electrical machine failures. As for the remaining parts of the electrical machine, electrical failures on the rotor have equivalent effects as those on the stator. For the machine enclosure, failures are commonly caused by a design failing to account for the environmental conditions. Misuse of the generator in an inappropriate environment would result in excessive oxidation due to bad protective coating or defects during fabrication. Below is a FMECA for the generators based in this UC. Different failure modes has been considered alongside with their causes, consequences and hence their potential risks.



| Component | Function | Failure mode | Failure mechanism or cause | Detection | Consequence | Risk Ranking | | | Recommended Actions | Updated Risk Ranking | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cons. | Prob. | Risk | | Cons. | Prob. | Risk |
| **Generator** | Mechanical to electrical energy conversion | | | | | | | | | | | |
| Generator | | Stator winding electrical failure | Overheating, thermal degradation | Temperature sensors | Asset - Breakdown or performance degradation | 5 | 4 | High | 1. Include temperature sensors at hot spots<br>2. Study overheating due to power peaks | 4 | 3 | Med |
| Generator | | Stator winding electrical failure | Spiking voltages, electrical degradation | Current signal analysis | Asset - Breakdown or performance degradation | 5 | 4 | High | 1. Use reinforced winding insulation<br>2. Study effects from voltage spikes due to power peaks | 4 | 3 | Med |
| Generator | | Encoder failure | Product failure | No signal from encoder | Operation - Turbine cannot be controlled precisely | 4 | 2 | Med | Minimize the use of terminal boxes in installations | 4 | 1 | Low |
| Generator | | Rotor Failure | Broken end rings, broke bars | Performance degradation in time | Asset - Breakdown or performance degradation | 4 | 2 | Med | Better QC for rotor fabrication | 3 | 1 | Low |
| Generator | | Bearing Failure | Fatigue failure | Induced vibrations | Operation - Generator out of service | 5 | 2 | Med | Utilize thrust bearing to handle thrust loads | 4 | 1 | Low |
| Generator | | Machine enclosure | Cracks, corrosion ingress of moisture | Performance degradation in time, physical damage | Asset - Accelerate degradation of machine lifetime | 5 | 2 | Med | Design machine with better enclosure to handle harsh marine environment | 3 | 1 | Low |

*Figure 7: FMECA of induction generator.*

As a result, the stator winding insulation failure since it is regarded as the most relevant fault cause for the application considered in this UC [1], [2]. A detailed analysis presented hereunder is focused on the thermal and electrical degradation process.

## 2.2 Detailed definition of the UC failure mode

Insulation failure of the stator winding can cause multiple types of faults. For instance, single-phased, phase-to-phase shorts, turn-to-turn shorts, coil shorts, accidental grounding of windings etc. These failures are mainly due to degradation of the insulations on the stator winding. Common cases are cracked enamel coating on the copper windings and break down of winding insulation sleeves. Both the thermal and electrical stresses are the main factors causing insulation failure which will be deliberated in the following section.

## 2.3 Stress factors

### 2.3.1 Thermal degradation

Thermal stress is one of the factors with greatest influence on insulation lifetime. It can be classified to two degradation processes [3]. The first one is related to the operation temperature, which is commonly assumed to halve the lifetime each 10-degree rise. Under operation conditions, the temperature itself does not cause a fault, but makes the insulation more vulnerable to other stresses. The second process concerns the thermal cycling, in which temperature increments over the thermal class temperature are achieved for short but repeated periods of time.

When temperature in insulation rises, and mainly when it does over the thermal class temperature, a chemical process takes place, which results on the degradation of the insulation due to the rupture of molecular connections that represent a mass loss on the insulation system in the form of ion leakage. Furthermore, this chemical process can lead to an increase of internal gas pressure and a decrease of adhesive strength of the insulation. The existence of moisture and contaminants escalate this degradation process. Macroscopically, the result is a brittle insulation with lower mechanical endurance.

The increment in brittleness can provoke the emergence of cracks on the insulation that could cause a fault under mechanical or electrical stresses, as it is explained on latter sections.

Regarding instantaneous temperature peaks over normal operation limits, the faster the increment the more detrimental the consequences. Besides the chemical effect that excessive temperatures have on insulation, which is escalated when the rise is significantly sharp since the conduction heat transfer along the wire is not quick enough and the hotspot effect gets accentuated, the high dilatation factor of the copper compared with the insulation induces mechanical stresses that lead to a separation of the bond between copper and insulation, allowing the relative movement between them and abrasing the insulation. Additionally, this separation between the insulation and the copper wires can generate air pocket, which facilitates the appearance of partial discharges (PD).

A usual approach for estimating and modelling the effect of thermal stress is the utilization of the Arrhenius model [4]:

$$L = Be^{\frac{\phi}{kT}} \tag{1}$$

Where *L* is the lifetime of the subject, *B* is an experimental constant, *Φ* is the activation energy, *k* is Boltzmann's constant and *T* the absolute temperature.

This equation represents a very versatile model that can take many different forms for adapting to the necessities of different tests or to temporary conditions as thermal cycling stress. An example of its versatility is the possibility of defining it as a function of the concentration of an element, since in many tests the condition of the subject tested is determined by means of a particular concentration.

Due to the strong influence on reaction rates of the relationship between temperature and humidity, variations of this model have been developed for including its effect. One of the most spread ones is the combination of the Arrhenius model and Peck's relationship, which introduces an acceleration factor to the model that represents the effect of moisture on the degradation process [5] [6].

$$L = (RH)^{-n}Be^{\frac{\phi}{kT}} \tag{2}$$

Where *RH* represents the relative humidity and *n* is a constant.

External influencing factors:

- <u>Humidity</u>. The effect of this factor, and mainly the speed of its influence, is highly dependent on the material of the insulation. On a general way, moisture tends to leak into the insulation and migrate along it. Once the insulation is saturated, this ingress reduces the electric and mechanical strength of the insulation, causing it to delaminate or swell.
- <u>Aggressive environments</u>. Coming to the application to be considered on the current project, offshore environment meaning high levels of humidity and salinity represent an aggressive environment. Salt on its own will not influence the degradation process but escalates the effect of humidity [7].

- Dirt. As with the salt, the main effect of dust or other particles is aggravating the effect of humidity, since these elements tend to lie on insulation surface and absorb moisture, facilitating its introduction in the insulation.
- Loose connections
- Existing defects on the insulation

Causes:

- Operation at loads over the design loads. In this case the generator generates currents higher the rated value of the wires, hence causing an excessive heating beyond the designed temperature rise class.
- Quick load changes. This factor appeals to the thermal cycling. escalating the effect of the overload if this is produced by a quick load increase. This rapid raises the current in the windings thus the heat generation and the overall temperature of the generator.
- Operation at high temperatures. As explained, the extended 10-degree rule halves the lifetime every 10-degree rise, having a significant influence. Besides, the higher the temperature the weaker the bond between the insulation and the copper wire. However, despite a significantly long period of successive power peaks, the temperature is not expected to rise substantially on the application studied.
- An inadequate design of the insulation can be responsible for a premature degradation thereof. Besides the operating conditions, environmental stresses must be taken into account.

Good practice to avoid degradation:

- Effective insulation thermal class selection looking at maximum power peaks. These peaks are a key parameter that determine the insulation to be used, since a hot-spot phenomenon is likely to be responsible for the thermal failure of the insulation, taking place on high power peaks with significant temperature rise rates.
- Vacuum Pressure Impregnation (VPI) process. This advanced procedure in which dry and wet vacuum and pressure cycles are concatenated to insulate an electric machine, usually more efficient for small ones, present several benefits mainly on harsh environments. Mechanical and dielectric strengths are improved, greater thermal inductivity is achieved, and the insulation becomes more reluctant to the ingress of moisture and contaminants.
- Improved cooling system. The cooling system must be properly designed for the application, since besides being responsible for heat dissipation of the generator, which has already been stated as a highly influencing factor on the lifetime thereof; an environment with high humidity implies an increase on the possibility of the obstruction of the cooling ducts, which would provoke a failure on the machine.
- Auxiliary protective device. Condensation within motors is common in offshore environments due to the high moisture content in the atmosphere. It could result in the industry practice is to install space heaters to keep internal temperature of the motors above the ambient dew point with the motors are not in operation.

### 2.3.2 Electrical degradation

Electrical degradation of the insulation has been mainly associated over the years to high voltage electric machines, since this degradation is linked to the appearance of partial discharges (PDs) caused by voltage surges, which require high voltage levels to occur. However, short risetime voltage transients created by power electronics could lead to this phenomenon. When a very high frequency is applied to the stator, such as the one generated by the power electronics, the voltage distribution, which is usually linear and equally distributed along the turns of a coil, becomes nonlinear, presenting the first turns a significant percentage thereof. This unequal distribution can provoke high voltages over the dielectric limit of the insulation across the turns, which can lead to a PD if there is an air pocket near the turns. When a PD occurs, the insulation suffers a light damage, so if voltage surges are a common phenomenon during operation a progressive degradation takes place, which can lead to a turn-to-turn fault and, as explained previously, develop onto a catastrophic failure.

Electrical tracking represents another process of insulation degradation. When the generator operates on high moisture and contamination rate environment, these elements can create a thin film due to humidity condensation over insulation that makes it conductive. The presence of other dust or any kind or dirt tends to escalate this problem since they act like a moisture accumulator. If a crack appears due to any other deterioration process or these elements are capable of ingress the insulation a fatal failure can occur.

As for thermal degradation, consequences of electrical stresses can also be modelled by a simple equation, known as Inverse Power model.

$$L = \frac{1}{kV^{n}}\text{s} \qquad (3)$$

Where *L* represents the lifetime of the sample, *k* and *n* are positive analytical parameters related to the material and the test kind and *V* is the stress. This last parameter enables the use of the equations for modelling diverse stresses, but it is usually applied to electric or mechanical stresses individually.

External influencing factors:

- <u>Moisture and dirt</u>. The existence of this factors due to a harsh environment or water leaks, besides weakening the insulation by themselves, tend to increase the likeliness of a PD, as happened with the thermal stress.
- <u>Salinity</u>. The presence of salinity increases the effect of moisture, since once the condensation occurs, the conductivity of seawater is higher than water, aggravating its influence on electric stresses.
- *Existing defects*
- *Loose elements*

Causes:

- Repetitive voltage surges with fast risetimes. Usually, these risetimes are less than 200 ns, being the voltage on the first coil inversely proportional to this value.
- Air pockets between the turns. These air pockets are necessary for the PD to occur, which is usual on random-wound stators.
- High humidity and/or contamination. These elements are responsible for the occurrence of electrical tracking.
- Prior deterioration. The existence of cracks or defects on the insulation supposes a reduction on dielectric strength, what increases the possibility of having a PD and enables the ingress of water on the insulation.

Good practice to avoiding degradation:

- Use higher PD-resistant magnet wire. The insulation can be designed for having an improved resistance to the occurrence of PDs if this phenomenon is foreseen.
- Install a low-pass filter or a load reactor. This element lengthens the risetime of the surge, eliminating the voltage imbalance that it introduces.
- VPI. As explained for the thermal stress, this modern insulation procedure increases the dielectric strength and its resistance to external elements, improving its effectiveness.

### 2.3.3 Multi-stress degradation

However, the different stresses presented rarely appear individually on real working conditions. The most usual case is having more than one stress acting simultaneously and even interacting synergistically. The degradation generated by thermal stresses on insulation increases the likelihood of having a PD. The same process happens inversely, any degradation caused by electrical stress will escalate the effects of thermal stresses.

The main issue here is that any degradation that the insulation endures, independently of the stress that causes it, means a reduction of its insulating capacity, what makes it more prone to suffer from other stresses. This fact generates a situation in which different processes are combined, usually aggravating the effect of each other and making it very difficult to differentiate the original stress or even the one that finally meant the failure of the machine.

For the representation of this interaction between different stresses, the Eyring model appears as the most thermodynamically efficient model that can include different stresses.

$$L = AT^{\alpha}e^{\left[\frac{\Delta H}{kT}+\left(B+\frac{C}{T}\right)S_1\right]} \qquad (4)$$

Where L is the lifetime again, *A*, *B*, *C*, *α* and *ΔH* are experimental parameters, *T* is the absolute temperature, *k* is Boltzmann's constant and $S_1$ is the applied stress. In the case that another non-thermal stress $S_2$ would be introduced the parenthesis multiplying $S_1$ should be repeated introducing two additional experimental parameters *D* and *E*. On the definition of this analytical values is where the major difficulty of applying this model resides.

$$L = AT^{\alpha}e^{\left[\frac{\Delta H}{kT}+\left(B+\frac{C}{T}\right)S_1+\left(D+\frac{E}{T}\right)S_2\right]} \qquad (5)$$

Due to the complicated determination of the needed parameters of the Eyring model, the extended Arrhenius equation with simultaneous stresses appears as a simple alternative that can also properly represent the effect of various simultaneous stresses from a more analytical formulation.

# 3 Relevant Standards – Best Practices

A general review of relevant standards and guidelines for component design and testing for WEC technologies was performed in Section 4.6 of *D1.1 Accelerated Testing Requirements*. This chapter aims to extend such information by applying the standards and guidelines listed in the aforementioned document to the requirements of this specific User Case and including others that are related to this UC#2.

A wide range of standards and guidance documents have been developed covering differenced topics related to MRE technologies, from early stage of development to real sea deployments and focusing on MRE converters as well as their key components and subsystems. Some standards and guidance issued by many organizations and standard bodies such as the International Electrotechnical Commission (IEC) are general terms that can be applicable to a broad variety of sectors. Others, however, are technically focused sector-specific standards, technical specifications or recommended procedures which are focused on more technical aspects for specific sectors or key-elements used in a particular technology. The most significant technical specification for MRE sector is *IEC TS 62600 Wave, tidal and other water current converters*, but for example, other organizations such as DNV or IEEE have issued sector-specific standards for wind energy or electrical generators, respectively that could be useful for this review.

## 3.1 Methodology for evaluating the environmental conditions

To successfully design an accelerated reliability test it is necessary to have a good understanding of the intended use environment, environmental and operational conditions of the system, and equipment design capabilities.

According to **IEC 62506** standard, environmental stresses can be climatic (thermal exposure and cycling, humidity, temperature variations, etc.) and dynamic (vibrations, shock, etc,) [8]. Their application and levels depend on the product use environments, in terms of both average and extreme conditions.

**IEC TS 62600** offers a set of standards oriented to provide information on environmental factors that may affect the ageing process of MEC components. In particular, **IEC TS 62600-101** focuses on the assessment and characterization of wave energy resource, whereas **IEC TS 62600-2** presents design requirements for MEC and its subsystems including electrical components.

Though no relevant certification entity has issued standards or guidance related to ocean energies and, particularized to this User Case, wave energy, in a more developed sectors such as wind energy these recommendations are already available. **DNV-ST-0076** stands among existing recommendations issued for wind energy sector. In particular, the Section 1 provides information about the environmental conditions that electrical components of wind turbines shall comply with. According to DNV-ST-0076 standard, the environmental condition shall be defined in terms of representative values by the limits of the variable conditions [9]. In addition, the probability of the simultaneous occurrence of environmental conditions shall be taken into account. External environmental condition values are defined in **IEC 61400-1**.

On the other hand, **IEEE Std 43-2000** standard defines a set of environmental factors that may affect the ageing of generator components [10] . These factors are listed below:

- Surface condition: the oil or dust on the surfaces of the winding may affect the surface leakage current. The surface leakage current may be significantly higher on large turbine rotors and DC generators, which have relatively large exposed leakage surfaces. Dust or salts on insulation surfaces, which are usually not conductive when dry, may become partially conductive when exposed to moisture or oil, and therefore may decrease insulation resistance.

- Moisture: a moisture film may be formed on the insulation surface, which can reduce the insulation resistance. The effect is more pronounced if the surface is also contaminated or if there exist cracks in the insulation. The absorbed moisture increases the conduction current and significantly reduces the insulation resistance.
- Temperature: The value of insulation resistance varies inversely and exponentially with the winding temperature. There is a contrast between the temperature dependence of resistivity. For example, in metals, higher temperature introduces higher thermal agitation, which increases the resistivity. However, in insulators, and especially in good insulators, a temperature increase provides thermal energy, which releases additional charge carriers and reduces resistivity.
- Test voltage magnitude: The insulation resistance value may slightly decrease with an increase in applied voltage; nevertheless, a significant decrease in insulation resistance with an increase in applied voltage may be an indication of insulation problems. These problems may be due to imperfections or fractures of the insulation, aggravated by the presence of dirt or moisture; alone or in combination with other deterioration events. The change in resistance is more pronounced at voltages considerably above rated voltage (**IEEE Std 95-1977**).
- Existing charge on winding resistance measurements: The insulation resistance measurements will be wrong if there exist residual charges in the insulation. For this reason, before the insulation resistance is measured, windings must be completely discharged.

### 3.1.1 Summary of relevant standards for evaluating the environmental conditions

*Table 2: Summary of relevant standards for evaluating the environmental conditions*

| | |
|---|---|
| **IEC TS 62600-101:2015** Marine energy – Wave, tidal and other water current converters – Wave energy resource assessment and characterization | This standard establishes a system for estimating, analysing and reporting the wave energy resource at sites potentially suitable for the installation of Wave Energy Converters (WECs). |
| **IEC TS 62600-2:2019** Marine energy – Wave, tidal and other water current converters – Design requirements for marine energy systems | This standard provides design requirements to ensure the engineering integrity focusing on MEC structural, mechanical, electrical and control systems. |
| **DNV-ST-0076** (2021) Design of electrical installations for wind turbines [9]<br>Section 2.1 | This standard contains guidelines regarding environmental conditions that electrical systems shall comply with in wind energy installations. |
| **IEC 61400-1:2019** Wind energy generation systems – Design requirements | This standard specifies essential design requirements to ensure the structural integrity of wind turbines. |
| **IEEE Std 43-2000** IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery [10]<br>Section 6 | This recommended practice reviews the environmental factors that affect or change insulation resistance characteristics, as well as recommends uniform test conditions. |
| **IEEE Std 95-1977** IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage | This recommendation provides selection of metric units, so as to promote uniformity in the use of metric units and to limit the number of different metric units that will be used in electrical and electronics science and technology. |

## 3.2 Methodology for testing

An overview of accelerated testing methodologies was presented in Section 4.2 of *D1.1 Accelerated Testing Requirements*. This section aims to review the existing relevant standards focused on generator testing, mainly to analyse the status of the generator or any other key-component within the generator.

There are several relevant standards that analyse different methodologies to be applied in rotating electrical machines. Though most of the standards are focused on evaluating the reliability levels in machinery during its design and manufacturing, the same approach could be easily applied to evaluate the degradation degree on already operational equipment. For example, **IEC 60034** series provide guidance and recommendations for rotating electrical machinery, which completely stands in line with this UC#2.

In particular, **IEC 60034-18** subsection deals with general guidelines for functional evaluation of insulation systems used or proposed for use in rotating electrical machines and provides test procedures for the thermal evaluation and classification of insulation systems. IEC 34-18 is divided into three parts:

- **IEC 60034-18-1** deals with general guidelines [11];
- **IEC 60034-18-21** deals exclusively with insulation systems and provides test procedures for wire-wound windings;
- **IEC 60034-18-31** deals exclusively with insulation systems and provides test procedures for form-wound windings.

The standard describes the thermal and electrical endurance testing procedures. Principles of mechanical, environmental and multifactor functional testing are briefly described to provide a basis for the procedures to be developed further where appropriate.

IEC 34-18 contains provisions, among others, of:

- **IEC 610:1978**, Principal aspects of functional evaluation of electrical insulation systems: Ageing mechanisms and diagnostic procedures;
- **IEC 792-1:1985**, The multi-factor functional testing of electrical insulation systems – Part 1: Test procedures.

This standard proposes a comparative functional test approach between an insulation system with no proven service experience and a reference system whose insulation has a proven service experience. It is generally proposed that functional tests be conducted in cycles, where each cycle consists of an ageing sub-cycle where the test samples are exposed to the adequately accelerated ageing factor, and a diagnostic sub-cycle in which the test samples undergo appropriate diagnostic tests to determine the end of test life or to measure relevant properties of the insulation system.

### 3.2.1 Thermal functional tests

**IEC 60034-18-1** establishes guidelines to perform thermal functional tests whose objective is originally to provide data which may be used to establish the thermal class. However, these tests might also be useful for thermal stress evaluation applied to this UC#2.

Thermal functional tests, according to **IEC 34-18**, aim to induce adequate heat exposure in repeated thermal ageing sub-cycles, which will produce thermal degradation effects similar to those in service on insulation systems. In this sense, accelerated bases are specified and diagnostic tests are described to check the status of the insulation system. Ageing temperatures and corresponding exposure periods in each thermal ageing sub-cycle for insulation systems of the various thermal classes are also suggested.

Despite some disadvantages, it is suggested to use closed furnaces with sufficient ventilation or forced convection to maintain uniform temperatures to perform thermal functional tests. However, other means might be used to simulate similar service conditions such as,

- Direct heating by electric current;
- Starting and reversing duty;
- Application of direct current on the alternating current of a motor running at no load.

After each ageing sub-cycle a corresponding diagnostic sub-cycle must be applied. According to the experience, the best diagnostic evaluation of a thermally degraded and weakened insulation system is obtained by exposure to mechanical stress to produce cracks, then exposure to moisture and finally application of test voltage. In other cases, it may be appropriate to conduct dielectric tests to verify the insulation status after each thermal ageing sub-cycle.

The suggested diagnostic tests are,

- Mechanical tests: of the same nature as those experienced in service. The most commonly used methods are shake table, repeated impact and bending, and start-stop or reversing duty cycle.
- Moisture tests: moisture deposition on the winding without applied voltage.
- Voltage tests: application of voltage from coil to frame, coil to coil, turn to turn, and wire to wire.
- Other tests: periodic measurements to detect variations on insulation resistance, loss tangents or partial discharges.

According to **IEEE Std 43-2000**, insulation resistance test data may be useful in assessing the presence of some insulation problems, such as contamination, absorbed moisture, or severe cracking; however, some limitations must be considered [10]:

- The insulation resistance of a winding is not directly related to its dielectric strength;
- Windings having an extremely large arm surface area may have insulation resistance values below the recommended value;
- DC measurements might not detect gaps in the internal insulation caused by inadequate impregnation, thermal deterioration, or thermal cycling in form-wound stator coils;
- Because the insulation resistance tests are performed with the generator stopped, problems due to rotation such as loose coils or vibrations are not detected.

**IEC 60034-18-34** exclusively deals with thermal cycling evaluation of insulation systems for form-wound windings [12]. This standard is of special importance for long rotating machines (especially indirectly cooled) and machines that are exposed to a very large numbers of considerable load changes during normal operation. In this sense, because the operating principle of Oscillating Water Column devices under study in this UC#2, the generator is often subject to variable loads and air-cooled, which would be completely in line with the previous assumption.

According to IEC 34-18-34, six ageing processes can occur in the winding insulation:

- Loss of adherence;
- Delamination between insulation layers;
- Delamination between the insulation and conducting layers;

- Wear on the outer surface of insulation;
- Cracking of the insulation;
- Mechanical damage to the insulation caused by distortion of the winding end turns.

The thermomechanical cycling is achieved by alternatively heating and cooling the test samples between fixed upper and lower limit temperatures. Measurement can be done by thermocouples, thermistors or fibre-optic sensors. For good contact with the surface of the conductors, the temperature sensor must be integrated into the bare-bar construction, or inserted into a drilled orifice through the insulation on a separate control bar. IEC 34-18-34 suggests appropriate upper and lower limits, as well as heating and cooling times.

The following heating methods may be used:

- Heating with electric AC or DC current through the conductors;
- Internal heating with liquid or steam, especially when test samples are cooled directly by water or gas;
- A combination of previous methods.

Similarly, the following cooling methods may be used:

- Cooling with fans where the forced air is directed to the surfaces of the bars/coil throughout the entire length. This method is suitable in generators whose bars/coils are externally cooled as it happens in OWC;
- Cooling of the generator core by means of fluid.
- Cooling with internal fluid.

On the other hand, the following diagnostic tests are suggested:

- Measurement of the loss tangent;
- Partial discharge test;
- Measurement of insulation length, where permanent changes in the insulation length indicate an emerging mechanical failure of the insulation;
- Measurement of surface resistance of conducting surfaces;
- Measurement of width and depth;
- visual inspection.
- Measurement of bar/coil-to-core resistance;
- Voltage tests according to **IEC 60243-1** or **IEC 60034-1**.

In this sense, **IEEE Std 56-2016** provides some guidelines for visual inspection of electric machines. According to this standard, limited visual inspection might be carried out with the rotor in place or out for a detailed condition assessment of the rotor and stator [13]. From visual inspection the following defects could be observed and are listed in IEEE Std 56 accordingly:

- Armature winding: thermal aging (puffiness, swelling in ventilation ducts, lack of firmness of the insulation, etc.), cracking (loosening of the bracing structure), girth cracking, dirt (oil, moisture, etc.), partial discharge erosion, etc.;
- Field windings: coil distortion, loose collar or coils, rotor coil tightness, etc.;

- Assembly of core and frame: mechanical damage, surface friction, vibration, excessive heating, etc.

### 3.2.2 Electrical functional tests

The electrical ageing process can be accelerated by increasing electrical stress and/or the frequency, though the acceleration may not be always proportional to the frequency.

Electrical functional tests can be conducted by applying a suitable voltage level, fixed voltage, step-by-step voltage, and acceleration by increased frequency (**IEC 727-1**). The frequency and wave shape shall comply with **IEC 60-2**.

On the other hand, diagnostic tests can be especially destructive (e.g., breakdown voltage setting of turn insulation), potentially destructive (e.g., high-voltage tests of different parts of the insulation), or non-destructive (e.g., measurement of loss tangent or partial discharge).

**IEC 60034-18-32** distinguishes between the electrical ageing process of the main insulation and the insulation between turns [14].

Electrical ageing of the main insulation is mainly due to a continuous electrical stress at power frequency. In addition, the insulation must withstand transient over-voltages arising from switching surges. It is proposed that the ageing of the main insulation be carried out under increased power frequency stress.

Electrical ageing of the insulation between turns may arise due to the steady-state stress applied through the main insulation. Electrical ageing of the insulation between turns may be performed at increased power frequency (**IEC 34-15**).

According to IEC 34-18-32, the electrical ageing voltage must be applied between the stator core or the outer conductive layer on the generator surface and the conductors. In case of multiturn coil, both the main insulation and the insulation between turns are aged by the electrical stress. To reduce the duration of the test, a higher frequency may be used. Similarly, when evaluating the ageing of the insulation between turns, the ageing sub-cycle of the main insulation is followed by an ageing sub-cycle of the insulation between turns.

### 3.2.3 Mechanical functional tests

The effects produced by the mechanical ageing process can be significant. However, IEC 34-18-1 considers that there is not enough technical information available at the time of publication of this standard to present any relevant mechanical ageing test procedure.

### 3.2.4 Environmental functional tests

It is recognized that environmental factors in some applications act as ageing factors, especially in marine environment where there exists high moisture content in the ambient air or mechanically abrasive materials (e.g., sand or salt) in the cooling air. The environmental factors have been extensively described in the previous subsection.

However, IEC 34-18-1 considers that there is not enough technical information available at the time of publication of this standard to present any relevant environmental ageing test procedure.

### 3.2.5 Multifactor functional tests

Multifactor ageing may occur in machines such as high-voltage industrial motors, mechanically highly stressed machines and turbo-alternators subjected to thermo-mechanical stresses. The latter might be applied to the generators used in OWC.

**IEC 792-1** includes the current state-of-the-art of multifactor ageing processes. Some principles are as follows:

- Factors acting simultaneously in service should be simulated in simultaneous ageing tests, while sequentially acting factors should be simulated with sequential ageing cycles;
- When one of the ageing factors is known to be more important than the others, multifactor tests may be conducted by accelerating the effects of that factor only while keeping others at service levels.

**IEC 60034-18-33** exclusively deals with insulation systems for form-wound windings, and is focused on multifactor functional evaluation limited to thermal and electrical ageing [15]. According to this standard, oven or current heating can be used to assess thermal stress. It is recommended that the temperature be measured in two steps when the electrical and thermal ageing stresses are applied simultaneously, when only the thermal stress is applied and after additional application of the electrical stress.

The acceleration factors should be related to the reference ageing factor levels:

- Electrical ageing at the maximum voltage to earth;
- Thermal ageing at the maximum service temperature.

When there is no interaction between thermal and electrical stresses, the principle of equal accelerations can be expected by selecting ageing combinations in which the acceleration factors for thermal and electrical stresses are the same when used alone. If the electrical stresses or ageing temperatures are known from previous single-factor tests, then those stress values shall be used. Instead, if acceleration factors are unknown, stresses suggested in IEC 34-18-33 should be used during the tests.

If an interaction is known to occur, the combination of stresses may be modified depending on the relationship between the effect of thermal stress on electrical ageing, and the effect of the electrical stress on thermal ageing. If the interaction results in similar accelerations of the electrical and thermal ageing, the suggested values shall be used. If the interaction results in greater acceleration of electrical ageing than thermal ageing, then for each stress combination an electrical stress with and acceleration factor that is half of the one used for the thermal stress shall be used. If the interaction results in a higher acceleration of the thermal ageing than the electrical ageing, it should be modified accordingly.

### 3.2.6 Summary of relevant standards for testing

*Table 3: Summary of relevant standards for testing*

| | |
|---|---|
| **IEC 60034-18-1:2010** Rotating electrical machines – Functional evaluation of insulation systems – General guidelines | This standard provides general guidelines for functional evaluation of different types of windings. |
| **IEC 60034-18-21:2012** Rotating electrical machines – Functional evaluation of insulation systems – Test procedures for wire-wound windings – Thermal evaluation and classification | This standard gives test procedures for the thermal evaluation and classification of insulation systems used or proposed for use in wire-wound alternating current (a.c.) or direct current (d.c.) rotating electrical machines. |
| **IEC 60034-18-31:2012** Rotating electrical machines – Functional evaluation of insulation systems – Test procedures for form-wound windings – Thermal evaluation and classification of insulation systems used in rotating machines | This standard describes thermal endurance test procedures for classification of insulation systems used in a.c. or d.c. rotating electrical machines with indirect cooling and form-wound windings. |

| | |
|---|---|
| **IEEE Std 43-2000** IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery [10] | This recommended practice reviews the environmental factors that affect or change insulation resistance characteristics, as well as recommends uniform test conditions. |
| **IEC 60034-18-34:2012** Rotating electrical machines – Functional evaluation of insulation systems – Test procedures for form-wound windings – Evaluation of thermomechanical endurance of insulation systems [12] | This standard gives test procedures for the evaluation of thermomechanical endurance of insulation systems of form-wound windings. |
| **IEC 60243-1:2013** Electric strength of insulating materials – Test methods – Tests at power frequencies | This standard provides test methods for the determination of short-time electric strength of solid insulating materials at power frequencies between 48 Hz and 62 Hz. |
| **IEEE Std 56-2016** IEEE Guide for Insulation Maintenance of Electric Machines [13] | This guide provides an overview of insulation systems and suggests various tests and inspections employed for maintenance of rotating electric machines rated from 35 kVA and higher, though they may be useful for other types of machines. |
| **IEC TS 60034-18-33:2010** Rotating electrical machines – Functional evaluation of insulation systems – Test procedures for form-wound windings – Multifactor evaluation by endurance under simultaneous thermal and electrical stresses [15] | This standard describes procedures for evaluation of insulation systems by endurance testing where thermal and electrical stresses are applied simultaneously. |
| **IEEE Std 112-2004** IEEE Standard Test Procedure for Polyphase Induction Motors and Generators | This standard covers instructions for conducting and reporting the more generally applicable and acceptable tests of polyphase induction motors and generators. This standard has been defined specifically for three-phase induction machines. |
| **IEEE Std 1812-2014** IEEE Trial-Use Guide for Testing Permanent Magnet Machines | This guide contains instructions for conducting tests to determine the performance characteristics and machine parameters of permanent magnet (PM) machines. |
| **IEEE Std 115-2019** IEEE Guide for Test Procedures for Synchronous Machines Including Acceptance and Performance Testing and Parameter Determination for Dynamic Analysis | This guide contains instructions for conducting the more generally applicable and accepted test to determine the performance characteristics of synchronous machines and provides instructions for performing normally required tests |

## 3.3 Methodology for scale effects

Many reliability or failure test methods are often lengthy, especially when the object under study shows a high level of reliability. Thanks to accelerated test procedures, the tests are shortened by applying higher stress levels or increasing the application frequency of repetitive stresses.

**IEC 62506** suggests three accelerated test approaches [8]:

- Type A: qualitative accelerated testing for failure mode detection with the aim of identifying potential failures that may finally result in machine failures;
- Type B: quantitative accelerated testing to predict the failure distribution in normal use, where machine reliability may be estimated based on the results of accelerated simulation tests;
- Type C: quantitative time and event compression tests to predict the failure distribution in normal use.

Type A accelerated tests are designed to identify potential design and/or manufacturing weaknesses. Therefore, the analysis of this type of accelerated methods is not aligned with the objective of this UC#2 and thus they will not be further analysed in this section.

Type B tests use cumulative damage methods to determine machine reliability until the end of the expected product life. Information collected from separate accelerated tests is used to determine the failure distribution. In this way, product reliability can be estimated through the estimation of reliability or probability of occurrence of individual failure modes.

Type C tests are mainly used to estimate the service life of components where wear is the dominant failure mode. Time or event compression methods are normally used, where the stress is accelerated by the duration or frequency of its application but not by the increase of its level. Time compression can be applied when the product is operational in a state that produces significant damage only at a particular time, whereas event compression can be considered when the stress is repetitive and tests can be accelerated by increasing the frequency of stress.

### 3.3.1 Type B and C – Quantitative accelerated test methods

Quantitative accelerated tests aim to estimate some aspects of product reliability, such as failure rate, probability of failure, time to failure (TTF), etc. In addition, they allow the estimation of the service life of components and help determine and improve the reliability of systems and components.

In this sense, it is deemed necessary to have a deep knowledge of potential failure modes and operational and environmental stresses of the object under study. This can also be achieved by performing failure mode analysis, e.g. using a FMEA (**IEC 60812**).

Type B tests can be run by increasing the level of a variety of loads such as thermal loads (e.g. temperature, temperature cycling, and rates of temperature change), chemical loads (e.g. humidity, corrosive chemicals and salt), electrical loads (e.g. steady-state or transient voltage, current, power), and mechanical loads (e.g., quasi-static cyclic mechanical deformations, vibration, and shock/impulse/impact).

However, Type B accelerated tests might show several disadvantages:

- A risk that the stress acceleration may exceed the physical properties of product materials and cause unforeseen damage;
- A risk that the acceleration of combined stresses may cause additional unforeseen damage to the product that would not have happened in actual use;
- The base line for acceleration testing not to be a single stress but a multiple stress that varies with user and location.

#### *3.3.1.1 Time compression*

Time compression is achieved by eliminating "non-damaging time" (e.g. operation below nominal power) by compressing the duty cycle through addressing just the "damaging time". When products are exposed to a wide range of stresses, it is typical that the highest stresses (the primary stresses) will induce the most damage, and others are assumed to produce negligible damage. In this way, products with a minimal or short operating use time compared with calendar time can be tested within a very reasonable test time relative to its required life. However, concentration exclusively on operational time means considering the operational environment only with its associated failure modes, while the failure modes occurring in the "non-operational" environments may be neglected. For this reason, for products where active time is considerably shorter than the passive, it is necessary to combine time accelerated testing for the operational periods with tests that accelerate the passive periods, e.g. corrosion tests, humidity tests etc.

#### *3.3.1.2 Event compression*

The event compression tests apply repetitions of events with considerably higher rates than those applied in actual product use. These tests can be combined with the time compression tests or stress acceleration tests for further test acceleration. However, the time compression may influence the stress acceleration, so that caution should be exercised. Nevertheless, this type of testing may also produce some negative effects by applying continuous stress and in a manner that precipitates failures that normally would not occur. For example, in electrical windings overheated for having operated above nominal value, the overcurrent may produce heat that would further precipitate a failure that would normally be delayed by periods of cooling.

### 3.3.2 Acceleration models

**IEC 62506** determines single and multiple stress acceleration methodologies, in which different acceleration models are considered and extensively described:

- Inverse power law model, used for test acceleration when stresses other than constant temperature are considered, such as electrical, mechanical, chemical, etc.;
- Arrhenius reaction rate model, used for constant temperature stresses, based on the effect that the absolute temperature has on a failure mechanism;
- Eyring model which is used in cases where the acceleration is achieved with temperature and moisture stress levels;
- Time varying stress models that are used to account for precipitation of failure modes in order to shorten the test time;
- Fatigue models that take into account mechanical, dynamic, thermal cycling or voltage cycling loads.

Other acceleration models can be found in **IEC 61163-2**.

There are several major limitations of accelerated reliability testing methodologies, such as complexity, high economical and effort cost, the need of complex equipment, difficulties to determine stress factors, etc.

### 3.3.3 Procedure for accelerated testing

Before applying ageing process over the test object, it is important to understand the operational and environmental stresses that generate the failure mode based on physics of failure.

IEC 62506 suggests the following procedure to conduct the accelerated tests:

1. Identify the relevant stress factors from the field, including storage and transportation (**IEC 60721**);
2. Determine which stress types have to be accelerated, which will be nominal and which can determine which stress types have to be accelerated, which will be nominal and which can be omitted, e.g. because they are covered by other tests;
3. Determine if the stresses can be applied simultaneously to include stress interactions or whether they will have to be applied sequentially, e.g. in a test cycle (**IEC 60605-2**);
4. Determine if the acceleration factor can be estimated from the test or estimate the acceleration factors based on relevant acceleration equations and relevant empirical factors;
5. Determine the sample size (**IEC 61649**, **IEC 61123** and **IEC 61124**);
6. Perform the test (**IEC 60300-3-5**);
7. Perform failure analysis;
8. Analyse the test – each failure mode separately (**IEC 61649**, **IEC 61710** and **IEC 61124**);
9. Report test results (I**EC 60300-3-5**).

### 3.3.4 Summary of relevant standards for scale effects

*Table 4: Summary of relevant standards for scale effects.*

| | |
|---|---|
| **IEC 62506 IEC 62506:2013** Methods for product accelerated testing [8] | This standard provides guidance on the application of various accelerated test techniques for measurement or improvement of product reliability. |
| **IEC 60812:2018** Failure modes and effects analysis (FMEA and FMECA) | This standard explains how failure modes and effects analysis (FMEA), including the failure modes, effects and criticality analysis (FMECA) variant, is planned, performed, documented and maintained. |
| **IEC 60605-2:1994** Equipment reliability testing – Design of test cycles | This standard applies to the design of operating and environmental test cycles referred to IEC 605-1. |
| **IEC 60300-3-5:2001** Dependability management – Application guide – Reliability test conditions and statistical test principles | This standard provides guidelines for the planning and performing of reliability tests and the use of statistical methods to analyse test data. Describes the tests related to repaired and non-repaired items together with tests for constant and non-constant failure intensity and constant and non-constant failure rate. |

# 4 Hybrid Modelling

Hybrid testing will be performed in a staged manner starting with a fully numerical model and finishing with fully hybrid scheme. The fully numerical models will be used to design and plan the hybrid testing, which will provide an initial estimate on the damage produced on the generator per sea state. Depending on the necessary sea states, capabilities of the physical infrastructures and the identified acceleration strategy, the size of the generators to be tested will be defined. Afterwards, numerical models in Model.CONNECT™ could be gradually replaced through Testbed.CONNECT™ with the corresponding physical models, e.g. the test bench at Tecnalia, with the generator to be tested.

## 4.1 Hybrid testing arquitecture alternatives

Regarding hybrid modelling, AVL provides to VALID project Model.CONNECT™ and Testbed.CONNECT™ capabilities. Model.CONNECT™ is a model integration and co-simulation platform, connecting virtual and real components. Testbed.CONNECT™ helps you harness the benefits of model-based testing. As an open platform it facilitates early integration tests by connecting simulation models to the testbed. In alliance with Model.CONNECT™ it opens the testbed to the whole world of office simulation. Currently the test bench has the following configuration:

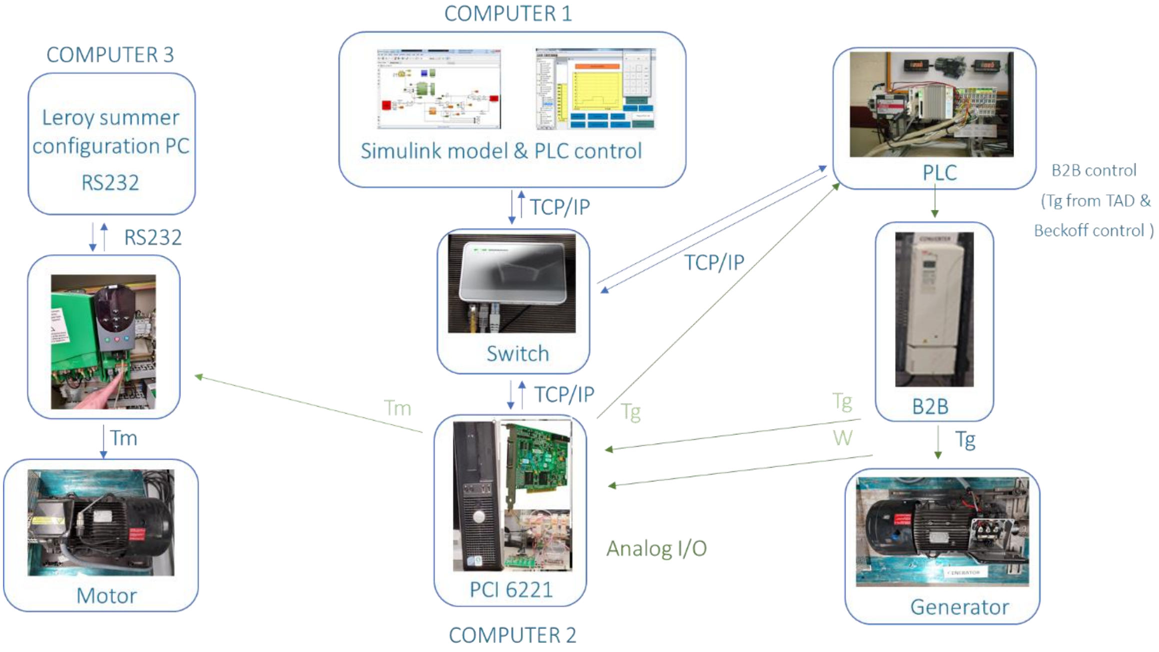


*Figure 8: Squeme of communications and signals between the different elements of the Tecnalia's test bench.*

Where the motor and generator control torque references cames from NI PCI 6221 drived by Simulink-Matlab model. Additionally, the test bench has global control (state machine) developed in Beckoff PLC environment. In order to improve the capabilities of the test bench the option of including Model.CONNECT™ and/or TestBed.CONNECT™ is being in consideration. Two options of improving the test bench have been identified. The first one consists on using Model.CONNECT™ where Simulink-Matlab model will be run with no Real time guaranteed. This option will give more flexibility of including more simulation tools, such as Ansys or Python which will be explored during the project.

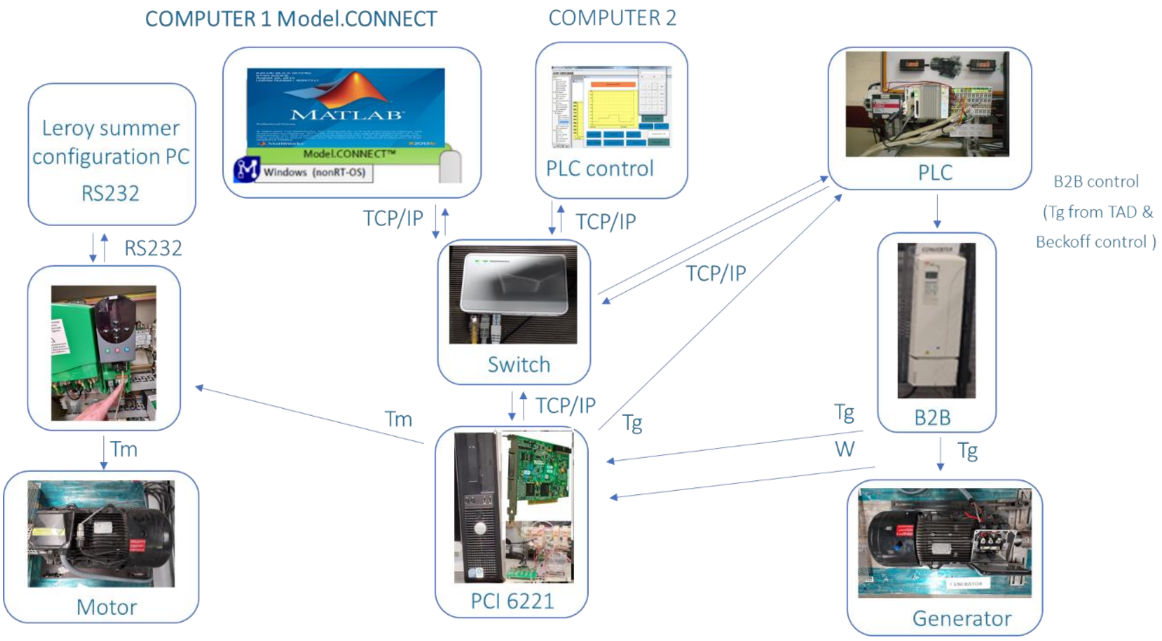


*Figure 9: Tecnalia's test bench and Model.CONNECT™ integration squeme, option 1.*

The second option is to include TestBed.Connect and Model.CONNECT™. With this platform Real Time will be guaranteed:

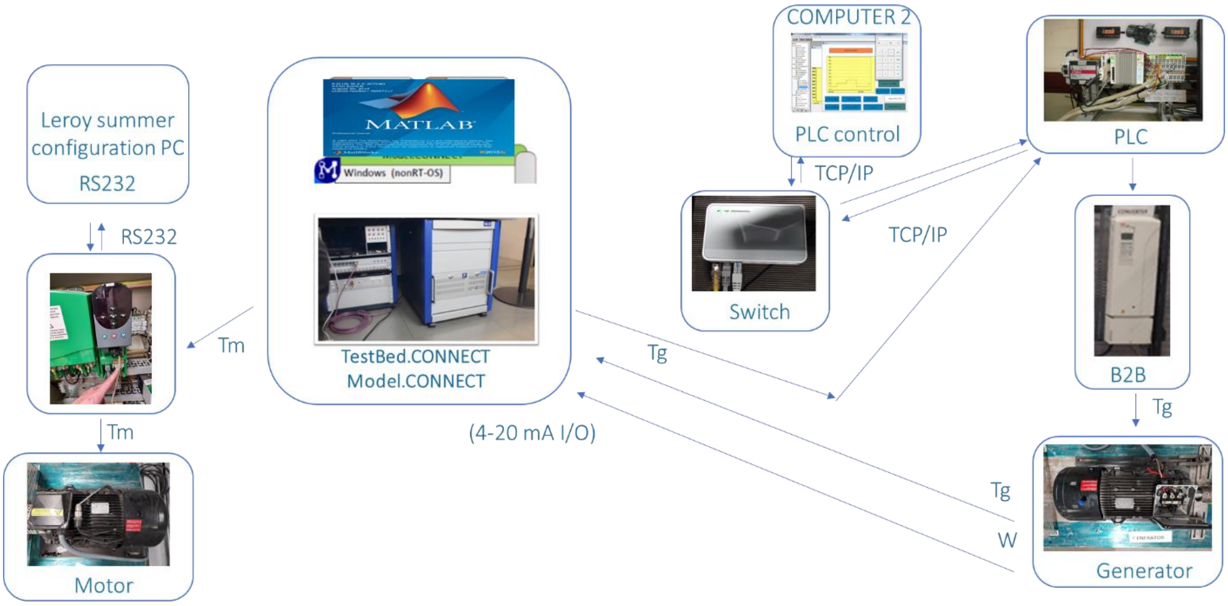


*Figure 10:Tecnalia's test bench and Model.CONNECT™ integration squeme, option 2*

The decision about the option to be selected will be taken based on technical restrictions, compatibility of delivery times according to the project calendar and budget availability of the project partners.

## 4.2 User case in Model.CONNECT™

The first natural step for any of the alternatives above is to take the model integrated in simulink and separate it into functional blocks for its integration in model.CONNECT™. In a second step, they can then be substituted by their physical counterparts in the test bench.

### 4.2.1 Numerical Model of a Chamber of the Mutriku Wave Power Plant

The numerical model of the MWPP consists of five numerical sub-models, i.e. Surface Water Level (SWL) motions, the air chamber, the air turbine, the electrical power generator and the control model of the air turbine. The mentioned models are described along the following subsections indicating the corresponding modelling approaches for each one.

#### *4.2.1.1 Surface Water Level Motions*

Surface water level motions are based on the newton's second law, accounting for the hydrodynamic interaction forces, as explained in [16] or [17] computed with a software based on the Boundary Element Method (BEM), which is based on the linear potential theory, such as Nemoh [18], Ansys-AQWA [19] or Wamit [20].

The corresponding modelling has been carried out through a diffracting fixed body, representing the Mutriku breakwater and seabed, and a massless surface, representing the internal free surface of a chamber of one oscillating water column (OWC) of the MWPP, well described in [17]. The convolution term has been approximated through a state space model by means of the Prony method [21].

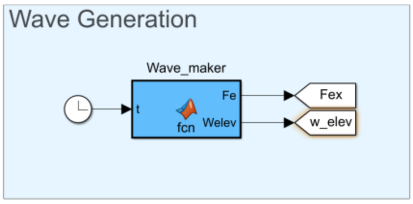


*Figure 11: Wave force and elevation based on the specified spectrum and Excitation force per unit wave amplitude obtained with the corresponding BEM code.*

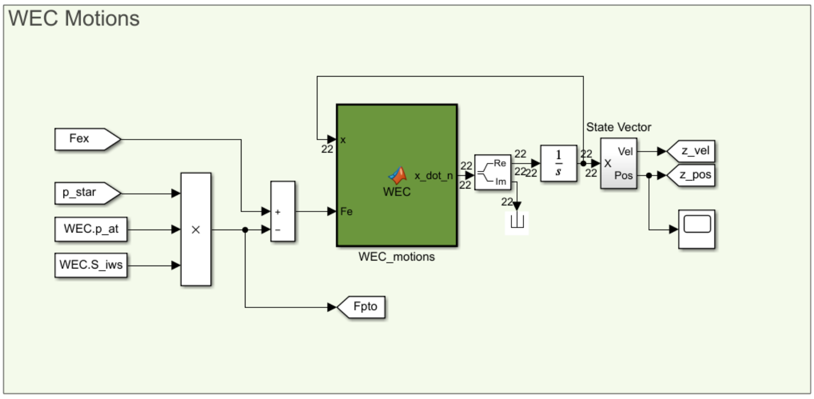


*Figure 12: Simulink model for the internal SWL motions, based on the generated wave forces.*

Time series of wave elevation, and the corresponding heaving forces, are generated with the Simulink model in Figure 12. In addition, the state space model is built up and solved at each time step with the model showed in Figure 12. It should be noted that it accounts for the power take off (PTO) force, represented by 'Fpto' and induced by the turbine resistance to the air flow through the chamber pressure. It is explained in Section 4.2.1.2.

#### *4.2.1.2 Air Compressibility*

The air compressibility model accounts for the total mass flow rate of air as a function of both the water surface elevation and pressure changes in the air, considered as an ideal gas, as explained in [22] or [17].

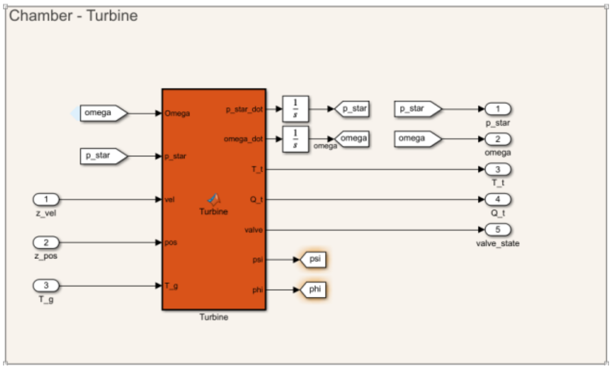


*Figure 13: Simulink model of the air compressibility and turbine rotational speed.*

The compressibility model has been integrated into the same Simulink model of the turbine in order to reduce the number of blocks.

#### *4.2.1.3 Air Turbine*

The air turbine is based on the turbine's stationary properties of pressure drop along the turbine rotor and the induced mechanical torque/power on the turbine. It is based on non-dimensional properties of the turbine, as shown in Figure 14 and Figure 15, which are applicable to any turbine diameter and rotational speed.

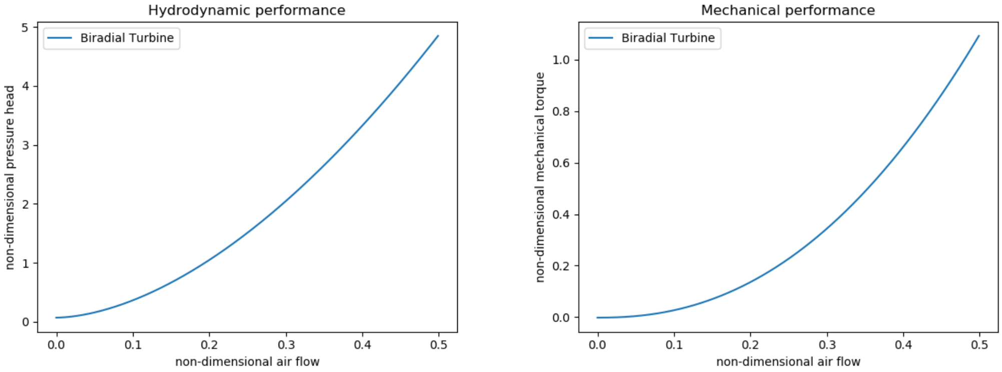


*Figure 14: Non dimensional Turbine properties of the Biradial turbine [23]. Pressure drop (left) and Mechanical torque (right) as functions of the air flow, non-dimensional.*

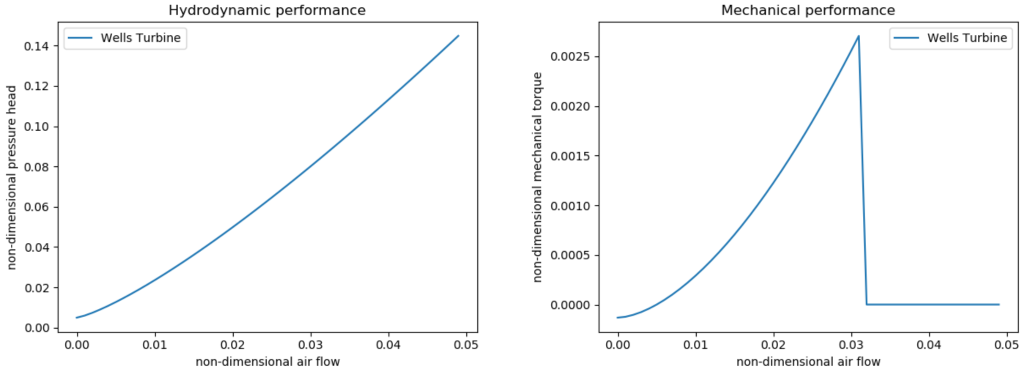


*Figure 15: Non dimensional Turbine properties of the Wells turbine [24]. Pressure drop (left) and Mechanical torque (right) as functions of the air flow, non-dimensional.*

The air turbine, given the air flow through the turbine, produces an excitation torque on the shaft to which it is coupled. The rotational speed of the corresponding shaft is modelled, along with the chamber pressure, in the model represented in Figure 13. The resisting torque is applied by the generator, which is controlled by the corresponding control strategy.

### *4.2.1.4 Electrical Power Generator – Squirrel Cage Induction Generator*

The model of the electrical power generator aims at representing a Squirrel Cage Induction Generator (SCIG). It is also based on its properties working at stationary rotational speed. Its electrical efficiency is computed based on several estimated losses, i.e. mechanical, iron and winding losses, modelled in the block represented in Figure 16.

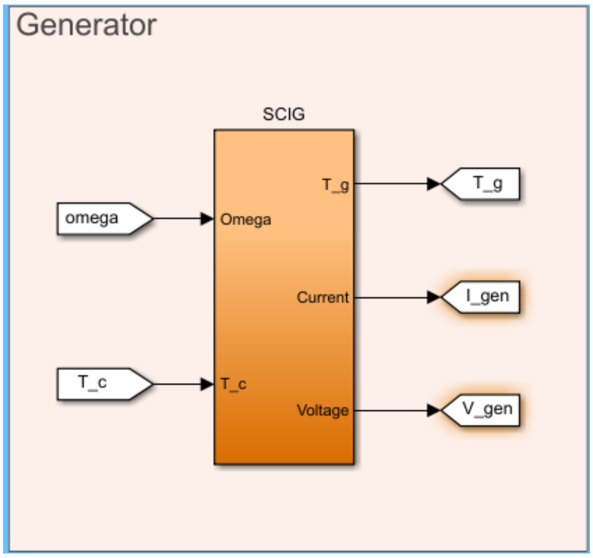


*Figure 16: Simulink model of the SCIG.*

In addition, the generator voltage control is assumed linear up to the rated rotational speed and constant over that value. Therefore, for rotational speeds over the rated, the current is limited to provide the maximum power of the generator, inducing a torque weakening as the rotational speed is increased.

#### *4.2.1.5 Control Model*

The control model is a key component of any WEC, since it defines the corresponding damping on the motions so that the delivered energy is maximised.

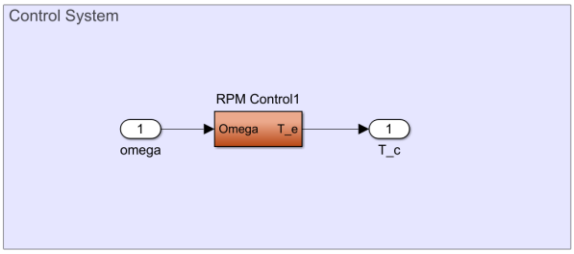


*Figure 17: Control model as defined in Simulink.*

The torque is defined by the control model, showed in Figure 17, as a potential function of the rotational speed of the drivetrain in this work, as suggested in [25]. It is a simple and robust control strategy, however there can be more complex control strategies and a large amount of research is underway so that the captured energy can significantly be increased.

#### *4.2.1.6 Model Interfaces*

In order to enable the numerical model to be as modular as possible the numerical model is broken down into the subsystems specified in previous sections. The corresponding subsystems have been defined bearing in mind the boundaries of each model but also the most easily available sensors in a WEC, such as SWL elevations, pressures or rotational speeds. Therefore, the interfaces of the current model are specified in Table 5:

*Table 5: Interfaces of each subsystem defined in the numerical model.*

| Model | Inputs | Outputs |
|---|---|---|
| Wave Maker | Hs, Tp, speed | Wave Force & elevation |
| Mutriku WEC | Wave Force, Chamber pressure | SWL position & velocity |
| Chamber & Turbine | Shaft rotational speed, Chamber pressure, SWL position & velocity, Generator Torque | Shaft rotational speed, Chamber pressure, Air flow, Turbine Torque, Control valve state |
| Control | Shaft rotational speed | Ideal Generator Torque |
| Generator | Shaft Rotational speed, Ideal Generator Torque | Generator Torque, Generator Intensity (electrical), Generator Voltage |

Even though in an eventual coupling with a physical infrastructure the interfaces may be altered, those here defined aim at enabling direct replacement of numerical subsystems with physical ones, one of the main objectives of the VALID project.

### 4.2.2 Requirements of the Model.CONNECT™ for Matlab/Simulink Models

The Model.CONNECT™ software has been used as a platform to couple the numerical models introduced in Section 4.2.1 defined in Matlab-Simulink. In addition, several partial validations are presented so that the numerical models are duly validated to be used as the corresponding digital twins.

#### *4.2.2.1 Requirements of the Model.CONNECT™ for Matlab/Simulink Models*

The coupling between the identified subsystems has been carried out through MAT-ICOS blocks, and the following requirements have been identified:

- Each subsystem shall have input and output ports (not necessarily ICOS in most recent Matlab distributions) that will be identified as I/O by the MAT-ICOS blocks
- Each MAT-ICOS block should point at the corresponding Simulink model with its path (Model.CONNECT™ will make a copy to a specific folder in the project)
- Each MAT-ICOS block will have to point at the Matlab.exe, executable file of the installed version in the computer
- All INPUT ports of the MAT-ICOS model have to be connected
- All the required variables (parameters) are convenient to be defined in a Model-Workspace of the Simulink model

##### *4.2.2.1.1 Initial Verification. Simulink Models Connected through Model.CONNECT™*

Even though all subsystems are already coupled in the corresponding Simulink model, the same exercise has been carried out in Model.CONNECT™ in order to set a feasible basis over which to work in the near future with physical systems, obtaining the model represented in Figure 18.

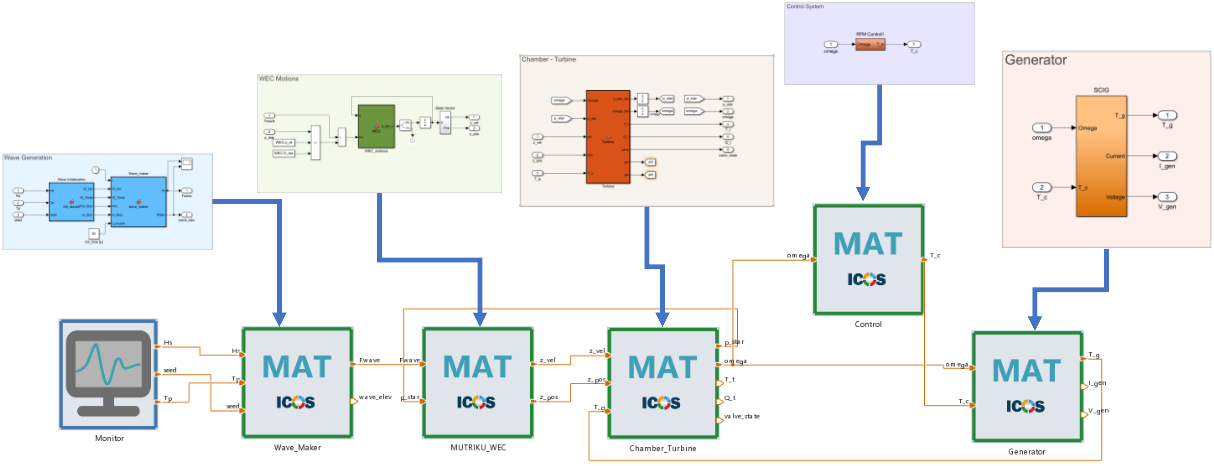
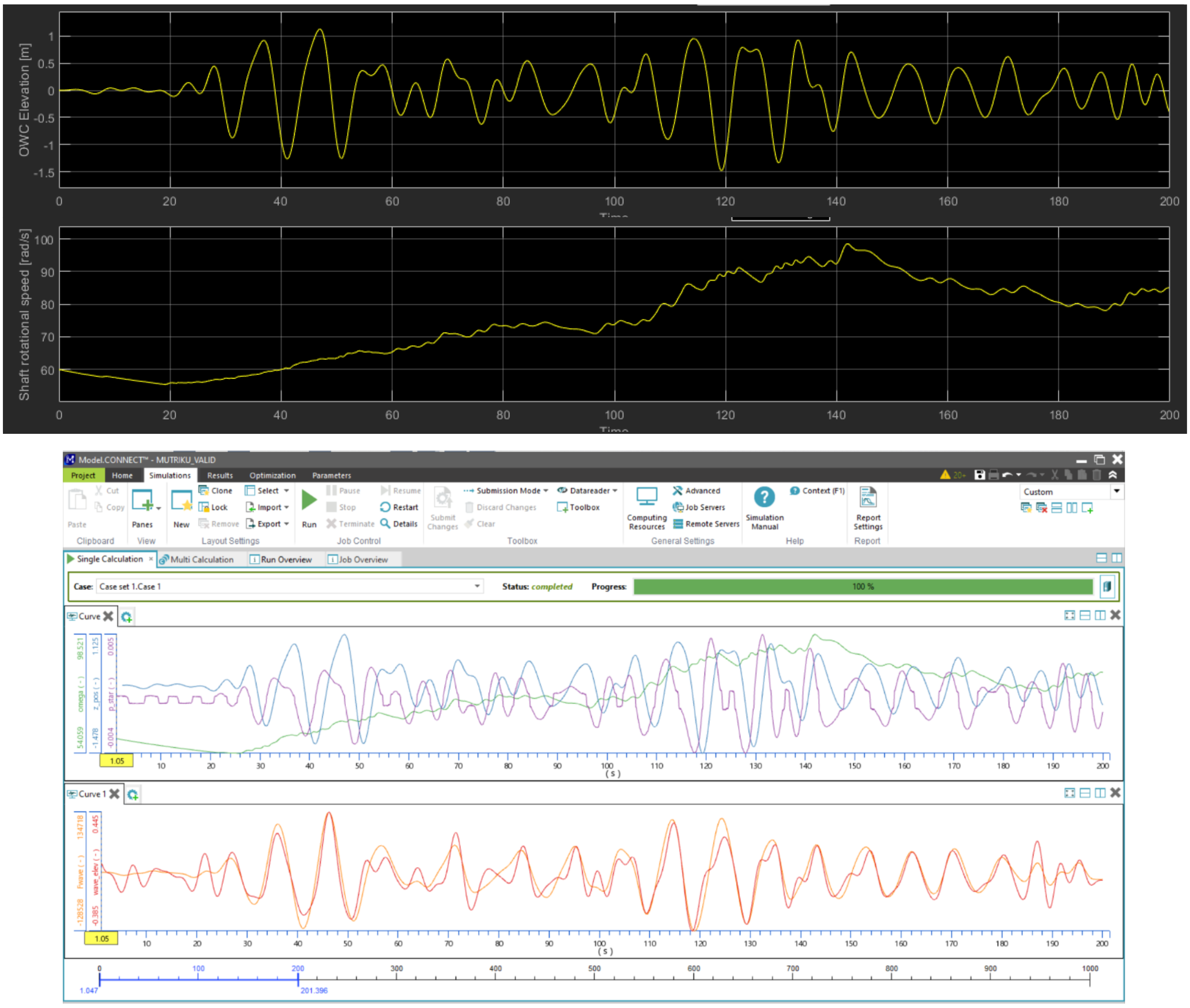


*Figure 18: Fully coupled MWPP numerical model built up on Model.CONNECT™.*

In order to verify the Model.CONNECT™ based numerical model, a comparison with the corresponding Matlab-Simulink model results has been done, obtaining the same results (see Figure 19) under a sea state equivalent to: Hs=1m, Tp=10s and seed=1.



Case: Case set 1.Case 1

Status: completed

Progress: 100 %

*Figure 19: Same model performance reproduced with the coupled Matlab-Simulink model (top) and the corresponding Model.CONNECT™ model (bottom).*

### 4.2.3 Conclusions

The numerical model of one chamber of the Mutriku wave power plant, based on MATLAB-Simulink has been broken down into the main functional subsystems, i.e. wave generation, surface water level motions, air chamber (turbine included), electrical power generator and control strategy. The corresponding sub-models have been integrated into a model developed in Model.CONNECT™ software. In addition, the coupling between the sub-models has been carried out within the mentioned platform, obtaining the same results that were obtained with the MATLAB-Simulink model, which confirms the validity of the Model.CONNECT™ for the proposed system. It will also be used for validation of individual numerical models (e.g. the generator).

The coupled model sets a basis for substituting numerical models with the corresponding physical ones during next steps of the VALID project. The envisaged tasks will primarily consist in coupling the physical MWPP with the numerical drivetrain, coupling the numerical MWPP with the test bench at TECNALIA and, eventually, coupling the physical MWPP with both the test bench at TECNALIA and the numerical model of the drivetrain.

These envisaged tasks will eventually lead to building feasible degradation and performance models of electrical power generators in a WEC with the corresponding variability and working conditions.

# 5 Testing Specification

The definition of the test plan is a key feature that will drive the complexity and achievability of the main objectives of the project. While the hybrid essence of the tests must be maintained, a balance between testing innovation and its practicity and feasibility must be pursued.

While a full understanding of the different phenomenas that take part on the degradation of the insulation of the generator and its modelling appears to be out of the scope of the project due to its significant complexity and the required time for its consecution, after the basic understanding of the processes presented in previous sections, a path for the consecution of a testing campaign from which clear conclusions on the operation and failure of the generator can be obtained has been drawn. On the current section the details of this tensting campaign are presented.

## 5.1 Definition of load cases

The definition of the load cases of the tests to be performed during the current project represents the major challenge thereof, mainly due to the lack of a generalized model capable of predicting the effect of the different stresses that take place during the operation of the generator on the present UC. Consequently, although the standards presented on Section 3 provide diverse options for the execution of degradation and diagnosis tests for the evaluation of the insulation, the direct suitability of each of them for a particular practical application of an electrical machine is still to be defined due to the interrelation of the different stresses and the impossibility, on a general basis, of stating the main stress causing a failure when multiple stresses act at the same time, as exposed on Section 2.3.

For these reasons, the definition of the load cases will represent a part of the testing itself. A series of battery tests will be performed to the electric generator on an intent to characterise the degradation that is introduced, for which the component diagnosis that is presented hereunder will have an essential role. On a parallel basis, a development/calibration of a power peak-degradation model is intended to be developed if the complexity that introduces does not exceed the scope of the project. On an attempt to simplify the scope [effects and stresses that the model should represent], it can be considered that the main stresses have a thermal origin/effect. Hence, the potential model to be defined will combine a thermal numerical model and a subsequent degradation model. These models would be fed with the characterization tests' results for their calibration and validation.

The inputs that the generator will receive on a regular operation window have been extensely studied for IDOM's MARMOK-OWC WEC and can be predicted for any defined test site. However, the particularities of the application are the ones introducing a significant degradation on the electric machine, mainly due to the high peak to average ratio on the electric power. It is understood that the degradation process that the generator endures is exclusively caused by the power peaks that it occasionally experiences during energetic sea states, i.e. a regular operation conditions do not introduce degradation to the system.

On the definition of these degradation characterization tests, three main variables have been identified to have a key effect on the influence of a peak on the electric machine:

- Peak magnitude
- Peak duration
- Time between peaks

Several combinations of different values for these variables are to be tested on Tecnalia's testbench over more than one electric generator. By these means, a proper understanding on the effect of each variable on the degradation process is to be assessed, with the objective of obtaining an experimentally based transfer fuction from these input parameters to the degradation measured.

The reference values for the magnitude, duration and spacing of the peaks is to be defined looking at a common power series of a representative site that still has to be selected. Once the reference values are defined, the detailed characterization test plan will be established. Two main uncertainties arise when defining the exposed test procedure.

The first uncertainty is related to the effect that a stress has on the insulation once this element is already deteriorated. An uncertainty that may appear when performing the tests is the fact that a stress may not have the same impact or contribution to the degradation process on a brand new machine or on a generator that has already withstood damaging power peaks. However, according [26], the impact on the electric machine can be considered independent of the degradation level .

The second uncertainty concerns the needed sensoring for the assessment of the degradation grade and the input provision for the numerical models. A good candidate for monitoring the degradation level is presented on the following subsection. On the thermal model input definition, a temperature sensor appears as the simplest way to proceed, while an adaptation of the existing model must be done since most of them asses the effect of temperature thinking of it as a constant while on the application of this UC this parameter will be constantly varying.

## 5.2 Component diagnosis

There are different ways to detect faults in motors and electrical machines, reference [27] gives a summary :

- Magnetic field monitoring and axial flow measurement
- Temperature measurement
- Inflow recognition
- Monitoring of radio frequency emissions
- Spectral analysis of acoustic noise and vibrations
- Chemical analysis
- Modeling techniques, artificial intelligence, neural networks
- Current spectral analysis, MCSA (Motor Current Signature analysis)

From the different options, MCSA has been selected because is a condition monitoring technique that is used to diagnose future problems at early stage and the tests can be performed online without interrupting the production. Over 90 percent of developing failures can be detected up to five months in advance, so the required maintenance can be scheduled precisely, in optimally planned windows [28].

### 5.2.1 MCSA, Motor current signature analysis

Machine current signature analysis (MCSA) is a non-invasive, online or offline monitoring technique for the diagnosis of problems in induction machines. It uses spectrum analysis of machine line current (MCSA) to detect different faults [29]-[30]:

- Broken rotor bar
- Stator winding
- Bearing Damage
- Gearbox Damage

- Air Gap Eccentricity
- Rotor Asymmetry
- Rotor Unbalance

The postprocessing signal algorithms convert the data into a pattern of behavior that defines the range of sine wave shapes and ripples that occur under normal circumstances. Anomaly detection algorithms track the changes over time and identify "unhealthy" deviations that cannot be explained by operational factors such as changes in load and power [31].

The first step in spectral analysis, is to convert the captured signal from the time domain to the frequency domain. The most common way to convert from time domain to frequency domain is the fast Fourier transform or FFT. The FFT tells you how much of each sine wave you need to build the signal you gave it. A longer time window could mean a different signal, and thus a different answer. If the sampling window is too long, the answer obtained could not reflect the machine's actual state at any point. Because of that, short-time Fourier transform term should considerate to define the windows to capture machine behavior accurately [28].

So the first way that spectral analysis (example in Figure 20) helps detect developing problems is to track these changes over time and compare them with a library of known failure mechanisms [28].

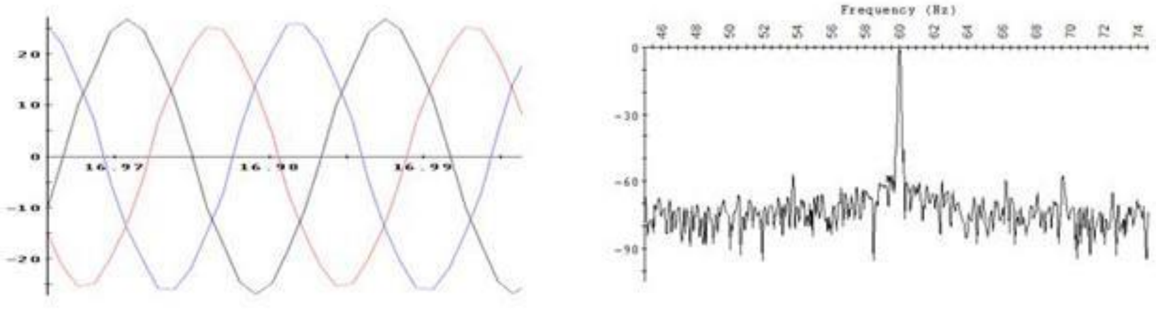


*Figure 20: Example of an FFT spectrum [32].*

The generator can run at different operating points. These changes can run the gamut from occasional and planned (a fan that runs faster when more ovens are in production) to constant and unpredictable (a wind turbine subject to changing wind speeds and directions).

This methodology should contribute to increase the time in which the generator will produce energy, by reducing the time spent in operating in undesirable load or fault conditions [29].

One important question regarding lifetime statistics is: at which point of the lifetime does the breakdown occur? In generator stator windings, aging and failure mechanisms find the beginning in the change of the material due to stress. This stress can be described as impact from thermal, electrical, mechanical or chemical energy [33].

### 5.2.2 MCSA for Stator winding diagnosis

The objective MCSA method at this case study, is to identify current components in the stator winding that are only a function of shorted turns and are not due to any other problem or mechanical drive characteristic [29]. Figure 21 shows a diagram of the current monitoring system [34]:

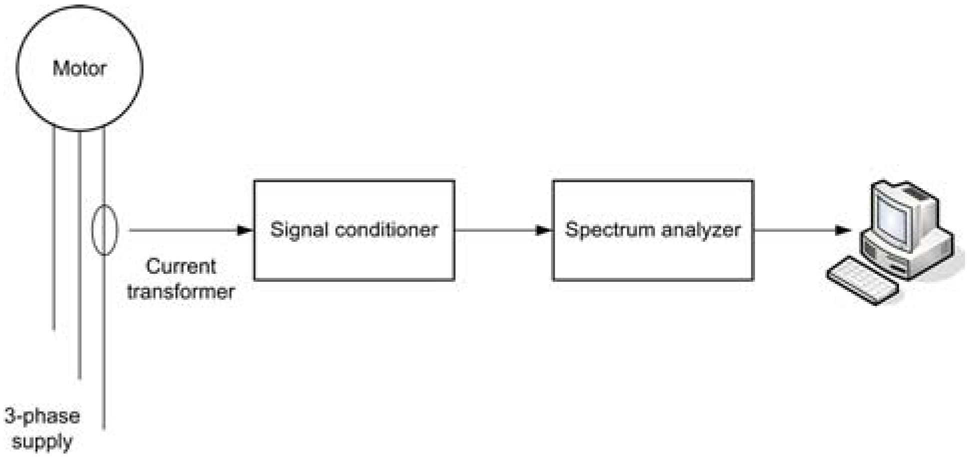


*Figure 21: Stator current monitoring system [34].*

The stator winding and rotor windings consist of several components, each with its own function. Furthermore, different types of machines have different components. The three main components in a stator are:

- Copper conductors (aluminum is rarely used)
- Stator core
- Insulation

The copper is a conduit for the stator winding current. In a generator, the stator output current is induced to flow in the copper conductors as a reaction to the rotating magnetic field from the rotor. In a motor, a current is introduced into the stator, creating a rotating magnetic field that forces the rotor to move. The copper conductors must have a cross section large enough to carry all the current required without overheating [35].

The final major component of a stator winding is the electrical insulation. The insulation is passive component; that is,which it doesn’t help to produce a magnetic field . The insulation increases machine size, cost and reduces efficiency but prevents short circuits between the conductors or to ground. Without the insulation, copper conductors would come in contact with one another or with the grounded stator core, causing the current to flow in undesired paths and preventing the proper operation of the machine. The life of a stator winding is limited most often by the electrical insulation rather than by the conductors or the steel core [35].

Stator winding faults start as inter-turn short circuits [36] [30]. A negative magnetomotive force is initiated when the short-circuit current flows in the inter-turn short circuit windings. This reduces the net magnetomotive force, changing the air-gap flux, which induces harmonic frequencies in the stator current [37]. Next equation represents the stator frequency components that are a function of shorted turns:

$$f_{st} = f_1 \left[ k \left( \frac{1-s}{p} \right) \pm n \right] \tag{6}$$

Where $f_{st}$ represents the stator frequency components that are a function of shorted turns, $f_1$ is the supply frequency, $n$ is 1,3,5, k is the harmonic index [k/p=1,5,7], $p$ is pole pairs, and $s$ is the slip, difference between synchronous speed and operating speed $s$=(ns-nr)/ns. Where *ns* is the stator electrical speed and *nr* is rotor mechanical speed. At full rated load, slip varies from more than 5% for small or special purpose motors to less than 1% for large motors.

MCSA requires high precision of slip frequency information to guarantee the reliability of a diagnosis result. All abnormal harmonic frequencies are a function of slip [36]. Therefore, the result of a motor diagnosis using MCSA is incorrect if the detected slip has an error. When the processing of the motor diagnosis is included in the motor-drive systems, slip frequency is easily obtained from the outputs of speed sensors such as encoders. However, if diagnosis processing is independent of motor-drive systems, slip frequency is gathered only from the stator-current spectra in an MCSA-based diagnosis system [36]. In addition, stator current data should be sampled after motor speed arrives at the steady state. If the motor speed varies during the sampling operation this invalidates the sampled data.

Once the stator current signal is well monitorized, the possibility of analizing the accumulated damage with the combination of stator frequency and flux of the generator will be considered.

### 5.2.3 Instrumentation requirements

As explained in Section 5.2.2, the stator frequency components are function of the supply frequency, pole pairs, slip and harmonic index.

The following instrumentation may be needed for performing MCSA analysis:

- Current sensor (not defined yet, depends on the generator to be studied, for example "LEM" sensors)
- Data acquisition target (National Instruments data adquisition target connected to Matlab-simulink real time environment, where:
    - Signal conditioning (Matlab-simulink and maybe an external filter) .Is composed of an optimal-slip-estimation algorithm, a proper-sample-selection algorithm, and a frequency auto search algorithm for achieving MCSA efficiently [36]
    - Data processing (Matlab-Simulink)

## 5.3 Accelerated tests

Having the baseline knowledge presented on Section 3.3 regarding the different methods for scaling and accelerating the impact of a stress, different practical ways of accelerating the current test campaign have been identified:

- *Accelerate product use rate*. Appropriate for products of intermittent use in which the number of uses on a particular time is increased so the degradation takes places on a shorter period.
- *Accelerate product ageing.* This process consists of varying the boundary conditions (relative humidity, environment temperature, etc) so the stress responsible for the degradation process increases its influence and/or likeliness.
- *Accelerate by increasing stresses*. Increasing the magnitude of the stress accelerates the deterioration.

Although increasing the magnitudes of the stresses appears to be the best option on most of the cases, since it results pretty simple to accelerate the test, it also introduces some factors that could mislead the tests. For instance, the stress increase must be treated carefully, as an excessive increment could provoke the appearance of failure modes that would not happen under operational conditions. In addition, if more than one stress is intended to be accelerated for modelling real operating conditions in which different stresses take place at the same time,the increment of each of them must be precisely designed for introducing a very similar accelerating factor, so the contribution of each of them on the accelerated test is the same than that on common operation.

Adding these reasons to the difficulty of varying boundary conditions such as relative humidity, the use rate acceleration stands as the most appealing option, making the already mentioned assumption that just the power peaks deteriorate the generator. On this sense, the accelerating factor will be the concatenation of sea states or time windows in which the degradation process happens, avoiding the representation of non damaging conditions that will not add value to the experimental procedure.

Following this approach, an analysis of the site representative sea states is to be done, identifying the power peaks that match the characteristics to be considered as detrimental for the generator, which will be defined within the degradation characterization tests. The implementation of these peaks on the actual tests can be done in two different ways.

### 5.3.1 Peak concatenation

The most intuitive procedure to be followed once the damaging peaks have been identified is the testing of the bear peaks, concatenating them on a time series while leaving non operation windows among them for representing the non demanding wavetrains that will enable the generator to reach its regular operational values mainly in terms of temperature.

This procedure presents the main advantage that the tests are uniquely focused on the wavetrains that have a negative impact on the generator, maximising the acceleration rate for the acceleration method selected. Besides, the numerical degradation model calibrated on the characterization tests can be validated since the main parameters used for this purpose will be clearly established.

On the other hand, the definition of the actual test introduces the difficulty of needing to determine the spacing between peaks. This spacing will determine the capability of the generator of recovering nominal values after enduring a peak and before experiencing another one. However, on a real application this recovery will not always happen, the generator being forced to withstand consecutive power peaks that will increase their impact on the deterioration.

### 5.3.2 Damaging sea state reproduction

Another test definition consists of the testing of the complete sea states. The sea states to be reproduced on the testbench would be previously selected according to some specifications defined by the conclusions of the characterization tests, what would imply that the sea state introduces a significant amount of degradation to the system. These test may be used as a validation of the charachterization tests previously performed.

The main benefit is that they will represent a real situation to which the generator will be exposed during operation, without needing to define any of the parameters of the tests (such as peak magnitudes and duration, and time between peaks). This makes the experimental test as similar to reality as possible, reducing the uncertainty introduced by the tests and the needed correcting factors to be applied.

However, this procedure is not as accelerated as the one presented before, since it implies the reproduction of windows inside the sea state in which no degradation takes place. On this sense, the selection of the appropriate sea states must be carefully done for its periodical repetition on an attempt to optimize the acceleration rate.

The validation of the adjusted numerical degradation model would also be conducted with this testing procedure, verifying that the degradation introduced by each sea state can be correctly predicted with the model.

## 5.4 Other combined tests

Regarding the tests that could be completed at Tecnalia's test bech, the first option is based on MARMOK OWC concept, run different case studies with different resource power levels and analyze the degradation of the generator.

On the other hand, if we consider Mutriku test site inputs, a digital hybrid twin could be developed in Tecnalia's test bench with real input data, at this point mechanical power from Mutriku could be represented in the test bench and analyze the behavior of the generator under controlled testing conditions.

There will be some differences between Mutriku and test bench such as external influencing factors (aggressive environments, humidity, salt), vibrations and the orientation of the generator.

There are two testing possibilities for testing in the test bench the resource from Mutriku: 1) online real time connection, directly connecting the test bench and Mutriku; and 2) storing input data from Mutriku and using them for running offline tests at the test bench. In both options additional sensors should be installed in Mutriku as described in the previous sections.

### 5.4.1 Mutriku cloud

As a first approach, sensor data collected from Mutriku plant will be accessible from Tecnalia though a cloud storage system and VPN (Virtual Private Network) are in consideration. Bearing in mind the Mutriku network configuration and the flexibility of access that cloud storage system gives, probably will be the option selected.

There are two testing possibilities for testing in the test bench the resource from Mutriku: Online, directly connecting the Tecnalia's test bench and Mutriku, or keeping input data from Mutriku and running offline the test bench. For the two options additional sensors should be installed in Mutriku, mainly the turbine torque must be measured, through installation of strain gauges.

### 5.4.2 Failure data analysis

The operation data of the Mutriku Wave Power Plant have been collected since its early years of operation of the facility. In addition to the aforementioned testing activities, a post-analysis of the failure events happened during the operation of the power plant can be also conducted by using the available data.

The currently available data cover measurements coming from different sensors installed along the power plant and are described in Section 6, and parameters registered by the power electronics. In addition, Table 6 summarizes the most relevant signals monitored in the Mutriku Wave Power Plant.

*Table 6: Open access signals in the Mutriku Wave Power Plant.*

| Signal | Source | Unit | Type | Scale | Max.Scan Rate |
|---|---|---|---|---|---|
| Active Current | VFD | A | INT | x10 | 10 Hz |
| Automatic* | PLC | - | INT | - | 10 Hz |
| Avg. Power 1 min | PLC | W | INT | x1 | 10 Hz |
| Avg. Power 5 min | PLC | W | INT | x1 | 10 Hz |
| Damper Position | Sensor | º | INT | x1 | 10 Hz |
| Drive Healthy** | VFD | - | INT | - | 10 Hz |
| Generator Speed | VFD | rpm | INT | x1 | 10 Hz |
| Output Voltage | VFD | V | INT | x1 | 10 Hz |
| Output Frequency | VFD | Hz | INT | x10 | 10 Hz |
| Overload Accumulator | VFD | % | INT | x10 | 10 Hz |
| Percentage Load | VFD | % | INT | x10 | 10 Hz |

| | | | | | |
|---|---|---|---|---|---|
| Power | VFD | kW | INT | x1000 | 10 Hz |
| Chamber Pressure | Sensor | Pa | INT | x1 | 10 Hz |
| Reactive Current | VFD | A | INT | x100 | 10 Hz |
| RMS Pressure | PLC | Pa | INT | x1 | 10 Hz |
| Vibration | Sensor | mmps | | x1000 | 10 Hz |
| *Only available on certain turbines* | | | | | |
| Winding Temperature | Sensor | ºC | INT | x10 | 10 Hz |
| Water Level | Sensor | m | INT | x1000 | 10 Hz |
| Differential Pressure 1 | Sensor | Pa | INT | x1 | 10 Hz |
| Differential Pressure 2 | Sensor | Pa | INT | x1 | 10 Hz |
| Outlet Pressure | Sensor | Pa | INT | x1 | 10 Hz |

**Indicates different states of operation within state machine (number code)*
***Indicates the state of VFD (digital)*

In this sense, In October 2018 one of the generators showed a short-circuit event in one of the windings, the only failure event of this kind occurred during the 10-years operation of the power plant.

In order to assess the input conditions during the failure event and try to estimate the cause of the cause of the fault, time series of chamber pressure and generator power have been analysed in order to determine the evolution of input and output conditions during the previous 14-days period to the generator fault. Figure 22 shows the RMS chamber pressure and the average output power of the degraded generator recorded in the days leading up to the failure event.

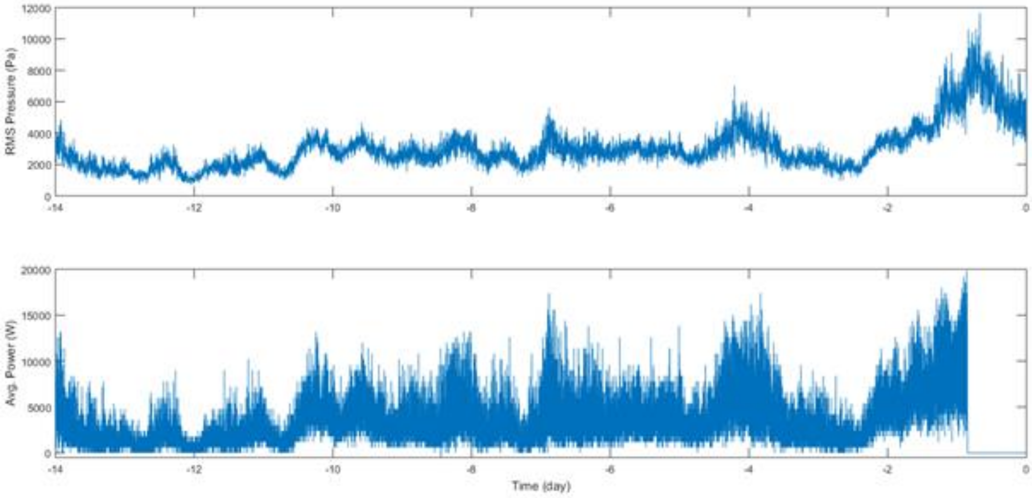


*Figure 22: Time series of the chamber pressure and generator average power prior fault*

From this analysis it can be concluded that at the time of insulation fault the amount of average power supplied by the generator was similar to the rated power, which demonstrated that the generator was working above its rated capacity if the instantaneous power is considered. However, this analysis cannot be used to determine that the cause of the failure was related to the overloading of the generator as squirrel cage-type induction generators should easily be able to manage such power levels without suffering excessive overheating in their windings.

Unfortunately, the generator that suffered the fault was not fitted with temperature sensors on the generator windings so that this information remains unavailable and cannot be used to assess the temperature conditions during the fault.

As next steps, available data might be used to apply different data analysis methods in order to assess the cause of the event failure that might be helpful when designing the accelerated tests to be performed within this User Case. In this sense, the knowledge on data analysis acquired by some VALID partners might be very helpful in carrying out the analysis.

# 6 Requirements for Upgrading Mutriku Site and Tecnalias's Test Bench

Section 5 defined the different kind of tests that will be performed in the UC#2. For this purpose, available testing facilities will have to be updated to provide them with the needed capabilities.

A preliminary analysis of the requirements is performed in this section. It will be updated in *D4.2: Description of User Case 2 hybrid testing platform* when the tests are completely defined and a detailed test plan is developed.

## 6.1 Mutriku site

### 6.1.1 Constraints

Despite of having been commissioned as demonstration project for wave energy generation and its supply to the power grid, some OWC chamber positions were upgraded with additional sensors and equipment to house testing activities of novel concepts of turbines and different equipment used in OWC technology, but limited to demonstrate their capacity on power conversion, controllability and reliability. However, a proper thermal fatigue analysis of the generator requires additional features to be monitored, both from electrical and mechanical point of view.

Furthermore, the turbogenerator system at Mutriku is not fully fitted with sensors as, as it has been mentioned above, the main purpose of the Mutriku project at early stage was to set up a commercial power plant able to produce electricity from waves, without considering the opportunity this meant to conduct different technology-related tests. For this reason, the sensors and monitoring equipment installed in the power plant were designed to provide necessary inputs to the control system to keep the correct operation of the turbogenerators and power electronics, as well as to provide electrical and mechanical protection to the overall system.

Figure 23 shows the current configuration of one of the turbogenerator set at Mutriku Wave Power Plant. Sensors that are already available in Mutriku have been indicated in black. However, there are many operation parameters that to date have not been properly measured but may help to understand the operation of the turbine, and for this particular case, help to clarify the thermal ageing process that a generator might suffer when it is operating under such demanding conditions as it happens in OWC-based devices. In this sense, additional sensor that might be added to the already existing measurements have been identified divided into three main areas: pneumatic (blue), mechanical (yellow) and electrical (red) parameters. There are plenty of possibilities to measure each parameter and in this section the most used solutions are analysed. However, in the following task (T4.2.) the usefulness of each solution will be evaluated to address the objectives pursued in this UC#2 and the technical suitability of each solution will be further analysed. Hence, the new measurements that will be included as inputs will help estimate the thermal process of the generator, and thus they may contribute to a more exhaustive analysis.

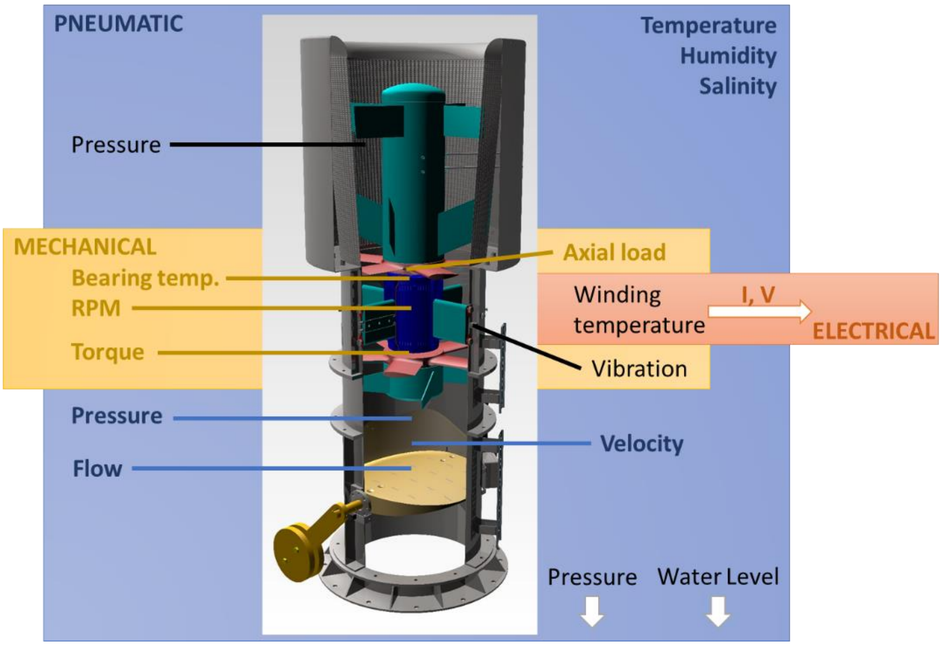


*Figure 23: Turbogenerator set in Mutriku. Already available sensors (black) and other sensors that might be installed.*

However, the Mutriku Wave Power Plant shows a number of constraints that should be taken into account before starting to plan different tests under this UC#2. Some of the constraints might be solved with an adequate upgrade of the test rig, whereas other limitations shall be assumed and, if so, some tests could only be conducted in Tecnalia's test bench.

Some of the constraints that have been identified at this stage are:

- The limited number of sensors that monitor the turbogenerator and pneumatic chamber. Some parameters such as chamber pressure or vibrations are properly monitored with sensors that provide sufficient quality, precision and reliability. However, many other parameters are not measured by adequate and precise sensors and meters (e.g. output current, frequency...) or simply some are still not monitored (e.g. output voltage, airflow, rotational speed, torque...). This issue could be addressed by the acquisition of proper sensors and/or meters.
- The turbogenerator and its housing at Mutriku have very specific and exclusive distribution that makes almost unique. Related to the previous limitation, this makes the installation of additional sensors often difficult as minor changes can only be made over the housing structure. That is to say, the original design must be kept to the extent possible and the sensors can only be placed in empty spaces around the turbogenerator. In addition, the number of moving parts makes the installation of cables difficult, for instance in the case of torque transducer. The selection of the generator to be used during test campaigns is also bound to its structural design (shape and size), otherwise major changes might be required. To overcome this limitation a deep analysis is required to select best choice that shows the best feasibility both technically and to be delivered on time and within available budget.
- The rated power of the variable frequency drive that controls the generator is large enough to operate the turbogenerator system under desired conditions and operating point. Nevertheless, to pursue the objectives established in this User Case, the capacity of the drive could fall short if it is intended to operate with peaks three times the nominal power of the generator. In such a case, the turbogenerator should be carefully operated in order to

prevent an irreversible early damage, or failing this, such tests should be conducted in Tecnalia’s test bench.

- The Mutriku Wave Power Plant operates at given input conditions as the sea conditions cannot be controlled. This limits the time period in which desirable input conditions can be obtained for the purposed of this User Case. Furthermore, the non-controllable and variable input conditions might make testing campaigns time-limited and to be conducted mostly during winter season. The inability to reproduce desirable input conditions also make it difficult to conduct appropriate accelerated life tests. For this reason, Tecnalia’s test bench is initially deemed more appropriate to conduct accelerated tests.
- The communication and DAQ system in Mutriku are based on a fieldbus topology that makes it difficult an adequate and reliable data handling if a remote access to the data is desired. This requires and exhaustive analysis of possible solutions as significant modifications on communication system topology (new system topology and use of communication protocols) might be required.

### 6.1.2 Upgrade requirements

Taking into account the constraints described in the previous section, the measurement of some relevant parameters is deemed necessary to pursue the objectives of this UC#2. For this purpose, the existing test rigs in both Tecnalia and Mutriku shall need to be improved by including additional sensors and, if any, expanding capabilities to conduct tests that are hardly doable with the existing equipment.

This section aims to review the operating parameters that are deemed interesting to pursue the objectives established under this case study. However, the technical feasibility of different solutions described in this section has not been addressed yet. This analysis is estimated to be concluded by the beginning of the next task.

#### *6.1.2.1 Generator*

Discussion on the size and type of generator to be tested has been extensively addressed. The use of smaller rated generator seems to show real benefits in front of higher rated generators so that they can be subjected to high power peaks of several time the rated value of the generator most of the time.

However, the structural design of the generator hinders the installation of other generators that are reduced in size as the flange, housing and key way of the shaft were designed for the specific generator model currently employed in Mutriku. Furthermore, the significant axial forces due to bidirectional airflow happening in Mutriku require deep analysis when assessing the suitability of the use of a smaller generator while keeping the same structure. Otherwise, a complete replacement of the turbogenerator might be necessary.

On the other hand, as it has been mentioned in the previous section, there exists some limitations both in input conditions and equipment that may limit at some extent the set of tests that are achievable at Mutriku Wave Power Plant. Nevertheless, generators that are currently being used in Mutriku seem to be the most suitable solution to address the requirements of the user case and the selected generator for Tecnalia’s test rig would mimic at a reduced scale the same behaviour of the generator installed at Mutriku. In this sense, the selection of the generator to be installed in the test rig, if different, requires special attention if the performance of the test rig is intended to be validated with Mutriku’s data.

Conversation has been open with the generator manufacturer to check the possibility of acquiring an instrumented generator fitted with sensors, (e.g. encoder, winding and bearing temperature sensors, torquemeter) that are not available in the currently employed generators in Mutriku and might be useful to provide as much information as possible about the behaviour of the generator.

#### 6.1.2.2 *Electrical parameters*

A proper monitoring of electrical parameters may have a significant impact when analysing the generator behaviour, especially if the analysis is mainly focused on generator windings. No measurement is currently available between the generator and the variable frequency drive in Mutriku. Measurement on currents is provided by the VFD but all of them are r.m.s. values obtained from three-phase instantaneous values. Therefore, the measurement accuracy might not follow the existing rules and standards for types of analysis required in this user case as the only purpose in Mutriku is to provide protection of the VFD and generator. In addition, voltage as well as frequency are referenced according to V/f control rather than measured.

With the lack on the measurements in three-phase voltage and current, sufficiently relevant estimation on generator thermal fatigue can barely be obtained being difficult reaching meaningful conclusions. In addition, the AC current cycles and harmonics, of the cause of thermal ageing of the generator, can hardly be analysed if r.m.s. values are considered.

In this sense, a suitable power analyser should have the following features to meet the test requirements to be conducted:

- Capacity to measure voltages and currents up to 1 kV and 200 A, respectively.
- Capacity to measure harmonics up to 5 MHz.
- Precision of 0.03%.
- Communication interface to monitor the data in continuous mode.

#### 6.1.2.3 *Mechanical parameters*

In order to characterize the turbogenerator system of Mutriku in the most reliable way possible and to mimic its behaviour on a laboratory test rig, it is deemed necessary to measure some mechanical parameters, namely torque and rotational speed, present in the turbo-generator system.

The turbogenerators in the Mutriku Wave Power Plant are not fitted by an appropriate encoder to measure the rotational speed of the turbine. The control of the turbogenerator is based on an open-loop scheme, so that the encoder is not required. To monitor the rotational speed of the system the estimation is based on the frequency produced by the generator. However, this estimation does not consider the slip of the generator and thus an error is assumed in the estimation. For this reason, installation of a suitable encoder is deemed appropriated in order to have actual measurement of the rotational speed rather than an estimation.

The main constrain in the encoder installation is that the generators in Mutriku are double shaft so that drive and non-drive ends are not clearly defined and due to the adjusted design little space is available between the generator and turbine rotor to install the encoder. To this end, the generator manufacturer has been contacted to explore the best option to install an encoder that measures the rotational speed of the shaft. In this particular case two options might be considered, the use of contact or non-contact sensor. The former solution can be approached by the use of hollow shaft-type sensor that embraces the shaft. This solution requires further analysis due to the reduced space available between the generator and turbine. The latter, however, can be addressed by optical or magnetic encoders. In this case, the presence of moisture and dust require special consideration as well as the installability of the sensor to evaluate their suitability in Mutriku. In general terms, the encoder should be able to operate in rotational speeds up to 4500 or 5000 rpm.

The second measurement which might provide necessary inputs to the laboratory test rig and help to validate the existing models is the torque measurement. This parameter might be considered of the vital importance to evaluate the input conditions of the generator. However, the installation of the torquemeter is often difficult for several reasons:

- Some solutions require the installation of the sensor in the middle of the shaft and thus the shaft must be split in two parts acting the sensor as joint element between both sections. Due to operating conditions in Mutriku this solution may not meet the mechanical requirements to ensure a safe operation.
- Axial loads in OWC might be significant and, in addition, are bidirectional increasing the mechanical stress of the sensor.
- The system comprises many moving parts in which the sensor must be installed, thus difficulting the cable junction.

In this context two types of torquemeters have been considered, namely the reaction torque transducer and strain gages. The former has been concluded to be unfeasible solution for Mutriku as these sensors often have large dimensions that make them unsuitable due to the reduced space in the turbogenerator system of Mutriku. In addition, the reaction torque transducer must be placed between the generator and turbine through an intrusive solution that would consist in cutting the shaft in two sections which may lead to significant loss of shaft rigidity and consequently the integrity of the entire turbogenerator system. Furthermore, some studies agree that the reaction torquemeter may produce undesirable vibrations.

For this reason, an initial tests has been performed to check the functionality of the strain gages concluding that their use can be feasible for the application. A future test is envisaged to introduce the gages in the Mutriku power plant.

#### *6.1.2.4 Pneumatic parameters*

The measurement of the pneumatic parameters could provide useful information when assessing the operating conditions of the turbogenerator. Thus, the input parameters to the turbo-generator system can be more accurately characterised and might help to estimate in a more reliable way possible some parameters that are difficult to measure, for example the generator torque. Furthermore, in Oscillating Water Column devices that generators are not often fitted with forced cooling system and the air through the turbogenerator is normally used to cool the generator. Therefore, the influence of the airflow passing through the turbogenerator might have a strong impact when the thermal behaviour of the generator is assessed.

The main two types of sensors that might be used in OWC systems are differential pressure flow sensors and thermal mass flow sensors. The former measures the airflow velocity based on differential pressure. In such cases, a single pressure sensor, e.g. venturi or pitot tube and orifice plates, is placed at the inlet of the turbine duct and measures the pressure at this position. Similarly, other pressure measurement is taken in another point of interest. Once the sensor determines the pressure difference, Bernoulli's equation can be used to estimate the airflow velocity. The later, however, uses thermal properties of a fluid that basically absorbs thermal energy and measures the amount of energy in the fluid, thus estimating the flow. The slower the air flows, the more time the energy has to transfer from the heating element. These sensors can be extremely precise and reliable.

### 6.1.3 Conclusions

The Mutriku Wave Power Plant offers a unique opportunity to analyse the performance of Oscillating Water Column devices operating under real conditions. The plant was commissioned as a demonstration project, whose main objective was to produce electricity from waves and supply it to the local power grid. For this reason, the sensors and equipment installed in the power plant were designed to provide necessary inputs to the control system to keep the correct operation of the turbine, as well as to provide electrical and mechanical protection to the overall system.

Therefore, the existing equipment might not allow a deep analysis of the thermal behaviour of the generator as many internal parameters (such as airflow, rotational speed, torque…) are not measured and the accuracy of other parameters (such as currents, voltage, rotational speed…) might not be enough to draw any relevant conclusion. For this reason, installation of new more precise sensors and meters could contribute to improve the accuracy and reliability of the measurements, being necessary to make all the necessary arrangements in the turbo-generator housing for that purpose.

## 6.2 Tecnalia's Test Bench

After analysing the possible tests, there are some modifications on the test bench that should be completed before starting the tests. First of all, the generator to be tested should be defined and installed. Since the main objective is to study the behaviour of a generator with power input up nominal power (3 times max ), smaller generator of nominal $P_{nom}$=5kW power its being in consideration (the motor is a 15kW LSMV160LV-T). Currently , there is an additional inertia in the shaft of the test bench, the operational requirements of the new generator should be known in order to decide to eliminate this additional inertia.

Going deeper on the tests, some extra instrumentation must be installed: Current sensor on the stator of the generator, flow sensor, temperature sensor, the torque is to be measured through installation of strain gages in the shaft connecting the generator with the motor. Gages will be installed configured in a diamond shaped schematic, each at 45º with the axis of the shaft and connected in a wheatstone bridge arrangement. The new sensors will be included as an input in a Simulink model throughout a NI data adquisition target (NI-DAQmx 15.0).

# 7 Preliminary Test Plan for UC#2

Three kind of tests have been envisaged within the UC#2 and have been described in Section 5:

1. Diagnostics tests – MCSA: will determine the condition of the generator insulation at the beginning of the tests and give information about the degradation during the accelerated tests. There is an ongoing work on how to calibrate the generator degradation / failure model postprocesing sensors information.
2. Accelerated tests: will apply to the generator the most damaging conditions to accelerate the degradation process.
3. Condition monitoring tests – inputs from Mutriku power plant: allow the record of real data to be applied in the test bench.

The detailed testing plan will be developed in the following task (T4.2). However, the first testing activities have already been foreseen:

- Start up the test bench: During the last years, different groups have used the test bench in several projects adapting its functionalities for their needs. An initial set up has been already done during T4.1 to ensure the current configuration is the most suitable for the User Case. The test bench is now working with the wave to torque model of Mutriku power plant, and at the time of writing this report, it is being adapted to the model described in section 4.2.1.
- Following the analysis of Section 6, define the sensors that finally can be added in Mutriku power plant. Send the selling orders to buy and install them.
- Define and create a cloud to collect the data obtained from the Mutriku sensors and enable the data sharing.
- Validate numerical performance models of the generator (and the thermal one if any) - as soon as the bench is with its sensors running. This can be first done with the existing generator.
- Validate that the architecture that is finally agreed with AVL is working as it should - with numerical / bank / Mutriku data.
- Specify type and quantity of generators needed for the tests.
- Launch test tests with what is already in the bank and in Mutriku with the hybrid platform and evaluate first results

Once the previous activities have been carried out, both, testbench and Mutriku power plant will be ready for the User Case tests. The first step will be to perform diagnosis tests to understand the suitability of the MCSA techniques and have a first feedback of the generator status. Diagnosis tests, as explained in Section 5.2 are just a monitoring technique that can be continuously giving information about the status of the generator so once validated, they will be active during the whole testing phase of the User Case.

# 8 Conclusions

The particular operation of an electric generator presented on the current user case as part of IDOM’s MARMOK WEC and its consequent degradation is to be analysed on the current WP. This use involves the generator to endure load peaks several times over its nominal power, an unusual situation among the industry and whose consequences are still to be studied. By means of the hybrid testing philosophy of the VALID project, an investigation of the degradation of the generator during its operation on the MARMOK technology is to be conducted.

A review of the state of the art of the known failure modes of an electric generator has been analysed, putting the focus on the failure of the insulation, which has been identified in both, the literature and partner’s experience, as one of the most likely ones. This degradation process is influenced by several stresses, whose exact contribution and interrelation appears to be very complex to quantify. However, a thermal origin (thermal cycling) or consequence (a defect on the insulation) has been identified on the different degradation mechanisms analysed.

Regarding the appropriate standards to be applied on the user case, a lack of particular regulation for marine energy devices has been found, mainly regarding the effect of environmental conditions on an electric machine as the generator studied on the current project. However, other related standards have been identified for its application due to their similarities. The detailed design of the aging tests and its acceleration process will be driven by the regulation presented on Section 3.

For the sake of the achievement of a hybrid identity, an introduction on AVL’s Model.CONNECT™ and Testbed.CONNECT™ platforms has been conducted. These platforms will be responsible for the communication between the numerical and physical components of the testing. Starting from a Matlab-SIMULINK model of the chamber of the Mutriku Wave Power Plant divided on the different subsystems of the plant, such as the air chamber or the electric generator, its equivalent Model.CONNECT™ version has been developed and validated. The separation of the model into its different subsystems eases a potential substitution of any of them by their physical equivalent.

While the detailed specifications of the testing campaign are still to be defined, a roadmap thereof has been built. Aiming an understanding on the degradation introduced on the insulation by a harmful power peak, a set of characterization tests are to be conducted, in which generic peaks will be introduced varying some significative parameters. This sensitivity analysis will enable the development of an analytical degradation model, which later is to be validated with a real-condition time series introduced on Tecnalia’s test-bench. The accelerated essence of the testing campaign will be introduced by a pre-processing work, in which the damaging sea conditions are identified for its reproduction on the testbench and the scaling of the characterization tests.

The combination of the flexibility of Tecnalia’s testbench and the possibility of having test in real sea conditions that Mutriku power plant supposes a very good opportunity for achieving a good understanding of the degradation process that a generator would have while operating on IDOM’s MARMOK. However, for a correct conduction of the tests, Mutriku power plant presents a great necessity of upgrading its facilities and the main aspect to be improved has been related to its sensoring. Similarly, Tecnalia’s testbench has also been identified to require an increment of its sensoring capabilities, besides the need of acquiring several electric generators for its testing.

# 9 Nomenclature

## Abbreviations

| | |
|---|---|
| AFE | Active Front End |
| BEM | Boundary Element Method |
| EC | European Commission |
| EU | European Union |
| H2020 | Horizon 2020 |
| MCSA | Motor Current Signal Analysis |
| MWPP | Mutriku Wave Power Plant |
| OWC | Oscillating Water Column |
| PD | Partial Discharge |
| PTO | Power Take-Off |
| SCIG | Squirrel Cage Induction Generator |
| SWL | Surface Water Level |
| UC | User Case |
| VFD | Variable Frequency Drive |
| VPI | Vacuum Pressure Impregnation |
| VPN | Virtual Private Network |
| WEC | Wave Energy Converter |
| WP | Work Package |
| UC | User case |
| IEEE | Institute of Electrical and Electronics Engineers |
| ULS | Ultimate Limit Stress |
| MRE | Marine energy renewable |
| DNV | Det Norske Veritas |
| IEC | International Electrotechnical Commission |
| FMEA | Failure Modes and Effects Analysis |
| TTF | Time to failure |
| Etc | Et cetera |
| NI PCI | National Instruments Peripheral Component Interconnect |
| FMECA | Failure mode effects and criticality analysis |
| SCIG | Squirrel Cage Induction Generator |
| FFT | Fast Fourier Transform |

## Variables

| | |
|---|---|
| A | area |
| $\sigma$ | Stress |
| Hz | Hertz |
| kW | Kilowatt |
| Hs | Significant wave height |
| Te | Energy period |
| Fpto | Force of power take off |

# 10 References

[1] L. M. Monge-Guerrero and A. A. Irizarry-Rivera, 'A degradation model of synchronous generator stator insulation', in *Proceedings of the 37th Annual North American Power Symposium, 2005.*, Ames, IA, USA, 2005, pp. 281–286. doi: 10.1109/NAPS.2005.1560539.

[2] S. Grubic, J. M. Aller, Bin Lu, and T. G. Habetler, 'A Survey on Testing and Monitoring Methods for Stator Insulation Systems of Low-Voltage Induction Machines Focusing on Turn Insulation Problems', *IEEE Trans. Ind. Electron.*, vol. 55, no. 12, pp. 4127–4136, Dec. 2008, doi: 10.1109/TIE.2008.2004665.

[3] G. C. Stone, Ed., *Electrical insulation for rotating machines: design, evaluation, aging, testing, and repair*. Piscataway, NJ : Hoboken, NJ: IEEE ; Wiley-Interscience, 2004.

[4] D. G. Cain, 'A review of Equipment Aging Theory and Technology', p. 464.

[5] H. Pham, Ed., *Springer handbook of engineering statistics*. London: Springer, 2006.

[6] D. S. Peck, 'COMPREHENSIVE MODEL FOR HUMIDITY TESTING CORRELATION', p. 7.

[7] C.-P. Malliou, A. Karlis, M. G. Danikas, and B. Lloyd, 'The effect of water droplets and salinity on the offshore wind turbines windings insulation: A short review', in *2015 IEEE Industry Applications Society Annual Meeting*, Addison, TX, USA, Oct. 2015, pp. 1–7. doi: 10.1109/IAS.2015.7356928.

[8] I. Touzon, V. Nava, Z. Gao, I. Mendikoa, and V. Petuya, 'Small scale experimental validation of a numerical model of the HarshLab2.0 floating platform coupled with a non-linear lumped mass catenary mooring system', *Ocean Eng.*, vol. 200, p. 107036, Mar. 2020, doi: 10.1016/j.oceaneng.2020.107036.

[9] F.-X. Faÿ, E. Robles, M. Marcos, E. Aldaiturriaga, and E. F. Camacho, 'Sea trial results of a predictive algorithm at the Mutriku Wave power plant and controllers assessment based on a detailed plant model', *Renew. Energy*, vol. 146, pp. 1725–1745, Feb. 2020, doi: 10.1016/j.renene.2019.07.129.

[10] S. Jamet, 'NEMOH-Presentation', *LHEEA*. https://lheea.ec-nantes.fr/logiciels-et-brevets/nemoh-presentation-192863.kjsp?RH=1489593406974 (accessed Oct. 27, 2019).

[11] 'ANSYS Aqwa | Hydrodynamics Simulation & Diffraction Analysis'. https://www.ansys.com/products/structures/ansys-aqwa (accessed Oct. 27, 2019).

[12] 'Wamit, Inc. - The State of the Art in Wave Interaction Analysis'. https://www.wamit.com/ (accessed Dec. 19, 2019).

[13] G. Duclos, A. H. Clement, and G. Chatry, 'Absorption of Outgoing Waves in a Numerical Wave Tank Using a Self-Adaptive Boundary Condition', *Int. J. OFFSHORE POLAR Eng.*, vol. 11, pp. 168–175, 2001.

[14] R. P. F. Gomes, J. C. C. Henriques, L. M. C. Gato, and A. F. O. Falcão, 'Hydrodynamic optimization of an axisymmetric floating oscillating water column for wave energy conversion', *Renew. Energy*, vol. 44, pp. 328–339, Aug. 2012, doi: 10.1016/j.renene.2012.01.105.

[15] A. F. O. Falcão, L. M. C. Gato, and E. P. A. S. Nunes, 'A novel radial self-rectifying air turbine for use in wave energy converters. Part 2. Results from model testing', *Renew. Energy*, vol. 53, pp. 159–164, May 2013, doi: 10.1016/j.renene.2012.11.018.

[16] A. F. de O. Falcão and R. J. A. Rodrigues, 'Stochastic modelling of OWC wave power plant performance', *Appl. Ocean Res.*, vol. 24, no. 2, pp. 59–71, Apr. 2002, doi: 10.1016/S0141-1187(02)00022-6.

[17] F.-X. Faÿ *et al.*, 'Comparative assessment of control strategies for the biradial turbine in the Mutriku OWC plant', *Renew. Energy*, vol. 146, pp. 2766–2784, Feb. 2020, doi: 10.1016/j.renene.2019.08.074.

[18] Oscar Poncelas López, 'Diagnóstico de motores de inducción mediante la adquisición de corrientes de estator con sonda Rogowski', Tesis Máster Ingeniería Electrónica.

[19] Samotics, *Electrical signature analysis explained*.

[20] 'Popa et al. - Current Signature Analysis to Diagnose Incipient F.pdf'.

[21] 'Joksimovic y Penman - 2000 - The detection of inter-turn short circuits in the .pdf'.

[22] J. Wood, *Local energy: distributed generation of heat and power*. London: Institution of Engineering and Technology, 2008.

[23] 'Identifying Mechanical Faults with Motor Current Signature Analysis'. https://www.reliableplant.com/Read/28633/motor-current-signature-analysis (accessed Jun. 23, 2021).

[24] C. Sumereder, 'Statistical lifetime of hydro generators and failure analysis', *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 678–685, Jun. 2008, doi: 10.1109/TDEI.2008.4543104.

[25] '2_Brief_Review_of_Motor_Current_Signature_Analysis.pdf'.

[26] 'Stone - Electrical Insulation for Rotating Machines.PDF'.

[27] J.-H. Jung, J.-J. Lee, and B.-H. Kwon, 'Online Diagnosis of Induction Motors Using MCSA', *IEEE Trans. Ind. Electron.*, vol. 53, no. 6, pp. 1842–1852, Dec. 2006, doi: 10.1109/TIE.2006.885131.

[28] 'Andicoberry - Current signature analysis to diagnose doubly-fed .pdf'.