

# Experimental assessment of condition monitoring techniques for an OWC electrical generator operating at overload

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## ABSTRACT

Traditionally, the nominal power of a generator in renewable energy converters is determined based on its maximum mechanical input power within the drive train. Implementing this procedure for Wave Energy Converters would result in a generator operating well below its nominal power, leading to prolonged periods of suboptimal efficiency depending on the location of the device.

Generators are generally engineered to manage brief periods of overload. Consequently, opting for a smaller generator and permitting it to function above its nominal power can be a viable strategy. However, it is essential to carefully evaluate the limits and operational durations specific to each application. Enhancing the operational speed may result in increased vibrations, while boosting the torque can elevate the temperature of the stator winding. This temperature rise can eventually compromise the insulation of the stator winding, leading to potential failure.

At the present work, an overload operational regime of a generator, under the special operation mode of the MARMOK-Idom Oscillating Water Column (OWC) Wave Energy Converter (WEC), will be evaluated at overload till the end of its life. The testing procedure uses an “accelerated testing” concept, introducing consecutive representative power peaks instead of real wave trains, reflecting the probable mechanical power peak magnitudes and durations to simulate real conditions. Several generator condition monitoring alternatives will be evaluated to identify the best option to detect and predict a future failure of the generator stator winding, such as Electrical Signature Analysis, Park’s Vector Approach, or direct monitorization of stator temperature and insulation. Through an appropriate condition monitoring technique, a stator winding degradation model will be developed, which could assist in the sizing phase of the generator’s nominal power in future designs, as well as in making decisions to modify the control law based on the degradation of the generator during the operation of the wave energy converter.

## 1. Introduction

The recent Net Zero Roadmap outlined by the International Energy Agency (IEA), elucidates that meeting the imperative to limit global warming to 1.5 °C necessitates a multifaceted approach [1]. The IEA underscores the magnitude of the challenge, emphasizing the necessity to triple the global installed renewable energy capacity by 2030 [2]. The harnessing of wave energy represents a pivotal frontier in the pursuit of sustainable and renewable energy sources [3]. The EU Strategy on

Offshore Renewable Energy set deployment targets for ocean energy of 100 MW by 2025 and 1 GW by 2030 [4]. Wave energy converter devices are tasked with the formidable challenge of converting the kinetic energy of waves into usable electricity, thereby contributing to the diversification of the energy portfolio.

However, amidst the promise of this technology lies a critical operational concern, the maintenance and longevity of WECs. The harsh marine environment, characterized by corrosive salt water, dynamic wave forces, and unpredictable weather patterns, poses a formidable challenge to the structural integrity and performance of these

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### Nomenclature

|               |                                              |
|---------------|----------------------------------------------|
| <b>B2B</b>    | Back To Back                                 |
| <b>CF</b>     | Capacity Factor                              |
| <b>DC</b>     | Direct Current                               |
| <b>EPVA</b>   | Extended Park's Vector Approach              |
| <b>ESA</b>    | Electrical Signature Analysis                |
| <b>EU</b>     | European Union                               |
| <b>FF</b>     | Failure Frequency                            |
| <b>FFT</b>    | Fast Fourier Transform                       |
| <b>IEA</b>    | International Energy Agency                  |
| <b>IEC</b>    | International Electrotechnical Commission    |
| <b>IPSA</b>   | Instantaneous Power Signature Analysis       |
| <b>MCSA</b>   | Motor Current Signal Analysis                |
| <b>MW</b>     | Megawatt                                     |
| <b>MWPP</b>   | Mutriku Wave Power Plant                     |
| <b>OWC</b>    | Oscillating Water Column                     |
| <b>PTO</b>    | Power Take Off                               |
| <b>RULVSA</b> | Remaining Useful LifeVoltage Signal Analysis |
| <b>WEC</b>    | Wave Energy Converter                        |

installations [5]. Traditional maintenance approaches, often reliant on scheduled inspections and reactive repairs, are both cost-intensive and potentially unreliable in this context.

The variability of wave energy is a crucial consideration in the design of WECs because it directly affects the converter's efficiency, reliability, and overall performance [6,7]. The power harnessed from the sea by WECs shows considerable variability. For instance, Oscillating Water Column (OWC)-based WECs exhibit a peak-to-average power ratio of 4.5–5 [8]. This ratio can rise to 7 or more for point absorbers depending on the control strategy employed [7]. There are two main mechanisms for controlling the mechanical input power: A valve on the chamber [9] or a valve in series with the turbine such as in the Mutriku Wave Power Plant (MWPP) [10,11,12].

It has been established that optimum energy absorption from a single mode of oscillation unconstrained WEC in regular seas can be achieved when the following two conditions are fulfilled [13]: i) The device oscillating velocity must be in phase with the wave excitation force (automatically satisfied if the body is in resonance with the wave); ii) The amplitude of the oscillation must be adjusted to the optimum value where absorbed power equals the power radiated into the sea by the oscillating device. The result of optimal control is that a small portion of the energy must be returned to the sea during certain parts of each oscillation cycle. For this reason, many developers lean towards low-inertia rotational shafts. Despite this option seems promising in terms of increasing the energy capture range, it has the disadvantage of absorbing high peaks of energy, and the generator is one of the PTO components that suffer the most.

Typically, the nominal power of a generator for renewable energy converters is defined at its maximum mechanical input power on the drive train. However, for wave energy devices, this procedure would imply a generator size that operates below its nominal power with reduced efficiency for extended periods, due to the high variability of the wave resource. Some studies present the option to operate the generator in OWCs above its nominal power such as [14] and [15]. Another study, [16], showed how the relative increment of annual energy production (AEP), varying  $P_{nom}$  and  $P_{max}$  is interesting for device optimization.

Operating the generator above nominal torque implies increasing the temperature of the stator winding, at its thermal limit in a wave energy converter becomes an option to maximize the power absorption with optimal efficiency [17]. At this special operational regime, the temperature of the stator will increase over the limit and bearing in mind that

50 % of machine failures are caused by winding insulation failure [18], condition monitoring, and insulation degradation model emerge as a strategic paradigm shift.

Diagnostic tests such as insulation resistance, polarization index, dissipation factor, capacitance and partial discharge can be useful to diagnose the condition of the stator winding insulation and identify many problems that could lead to insulation failure. However, these tests alone cannot predict the remaining life of a winding [19]. Predicting the remaining life of stator winding insulation is complex due to [19,18]:

- The existence of over 20 different winding insulation failure processes, making it unrealistic for a single test to detect all these mechanisms.
- The varying speed of failure processes, with some like end winding discharge being slow and others like vibration sparking or slot discharge being relatively fast. These mechanisms can produce similar high PD or high tip-up values.
- The actual moment of failure depending not only on the reduced mechanical and electrical strength of the winding but also on the applied stresses. Often, failure time is associated with a voltage or current transient that exceeds the strength of the winding in its deteriorated condition.
- Some common failure processes, such as end winding vibration leading to insulation cracking or abrasion, not changing any known dielectric property, except breakdown strength. Without knowledge of the transient environment, reasonable estimates of remaining life will be very imprecise.

Detecting inter-turn faults at their early stages is challenging because they do not significantly affect the terminal currents [20], the difficulty is further compounded when attempting to detect these minor faults online. Fault diagnosis techniques, usually have been demonstrated by introducing the short turns directly on the generator such as in [21], or for example in [22], where the fault was identified throughout EPVA method but not in the specific degradation process associated with the user case. In other studies such as [23], the estimation of electrical insulation have been completed with not the real input mechanical power in the generator.

The objective of this research is the condition monitoring alternatives evaluation and the generator behaviour study at overload regime under the specific operating conditions of the case study of the MARMOK-Idom [24] OWC, which will cause the stator winding failure. Moreover, a degradation model will be developed based on the temperature measurements obtained from real mechanical input power peaks.

To achieve this, a 3 kW small-scale generator has been operated in a controlled test bench under a variable load regime tailored to this particular case study until the end of its operational life. The tests aim to analyse the thermal operational limits of the generator and assess the effectiveness of different condition-monitoring techniques under this particular operational mode.

The manuscript is structured as follows: Section 2 presents the condition monitoring alternatives evaluated. Section 3 introduces the case study, the wave energy converter, the test bench description, and the methodology for the definition of the mechanical input power with the “accelerated testing” concept. Section 4 presents the condition monitoring results and the comparative analysis of the different techniques, and, finally, Section 5 gathers the conclusions.

## 2. Generator condition monitoring alternatives

The implementation of condition monitoring can be instrumental in the successful execution of predictive maintenance strategies for WECs. This approach provides an increase in availability by facilitating early fault detection, which consequently leads to well-timed maintenance.

This minimizes downtime and reduces operational costs [25], ensuring efficient and reliable renewable energy generation [26]. The currently integrated wave device monitoring systems have been developed based on existing technologies and advancements from the wind energy sector and other industries [27]. There are several options for condition monitoring a generator depending on the possible failure [28,29,30]. Fig. 1 provides a summary of the condition monitoring options, categorized based on the type of failure that needs to be identified:

The focus of the current study is on monitoring and detection of insulation faults within the operational regime of MARMOK-Idom WEC. For this, several monitoring alternatives will be tested. Each of these approaches is elaborated upon in the section.

### 2.1. Electrical Signature analysis (ESA)

This methodology encompasses a range of techniques for monitoring the condition of electrical machines by analysing electrical signals, including current (MCSA) and voltage (VSA). MCSA is a methodology to detect and diagnose faults or abnormalities in the generator. It relies on the principle that the current waveform carries information about its condition and performance. VSA is a similar methodology, which analyses the voltage of the three phases.

To develop a correct MCSA the current signal must be analysed using appropriate techniques and methodologies [32]–[33]. The first step involves acquiring the current signal from the generator. This can be achieved by using current sensors, such as current transformers or clamps, which are placed around the generator's conductors. Afterward, techniques such as Fourier analysis or wavelet transforms are used to identify the spectral content of the current signal. This spectral analysis aids in detecting specific frequencies or harmonics associated with faults including rotor misalignment, unbalance, bearing defects, broken rotor bars, stator winding faults, air gap eccentricity, and gearbox damage [24,25,34,35,36,37]. Once the signal has been pre-processed, comparative analysis starts by comparing the acquired current signal with reference or baseline data. This can be achieved by creating a database of healthy motor signatures or utilizing historical data. The final step involves diagnosing the identified deviations or anomalies in the current signal. By correlating the observed patterns with known fault signatures, specific generator faults can be accurately identified.

Faults in the stator winding, such as short circuits, turn-to-turn faults, can be detected by deviations in the current signature. This identifica-

tion is made with the frequencies obtained from the expression [32] as follows:

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

Where  $f_{sw}$  is the Stator winding failure frequency,  $k$  is the stator winding constant ( $k = 1, 2, 3, \dots$ ),  $n$  is a constant ( $n = 1, 2, 3, \dots$ ),  $f_s$  supply frequency,  $p$  pole pairs, and  $s$  slip.

VSA can also be a useful technique for identifying potential future failures in a generator. While MCSA primarily focuses on analysing the current waveform, VSA involves analysing the voltage waveform to detect abnormalities and predict failures [31]. Similar to the previous method, establishing a baseline voltage is crucial. This involves recording and analysing the voltage waveform during normal operating conditions when the generator is known to be in a healthy state. The results provide a reference for future comparisons. By monitoring the voltage waveform over time, deviations from the established baseline can be detected. Significant variations in voltage amplitude, frequency, waveform distortion, or voltage unbalance can indicate potential issues within the generator.

### 2.2. Park's vector approach (PVA) and extended Park's vector approach (EPVA)

Park's vector approach has been developed to enable multiple fault diagnosis in induction motors [38]. The methodology combines information from three-phase currents into two equivalent currents using Park's or Clark's transformations. This can be represented as follows [39]:

$$i_\alpha = \sqrt{\frac{2}{3}} i_a - \frac{1}{\sqrt{6}} i_b - \frac{1}{\sqrt{6}} i_c; i_\beta = \frac{1}{\sqrt{2}} i_b - \frac{1}{\sqrt{2}} i_c \quad (2)$$

Where  $i_a, i_b, i_c$  are the 3 phases.

If the system is in a healthy state, the three-phase currents remain balanced, causing Park's vector to trace a circular trajectory in the alpha-beta plane. However, when the system deteriorates, the three-phase currents exhibit some degree of imbalance, resulting in the Park's vector trajectory transforming into an ellipse.

EPVA builds upon the traditional Park's Vector Approach [31,40]. However, EPVA advances further by incorporating sophisticated signal

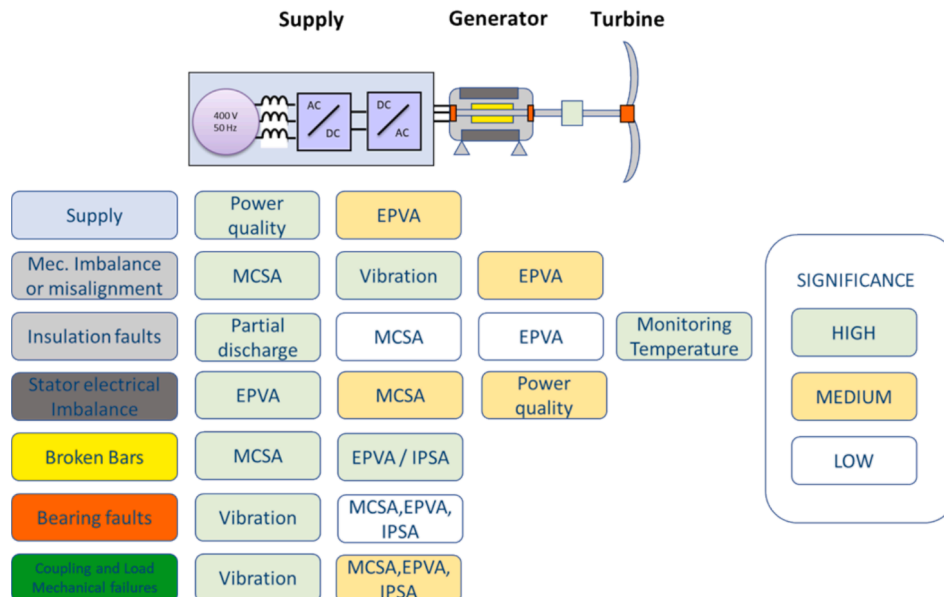


Fig. 1. Wave energy converter drive train condition monitoring options, based on [31].

processing algorithms and computational methods to detect various types of faults in the generator including issues with the stator winding, rotor, and air gap eccentricity. By observing changes in the vector patterns, abnormalities can be identified. EPVA technique can diagnose the inter-turn fault, by monitoring the (2f) component in the park current spectrum [41,38,42].

### 2.3. Direct measure of the insulation

The measurement of stator winding insulation degradation in a generator presents multiple challenges. Direct assessment is often hindered by the insulation being embedded within the winding structure and the harsh operating conditions, including high temperatures and electrical stresses, which accelerate aging and complicate the identification of degradation. Despite these challenges, there are some alternatives for measuring the insulation degradation:

- Partial Discharge (PD) measurement is used to detect and monitor partial discharges within insulation materials. Utilizing sensors to detect PD within the insulation is a common approach being those indicative of insulation degradation.
- The Megger instrumentation is employed for regular measurement of insulation resistance, and it can reveal its integrity. A decrease in insulation resistance over time may indicate degradation. However, this method might lack sensitivity in detecting localized or early-stage faults. It operates by applying a high voltage (usually DC) to the component under test. Some examples are the M70 megohmmeter [43], and ISOMETER [44].

### 2.4. Thermal monitoring and insulation degradation model

Thermal stresses that cause the breakdown of winding insulation have been identified as a significant factor, contributing to approximately 30–40 % of stator winding failures in traditional induction machines [45], therefore it is of paramount importance to conduct a thorough thermal characterization when operating a generator at over-torque conditions to have a stator winding degradation model to quantify remaining life.

The torque produced by the generator is directly proportional to the current passing through its windings (IEEE Std 620™-1996 (R2008) [46]) and the temperature of the stator is directly influenced by the current. This current can be maintained at high levels for brief periods until the temperatures of the windings reach a threshold where the

insulation may break down or damage to the windings may occur, as illustrated in Fig. 2, where X axis refers to generator current capacity factor [0–1] and y axis to generator operational limit time. Capacity factor (CF) is defined as the ratio of the electrical power output produced by the generator with the nominal power of the generator.

Nevertheless, each overload surpassing the thermal limit results in loss of motor lifespan. On the other hand, IEEE Std 620™-1996 [46] also clarifies that thermal limit curves do not represent the motor's capacity to handle overloads and should not be used as a basis for planning operations under high loads.

The relationship between temperature and material longevity is often explained using the Arrhenius equation, which suggests that even a minor increase in temperature can significantly accelerate degradation rates. This concept is encapsulated in the “Rule of 10 °C,” referenced in various standards such as IEEE Std 117–2015 [47] and IEEE Std C37.101–2006 [48].

This rule is a general principle stating that for numerous chemical reactions, including those associated with material degradation, a rise in temperature of 10°C approximately reduces a 50 % the life of the material.

Under thermal stress, insulation degrades due to irreversible alterations in the chemical composition and physical properties of its organic materials [49], so that lifetime can be expressed as follows:

$$\ln(L) = -kt + \ln(L_0) \quad (3)$$

Where  $t$  is time and  $k$  is the Arrhenius reaction relationship [50], which can be represented as follows:

$$k = Ae^{-(E/RT)} \quad (4)$$

here  $A$  is the frequency constant,  $E$  is activation energy,  $R$  is gas constant and  $T$  is Temperature. Considering this relation, the equation can be rewritten [51] to represent real-time lifetime varying temperature:

$$\ln\left(\frac{L}{L_0}\right) = -C_1 t e^{-\frac{C_2}{T}} \quad (5)$$

Where  $L$  is lifetime,  $L_0$  is the initial lifetime,  $C_1$  and  $C_2$  constants, which can be adjusted from standards [47], literature [51,52] or tests, like at the present study in section 4.5.2.

## 3. Case study definition

This section presents the case study, starting with a brief overview of the MARMOK-Idom WEC, including the various energy transformation steps and the generator's operational parameters. The following subsection describes the test bench where the experiments will be conducted. Finally, the methodology for selecting mechanical input power peaks for the accelerated tests is outlined.

### 3.1. WEC description

For this study, the the MARMOK-Idom WEC [24] has been used. The device operates on the principle of the OWC (Fig. 3 presents de energy transformation steps). It consists of a partially submerged chamber opened to the ocean. As waves approach the device, they enter the chamber, causing fluctuations in the water level within the device. This cyclical movement results in the compression and expansion of the air within the chamber moving an air turbine.

As mentioned before, the mechanical input power is variable in this WEC. The excess mechanical input power at the test, has been absorbed by the generator, thereby maintaining nominal speed while increasing the nominal torque ( $T_{g,nom}$ ) to its maximum torque ( $T_{g,max}$ ). Fig. 4 represents the operation region of the generator torque, where the green line represents the operational range of the generator during these tests per generator rotational speed ( $\Omega$ ).

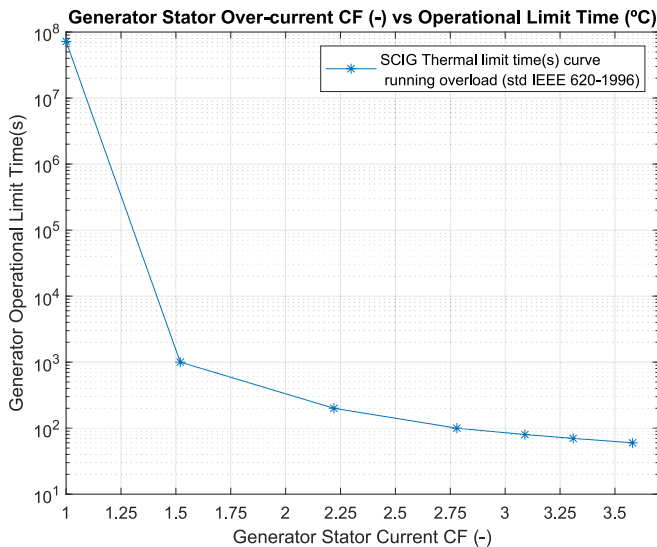


Fig. 2. Typical thermal limit curves for SCIG, based on IEEE 620–1996 [46].

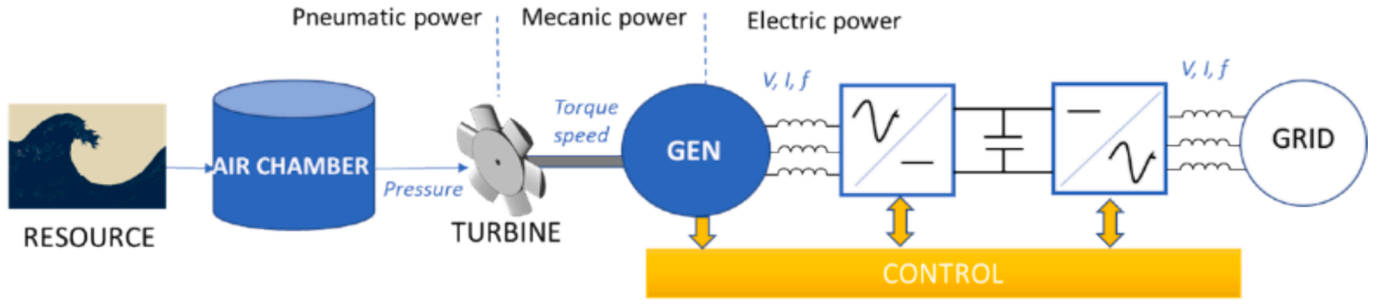


Fig. 3. The MARMOK-Idom WEC energy transformation steps.

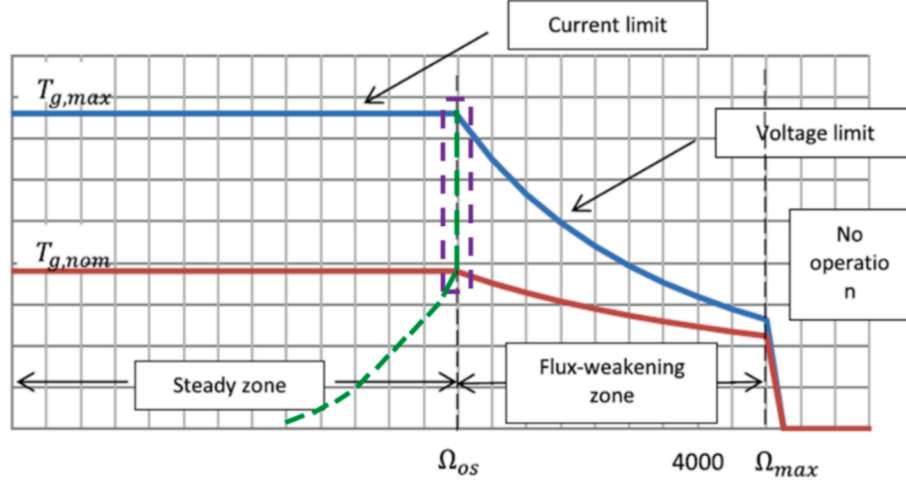


Fig. 4. Generator torque operation ranges (based on [14]) per rotational speed ( $\Omega$ ). Blue line: maximum torque (Nm), Red line: Nominal Torque (Nm), Green line: new control law optimizing electrical power.

### 3.2. Test bench description

The test bench used [53], replicates the rotational-mechanical output of a WEC. This is achieved through a numerical model representing the primary energy conversion processes, including hydrodynamic-mechanical interactions, ultimately generating a motor torque or speed reference. Fig. 5 depicts the schematic diagram of the test bench, including sensors and data acquisition equipment:

The motor area is composed of the LSMV160LU-T 15 kW motor, the

LS UMV4301 frequency converter to control the motor, and the motor control software (CT-soft V01.14.02). These components aim to emulate the behaviour of the WEC under different operational conditions. The emulation occurs through the programming of mathematical equations in the motor control software, enabling it to replicate the behaviour of the WEC.

The generator area includes a 3 kW squirrel cage induction generator (SCIG) supplied by OBEKI [55], the frequency converter (ABB ACS-800 with window drive light software) to control the generator, and a

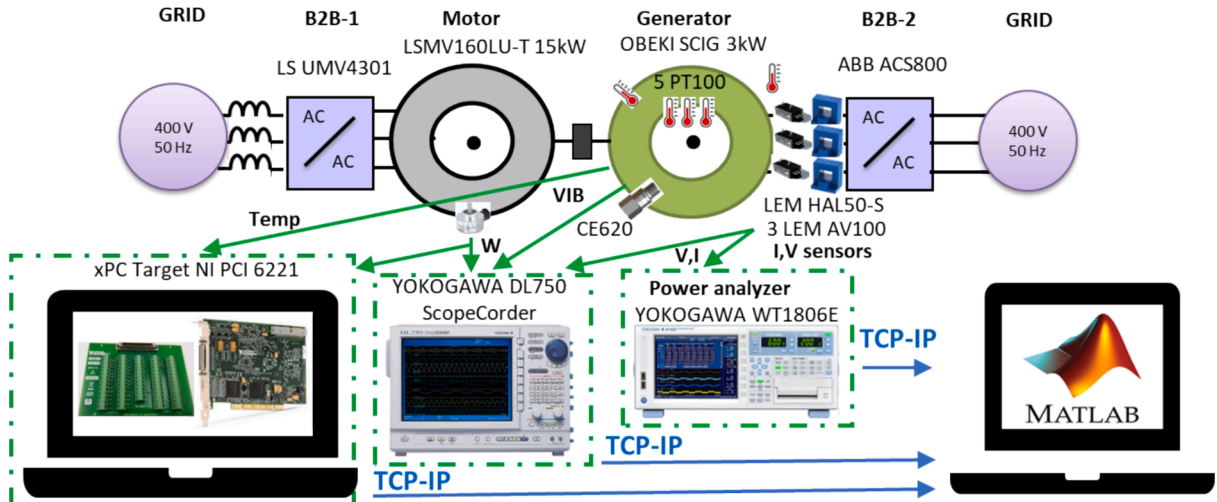


Fig. 5. Test bench General scheme and data acquisition systems [54].

Beckhoff PLC with the generator and B2B control state machine. This part represents the current equipment that could be placed between the hydrodynamic-mechanical transformation and the grid within the WEC system. Table 1 describes the main features of the electrical generator [55] under test:

In terms of instrumentation, the YOKOWAGA DL750 ScopeCorder [56] was utilized primarily for recording Voltage and Current data from sensors at a frequency of 1 kHz. Additionally, an xPC Target NI PCI-6221 [57] was employed to acquire data from temperature sensors and transmit the torque reference. In Table 2 a detailed description of the sensors used for the tests is given:

### 3.3. Definition of accelerated tests

An in-depth analysis of real and simulated WEC time series has revealed that the mechanical input power peaks are not individual, usually arrive in trains, in such a way that several peaks are repeated during various semi-periods of waves and then there are no peaks for a certain time per sea state. No relationship has been found between the number of peaks in a train and the power of the peaks or the sea state that produced them. The same can be said for rest time between trains.

Proceeding to the tests to be completed, a representative case of the analysis conducted to the peaks has been defined to be tested in the test bench. Instead of a real wave trains, bearing in mind the hypothesis that just the peaks over nominal power induce over-temperature and damage in the generator stator insulation, consecutive power peaks will be introduced, on an accelerated testing procedure concept. The peaks to be introduced are a representation of the most probable peaks for the generator to face on a real application of MARMOK-Idom device, introducing different peak magnitudes with their respective durations and time between them using the polynomial obtained for their representation.

The characterization of mechanical input power peaks has been performed using an occurrence matrix obtained from wave resource data spanning decades of real sea conditions specific to the BIMEP location [62]. This matrix provides information regarding the probability of occurrence of waves with specific conditions, such as significant wave height and peak period. The available sea states, characterized by these two parameters, have been clustered into 30 groups by considering adjacent sea states from the occurrence matrix. This clustering process establishes the energy of each group by weighting the energy of individual sea states within them. For hardware-in-the-loop simulations, the first sequences of wave trains were generated with different seeds. These wave trains have been inputted into the hydrodynamic model of the MARMOK-Idom device, which translates them into displacements of the main degrees of freedom. The computation of the main parameters in the air chamber, based on the heave motion of the buoy and the oscillating water column, determines the power extracted by the air turbine. Fig. 6 shows the summary of dimensionless peak power for BIMEP locations at 6 different  $H_s$ .

The peaks time series used in the test campaign (description in Annex 1) of the generator have been divided into 3 different peaks amplitudes (0.5–1–1.75) at 6 different mean capacity factors (1.2–1.3–1.4–1.5–1.6–1.8), which respect the nominal power of base

**Table 1**  
The main features of the electrical generator.

| Parameter     | Unit | Value   | Parameter       | Unit | Value |
|---------------|------|---------|-----------------|------|-------|
| Rated power   | kW   | 3       | N° of phases    | –    | 3     |
| Voltage       | V    | 230/400 | Pole number     | –    | 4     |
| Frequency     | Hz   | 50      | Enclosure       | –    | IP 55 |
| Rated torque  | Nm   | 21      | Isolation class | –    | F     |
| Speed         | Rpm  | 1565    | Duty service    | –    | S1    |
| Cos phi       | –    | 0.78    | Cooling         | –    | IC411 |
| Efficiency    | %    | 87.7    | Connection      | –    | D/Y   |
| Rated current | A    | 11/6.4  | Weight          | kg   | 38.5  |

**Table 2**  
Available sensors at the test bench.

| Type        | Number | Detail                                                     | Position                                                             |
|-------------|--------|------------------------------------------------------------|----------------------------------------------------------------------|
| Current     | 3      | Hal 50-S [58]                                              | Sensor at each phase of generator                                    |
| Voltage     | 3      | LEM AV100 [59]                                             | Sensor at each phase of generator                                    |
| Temperature | 5      | PT100-3 wire [60] and temperature transmitter SEM206P [61] | At generator, at each phase stator winding, one at case, one ambient |

dimension of generator. The typical energetic sea state of BIMEP has a wave period of 12 s, so its half-period is 6 s. The half-period for all individual peaks has been set to 2 s after applying the scale factor of 3. This scale has been decided based on the cooling curve constant relation between 75 kW (full scale nominal power defined by IDOM) and 3 kW Test bench generator, obtained by ANSYS software.

One of the primary objectives of the test campaign is to compare the performance of the 3 kW generator with a larger generator from an operational real WEC. To ensure comparability, the power peaks associated with the waves were scaled in time, maintaining thermal inertia equal in both environments. Each test has been conducted until a stable temperature of the stator winding was achieved.

To create the peaks time series with varying amplitudes, a mean peak has been generated. The analysis involved discretizing the magnitude of power peaks and identifying the polynomial that best represents each band. An average power was then defined between the peaks identified in each strip and the nearest peaks were utilized to define the polynomial that best represents them via least squares regression. This process resulted in a 7th-degree polynomial.

Consequently, peaks have been generated to ensure representation for each condition (description in Annex 1). The first five peak series have been designated for testing purposes and do not adhere to the same structure as the rest of the time series. Similarly, an additional peak series with extreme classifications (21\_Peaks defined at Annex 1) was incorporated.

## 4. Condition monitoring results and discussion

This section first presents a summary of the tests completed till the end of the generator's life. The following subsections present the results of the monitoring techniques applied. The discussion begins with the results derived from Electrical Signature Analysis, MCSA, and VSA techniques. This is followed by the findings from the direct measurement of insulation and partial discharge measuring approach. The section concludes with the outcomes from temperature monitoring and the corresponding degradation model developed based on these temperature measurements.

### 4.1. Tests results summary

A total of 84 mechanical input power tests were conducted until the end of the generator's operational life, with 29.58 % of the test campaign operating at over torque levels exceeding 100 % of the generator CF. Among these, 30 tests utilized constant mechanical input power peaks, while 54 tests employed variable mechanical input power peaks. In Fig. 7 a summary of the operational hours at different temperature regions of stator, constant, and variable mechanical input power is presented, where Thermal Limit is 155 °C and Breaking Limit is 220 °C, based on generator insulation class F characteristic.

Fig. 8 represents the exposure time (h) vs Stator Winding temperature (°C) with constant and variable mechanical input power.

The consequence of operating the generator at over torque has been the degradation of the insulation. This failure can be observed in Figs. 9 and 10

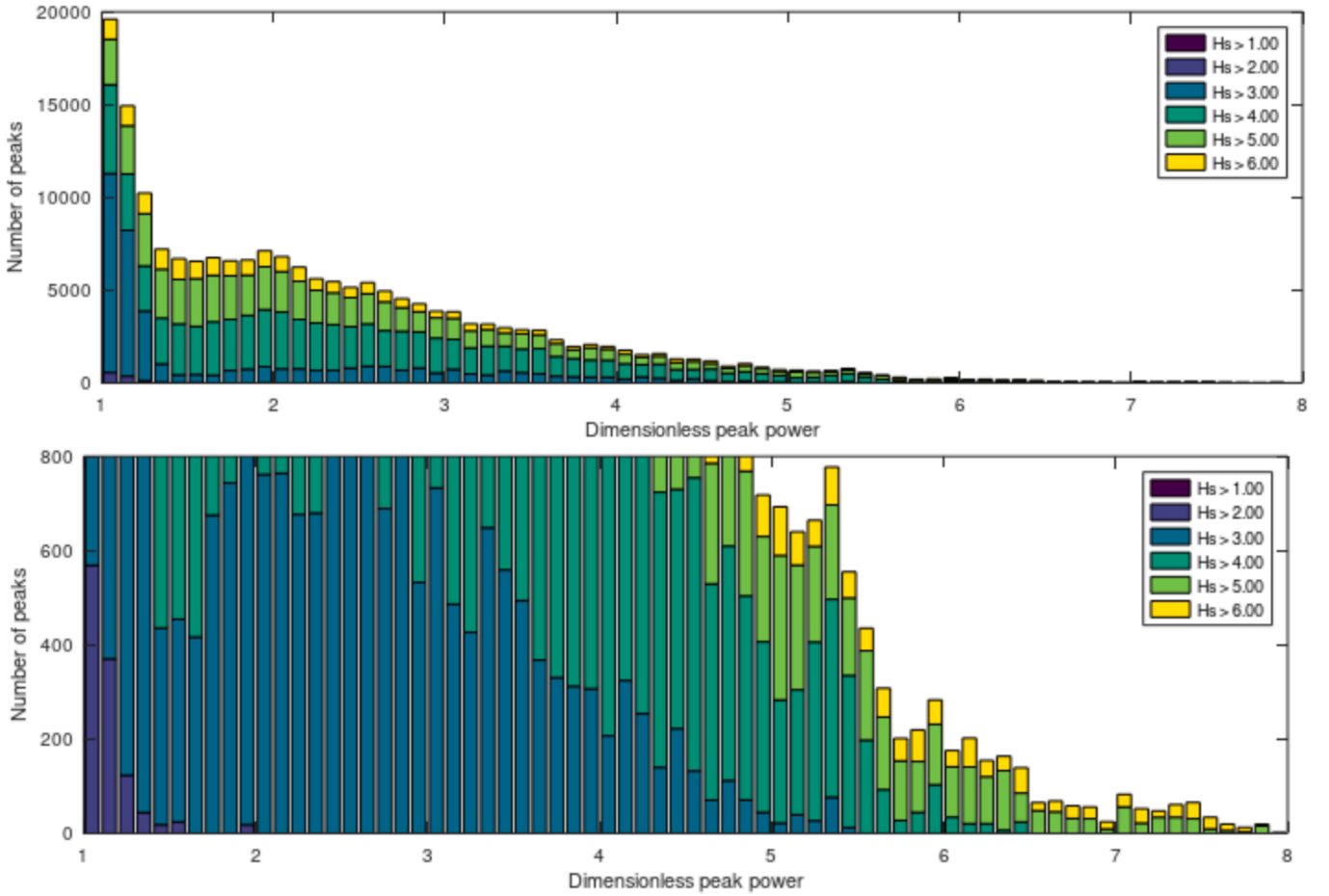


Fig. 6. Histogram of the number of peaks at various powers for one year in BiMEP.

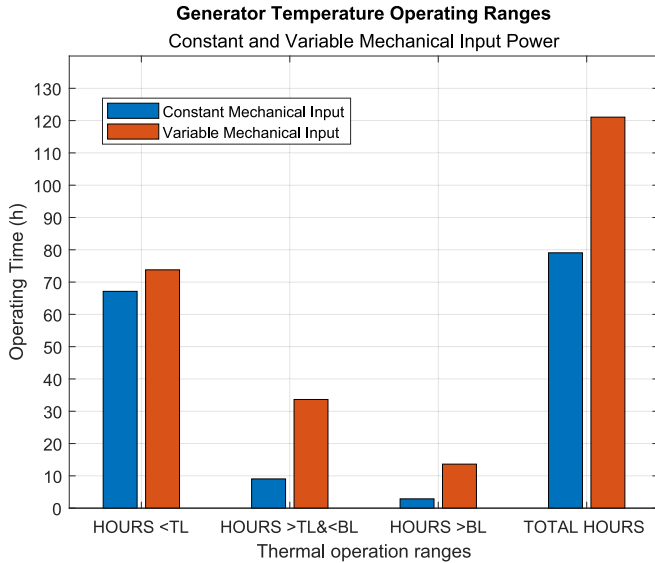


Fig. 7. Summary of tests operational hours at different temperature regions of the stator. Constant and variable mechanical input power. (TL: Thermal Limit, BL: Breaking limit).

#### 4.2. Electrical Signature analysis

At this section results from MCSA and VSA area presented. Based on equation (1), and the methodology described in section 2.1, stator

winding failure frequencies have been identified. The methodology, consist of identifying and analysing failure frequencies based on a healthy Base test. Fig. 11 represents the periodogram of the current signal using FFT (Fast Fourier Transform) at the beginning of the tests, where it can be appreciated how there are no significant amplitudes at the stator winding failure frequencies. From the other hand, at final test monitorization, it can be appreciated how several stator winding failures have been detected.

Table 3 summarizes the calculated fault frequencies depicted in the periodograms of current (MCSA) and voltage (VSA) with a slip frequency of  $f_s = 48.7213$  Hz and a rotational frequency of  $f_r = 24.9939$  Hz.

Regarding the evolution of the MCSA failure frequency peaks, several monitorization tests have been completed during the test campaign. Fig. 12 represents the evolution, where it can be appreciated that depending on the test the evolution of the failure frequency peaks is not ascended in all the tests completed, but yes the periodicity of frequencies and the number of harmonics increases.

About VSA, Fig. 13 represents the periodogram of voltage using FFT at the beginning of the tests and the generator's final life. While numerous frequencies have been identified, the peaks are not pronounced, making it challenging to discriminate real faults from stator voltage supply imbalances [63].

In conclusion, both MCSA and VSA detect the failure frequencies, but MCSA failure frequency peaks are much more consistent than VSA failure frequencies. Regarding the evolution of failure frequency amplitudes, the results are not consistent enough to predict the failure in advance or to develop a stator winding degradation model.

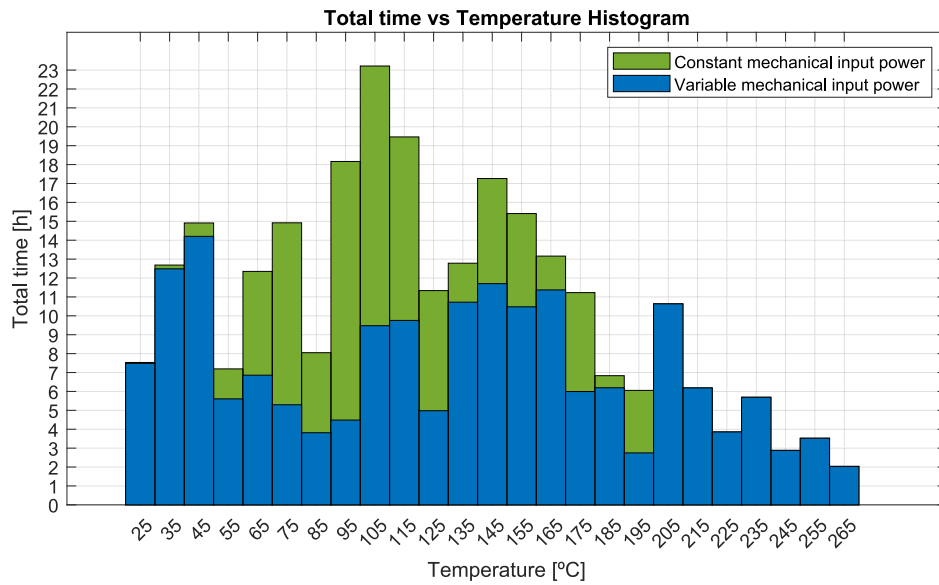


Fig. 8. Exposure time (h) vs Stator Winding temperature (°C) with constant and variable mechanical input power.

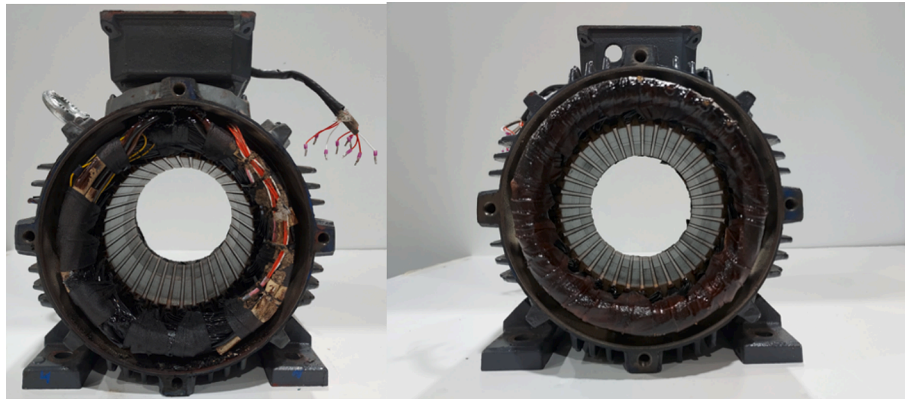


Fig. 9. Picture of the broken generator and stator windings, front and back.

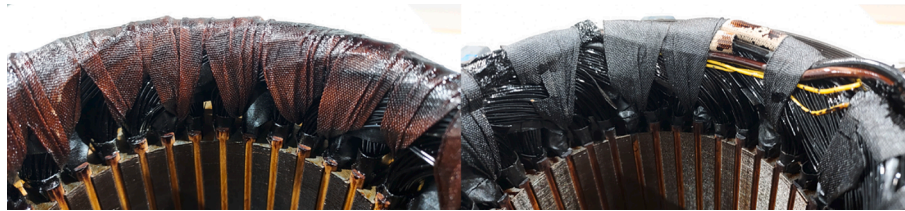


Fig. 10. Detail of the insulation, front, and back position of the generator.

#### 4.3. Park's vector approach (PVA) and extended Park's vector approach (EPVA)

In this section, the evolution of the results of PVA and EPVA monitoring techniques is presented. Fig. 14 represents the current and PVA results comparative between healthy and damaged generator. It can be observed that the healthy generator presents a set of balanced three-phase currents (left side of Fig. 14). Consequently, the trajectory that the Park's current vector is following in the alfa-beta plane is circular. On the other hand, in the final test, where the generator is already deteriorated (right side of Fig. 14), the three-phase currents presents a certain degree of unbalance that makes the current Park's vector trajectory to start taking the shape of an ellipse.

Finally, Fig. 15 represents a comparative of EPVA results between healthy (left side of Fig. 15) and deteriorated (right side of Fig. 15) generator. It displays the Fourier harmonic decomposition of the magnitude of the Park's current vector. It can be observed that when the generator is deteriorated, a second harmonic appears on the amplitude of the current vector as a consequence of the unbalance in the currents.

The efficacy of diagnosing stator winding insulation faults throughout unbalance between phases using this approach has been confirmed. However, prediction of the failure in advance is complex, due to the small unbalance observed.

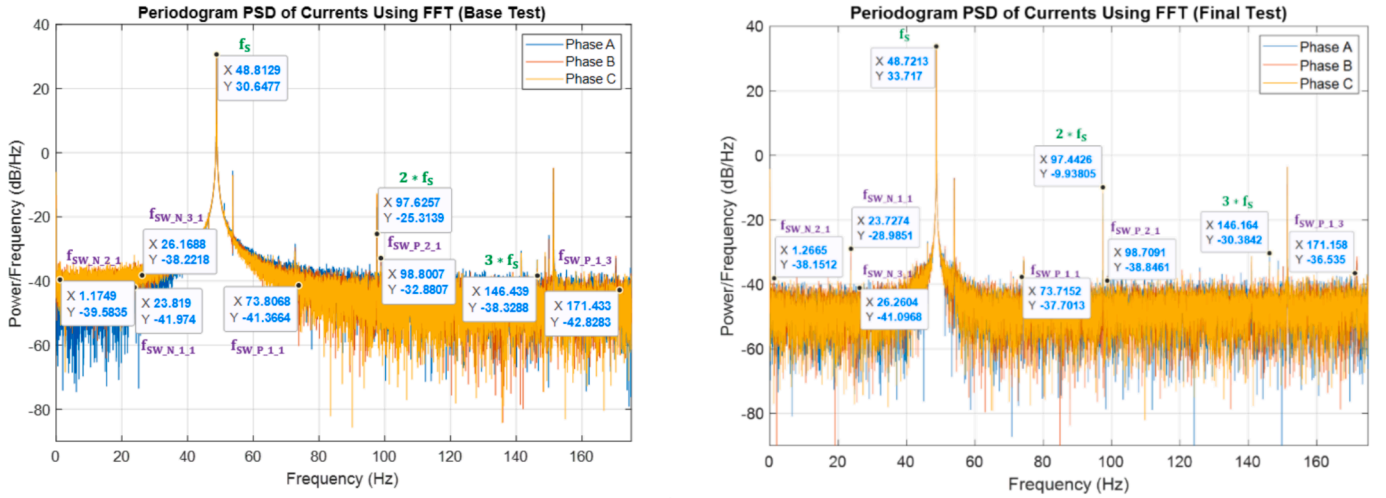


Fig. 11. Periodogram PSD of 3 phases currents using FFT. Initial condition and final condition.

Table 3

Summary of calculated and detected failure frequencies (FF) for MCSA and VSA,  $s = -0.0260$ ,  $f_s = 48.7213$  Hz,  $f_r = 24.9939$  Hz at the latest operative Test.

|                | FFp (Hz) | MCSA | VSA | FFn (Hz) | MCSA | VSA |
|----------------|----------|------|-----|----------|------|-----|
| $f_{SW\_1\_1}$ | 73.7152  | Yes  | Yes | 23.7273  | Yes  | No  |
| $f_{SW\_1\_3}$ | 171.1578 | Yes  | Yes | 121.1700 | No   | No  |
| $f_{SW\_1\_5}$ | 268.6004 | No   | No  | 218.6126 | No   | No  |
| $f_{SW\_2\_1}$ | 98.7090  | Yes  | Yes | 1.2665   | Yes  | No  |
| $f_{SW\_2\_3}$ | 196.1517 | No   | No  | 96.1760  | No   | No  |
| $f_{SW\_2\_5}$ | 293.5943 | No   | No  | 193.6187 | No   | No  |
| $f_{SW\_3\_1}$ | 123.7030 | No   | No  | 26.2604  | Yes  | Yes |
| $f_{SW\_3\_3}$ | 221.1456 | No   | No  | 71.1821  | No   | No  |
| $f_{SW\_3\_5}$ | 318.5882 | No   | No  | 168.6248 | No   | No  |

#### 4.4. Direct measure of the insulation

In this section direct measure of the insulation is presented as condition monitoring method. First, Partial Discharge (PD) procedure has been analysed. For this issue, Montesto 200 [64] equipment has been

tested. In the tests conducted, both capacitive and inductive sensors were used with a high non-desirable level of noise. The noise level was exceedingly high ( $>1\mu C$ ), obscuring any potential underlying occurrences. Typically, partial discharges are around the nC range, which is approximately 1000 times lower. Consequently, this option was ultimately dismissed.

Regarding direct insulation measurement, A M70 megohmmeter [43] has been used for measuring the evolution of the insulation resistance which is a specialized instrument used to measure the insulation resistance of electrical systems. Table 4 provides a summary of the measurements taken at the start and end of the test campaign. A fault was detected between phases U-V, and a significant decrease in insulation was observed between these phases and the casing. Despite periodic measurements, no significant variations were noted until the generator reached the end of its operational life. This could potentially be attributed to the sensitivity of the instrumentation used.

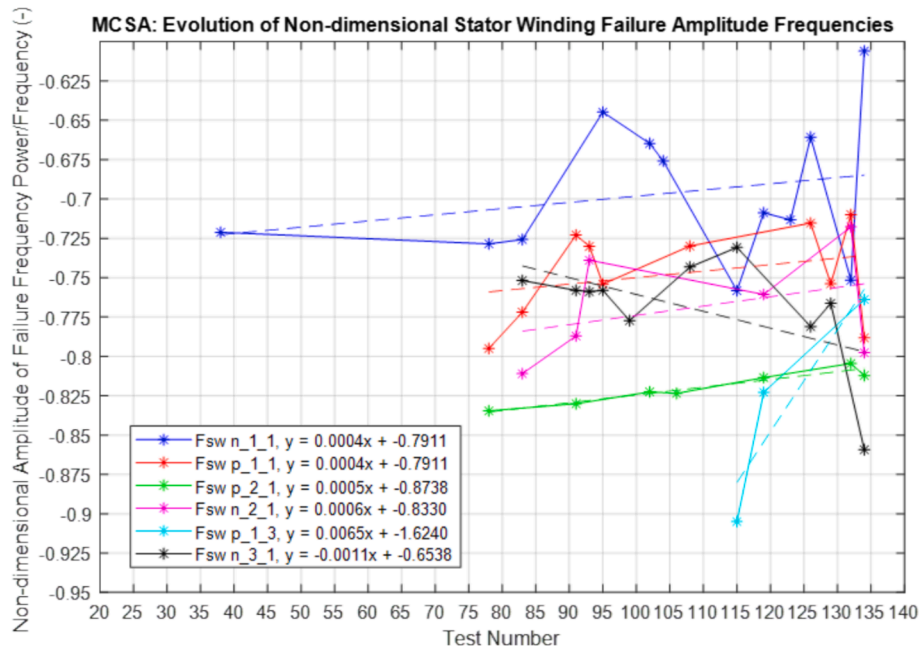


Fig. 12. Failure frequencies peaks evolution during the test campaign.

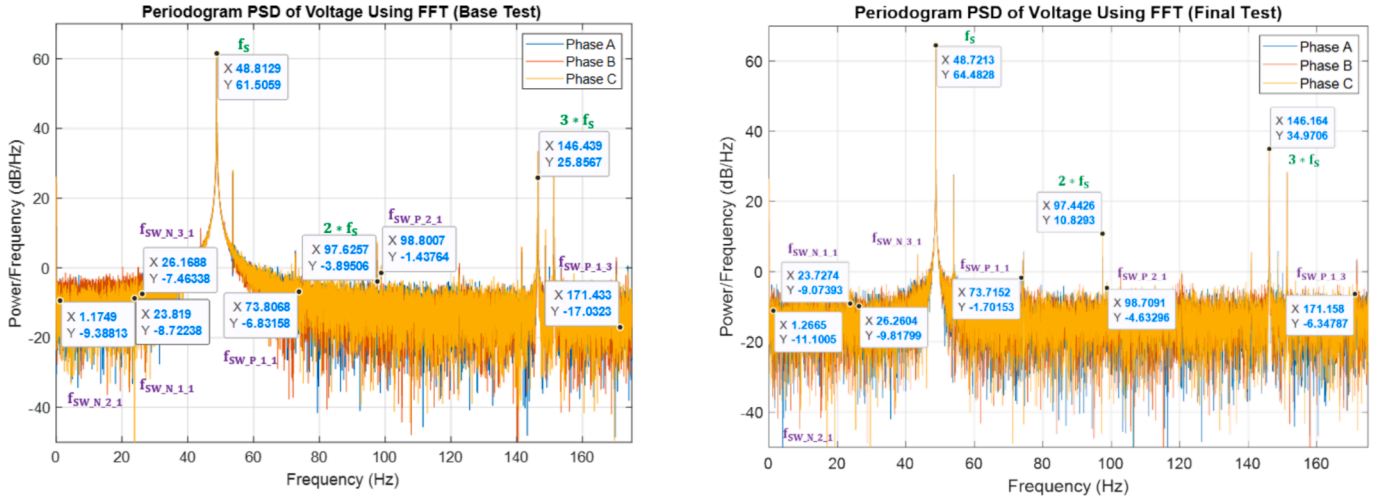


Fig. 13. Periodogram PSD pf 3 phases voltage using FFT. Initial condition. And final condition Annex 1.

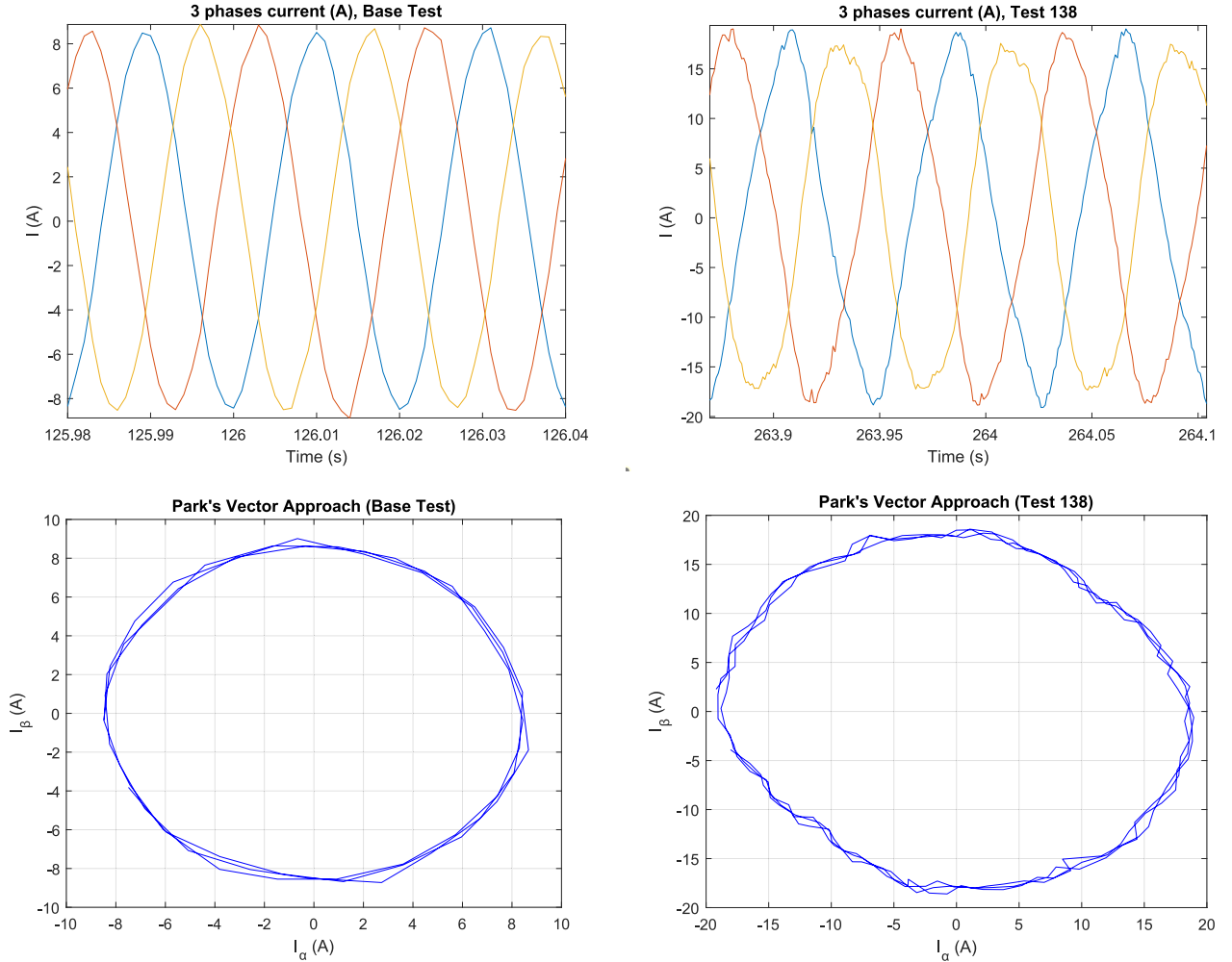


Fig. 14. Current and PVA comparative between healthy and broken generator.

#### 4.5. Thermal monitoring

At this section stator winding temperature monitoring results are presented and based on these results, a degradation model has been completed considering the model explained in section 2.4.

##### 4.5.1. Stator thermal response

The temperature of the generator has been monitored at the stator winding for three phases, as well as the case using PT100 sensors. Fig. 16 represents an example of the generator case temperature after 2.75 h with mechanical input peaks power  $P_{mec} = 1.8 \cdot P_{nom}$  1.8, at nominal

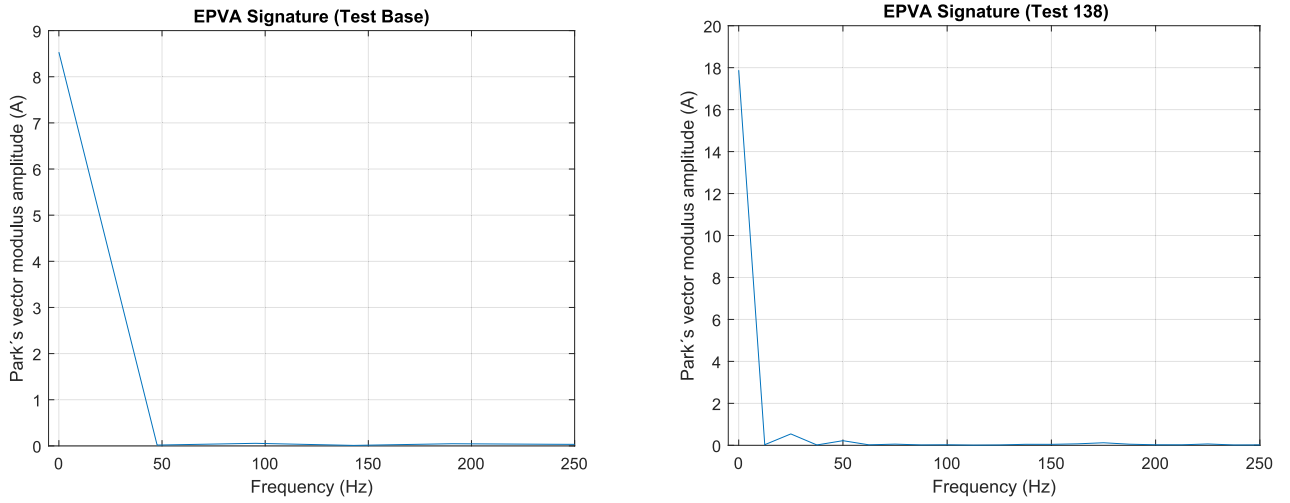


Fig. 15. EPVA comparative between healthy and broken generator.

Table 4

Initial/final insulation measurements with M70 megohmmeter.

| Connection          | Initial measurement ( $M\Omega$ ) | Final measurement ( $M\Omega$ ) |
|---------------------|-----------------------------------|---------------------------------|
| $U_1 - V_1$         | 4000                              | 0                               |
| $U_1 - W_1$         | 4000                              | 4000                            |
| $V_1 - W_1$         | 4000                              | 4000                            |
| $U_1 - \text{case}$ | 4000                              | 303                             |
| $V_1 - \text{case}$ | 4000                              | 325                             |
| $W_1 - \text{case}$ | 4000                              | 4000                            |

speed and with an over torque of  $T_{gavg} = 1.8 \cdot T_{nom}$ :

Fig. 17 represents the thermal response of the generator stator winding for several mechanical power input peaks: 3 different non-dimensional power peak amplitudes with the nominal power (0.5–1–1.75) at 6 different average capacity factors (1.2–1.3–1.4–1.5–1.6–1.8). Each test has been completed till a stable temperature of the stator winding (starting for about 1–2 h, at a low-capacity factor, and more than 4 h at a high capacity factor).

Analysing the results presented in Fig. 17, the temperature increases to different levels depending on the type of power peaks. This means

that depending on the location of the wave energy converter (variability of the resource), the inertia of the PTO, and control law, the thermal behaviour of the generator will change, as thermal cycling, which affects the properties of the material. Summary of thermal results:

- The results of this study show how there is a margin between the temperature of the generator at nominal power and the thermal limit ( $155^\circ\text{C}$ ).
- The generator can operate below the thermal limit of  $155^\circ\text{C}$  continuously at an average power of 1.3CF with peaks from 0.5 to 1.75CF.
- At 1.4CF average power, the generator raises the thermal limit with peaks of 1.75CF.
- At 1.5CF average power, the generator raises the thermal limit with peaks of 1CF.
- At 1.6CF average power, the generator operates above the thermal limit.
- At 1.8CF average power, the generator arrives at the insulation broke limit, but the insulation takes some time to break.

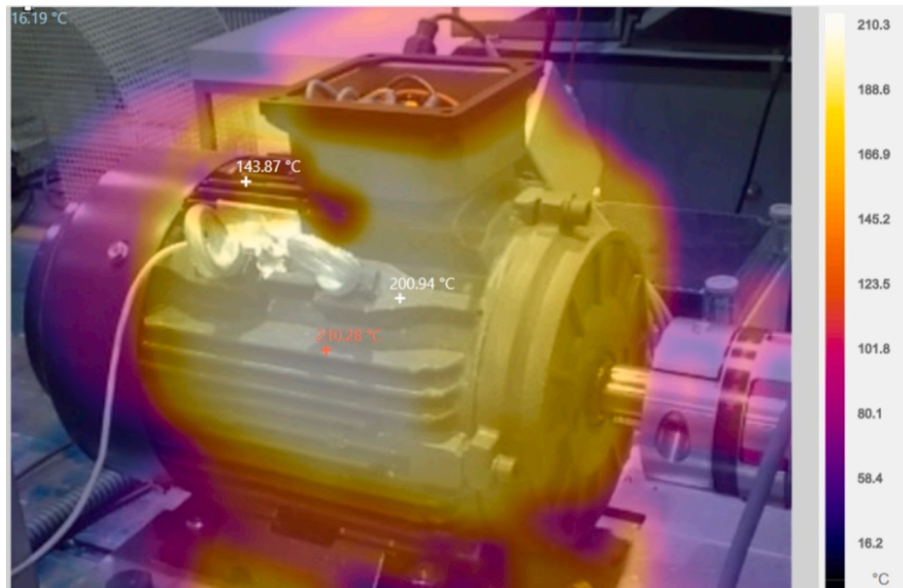


Fig. 16. Generator case temperature after 2.75 h with mechanical input peaks power ( $W = W_{nom}$  and  $T_{gavg} = 1.8 \cdot T_{nom}$ ).obtained with Fluke TiS65 [65].

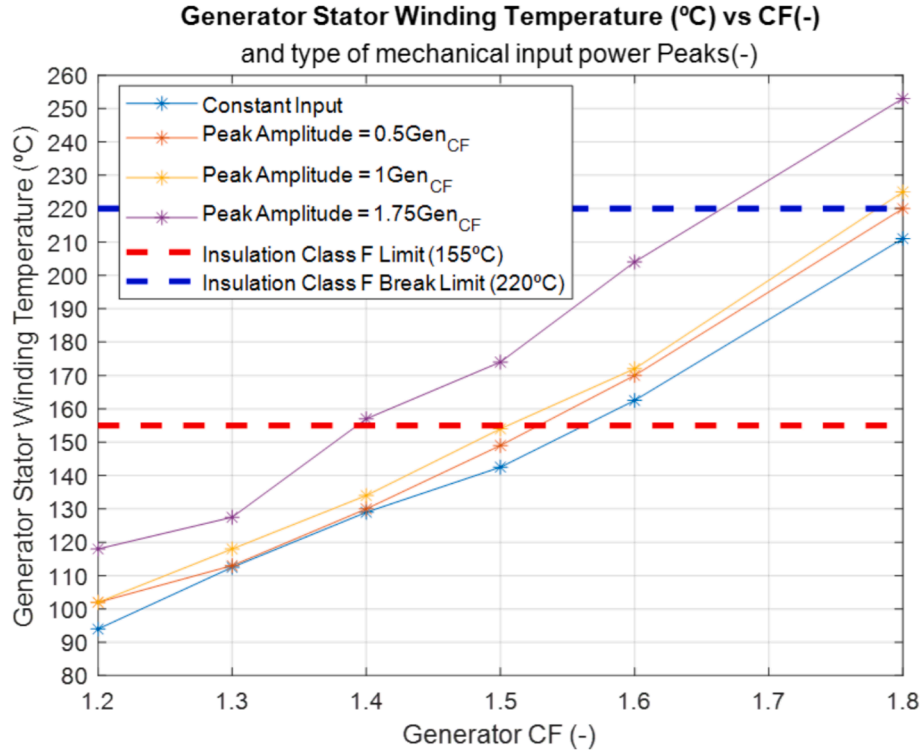


Fig. 17. Generator Stator Winding Temperature per several CF and amplitudes of mechanical input power peaks.

#### 4.5.2. Stator winding insulation degradation model

In this section, the results of the stator winding insulation degradation model developed considering thermal monitorization results during the tests on stator winding are presented. In Fig. 18, the red solid line corresponds to the remaining useful life (RUL) according to the degradation model explained in section 2.4, the blue line represents the instantaneous temperature (°C) during each test.

Thermal cycling can accelerate the aging processes of insulation materials. Therefore, it is important to adjust  $C_1$  and  $C_2$  constants with real operational data of the generator. In this special operational regime, the parameters have been adjusted to  $C_1 = -33.48$  and  $C_2 = 18576$ .

For example, at reference [66] the effects of start-stop cycles on the generators of a hydroelectric power plant using two methods (Weibull

analysis and Coffin-Manson Model). Both methods indicate that frequent start-stop cycles decrease the generators' lifespan. The first method estimates the generators' lifespan based on historical data using Weibull analysis. Generators were grouped by the number of start-stop cycles they underwent. Results show a 17 % reduction in lifespan for generators subjected to more frequent cycling. To mitigate the effects of thermal cycling on insulation degradation, design considerations such as proper material selection, adequate thermal management, and appropriate insulation system design are required. Several strategies may be employed to mitigate thermal risks. These could include the utilization of insulation materials characterized by high thermal stability or the reduction of thermal gradients within the system.

#### 4.6. Key findings in the assessment of the stator winding insulation failure monitoring techniques

In this manuscript, several methods have been explored to analyse the behaviour of the generator under this specific overloading operational regime. Three of these methods involve the post-processing of current and voltage data (MCSA, VSA, PVA, and EPVA), to predict potential future failures. While the methods have proven effective in detecting stator winding failure, their results have not been consistent enough to accurately predict the remaining lifespan of the stator winding in the event of an overload.

About the direct measurement of insulation, it was not feasible to conduct a partial discharge study due to the high noise level of the test bench. Periodic insulation measurements proved beneficial in identifying and confirming the stator winding failure at the end of the generator's operational life. However, tracking the progression of insulation degradation over time proved to be a challenge. A comparative analysis of all monitoring techniques has revealed that the reduction in winding insulation does not follow a linear pattern. Even though these monitoring techniques begin to identify imminent failure, it has not been possible to quantify reduction in insulation. This is likely due to the non-linear nature of the insulation failure. It is noteworthy that the degradation of the material begins to escalate exponentially once the process

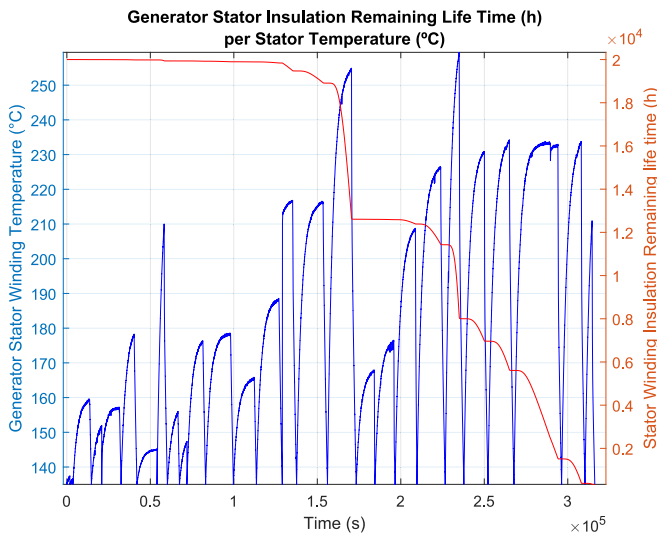


Fig. 18. Generator stator winding temperature vs Degradation model (red line).

commences [18,19]. This observation could explain the inability of the current instrumentation to detect the initial stages of the insulation reduction.

Finally, a temperature monitoring of the generator has been conducted. This monitoring did not reveal any unusual behaviour of the generator. However, based on the results, an insulation degradation model has been refined following the Arrhenius reaction relationship. Utilizing this model, along with the temperature monitoring of the stator windings, the degradation of the winding could be fully assessed. This, in turn, allows for an estimation of the remaining lifespan of the generator.

A generator degradation model could be instrumental in determining the operational limits of the generator (Fig. 19). For a particular site and configuration of the wave energy converter, such a model can assist in designing an optimal generator, along with appropriate control strategies and operational boundaries.

The results of the completed monitoring techniques are summarized in Table 5.

## 5. Conclusions

This study has introduced several generator stator insulation winding monitoring strategies applied to a specific operation regime of an OWC MARMOK-Idom device. The monitoring techniques have been tested during cyclic mechanical loads applied to the generator till the end life of the generator due to stator winding failure.

In conclusion, MCSA and VSA methods have been useful in identifying a future failure but not predicting when future failure will happen or to analyse the remaining life. PVA and EPVA techniques identified phases unbalance and therefore the failure of the stator winding but did not predict this future failure. Regarding the direct measurement of insulation, a partial discharge has proven unfeasible due to excessive noise on the test bench. Which refers to periodic insulation measurements, they have been confirmed stator winding failures at the end of the generator's lifespan, but it has not been possible to track the evolution of insulation. Temperature monitoring of the generator has been

**Table 5**

The main features of generator monitoring.

|                            | Detects the failure | Degradation detected | Comments                                                                             |
|----------------------------|---------------------|----------------------|--------------------------------------------------------------------------------------|
| MCSA                       | Yes                 | No                   |                                                                                      |
| VSA                        | Yes                 | No                   | Less efficient than MCSA                                                             |
| PVA, EPVA                  | Yes                 | No                   | Helps to detect failure                                                              |
| Partial discharge          | No                  | –                    | It has not been possible to use the instrumentation                                  |
| Measuring insulation       | Yes                 | No                   | The instrumentation used didn't give accurate numbers, it depends on the temperature |
| Temperature monitorization | No                  | No                   | Based on the results, throughout a degradation remaining life can be estimated       |

completed during the generator degradation tests, revealing no abnormal behaviour. However, utilizing the thermal results, an insulation degradation model has been fine-tuned specifically for this operational regime. By employing this model alongside continuous temperature monitoring of the stator windings, it becomes feasible to comprehensively assess the stator winding degradation model and estimate the remaining lifespan. The results demonstrate how the generator could operate at overloading in this specific operating mode below the thermal limit, thus, without reducing its lifespan.

In future developments, when sizing a wave energy converter generator for various locations with differing environmental conditions, it is essential to adapt the control law to accommodate different power peaks. Therefore, it is recommended to perform a pre-sizing of the generator by considering the stator winding degradation model. Similarly, future work involves using the knowledge developed in this study to modify the control strategy applied to MWPP [67], Europewave project phase III [68], and The TurboWave Public Procurement of Innovation action [69], where Oscillating water column PTO's will be

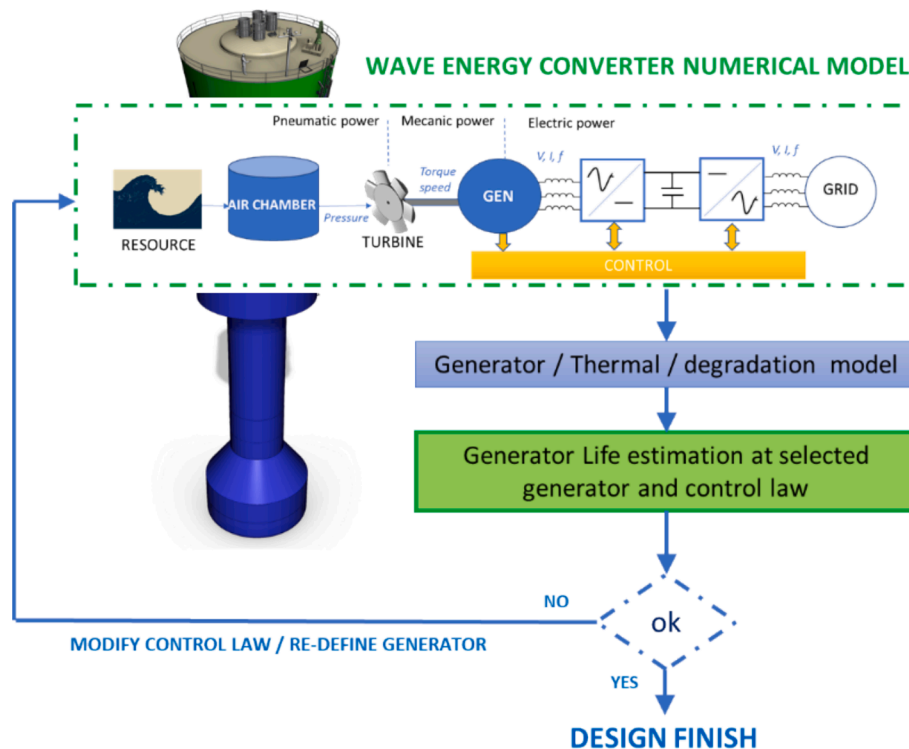


**Fig. 19.** Sizing of the generator and definition of the control law based on generator stator winding degradation model.

tested at MWPP.

### CRedit authorship contribution statement

**Joseba Lopez-Mendia:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Iker Erkiaga:** Validation, Software, Investigation, Data curation. **Pablo Ruiz-Minguela:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Ivan Ruibal:** Software, Formal analysis, Data curation, Conceptualization. **Eider Robles:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Salvador Ceballos:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Annex 1. Description of peaks

**Table A1**

Description of mechanical input power peaks.

| Test     | $P_{RMS}(-)$ | $P_{AVG}(-)$ | High Peak (-) | LowPeak (-) | Peak Amplitude (-) | Class   |
|----------|--------------|--------------|---------------|-------------|--------------------|---------|
| 1_Peaks  | 0,52         | 0,44         | 1,00          | 0,25        | 0,75               | low     |
| 2_Peaks  | 0,77         | 0,61         | 1,50          | 0,25        | 1,50               | medium  |
| 3_Peaks  | 1,04         | 1,01         | 1,45          | 0,80        | 0,65               | low     |
| 4_Peaks  | 1,14         | 1,03         | 1,95          | 0,60        | 1,35               | medium  |
| 5_Peaks  | 1,30         | 1,02         | 2,48          | 0,30        | 2,18               | high    |
| 6_Peaks  | 0,83         | 0,80         | 1,10          | 0,60        | 0,5                | low     |
| 7_Peaks  | 0,90         | 0,82         | 1,50          | 0,50        | 1                  | medium  |
| 8_Peaks  | 1,04         | 0,80         | 2,00          | 0,25        | 1,75               | high    |
| 9_Peaks  | 1,21         | 1,19         | 1,50          | 1,00        | 0,5                | low     |
| 10_Peaks | 1,25         | 1,19         | 1,9,0         | 0,90        | 1                  | medium  |
| 11_Peaks | 1,37         | 1,20         | 2,35          | 0,60        | 1,75               | high    |
| 12_Peaks | 1,33         | 1,32         | 1,65          | 1,15        | 0,5                | low     |
| 13_Peaks | 1,37         | 1,32         | 2,05          | 1,05        | 1                  | medium  |
| 14_Peaks | 1,45         | 1,31         | 2,50          | 0,75        | 1,75               | high    |
| 15_Peaks | 1,42         | 1,41         | 1,80          | 1,30        | 0,5                | low     |
| 16_Peaks | 1,45         | 1,40         | 2,10          | 1,10        | 1                  | medium  |
| 17_Peaks | 1,56         | 1,42         | 2,60          | 0,85        | 1,75               | high    |
| 18_Peaks | 1,53         | 1,52         | 1,90          | 1,40        | 0,5                | low     |
| 19_Peaks | 1,55         | 1,51         | 2,20          | 1,20        | 1                  | medium  |
| 20_Peaks | 1,65         | 1,52         | 2,70          | 0,95        | 1,75               | high    |
| 21_Peaks | 1,96         | 1,64         | 3,60          | 0,60        | 3                  | extreme |
| 22_Peaks | 1,61         | 1,6          | 1,96          | 1,46        | 0,5                | low     |
| 23_Peaks | 1,63         | 1,59         | 2,30          | 1,30        | 1                  | medium  |
| 24_Peaks | 1,74         | 1,62         | 2,80          | 1,05        | 1,75               | high    |
| 25_Peaks | 1,81         | 1,8          | 2,15          | 1,65        | 0,5                | low     |
| 26_Peaks | 1,84         | 1,8          | 2,50          | 1,50        | 1                  | medium  |

## Annex 2. Description of tests above 135 °C

**Table A2**

Description of tests completed (Temperature reached at least 135 °C).

| Test Number | Constant/ Variable | Test Type | Duration (H) | Temp(°C) reached |
|-------------|--------------------|-----------|--------------|------------------|
| 1           | Variable           | 14_Peaks  | 2:00         | 137,33           |
| 2           | Variable           | 16_Peaks  | 3:00         | 136              |
| 3           | Variable           | 17_Peaks  | 3:00         | 159,33           |
| 4           | Variable           | 18_Peaks  | 3:00         | 152              |
| 5           | Variable           | 19_Peaks  | 3:00         | 157              |
| 6           | Variable           | 20_Peaks  | 3:00         | 177,33           |
| 7           | Constant           | CF = 1.5  | 5:00         | 144,83           |
| 8           | Variable           | 21_Peaks  | 4:00         | 209,83           |
| 9           | Variable           | 17_Peaks  | 2:00         | 156,37           |
| 10          | Variable           | 18_Peaks  | 3:00         | 147,5            |

(continued on next page)

Table A2 (continued)

| Test Number | Constant/ Variable | Test Type | Duration (H) | Temp(°C) reached |
|-------------|--------------------|-----------|--------------|------------------|
| 11          | Variable           | 20_Peaks  | 3:30         | 177              |
| 12          | Variable           | 20_Peaks  | 5:00         | 178,33           |
| 13          | Constant           | CF = 1.6  | 4:30         | 165,5            |
| 14          | Constant           | CF = 1.7  | 4:30         | 188,33           |
| 15          | Constant           | CF = 1.8  | 5:00         | 216,33           |
| 16          | Constant           | CF = 1.8  | 5:00         | 216,33           |
| 17          | Constant           | CF = 1.9  | 4:30         | 254,67           |
| 18          | Variable           | 22_Peaks  | 4:30         | 167,5            |
| 19          | Variable           | 23_Peaks  | 4:30         | 176,33           |
| 20          | Variable           | 24_Peaks  | 4:30         | 208,67           |
| 21          | Variable           | 25_Peaks  | 4:30         | 226              |
| 22          | Variable           | 27_Peaks  | 2:45         | 258,67           |
| 23          | Variable           | 26_Peaks  | 4:00         | 225              |
| 24          | Variable           | 26_Peaks  | 4:00         | 234,10           |
| 25          | Variable           | 26_Peaks  | 8:00         | 233,02           |
| 26          | Variable           | 26_Peaks  | 4:00         | 233,6            |
| 27          | Variable           | 26_Peaks  | 4:00         | 210,87           |
| 28          | Variable           | 26_Peaks  | 2:00         | 192,97           |

## Data availability

Data will be made available on request.

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