Fatigue and Aerodynamic Loss in Wells Turbines: Mutriku Wave Power Plant Case

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Abstract- Wave Energy Converters (WECs) need to operate in a harsh environment, where fatigue in materials and salt accumulation regularly lead to premature failures of components. In the course of seven years of continuous operation of the Mutriku Wave Power Plant, several events of this kind have occurred and are described in detail in this article. Preventive maintenance is conducted regularly in the plant. However, the novel machine learning approach could help to optimize maintenance works, as failure can be predicted without unnecessary replacement of components.

Keywords- Machine learning, Operation & Maintenance, Oscillating Water Column (OWC), Wave power generation, Wells turbines.

I. INTRODUCTION

In July 2018, the Mutriku Wave Power Plant will complete its first 7 years of operation. During this period, the power plant has supplied over than 1.6GWh of energy to the power grid, a figure representing significant progress within the wave energy sector. The Basque Energy Agency (EEE/EVE) commissioned the wave power plant in 2011 with the support of the 6th Framework Programme of the European Commission (through the Nereida MOWC project) and the Basque Government. Figure 1 shows an aerial view of the wave power plant.

EVE is currently responsible for operations and maintenance work. Information on the reinforcement work required due to winter storm damages and the first year of operation is detailed in [1] and [2], respectively. The aim of this paper is, on one hand, to present particular events which have occurred during the plant operation and, on the other hand, to inform on the regularly performed maintenance procedure.

Figure 1: Mutriku Wave Power Plant located at the breakwater of Mutriku's harbour.

Although [3,4] give a brief explanation of the working principle of the Mutriku Wave Power Plant, more technical aspects are addressed in this section to bring the reader closer to the day-to-day operations of the power plant. It is well known that the wave power plant located in the breakwater in the harbour of Mutriku uses the Oscillating Water Column (OWC) principle to harness energy from waves. The plant is composed of 16 OWC air-chambers that generate pneumatic pressure variations which trigger a two-way oscillating air flow through the turbine. All chambers are the same size: 4.5m long, 3.1m wide and 9.7m high above the MLWS (Mean Low Water Springs) level. The co-rotating double monoplane Wells turbine always rotates in the same direction regardless of the air flow direction, as this kind of turbine is self-rectified. The diameter of the 5-bladed Wells turbine is 0.75m. The turbine is connected to an 18.5kW induction generator with squirrel-cage rotor. The generator voltage is 460V and its nominal speed is 3000rpm. Since variable speed operation is allowed, the generated power is first turned into DC and, at a later stage, switched to AC with the same 50Hz frequency and phase as the

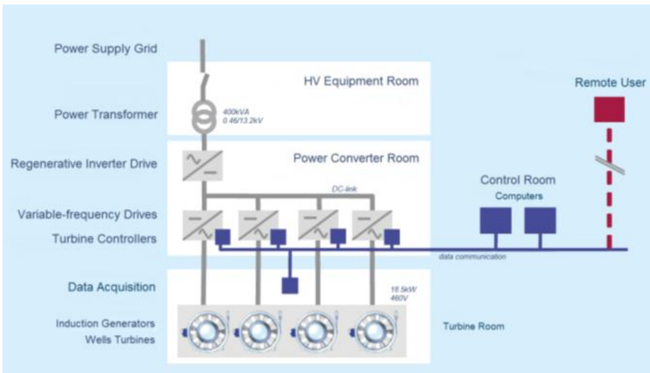


Figure 2: Instrument layout drawing of Mutriku Wave Power Plant.

power supply grid. Thus, each generator is connected to a variable-frequency drive which acts as a rectifier as well as holding primary control over the turbo-generator. A group of eight power converters are arranged in a unique 700V DC-link, which uses a single regenerative inverter drive for each group to convert DC into AC. The Mutriku Wave Power Plant is one of the few wave power plants, and the first of its kind, to be connected to the local power supply grid. The generated power is delivered through the output power transformer in 13.5kV. Figure 2 shows a schematic view of the Mutriku Wave Power Plant.

This paper is organized as follows: Section II describes the events occurred and difficulties faced over seven years of continuous operation, due to the harsh environment where the equipment is located. The maintenance work regularly carried out to prevent the equipment failure is detailed in Section III. Section IV outlines an approach to the machine learning technique to predictive maintenance. Finally, Section IV ends the paper with a series of conclusions.

II. HARSH ENVIRONMENT

Several factors were taken into consideration in the design of the turbo-generator set of Mutriku: safety of operation, efficiency, service loads, cost, corrosion and ease of maintenance. However, the adverse conditions at the Mutriku Wave Power Plant, where many components are exposed to high humidity levels and a saline environment, produce fatigue on the materials that impact on the performance of WECs and lead to failure of the power equipment.

A humidity sensor was installed in the turbine room within the European project Opera [5] to gauge the impact of saltpetre on components. As expected, results showed a high percentage of humidity in the turbine room where most of the components are located. Constant exposure to saltwater corrodes the components and, together with strong oscillating mechanical forces that OWC devices are subject to, may produce fatigue and the subsequent breakage of a component. Figure 3 shows the corrosion in one of the Wells turbines at the Mutriku Wave Power Plant. Furthermore, high levels of salt concentration may provoke aerodynamic losses in Wells turbines. Both events are addressed below.

Figure 3: A Wells turbine after five years of operation.

A. Material fatigue

As has been mentioned above, OWC devices usually work with two-way air flows. The force applied by non-constant air flow can be decomposed into two axes. The force of the horizontal axis causes the turbine to rotate always in the same directions. However, the force of the vertical axis has a different direction depending on the air flow and is absorbed by the turbine itself as there is no vertical displacement. This produces stress on the material resulting in possible premature breakage of the component. Figure 4 shows the breakage of one of the blades of a Wells turbine installed in the Mutriku Wave Power Plant as a result of the winter storms in February 2016. The broken blade also hit the generator housing violently, producing the crack seen in Figure 4(b).

The broken turbine was analyzed to identify the cause of the turbine breakage and rule out possible risks on the rest of the

(a)

(b)

Figure 4: Breakage of a blade. (a) Wells turbine with a broken blade and the breakage detail; (b) Damages in the generator.

turbines. To conduct the tests, the damaged areas were first defined. Figure 4(a) shows the failure analysis area and the metallographic specimen and the tensile specimen extraction areas.

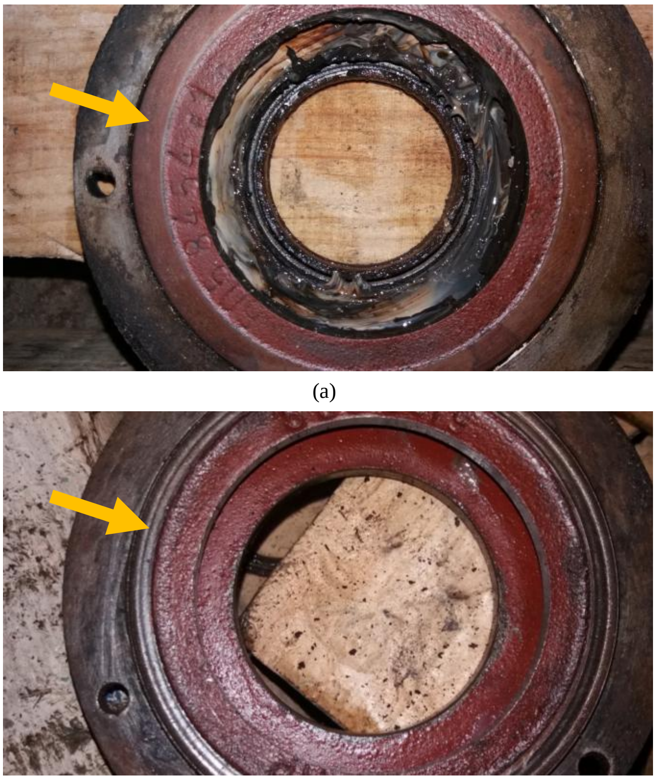
The failure analysis study was carried out by inspecting the fracture area in micrographic detail using optical microscopy and scanning electron microscopy, as shown in Figure 5. Initial inspection revealed a large amount of salt residue embedded on the surface. Therefore, the sample needed to be cleaned in an aqueous solution with 5% nitric acid in order to observe the metallic material.

Figure 5: Failure analysis study of the broken turbine.

The tensile tests were carried out in accordance with the UNE-EN ISO 6892-1 B: 2010 standard, with a specimen of ϕ10 extracted in a radial direction on one of the blades adjacent to the broken blade.

From the morphology of the breakage, where well-defined fatigue slip-bands can be observed, it is possible to determine the origin of the initial crack that gave rise to the breakage. It can therefore be deduced that the blade breakage was produced by fatigue. In addition, numerous holes and spots of oxidized aluminium in the central area of the beginning of the rupture suggest that the breakage could have been initiated by pitting corrosion from the surface. Pitting corrosion was also observed inside the specimen extracted from the blade adjacent to the breakage.

Signs of wear produced by vertical-axis forces have also been observed in the generator. The most frequent failure caused by oscillating forces in the turbo-generator shaft is usually breakage of the washer between the bearing and the housing of the generator. Due to the force exerted by the shaft, the washer is subject to high pressure that causes it to fail. The bearings consequently rub against the inside of the generator cover and wear occurs. This wear can be clearly appreciated in Figure 6. Figure 6(a) shows a generator cover prior to its installation in Mutriku, whereas Figure 6(b) displays a worn-down generator cover. The inner steel band (indicated with an arrow) can be seen to have worn away considerably. This may produce undesirable high vibrations attributable to the friction of the bearings against the generator cover. For safety reasons, turbine high vibrations are not permitted during normal plant operation, so the turbo-generator must be shut down.



(a)

(b)

Figure 6: Bearing cover of the generator. (a) Before being installed; (b) Worn-down.

B. Salt accumulation

Another factor to take into account is salt accumulation. The air flow through the turbine contains a large amount of saltpetre that remains embedded on the turbine blades, as shown in Figure 7. This may lead to a sudden performance drop, as it not only causes vibration but also significant aerodynamic losses.

To avoid this, the turbine blades are regularly washed with fresh water. The interval between each wash depends on the rotational speed of the turbine and the amount of vibrations, but is usually around 90 minutes.

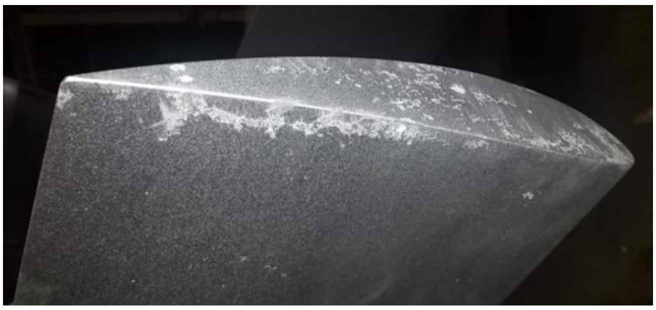


Figure 7: Salt accumulation on the surface of the Wells turbine blade.

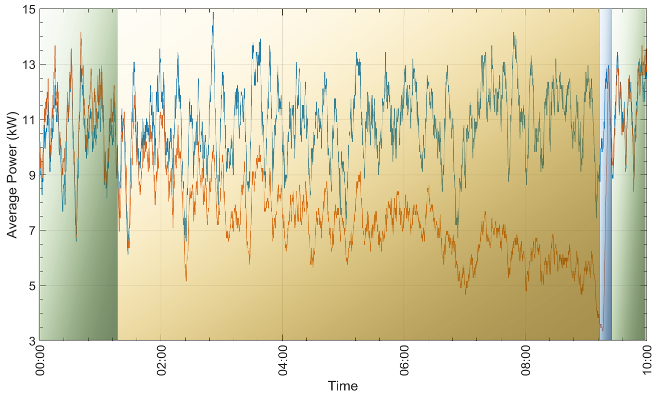
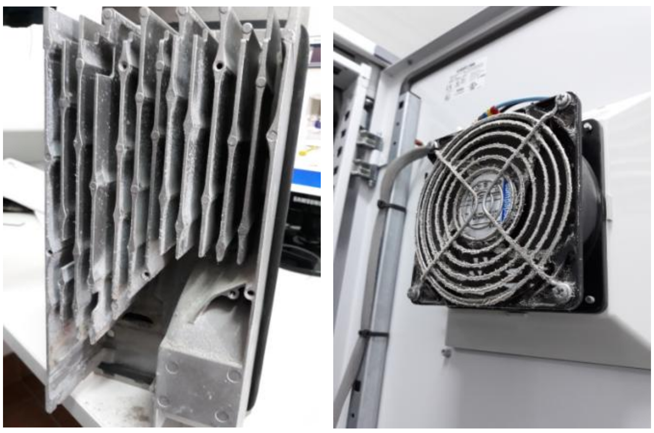


Figure 8: Average power of two turbines, each associated to a different regenerative inverter drive.

A real example of performance drop attributable to a lack of blade-washing is shown in Figure 8, which shows the average power generated by two different turbo-generators. The blade-washing event is controlled by the regenerative inverter unit, which handles a group of eight turbines. The green area indicates the operation of both regenerative inverter units with regard to blade-washing. Thus, the red line in Figure 8 is a consequence of a failure in one of the regenerative inverter units, where the blade-wash function ceased to work. The blue line, however, shows the average power of the second turbo-generator controlled by the other regenerative inverter unit, which performed the blade-wash function normally.

From Figure 8 it can be deduced that average generated power dropped almost 7kW in eight hours (yellow area) due to blade-wash failure, which corresponds to a 54% of efficiency loss in the case of a single turbine in this particular case. Taking into account that a group of eight turbines is controlled by each regenerative inverter drive, the losses can be very significant in case of blade-wash failure in one of these units. Hence, it is vital to ensure that the turbine blades are washed regularly.



(a) (b)

Figure 9: Salt accumulation on the cooling system. (a) Variable-frequency drive heatsink; (b) Cabinet cooling fan.

Nevertheless, once the plant operator made blade-washing compulsory, the average power rose steadily to its normal level in a few minutes, as the blue area in Figure 8 shows. Once again, this demonstrates the importance of washing the blades properly.

The salt accumulation also produces negative effects in the power electronics. Although the equipment is located in a power converter room, far away from the turbine room and its salty environment, the accumulation of the salt is visible. As the nearshore air contains large amounts of saltpetre, the cooling system of the generator drives is affected by the salt. The variable-frequency drive heatsink is the component mostly affected by salt accumulation, causing drive overheating and subsequent turbine trip. Figures 9(a) and (b) show the back of the drive heatsink and the cooling fan of the cabinet where the power converters are located, respectively.

III. PREVENTIVE MAINTENANCE

Preventive maintenance is regularly carried out in Mutriku Wave Power Plant so as to avoid failure or breakage, as explained in the previous section on the equipment and components installed in the power plant. Regular maintenance is carried out monthly and annually depending on the degree of wear of each component, and covers both mechanical and electrical components as well as control equipment and server checking.

During scheduled monthly maintenance, a visual inspection of the plant is carried out. The following components are revised: sensors, emergency stop switches, fasteners (i.e. concrete interface, damper, turbo-generator, attenuators, etc.), the generator terminal box, cable trays and cables, fresh water piping and the damper actuator. A general review is also conducted for signs corrosion, including staining on surfaces. The power converter room cooling fan is also checked.

In the course of annual maintenance, mechanical maintenance is completed with the lubrication of the

Figure 10: Greasing of roller bearings during scheduled maintenance work.

generator bearings. Figure 10 shows the annual mechanical maintenance carried out in the Mutriku Wave Power Plant. This kind of maintenance work is generally performed during the summer months due to better weather conditions. It must be taken into account that working with RMS chamber pressures above 8000Pa is a safety hazard for maintenance personal: precautionary measures are recommended to be taken when the RMS pressure exceeds 4000Pa. Apart from greasing the bearings, an electrical inspection is conducted annually, covering control system cabinets in the turbine room, the power converters cabinet to detect any sign of overheating and the cables, as well as the SCADA alarm and trip indicators.

After five years of continuous operation of the power plant, generator bearings and turbine rotors were renewed as per the recommendations of the equipment manufacturer. Due to the breakage of the blade in one of the turbines caused by fatigue, the decision was taken to replace the rest of the turbine rotors during the second quarter of 2017. The replaced Wells turbines can be seen in Figure 11.

Figure 11: Replaced Wells turbines in Mutriku Wave Power Plant.

IV. PREDICTIVE MAINTENANCE

Following a traditional maintenance approach, failures or breakages may occur, thereby necessarily triggering a reactive maintenance response to change or repair the component(s) in question. As a result, costs associated with plant shutdown during maintenance work may have a considerable impact on the cost of energy.

Scheduled maintenance may also be carried out based on prior knowledge, the average times between failures, etc. In this case, the supervisor decides that after a certain number of cycles or a determined period of time or number of operational hours, certain elements must be replaced. However, planned maintenance may also prove uneconomic, as the plant is once again likely to be shut down more than necessary. Using this approach, no information is available on the state of repair of the component or how long the component can remain operational before it's likely to fail.

Certain mathematical approaches can be used to try to adjust this type of maintenance. By collecting data from the facility and applying machine learning techniques, it is possible to develop algorithms that enable predictive maintenance to be performed. The machine learning techniques may be either supervised or unsupervised. In the case of unsupervised techniques, just operating data is used. In the case of supervised algorithms, however, information on when the failure occurred or when the performance dropped significantly that triggered a maintenance action is known.

In the case of unsupervised algorithms, pattern recognition or clustering techniques can be applied to detect the settings in which normal operation occurs. This requires looking at the underlying infrastructure to detect any natural pattern that helps to understand the performance of the plant. On the other hand, in the case of automatic learning techniques with supervision, it is a matter of predicting failures, i.e. how long is left until breakage. Depending on the state of repair of each component, it may be necessary and convenient to perform maintenance. In the case of the Mutriku Wave Power Plant and WECs in general, using machine learning techniques applied to predictive maintenance, it is possible to schedule maintenance works taking into account wave forecasts throughout the year and, consequently, the availability of the power plant may be improved.

There are a large number of algorithms that can be used with the same data to choose the one that best predicts the behaviour of the system and when maintenance has to be performed. In general, the workflow should be as follows:

- Data collection from sensors.
- Pre-processing of data by filtering to detect corrupt data coming from sensors.
- Extraction and selection of characteristics, e.g. through principal components analysis (PCA) or other techniques.
- Predictive model training based on the operational data.

Once a point cloud is obtained from collected data, the challenge is to find the dimension or axis in which the cluster shows more variations. In this sense, the first step of PCA is to analyse which straight line explains the maximum variance, i.e. the maximum dispersion of the data. The first principal component, i.e. the one that contains the highest percentage of information and best explains the behaviour of collected data, is thereby obtained. The second principal component explaining the remaining variance can then be found. This brings a new set of axes where the data can be drawn and measured, as shown in Figure 12. PCA enables most of the information to be captured and summarised in a small set of dimensions.

In the case of OWC devices the nature of the collected data is usually oscillating and the operating point depends on input conditions. Hence, it may be difficult to determine a single pattern that describes the wear-trend of a component.

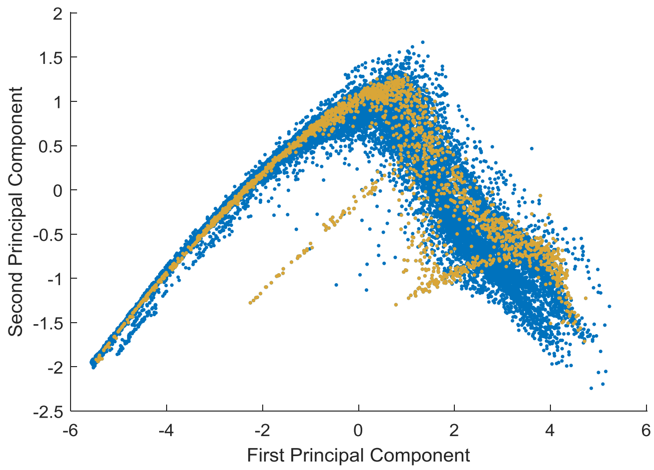


Figure 12: The point cloud of PCA obtained from a case study.

Nevertheless, the Mutriku Wave Power Plant has the advantage of having more than one turbo-generator, enabling comparison of the behaviour of each device. Thus, healthy turbines may coexist alongside others requiring maintenance, and their parameters can be analyzed to decide whether they need maintenance or not.

In Figure 12 data from only eight of the turbines have been analyzed to reduce the computational workload. The parameters analysed include output voltage and currents, generated average power, rotational speed, output frequency, chamber RMS pressure, vibration and damper position. Due to the oscillating nature of the data and to simplify the study, the average hourly value of each parameter has been calculated. The results of the PCA approach demonstrate that some turbines need maintenance, as some components are outside the desirable operating range as indicated by the yellow dots.

Having detected that a turbine is in need of maintenance, or that a particular component is reaching the end of its useful life, regression models can be trained so as to predict the normal response of the entire system or a single component. In Figure 13 one of these turbines has been analyzed to study the deviation that some parameters show when they are near the failure or breakage point. In this sense, the figure compares rotational speed (horizontal axis) and vibration (vertical axis). Vibration is the parameter that usually shows the highest degree of deviation when some components begin to suffer wear and tear. Figure 13(a) shows vibration levels during normal turbine operation. The turbo-generators in Mutriku Wave Power Plant are balanced around 2500rpm and both ends of the valley reveal undesirable vibration levels.

The machine learning approach can be used to predict the response, where the yellow dots indicate the predicted model. Hence, any turbine should show vibration levels around the predicted values during normal operation. However, through the data in Figure 13(b) are obtained from very similar wave conditions and the same turbine as in

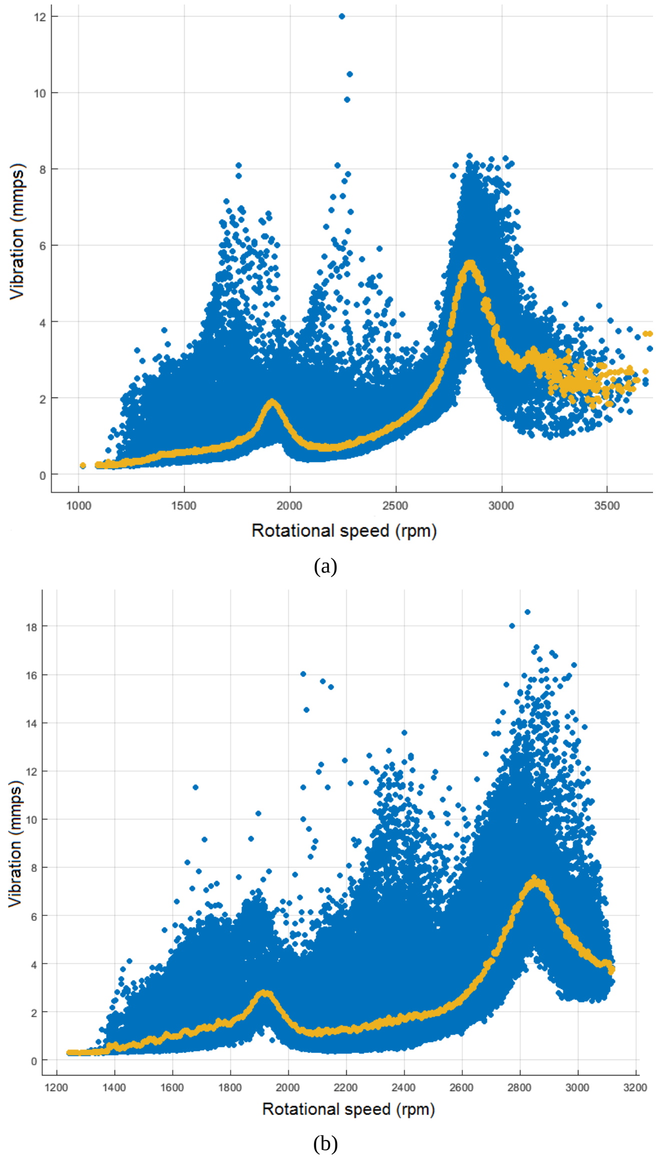


Figure 13: Turbine rotational speed vs. vibration level. (a) non-degraded turbine; (b) degraded turbine.

Figure 13(a), according to PCA analysis the turbine should be in need of maintenance. The trained model demonstrates that, in effect, the values stand outside the regular operation range, as the turbo-generator system produces higher vibration levels at the same rotational speeds. Thus, the decision can be made about whether maintenance is to be performed or not.

V. CONCLUSION

Seven years of continuous operation have been reviewed in this article. Over this course of time, several undesired events have occurred and have been described in detail. Fatigue and salt accumulation are the most important factors which cause the WEC to fail. Moreover, if regular maintenance is not performed, some components wear away due to continuous fatigue and breakages may occur.

Replacement of all of the turbines has been the most significant maintenance work carried out recently. This decision was taken after a breakage of the blade in one of the turbines.

To avoid premature failures or unnecessary replacements of components, a preliminary study of a predictive maintenance approach has been conducted as a first contact with machine learning concept. Thus, predictive maintenance may bring significant benefits. The availability of WECs can be improved through an acquired ability to predict breakages. In addition, maintenance costs can be reduced, as we know how and when to conduct maintenance, which enables us to optimize the supply chain. Predictive maintenance leads to greater reliability of components, improved planning and scheduling of maintenance work and engaged staff, as well as better service provision and reputation.

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