The Effect of Pulse Magnetic Field (PMF) on Life Service of Scandium Reinforced (0.4wt %) Aluminium Alloy

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Abstract: A high concern is directed to the renewable energy sector, harvesting the potentials in nature to convert into electricity have different economic and environmental benefits. Unfortunately, harvesting renewable energy is expensive and taking an appropriate decision regarding its installation is not simple as it seems to be. As installing renewable energy plant should assure a minimum level of stability, sustainability and should be able of achieving such economic benefits. Among all available renewable energy resources, tidal energy has been paid the highest attention in this paper. This paper directed the main attention to fatigue failure due to the seasonal fluctuations of tides. As these fluctuations result in a cyclic loading on the tidal turbine resulting in fatigue failure, which is considered as being one of the most common mechanical fracture forms. The study had been applied on a 3-blade horizontal tidal turbine and assumed the blade is made of 0.4wt % Scandium aluminium alloy. Rainflow algorithm had been used in dealing with the thrust forces applied on each blade in order to ease predicting fatigue life of the studied turbine. A Matlab code was used in describing fatigue mechanism mathematically and obtained results showed that, increasing blade thickness results in a significant increase in the turbine service lifetime. The study considered varying the installation depth under seabed of the studied turbine as well as its operating time to investigate their effect on the fatigue lifetime. A noticeable reduction in the fatigue lifetime is observed when either increasing the installation depth or the operating hours of the turbine. Hence, optimizing the blade thickness is vital to be applied based on the operating and environmental conditions as well as the desired output of the turbine as increasing thickness would result in increasing its mass resulting in reducing its efficiency.

Keywords: Rainflow algorithm, Tidal turbines, Fatigue failure, Matlab, Aluminium alloys, Pulsed Magnetic Field.

1. INTRODUCTION

A very high attention is directed to the energy sector, which tends to reduce the negative consequences resulted from the recently seen global electricity consumption. As increasing consuming electricity resulted in a lower air quality, water purity and human health due to the emissions released from conventional power stations. In addition, a significant increase in the fossil fuel prices is estimated to take place due to increasing its demand in the global market. Renewable energies are considered as being modern techniques that are allowed reducing theses negative consequences. As generating electricity from natural energy sources allowed satisfying the global energy demand sustainably and without resulting in emitting toxic gases. Renewable energy techniques allowed achieving that economically as well. According to IRENA, renewable energies share a high percentage of the global electricity generation rate. The expected prices of each technique (according to its capacity) is represented in the following figure, while the availability is represented in figure 2 [1].

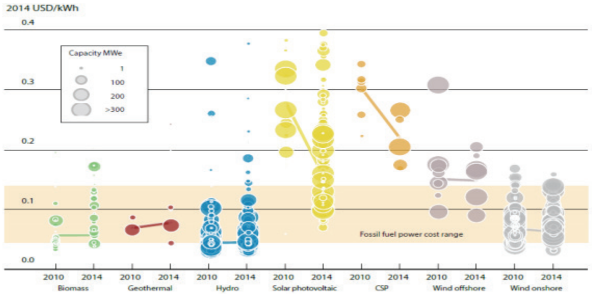


Figure 1. Expected energy unit price for each renewable energy technique [1].

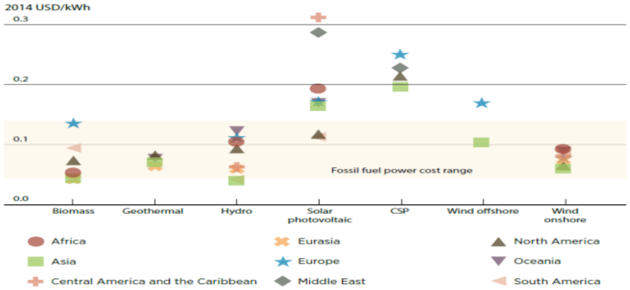


Figure 2. Expected availability for each renewable energy technique [1].

Tidal energy is estimated as being one of the most important renewable energy source, it can be converted into electricity using a specially designed turbine. Different types of tidal turbines had been developed by researchers aiming to enhance the energy conversion efficiency, which leads to a significant increase in the electrical power output. For example, an axial flow turbine converts the hydrodynamic forces applied on the blade into mechanical torque and rotating the blades. The generated mechanical power is to be converted into electricity using an electric generator [2].

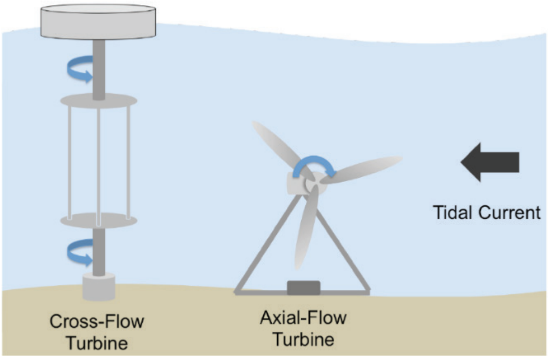


Figure 3. Schematic of tidal turbines operation [2].

The especially designed turbine blade is expected to operate under tough conditions. As it is expected to be affected by such hydrodynamics forces that are differ respect to their magnitude and direction. Factually, the aforementioned operational circumstance cannot be neglected and it may result in mechanical failure. As changing an applied force's magnitude and/or direction traditionally results in applying a fatigue stress on the structure that results in certain failure after a certain number of cycles. This number of cycles highly depends on the material type, geometrical parameters, the operating parameters and other parameters [3].

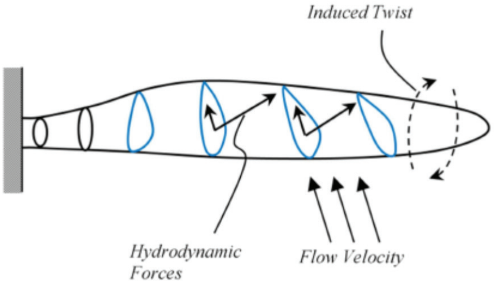


Figure 4. Hydrodynamic forces applied on a tidal turbine blade [3].

Turbulence intensity variation is the main source of hydrodynamic forces' fluctuations, which varies from a season to another and from a geographical location to another. Fatigue stress is one of the most common fracture forms of tidal turbine blades. It had been focused in details by researchers and scientists aiming to be able of predicting it (an engineering structure lifecycle when it is affected by a periodic loading). However, the blade resistance against fatigue failure can be determined by different techniques that vary respect their accuracy, cost and complexity. Experimental investigation of fatigue stress of an engineering structure is one of the most accurate tests but it is expensive and results in destructing the structure itself. Computational fluid dynamics modern tools are investigated to be able of predicting fatigue failure, but these studies are complex and require special workstations. Mathematical predictions of the fatigue mechanism can be achieved using Rainflow algorithm, which can deal with such huge data as the variant hydrodynamic forces applied on the blade over the year [4], [5] and [6]. This study concerns about studying the effect of the seasonal fluctuations of the hydrodynamic force applied on a tidal turbine blade made of an Aluminium alloy. This alloy will be enhanced using pulsed magnetic field technique aiming to increase its performance for the same thickness. This would help in achieving a higher lifespan of tidal turbines and a higher electricity output. As increasing the blade resistance against fatigue for the same thickness but by applying a pulsed magnetic field would allow avoiding increasing blade mass. Consequently, the mechanical performance is increased without changing the energy conversion efficiency. The study is decided to be applied using Rainflow algorithm, which will be discussed. Results will be compared, analysed and discussed aiming to remark the concluded points and the effect of the pulsed magnetic field on the fatigue stress of the studied blade.

2. LITERATURE REVIEW

III. Tidal turbines

A tidal turbine is designed mainly for a purpose of converting the kinetic energy of tides into mechanical power that can be used in generating electricity. A tidal turbine is designed to operate identical to wind turbines but is much stronger to resist the higher mechanical stresses applied on it. As the significant increase in density from air to seawater increases the applied dynamic forces (lift and drag forces) resulting in a significant increase in the generated mechanical stresses on the blade. In addition, installing a turbine under seabed is predicted to be affected by such environmental conditions that are extremely tough. Researchers paid tidal energy a high attention, which allows developing different types and techniques that allow harvesting tidal power from different locations and at different depths under seabed. The following figure five, represents the most five types of tidal turbines that had used in generating electricity from tidal power. They differ respect to their configuration and blade design that allows fitting with such special requirements that are differ from a geographical location to another [7].

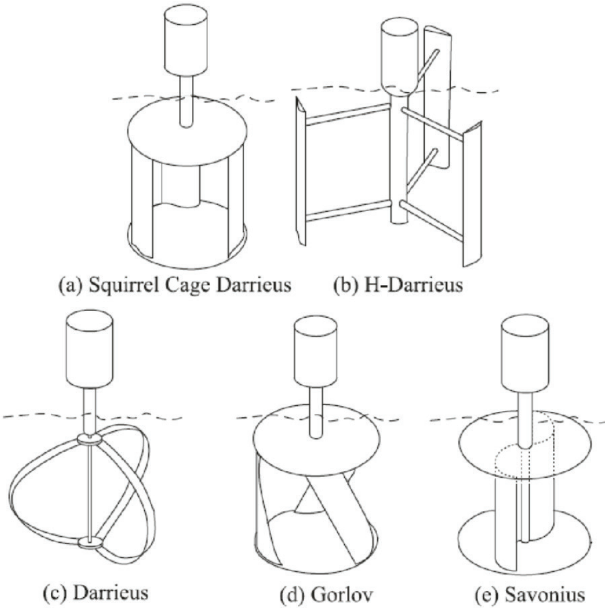


Figure 5. Most common types of tidal turbines [7].

Regardless the type of the tidal turbine, the blade design is considered as being the most important parameter that indicates the energy conversion efficiency of the turbine. As a blade profile is designed to be able of converting the applied thrust force into mechanical torque. Referring to figure 6, it is clear that, the applied hydrodynamic force is separated into a drag and lift force. Drag force is the main source of stresses applied on the blade, while the lift force is the main source of the mechanical torque required to be exerted on the hub to generate electricity. A tidal turbine blade should be designed to reduce the applied mechanical stresses (drag force) as well as maximizing the lift force to enhance the turbine's output [8].

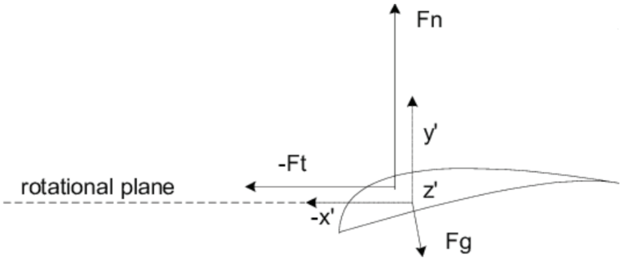


Figure 6. Schematic representation of the applied forces directions [8].

IV. Operating conditions

The operating and environmental conditions expected to effect on a tidal turbine blade are estimated to be extremely tough. This is due to the high level of corrosion under seabed, high possibility of unexpected impacts and collisions, etc. However, these conditions are estimated to be related to the geographical location of the tidal turbine. To be more specific, the installation geographical location is considered as being one of the most parameters that influence the operating conditions of a tidal turbine. Referring to the tide height variation represented in figure 7, it varies noticeably from a geographical location to another. This change in the tide height is predicted to result in a significant change in the performance of the tidal turbine itself as well as its lifespan, operation efficiency and electrical output [9].

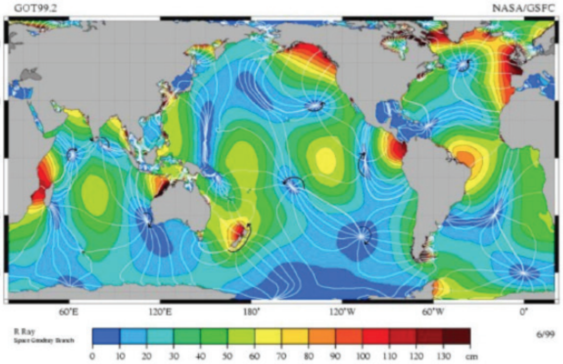


Figure 7. Recorded tide heights for different geographical locations around the world [9].

This environmental and operating conditions are not estimated to result in a negligible effect on either the turbine operation or lifespan. For example, biofouling results in increasing the blade surface roughness that results in a significant reduction in the tidal turbine energy conversion efficiency. Unexpected collision between the tidal turbine and marine life or rocks can result in undesirable circumstances. A tidal turbine should be designed to withstand against these unexpected collisions, which enables assuring avoiding unnecessary economic losses resulted from the breaking down the turbine for maintenance purposes. In addition, the seasonal fluctuations in the hydrodynamic forces applied on the turbine result in a cyclic loading, which is the main source of fatigue failure. Fatigue failure is outlined as being one of the most important and most common fracture forms in tidal turbines. Assuring a proper, smooth, efficient and safe operation of a tidal turbine can be predicted based on studying its resistance against the fatigue stresses applied on it in such a selected geographical location [10] and [11].

V. **Fatigue mechanism**

A tidal turbine is designed to generate electricity from tidal energy for long lifetime. This expected long lifetime allows making such economic profits that can cover the initial and running cost of the turbine as well as assure achieving economic and environmental benefits. Hence, designing a tidal turbine that is not able to satisfy the latter discussed desirable property would result in economic losses. A tidal turbine should be designed to be able of achieving the highest efficiency. This can be achieved by using such efficient equipment and instrumentations and highly operating blade. A tidal turbine blade's design is not simple as it seems to be. As its hydrodynamic profile should assure achieving the highest magnitude of the lift force to maximize the generated mechanical torque leading to maximizing the electrical power generation rate. Forms of fracture and mechanical failures are several and fatigue failure is one of the most important fracture forms in tidal turbines [11].

Fatigue life describes the quantity of load cycles of a certain parameter that a sample can contain just before any kind of failure happens. There is an existed relationship between the quantity of cycles and the vibrational forces applied on such a rotary machine as internal combustion engines. Therefore it can be equated to simulate its span in hours. Some other factors that affect the fatigue life include; cyclic loading, residual loading, nature of material used, internal weakness, grain dimensions, temperature ranges, design configuration, surface roughness, and corrosion. Fatigue life of a material under divergent fatigue mechanism may be rated as high or low, fatigue mechanisms include; heat shock, low and high temperature LCF and HCF. While evaluating the possibility of a fatigue, it can be presumed that the material component is very safe for uncountable number of periods if no failure is evident after ten million cycles are surpassed. The entire fatigue life is equated to the time it takes for a crack to be formed and the time it takes for the crack to extend. Fatigue life is reliant on past subjected stress level. Because for a crevice to be formed, a substantial amount of stress is needed as compared to that needed for crack propagation. Fatigue life of a material can be estimated by the strain, loading and energy approach. Fatigue is quite a complex mechanism that is affected by several factors. Usually, it is efficient to employ macro phenomenological technique to imitate the impacts of fatigue systems on fatigue spans as compared to using microscopic technique [12].

Fatigue life is greatly influenced by the crack formation stage, this means that most of its cycles are related to crack formation. Fatigue crack formation on the surface only happens when there are subsurface flaws, crevices on the surfaces are usually as a result of surface loading concentration like at the edge, weld toe etc. therefore, surface polishing is very important. For examination samples specimens fabricating utilizing FSP, the top surface in the examined information was ground to remove marks caused by surface tool due to the rotating nature of FSP equipment. Also, every flash was eliminated. Therefore, as per the FSP and prior bending, the surfaces should not be rough at all and should not exhibit any possibility of configurational discontinuities. Lack of surface configurational discontinuities, crack formation can be proportionately related to the metal yield strength. Similarly, a slight change in yield strength can influence the fatigue life. The figure below illustrates the micro tensile characteristics for the various positions for friction stir processed 5083-H116 plate that follows FSP. Positions 1 & 5 are the original metal features. Yield strength for the initial metal ranges between 290 to 300 MPa, they are the minimal yield strengths that were recorded when contrasted to specimens within and near the FSP region. The FSP region i.e. 3-1 has an approximate yield strength of >360 MPa. The HAZ region i.e. positions 3-2 & 3-4 and that of TMAZ i.e. positions 2-4 possess an approximate yield strength of >330MPa. Therefore, 5083-H116, its yield strength in the FSP region and the nearest zones is relatively than the original material. This can be predicted from hardness out-turn, this means that, the higher hardness was noted at the FSP region. Extrapolating the yield strength to fatigue, one would expect a fatigue life span similar to or higher than the original metal. The disadvantage is that information on fatigue resistance for friction stir welded AA 5083 is not very comprehensive [13].

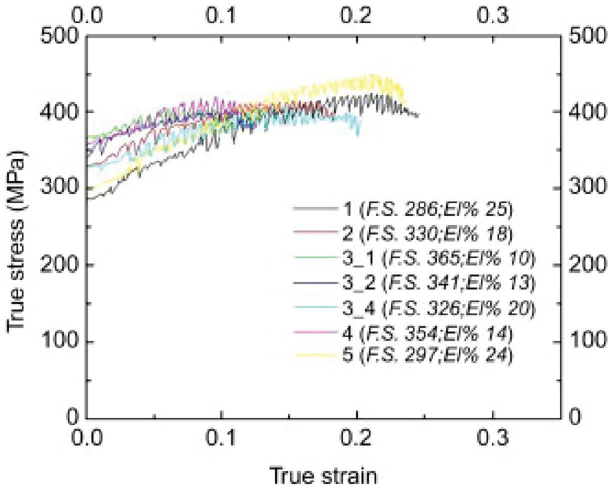


Figure 8. Micro tensile features for varying positions for friction stir processed 5083-H116 plate that follows FSP.

Fatigue life highly affected by the material type due to the change in the mechanical properties from a material to another. A tidal turbine blade should be fabricated from a low dense material to reduce the energy losses during the energy conversion process. Different aluminium alloys had been developed by researchers aiming to achieve such a desirable performance of a blade. Aluminium alloy (Scandium-reinforced) is known by its wide range of application due to its unique physical, chemical, thermal and mechanical properties [14].

VI. Material performance

A significant enhancement had been achieved in material science, which allows developing such modern materials and alloys enable achieving unique performances of different engineering applications. A tidal turbine is expected to operate under seawater level, which refers to the high level of corrosion rates, high possibility of impacts and collisions and high fluctuations of the applied hydrodynamic forces that results in high fatigue stresses. The blade installed in a tidal turbine is the most important part, which is responsible of converting the flow energy into mechanical power. Its design is complex and the material used in its fabrication should be selected based on such critical parameters that ensure achieving high efficiency as well as high safety against corrosion, erosion, impacts and fatigue failure. Blades are preferred to be manufactured from either metallic or composite materials. Each type is estimated to provide a group of advantages and disadvantages that fit with such operating and environmental conditions. A blade material should not be characterized by its high density, which would result in reducing its output. It should be advantaged by high mechanical performance to avoid either increasing the blade thickness (increasing weight of the blade) or increasing its initial and running costs. As increasing thickness to attain a predetermined safety factor against the expected conditions is investigated in different studies to result in reducing the power coefficient of the turbine resulting in reducing its output. This is assumed to raise its running cost and increase its payback period [15].

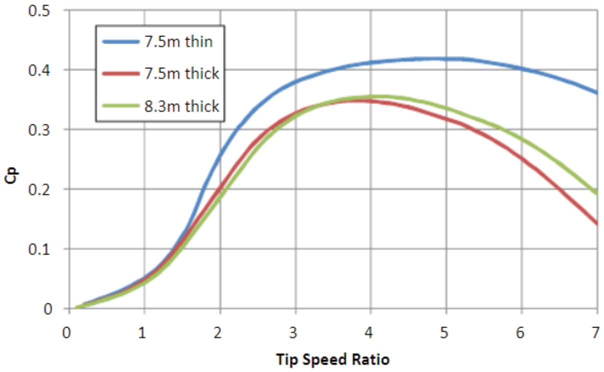


Figure 9. Effect of increasing the blade thickness on the power coefficient of a tidal turbine [15].

Aluminium alloys had been developed noticeably last few decades, their unique mechanical, thermal, chemical and physical properties enhanced engineering applications' performances noticeably. Aluminium is light, available and advantaged by high manufacturability, which encourages considering it in the concerned application. Aluminium is less expensive than other light materials (such as Titanium alloys), which attracts design engineers to consider it in blade manufacture. The interesting material's properties can be enhanced by adding such additives, which helps in increasing its desirable properties and reducing the undesirable ones [16]. Scandium material is investigated to have a positive effect on the corrosion resistance of such a material, it can be added by a predetermined mass percentage content to enhance an alloy's resistance against corrosion and erosion especially in such applications that are designed especially to be operated under seabed. Unfortunately, Scandium is expensive and considering it should be limited to such critical applications as tidal turbines blades, etc. [17]. Scandium-reinforced aluminium alloy showed a unique performance regarding satisfying such duties of a tidal turbine blade. The following figure shows its structure [18].

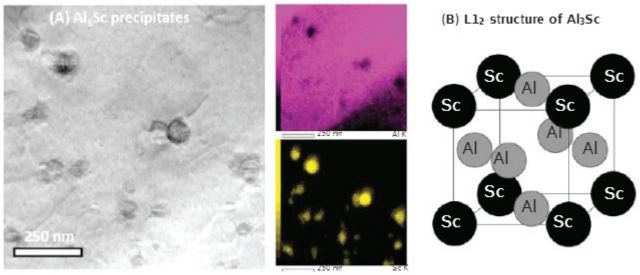


Figure 10. STEM image of Scandium-reinforced aluminium [18].

The performance of such material as aluminium alloys can be enhanced using such modern technologies as pulsed magnetic field. A study applied on a 6063 Al alloy showed that, varying the pulsed magnetic field resulted in changing its microstructure. The following figure represents the microstructure of the studied Al alloy with and without affecting by a pulsed magnetic field where; (a) without pulsed magnetic field, (b) with a pulsed magnetic field at a current (I) of 180 A, (c) with a pulsed magnetic field at a current (I) of 380 A and (d) with a pulsed magnetic field at a current (I) of 500 A [19].

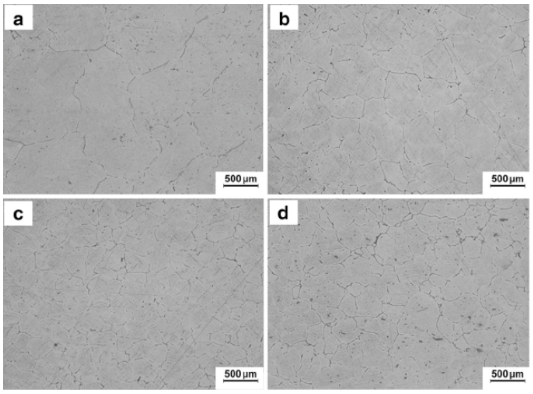


Figure 11. Effect of pulsed magnetic field of microstructure on a 6063 Al alloy for different pulsed magnetic field [19].

A significant enhancement in the mechanical performance of the studied alloy had been investigated experimentally, which is presented in figure 12. Obtained results showed that, the hardness of material increased noticeably in addition to the fracture elongation and the ultimate strength [19].

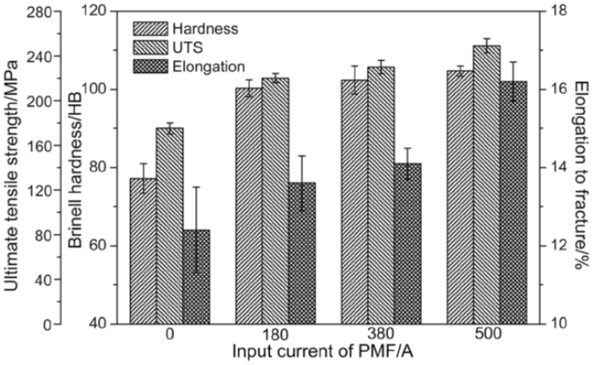


Figure 12. Effect of pulsed magnetic field on the mechanical performance on a 6063 Al alloy for different pulsed magnetic field [19].

VII. **Rainflow algorithm**

Fatigue mechanism is extremely complex to be expressed mathematically especially when dealing with huge amounts of data such as the recorded thrust forces in such a geographical location over the year. However, this can be simplified by converting the complex lifecycle loading to be discrete loads. This would allow predicting the fatigue lifetime of the studied structure more simply with a higher accuracy level. Performance predictions of a tidal turbine is not simple and different methods had been proposed aiming to satisfy this criteria. Fatigue stress is predicted to be generated due to high cyclic loads that varies periodically over the year, which increases the complexity of the study. Rainflow algorithm had been estimated as being the most accurate tool can be used in fatigue life prediction of a tidal turbine affected by oscillating hydrodynamic force. In fact, there several techniques had been developed by researchers that can be used in counting load-cycles. Unfortunately, these methods are complex and require sequencing and arranging huge amount of data. Rainflow counting methodology is easier to be applied and can be used with huge number of data. It mainly depends on the response of the stress-strain characteristic of the material due to applying an external load. A rainflow counting method tends to convert the extremely complex stress cycle (due to fluctuating hydrodynamic forces applied on the blade) into maximum and minimum cycles (also known as major and minor cycles). For a clearer vision, assume an oscillating force is applied on an engineering application and it is required to predict its effect on the structure safety. The applied force is predicted to fluctuate respect to time, which refers to the high possibility of fatigue stress occurrence. For such huge data, using Rainflow counting would be extremely complex and consume very long time. The newly developed software packages allow either coding it as it is represented in the following flowchart or inserting it in such software as Matlab. Matlab has an already prepared function of the rainflow counting that requires only identifying the cyclic loading to start counting them [20].

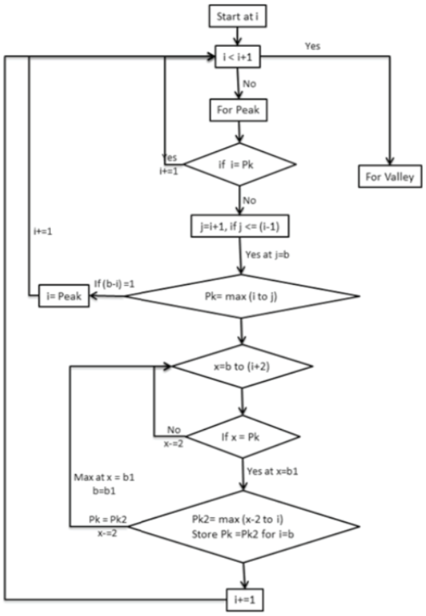


Figure 13. Flowchart of the Rainflow counting coding procedure [20].

Different studies had been applied to investigate the blade lifespan according to fatigue stress aiming to be able of predicting the feasibility of installing a tidal turbine in such a predetermined geographical location. Fatigue stress of a material or an engineering application is commonly investigated either experimentally or mathematically. The experimental approach requires high initial costs and result in destructing the tested specimen while simulation and mathematical studies are much easier. Unfortunately, experimental studies are more accurate and provide a deeper comprehension of the studied case. However, following such a scientific approaches and exact assumptions of simulation studies would help in enhancing its accuracy significantly. The following figure 14 refers to the headlines of these type of studies that tend to count the applied periodic loadings on a tidal turbine blade. Firstly, the time history of the oscillating hydrodynamic force is recorded respect to time, which is counted using Rainflow algorithm. The counted forces are then to be arranged in a histogram to be used in evaluating the mathematical correlation of fatigue life prediction [21].

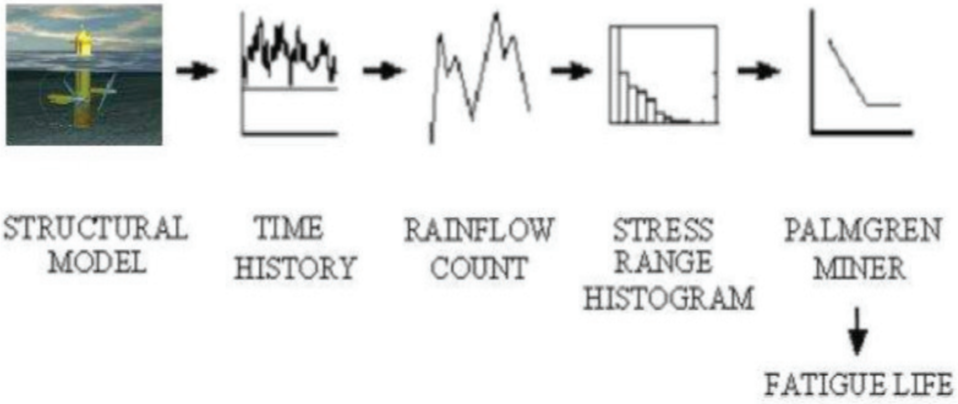


Figure 14. Steps of predicting fatigue life using Rainflow counting [21].

3. METHODOLOGY

The main objective of the proposed mathematical study tends to predict the fatigue life of a blade made of Scandium reinforced (0.4wt %) aluminium alloy when it is affected by a pulsed magnetic field. The decision is taken to assume that; the studied tidal turbine has a diameter of 1000 millimetres, hub diameter of 1788.46 mm, blade pitch is 6 degrees, Length x Width x Height is 150000 x 50000 x 50000 millimetres and the tip speed ratio is 3.61. The horizontal 3-blade tidal turbine 3D model represented below figure 15, while the detailed description of the turbine represented in table 1.

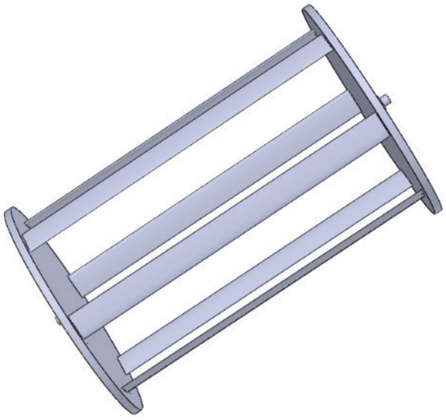


Figure 15. 3D model of the studied turbine.

Table 1. A detailed technical description of the studied turbine.

Parameter	Value	Units
Turbine Diameter	10000	mm
Hub Diameter	1788.46	mm
Blade Pitch	6	Deg
Distance From Centre of Turbine Blade to Centre of Stanchion	2500	mm
Stanchion Diameter	1500	mm
Fluid Domain (Box)		
Length	150000	mm
Width	50000	mm
Height	50000	mm
MRF Domain (Cylinder)		
Depth	4500	mm
Radius	6000	mm
TSR	3.61	
V	3.086	m/s
TurbRad	5	m
Omega	2.228092	rad/s

The decision is taken to examine the effect of the pulsed magnetic field on the blade performance against fatigue. This is decided to be achieved through applying a pulsed magnetic field (180 Voltage) on the blade to refine its structure. Obtained results showed a significant enhancement in the microstructure of the material. In order to attain a deeper vision, SEM image had taken for both the original material figure 16 and pulsed magnetic field material figure 17 to investigate its effect on the microstructure of the material.

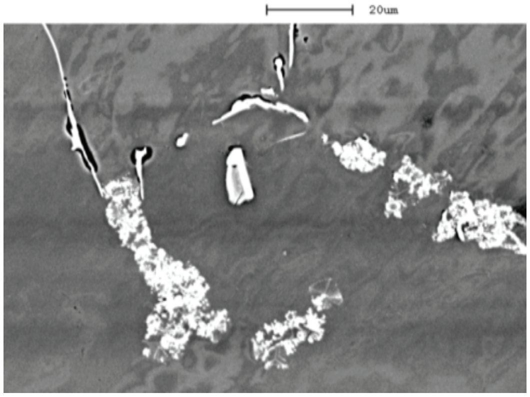


Figure 16. Scandium reinforced (0.4wt %) aluminium alloy without PMF.

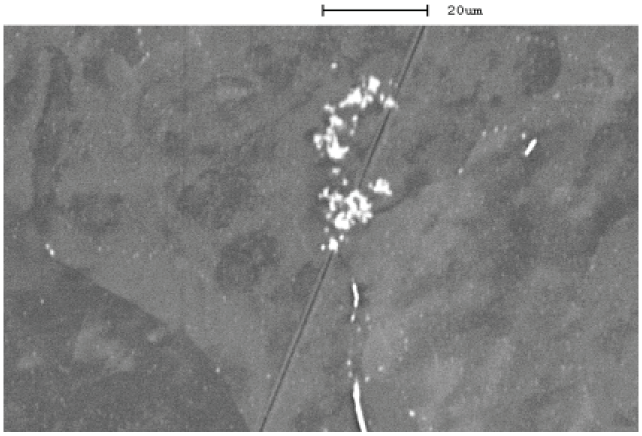


Figure 17. Scandium reinforced (0.4wt %) aluminium alloy with PMF (180 volt).

Fatigue strength of the concerned materials had been investigated experimentally. As specimens of the studied material (0.4%wt Sc.) aluminium alloy with and without applying pulsed magnetic field had been tested experimentally. The specimens' geometrical description (according to the utilized test rig's standard) represented in the following figure 18.

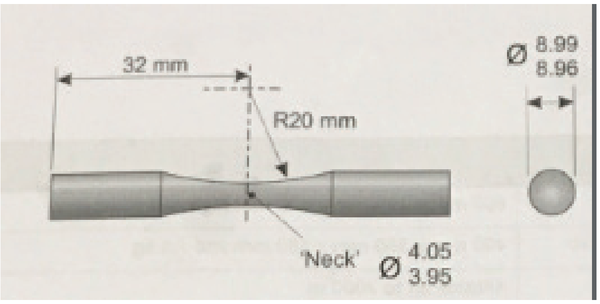


Figure 18. Geometrical description of the studied specimen.

The prepared specimens had mounted to the machine as it represented below figure 19.

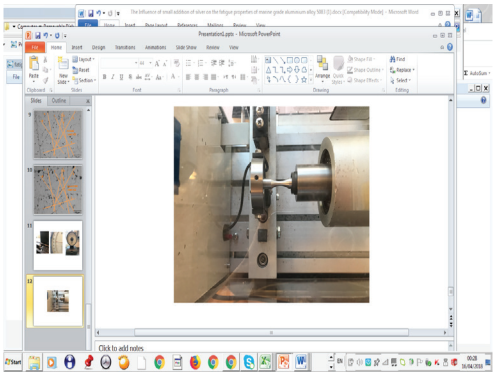


Figure 19. Mounting the studied specimen to be tested.

The utilized test rig applied a cyclic loading until fatigue fracture takes place as it represented below figure 20. Obtained results had plotted graphically and the fatigue failure (at each studied number of cycles) had expressed using a fitted curve using MATLAB figure 21.

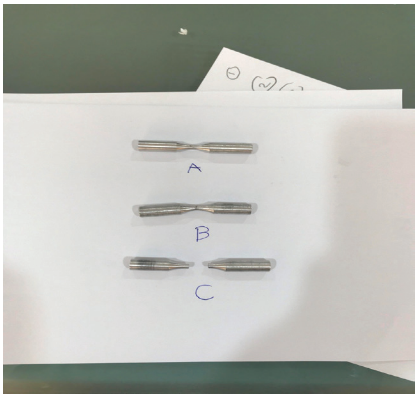


Figure 20. Fatigue failure of the studied specimens.

The S-N diagram for the studied materials can be then used in predicting the fatigue lifetime using rainflow algorithm. Cyclic force is the major cause of fatigue stress, which should be analyzed in order to be able of predicting the turbine fatigue life. The analysis assumed that, tidal turbine blade life cycle is subjected to flow thrust stress. The major factor influencing the life span of a turbine, is the nature of material used in constructing the turbine blades. There exists various materials used in constructing turbine blades, such materials include; steel, aluminum or their alloys. Hence, cyclic stress mathematical expression is quite complex unless dividing these cyclic loads into frequencies. The prediction of fatigue life considered that, the cyclic stress is subjected micro cracks generation as it is a main source of energy loss, vibration and improper operation of the turbine. Experimental investigation of fatigue for a turbine blade is very expensive especially for heavy duty blades, as it depends on effecting on the blade by a cyclic loading until fatigue fracture takes place. This is predicted to result in an unnecessary economic loss. Simulation and experimental studies were executed in various studies to predict the life span of a turbine blade according to fatigue only, as involving more than a single form of failure would result in a significant increase in the study's complexity. The life cycle was pointed out in this study as per the executed thrust force on turbine blades for a given period of time [22]. MATLAB is used in providing the feed parameters that rely on the preceding measurements.

To measure the effecting hydro-forces on the turbine blades, knowledge on their main source is essential. The stored kinetic energy presents in the flowing fluid (seawater) is converted into mechanical energy through the turbine hydro-dynamic pattern. This hydrodynamic force results in affecting two main forces, drag and lift forces. The environmental conditions under which the turbine blade operates below the sea level are not constant.

Hence, both the lift & drag forces regularly oscillate from a time to another. For a wider vision, assume that; the concerned fluctuating forces are represented in the following two figures 21and 22. It is clear that, the turbine blade thrust force executed with a mean thrust power. The sinusoidal characteristics of thrust power is because of the rotational motion of the blades as well as the turbulence intensity from a time to another.

The graphical description of drag and lift forces is shown in the relationship between time ranges of 0-27 seconds alongside the rotational angles of 0-3300 degrees Celsius. Numerical values recorded will help in the generating the algorithm of the rain-flow with a motive of enumerating the quantity of cycles in each loading cycle.

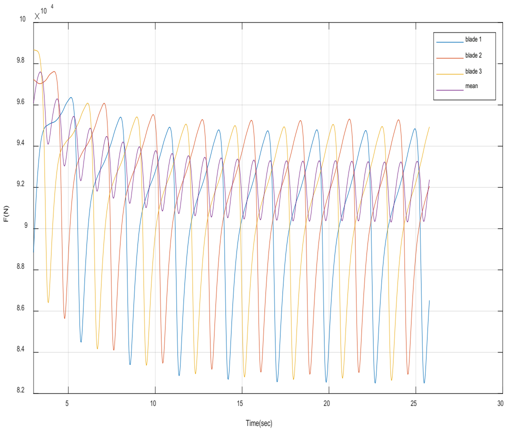
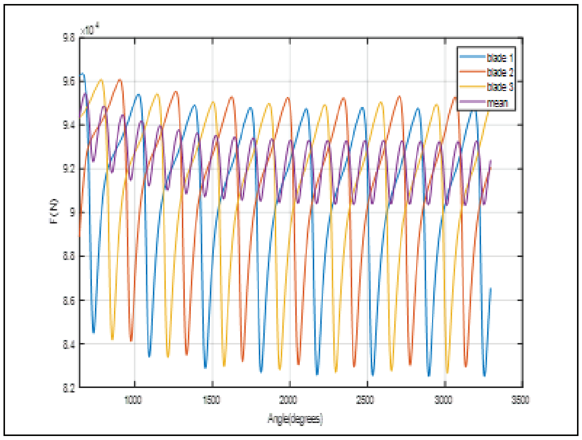


Figure 21. Thrust forces applied on the blades from 0 to 27 seconds.

Figure 22. Thrust forces applied on the blades from 0 to 3300 degrees.



Predicting fatigue stress using rainflow algorithm using MATLAB is not simple and require following such steps that are described as follow;

(a) The numerical values were inserted in the software (MATLAB): where, thrust force applied on every blade, oscillation angles, periods and mean thrust forces are assumed as being the important and influencing parameters and considering more parameters would result in a significant increase in complexity of the study.

(b) Estimating the cyclic force using the rain-flow algorithm, which is a technique that involves mathematical expressions used for enumerating the cycles by rearranging the amplitudes of the cycle identically similar to rains. The following figure 23 shows the methodology for cycle enumeration with the help of command of the algorithm that influences the histogram pattern, which confirms the enumerated quantity of cycles within the stress range.

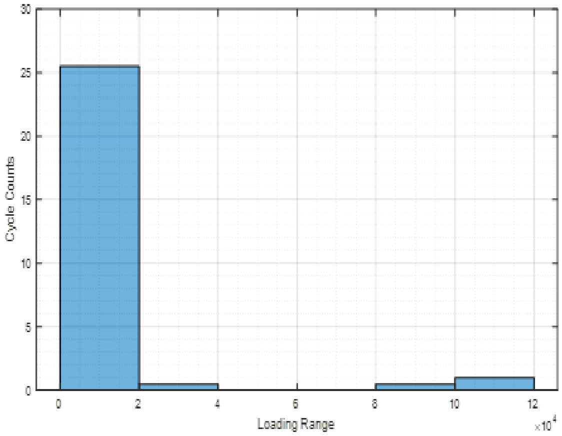


Figure 23. Average thrust fore frequencies using rainflow algorithm.

(c) The damage equivalent load (also known as D.E.L) can be mathematically expressed as follow;

$$D.E.L = \left(\frac{\sum_i (l_i^m * n_i)}{t}\right)^{m^{-1}}$$

Where; t refers to the blade thickness (mm), is the time history, m refers to the negative inverse S-N curve slope m (differs depending on the type of material used in the construction of the blades) and quantity of cycles is . The empirical relationship for the studied depths (5, 10, 15 and 20 m) and different operating times (8, 16 and 24 hours) had been solved the turbine using MATLAB. (i) refers to the number of trials made (for this study 20 trials were done).

The rainflow algorithm automatically coincided with the history of time and the span of fatigue stress. m had been indicated based on the S-N diagram had been formulated experimentally as it is discussed before. m varies from a case to another, as the S-N curve of the studied material is investigated to differ by varying the voltage of the applied pulsed magnetic field. The following table shows the indicated m for the studied Aluminum alloy with and without applying a pulsed magnetic field. These values are constant for each case and will not be changed by changing the cyclic loading, depths, etc.

Table 2. Effect of PMF on the material's negative inverse S-N curve slope (m).

	With PMF (180 v)	Without PMF
m	6.79	7.18

(d) The same analysis of equivalent damage fatigue loading had been applied depending on the calculated damage equivalent load together with the projected area of the blade, which is assumed as a rectangle.

$$\mathrm{S.E.L_i} = \frac{\mathrm{D.E.L}}{A}$$

(e) The predicted life span of the blade is calculated using the following equation [23];

$$\mathrm{lifetim\ e_i} = \left(\frac{\mathrm{S.E.L_i}}{\mathrm{S_f}}\right)^{-\mathrm{m}}$$

Given that, (S_f) represents the end fatigue loading, S_f value for the material from each case (had been investigated experimentally).

(f) As soon as investigating the pulsed magnetic field effect on the studied aluminium alloy, different depths and operating hours will be studied mathematically to be able of predicting their effect on the lifespan of the studied tidal turbine.

4. RESULTS ANALYSIS

X. Experimental results

The experimental study had been applied on the standardized specimens made of the studied aluminium alloy (with PMF) allowed predicting the fatigue failure at a cyclic load after certain number of cycles. Obtained results represented in the following figure 24 and it is clear that, increasing fatigue stress results in a noticeable reduction in the number of cycles. Points had plotted using Matlab and a fitted curve had commanded as it represented in the figure 24. In fact, plotting the S-N diagram of the material is vital to calculate the fatigue lifetime of the turbine. As factor (m) had been indicated based on the figure shown below, which represents the negative slope of the S-N diagram of the material.

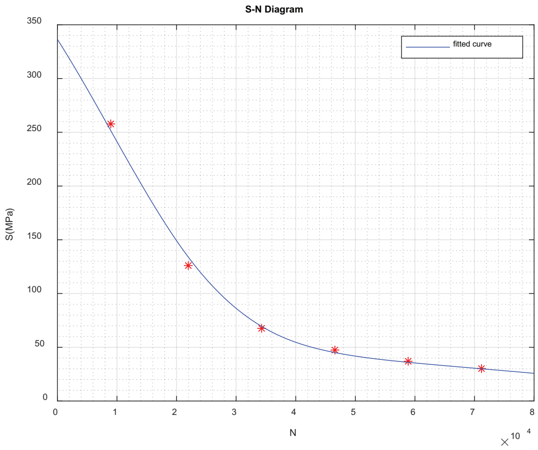


Figure 24. S-N diagram for the aluminium alloy with PMF (180 v).

XI. Mathematical results

By following the steps had been discussed in details in the methodology section, the fatigue lifetime (years) can be indicated for different thicknesses. It was clearly investigated that, increasing thickness of the material would result in increasing its service lifetime. However, increasing the blade thickness is not favourable due to the noticeable increase in the blade mass resulting in reducing its efficiency as well as increasing its initial cost. The results represented in figure 25 when the studied tidal turbine is installed under seabed by 5 metres and it is assumed to operate for 8 hours.

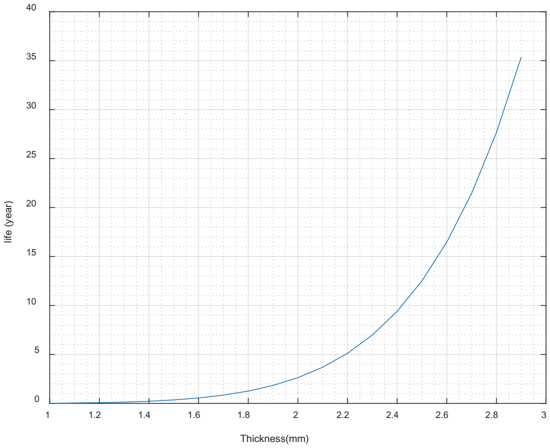


Figure 25. Fatigue lifetime for the aluminium alloy with PMF (180 V).

Aiming to widen the study's comprehension regarding the parameters that influence the fatigue resistance of a tidal turbine, four different depths had been considered in the study. Each tidal turbine installation depth had been solved using the same scientific approach to attain a reprehensive comparison. Obtained results showed that, increasing the installation depth of the studied tidal turbine has a significant effect on the fatigue service lifetime for all the studied blade thicknesses. It was predicted that, the maximum service lifetime is achieved when the tidal turbine is installed under 5 metres beneath seabed while the minimum service lifetime is achieved when the tidal turbine is installed under 20 metres beneath seabed. Obtained mathematical results are represented in figure 26.

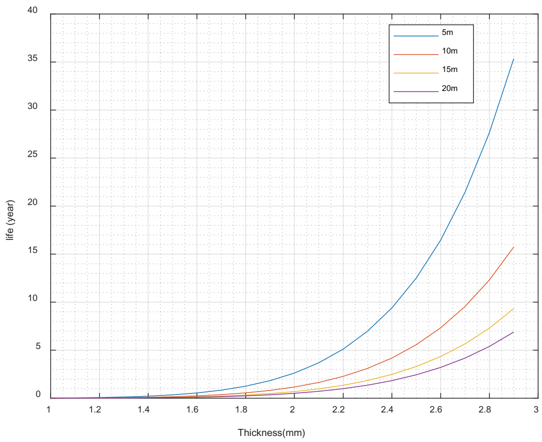


Figure 26. Effect of the tidal turbine installation depth on its fatigue lifetime with PMF (180 V).

Additionally, the operating hours of the studied tidal turbine was investigated to be highly influence its fatigue lifetime that encourages studying its effect. Three different operating times had been considered in the study and obtained results were logic. Obtained results allowed predicting that, increasing number of operating hours results in a significant reduction in the tidal turbine fatigue service lifetime for each studied blade thickness. Obtained mathematical results are represented in figure 27. It was predicted that, the maximum service lifetime is achieved when the tidal turbine is operated for 8 hours daily while the minimum service lifetime is obtained when it is operated 24 hours a day.

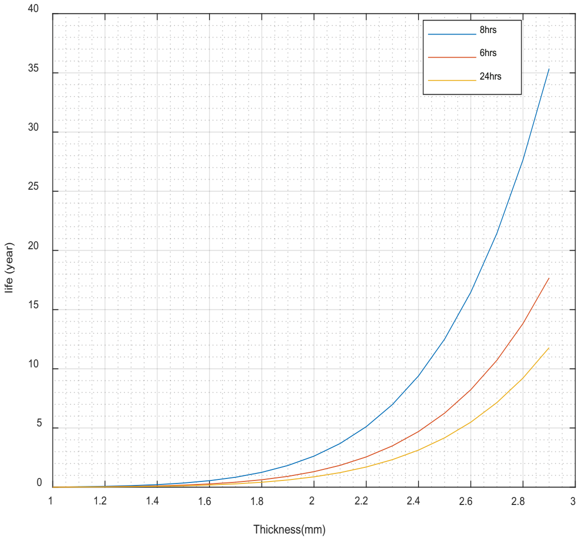


Figure 27. Effect of the tidal turbine operating hours on its fatigue lifetime with PMF (180 V).

5. DISCUSSIONS

Tidal energy had been paid a noticeable attention last few decades due to its promising performance and ability of sharing a high percentage of the global energy demand. This performance had been achieved based on optimizing such parameters that enhanced tidal turbine efficiencies, reduced their initial costs and decreased their maintenance requirements. Designing, manufacturing, installing and operating a tidal turbine is complex processes that require deep recognition of the expected operation scenarios. Different parameters are investigated to influence the performance of a tidal turbine as well as it safety.

Fatigue failure is one of the most important mechanical fracture forms that should be determined accurately to be able of predicting the service lifetime of the turbine, which helps in determining its economic feasibility. Fatigue starts as soon as micro cracks are generated on the blade surface, which results in increasing its surface roughness leading to a noticeable reduction in its energy conversion efficiency.

The material selection decision is considered a key issue of the tidal turbine efficiency and safety. Each material can be selected in satisfying such requirements is estimated to provide a group of advantages and disadvantages that fit with such operating and environmental conditions. A blade material should not be characterized by its high density, which would result in reducing its output. It should be advantaged by high mechanical performance to avoid either increasing the blade thickness (increasing weight of the blade) or increasing its initial and running costs. As increasing thickness to attain a high safety factor against the expected conditions is investigated in different studies to result in reducing the power coefficient of the turbine resulting in reducing its output. Aluminum alloys are known by their high mechanical performance, high manufacturability and low density. Its performance can be enhanced by the modern techniques such as pulsed magnetic field.

Fatigue life of an operating tidal turbine is highly affected by it's the material properties and the blade thickness as well as the environmental and operating conditions. Due to the high complexity of fatigue mechanism description as well as the seasonal fluctuation of the applied thrust forces on each blade. Rainflow algorithm had been used in rearranging these forces. This allowed investigating the fatigue lifetime of the studied turbine for different thicknesses. Increasing the blade thickness investigated to effect positively on the turbine lifetime, while it expected to affect negatively on its energy conversion efficiency.

In fact, fatigue lifetime is investigated to be affected by different parameters as well. These parameters are either related to the operation of the turbine or the environmental conditions. The installation of the tidal turbine under sea level is investigated to highly effect on the fatigue lifetime of the turbine due to the higher thrust forces applied on the turbines. The mathematical model of fatigue had been coded using Matlab allowed predicting the noticeable effect of the installation depth of the turbine on its service lifetime as increasing it resulted in a dramatic reduction in its life. Moreover, heaving the turbine duty by increasing its operating hours on a daily paces investigated to negatively effect on the turbine fatigue lifetime. Hence, it is highly suggested to optimize both of the installation depth as well as operating hours based on the required electrical power output and expected turbine service life.

6. CONCLUSIONS

Tidal turbines are such energy converters that affected by a group of tough environmental surroundings and diverse operating conditions. These circumstances fluctuate over the year, which makes predicting their life cycle complex. The material used in manufacturing a tidal turbine blade is a key issue of its performance and efficiency. Aluminium alloys provided promising performances regarding satisfying the duties of a tidal turbine efficiently. Their mechanical properties can be enhanced using pulsed magnetic field (PMF) as well. Using PMF Aluminium alloys tidal turbine blades should optimized to achieve a desired lifespan tidal turbine as well as high-energy conversion efficiency. In addition, the blade thickness highly influences the fatigue lifetime of the turbine. On the other hand increasing thickness of the blade results in increasing the blade density, which results in a significant reduction in the turbine electrical power output. Both of the turbine installation depth under sea level as well as the number of operating hours of the turbine highly effect on the fatigue lifetime, which encourages suggesting paying a high attention to them during designing and operating a tidal turbine.

They should carefully monitored in order to maintain the electrical load required. In addition to accomplishing the payback period of the turbine to assure achieving economic benefits.

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APPENDIX A: ABBREVIATIONS

LCF: Low Cyclic Fatuige

HCF: High Cyclic Fatuige

FSP: Fatuige Samples Polishing

HAZ: Heat Affect Zone

TMAZ: Thermomechanically Affect Zone

DEL: Design Equivelent Load

SEM: Scaning Electron Microscopic