Fatigue Analysis for Fe-34.5Mn-l0Al-0.76C Tidal Turbine Blades using Rainflow Algorithm

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This study investigates the effect of the environmental conditions (seawater mean thrust force and flow velocity) on a tidal turbine for different thicknesses mathematically. This had been achieved through predicting the fatigue stresses applied on the turbine for different conditions using Rainflow algorithm. The blades of the tidal turbine should be characterized by a low roughness to reduce eddies formation downstream the seawater flow. Fe-34.5Mn-l0Al-0.76C alloy had been selected in this study. Obtained results showed that, increasing thickness of the blade resulted in increasing the turbine lifespan for each studied flow velocity and thrust forces. However, increasing the flow velocity is predicted to increase the thrust forces due to the wake region formed downstream the flow leading to increase the fatigue stress on the blade. Consequently, the blade thickness should be optimized based on the geographical location decided to be installed by a turbine. As the geographical location effects on the environmental conditions significantly, which should be considered during the design stage to prevent fatigue failure of the turbine. Optimizing the blade thickness would help in maximizing the energy conversion efficiency of the turbine as well, as a lightweight blade would be able of generating electricity higher than heavy ones.

Introduction

The clean source of energy is highly demanded nowadays than before, that is why governments are paying attention towards developing this green energy. The main concept of generating electricity based on clean sources of energies had become a vital demand. These renewable sources of energy as the geothermal, tidal, solar, etc. the governmental organizations are planning to invest in these green energy sources, they are also supporting the researches to develop, enhance and discover this sustainable power [**1**].

Recently, different methods are introduced to generate electricity. Researchers and engineers are taking into consideration replacing the conventional generating techniques with newer, smarter, cleaner and more durable sources of power, the MTA technique is considered a very successful technique in this field, the abbreviation MTA stands for (Marine Turbine Array). Unfortunately, this promising technique needs a proper maintenance plan along with neat monitoring system resulted an effective electricity generation plant. Nowadays, engineers and scientists are paying high level of attention towards building these techniques economically while attaining high energy conversion efficiency. The part of explaining and introducing a proper presentation about this studied technique (MTA) should consider the processing principles and provides a brief introduction about its different parts and elements affecting the performance of these systems. These procedures are helping in maintenance plan selection operation as well. A turbine array has similarly the same principle of operation for wind turbines but still be a difference between them, which is the working fluid. The main working theory starts by the incoming waves, these waves strikes the blades which are linked together at the hub of the turbine. Consequently, the blades start to rotate and transmit the mechanical power to a rotary shaft, this shaft transmits the received mechanical energy to a generator that is responsible for producing electrical power. It is also considered an example for energy conversion process whereas the input is a mechanical force applied and the output is an electrical power by an electrical generator. In other words, converting the mechanical energy to electrical energy by an electrical generator [**2**].

Multiple turbines are installed in a specific coastal location to improve the output, which increases the dependency level of this technique. The marine turbine's direction of installation got an important relation to the waves vector as the appropriate direction leads to a higher efficiency level to be obtained by the turbine, this raise in the mechanical energy level is also resulted in enhancing the electrical energy generation rates [**3**]. The output power in Watts varies as the waves haven't stable motion, so it ranged from megawatts to gigawatts as for little stations and large ones respectively. As for that, receiving these huge amounts of energy will definitely meet the high global energy demand. The difference between isolated arrays and turbine arrays is that, last one takes place after examining much greater performance, thus, the synchronization between both of them greatly helps in achieving the required output and enhances the reliability and dependency of it [**4**].

Energy engineers illustrated the main reason for determining the payback period of the plant based on the initial cost and weather changes. Climate changes occur in any location results in reducing the stability of tidal turbines. the procedure is by maintaining the output power range as desired as possible as it could be. Experienced designers advise to follow their specific rules in order to detect the most convenient maintenance plans according to some specific failure scenarios. As for that, longer working hours and much more efforts expected to be saved. These recommendations are varied in case of comparing wind turbines with tidal turbines as the wind potentials are extremely low. It is worthy to state that, the wind turbines are very small to be affected by weather fluctuations as opposed to tidal turbines, moreover, the seawater got a higher density rate than the air, which means more applied stress on the turbine blades. The global market covers nearly all the needed turbines as per their characteristics and types. The scientists are considering that the appropriate turbine should be fitted with a suitable sizable application in order to generate appropriate power rate. On the other hand, bigger plants are storing greater amounts of hydromechanical power that could be obtained only by huge capacities turbines. The manufacturers and suppliers are providing a large rate of different turbines capacities, each turbine should be maintained periodically and using the appropriate maintenance processes that assures achieving the highest performance and lifetime of the turbine [**5**]. Blades play an important role in improving the performance of the turbine, so it is necessary to design such profiles of these blades that are not complex to be manufactured. In addition, the turbine should be able of withstanding against the loads applied on it in the harsh environments. In addition, producing energy effectively. The efficiency of a blade can be improved by increasing the thickness of the hydrophilic and thus increasing the hardness in the area of the blade root. Another important factor that can improve the performance of the turbine is the appropriate selection of the blade material, as it should have higher levels of strength than the applied hydrodynamic forces [**6**] and to have the ability to resist the corrosion of the working environment. For this project, the life service of turbine blades made of Fe-34Mn-10Al-0.76C alloy was investigated. This high strength steel alloy contains row materials of iron (Fe), Magnesium (Mn), Aluminum (Al) and carbon (C) in different proportions. The Fe-Mn-Al-C alloys are distinguished with their low density that offers superior mechanical properties with specific lightweight. In addition to high strength and toughness, good fatigue and corrosion resistance. These characteristics allow the selected alloy to be a promised selection for the tidal turbine industry [**7**]. The alloy Fe-34Mn-10Al-0.76C was firstly developed by Ham and Cairns in 1958. They aimed mainly to replace the nickel or chromium in steel by less expensive Aluminum and Magnesium, this action can improve the corrosion resistance characteristics of the resulted alloy as well as decreasing its weight [**8**]. The impact of Aluminum and Carbon content on both the tensile and stiffness characteristics of Fe-Mn-Al-C alloys in the case of hardening has been studied. It has been shown that the properties of the Fe-Mn-Al-C alloy are based on the phase components in addition to their distribution [**9**].

Although the concerned stainless-steel alloy provided promising performance regarding satisfying the expected duties, it is not the only material used in tidal turbine blades' manufacture. According to data provided by [**10**], about 88.8 of SeaGen tidal turbine blades manufactured from steel. On the other side, a minor percentage of this turbine is manufactured from copper (for exteremely corrosive environments), iron, stainless steel and other materials.

Another study concerned on comparing the mechanical characteristics of two stainless steel alloys, Fe-34.5Mn-l0Al-0.76C and Fe-30Mn-8Al-1.5Si-1.0C. This study concluded that when the Aluminum content is higher than 10%, d-ferrite can be inserted into the microscopic structure in the form of a banded phase, which leads to reducing the plasticity and durability of the produced alloys in addition to improving the mechanical features. In this case, the origin of the major crack is the c / d interfaces due to the mismatch in the deformation of the two phases. However, the increase in Carbon content up to 0.7% leads to an increase in strength, stiffness and ductility. And when the Carbon content exceeds 0.7%, the strength stays on increasing while the deposits lead to reducing the ductility and hardness [**10**]. According to the massive importance directed to the marine turbines, the researchers have started to produce more and more studies and simulations to detect the worst-case scenario for different operating situations, as a result, those simulations and studies have supplied the manufacturing sector with the most maintenance plans in order to reduce potential mechanical failure as well as sudden system shutdowns. The process of converting mechanical energy load to electrical power requires great cost as for modelling, installing and introducing a proper maintenance plan. The prime target of this review is to detect and determine multiple maintenance plans on a marine turbine, to achieve that, a short briefing about the primary and secondary objects for the turbine will be studied in order to identify the various processing situations, thus, detecting the most appropriate maintenance plans. Factually, the hard-environmental fluctuations affecting this turbine may cause sudden shutdown cases and failure scenarios. The valid expectation of the worst-case scenario is the main factor that detects weakness points for the turbine array.

Technological review

The marine turbine array consists of multiple number of components that are responsible of transforming the hydrodynamic energy from tides to electricity by taking the advantage of a rotary shaft. Exact installation and fitting for these components is the key issue of improving the plant's performance. Therefore, additional equipment and tools are used to enhance the turbine's output performance, these major components are generator, high-speed rotary shaft, blades, support and controlling system, gearbox, drive shaft, hub and support. One of the man operating principles for the turbine is outer blades design that should be able to convert the incoming tidal waves motion into another form of power by the rotating shaft. One way or another, the turbine blades are rotating because of the flow stream force, that's why the main turbine's performance is highly depends on how these blades are constructed and designed. **Fig. 1** indicates the vertical construction for the blades [**11**].

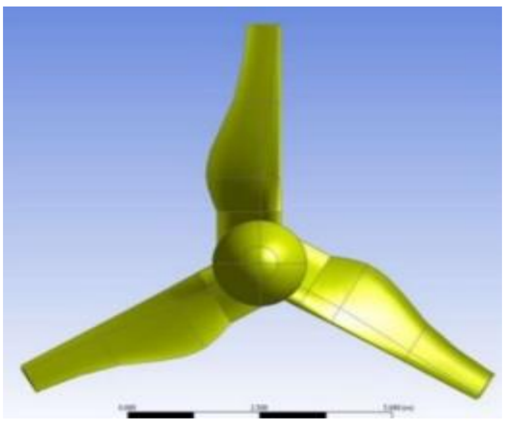

Fig. 1. Configuration for the blades installed in a turbine [11].

Factually, marine turbine array is characterized as per various elements as the blades size, filled area and the dispositioning either vertical or horizontal. As aforementioned, the principle of operating is highly demanding on the aerodynamics design of the blades, thus, various factors are determining the design behavior for this blade. As before, the dispositioning process either vertical or horizontal is highly important technique and should be identified before initiating the design operation. There is another essential factor to be determined in the beginning of the design as well which is the cross-sectional area for the blades. The NACA aerofoils are one of the most famous procedures followed to detect this cross-section structure, the exact number of blades as well as the chord length for the turbine is greatly important and shall be pre-identified by scientists. The modelled blades have to be mounted on an assembly point (hub) to assure a convenient fitting for the overall body and this is the ultimate purpose for the hub. To identify the hub part among all these important parts, it is the rotary part connected to the generator and holds the blades from the outside. When an incoming air streams strike the outer surface of the blades, mechanical torque is produced then which always leads to generate great torsional forces applied. These applied forces are important to be considered in the initial selecting decisions for the hub, some other economic decisions have to be considered as a step to build the turbine properly and accurately. The produced torque taking place on the prime shaft is directly or indirectly (in some cases) linked to the hub. The naming of the (low speed shaft) returns to the prementioned prime shaft, some sensitive operating situations as shutdowns and startup system tasks may cause some torsional defects in the shaft. The gearbox's main mission is to handle the rotational speed for the shaft as s pre-step before delivering it to the generator, by other words, it is the frequency controlling part (speed regulator). Speaking of the main importance to the transmission system (gearbox), it supports the generator in the low rotating speed conditions, on the other side, the overcome speed values (greater than the cut-off value) for the blades are considered dangerous and could harmfully affect the generator, that is why there is a proper protection system for such cases [**12**]. The following **Fig. 2** indicates a gearbox system for a tidal turbine's plant in the United Kingdom [**13**].

The showed mechanical parts are considered energy converter equipment by transforming the kinetic energy saved in seawater motion into mechanical power and then comes the electrical system that converts this mechanical power into the electrical one. The master piece for the electrical system is the generator of course which is easily available in the global market with different cost ranges and characterizations. Selecting the most appropriate generator is not as easy option as it will lately determine how sufficient is this plant as well as the economical side, to insure selecting the desired generator, some required elements must be verified as the desired mechanical power out of the turbine along with the overall electricity rate for the plant and the blades rotational velocity [**14**].

Fig. 2. A turbine gearbox [13].

The next stage in the electrical power delivery process is saving the generated electricity in large rate capacitors or any other direct current (DC) storage options as batteries, additionally, it can be directly connected to the alternate current distribution network [**14**]. The engineers are highly recommending understanding and identify the lifespan for the turbine as a step towards saving the turbine's performance at the desired level, additionally, they are stating that the maintenance plan is ultimately important than any other stage mentioned before to guarantee a smooth-running operating, the environmental effects are equally important to the maintenance plan. Thus, providing a proper maintenance strategy shall be considered as well as a regular monitoring to check the turbine's operating status. The proper maintenance plan could evade unwelcome failure cases for the turbine. The following **Fig. 3** is the whole lifespan for a tidal turbine was built and used inside the United Kingdom. [**15**] stated that the maintenance operation is highly important and critical as its absence may lead to great economical losses for the lifecycle of the turbine and the overall electrical power output.

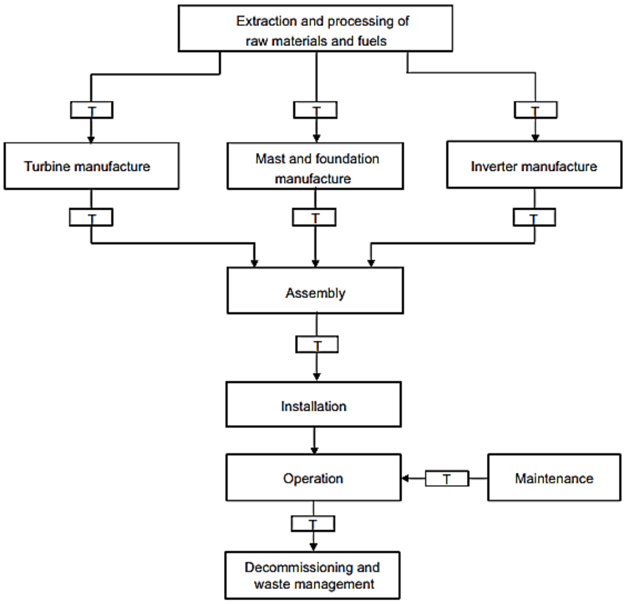

Fig. 3. The micro hydro-turbines lifecycle [15].

No matter how the marine turbine's type varies, the operating principle remains the same, there are various operating conditions should consider to properly indicate the most suitable type, hence, a proper background about the available turbine types in the global markets is very essential step for designers which results the desirable lifespan and overall performance. Nearly all the available global market turbine types are illustrated in Table 1 alongside with characteristics, these different types are varying according to multiple purposes and needs. The contents in this table have been gathered from suppliers and manufacturing companies after many examinations and conclusions. As for that, some vibrations cases strictly forcing the whole system to be shutdown to perform maintenance or even during the operation. Selecting the proper turbine for the desired application is highly important as aforementioned, ignoring such a prime factor may cause massive losses in lives and among the wildlife as well, ignoring this factor is occurred by selecting improper turbine for the detected load, which means a totally different operating condition. Not just the wildlife is affected, human injuries could happen for workers and technicians. As a result, determining the desired turbine based on the project is the best way to keep and maintain the desired output level and to evade losses in maintenance running cost as much as possible [**15**]. This part is taking care of comparing between different parameters affecting the efficiency and overall performance for the turbine among different kinds of them.

On the contrary, the installed transmission system (gearbox that transmits and regulates power from blades shaft to the generator) is highly expensive as comparing with other kinds, this SR2000 turbine is perfectly converting the received mechanical energy input into electricity. The factor that deeply determines how efficient the selected turbine is; goes back to the energy intensity and definitely not the output power. The energy intensity term refers back to the amount of energy per surface area, the vertical and horizontal configurations are both serving the required energy conversion operation and they are both utilized based on sensitive parameters that deeply determine the turbine's type. The blue turbine is featured with the highest speed ever if comparing with different types of turbines, but the Tocardo DD1000 is known for its light weight among all the others. The manufactured materials are differing in their characterization depending on their stress withstanding ability, the applied mechanical force acting on blades should help in determining the appropriate material used to insure greater rate of safety and efficiency, on the other side, selecting improper materials for the turbine leads to different cases of shutdowns and failure processes as this material selection process is not that easy as it looks like, the engineers are recommending to have a deep knowledge about the possible applied force on the blades and the turbine as well before even taking any other steps, they are also considering the mass limitation is a possible factor and should be considered as well if it is there.

The manufacturers are putting another factor into the area of importance which is the Cp (power coefficient), this factor expresses a dimensionless number refers to the performance to be achieved by the turbine. The main purpose of this factor is to understand how the turbine really operates. As for the power coefficient calculations and examinations, the sea flow turbine is the highest performance turbine as it delivers the greatest performance operated by an asynchronous generator (Squirrel cage type), as it also provides a big rate of frequencies owing to the gearbox. This turbine is also characterized by a perfect ratio between the swept area according to the overall weight if comparing with many other types. There are more related to the overall performance factors as the occupied area, rotational velocity for blades, the hub and the measured rotor diameter.

The environmental effects

The marine turbine has a tough mechanical design to withstand different operating scenarios and environmental circumstances, for example, this turbine is designed to be operated beneath the sea water level and as for that; multiple characterizations must be considered during designing the turbine. Factually, the environmental effects cannot be completely defined since the fluctuations are not predictable for all seasons. The ocean turbulences are the main mechanical failure reason, additionally, gathering the needed info out of the selected location important for building the turbine properly. Sea waves are causing massive harm for turbines parts, as for that, multiple studies represented to indicate the essential fatigue applied for the horizontal axis turbine [**16**]. The random turbulence motion is a big effecting factor that takes place on the turbine's lifecycle. As [**17**], it was dedicated that the spreading characterization of the waves post motion will absolutely affect the turbine's speed, thus, maintaining turbulences is highly important for the overall station. Technically, studding the different environmental effects on the turbine's performance helps to bring out the most effective maintenance plan as a method to save the electricity generation. Thus, nearly all the effecting elements must be considered while manufacturing the turbine. Salt concentration in seawater determines the density rate for the water, this deeply effects the turbine's performance as well as the overall lifespan.

The drag force expected to be held by blades could vary according to water density fluctuations. [**18**] stated recently that variable salt concentrations are the main cracking reason over the years. The researchers are stating that the density rate fluctuations is not the most dangerous factor for salt concentration as they have raised the safety factor level to assure a proper enduring against any undesired fatigue cases for the turbine. As it is very preferable not to implement high erosion materials rate refers back to their harmful effect on the overall performance and lifespan [**19**]. Therefore, the selected Fe-34Mn-10Al-0.76C alloy for this project (Fe-34Mn-10Al-0.76C), is expected to provide improved performance for the designed turbine blade.

The resulted erosion because of the concentrated salt rate is badly effect on the blades performance. **Fig. 4** illustrates the erosion impact taking place on the blades. As the surface roughness increases due to the erosion factor, the experimental studies showed that the drag factor decreases as well. For all of that, the changeable resonance waves are the main mechanical failure causing factor and as aforementioned, whenever the surface roughness rises, the erosion factor goes with it while the magnitude of vibration is maintained to set it at a reasonable rate.

Fig. 4. Erosion impact for a turbine blade [20].

Additionally, the weak surface roughness rises the outer flow resistivity which can disfigure aerofoil designing that leads to decrease the overall output because of the power dissipation. The engineers are representing multiple studies in a step towards investigate how the Molecules react versus erosion. Measuring the erosion ratio is considered the main barrier as there are no modern tools capable of doing this task precisely so far. The precaution maintenance plan is one way or another capable of detecting an approximate range for the erosion level. Thus, critical precautions are put into consideration to evade raising this level [**21**]. The Biofouling formation is also a very harmful impact on the marine turbine overall performance, this wild phenomenon cannot be totally terminated although it can be decreased. These Biofouling are some existed growing up plants lives beneath the seawater level; these plants are causing serious erosion effects on the running blades [**22**]. Well understanding for these live creatures could result in decreasing the erosion effect, thus implementing the proper maintenance plan. Periodic maintenance plans must deeply put into consideration these different plants to clean up this mess, this leads to remain the overall performance as desired and to prevent any undesired erosion cases. This phenomenon is also affecting some internal parts as the hub and so many components. **Fig. 5** shows an accumulated biofouling on a turbine's blades [**21**].

Fig. 5. Some Biofouling accumulated on tidal turbines [21].

The unstable climate fluctuations occurring these days are causing serious variety in wind velocity which leads to maximize the seawater turbulence rate. Designers must put these different fluctuations into consideration in order to build a proper turbine structure stands against the different environmental impacts. After many years of operation, the resulted fatigue react becomes the overwhelming mechanical stress. Thus, not considering performing a proper visualization may lead to sudden facture cases without any pre-alerts. As the depth increases, the electrical generation comes bigger too, that is why these marine turbines should be installed under the sea level where the speed magnitude is at its ultimate rate with a uniform flow rate.

On the other hand, as the depth maximizes, the overall applied pressure goes with it which means raising the risk level, this applied pressure may cause some fatigue occurrences. As the depth decreases it obviously harden the maintenance operation. Practically, installing these turbines under unidentified depth may makes it harder to build them properly. Thus, a proper depth estimation must be identified for the turbine. The following factors must be considered when performing this maintenance plans; net cost estimated, the desired output range, expected risk besides some familiar environmental factors [**23**].

Maintenance review

The most appropriate maintenance plans are only applied successfully by seriously understanding the most common failure cases alongside with observing and studying the most fit maintenance plan that goes with the required output. The following **Fig. 6** is about an overall turbine model, this figure tends to illustrate some suitable maintenance techniques as well as the main failure source for some parts. Practically, organizing the maintenance plans period is highly important to keep the turbine as long as possible, which means, if the output rate for the turbine stood still as it is expected then the maintenance must be scheduled and applied properly.

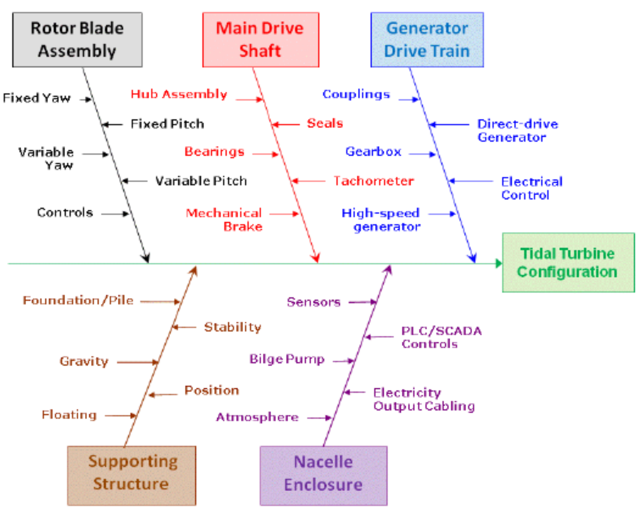

Fig. 6. Chart for Tidal Turbine model [24].

Supporting structure

The supporting structure is designed to withstand the outer load applied on the tidal turbine as a result of the ocean water drag forces, furthermore, the turbine's structure is estimated to be affected by non-negligible load. Additionally, engineers and experts are considering high safety levels to rate the unexpected effective factors that may cause serious failures, the most common failure cases are fracture, impacts, creep and buckling. The buckling failure does not bring out immediate cracks or fractures, the electrical energy decreasing rate might be the first evidence for the buckling failure.

Thus, it is very recommended to install a monitoring system to keep an eye on every single crack happens inside the structure. The buckling failure is also deviating the angle the thing that will notably reduce the output. The turbine structure's maintenance is considered the most complicated if compared with to the other parts. Speaking of the creep failure, it is a time relative failure resulted due to fixed force applied with no temperature variation in degrees.

The operated monitoring system is an integrated sensitive system that contains multiple sensors, strain measurements tools are estimated to measure the strain force applied on the frame in order to determine the appropriate maintenance plan especially if the situation required to pull the turbine out of the seawater to add some needed supporting parts. [**24**] stated that the last two factors which are the unexpected effects and the mechanical failures are considered an essential threating source, these two factors must be evaded by certain conservation plans taking place during the periodic maintenance.

Gearbox

Scientists are referring back the importance of the gearbox to control and maintain the resulted frequency of the produced alternating current, by other words, the gearbox system is highly assisting to minimize the destabilization cases caused by the various seawater motion. As any essential part of a successful structure, the gearbox is designed to face different cases of failures to keep the desired output of course. Seeking inside the gearbox structure, the internal rotary mechanical parts are affecting the output electrical rate because of the vibrations occurrences no matter its type was, additionally, to treat this undesired failure, engineers are recommending using the modern magnetic gearbox system.

This magnetic model is significantly smoothing the maintenance operation and also reduce the lost power that happens because of the friction between metal parts and any other lubricant oil leakage cases that may raises the friction rate between metal parts and this may lead to another failure case [**25**].

Main drive shaft

The exerted seawater kinetic energy is converted to mechanical energy that comes out with mechanical torque and rotational speed. This drive shaft's main job is to deliver the generated mechanical energy and modify its velocity alternating as per the implemented gearbox. This sensitive part could be affected with multiple stress types and operating scenarios. What does deeply affect the driving shaft is the normal fatigue applied on it as it is considered the main failure reason, this normal fatigue type is highly recommended to be recognized and rated while the modelling operation and replacing the damaged shaft with another one. Selecting this shaft's material is very essential process when designing this part of the turbine and should also put into consideration the implemented maintenance plan.

The periodic maintenance plan should also consider changing the lubricant oil as it significantly reduces the erosion rate occurred by unusual metallic parts friction. The resulted vibration waves are occurred because of the shaft misalignment, this misalignment case could be fixed using laser beams techniques and minimizing the wear level by coating the shaft [**26**]. The periodic conservation plans are a main efficiency rate and performance saver, also the bearings lifetime must be identified throw the manufacturers given data and put a stand by part in case of the bearing failure, at this case of failure for the bearings; the friction factor will maximize which will raise the power loss rate and increases station failure occurrences [**26**].

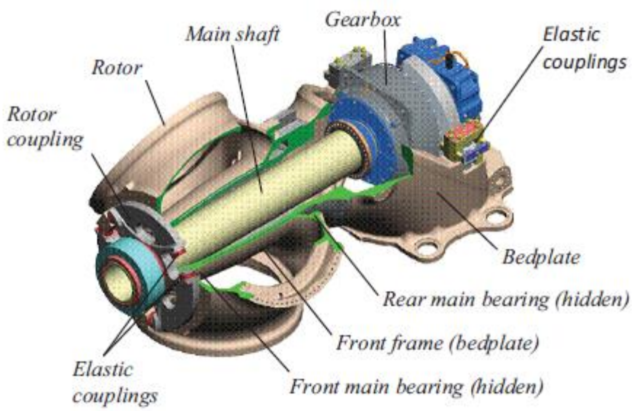

Fig. 7. Gearbox of a tidal turbine [27].

Electrical generator

The electrical generator main purpose is to generate electricity of course by taking advantage of the incoming mechanical force. Factually, the generator's performance is highly important, thus, the same performance level must be kept as could as possible and if there were any undesired failure noticed, it should be dealt with immediately. The output efficiency rate expected varies from 98% and goes down to 95% but not less than that, because if so, great economical losses will take place [**28**]. Following are some failure cases for generator performance which are predicted to cause abrupt shutdown events as overload current, weak resistance level, misalignment and unbalances. Consequently, it is very popular to install the generator itself onshore to assure a simple maintenance operation for workers and technicians. Nowadays, modern safety technology had introduced some safety parts to attain the required safety rate [**28**].

Yaw system

Obtaining the yaw system gains the tidal turbine's stations a lot of advantages and yet still not utilized that much. The maintenance engineers are complaining about this system illustrating it has more mechanical parts which means more complicated internal network besides making the maintenance process much harder. Additionally, the bearings used in this system are giant sized and causing serious operating issue. The most known failure for this system is wear which is striking the control system. Moreover, the yaw system failure source cannot be estimated well even if high precision measurement tools are involved, it is because of the massive complexity rate for this system. However, the following tow measuring systems are introduced to visualize and maintain which are CDS (Condition Diagnostics System) and the CMSW which refers back to condition monitoring system wind [**29**].

Blades

This very effective element is considered the most sensitive part all over the other turbine components which is precisely manufactured to introduce the required turbine's performance, the expected lifespan for blades is around quarter a century as per its own tidal act. As any mechanical part, there must be defective factors taking place on the overall mechanical performance as erosion, expected and unexpected impacts, strain and fatigue. Beginning with the normal erosion factor which creates a reduction rate in the generated power out of the turbine, this factor got another negative effect on the blades which is the delayed declaration that takes place after a while since the failure event starts. Unluckily, there is no successful measuring techniques to evaluate the erosion rate on blades till date, therefore, a scheduled maintenance plan must be put into consideration especially if the electrical output rate is notably decreasing as well as observing the blades health. What could seriously cause some damage on blades are the living aquatic creatures and the nearby rocks or stones, thus, the blades design must be in line with these different harmful circumstances and evading any unnecessary failure cases or economical losses. The blades fracture is considered really important failure case and can take place anytime due to the unorganized maintenance plans. The selected material for the blades has to be convenient to withstand the hydro-force acted on it. The pressure divergence between the upper and the lower area of the blades are impacted by the drag force act, and overtime, blades will be seriously impacted by fracture. The previous failure type is making a terrible efficiency decreasing for the whole mechanism, it deeply also impacts the aero-dynamical design for the blades, this will definitely minimize the turbine's output rate. The fatigue fracture happens because of the seawater streams which causes serious load changes act on blades. What really determines the fatigue lifetime is the material used and the operating period. The fatigue element considered an essential one while designing the blades while this material really depends on the failure's type. Involving composite materials is an important factor towards increasing the overall performance versus different fatigue failures. Equation (1) presents different manufacturing factors effecting on the fatigue fracture [**30**];

$$Se = k_a\, k_b\, k_c\, k_d\, k_e\, k_f\, (Su) \qquad (1)$$

Ka stands for industry operation; this coefficient is related to some experimental relations [**31**].

Kb stands for blades size; this one can be obtained out of manufacturer's given data.

Kc stands for force vector; this factor is hard to be calculated as the hydro-force is acting randomly as known and cannot be accurately identified.

Kd is the operating temperature coefficient which it is by the way considered for great temperatures turbine which means it doesn't related to the tidal turbine.

Ke is a blade geometry related factor which is greatly efficient while identifying the fatigue applied force on blades design. The aerodynamic status must be experimentally calculated which is the main difficulty for calculating Ke.

Kf is the polishing operation coefficient, technically, when the drag force increases it is because of the blades roughness and that is the reason why the blades must be polished before being installed. These factors may impact the polishing operation finishing of the blade.

Su is the maximum fatigue applied force, this factor is highly depending on some mechanical characteristics related to the blade's material type and it must put the long-term life into consideration for these blades (around quarter a century).

Se stands for fatigue force applied while processing and the previously mentioned coefficients are to calculate this factor from formula.

Conclusively, the randomness in seawater motion is the prime element making fatigue facture, fortunately, the flow rate could be easily determined according to the recorded info for blades design. The following **Table 1** shows the turbulence severity impact on fatigue force, it also illustrates the resulted fatigue force is highly increased with a very small turbulence increasing rate (directly proportional relation).

Table 1. Turbulence severity against Fatigue force [30].

Fatigue stress margins for blade root component versus TI (H_s=0).

	Turbulence intensity (%)				
	0	5	7	10	12
Load (kN m) (SN=14)	543.3	1300.2	1979.4	2705.4	3348.1
Stress margin (%)	+85.6	+65.5	+47.5	+28.2	+11.2

The fatigue fraction is causing tiny cracks inside the blades which are extremely dangerous. The blades status must be checked periodically by hiring some force sensors, additionally, the maintenance operation is not that easy one especially in some fatigue fracture cases.

Maintenance plans

The maintenance plans are consisting of multiple stages while the first one is to get the failure's source and its type and to do such a thing, a proper acquisition system shall be engaged as a step towards detecting the failure's position. The tidal turbines are costing a lot for maintenance operations, also the overall performance must be kept as it is expected to be. According to the tidal turbine's maintenance data, there are a lot of plans can be achieved to accomplish the it as any tiny defected part will highly influences the turbine's overall performance.

Fig. 8. Sequenced Maintenance steps [20].

Fig. 8 is related to repairing turbines with some necessary steps, it all starts with correctly maintaining the failure positions and part and then take some serious and quick steps towards replacing the damaged part with a new one before the main process comes to life again. Once again, it starts with fitting-out the alternate part and then lift it to the proper position, also, climate expectations must be kept in mind and performed on reality by selecting the appropriate time to accomplish the maintenance operation. Between the investigation, monitoring, replacing, and repairing procedures, it is very allowed to organizational, logistics and waiting delays to be repeated and it is related to own prime devices and stand by ones available anytime.

The downtime for any turbine is defined as the time it takes the turbine to restart again after failure, of course it is very popular to be as minimum as possible to reduce the economical lose caused by replacing the desired component. Not all repairing or replacing operations are done on the turbine itself, some necessary repairing processes requires to disassemble some turbine parts and bring it to offshore to proceed the maintenance operation.

The newly maintenance techniques are dividing the main operation into a couple of phases, replacing and repairing. In some cases, the damaged part might be the largest ever, as for that, the maintenance procedures must be minimized, it is common to fix the defected part under water level or even take the while turbine out of its position to accomplish the fixing process. As the technology goes further, it really helped to determine the maintenance pre-cost rate and the required repairing plan must be followed, the **Fig. 9** illustrates some necessary maintenance strategies for a new tidal turbine [**20**].

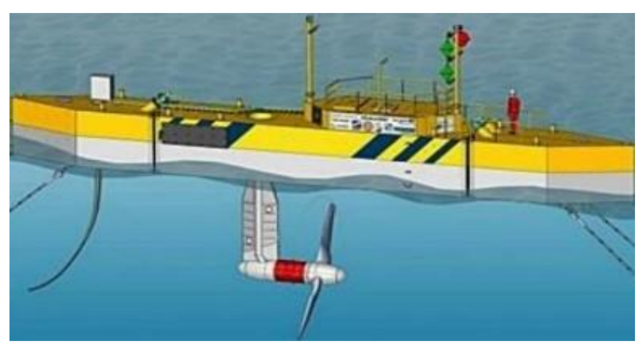

Fig. 9. Recent Tidal turbine configuration to simplify repairing [20].

For maintaining a big-scale hydro-farm turbine, divers are asked to accomplish the periodic repairing by replacing the desired part. Additionally, some maintenance operations are demanding on the ROVs to perform corrective maintenances process. Although, it is really recommended to pull the whole turbine out of the sea and isolate it form the rest (to prevent any unnecessary shutdowns) to perform the proper maintaining process and to reduce economical losses.

Different studies had been applied with a purpose of predicting the fatigue lifetime of tidal turbines blades made of aluminium and other metallic materials. These studies depend on either mathematical models of simulation studies that can be applied using simulation software packages. A study had been conducted that predicted the fatigue lifetime of a tidal turbine blade represented in the following figure [**12**].

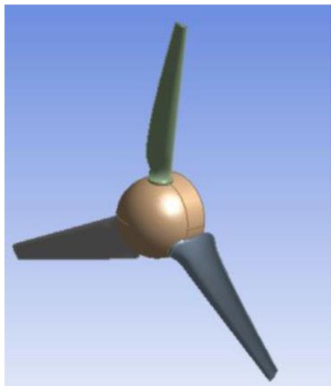

Fig. 10. 3D model of the simulated tidal turbine blade using ANSYS [12].

The applied study allowed predicting the equivalent alternating stresses per number of cycles, which is represented in **Fig. 10**. Obtained results showed that, increasing the number of cycles resulted in reducing the allowable equivalent alternating stress (Mpa) [**12**].

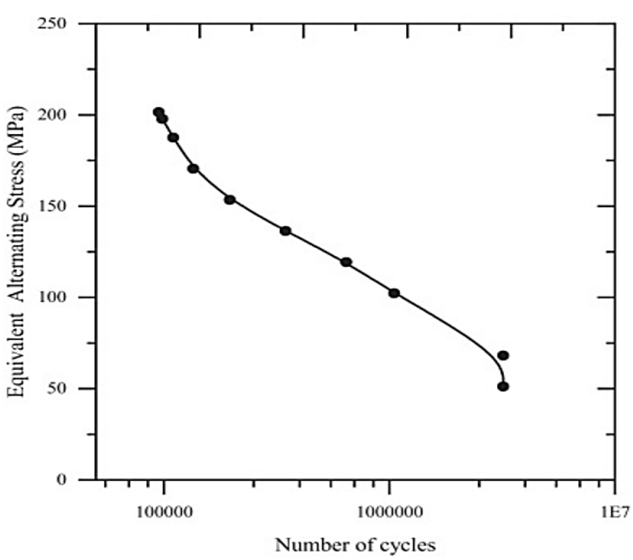

Fig. 11. Relationship between the equivalent alternating stresses (Mpa) and number of cycles using ANSYS [12].

Modelling

The periodic load on turbines is the main reason for the fatigue stress, this periodic load might be expressed mathematically to predict the lifespan for the blade using different techniques. This project tends to predict a blade lifespan, which was subjected to a determined loading condition.

A key issue of the blade performance as well as its lifespan is subjected to the material used in its manufacture. Abruptly, expressing the periodic loading on blades is complex and require detailed comprehension of the hydrodynamic forces behavior. Conventionally, fatigue failure is determined experimentally using destructive tests, which can be achieved by applying periodic loads on the blade till mechanical fracture occurs [**32**].

Experimental investigation of fatigue stress of such a blade is not simple, requires specially designed equipment and results in damaging the tested sample. The complexity of simulating the fatigue model is subjected to the thrust force variation effecting on the blade, which varies periodically over the year due to the seasonal fluctuations. Researchers paid a high attention to record these forces in such a location, while MATLAB can be used in analyzing these measurements to solve the governing equations that predict the fatigue stress [**32**].

Generally, the blades specially designed hydro-dynamic profile is the key issue of attaining a high energy conversion efficiency (from kinetic energy to mechanical power). An applied thrust force is a combination of two forces, drag and lift forces that effect on the blades.

The environmental conditions' circumstances beneath the sea level cannot be stable, thus, the two past mentioned forces are fluctuating over the year. The thrust force should be related to time, which increases the complexity of the study.

Table 2 represents the specifications of the turbine had been considered in the study, while **Fig. 12** and **Fig. 13** show the applied thrust force acting on each blade alongside with mean thrust force, which had been considered in the study. These forces were plotted using MATLAB and were also represented graphically as the rotation angle varied form 0-3300. Additionally, the time rate differs form 0-27 seconds. The data used to generate the rainflow algorithm alongside of evaluating rate of cycles for every loading rate.

Table 2. Specifications 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

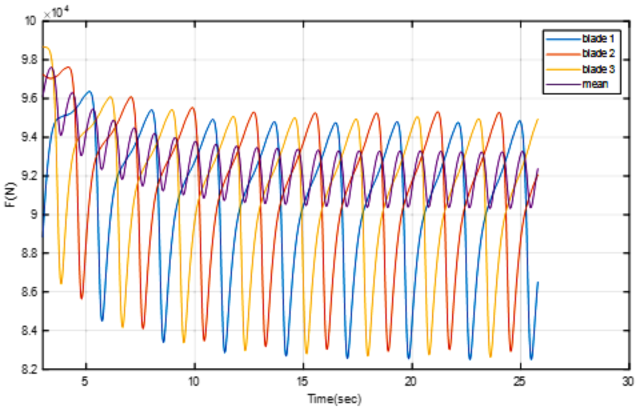

Fig. 12. Average thrust forces (N) against time (s).

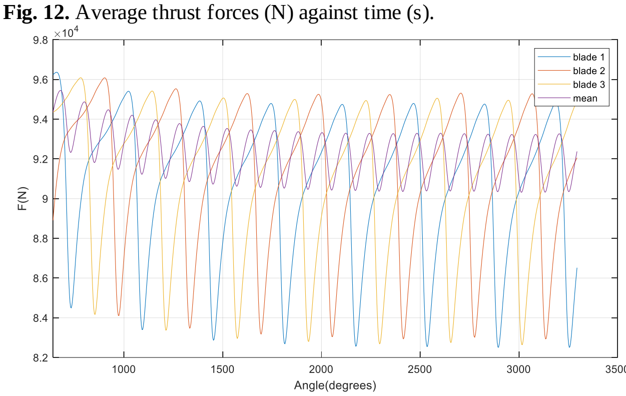

Fig. 13. Average thrust forces (N) against rotation angle (degree).

Results and discussion

The lifespan of the studied turbine had been predicted mathematically by following such steps that are represented below;

1. Identifying the average thrust forces to MATLAB code as well as the influencing factors.

   The periodic loading evaluated by Rain flow algorithm; this mathematical technique relies on resorting the periodic peaks. **Fig. 14** illustrates the frequency (cycles count) of the average thrust forces. This allows providing a histogram which indicates the cycles number evaluated for each loading rate. This step was implemented in the upcoming stage as input information, the cycles numbers are used as input in MTALAB code.

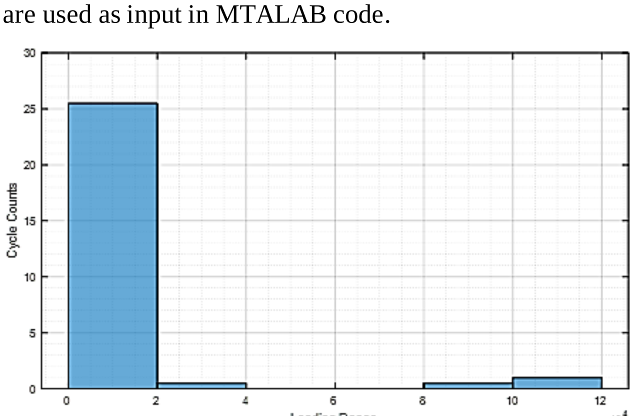

Fig. 14. Cycles numbers against loading range.

2. The following equation allows predicting the D.E.L (Damage Equivalent Load) of the studied structure (Blades) mathematically [**11**];

$$D.E.L = \left(\frac{\sum_i (l_i^m x n_i)}{t}\right)^{\frac{1}{m}} \quad (2)$$

   As per the DEL indicates the relation between L (Cycle Range), n_i (number of cycles), history of cyclic time, the negative inverse slope for S-N chart that varies from a material to another. The experimental correlation was solved by MATLAB for various blade thicknesses, (i) the number of attempts equals 20.

   Hence, the equivalence fatigue stress can be calculated using the following equation. as it is related to the DEL and the expected blade's projected area where this area (A), which is assumed to be rectangle.

$$\mathrm{S.E.L_i} = \frac{\mathrm{D.E.L}}{\mathrm{A}} \quad (3)$$

3. The predicted blades lifetime is calculated based on the next equation [**11**];

$$\mathrm{lifetime_i} = \left(\frac{\mathrm{S.E.L_i}}{\mathrm{S_f}}\right)^{-\mathrm{m}} \quad (4)$$

where, S_f factor stands for the fatigue stress of the material.

4. Obtained results will help in predicting the effect of the average thrust forces and blade thickness on the turbine lifespan.

Discussion

The selected alloy (Fe-34Mn-10Al-0.76C alloy) enables attaining a high resistance against corrosion (didn't considered in the study) and mechanical stresses. For the first average thrust force, the following figure shows the predictions of the thickness effect on the lifespan of the studied turbine. As increasing blade thickness had enhanced the mechanical resistance of the blade leading to increasing its lifespan.

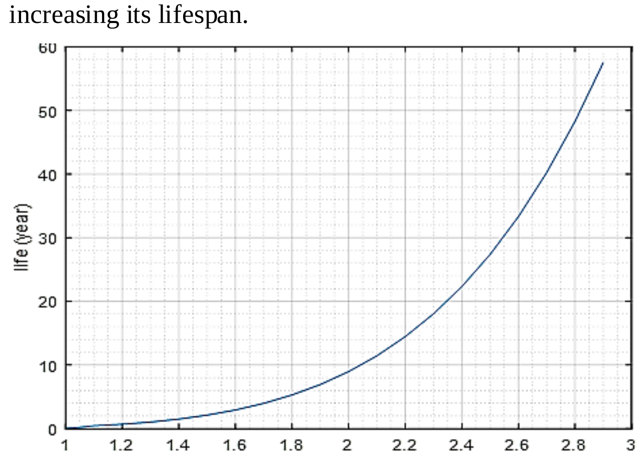

Fig. 15. Expected lifespan (years) of the turbine for different thicknesses (mm).

The same approach is repeated for different average thrust forces, which enables predicting their effect on the life span of the turbine. Obtained results predicted that, increasing thrust forces applied on the blade would reduce its lifespan significantly as it is represented in **Fig. 16**.

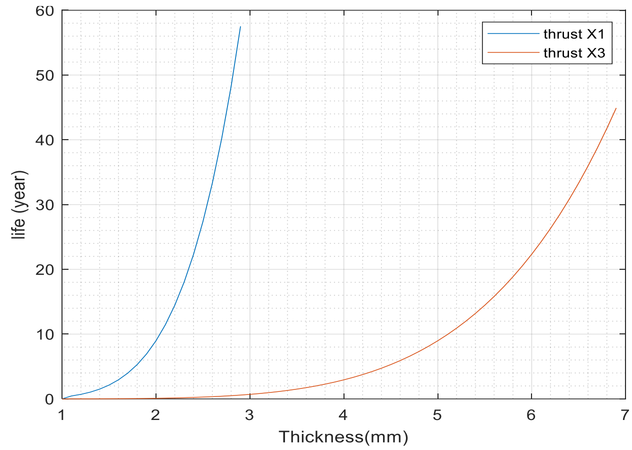

Fig. 16. Expected lifespan (years) of the turbine for different thicknesses (mm) and thrust forces.

Moreover, the flow velocity had been varied twice to investigate its effect on the turbine service lifetime. **Fig. 17** shows that, increasing flow velocity of seat water would result in reducing the service lifetime of the turbine.

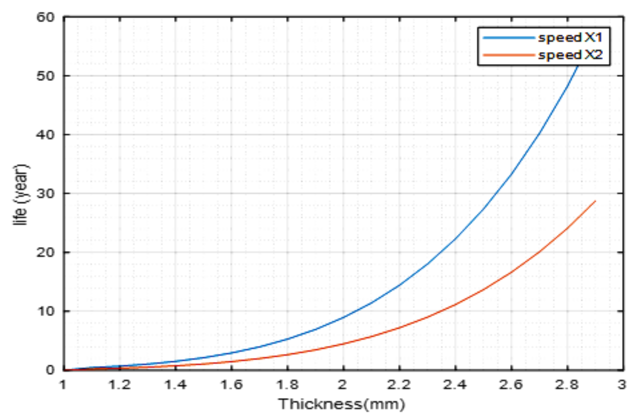

Fig. 17. Expected lifespan (years) of the turbine for different thicknesses (mm) and seawater flow velocity.

A high attention had been paid to tidal power, the high demand on durable sources of sustainable power sources become more desired due to the electricity demands have been notably increased in this 21st century. Tidal turbines are expensive and taking a decision regarding designing, manufacturing and installing it in such a location should be studied in details to prevent unnecessary economic losses. A tidal turbine should operate for long time with low maintenance requirements to assure achieving a high economic benefit and reduce its long payback period resulted from its very high cost.

The lifespan and safety of a tidal turbine are influenced by different parameters that should be recognized in details starting from the design phase until reaching its operation. This would help in increasing its safe operation and reducing its maintenance requirements, which is translated into a higher electrical output, economic benefits and lower environmental impacts. Fatigue failure is considered as being one of the most common mechanical fracture forms that threat smooth operation of a tidal turbine and would reduce its efficiency as well as lifespan.

The key parameters influences the performance of a turbine is the material used in manufacturing its blades. it should be able of serving under tough environmental conditions, high corrosion rates and unexpected impacts. The material should be lightweight to reduce the energy losses as well. Its surface should be characterized by a low roughness to reduce eddies formation downstream the seawater flow. Fe-34.5Mn-l0Al-0.76C alloy had been selected in this study. As it is predicted to satisfy the desired performance. However, its mechanical resistance against the fatigue stresses applied due to the fluctuating hydrodynamics forces effecting on the blade should be estimated to assure achieving a smooth, efficient and safe operation.

Referring to the point of interest of the proposed research, this study had been not considered changing the material but changing the blade thickness and the operating conditions. Simulating the fatigue mechanism of a blade is extremely complex and should consider different parameters.

However, the most three influencing parameters had been taken into account for a purpose of reducing the study's complexity. These parameters are the blade material thickness, thrust force magnitude and the flow velocity. Obtained results showed that, increasing thickness of the blade resulted in increasing the turbine lifespan for each studied flow velocity and thrust forces. However, increasing the flow velocity is predicted to increase the thrust forces due to the wake region formed downstream the flow leading to increase the fatigue stress on the blade. Consequently, the blade thickness should be optimized based on the geographical location decided to be installed by a turbine.

As the geographical location effects on the environmental conditions significantly, which should be considered during the design stage to prevent fatigue failure of the turbine. Optimizing the blade thickness would help in maximizing the energy conversion efficiency of the turbine as well, as a lightweight blade would be able of generating electricity higher than heavy ones.

Obtained simulation results allowed predicting the effect of the thrust force on the fatigue lifetime of the studied blade. Comparing with results provided by [**14**], it was investigated that, the higher thrust force would result in reducing the expected lifetime of tidal turbine as it is represented in the following figure for different materials. The study was established based on experimental investigation of the material properties as well as simulation study on the blade.

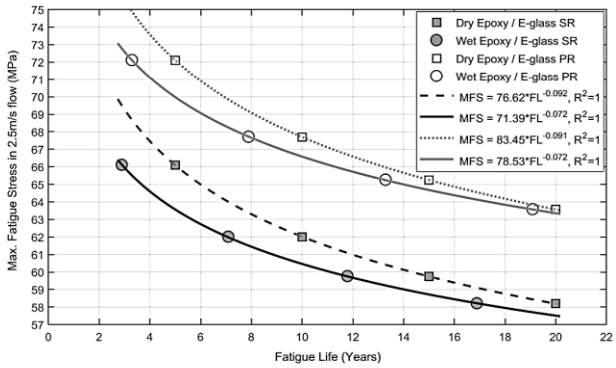

Fig. 18. Effect of the thrust force on the fatigue lifetime of tidal turbines for different materials [14].

Conclusion

The proposed study allowed investigating the lifespan of a blade made of (Fe-34.5Mn-l0Al-0.76C) for different thicknesses and operating conditions (thrust forces and flow velocities). This had been achieved mathematically using Matlab. Results showed that, the damage resulted from the average thrust forces (hydrodynamic forces of seawater) is subjected to different parameters, which are the blade material, thickness, flow velocity and the thrust force magnitude. Analysing the average thrust forces allows the blade thickness should be optimized according to the environmental conditions as well as the selected material. This would help in achieving a desired lifespan of the turbine with high safety level against fatigue failure.

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Conflicts of interest

"There are no conflicts to declare".

Keywords

Tidal turbine, Fe-34.5Mn-l0Al-0.76C, blades, rainflow algorithm, fatigue stress, MATLAB.

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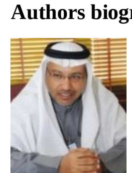

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Graphical abstract