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A review of survivability and remedial actions of tidal current turbines

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ABSTRACT

Tidal current energy is one of the most predictable ocean renewable energies. Survivability of the device used to harness tidal power and its remedial actions are critical to ensure a successful power generation. Marine environment is harsh with the continuous attacks of waves, current, saline water and microorganism. Support structures are discussed including gravity base, monopile, tripod/piled jacket and floating structure. Extreme weather increases the wave height and current speed to produce high loading at the turbine. Support structure is designed to sustain the loadings from the extreme weather. Protective seabed unit should be included to prevent the seabed scouring. Corrosion reduces the strengths of rotor, support structure and nacelle. Penetration of sea water into nacelle may damage the generator. Scheduled examination is important to ensure water tight condition of nacelle. Marine fouling from microorganism needs the proper painting as protection. The study presents the survivability of tidal current turbine and suggests the remedial actions to protect the device.

Contents

1. Introduction

Brundtland Report from United Nation coined the term "sustainable development" in 1987. Sustainable development refers to the development that meets today's generations needs without compromising those future generations [1]. As world population grows at an average rate of 0.9% per year to an estimated 8.7 billion population in 2035, the energy consumption will sharply increase when more peoples move to urban areas [2]. Energy demands depend on the world energy policies, global GDP growth, world population growth, energy pricing, fossil-fuel subsidies CO_2 pricing and development of energy technologies as described in World Energy Outlook 2013 [2]. Future energy demands are hard to meet without burning of fossil fuels continuously or depending on nuclear power. Exploration of renewable energy is one of the expected solutions to achieve the sustainable development.

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The oceans have tremendous untapped natural resources, which are able to make significant contribution to our future energy demands. Several types of ocean sources have been defined as potential sources to generate electricity including tidal barrage, tidal current energy, wave energy, ocean thermal energy and salinity gradient energy [3,4]. Researchers face many barriers on finding highly applicable and cost effective technologies to develop these sources.

Tidal current is one of the most advantageous resources, which can be extracted from the rise and fall of sea levels caused by the gravitational force exerted by the moon and sun and the rotation of the earth. Tidal current energy is more predictable compared to wind and wave energies. Tidal current sources are easier to be quantified and predicted [5,6]. A number of devices have been designed to harness tidal energy with wide range of shapes, sizes and forms [6]. These inventions harness potential kinetic energy of tides and convert the energy to electricity principally. Tidal current turbine can be categorised as horizontal axis and vertical axis tidal turbines [8]. Horizontal axis tidal current turbines (TCTs) are the most common device with the rotation axis in parallel to the direction of current stream [9]. Vertical axis TCTs rotates about a vertical axis in perpendicular to the current stream [10].

Extracting the kinetic energy from ocean is more challenging compared to the wind on land. Wind turbine is vulnerable to the cyclones in the extreme weather [11]. For the marine environment, extreme sea conditions have to be considered for the survivability of TCTs. Sole consideration of the extreme weather in ocean is not able to ensure the survivability of tidal current turbine. The effectiveness of mooring system to hold the tidal current turbine under extreme condition is examined to provide guideline in design. The current work firstly introduced the mooring systems of gravity base, monopile, tripod and floating structure. Tidal current turbines are vulnerable to the damage of seabed scour. The potential scour of various foundations are discussed and followed by the discussion on the fatigue failure of blades, corrosion failure of saline water attack and the hydrodynamic failure of befouling at the blades. Installation and operation of TCTs are harsh in the marine environment. The current work unveiled the potential damages of the tidal current turbine in ocean and provided protective actions to ensure the survivability of turbine.

2. Support structures

The support structure of TCTs is of significant importance in tidal current energy system. Prior assessment of the support structure of TCTs was carried out before approaching the survivability of TCTs. Based on the current status of TCTs, four basic support structures for TCTs are as follows [6]:

(1) *Gravity structure*: this gravity structure is made up of large steel or concrete base column. It can resist overturning by its self-weight. The steel component of this gravity structure adds some advantages to itself, such as ease of production, transportation, and installation.
(2) *Monopile structure*: this type of structure is made up of a large-diameter hollow-steel beam. The beam is penetrated approximately 20–30 m into seabed while the seabed conditions are soft. If the rock is harder, pre-drilling, positioning and grouting may be the methods to install this structure.
(3) *Tripod/piled jacket structure*: each of the corners of the structure's base is anchored to the seabed by using steel piles. The steel piles are driven approximately 10–20 m into the seabed depending on the seabed conditions. This type of structure is well understood since it has been widely applied in the oil industry. Compared to other structures, this structure has lighter structural loading.
(4) *Floating structure*: floating structure provides the optimum solution for the placement of devices in deeper water conditions. This type of structure is made of mounting device and floating vessel which is moored to the seabed using chains, wire or synthetic rope. The illustration of all the aforementioned support structures can be found in works [12,13].

Monopile structure has been applied on the Seaflow and Seagen from marine current turbine (MCT). Monopile was used to support the single rotor of Seaflow rated 330 kW and twin-rotor of Seagen rated 1.2 MW. Monopile is able to provide firm support with the lifting ability to rise up the rotor for maintenance. The cost is higher compared to the floating structure. Size and weight of turbine are increasing in parallel to the demand of higher rated power for a single device. Tripod is more suitable to hold the heavier turbine. However, tripod and gravity base structures have larger contact area between the structure and seabed leading to higher chances of seabed scour. Rourke et al. [6] has summarised all the devices in detail including their dimensions, features and status of development. The condition of TCTs under the extreme weather, seabed scour, blade failure, corrosion and biofouling are discussed by relating to the support structures.

3. Survivability of tidal current turbine

3.1. Extreme weather

The impacts of extreme weather to the TCTs and its support structure are discussed substantially in this section. Sea environment is harsh due to the intrinsic nature of sea state. Extreme events occur frequently such as hurricane, typhoon, tsunami and storm. The extreme events bring along the extreme wave and strong wind which would have severe impacts on the survivability of TCTs.

McCann et al. [14] stated that the extreme conditions considered are based on the combined probabilities of governing environment, such as current speed and wave height. Identification of the maximum loadings of storm can prevent the turbine components from damages. The generic tidal blade model used requires the blade root and tower base to withstand the moment approximately at 5 and 50 MN m, respectively. The simulated environmental condition is a 50-year return storm with 13 m wave height and 10 s wave periods. The detail of the simulation is shown in Table 1 [14].

Grogan et al. [15] presented a combined hydrodynamic-structural design methodology for a commercial scale (1.5 MW) tidal turbine. The loading analysis of the turbine blades has been conducted. Grogan et al. [15] found that the high bending moments of the turbine blades during operation life may prohibit the up-scaling of

Table 1
Extreme 50-year storm design load case conditions.

Design load case	50-Year return storm
Wind speed	25 m/s at 10 m height
Wind-induced surface current	0.625 m/s
Extreme 50 year regular wave	
H_s (wave height)	13 m
T_p (wave period)	10 s
Normal current speed at hub height	2.2 m/s
Current direction	Co-direction with wind and waves
Water level	40 m (MWL[a])+2 m (storm surge)

[a] MWL: mean water level.

the blades. The structural performance of glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP) as spar cap materials has been compared. Grogan et al. [15] claimed that GFRP is not a suitable material used to construct the main structural components of a large tidal turbine blade. The selection of materials is of significant importance for the TCTs to sustain storm during the service life.

The reliability of rotor blades of TCTs have to be considered to avoid the interruption of electricty generation during extrem weather. Val et al. [16] presented a probabilistic model to analyse the reliability of rotor baldes. The model considered the uncertainities associated with tidal current speed and the blade resistance. The model is able to calculate the bending moments in blades. Grogan et al.'s [15] results could be used in the blade design of TCTs. However, the proposed model is only applicable for pitch-controlled devices.

The underwater conditions are more predictable and calm compared to the water surface in sea. Atmospheric hurricane does not exist underwater. Less action need to be taken to the tidal current power compared to the wind power technologies [2]. However, the surface wave generated by the extreme events may have negative influences on the performance of TCTs. Barltrop et al. [17] adopted linear wave theory into blade theory to investigate dynamic problems of TCTs. It shows that wave height has significant effect on the torque of rotor blades. The range of variation of torque on rotor blades is doubled when the wave height increases from 35 to 84 mm. The torque further increases by 20% if 42 mm increment of wave height occurs. Galloway et al.'s [18] results agreed with Barltrop et al.'s [17] findings. Significant variation of thrust and torque was observed. These variations could influence the sustainability and fatigue of TCTs. Luznik et al. [19] demonstrated additional results of TCTs performance in an unsteady flow condition imposed by the surface wave. Luznik et al. [19] showed that the average power coefficient with waves is similar to the cases with the wave absence, but it has pronounced differences on the power production and blade loading. The extreme events could also bring flow debris in the marine environment. Most of manmade discarded objects are semi-submersible. The blade tips may be damaged by the debris.

The support structures of surface-piercing TCTs will be subjected to wave directly under extreme event. Wave studies on offshore wind turbines have been carried out extensively. The effect of extreme event on the tower base of TCTs can be referred to the established analogous knowledge from wind energy sector. Myrhaug and Holmedal [20] provide a practical method to estimated the wave run-up height on a slender circular cylindrical foundation for wind turbine. Zernov et al. [21] studied guided waves in a monopile for an offshore wind turbine. Marino et al. [22] draw some preliminary considerations about the direct wind effects on the kinetic and dynamic of steep extream waves propagating near offshore wind turbines. Marino et al. [23] presented a numerical model to simulate offshore wind turbine exposed to the extreme loading conditions. The mechanisms of kinetic energy to electricity conversion of these two technologies are similar [24]. The main difference between these two technologies is the fluid, where the density of seawater is approximately 832 times greater than the density of air [25]. But, the tower base of wind turbines and tidal turbines are subjected to seawater.

Generally, a 50-year return period wind speed has been assumed as the main design variable for the simulation of offshore wind turbines undergoing severe environmental conditions [23]. Such an extreme mean wind velocity induces sea states that is characterised as highly nonlinear irregular waves and this may break in proximity of the support structure giving rise to dangerous impact loads. International Standards such as IEC1400-3 [26] had recommended considerations for the extreme wave load.

Table 2
Main tower and substructure properties [33].

Main tower	
Tower base diameter, wall thickness	6.00 m, 0.027 m
Tower top diameter, wall thickness	3.87 m, 0.019 m
Main substructure	
Pile length, diameter	20.00 m, 6.00 m
Pile wall thickness, total mass	0.06 m, 190 t

Marino et al. [23] in 2011 simulated offshore wind turbine under the exposure of extreme wave conditions. External condition-based extreme responses are reproduced by coupling a fully nonlinear wave kinematic solver with a hydro-aero-elastic simulator. This study was carried out based on “5-MW Reference Wind Turbine for Offshore System Development”. All the technical characteristics of the model were documented by Jonkman et al. [27]. Relevant characteristics for the tower and substructure are demonstrated in Table 2. Jonkman et al. [27] simulated the overturning plunging breakers with high accuracy. The highest tower base bending moment can reach approximately 160 MN m (wave height $H_s=11.5$ m, wave period $T_p=10.6$ s). The impulsive force impact imposed to the substructure could be computed precisely when the kinematic of the plunging breakers is known [23].

Parambath [28] conducted a study to identify the impacts of tsunami on onshore wind power units. It concluded that surge/bore more than 5 m brings failure to wind power unit tower. On the other hand, offshore wind turbine seems have survived in the Japan's tsunami in 2011 [29]. It concludes that support tower of TCTs may be able to survive under moderate extreme weather condition which does not induce significant wave height. However, the failure of TCTs is quite costly and some extreme events are not predictable. The potential sites of tidal farms with possibly low occurrence of extreme event has the priority for tidal energy development.

3.2. Seabed scour

At the planning stage of marine projects, the physical impacts imposed to the seabed by installing structures are required to study as part of environmental studies [40]. In this section, the local scour around the TCTs foundation is discussed. Scour around marine structures have been well recognised as an engineering issue where scour is likely to cause structural instability. Seabed protection for the foundation of marine structure is required [31–33]. As a marine structure, TCTs have the possibilities in experiencing seabed scour problems during its lifespan. Seabed scour issues have to be taken into account for a sound design of TCTs and their support structures.

Rambabu et al. [34] stated that the fluid flow, geometry of foundation and seabed conditions are the governing factors for the seabed scouring. The characteristics of fluid flow include the current velocity, Reynolds number and Froude number of flow. The above mentioned four types of foundations have different areas of contact to the seabed. The selection of support structures leads to different flow patterns occurring at the foundation with different formation of flow-induced vortices in the vicinity of support structures. Different scouring patterns are induced by different geometries of foundation.

The gravity structures of TCTs are most susceptible to seabed scouring due to its large contact area with the seabed compared to the other three types of foundation. The determination of geometry size and seabed preparation is required in order to implement the gravity structure as the foundation of TCT. The scour of monopile structures are less susceptible compared to gravity structures due to the low contact area with the seabed [6]. The

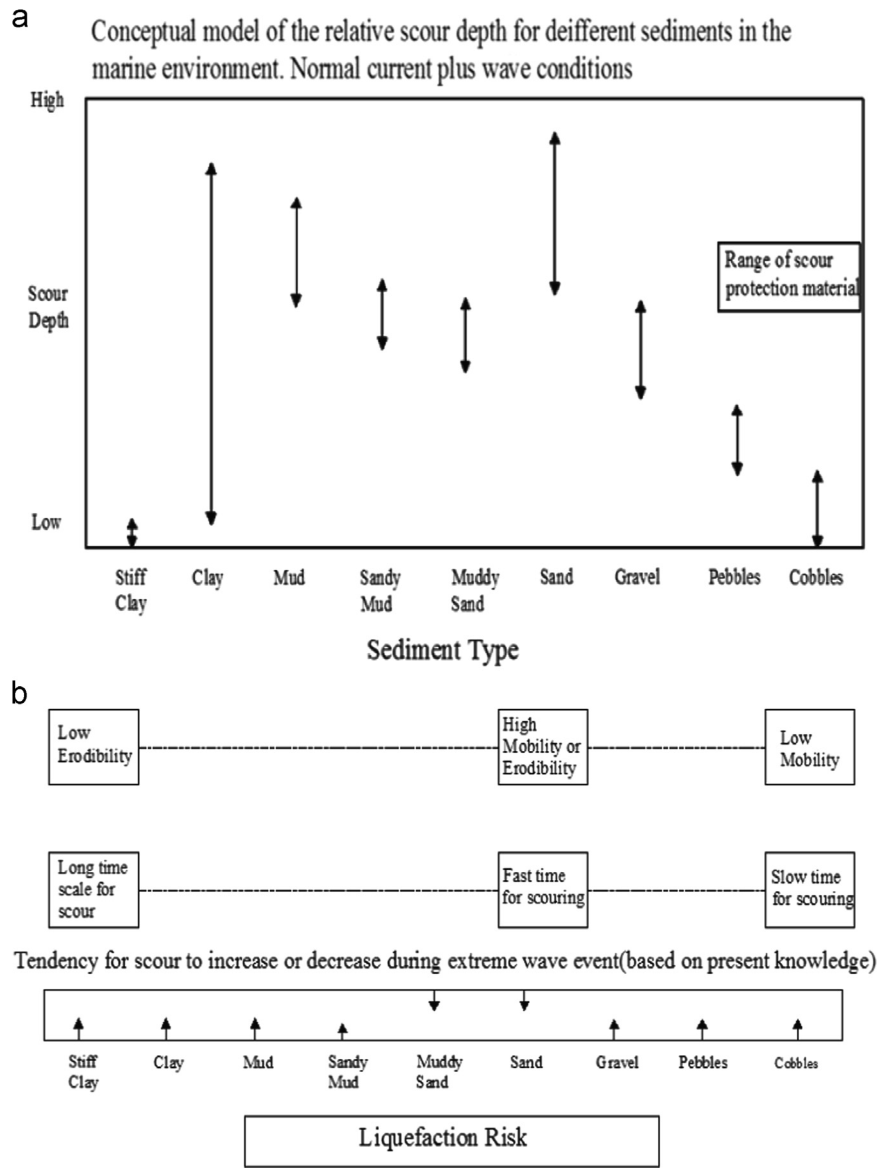

Fig. 1. Conceptual model for scour development around marine foundations.Modified from Whitehouse [38]

scour development around monopile structures has been studied extensively for the foundation of offshore wind turbine in the past few decades. The application of monopile structures in TCT is suggested for both the cost and structural stability [2]. The first tidal turbine in the world Seaflow is supported by a monopile, which succeeded in generating electricity [35]. The scour development of piled jacket structures is more complicated compared to the other support structures due to its footing shape [36]. McDougal and Sulisz [37] stated that the floating structures give lowest impact on the seabed scour due to the low area of contact between the structure base and seabed. However, floating structure may have weaker mooring on the positioning of the turbine in harsh marine environment.

The seabed preparation is time consuming and the construction process of the foundation is costly. The potential sites for tidal current energy have normally fast flowing fluid, which may be dangerous for divers. Gravity structures may be suitable to the sites without the needs of excessive seabed preparation. Monopile structures can be used to replace the gravity structure as no seabed preparation is required prior to the installation [6]. The piled jacket and floating structures are both alternatives without seabed preparation. The floating structure needs solid points at seabed, fixing the structure to the seabed through chains.

Whitehouse [30] developed a conceptual model of scour sensitivity which includes full range of marine sediment types (Fig. 1a). The clay has the largest range of scour depth, where stiff clay has the lowest range of scour depth. The gravels, pebbles, and cobbles are suitable scour protection materials. According to Whitehouse [30], as the susceptibility of sediments to erosion reduces, the scour is expected to decrease for both coarser and finer soils in general terms, although muds and clays have more uncertainties regarding the response of scour due to their formation history and degree of compaction. Moreover, cyclic loading by waves may result in scouring due to pore pressure built up in the soil. Wave-induced liquefaction may occur and it could decrease the strength of soil. The information of soil subjected to liquefaction is illustrated in Fig. 1b [38]. The soils subject to liquefaction risk are clay, mud, sand mud, muddy sand and sand. Potential TCTs site with aforementioned soil condition need to be aware of liquefaction issue.

Meanwhile, further investigation of resistance to scour provided by clay in marine environment is needed and clay with undrained shear strength of order 100 kPa is likely resistance to scouring under the condition of open sea environment. Jiang et al. [39] found a scour with 5 m depth in firm clay adjacent to an oil-unloading terminal in a tidal river. Thus, stiff clay may also be treated as a scour hazard in some environments. Besides, marine soil consists of various layers and the understanding of multi-modal sediment distribution is important for scour prediction [40]. Porter et al. [41] found that the seabed with the coarse sand overlaid by fine sand is more vulnerable to scour compared to the bed with uniform coarse sand.

In extreme events, the hydraulic force increases whilst the scouring depth of some sediment increases. On the contrary, some sediment waves may result in a decrease of scour depth. The scour depth of muddy sand and sand will decrease under extreme wave event. In addition, the events either with high energy for erosion occurrence or in long duration increase the rate of scour. Nevertheless, the scour response of the seabed in time-limited event depends on the sensitivity of the seabed to increased shearing force on seabed, and the severity of the event [30]. The extreme event not only impose direct load to the structure of TCTs (as discussed in Section 3.1), but also cause substantial erosion and scouring around the foundation of TCTs. The scour around the foundation of TCTs may result in instability of the support structure of TCTs.

To the best of authors' knowledge, no documented field measurement is available on the scour condition at real tidal farm sites. However, the filed measurements of scour condition in analogous wind turbine industry have been well documented. Whitehouse et al. [30] assessed the scour condition of several offshore wind turbine farms with monopile structures. The data of water depth, wave and current condition were collected for each site. The field measurement was made after 6 months of installation. The deepest scour was 1.47 D_{pile} (pile diameter 1.5 m) in the current-dominated sandy environment according to Whitehouse et al. [30]. The offshore wind turbine was installed in a site with strong tidal current (peak current speed at 1.4 m/s) and also sheltered from waves. A wider range of offshore wind turbines have been assessed to further include the different scour conditions. The assessment concluded that scour of monopile at wind farm is a progressive process. The scour development depends on a range of tidal, seasonal and longer term variations in currents, wave action and the water depth at the foundation.

Additional factors need to be considered in the scour prediction of TCTs. TCTs has the special features of rotor, which may need to be taken into account. A seabed boundary layer is in the region between the seabed and rotor that will hit the foundation structure. The rotor causes the acceleration of the bed velocity between the rotor and seabed. The suppression of flow occurs to increase the stresses exerted on the seabed and consequently leads to the seabed scouring. Chen and Lam [42] claimed that the clearance between rotor and seabed becomes critical in the TCTs induced scour prediction. The closest equations can be used to predict the scour of TCT's monopile discussed by Chen and Lam [42].

3.3. Fatigue failure

The blades of TCTs are generally designed for 25-year lifespan and the blades are expected to withstand all potential loads during the lifespan. The static load imposed on TCTs is higher than wind turbine due to the high density of seawater. On the other hand, the randomness of ocean current integrated with turbulence and velocity shear generate fatigue load on the TCTs' blade. Furthermore, the TCTs' blades are submerged in corrosive marine environment. Thus, investigations of TCTs under static and fatigue load are necessary. Survivability of TCTs under fatigue load could help in sound design to ensure safe operational life cycle and successful energy extraction [43]. Composites materials have been adopted in the prototype turbines for better fatigue behaviour. A 65 mm thick carbon fibre-reinforced spar bonded to fibreglass ribs and sheathed with a fibreglass-reinforced skin was featured in the rotor of Seaflow (2003). The rotor uses a marine-quality epoxy resin matrix. The spar was made of proprietary prepreg, and it vacuum-bagged and cured in an oven at a temperature of 75 °C [44]. The blades of commercial tidal project SeaGen (2008) consist of a hollow carbon fibre composite box spar. The spar acts as the main load bearing member [45].

Fatigue failure is potentially caused by the load that varies with time. The load tends to vary in amplitude and frequency over time. McCann et al. [46] carried out analysis on the fatigue loading sensitivity of TCTs to waves and turbulence. McCann et al. [46] assessed the loading sensitivity to variations in flow turbulence intensity (TI) and wave actions (characterised by wave height H_s and period T_p). McCann et al. [46] chose blade root out-of-plane bending moment (M_y) in order to investigate the critical fatigue load.

The fatigue load simulations were modelled based on the Germanischer Lloyd guidelines for ocean energy converters [47]. A 2 MW tidal turbine has been used for the simulation. The detailed description of the turbine model is indicated in Table 3. The critical fatigue load has been identified throughout the simulation. The material properties, safety factor adopted and actual load level involved in the TCTs are the variables of critical fatigue load and extreme loading. To offer a benchmark for assessing the critical fatigue load, simulation of a single extreme load case was conducted based on 50-year extreme wave event at peak current, as shown in Table 4. In this extreme load case, maximum blade root bending moment (M_{xy}) is extracted. From the simulation results, maximum blade root out-of-plane bending moment (M_y) has been extracted with a value of 4429 kN m before the adoption of safety factor. To analyse the extreme yield as well as comparing the extreme and fatigue loads, blade root component has been modelled through simulating a simple cylindrical section of constant wall thickness. The material used to manufacture the root is assumed to be CFRP. The properties of CFRP are demonstrated in Table 5.

According to fatigue load, blade root geometry and materials properties, the fatigue stress reserve margins has been calculated by McCann et al. [46]. It has been observed that the stress margin fall to as low as 8% under certain environment, as shown in Tables 6 and 7. A positive margin indicated that fatigue failure is not predicted to

Table 3
2 MW turbine specification.

Rated power (MW)	2.0
Rotor diameter (m)	22.8
Blade length (m)	10.5
Number of blades	3
Rated hub flow speed (m/s)	3.0
Rated rotor speed (rpm)	12.0
Hub height above seabed	29.0
Control type	Pitch regulated, variable speed
Transmission	Gear-box
Support structure	Bottom-mounted tripod
Foundation stiffness	Rigid

Table 4
Extreme load case – 50-year wave event.

Peak flow speed (m/s)	3.5
Mean flow turbulence intensity (%)	10
Extreme stream f_n wave H, T (m, s)	10, 15
Wave, current direction	In line

Table 5
Material properties of CFRP.

Property	Unit	Value
Specific gravity	n/a	1.58
Young's modulus	GPa	142
UCS[a]	MPa	1105
MFS[b] (10^7 cycles)	MPa	350

[a] Ultimate compressive strength.
[b] Mean fatigue strength, corresponding to a material inverse-SN slope = 14.

Table 6
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

Table 7
Fatigue stress margins for blade root component versus H_s (TI = 10%).

	Significant wave height H_s (m)			
	1.5	3.0	4.5	6.0
Load (kN m) (SN = 14)	2627.9	2961.9	3273.2	3467.7
Stress margin (%)	+30.3	+21.4	+13.1	+8.0

occur within the lifetime of the component. McCann et al. [46] declared that extreme loading is highly important in blade root component design for all flow turbulence and sea-state severity consideration. The selection of extreme wave height (H_{max}) is critical. TCTs may experience a larger H_{max} in actual site and subsequently a larger critical fatigue load. The interaction between wave and current also plays a crucial role for the loadings of TCTs. Gaurier et al. [48] demonstrated a study investigating the behaviour of strain gauged scaled turbine blades under wave and current condition in a flume tank. The standard-deviation of the strains represents less than 5% of the mean for the current alone case when the tip speed ratio equals to 6. The standard-deviation increased for the wave and current combined condition, which is more than 10–15% of the mean. This may lead to premature fatigue damage of the blades. Therefore, the wave–current interactions need to be considered in the fatigue analysis of blade design stage.

Nicholls-Lee et al. [49] stated that blade fatigue is an important consideration as a blade would experience 1×10^8 cycles over a 20-year service life. Besides, Akram [43] carried out a fatigue modelling of composite ocean current turbine blade. His study investigated the stress along the entire length of blade. The location of failure points has been identified, which is near to the root of blade and at the joining of the web and skin. Moreover, it concluded that the blade will have approximately 28.5 years safe operational life under given loading condition. However, TCTs are vulnerable to corrosion and marine fouling which may affect the fatigue behaviour of TCTs. Consideration of minute particles, dislocation or pre-crack was not included in his study [43].

Meanwhile, the different system designs have different loadings. For instance, horizontal axis turbines subject to high static loads but is a moderate fatigue loading and turbines with vertical axis subject to severe fatigue loading due to complete load inversion during each cycle [50]. TCTs with vertical axis is more vulerable compared to TCTs with horizaontal axis in terms of fatigue failure. Dai and Lam [51] incoporated computatioal fluid dynamic (CFD) method to investigate the performance and loading condition of straight-bladed Darrieus-type tidal turbine (vertical axis). It has been found that the propsed CFD model can effectively predict the hydrodynamic load of TCTs for structural design. CFD could be a cost effective method to invetigate the structural loading of TCTs and offer a reliable design.

3.4. Corrosion/erosion

Corrosion and corrosion-related problems are considered to be a significant engineering issue for ship, offshore structures and pipelines [52,53]. The TCTs face corrosion issue in their lifetime and the corrosive environment bring uncertainty to the reliability of TCTs. TCTs operate in such environment with the presence of large suspended solids which may possibly lead to erosive damage over lifetime of the device [54]. The loss of materials on the overall TCTs system may cause severe negative effect on the durability of TCTs.

Some of the TCTs are partially submerged, such as Seaflow and SeaGen. The upper part of the TCTs are affected by aggressive atmospheric environment which contain high content of chloride, oxygen and other corrosive minerals. In addition, the seawater arising from wave effects could spray on the upper part of TCTs. Salts may be detected in the air due to salt spray blown by wind. Moreover, carbon dioxide (CO_2), hydrogen sulphide (H_2S), sulphur dioxide (SO_2), and sulphur trioxide (SO_3) are the gases contained in the air. They accelerate the corrosion rate through activating the thin layer of electrolyte [52]. On the other hand, the submerged structure of TCTs could experience immersion corrosion.

In general, strength capacity and integrity are two critical design criterions for marine structural system such as ships, offshore platform, pipelines and pressure vessel. Strength capacity is defined as a function of the quantity of material loss result from surface or general corrosion (although local corrosion may occur). On the other hand, strength integrity is mainly localised and particularly due to pitting corrosion. Structural capacity is mainly dependent on the cross-sectional dimensions of a structural member [53]. The ocean energy field is naturally turning to use composite material as their perceived non-corrosive properties in the harsh marine environment as well as their high specific strength and stiffness. As mentioned previously, Seaflow (300 kW) and SeaGen (1.2 MW) tidal turbines are the ocean energy devices partially made by composite material [44,45]. However, the durability of composite material is considerably inferior to metals in terms of erosion [55]. Besides, tribocorrosion are likely to occur on the blades and bearings lubricated with water-contaminated lubricants. The blades of turbines may operate in turbulent slurry flows (silt, sediments and sand-containing flows). The cavitation may interact with corrosion processes. Plastic deformation of the surface or puncture of the corrosion-resistant passive films on unprotected metallic surface may take place. The particles in the flow can even strip protective paints from metallic surfaces [54]. The loss of materials on the structural components of TCTs may influence their structure capacity.

The axial stress on TCTs and their support structure is highly large [35,66]. The structures have to sustain this force in order to not fail. It is known that at least three tidal developers (MCT, OpenHydro and Verdant Power) have experienced failure due to high axial thrust [56]. The loss of materials on the structure deteriorated the strength of TCTs. The fatigue behaviour of TCTs also will be changed if loss of materials occurred. The TCTs may not be able to sustain the extreme load and fatigue life as considered in the design stage. The loss of materials on the blades may increase their surface roughness which definitely will affect the TCTs hydrodynamic performance.

Steel is often used to construct marine structures even it is associated with corrosion [5]. It is still a common material in tidal current energy industry, especially for constructing the support structure of TCTs. Seawater velocity has influences on corrosion behaviour of TCTs. The detail of water velocity effect on corrosion loss has been presented by LaQue [57]. He claimed that the corrosion rate of steel increases with increase of water velocity at an exponentially decreasing rate. There is little effect on the corrosion rate for water velocity greater than 6 m/s. The potential sites for TCTs have fast flow which could wash away the corrosion-resistant passive films on the metallic surface of TCTs' components. The painting against corrosion and fouling on the surface of TCTs' components also face the same issue. The degradation of coatings of TCTs should be investigated in order to know the optimum schedule for maintenance.

3.5. Marine fouling

An assemblage of organisms that colonises various marine structures is defined as marine fouling. It is harmful to human economic activities and is significantly important in affecting the service life of marine structures [58]. Artificial constructed structures, a unit of offshore renewable energy device, provides new habitats for marine organisms, and can be defined as artificial reefs [59]. The constructed artificial structures are colonised by marine organism inevitably. Marine growth can be categorised into two groups, namely soft fouling and hard fouling. Soft fouling are seaweeds, soft corals, sponges, anemones, hydroids, sea squirts and algae. Hard fouling contains mussels, oysters, barnacles and tube worms which are rather thin but with hard encrustations [60].

Marine fouling could increase the hydrodynamic loading significantly due to increasing of marine structure's surface roughness and dimensions of submerged parts of marine structures [61]. Apparently, marine fouling can affect the performance of TCTs during their service life. The blades of TCTs can be fouled by seaweed and other filamentous plants so that the drag of blades increased [5]. Energy extraction efficiency can be affected as the hydrodynamic loading on blades altered. Furthermore, underwater operation and inspection could be impeded by the assemblage of marine organisms due to obscuration of underlying substratum [62]. It affects further maintenance and monitoring of TCTs. Hard fouling organism are potential to damage the diving and underwater device [59]. The submerged blades and nacelle are at high risk of breakdown once the hard fouling organisms attaches on them. Therefore, well understanding on the impact of marine fouling on TCTs and their support structure are important to enhance the reliability of this ocean renewable energy.

Orme et al. [63] realised that fouling species are likely to inhibit the blade of tidal current turbine and affect the performance of the energy extraction device in year 2001. Therefore, they conducted experimental work to assess the impact of marine organisms on the hydrodynamic efficiency of a TCT. The results indicated that higher level of fouling on the blade could cause 70% reduction of efficiency. Even small amount of marine organism inhibited on the blades could affect the performance of the device. Batten et al. [64] further studied the effect of blade fouling in 2007. It has been found that significant power reduction can arise at higher tip speed ratio. Obviously, the hydrodynamic load on TCTs can be affected and the performance of overall system may be deteriorated if it is fouled by marine organisms. It is necessary to take care of the cleaniless of turbine blades. Seriously fouled TCTs are not capable to generate designed electricity and may out of service worsely.

Recently, Shi et al. [65] carried a study on the marine growth effect on dynamic response of offshore wind turbines. Since the TCTs and wind turbines have similar support structure, this study is used as a benchmark to study the marine growth effect on the dynamic response of TCTs. In aforementioned work, marine fouling with different thickness, densities and hydrodynamics coefficients values have been selected as the parameters to investigate the effects on the offshore wind turbine with jacket foundation. It concluded that marine growth has a little effect on the first order natural frequencies while it has higher effect on second and third order natural frequencies of the support structure. Hydrodynamic loads can be influenced dramatically by thickness and densities of marine growth [65]. This study further testifies the survivability of fouled TCTs. The TCTs are not able to commit the designed electricity and service life if serious marine fouling occurred.

4. Remedial actions for tidal current turbines (TCTs)

As stated previously, the marine environment experienced by TCTs is considerably harsh. In order to develop TCTs economically viable for long term, reliability of TCTs must be guaranteed. Some prototype turbines experienced failure during trials at sea [56]. The aforementioned survival aspects of TCTs are possible to cause failures of TCTs. These survival considerations of TCTs have been discussed deeply. According to those considerations, proper remedial actions could be taken for the sake of enhancing the survivability of TCTs while meeting the designed electricity generation. Table 8 summarises the time scale effect of the discussed survival problems and respective remedial actions.

The severe loading of blades is the main concern of the long term reliability of tidal turbines. Extreme event could impose extra extreme load on the structures. This could influence the fatigue and sustainability of TCTs. Mitigation of the fatigue loading mechanism is of significant importance to avoid failure of TCTs blade root component. Sophisticated control strategies, such as individual blade pitch control has been applied in wind turbine. Selection of composite materials to construct the blades also enhances the durability of TCTs. The CFRP and GFRP are the good candidates for manufacturing the turbine blades. Composites materials are also feasible to manufacture shrouds, mounting frames and other components of the tidal current energy converter systems as they have lighter weight so that installation process is easier. It is also possible to disassemble the blades prior to the occurrence of any extreme event.

The metallic component of TCTs needs to be protected from seawater where the turbine nacelle has to be sealed tightly. Besides, the external surface, especially the turbines and its support structure have to be painted or galvanised. On the other hand, increasing the thickness of steel material is another method to prevent material

Table 8
Potential failure of tidal current turbine.

Concerns	Time scale	Risky component	Possibility of failure	Remedial actions
Extreme weather	Immediate	Blade, tower	High	Uninstall blades
Seabed scour	Long term	Foundation, cable	Medium	Scour protection
Fatigue	Long term	Blade	Medium	Composite material
Corrosion/erosion	Long term	Blade, tower, nacelle	Medium	Composite material and painting
Marine fouling	Long term	Blade, nacelle	Medium	Fouling release painting

degradation. Compared to coating of steel, this one has more economic feasibility. This support structure of TCTs could use thicker steel to build [5]. Meanwhile, application of composite materials to manufacture turbine blades can reduce the risk of corrosion related problem due to their high corrosion-resistance properties. Composite materials are also easy to be fouled in marine environment. The bio-fouling issue of TCTs might be difficult to tackle. Fouling release paint is available in the market and it is the current practice in most of the deployed large scale tidal current turbine to prevent fouling. Highly durable fouling release paint is required to decrease the intensive maintenance cost.

Scour protection units can be placed around the support structures of TCTs to prevent scour holes. The scour extent and depth should be quantified precisely before the placing of protection units. Giles et al. [66] presented an experimental study investigating the potential benefits of foundation-based flow acceleration structures for marine energy converters. It proved that such structure can bring lots of benefits including increase device power output, increase foundation footprint and scour protection. Therefore, such foundation-based flow acceleration structures can be placed at the foundation of TCTs as they have multiple benefits. However, secondary scour around the foundation-based structures may occur. The change of ocean floor may result in environmental problems as well as the decrease of efficiency of energy extraction device.

Maintenance of TCTs is necessary during their operational life. Proper and regular maintenance could enhance the lifespan of TCTs. The condition of TCTs is not easily to be known since they are situated in ocean environments. Effective monitoring system could help to conduct the appropriate maintenance works. Prickett et al. [67] proposed a methodology of using a microcontroller-based condition monitoring approach to perform early detection of possible failures of TCTs. It is an essential approach to avoid failure of TCTs as the potential causes of failures of TCTs are not yet well understood. The monitoring of foundation, bathymetry, and electric connectors (generator, gearbox, cable etc.) are also necessary if the monitoring cost is affordable. The suggested maintenances of TCTs at current stage are manual cleaning of fouled microorganisms; reapplying painting/coating on surfaces of TCTs; lubricant refilling, electric connectors checking; nacelle re-sealing. All the recommended methods for maintenance should be scheduled effectively in order to reduce the cost. Increase of the feasibility of maintenance is also vital. Many maintenance works are difficult to be conducted underwater. TCTs with facility to raise the turbine above water can make maintenance service on-going without any hitch on accessibility. The world's first tidal current turbine (Seaflow) rated at 300 kW has such facility to raise the turbine above sea surface [45]. Certainly, sound designs, good monitoring approaches and effective maintenance could remarkably strengthen the survivability of TCTs.

Incorporating nanomaterial into TCTs might also be beneficial for their long term reliability. Ng et al. [68] proposed that carbon nanotube can be applied in TCTs with inclusion of structural reinforcement, fouling release coating, structural health monitoring etc. These potential applications could largely improve the service life of TCTs. However, there is no objective measure indicating that nanomaterial can achieve the desired goals. The authors' research group have the interest to further justify the application of nanomaterial for TCTs.

5. Challenges and opportunities

Implementation of tidal current turbine is yet to be popular around the world. Through information searching of tidal current turbines, some challenges have been identified. Foremost, lifetime cost of this technology is a major concern. The capital expenses (CAPEX) and operational expenses (OPEX) per MW is remarkably high. The cost associated with the whole lifespan of the projects need to be identified as well as ensuring a return of investment [7]. Reduction of the cost of installation and operation is the key factor to achieve applicability of this technology. Environmental impact assessments (EIAs) have to be conducted prior to the application of this technology. The marine mammal may have collision with the turbines and the TCTs' structures and cabling may have an impact on fish stocks and their habitats [7].

The issue with the installation of devices in a hostile environment need to be addressed. The foundation or mooring issue, electric connectors, submarine cabling as well as network integration are very important for the development of tidal current energy [7]. Other than that, improvement of the reliability of tidal current turbine device and maximisation of the performance of device could increase the feasibility of tidal current turbine technology. The survival problems of TCTs are complicated. All the previously stated issue could have effects on the TCTs' structure. It is essential to conduct further research to investigate the survivability of performance of TCTs under combination of all severe marine conditions.

There are many untapped kinetic resources in the ocean around the world. Tidal current source as one of these sources has some advantages (as described in Section 1). Conversion of this kinetic energy to electricity is considered environmental friendly. Tidal current energy has the potential to play an important role in future energy supply. It is widely accepted that global tidal stream energy capacity is more than 120 GW. The UK has one of the largest marine energy resources in the world [17]. The authors' research team also addressed the potential application of tidal energy in Straits of Malacca [69,70]. Malaysia is a costal country with a long coastline. The tidal flow in the straits could contribute to the power generation for the nation. The authors' co-workers have reviewed 10 years research development of horizontal axis TCTs [71]. The review indicated that the tidal energy technology is developing well. Many methods to assess extractable tidal energy are available. The well-established knowledge is able to help researchers and engineers to further develop the tidal energy.

6. Conclusion

The study demonstrated that tidal current turbines (TCTs) experienced a harsh maritime environment for installation and operation compared to the wind turbine. Wind turbine experienced the blade and tower failures in the extreme weather. TCTs not only consider the extreme weather in ocean, but also take the scour effects, blade failure, corrosion and biofouling into consideration. The findings are as follows:

(a) TCTs should be designed to protect the TCTs from the extreme weather. Underwater has less turbulent compared to the area above water. Glass fibre reinforced polymer (GFRP) is not a suitable material used to construct the main structural components of a large tidal turbine blade.
(b) TCTs are susceptible to the seabed scour depending on the contact area between the structure and seabed. Gravity base and tripod have a larger contact area with seabed and therefore these structures are more susceptible to the scour effects compared to the monopile and flooding structure. The application of the protection unit to cover the bottom area of turbine support structure is able to protect the scour at seabed.
(c) Fatigue failure of TCTs needs diver to uninstall the blades for repair. The process is expensive and dangerous. Blade fatigue

has to be designed to sustain 1×10^8 cycles over a 20-year service life.

(d) Coating or painting on the turbine is suggested to prevent corrosion and marine fouling to TCTs. Corrosion reduces the structural strength of the support structure, blade, and nacelle. Corrosion of nacelle may lead to water penetration into the generator.

(e) Marine fouling increases the surface roughness on the blade leading to the losses of hydrodynamical performance of turbine. A higher level of fouling on the blade could cause 70% reduction of efficiency.

Consideration of the survivability due to extreme weather, scour, fatigue failure, corrosion and marine fouling of TCTs in capital investment (CAPEX) is able to reduce maintenance and operation cost (OPEX) in long term.

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