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Research Progress in Tidal Energy Technology-A Review

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Abstract- Tidal current energy is one of the most attractive renewable energy concepts due to its significant global potential and resources that are spread across the globe. Most of the countries have access to tidal energy resources available within their geographic boundaries. The tidal energy resource is predictable unlike some of the other renewable energy resources and hence is attracting significant research focus. Substantial research growth has taken place in the tidal energy technology over the past decade. This paper provides a review of the research progress leading to the development of tidal energy technology and explains the concepts and terminologies related to the subject area to provide a ready reference to the researchers. This work identifies new dimensions of the reviewed literature and also provides direction for future research with focus on areas, such as: performance prediction, structural loads, wake and tidal turbine arrays.

Keywords- Tidal Current Turbine, Marine Renewable Energy, Performance Predication of Tidal Turbines, Structural Loads in Tidal Turbines, Tidal Turbine Wake, Tidal Turbine Arrays.

I. INTRODUCTION

The society is faced with the issue of energy crisis and climate change and these two are susceptible to each other as the traditional fossil fuel energy production affects the climate while the later affects renewable energy like wind [i] and solar. The global energy consumption was 546 EJ in 2010 and is expected to grow by at least 27 percent till 2050 [ii]. The ever growing energy demand and the risks of carbon emissions associated with the traditional methods of burning fossil fuels are stressing the need for exploring alternate energy sources.

Renewable Energy Technologies are quickly maturing and in 2012 more than half of the new addition to global electrical power generation came from the renewable energy sector [iii]. The hydro, wind and solar energy sectors are witnessing a substantial growth. New concepts of Renewable Energy are also coming into the picture and extensive academic and industrial research is being conducted for the development of related technologies. It is expected that Renewable Energy will be able to replace fossil fuels in the near future. Tidal current energy is one such concept that is attracting a lot of interest from the developers and researchers all over the world. It is a form of hydrokinetic energy extracted from the water flow in the tidal channels. Such flow takes place due to the relative motion of the gravitational fields of the moon, sun and earth [iv] as depicted in Fig. 1.

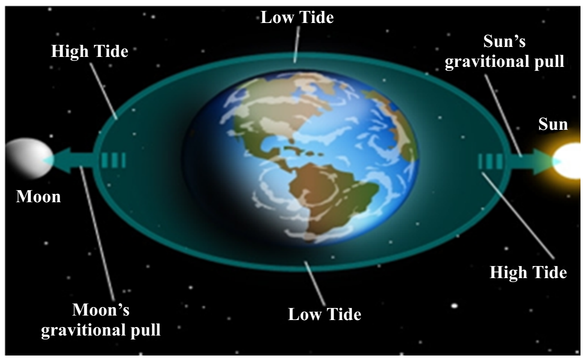

Fig. 1. Relative motion of the gravitational fields of the moon, sun and earth [v].

Normally the velocity of flow in tidal channels is very slow but in areas constrained with in the head lands and sea bed topography, narrow passages like creeks and estuaries, the currents are accelerated to higher velocities. Tidal current flow with velocities of 1.5-2 m/s are generally considered suitable for economic power production [vi, vii]. Efforts are being made to estimate the global tidal energy potential and several estimates are available in the current literature. One such estimate sets the value of global tidal energy potential to be in the range of 100-17500 TWh/yr [viii]. Other estimates show the figures of 8800 TWh/yr [ix] and 500-1000 TWh/yr [x]. Although these estimates are quite different from each other however, the potential can be safely assumed to be significantly greater than 100 TWh/yr [iv].

Tidal current turbine systems are generally classified as shown in Fig. 2. Some of the relative advantages and disadvantages of the horizontal axis tidal current turbines (TCT) are as in table 1.The tidal current energy has successfully advanced beyond the initial testing phase. Fig. 3 shows the technology readiness level (TRL) of tidal current energy. The full scale array demonstration projects are expected to be installed in 2016-17 [viii].

The initial research phase was focused on the resource characterization and site level resource assessments [xi-xxi] and development of prototypes or scaled models [xxii-xxxi]. As a result, forty new devices were introduced from 2006-2013 [vi] and the knowledge base of the technology was extended. The research focus then shifted to the development of commercial prototypes for real sea testing [iv, viii, xxxii]. Comprehensive information about the

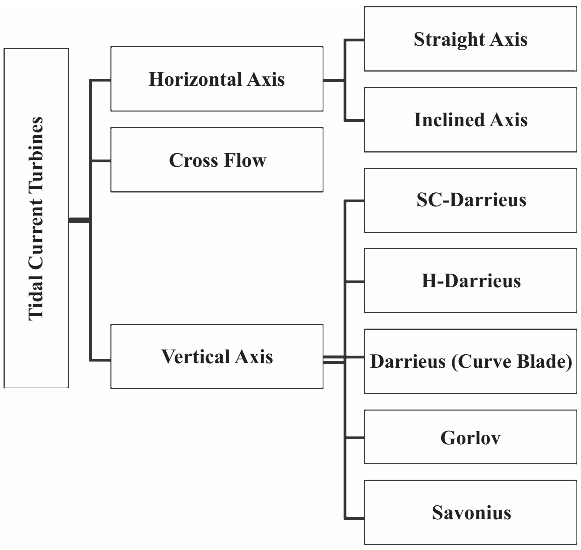

Fig. 2. Classification of Tidal Current Turbine Systems.

facilities for conducting real sea tests are available in [xxxiii]. These testing facilities are well established and the devices are now being tested in real sea conditions [xxxiv]. The results of most of these tests are encouraging with some exceptions. Some of the devices are successfully transmitting power to the grid as well [xxxv, xxxvi].

TABLE I
RELATIVE ADVANTAGES AND DISADVANTAGES OF TCT

Type	Advantages	Disadvantages
Horizontal Axis TCT	✓Rich knowledge base ✓Self-starting ✓Speed control ✓Annular ring duct augmentation ✓Large Capacity designs ✓Better Efficiency ✓Resistance to cavitation	×Complicated design ×Complicated blade manufacturing ×Under water placement of moisture sensitive parts ×Under water placement of power supply cable
Vertical Axis TCT	✓Simple design ✓Simple blade manufacturing ✓Moisture sensitive parts can be placed above water surface ✓Floating structures and ducts installation ✓Skewed flow	×Lower efficiency ×Poor self-starting ×Require additional starting mechanism ×Cavitation

This paper provides a review of the main research work that resulted in the current developments in the tidal energy technology. The review of the research progress will provide the direction for future research and identify new dimensions of the reviewed literature. Important concepts related to the subject have been explained to provide a reference to the researchers in this area. The paper is organized into five sections with section II giving the brief

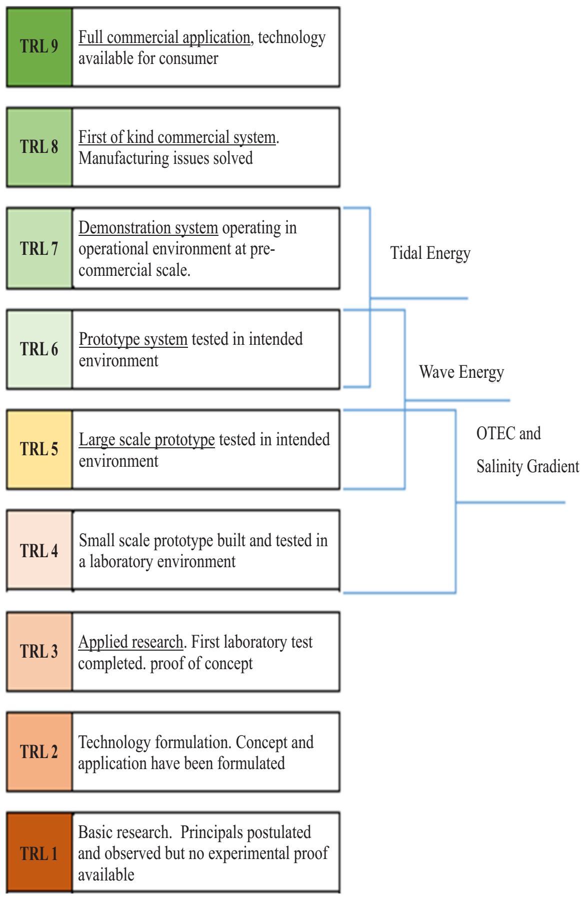

Fig. 3. TRL of ocean energy technologies [xxxvii]

historical background. Section III gives the performance prediction of the tidal current turbines followed by their structural load review in section IV. Section V gives wake of marine current turbine with the review of research carried out when the turbines are arranged in arrays in section VI. Finally the future research possibilities are given in section VII with concluding remarks in section VIII.

II. HISTORICAL BACKGROUND

History reveals that the tide/water mills existed in the 7th century. Al-Muqadassi, a famous Arab geographer, described the tide mills operating in Iraq (Basra) in the 10th century [xxxviii]. Ocean energy, particularly the tidal energy, for the production of electricity was first suggested by Romanoski in 1950 [xxxix]. However, literature pertinent to the concept of energy from the ocean currents exist well before him. Generation of electricity from the Ocean currents is being investigated for the last forty years [xl]. The first major tidal barrage for the extraction of tidal energy, was the La Rance tidal power station established in France on November 26, 1966 [xli]. Although a functional tidal power station was available at the Boston Harbor in Massachusetts, USA in the latter part of the 19th century, while another was operating in Husum, Germany that was dismantled in 1914 and another in China in 1958 [xxxviii]. The interest in research on generation of tidal electrical energy was also affected by the availability of fuel as the 1973 oil crisis provided the basis for increased interest in the Renewable Energy While on the other hand, the falling oil prices in 1980s caused a decline in the official support for developing Renewable Energy. In the mid-1990s, once again interest in the large scale deployment of Renewable Energy increased due to the perceived threat of global warming highlighted by the Koyoto Process [iv]. The world's first, 10 kW scaled model, tidal current turbine was tested on Loch Linnhe, a Scottish sea-loch, during 1994-95 by IT power UK [xl]. In 1998, the company initiated the world's first tidal current energy system called Seaflow. This 300 kW tidal turbine was installed in North Devon in May 2003[xlii]. Based on the concept of SeaFlow, Marine Current Turbine (MCT) installed a twin rotor steel mono pile mounted 1.2 MW commercial proto type turbine called SeaGen in July 2008[xl] that is still successfully providing power to the grid. The installation and successful operation of Seaflow in open sea proved to be the turning point for the present day development of tidal current technology.

III. PERFORMANCE PREDICTION OF TIDAL CURRENT TURBINES

The design and performance prediction of Tidal Current Turbines (TCT) remained the focus of research during the initial research phase of its development. This research resulted in the development of performance prediction methods that enabled the description of physical and operational performance of the tidal turbines. The development of such methods helped a lot in the design, optimization and performance evaluation. The base for the research was provided by wind turbines. Batten et.al [xxii] developed a numerical model for the performance prediction of a TCT and span wise distribution of blade loads. Their model was based upon the well-known Blade Element Momentum (BEM) theory. BEM is based upon the combination of General Momentum and Blade Element theory [xliii]. The momentum theory is used for the calculation of axial and tangential induction factors while taking into account the tip losses. The Blade element theory divides the blade into a number of sections to calculate the torque and drag at each section. The integration of these sectional drag and torque gives the values of total blade torque and drag. This numerical model was successfully validated through experimental test in a cavitation tunnel and towing tank [xliv]. The experimental work suggested that the developed tool can provide satisfactory accuracy for design exercises and parametric studies. In BEM method the blade is discretized as shown in Fig. 4a. The blade parameters at different stations at a radius, r, are evaluated. Fig. 4b shows a single blade element taken from the blade at a radius, r. The blade properties determined at each blade section along the blade length are averaged. Every blade element experiences fluid forces as shown in Fig. 4c.

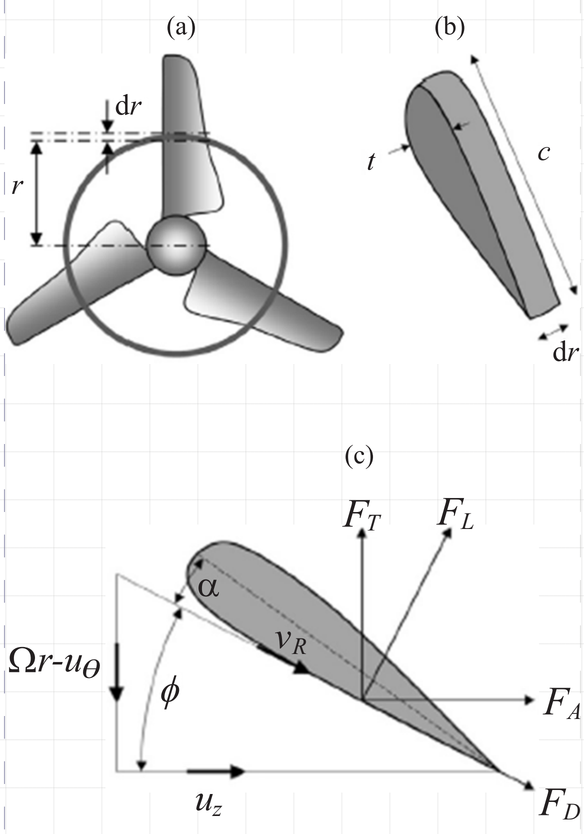

Fig. 4. [a]: Schematic diagram of the discretization of the rotor; [b]: cross-section of the blade; [c]: resolution of the lift and drag forces [xlv].

Xiao Zhang et.al [xlvi] performed the performance estimation of a dual rotor contra rotating turbine using computational fluid dynamics (CFD). CFD derives its basics from the fact that the physics of any fluid flow is described by three fundamental principles. These principals are the conservation of mass, momentum and energy. These fundamental principles, in their most general from, are expressed either in the form of integral or partial differential equations. CFD is the art for converting these integral or partial differential equations, governing the fluid flow, into its discretized algebraic form that can be solved numerically [xlvii]. These flow governing equations are called Navier Stokes equation. CFD utilizes various numerical schemes for the solution of Navier Stokes Equation to provide detail information of the fluid flow. The information about the fluid flow is translated into performance parameters of the TCT in different flow condition. The performance data includes thrust, torque and power estimates. CFD model maps the pressure distribution on the blade surface that enables the prediction of cavitation. The numerical model in [xlvi] was based upon the Incompressible Steady State Navier Stokes Equation. They used a computational CFD software package. The results of the study were not supported and validated through experimental work. Chul hee Jo et.al [xlviii, xlix] also used the Navier Stokes Equation model for the performance predication of an experimental model turbine. They used a finite volume solver of the commercial CFD software package ANSYS CFX. They predicted the optimum tip speed ratio and power co-efficient for their turbine in different flow velocities. The comparison between the numerical and experimental results has not been provided in the article. Patrick Mark Singh and Young-Do Choi [l] worked on the development of a hydrofoil and blade design having small chord lengths for the actual current data at the south-western region of Korea. They developed a new hydrofoil for working in rough conditions and studied the performance of rotors based on three different blade designs using CFD. The optimum TSR and power co-efficient was worked out. In order to compare the structural integrity of these blades against static loads, fluid structure Interaction (FSI) analysis were also carried out. For FSI analysis, the pressure mapped on the blade surface for performance analysis was coupled with a structural analysis system to perform the structural analysis. Chul-hee Jo et. al [li] conducted the performance analysis through FSI modeling of a tidal current turbine with pre-deformed blade. A pre-deformed blade is made with a built-in bend towards the current before the application of hydrodynamic loads. Once the flow exerts pressure, the blade regains it's unbend shape due to deformation. As such the deformation that was supposed to produce a power loss will be negated to create any power loss. The study compared the performance of two turbines having the same specification except that one was having the pre deformed blades. The power loss due to deformation of the blades was consequently estimated. The study used CFD analysis to model the fluid flow on the turbine blades and FSI analysis were performed to calculate the deformation of the blades.

The literature review presented above points out different approaches for the prediction of TCT performance. These approaches are not competing approaches but in fact they all have their own role in the research and development of TCT. The BEM approach is used in the preliminary design stage for the design and optimization of the hydrodynamic parameters of the TCT blade. The CFD approach is used later in the design stage for more detailed analysis and to reduce the load of experimental work. The experimental model is prepared after the implementation of first two approaches to get an optimized design for the preparation of a lab scale model. All these approaches have their own advantages and limitations. The BEM approach is quite easy to use and its computational cost is very low. But its limitations are that it cannot account for chord wise loading, variation in free stream flow and influence of rotor on the surrounding flow etc.[xliii, xlv]. Although, the addition of correction factors accounting for three-dimensional (3D) effects such as tip loss, rotational flow and dynamic stall to the originally proposed BEM method have improved the BEM predictions [lii, liii]. The 3D inviscid methods like lifting line, panel and vortex lattice methods [liv-lvi] can model the physics of the turbine hydrodynamics in more details as compared to the BEM method. But these models do not account for the viscous effects that are essential for the accurate prediction of turbine performance. In CFD simulations models the fluid flows using the first principal or laws of conservation and therefor, captures the viscous effects. CFD modeling accounts for the limitation of BEM and inviscid models but it is computationally expensive and have issues with turbulence modeling. The experimental approach have the scaling issues as well as the increased revolutions per minute of the scaled model produces swirl and pressure gradient that is not available in the real condition [lvii]. The research work conducted, related to performance, so far is invaluable and making ways for the future research. The coupling of the BEM and CFD numerical approach is currently being investigated for predicting the array performance [xlv, lviii].

IV. Structural Loads on Tidal Current Turbine

The wind and ocean current turbines have much in common but there are certain key differences. One of the differences is in the amount of structural loads and the sources as well as behavior of certain loads. Water being a denser fluid exerts more pressure on the turbine as compared to wind. As for as wind turbines are concerned, it is quite clear that TCT's will be subjected to a complex load regime. It is important to consider the effects of structural loads faced by various components of a TCT to ensure its reliable and safe design and operation. The most critical part of TCT subjected to structural loads is the turbine blade. Optimized design of blades is of utmost importance as its failures has been witnessed in some of the prototype test of TCT [lx]. Rotor of a TCT converts the kinetic energy of the flow into mechanical work governed by law of conservation of momentum. The exchange of momentum mainly takes place in the flow direction. Whereas, the power is produced in the rotor plane perpendicular to the stream direction. Lift and drag forces are caused by the fluid flow passing the turbine blade as shown in Fig. 5.The drag force is parallel, whereas the lift force is perpendicular to the resultant or relative flow velocity. The drag and lift force can be resolved into the axial force or thrust and tangential force or torque [lxi].

For a Horizontal Axis TCT, operating perpendicular to the flow, the thrust force acts in the direction of flow and induce bending movements. The torque acts around the rotor shaft and causes rotation. The possibility of failure due to constant thrust loads imposed by the flow can be easily eliminated, if properly accounted for in the design. Cyclic and stochastic loads caused by turbulence are

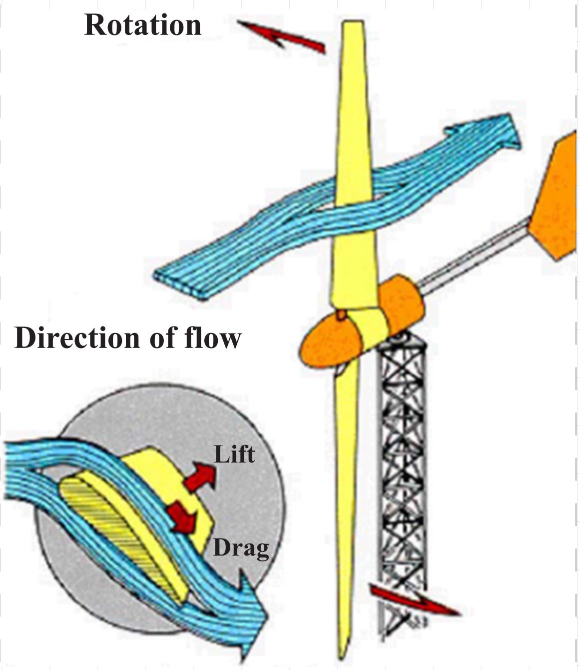

Fig. 5. Lift and Drag forces on TCT rotor [lix]

expected to cause most of the structural failure mainly due to fatigue. Turbulence, wave current interaction and some other situation specific phenomena like tower wake interaction or wake interaction with upstream turbines along with rotation of the turbine blades, randomness of ocean current, variation of current velocity with depths also called velocity shear are the sources of repeated cyclic loads on the TCT [lxii].

Numerous studies have been conducted during the last decade for static and dynamic analysis of TCT. Gunjit Bir et.al [lx] of the National Renewable Energy Laboratory performed the hydrodynamic and structural design of a composite TCT blade. The authors based their structural design on static structural loads and identified two extreme operating flow conditions and modeled them using CFD to compute the extreme loads. Simulation was carried out by taking the blade external geometry and the design load distribution as inputs to calculate the optimal design thickness of load-bearing composite laminates at each blade section using ultimate-strength and buckling-resistance criteria. The results also provided the optimum location for the webs. The dynamic loads, fatigue and stiffness criteria was not considered in this research work. Pascal W. Galloway et.al [lxiii] performed the experimental and numerical investigation of rotor power and thrust of a tidal turbine operating at yaw and in waves. A wave towing tank experiment and BEM code, including the effect of wave and yaw, was used for the investigation to understand the loading on the turbine rotor and blades. Results of the numerical investigation were in good agreement with the experimental results. Results of the study revealed that the wave current interaction will cause cyclic loading in a TCT that will cause an accelerated fatigue to the rotor and blade. The results also showed that a yaw drive is necessary to avoid the increased dynamic loading and power loss in a TCT. N Barltrop et.al [lxiv]also worked on the effect of wave current interaction on a TCT. In this study towing tank experiments and an extended BEM numerical model that included the wave effect was used. The numerical and experimental results were in good agreement. The study suggested that at lower current speeds the effect of wave will increase the torque and the thrust will not be affected. The change in wave height for longer waves will greatly affect the torque. At constant tip speeds the shorter waves may force a stall that will cause a sudden reduction in torque and increase in the thrust force. G. N. McCann [lxv] performed a parametric study on the sensitivity of fatigue loading experienced by a tidal current turbine due to the wave action and Turbulence caused by the sea-bed roughness and temperature effects etc. The study concluded that the fatigue load varies with mean flow turbulence and is very sensitive to the wave current interaction. The fatigue load due to flow turbulence and wave action may be duly considered in the design of TCT. Céline Faudot et.al [lxvi] used a quasi-state BEM theory combined with added mass force to numerically model the effect of waves on fatigue loads and life time of a TCT blade. The numerical model was also tested through tow tank experiments on a model TCT. Deviation between experimental and numerical results was observed. The study concluded that the consideration of extreme loads due to high and steep waves is necessary for the reliable design of TCT blade. The dynamic effects like dynamic stall and wake are important consideration for the estimation of loads in steep waves. The implementation of added blade mass is significant for elastic blade with the combination of hydro elastic model of the blade. Milne et.al [lxvii] investigated the blade root bending moment of TCT for oscillatory motion in a tow tank. The objective of the study was to analyze the role of unsteady hydrodynamic forces on the blade loads for their accurate prediction. It was established that unsteady bending moment is sensitive to oscillatory frequency and amplitude. The flow separation and dynamic stall caused unsteady loads are of higher magnitudes and cannot be predicted through quasi-steady state models. The prediction of such loads will require models accounting for unsteady flow and dynamic stall. Mohammad Wasim Akram [lxviii] computed the fatigue life of a composite TCT blade under the influence of random ocean currents due to turbulence and velocity shear. The Rain flow counting algorithm was used to count the number of cycles of loads within a specific mean and amplitude acting on the blade from random current data. The commercial Finite Element Code ANSYS was used to develop S-N diagram. Fatigue damage expected in thirty years of operation was estimated using Palmgren-Miner's linear hypothesis. In the analysis, fatigue loads due to velocity shear were considered. The contribution of fatigue loads due to velocity shear is quite low. On the other hand the fatigue loads due to wake was not considered. Fang Zhou et. al [lxii] in 2012 repeated the work using NREL dedicated codes due to their robustness as compared to ANSYS. The results showed that the designed blade have a fatigue life of more than twenty years. The study suggested that instead of using an NREL code CFD may be used for the calculation of loads for the computation of fatigue life. Junior Senat [lxix] used a combination of BEM and linear wave theory for the prediction of torque, thrust and blade root bending moments caused by wave current interaction. The study showed that in longer waves the torque is sensitive to the variation of wave height. The fluctuation in the in plane and out of plane bending movements is significant and can be predicted by linear wave theory combined with BEM theory. BEM theory with tip loss correction and 3D effects can analyze the power and thrust coefficient. Fang Zhou [lxx] developed a computational tool by integrating NREL odes, Sandia National Laboratories code NuMAD and ANSYS for the analysis of TCT. The aim of the study was to consider randomness of ocean currents, rotation of the blade and hurricane driven currents in the design, analysis and fatigue life prediction of composite TCT blade. In this study the dynamic response was computed by modifying the NREL codes AeroDyn and FAST. The tangential and normal forces were applied to ANSYS model to perform the static and buckling analysis for the identification of high stress regions. Useful life at various stress levels and ratios was calculated through Goodman diagram. Velocity time histogram of the experimental data was used to calculate the actual number of cycles. This enabled the calculation of damage and fatigue life of the blade was predicted using Palmgren-Miner's rule for cumulative fatigue.

V. Wake of Marine Current Turbines

Wake is the region of disturbed flow downstream of a solid body moving through a fluid or vice versa. A hydrokinetic turbine extracts momentum from the flow while the mass is conserved. The momentum loss downstream of the device creates a pressure jump and consequently an axial pressure gradient, an expansion of the wake and a decrease of the axial velocity. The wake is therefore characterized by a decrease in mean flow speed also called velocity/wake deficit and increased turbulence. Wake is a complicated and device specific phenomenon. The wake as shown in Fig.6is generally divided into near and far wake region to simplify the physics governing the wake structure [lxxi].

A strict distinction of near and far wake in terms of downstream distance may not be possible. In the wind turbine the near wake is from 1-2 rotor diameters downstream [lxxi], whereas for the TCT it is considered to be from 0-3/4 rotor diameter downstream [lxxii].

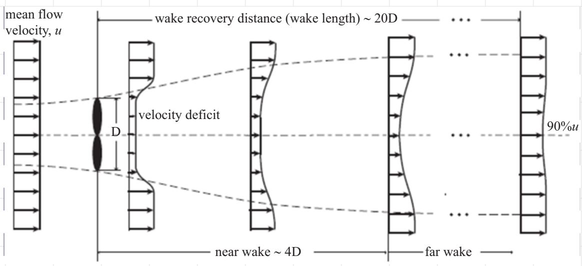

Fig. 6. Definition of wake characteristics [viii]

However, a clear understanding of the near wake is that it is the region where the geometry of the turbine has a direct effect on the fluid flow. A hydrokinetic turbine converts the energy extracted from the fluid flow into mechanical motion. The mechanical motion of the blades produce vortex shedding from the blade tip. Vortices shedding along with support structure has a direct effect on the flow in the near wake region. Shedding of the vortices by the blade tip creates sharp velocity gradients and peaks in turbulence intensity. On the contrary, the turbine geometry affects the far wake indirectly. The indirect effect of the geometry is in the form of decreased axial velocity and increased turbulence intensity. The wake structure is governed by convection and turbulent mixing. For a completely inviscid flow the volume of slow moving fluid will just be convecting downstream at a slower rate than the free stream flow. But due to the turbulent mixing the wake keeps on regaining energy and ultimately attains the free stream velocity farther downstream. In the near wake, the pressure field around the device is important whereas, in the far wake the turbulent mixing is important for the development of wake deficit. Mixing of the wake and recovery of the velocity deficit in the far wake takes place due to the turbulence and as result the overall turbulence decreases [lxxi, lxxiii]. Wake is one of the most extensively researched area of the tidal current energy. Wake studies are necessary to understand the effect of an upstream device on the performance and loading experienced by the downstream turbine. A brief review of research articles for better understanding of the wake is presented here.

A. S. Bahaj et. al [lxxii] carried out the experimental and theoretical investigations of the flow field around mesh disc rotor simulator in a tilting flume. The work was aimed to identify and investigate the parameters governing the wake structure and its recovery to free stream velocity profile. The identified governing parameters were intended to be used for the development of a numerical model for characterizing the wake of a tidal current turbine. The study concluded that porous disc experiments can effectively simulate the far wake of a TCT. The results showed that deficit is maximum in the immediate wake region and tends to recover with increasing downstream distance. However, the wake persists for quite a long distance and up to 20 rotor diameters only 90% of the velocity was recovered. The free surface and sea bed may restrict the vertical expansion of the wake. Hence further investigation was proposed to study the effect of water depth, proximity to the free surface and the influence of ambient turbulence on the initial condition and wake mixing. Luke Myers and A. S. Bahaj [lxxiii] further extended their work by testing the 1/30th scale model TCT in a circulating water channel. Performance and wake structure of the turbine was investigated at different flow speeds and thrust coefficients. An increase in surface turbulence was observed with increase in flow velocity. Between the rotor and the side of the channel, the velocity of flow was greater than the inflow velocity for all flow speeds. The effect was more pronounced for increased inflow velocities. The phenomenon was termed as blockage effect. Due to the blockage effect, an increase in channel head upstream of rotor and an immediate decrease due to extraction of energy in the downstream was observed. It was suggested that the blockage effects and variation in channel head may not be so exaggerated at full scale because Froude numbers will be much lower. However, it may still be significant. It was observed that the expansion of the wake took place downstream of the rotor and ultimately reached the surface. This will either increase the channel head further downstream or will mix with the wake of another adjacent TCT. Rate of wake recovery is dependent upon the ambient turbulence intensity and thrust coefficient of the rotor. MacLeod et. al [lxxiv] through CFD modeling also established that rate of wake recovery increases with increasing turbulence intensity and that higher thrust coefficient will cause slower wake recovery rate. F. Maganga et. al [lxxv] experimentally established the fact that the wake recovery is faster in the areas of greater turbulence intensity. The blockage effect may place restrictions on the maximum diameter of a TCT for a specific channel. The study suggested further investigation of the blockage effect, wake expansion and Froude number scaling with in TCT arrays. In another study L. Myers and A. S. Bahaj [lxxvi] measured the wake characteristics of a 1/20th scale TCT in a water channel. In this experiment the channel base flow and wake downstream of the turbine was mapped with laser and acoustic Doppler velocimeters. Wake mapping of both a stationary and rotating rotor was conducted to observe the effect of support structure on the flow properties in the near wake. Results of the experiment showed that the support structure has a noticeable effect on the near wake along with a synergetic effect from both the rotor and support structure near the center plane of the rotor in the downstream. This effect diminishes with increasing distance along the lateral direction of the channel. The higher turbulence intensity made it difficult to determine the flow properties in the near wake region. Luke Myers and A. S. Bahaj [lxxvii] also studied Flow boundary interaction effects for marine current energy conversion devices through mesh rotor disc experiments in a flume and circulating water channel. This experimental work concluded that TCT operating in shallow waters will produce a different wake structure than those operating in deep waters. A satisfactory wake recovery will not be possible, if the depth underneath the rotor is infinite. In 2010, Luke Myers and A. S. Bahaj [lxxviii] studied the wake characteristic of a TCT through mesh disc rotor simulator in a laboratory flume. It was observed that the wake velocity in the near wake region will decrease with increasing thrust. The results also validated the fact that the far wake recovery is a function of the ambient turbulence. Distance of the rotor from open surface and sea bed have an influence on the far wake recovery. The sea bed roughness contributes to the decrease in the downstream wake velocity. The results concluded that a number of interdependent variable can affect the wake recovery rate.

Apart from the experimental investigations presented above, various numerical studies have also been performed to characterize the wake of a TCT. M. E. Harrison and W. M. J. Batten along with L. E. Myers and A. S. Bahaj [lvii] used a commercial CFD software package to characterize the wake of mesh disc rotor and compare the CFD results with experiment. A good agreement between the CFD and experimental results was observed. The CFD results revealed that the main factors affecting the wake structure are the device thrust, ambient turbulence and potentially the disc induced turbulence. However, difference in turbulence intensity between the numerical and experimental results were observed. The results concluded that with further improvements in the CFD modeling techniques, CFD analysis of mesh disc rotors may be an accurate and valid numerical modelling method for TCT. Blackmore T along with Batten and Bahaj [lxxix] used large eddy simulation (LES) to study the effect of inflow turbulence on the wake of a rotor disc simulator of TCT. The simulation showed that an increase in the flow turbulence reduces the velocity deficit and the maximum velocity deficit shifts closer to the rotor. Higher inflow turbulence also results in faster wake recovery in the downstream. Recently, some work has been done to analytically model the wake of a TCT. Wei-Haur Lam et. al [lxxx] developed two analytical equation for the prediction of mean wake velocity of a TCT. One of the equation used for the prediction of initial velocity is based on the axial momentum theory and dimensional analysis. Whereas the other equation is used to predict the lateral velocity and it is based on the Gaussian probability distribution. Results of the equations were compared with other numerical and experimental results that showed some deviation. However, it was claimed that these equations will provide the basis for the formulation of an analytical model. Later the same author succeeded to develop an analytical wake model and presented his work in [lxxxi]. Results of the developed analytical wake model was compared with well accepted experimental results. The presented results showed that the analytical model can predict the wake profile for different turbulence intensities. More recent work related to the wake studies of TCT focuses on the wake interaction between devices or the effect of the wake of upstream devices on the downstream devices. Some of this work will be discussed in the next section.

VI. Tidal Turbine Arrays

A huge portion of the global tidal energy potential is available in the narrow channels [lxxii, lxxix]. Efforts are required to fully utilize the available space and extract maximum energy from these sites. The concept of tidal turbines arrays or farms seems to be the ultimate solution to the problem. In addition, only tidal array can make the technology commercial and justify the cost of grid connection along with establishing, maintenance and navigation facilities [lxxxii]. A standalone turbine cannot justify this huge cost [lxxiv].

Tidal arrays are classified into large and small arrays [lxxxii]. The term large array does not mean that channel will have a huge number of turbines. If the turbines extracts large portion of the channel potential, the array will be large irrespective of the number of turbines. A few turbines in a small channel can constitute a large array. Conversely, a number of turbines in a large channel can be a small array. A large array affects the “channel-scale dynamics” or improves the power co-efficient of turbines through “duct-effect”. Whereas a small array is one that cannot significantly affect the “channel-scale dynamics” and the performance of the individual turbine is not affected by other turbines or proximity to channel sides. It is essential to understand the dynamics of turbines with in large arrays for the development of tidal turbine arrays and the design of turbines in arrays [lxxxiii]. An array has two competing effects on the dynamics of flow in a tidal channel. One is the “channel-scale dynamics” and the other is the “duct-effect”. The channel-scale dynamics refers to the finite head loss as shown in Fig. 7 due to power extraction from a channel [lxxxiv].

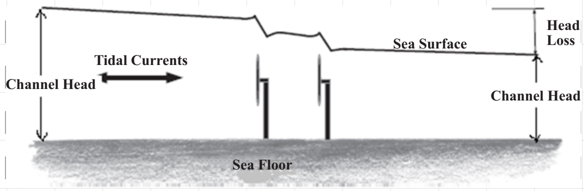

Fig. 7. Finite Head Loss due to power extraction from a tidal channel [lxxxii].

This finite head loss causes additional drag and reduces free stream flow that limits the array power output. Due to this the turbines in a channel interacts with each other even if they are far enough from the wake effects of each other. In addition, any Bitz turbine operating in an array, causes the array to lose 1/3 of its energy to turbulent mixing behind the turbine or near wake region [lxxxv]. About 5-10% of the energy is lost to the support structure [lxxxvi] and about 11% goes into electromechanical losses that imposes significant portion of the structural loads on the turbine. The proportion of these loads highly depends upon the number of turbines, their arrangement and tuning in the array. On the other hand, the duct-effect shown in Fig. 8, increases the free stream flow. Duct-effect improves the turbine thrust and power co-efficient of the turbine in the array. It is possible for the turbines operating in array to operate at higher thrust and power co-efficient than that of a Bitz turbine [lxxxiii].

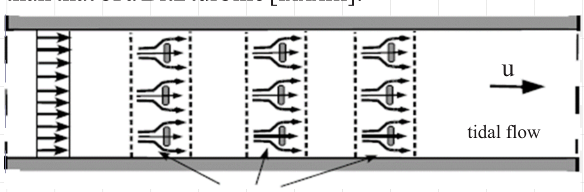

Fig. 8. Channel forming a duct around the turbines [lxxxvii].

In addition to these two effects, the design of array will dictate the amount of power output of the individual turbine. In an experimental study L.E. Myers and A. S. Bahaj [lxxxviii] established the fact that flow can be accelerated between two laterally adjacent porous discs causing an increased thrust and power for the downstream disc in a staggered array. Chul-Hee Jo et al. [lxxxix] also observed that staggered arrays are more productive as compared to the longitudinal arrays. Because in the staggered array, the downstream rotor can avoid the wake interference of the upstream rotors. In the axial array, increasing the inter device spacing reduces the power loss of the downstream devices. Chul-Hee Jo et al. [xc] through experiments and CFD simulation showed that downstream devices, in an axial array, received a reduced flow velocity at varying longitudinal spacing. As a result the predicted power output of the individual turbines in the array was much less than their designed power output. Rami Malki et al. [xlv] used a coupled BEM-CFD model for the simulation of tidal turbine array. The simulation revealed that the longitudinal and lateral spacing between the turbines in array have a significant influence on the velocity and turbulence intensity of the flow. The flow velocity increased between a pair of laterally adjacent devices. The authors observed a maximum turbulence intensity when the upstream devices were closely spaced in lateral direction and downstream turbine at increased longitudinal spacing. This increased turbulence intensity is critical for the structural integrity of the turbines and can only be modeled with an FSI modeling approach.

VII. FUTURE PERSPECTIVE

A turbine operating in array will experience different flow, will have a different power and thrust coefficient and will experience different structural loads than when operating as standalone. Therefore, the criterion used to design turbines needs to be adopted accordingly. A turbine must be designed for an array configuration rather than for isolated use. Power output of the individual turbine affects the total array output, which in turn affects the flow experienced by each turbine, the loads on the turbine and their outputs. In addition, for turbines operating in array, considerable loading will also come from the operation of the upstream turbine. Therefore, it is necessary to model the effect of operation of upstream device on the structural loads encountered by the downstream device and its fatigue life. The load forces will follow the trend of power output per turbine. The load will be distributed over the turbine blades and fixing arrangement as well as power train and mooring system. It is very imperative to understand the contribution of all the loads along with drag caused by power extraction for developing structural design specification. Increased power output from a turbine will produce higher structural loads on the turbine and thus the turbine should be more robust having a higher construction cost and vice versa.

Most of the current research is focusing the tidal turbine array Micro and Macro design/optimization to maximize the total array output. The other important array associated impacts of varying structural loads have not been investigated in details so far. The investigation of structural loads and the integrity/safety of the turbine against these loads is very important for the development of structural design specification. Other important consideration is the associated manufacturing cost. If the array associated structural loads is not given due consideration then the devices will either be over designed or under designed. Both the possibilities will make the technology costly and unreliable at the array scale.

The investigation of structural loads on the turbine in an array and their effect on the useful life of the turbine through numerical modeling and experiments should be the focus of future research for the development of large tidal arrays. Over the years substantial growth in the availability of computational resources has taken place. Due to which the numerical modeling technique of Fluid Structure Interaction (FSI) can be very useful for modeling such problems. FSI is a multi-physics problem. When a fluid flow exerts pressure on an elastic structure, the structure deforms. In return, the deformed structure disturbs the fluid flow. This disturbed fluid flow now exerts another form of pressure on the structure in a repetitive manner. This kind of interaction is called Fluid Structure Interaction (FSI). FSI is based upon the fundamental principle of dynamics (FPD), or Newton's second law, applied to the mechanical system. Some researchers have adopted the FSI modeling approach for other aspects of Tidal/wind turbine. CH Jo et al. [xci] performed the FSI analysis for the investigation of deformation along offshore pile structure of tidal current power and for the Performance Analysis of 200kW Tidal Current Power Turbine with Pre-deformed Blades [li]. R. F. Nicholls-Lee [xcii] used FSI for the performance analysis of TCT with bend twist coupled blades. B. S. Kim et al. [xciii] assessed the structural integrity of 50kW helical ocean current turbine using fluid structure interaction analysis. Ming-Chen Hsu and Yuri Bazilevs [xciv] performed the Fluid–structure interaction modeling of a full wind turbine. All these studies suggest that a coupled CFD and structural model (i.e., FSI Model) can provide satisfactory results for modeling the deformation of the TCT structures due to fluid loads imposed by the tidal currents.

VIII. CONCLUSION

The paper presented a thorough review of the tidal energy technology including all the modules like

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performance prediction, structural load analysis, wake effects and installation of the turbines in arrays. Based on the review, future research directions are also outlined addressing three key issues. These include investigation of structural loads and the integrity/safety of the turbine against these loads for the development of structural design specification. Another issue that need the focus of research community is the effect of structural load on the useful life of the turbine particularly in tidal arrays and the requirement of developing proper numerical and experimental models. The numerical modeling technique of FSI can be very useful though computationally expensive for modeling the above problem but can benefit from the computational power of current electronic device.

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