Unique Challenges in Harnessing Open Ocean Marine Hydrokinetic Energy

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Abstract— **The oceans are a tremendous source of clean, renewable energy, yet the majority of this resource is located far from shore and the population centers that could benefit from the generated power. Tidal energy has been harnessed in various ways over the last few centuries, for both mechanical and electrical power generation. Presently, tidal energy is quickly becoming a viable alternative to conventional fossil fuel electrical generation, especially in the upper latitudes such as Europe and areas of North America. These sites tend to be close to shore, in relatively shallow water, and benefit from at least one period of reduced flow, or slack tide, during which certain installation and maintenance activities may occur.**

Open ocean marine hydrokinetic (MHK) power generation, however, poses many more challenges, while retaining the issues that tidal systems must overcome. Ideal MHK sites, typically within western boundary currents such as the Gulf Stream, Kuroshio, and Agulhas Currents, are tens of kilometers offshore, in hundreds if not thousands of meters of water. The ocean currents are relentless, flowing continuously and without significant velocity changes over periods of weeks to months. The hydrodynamic drag on generators, cables, and support equipment can be tremendous. Once moored in the currents, access to the generators for inspection, maintenance, and replacement is extremely challenging, and in some cases nearly impossible.

FAU's SNMREC and Ocean Current Energy LLC (OCE) have developed equipment and procedures to address and overcome some of these difficulties. OCE has designed a novel device which utilizes generator "coins" which may be installed and removed while in the high current, similar to an aerial refueling operation. The OCE approach to these challenges demonstrate the required "out of the box" tactics of ocean engineering problem solving, while leveraging off the experience gained from similarities in tidal power generation.

Keywords—ocean; energy; MHK; Gulf Stream; mooring; generator; ocean engineering; tidal; renewable; SNMREC; OCE

I. INTRODUCTION

The challenges of tidal and open ocean electrical power generation have many similarities, most stemming from the audacious attempt to install and operate complex systems in an adverse environment such as the oceans on a large scale. This has been accomplished, of course, in the case of offshore oil production and civil engineering projects, yet the addition of continuous large velocities and dynamic near-shore ocean environments provides further complications in these systems with multiple moving components.

Common ocean engineering issues that must be addressed such as corrosion, biofouling, anchoring, drag and lift loads, scour, and wave forcing are still present, and may lead to frequent downtime and expensive maintenance activities if not properly addressed. There are significant differences, however, based upon the general environmental conditions where each type of generator is deployed. The purpose of this paper is to mention the differences between tidal and open ocean installations, and then describe the specific issues and proposed solutions to the open ocean situation. It is assumed the reader is familiar with the specifics of the tidal challenges.

II. MARINE HYDROKINETIC ENERGY PRODUCTION

A. Tidal Current Energy

Tidal water flow is the historical norm for hydrokinetic energy production, in the form of mechanical energy for pumping, grinding, or other physical work, and for generating electrical energy by driving turbines. Tidal sites are typically close to shore, such as ocean inlets and other conduits between inland water bodies and the ocean where differences in water levels must seek equilibrium by moving vast quantities of water. Consequently, these sites are usually located near the points of use, where infrastructure exists to distribute the electrical energy.

Geographically, many tidal energy sites are located in the upper latitudes, since tidal ranges tend to be larger closer to the poles than near the equator, and where substantial load centers exist, namely in Europe, Russia, and parts of North and South America. The 50 sites with the highest tidal ranges in the world are in just 5 regions (see Fig. 1):

- Bay of Fundy, Canada
- Bristol Channel and Cardiff Bay, UK
- Normandy, France
- Magellan Strait, Argentina and Chile
- Cook Inlet, Alaska, USA
- Penzhinskaya Bay, Kamtchatka, Russia

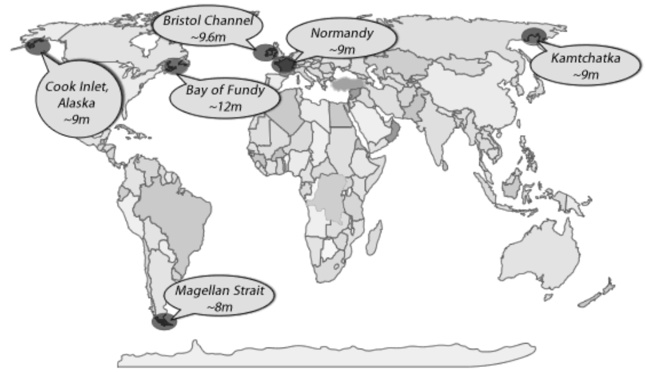

Fig. 1. Global Tidal Energy Resource Areas

The geographical distribution is typical of most marine renewable resources. They tend to be more localized in accessibility but most are conveniently located near points of use, such as large population centers. A number of governments have invested tremendous financial resources to install tidal generator projects, with significant success while also accompanied by numerous challenges typical of offshore projects.

B. *Open Ocean Current Energy*

Open ocean marine hydrokinetic (MHK) energy production relies upon the flow of open ocean currents, namely those that occur along the western boundaries of the ocean basins. Driven by the global thermohaline circulation, these massive water flows may be tens of kilometers wide and hundreds of meters deep, transporting billions of cubic meters of water per second from the equator towards the upper latitudes. While many substantial currents are found throughout the oceans, as shown in Fig. 2, only a few are close enough to shore and consistent enough to be useful and accessible for power production.

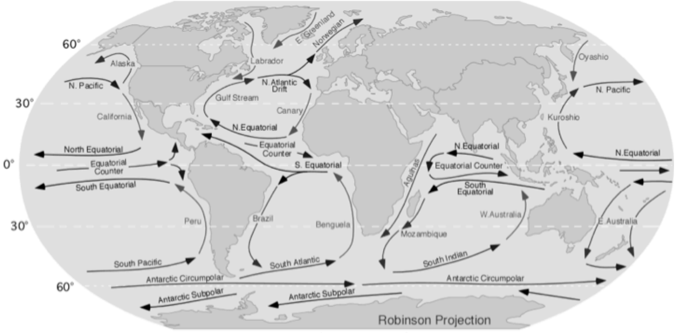

Fig. 2. Global Ocean Currents

The three primary candidate ocean currents are the Gulf Stream off the southeast United States, the Kuroshio off the western coasts of the Philippines, Taiwan and Japan, and the Agulhas off south Africa. While these resources are relatively close to shore, they are still substantially further away than most tidal sites, and electrical transmission infrastructure is similarly absent or remote. At some point in the renewable energy evolution, however, these vast resources will be harnessed and the unique challenges facing the design engineers must be identified and addressed.

III. OPEN OCEAN DEPLOYMENT CHALLENGES

Working in the open oceans is always challenging, even on the calmest of days, and spending long periods of time deploying complex systems in precise locations is very difficult. Fortunately technologies now exist to help, including dynamically positioned (DP) vessels to forgo the need to anchor, advanced remotely operated vehicles (ROVs) to replace the need for divers in deep water, and sophisticated computer modeling and design software to evaluate these novel systems under extreme environmental conditions. The following sections will describe the challenges and potential solutions to several major obstacles to MHK energy production, and will be accompanied by the corresponding challenge at tidal energy sites. The fundamental challenges include:

- High Continuous Current
- Water Depth
- Near Surface Current
- Distance from Shore
- Tropical Storms
- Power Transmission
- Installation and Maintenance

A. *High Continuous Current*

While both tidal and MHK energy utilize high currents, in most tidal sites there is a period, albeit short, where the flows typically diminish to near zero velocity, and then reverse in direction before increasing again. This affords some time to performs certain tasks in tidal systems in low to no current, and can save significant time, cost, and effort during installation, maintenance, and repair activities.

Open ocean currents, however, do not provide such a respite, and the water continues to flow relatively unchanged for days to weeks at a time. The velocities may exceed 3 m/s, although with the exception of infrequent passing eddies, the direction remains relatively consistent. The current profile is also important, as the highest velocities tend to be close to the surface, while the deeper waters are at a consistently low speed, between 0.25 to zero meters per second as shown in Fig. 3.

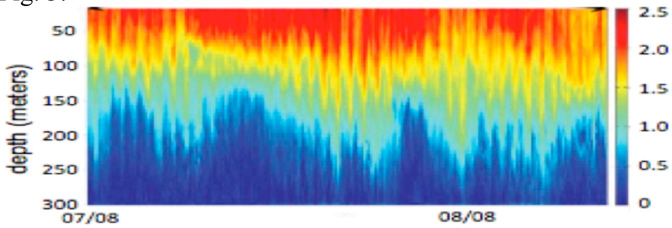

Fig. 3. Current Profile Record from 3/2009 to 3/2010

These characteristics afford the opportunity to design for a unidirectional flow, and use the current for stabilization and attitude control continuously instead of the variable flows found in tidal applications. Likewise, given the low speeds near the seafloor, maintenance and repair way be accomplished at depth and for much longer time intervals than those periods during slack tidal flows. Using ROVs and DP vessels, and the ability to 'fly' the devices to deeper water out of the main current actually provides a fairly ideal work environment where time constraints become more financial than environmental.

B. Water Depth

Tidal sites are typically near shore in relatively shallow waters of 30 to 40 meters, which affords the use of several methods not feasible in deeper water. MHK sites are generally located near the axis of ocean currents. The Gulf Stream core is located in about 300 meters of water about 30 kilometers offshore. The Kuroshio core off Japan is located in over 3000 meters, and poses significant challenges not only for installation and mooring, but power transmission back to shore even though located only a few tens of kilometers offshore.

Deep water precludes several tidal anchoring technologies, namely large concrete gravity anchors and pile driven or drilled anchors, since lowering these large devices and placing them precisely on the seafloor is very difficult in the high currents and long cable lengths to reach the bottom. The ability to drive a pile at the proper angle, or drill a precise anchor hole remotely is at present a very difficult and expensive approach. Furthermore, once installed the devices must be attached to the anchors in such a way that fatigue and load cycling are not substantial issues, and the method of holding the generators in place while this is accomplished is very daunting.

Fortunately MHK devices are located a distance far enough offshore where there is more room to install anchoring systems, and the unidirectional nature of the current enables the use of single and two-point mooring systems. These installations could use high scope moorings and drag embedment anchors, which generate substantially more holding power than their net weight, and may be removed easily during site decommissioning, which is becoming a permit condition for installations in many areas. Likewise, anchor chain could be used similarly to ships and offshore rigs, where progressively larger chain towards the anchor would provide shock load relief and reduce mooring fatigue, something difficult to achieve in more rigid anchoring methods. Mooring loads are expected to be substantial, and some preliminary designs have indicated generator drag loads of over 100 metric tons, plus mooring cable loads. For very deep water, novel mooring issues need to be developed with possible combinations of existing mooring technologies, as well as new concepts such as midwater static drag anchors and other water column solutions.

C. Near Surface Currents

Most ocean currents are highly stratified, with the largest velocities found near the surface, and the deeper currents lower in speed due to bottom friction. Velocity layers may be fairly deep, in most cases a few hundred meters, while others may reach much deeper. Tidal currents tend to occupy the entire water column, with no difference between surface and bottom velocities. As such tidal generators experience tremendous drag loads over the entire structure, requiring massive anchors and bottom armoring to protect cables and junction housings.

Since the generator portion of a MHK system is the only part that experiences the full force of the current, a majority of the mooring, and any required transformers, cable junctions, and power cables may be located near the bottom or on the seafloor where drag loads are much lower. This requires the generator to maintain position near the surface, however, while not actually floating on the surface and posing a navigational hazard. This feature may also utilize the existing current, employing a combination of static buoyancy and hydrodynamic devices to 'fly' in the current, changing depth as needed to maintain the maximum flow speed. Without the persistent current, lift based solutions to this problem would be unreliable at best. As mentioned earlier, maintenance activities may also benefit from this current profile, since the lower speeds near the bottom provide a stable environment for ROVs and intervention activities.

D. Distance from Shore

Tidal sites are typically near shore, since they operate on the flow generated from different water levels in a tidally forced region and the resulting movement of water at some velocity. This is typically an ocean inlet or passage between a body of water, such as an estuary, and the sea. The proximity to land has many benefits, such as shorter cable runs to bring the electricity to the grid or other point of use, short transits for support craft and personnel, and relative shelter from open ocean weather and waves.

Ocean currents are typically tens of kilometers from the coast, in hundreds if not thousands of meters of water. MHK devices are exposed to open ocean conditions, require long transits to reach the site, and impose a degree of self-sufficiency once on station. Long power cable runs are required, often passing over a variety of seafloor conditions, ranging from sand, rock, rubble, and reefs, each posing different challenges for cable design and means of laying. The persistent currents also pose challenges, since as the cables pass through the water column to the seafloor they are acted upon by various water velocities, which impart complex load distributions and tend to bow the cable downstream and away from planned cable routes. Depending on permit conditions or seafloor obstacles, this variance may be significant.

One possible solution is to lay the cables from the seafloor, below the high currents and exposing only a relatively small drag area of the lowering cable to the high currents, increasing control while decreasing offset. This affords the opportunity to utilize cameras and sonar on the cable laying device, similar to cable trenching machines. In most cases, however, given the distance from shore and depth of water, most cables do not need to be buried, as there are few deep water fishing activities in most candidate sites, at least to date. Lastly, to reduce drag loads and costs, lighter armored cables may be used for most of the lay length, due to water depth, low energy sediments, and absence of heavy fishing activity, which may help alleviate the cost of longer power cables.

E. Tropical Storms

One certainty in lower latitudes where ocean energy may be viable is a tropical storm. Whether a hurricane in the Atlantic or typhoon in the Pacific, these storms will eventually pass through an MHK site, as shown in this plot of hurricane tracks for the Atlantic Ocean in Fig. 4.

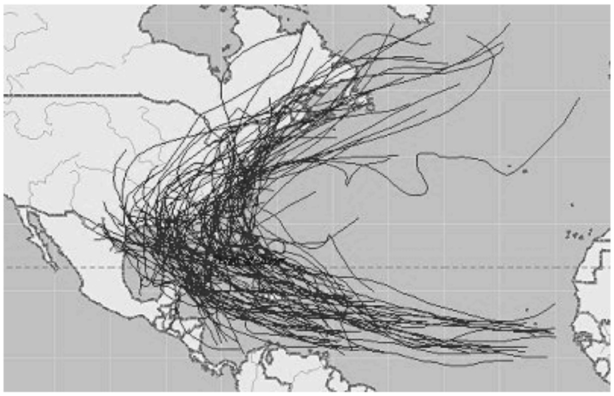

Fig. 4. Atlantic Tropical Storm Tracks Between 1851 and 2013

During the storms passage, the current profile is significantly altered due to Ekman forcing from high winds, oscillating currents from large waves, and possible destruction of onshore control infrastructures. There is also not an opportunity to recover equipment, so in situ protective measures are required. Based upon data from past storms, the upper 100 to 150 meters of current is dramatically affected, either experiencing an increase in speed or a drop to almost zero, depending on wind speed, direction, and duration. Measurements also show, however, that below this level the core of the current is relatively unaffected, and continues at a steady speed and without the storm wave effects.

As a protection strategy, devices would be directed deeper, away from the surface, and although in slightly lower velocities, would still be able to produce power and maintain position in the water column. Onshore, control systems would be ruggedized to the extent possible, and when restored, power would be available from the generator systems.

F. Power Transmission

Tidal sites typically either rest on a large base, or float on the surface and protrude under the surface to capture the current. Both configurations tend to integrate the mooring components with the power cables, and given the relatively shallow water and ability to connect and maintain connectors with divers, this has proven to be a robust approach.

In depths and currents where divers are not feasible and the use of anchoring chain as a means to reduce mooring fatigue, a hybrid power and mooring cable must be used. Similar designs are in common use in the ROV industry, utilizing a loadbearing member either around or central to power conductors and other members, such as hoses or fiber optic communication cables. This approach cannot pass through anchor chain, however, so the electrical components must at some point be separated from the load bearing members.

A proposed method is to use a flounder plate at some distance from the seafloor, and transition from the load bearing electrical cable to a wire rope and chain section of the mooring that reaches the seafloor and connects with the anchor. The flounder plate would transition the electrical conductors into a separate cable which would run to the seafloor and junction box decoupled from the mooring loads. This could enable the junction box to be retrieved and serviced while the generator remained moored, and would likewise facilitate generator removal without the complete loss of the mooring system through the installation of a support buoy in place of the generator. Not only would this provide a means to transmit the power to shore, it would also enable the networking of multiple generators back to a common, ROV-supported junction hub. This hub would be connected to a large trunk cable and run back to shore for grid connection. ROVs would be instrumental in these operations, and the proper design of connectors and tools would be essential.

G. Installation and Maintenance

Tidal generators are usually installed during slack tide, from large support vessels or jackup barges that sink large piles into the seafloor to resist tidal currents. Site preparations typically occur months if not years in advance, and substantial infrastructure is installed before the actual device ever arrives on site. Similar activities occur when conducting require maintenance and repairs, including replacement of generators and other equipment. In many cases, due to the integration of components, the entire generator device must be removed for servicing. This may be a very involved process, utilizing multiple vessels, divers, and other specialized tools.

MHK deployments are purely ship based operations, and must be managed in accordance with the sea conditions as well as the water currents. Similar to tidal devices, MHK generators will be very large, with ballast and buoyancy systems, hydrodynamic actuators, and complex mooring components and attachment points. Since the ocean currents rarely slow down, all operations must occur in high water velocities, sometimes approaching 3 meters per second. Drag loads are very large, so most deployment activities must occur 'on the fly', where the DP vessel is essentially in a controlled drift with the current as a means to reduce relative velocities and drag forces. This may require the deployment vessel to begin operations miles from the final location so that necessary launching activities may occur under these low drag conditions. In one possible scenario, the devices may be deployed similarly to an anchor-last buoy deployment, where the generator is paid out from the vessel until the anchoring system is at the stern, at which time the anchor will be deployed to the seafloor. Once anchored and in position, the shore cables will be connected via ROVs near the seafloor. Obviously these procedures will require more consideration and detail, but it is one way to avoid the persistent current drag loads. In any case, deep water MHK generator deployment will require new procedures and equipment to work at the required scales.

Maintenance would pose similar challenges, since the device cannot be easily removed and serviced without countering the same drag forces as during deployment. Simply lifting the device onto a vessel is not an option, so some means must be devised to service the generators at depth while deployed, or come up with some other method. It poses one of the most difficult problems for MHK power generation.

IV. CONCEPTUAL MHK GENERATOR DESIGN

Given the many unique challenges MHK generation poses, a conceptual generator has been developed to address many of these issues. Ocean Current Energy, LLC (OCE) of Aventura, Florida, has designed a device that enables in situ servicing of the generators, as well as improves deployment, maintenance, and recovery. The design is described as a 'coin and slot' device (CS), where a rotating mechanism moves generator 'coins' from an installed and generating position to one that enables removal and replacement of new components. The CS consists of a core module at the top of the device, and then up to three generator modules, where the coin generators are mounted. The modularity enables different configurations. Fig. 5 provides a conceptual view of the device with three generator sections.

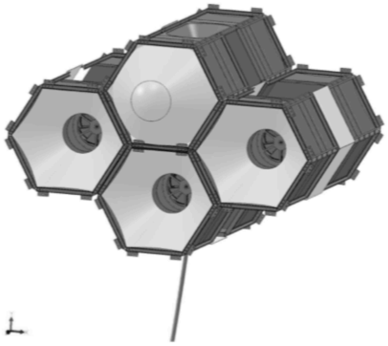

Fig. 5. 'Coin and Slot' Generator Device

The concept is similar to aerial refueling operations, where a probe is lowered from a lead aircraft to another, and the probe is guided into a receptacle on the top of the lower plane. In an analogous fashion, a generator module, or coin, would be lowered from a surface vessel to the CS device, and the coin would be guided into a recess. The coin would be captured in the recess, the deployment device recovered to the ship, and by using a series of actuators, the coin would be moved into one of three locations within the CS. Using guides and indexing devices, the coin would be locked into position and the locking actuators would also electrically connect to the generator. To remove a defective coin or as part of a maintenance program, the coin could be unlocked and moved back to the recess, where the deployment device would be lowered down, grab the coin, and recover it to the surface. Fig. 6 shows the progression for a test deployment, where a single CS and coin is used.

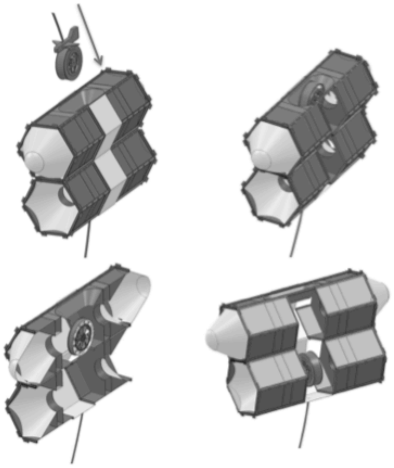

Fig. 6. Coin Installation Stages

The coin concept is useful for replacing generators while the CS remains deployed, and reduces the size and drag loads of items deployed and recovered from the surface. It also has the benefit that the CS unit may be deployed without the coins installed, so the drag forces would be significantly reduced due to less projected area into the flow. The core module at the top of the unit serves not only as a means to capture the coins, but it also houses the transformers and other power conditioning equipment, as well as buoyancy and attitude controls. These control and conditioning components may also be removed and replaced in a similar fashion to the coins. The CS is rated to the full water depth at the deployment site, enabling ROV maintenance while near the seafloor under the faster surface currents. This feature allows the shore power cables to be connected after deployment, since the mooring loads are reduced near the seafloor, enabling connections remotely. Lastly, the CS system utilizes a single point mooring so additional anchors and complexity may be avoided, allowing the CS to adjust to minor variations, or meanders, of the ocean current.

This concept is in development, and a prototype is scheduled for fabrication and testing in the near future. The project is part of a partnership between OCE and the Florida Atlantic University (FAU) Southeast National Marine Renewable Energy Center (SNMREC), and will be conducted at FAU's Harbor Branch Oceanographic Institute campus in Fort Pierce, Florida.

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