A 20 KW Open Ocean Current Test Turbine

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Abstract - Florida is faced with an energy crisis with respect to capacity, supply, cost, emissions, and stability. The untapped energetic waters of the Florida Current could provide a clean, reliable, base-load local renewable energy source for Florida. To facilitate the successful commercial harvesting of this hydrokinetic resource, Florida Atlantic University's Center for Ocean Energy Technology is designing, fabricating, deploying, and operating an experimental small-scale turbine. This 20 kW Ocean Current Turbine Testbed (OCTT) is an open-blade axial-flow horizontal underwater turbine driven by a 3 m diameter 3-blade rotor. It is intended to operate in the open ocean near the core of the Florida Current, offshore Ft. Lauderdale, for long periods of time. This turbine is not intended to be a scaled prototype of a commercial model, but it is intended to be an experimental system to assess technology, identify gaps, investigate and collect data about potential environmental impacts, and provide a foundation for commercial and policy development.

I. INTRODUCTION

The Florida Current off of the southern and eastern shores of Florida represents 20% of the Gulf Stream and North Atlantic Gyre, and has significant hydrokinetic energy available in its moving water and density structures. With a mass transport greater than 30 times the total freshwater river flows of the world, and an energy flux of some 25 GW [1], the Florida Current has a potential generating capacity of up to 10 GW [2]. Because the Florida Current never stops, and is constrained to flow between Florida, Cuba, and the Bahamas, meanders are physically bounded. Thus, with judiciously located arrays of turbines, the Florida Current is a base-load electrical energy generating possibility.

Nearly 2 years of measurements taken near the core of the Florida Current offshore Ft. Lauderdale, Florida show that the mean current speed near the surface is nearly 1.7 m/s, and can exceed 1 m/s, even at depths of up to 150 m. On average, the Florida Current decreases monotonically with depth to a weak 0.19 m/s near the ocean bottom at 320 m, on the outer edge of the Miami Terrace. The current speed ranges between 1 and 2 m/s 85% of the time, in the top 100 meters. At 50 and 100 m depth, the flow exceeded 2 m/s only 3.3 and 0.06% of the time, respectively. The predominate direction of the Florida Current offshore Ft. Lauderdale ranges between 15 and 16.5º. Directional consistency is dependent on velocity, and in the absence of velocity, or during periods of low velocity, the flow direction becomes confused.

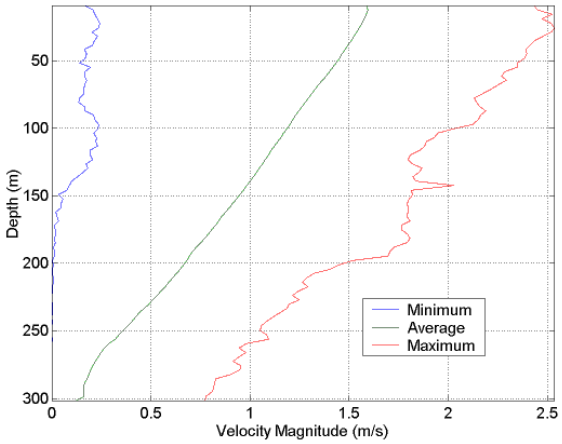

Figure 1. The maximum, average, and minimum ocean current speed measured offshore Ft. Lauderdale, FL over a period of nearly 2 years. Velocity measurements were made at 15 minute intervals with a 75 kHz ADCP.

The available kinetic energy of the Florida Current has potential to supply Florida with much needed clean, renewable, base-load electricity, provided that technically-feasible and environmentally-friendly harvesting technology can be developed. Although harnessing the energy of the Florida Current has been considered for decades, no commercial-scale system has been demonstrated or installed.

In 1974, the McArthur Workshop on Energy from the Florida Current took the first serious look at harnessing energy from sustained currents [3]. Although no technology was developed, this important meeting identified the Florida Current as a significant renewable energy resource. Through the mid and late 1970s, the Coriolis Program endeavored to address the technical and environmental challenges of harnessing sustained ocean currents. Although this effort funded several engineering and environmental studies aimed at installing large (~170 m diameter) ducted, horizontal-axis turbines, no turbines were ever installed. In the following decades, other efforts have investigated installing ocean current turbines, but none passed beyond paper design or small-scale laboratory prototypes.

No ocean current turbine or harvesting system has ever been installed and operated in the Florida Current, and thus, no technical or environmental knowledge-base exists for *in situ* operation of an open-ocean current turbine operating in that environment. Although many laboratory tests, tow tank experiments, and numerical simulations have been performed, they are only approximations of the real operating environment. As well, these laboratory experiments cannot replicate the long term operating effects of real system deployment and operation. Thus, a strong level of confidence cannot be placed in existing analyses. Since no turbines have been deployed in the Gulf Stream for any duration, no knowledge exists of any possible environmental and ecological interaction. Although some statistical estimates can be made based on the species density, the actual interaction of the turbine with local biota cannot be assessed without deploying a system. Because of macro level interaction between the biota and turbine system, laboratory experiments cannot be used either.

Thus, data is needed to support commercial-scale design and assess *in-situ* performance of proposed turbine technology to identify and map out areas of technology development, and to develop fair policy, permitting, and rules that are adequate and are not overly burdensome.

II. SYSTEM OVERVIEW

To quantify and understand technical gaps and environmental/ecological interactions, FAU's Center for Ocean Energy Technology has developed a small-scale ocean current turbine system to be deployed offshore of South Florida in the Florida Current. This Ocean Current Turbine Testbed (OCTT) is a unique experimental turbine that will be used to gain knowledge and insight into turbine operation, as well as, to provide knowledge needed to move forward to commercial implementation and policy development. Thus, the OCTT is designed to meet the following high level requirements:

- Operate in the sustained ocean current (the Florida Current) East of Ft. Lauderdale, FL with properties such as current speeds up to 2.5 m/s that linearly decrease to 0.5 knots at 150 m, and are constant at 0.5 knots below 150 m.
- Be moored to the ocean bottom at a depth of 330 m. The Miami Terrace is a relatively shallow plateau that extends from near shore to the mean core of the Florida Current, thus providing a shallow location to moor the OCTT, yet situate it in the current.
- Operate in maximum sea state of 6, but typically in sea state 4 or less.
- Be easily deployable and recoverable. Because this is a new system, it will likely experience initial technical challenges and unknown environmental interactions, and will need to be quickly and easily recovered.
- The anchor must have a small anchor impact area. The bottom of the ocean is often sensitive habitat, and the Miami Terrace is home to deep water corals, among other animals, which must be minimally disturbed.
- Operate at a 30 foot depth. The initial turbine must not only be monitored remotely, but direct visual observation is also necessary (diver activity is generally unsafe in strong currents) to observe ecological interactions. This also provides a worst-case baseline for fouling studies and other interactions with aquatic species.
- Extensive monitoring systems shall communicate to a shore base in near real-time. Although the Center plans to locate personnel on-station during operation, data must be fed back to shore for monitoring and prognosis by shore-based staff as well. During periods of inactivity, when the turbine is not installed and personnel are not on-site, the condition of all offshore apparatus needs to be monitored.
- Corrosion resistant in the salt water environment. Initially normal operating periods will be hours and increase to days, weeks, and possibly months. The turbine will be thoroughly analyzed between operating periods, providing ample opportunities to minimize material wear.
- Hydrostatically stable while operating. The pitch shall not exceed 2^o, and in a max expected constant current of 5 knots, the roll shall not exceed 30^o. Designing within these constraints prevents the turbine from porpoise-ing or spinning in circles due to the torque generated by the rotor blades.
- Slightly positively buoyant in seawater. As a contingency, being 20-50 lbs buoyant, will allow the turbine to float to the surface if it ever detaches from the mooring or experiences unexpected problems.

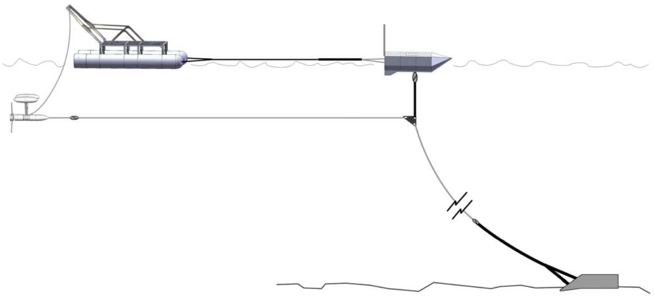

Figure 1. Diagrammatic representation of the Ocean Current Turbine Testbed (OCTT).

The overall system consists of a permanently anchored Mooring and Telemetry Buoy (MTB) with a gravity anchor, a 20 kW axial-flow horizontal turbine that is driven by a 3 m diameter 3-blade rotor, and a twin-hull Observation, Control, Deployment, Platform (OCDP). The MTB is a self contained buoy that is permanently moored directly to a large gravity anchor, and is designed for long term operation in the swiftly flowing Florida Current. A novel mooring system will be deployed that consists of a 5/8 inch 1000 meter long steel cable with fairing along the upper 300 m of mooring line, and strum reducer over the lower portion. One hundred meters of 2 inch chain is used at the lower end of the cable, attached to a 25,000 lb gravity anchor. The mooring scope is 3.

The OCDP is the main operations platform that contains all the instrumentation for operating and monitoring the turbine. The OCDP is not permanently moored to the MTB, but instead, it is towed to station where it is attached to the MTB using weighted synthetic mooring lines. The OCDP is used to house the turbine when out of the water, as well as, launch and recover the turbine as needed. When operating, the turbine is directly connected to a founder plate on the mooring line between the MTB and anchor. The turbine is also connected to the observation and control buoy by: (1) a synthetic rope which is used to deploy and recover the turbine, (2) communications lines used to monitor and control the turbine, and (3) power cables used to transmit power to/from the turbine. These tethers between the OCDP and turbine are not under direct loading when the turbine is operating. Using this configuration, the large drag load of the turbine is directly transferred to the mooring line, reducing load handling requirements, and hence, overall size and complexity of the OCDP. The turbine, OCDP and MTB will be equipped with a broad range of sensors to monitor system health, and environmental and ecological interactions.

The system has four modes of operation:

Mode 1 – Single Buoy: The MTB is attached only to the mooring line in a single point mooring configuration. The OCDP is not connected to the MTB and the turbine is not connected to the mooring line. This is the base mooring configuration that is “permanent.”

Mode 2 – Standby Mode: The MTB is attached to the mooring line and the OCDP is moored to the MTB. The turbine is out of the water, but attached to the flounder plate, 30 feet below the MTB.

Mode 3 – Operations Model: The MTB is attached to the mooring line and the OCDP is moored to the MTB. The turbine is in the water and attached to the flounder plate, 30 feet below the MTB. The turbine is also connected to the OCDP by a “slack line.”

Mode 4 – Recovery/Deployment Mode: The MTB is attached to the mooring line and the OCDP is moored to the MTB. The turbine is being launched or recovered while attached to the flounder plate, 30 feet below the MTB. The turbine is also connected to the OCDP by a “taut line.”

III. DETAILED SYSTEM DESCRIPTION

A. *Mooring and Telemetry Buoy (MTB)*

A buoy will be permanently moored at the experiment site, and it is designed with a streamlined hull to minimize drag while orienting the system into the current. The buoy is fabricated from 3/8 inch steel, with a one inch thick steel keel. The body is divided into three central water-tight compartments and two out-of-water wings. The outer wing walls are designed to not only provide additional buoyancy and stability, but to act as sacrificial chambers in the event of a collision or impact, allowing the buoy to survive. The buoy is designed with sufficient buoyancy to float with only two of the central compartments dry. Each of the 5 compartments were separately pressurized to 3 psi to verify integrity. When deployed, the buoy will orient pointing northward, parallel to the coastline. This buoy is 5.25 m long with a beam of 2.92 m. It weighs 2750 kg and displaces a maximum of 12,730 kg of water. Because the OCDP has an unconventional buoy hull form, much like a displacement vessel, it will roll and pitch. Thus a custom 3-degree-of-motion connection to the mooring line is used.

Figure 2. The completed Mooring and Telemetry Buoy (MTB) on stands.

The MTB includes an array of navigation, safety, communication, security, and environmental sensors. The navigational instruments include a variety of safety and navigation lights, GPS, passive and active radar target enhancers, and a proposed Automatic Identification System (AIS) transmitter that broadcasts to other vessels fitted with AIS receivers, information like: the buoy’s name, location, and status. Safety systems include: leak, fire, smoke, and intrusion detection, battery and charging system health and status, and redundant, independent communication and power packages that allow the buoy to minimally provide personnel with needed information regardless of overall system fidelity.

Communication capabilities include not only buoy-to-platform, but buoy-to-shore systems. A high-speed wireless Ethernet connection allows nearby observation and support personnel to communicate with, and troubleshoot, systems onboard. In addition, both a broadband cellular internet modem and an Iridium satellite modem allow the buoy to communicate via internet or email with personnel located anywhere in the world. Security instrumentation includes on-deck web-interfaced and recorded surveillance cameras, multiple method motion-detection, and intrusion detection. Environmental instruments include a buoy-mounted ADCP, a bottom-anchored ADCP that communicates with the buoy via an acoustic modem, mooring line tension sensors, and a weather and atmospheric sensory suite which provides wind speed and direction, barometric pressure, and solar radiance,

The MTB is powered by a combination of solar and water-generator systems that charge a battery bank. Two different styles of solar panels ensure that partial shading and/or regular immersion due to wave activity do not cripple the power regeneration available to the system. In addition, because the current will regularly be sufficiently fast, COTS sailboat water generators supply additional regenerative power to the battery system. The battery bank is sufficient to supply all power requirements for 7 days without recharging.

All of the MTB system and sensor information is processed, stored, and transmitted by an industrial embedded-PC platform operating with a Linux OS. The components have been specifically chosen to be rugged, durable, and low-power.

B. *Observation, Control, and Deployment Platform (OCDP)*

A twin hull observation, control, and deployment pontoon platform is designed to: (1) transport the surface tether and turbine mooring hardware during transit to and from the test site, (2) launch and recover the test turbine, and (3) support in-water operations. This platform consists of two cylindrical 1 m diameter hulls, each with five water-tight chambers (individually pressure tested to 3 psi) and a square steel tube platform frame. The hull thickness is 3/8", ¼" steel bulkheads are used between chambers, and each pontoon has a ½" steel transom. OCDP cargo and capabilities include: three custom hydraulic winches with up to 5,000 lb pull, an A-frame, able to support 5,000 lb dynamic loads, to facilitate on and off-loading, mooring, and deploying/recovering the turbine, a 24 hp gasoline powered hydraulic power pack, a turbine control and operation system, a power dissipation system, on-deck and below-deck cameras, above and below-water lighting, GPS, communications equipment, and other safety gear. The OCDP shall be moored directly to the MTB by a synthetic mooring line. The platform is 4.8 m long with a beam of 3.0 m. It weighs 5051 kg, and the twin hulls displace a maximum of 14,645 kg of water. The OCDP has tow/mooring points attached to the inside of the hulls at the bow waterline. The OCDP is the main operating platform, and will support up to 4 people for short periods of time. Although the platform is intended to support long term operations of up to 1 month, it will not house personnel. Instead, a ship with berthing and other amenities will be on station, and moored off the OCDP.

Figure 3. The complete OCDP without A-frame, hydraulic, and electronic systems.

C. *Experimental 20kW Turbine*

The underwater turbine is a 20 kW open blade axial-flow horizontal turbine design, driven by a 3 m diameter 3-blade rotor. A 30 kW generator is housed within a water-tight pressure vessel, and it is connected to the rotor through a 25:1 step-up planetary gear box with a 3 inch OD drive shaft.

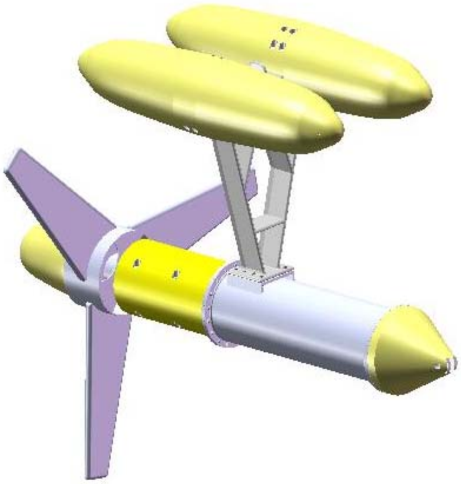

Figure 4. A diagrammatic representation of the 20 kW turbine.

All structural components, including: the main generator housing, the drive shaft, and the mooring connection assembly are made from 316L stainless steel. 316L was chosen for its strength, excellent forming and welding characteristics, high creep resistance, and corrosion and pitting resistance. Nickel

Copper Alloy 400 was the chosen material for all bolting hardware because of its anti-galling properties, and its proximity to 316L with regard to galvanic corrosion.

The turbine is connected to a flounder plate, approximately thirty feet below the surface, on the main mooring line, by a synthetic rope. The main mooring line is attached to a robust mooring connection part which is bolted to the forward end of the generator housing. This part supports the total load of the mooring line and provides open access to the penetrating connectors and cables entering and leaving the generator housing. The mooring connection nose assembly is covered with foam to provide protection to the housing penetrations, as well as improve the hydrodynamic near-field flow and turbine trim.

Ten pound per cubic foot density foam is used along the turbine body and atop the mast to compensate for the heavy generator to make the complete turbine system slightly positively buoyant. The high density foam will be coated with fiberglass cloth and epoxy resin to provide both a water tight, and impact resistant, outer coat. All foam parts are removable to facilitate maintenance of both the foam and the parts they obstruct. Stainless steel sleeves will be inserted into foam through–holes, and meshed into the fiber glass coat to prevent bolted connections from crushing or chaffing the foam.

Buoyancy is primarily provided by the buoyancy compensation modules mounted to the top of each trussed mast. With the mast acting as a moment arm, these modules provide a large force which both trims the turbine in pitch and roll, and counters the torque generated by the rotor blades. Having a 1.5 m mast length is sufficient to counter the 3000 ft-lb torque generated by the rotor at a max expected constant current of 5 knots. The mast is designed to be removable to facilitating assembly, maintenance, and mobilization. Making use of the strong trussed design, a surface accessible lift point is welded to the top cross member of the mast, enabling a quick turbine recovery.

To guarantee hydrostatic stability, the size of each buoyancy compensation module, and the placement of the mast mounting bracket, will be finalized after the initial dock-side weight and trim test of the fully assembled turbine housing assembly. This fabrication and testing sequence will ensure the buoyancy and pitch requirements will be met.

To further protect the turbine asset, several contingency features will be implemented to ensure the turbine is not lost at sea. This includes: (1) applying 1-atm above ambient pressure to the inside of the water-tight housing to provide extra leak resistance, (2) installing pressure-activated drop weights which will be released if the turbine begins to sink, allowing the turbine to rise to the surface, and (3) an underwater acoustic beacon to aid in location of a lost system.

A chamber at the tethered end of the turbine pressure vessel has been reserved for analog to digital signal processing, signal conversion and consolidation, and data transmission. This chamber is thermally isolated from the AC motor-generator. Data signals are converted, consolidated, and transmitted to the surface, on an open database connection protocol (ODCP), where it is stored locally with a digital video recorder (DVR) technology. Uniquely chosen data sources (such as underwater video) are broadcast via platform-to-buoy wireless networking to shore-based data centers, and also made available to any vessel-based communication links with the OCDP. The OCDP data link is proposed to be fiber-optic to accommodate the higher bandwidth signals from the high-density low-light underwater cameras that monitor blade activity during turbine operation.

The three-phase AC induction motor's generator characteristics are controlled by an OCDP-mounted 30 HP closed-loop AC drive system that has been customized to not only allow the turbine to be brought to speed in the flow, but to manage the chosen RPM set-points of the motor during generator activity with a brake chopper. Any excess voltage during RPM regulation will be dissipated in the AC drive's braking resistors. The AC link is a 0-240 Volt, 85 Amp (maximum) connection to allow for a manageable electrical current both below the surface, and on the platform. The DC side of the AC Drive allows a battery bank to provide the necessary power to jump-start the turbine blades in the flow. While the turbine is in operation, a charge controller mediates re-charging the battery bank, and any additional excess power is converted to thermal energy and dissipated into the atmosphere by a 630 Ohm resistor bank which has been retrofitted for offshore conditions. The battery charging system can also be replenished via generator or other available DC or AC power source (such as a nearby support vessel).

The turbine motor-generator (M-G) is a 3-phase AC-induction wound rotor motor typically found in industrial pump applications. It is fitted with a 25:1 gearbox to match expected flow speeds with desired electrical performance. The M-G is designed for horizontal mounting (the expected turbine orientation), and gearbox lubrication is designed accordingly. The M-G diameter is matched to provide appropriate hydrodynamic dimensions, matching the diameter of the blade rotor hub. Thermal analyses indicate that, in order to maintain a safe operating temperature, a contact-based conduction solution is necessary. The heat will be transferred to the stainless-steel pressure vessel shell which will then be absorbed by the very effective heat-sink available from the fluid constantly in contact with the outside of the turbine pressure vessel shell. However, since lab-based thermal analyses are approximate, full thermal testing and monitoring will occur *in situ*.

The Rotor blades were graciously provided by Verdant Power. These are the same blades used during Verdant's first test in the East River.

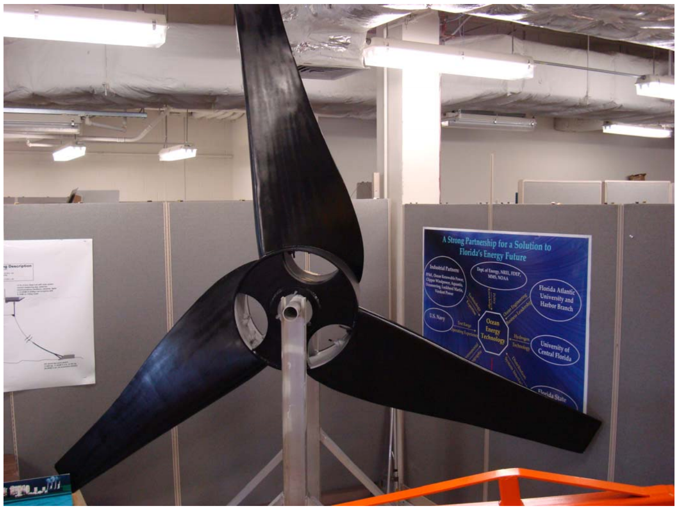

Figure 5. Rotor blades provided by Verdant Power.

IV. MONITORING SYSTEM

To increase the reliability and lifetime of turbine components, machine condition monitoring (MCM) techniques will be implemented to supervise the system. Through MCM efforts, failure and downtime of turbine components will be reduced. Critical components to be monitored include: the turbine nacelle pressure vessel, motor/gearbox, propeller, and electrical system. The temperature, position, roll, pitch, yaw, and bilge water level of the turbine nacelle pressure vessel will be monitored using thermometers, a 6-axis inertial measurement unit (IMU), and water sensors.

Vibrations in the transmission shaft, gearbox, and motor will be monitored using low and high-frequency accelerometers, indicating any imbalance or wear on bearings or gears. The torque, strain/vibration, water flow, turbulence, and immediate environmental surrounding of the propeller during operation will be monitored respectively by a load cell, strain gauge, flow meter, ADCP, and video cameras. This will indicate the loss of a propeller blade, excessive strain on the blades, or significant unbalance due to biofouling. In addition, a ground fault interrupter will detect and protect the system from ground faults in the electric motor or electric cable.

Monitoring of the system components by MCM techniques is critical to turbine operation. These factors must be quantified, through the use of monitoring sensors, to effectively and safely operate the turbine.

V. CONCLUSION

Florida Atlantic University's Center for Ocean Energy Technology had developed a small scale ocean current turbine testbed to install in the Florida Current off of Ft. Lauderdale, Florida. This turbine is expected to provide base-line technical, environmental, and ecological data to help guide the commercial and policy development of open ocean hydrokinetic resources.

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