FESC
Florida Energy Systems Consortium

Thrust Area 6: Ocean Energy

Buoy Array for Ocean Wave Power Generation

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Description: The objective of this project is to develop a novel design that can extract ocean wave energy for commercial consumption. The design detailed herein is unique in that it is a wave point energy harvester that is small in size and contains all of the mechanical components directly within the buoy. The project focuses mainly on the mechanical system within the buoy as well as methods to control the electrical load on the system. Different mechanical systems have been developed and tested on a motion platform to simulate a vertical wave motion—these systems have been analyzed and compared in order to provide an ever-increasingly effective design. The Harris Corp. have acted as new collaborators with the project since October 1st 2010, funding four UCF senior design teams in the development of a buoy for wave power generation.

Budget: $150,000
Universities: UCF

Executive Summary

This project involves an innovative design, development, laboratory prototype testing, and optimization of a wave power generation system which includes a set of mechanical devices and a permanent magnetic generator. The objective of this project is to build a wave power generation system that is light-weight, low-cost, small size, and easy to deploy. For this project, two laboratory prototypes have been built using machine components. The prototypes were mounted onto a 6-DOF motion platform that can oscillate vertically to simulate wave motion, which drives a shaft to produce electricity using a permanent magnetic generator.

The project began with a literature review, a Matlab/Simulink simulation, a 3-dimensinal viscous CFD (computational fluid dynamics) simulation, and mechanical Pro-E design. Such preparation work was essential to the study of ocean wave generation. Next, two prototypes were developed and tested. The first prototype shows that a simulated wave moving up and down with an amplitude of 15-cm, can generate between 35 to 40 watts electricity. The experiences gained in testing of this prototype helped design and build the second prototype. The second prototype uses two sprockets and a longer chain giving more mechanical advantages. In addition, a more efficient generator that requires less torque reduces frictional losses imposed on the shaft. Test results have shown that the power output increases from 37.34 to 206 watts. Afterwards, two alternative prototypes were tested. One uses a light-weight but large size aluminum flywheel to increase flywheel inertia; the other is specially designed to make it possible for the system to generate power in both directions.

In order to make the generator run more continuously and, thus, generate more power for a given wave input, a load control mechanism was designed to dynamically control the electric load based on the shaft RPM. This requirement is needed when there is no pulling force of the wave at the down-stroke and the load is not applied so that the flywheel runs continuously. Tests of the second prototype were done for a number of different configurations – a combination of different wave amplitude and frequency.

To improve the efficiency of the system, an updated mathematical simulation model was designed for system optimization. The optimization was to study how to choose the radius of sprocket, the inertia of the flywheel(s), the ratio of the gear set, and the controlled electrical load such that

maximum power can be generated, given a fixed wave amplitude and frequency. This allows for different design parameters to be varied to optimize design.

In addition to the prototype tests, the buoyancy force of the waves on a small buoy has been studied. For these experiments, the output of the force is recorded by a computer based data acquisition system and the results help verify the computation fluid dynamics model used in the mathematical simulation.

Due to the nature of wave motion, the electrical power output is not stable in voltage output and frequency. For this reason, a Wave Energy Conversion (WEC) simulation model was built for stabilizing the variable frequency, variable voltage output and for satisfying the grid requirements of constant voltage, frequency, and power. Using experimental three-phrase AC voltage data of the generator, a three-phase breaker is turned on and off by the control system to output DC voltage. The simulation is helpful to the design of a micro-controller to be used in load-control and power stabilization for future preparation once the buoy power system is deployed in the ocean.

Based on the finding of the experimental and analytical results of the mechanical design it was found that a different design concept would have more success in the field. Similar to the team's research in that bi-directional buoy motion is converted to uni-directional rotor rotation, a bi-directional impulse turbine was proposed. The bi-directional impulse turbine can be used in oscillating wave columns as it is able to convert bi-directional flow into uni-directional rotation.

The measured power output, RPM, torque, and the overall optimized system parameters such as the radius of sprocket, the inertia of the flywheel(s), the ratio of the gear set and the controlled electrical load added to the generator, are helpful to the design and optimization of a functional prototype running in the ocean. For the power output, the current laboratory prototype is capable of generating an average of 136W under the movement of a motion platform with 12cm in amplitude, 0.3Hz frequency, and 0.10kg-m^2 moment of inertia, and 206W with 10cm in amplitude, 0.3Hz frequency, and 0.25kg-m^2 moment of inertia.

The research group spent much efforts trying to leverage research funding. A joint proposal with Rostech, Inc. Oviedo, FL, was submitted to the U.S. Department of Energy for applying funding for Phase I SBIR, in an effort to continue the research and commercialize the laboratory prototype. And because of this project, the University of Central Florida has cooperation with the Harris Corporation for the powering of a far offshore buoy system named OceanNet. The company is very interested in developing a clean energy supply local to these far offshore buoys which drastically lowers the expenses involved in traveling out the buoys and refueling. For this reason they have funded the work of 7 senior design teams in the process of two years and are continuing support with the research project to obtain a commercially viable design and the construction of an offshore wave energy converter.

In addition, the research group attended various national and international conferences to attract attention to the work wave energy research in the state of Florida. Several presentations were made. Two conference papers were published and a journal paper based on the load control optimization scheme is revised and resubmitted to *IEEE Journal for Oceanic Engineering* for publication.

Florida has a long costal line and good power delivering infrastructure. The success of this system could provide clean, scalable, and supplementary electric power to Florida coastal communities with lower costs in the long term, and lessen burden from main power grids and fulfill responsibilities of environmental protection.

Goals and Objectives

The objective of this project is to analyze, design, and demonstrate a novel wave power generation system that can extract ocean wave energy for commercial consumption. The design detailed herein is unique in that it is a wave point energy harvester that is small in size and contains all of the mechanical components directly within the buoy. As such, the buoy would simply need to be moored to the ocean floor and have cables to transport power to the shore, making it ideal for use in a multiple-unit wave farm. The project focuses mainly on the mechanical system within the buoy as well as methods to control the electrical load on the system. Different mechanical systems have been developed and tested on a motion platform to simulate use within a buoy in vertical heave—these systems have been analyzed and compared in order to provide an ever-increasingly effective design. Mathematical simulations have been developed to help optimize design parameters for use in subsequent prototype designs that will be able to be implemented in a wave pool or saltwater environment.

The ultimate goal is to deploy an array of buoys floating on the ocean and tethered to the floor. Each of them has one or multiple devices inside that can convert the kinetic energy of the motion of the waves into electrical energy. The electricity generated is then transmitted through the cable that goes along or inside the tether to the ocean floor, expending to an energy processing/storage station on the ocean shore.

Project Activities, Results and Accomplishments

Introduction

Nature offers a tremendous source of renewable energy in the kinematic motion of ocean waves. It is estimated that if 0.2% of the ocean's untapped energy could be harvested, it could provide power sufficient for the entire world. Compared with other forms of generation of electricity such as wind and hydro power, research on wave energy is still in its infancy because wave energy development is a field that requires multi-discipline cooperative efforts including technologies in hydro-dynamics, mechanical engineering, control, and power system. There is much room to be improved such as, efficiency, cost of system, reliability, scalability, to name a few, such that wave energy is made affordable to consumers. The project began with a literature review, a Matlab/Simulink simulation, and mechanical Pro-E design. Then, laboratory prototypes were built and tested on a motion table. Figure 1 is an overview of the laboratory prototype.

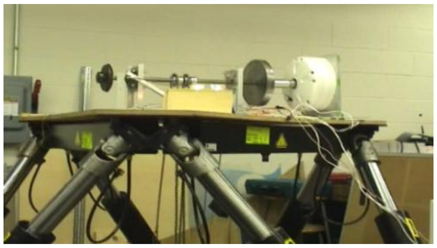

Fig. 1: An overview of laboratory prototype

Simulation and Pro-E mechanical design

A Matlab/Simulink Model shown in Fig. 2 was created to simulate wave movement and power output. This model was based on the differential equations which include all forces dynamically applied to the buoy. Fig. 3 is the simulation results for mechanical and electrical power outputs.

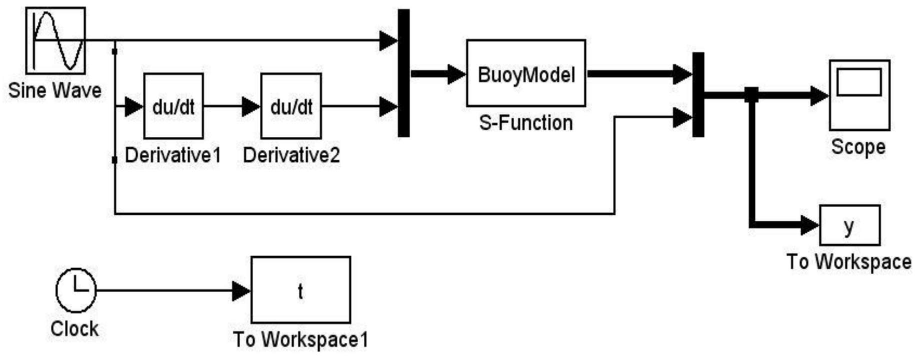

Fig. 2: Matlab/Simulink Model

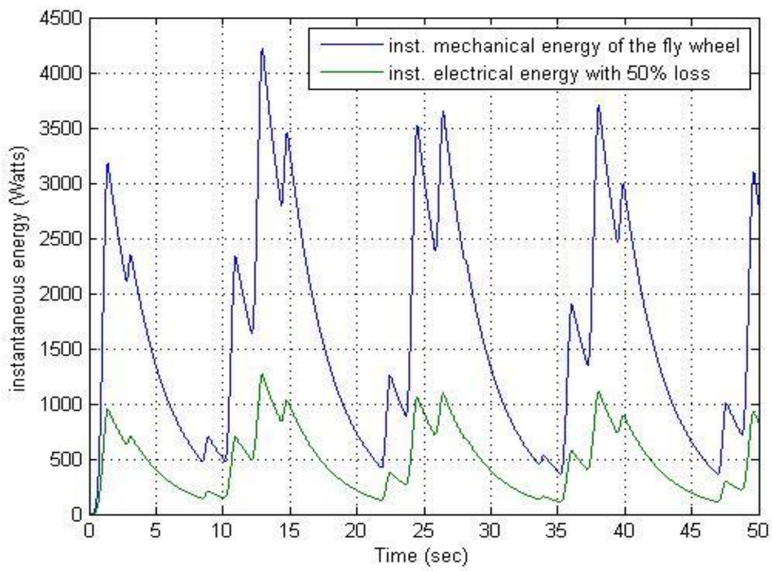

Fig. 3: Simulation results

Before building the prototypes, the mechanical components in the wave power generation system was designed and simulated in Fig. 4 using Pro-E, a professional mechanical engineering tool. This significantly decreased time to build the lab prototype by making development changes and modifications using the software.

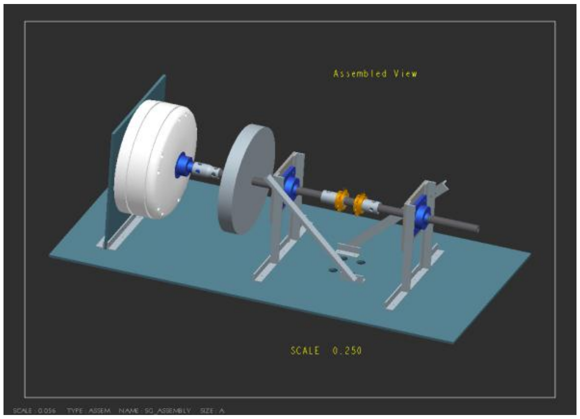

Fig. 4: Pro-e design of the vertical wave system prototype

Laboratory prototypes

Two laboratory prototypes were developed and tested. The first prototype (Figure 5) shows that a simulated wave moving up and down with an amplitude of 15-cm, can generate between 35 to 40 watts electricity. The experiences gained in testing of this prototype helped design and build the second prototype (Figure 6). The second prototype uses two sprockets and a longer chain giving more mechanical advantages. In addition, a more efficient generator that requires less torque reduces frictional losses imposed on the shaft. Test results have shown that the power output increases from 37.34 to 206 watts.

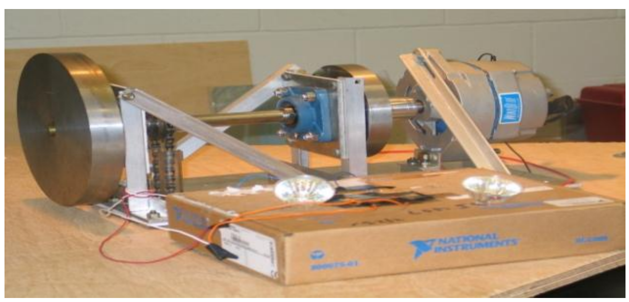

Fig. 5: First generation of prototype

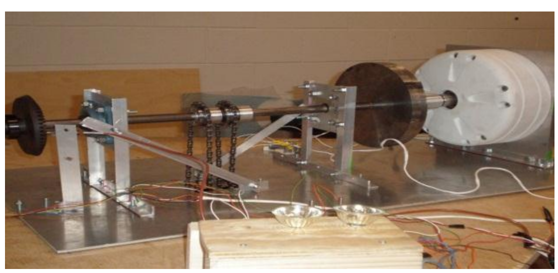

Fig. 6: Second generation of prototype

In order to make the generator run more continuously and, thus, generate more power for a given wave input, a load control mechanism was designed to dynamically control the electric load based on the shaft RPM. This requirement is needed when there is no pulling force of the wave at the down-stroke and the load is not applied so that the flywheel runs continuously. Figure 7 is the electrical components of the generation system.

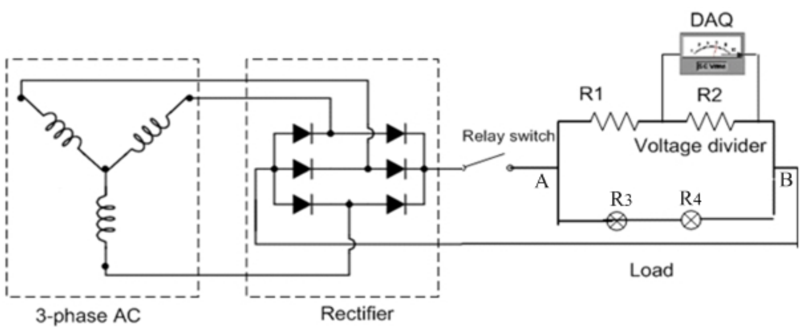

Fig. 7: Electrical components of the generation system

Tests of the second prototype were done for a number of different configurations – a combination of wave frequency and amplitude using a 6-DOF motion platform.

In addition to the current prototype, the following two alternative prototypes were built and tested:

Alternative prototype 1

This first alternative prototype (Fig. 8) was built with the following main characteristics: (1) A cable is used instead of a chain to improve reliability (2) A large size aluminum flywheel to increase flywheel inertia (3) A 4:1 gear set for increasing RPM. The only drawback of this design is that although adding a gear set increases RPM, it also increases the torque.

Fig. 8: Alternative Prototype 1

Alternative prototype 2

This second alternative prototype (Fig.9) was built in order to generate consistent power in both directions (up and down). The rack has teeth on both sides which mesh with two gears on two separate shafts. When the motion platform moves up, one shaft runs clockwise; when moving down, the other shaft runs counter-clockwise. The movements of both shafts rotate the generator in the same direction, thus developing consistent power in both directions. Each shaft has one gear set installed to increase RPM. The drawback of this prototype is that it is difficult to fix the top of the rack in the ocean, and it is possible for the rack and gears to become unmeshed.

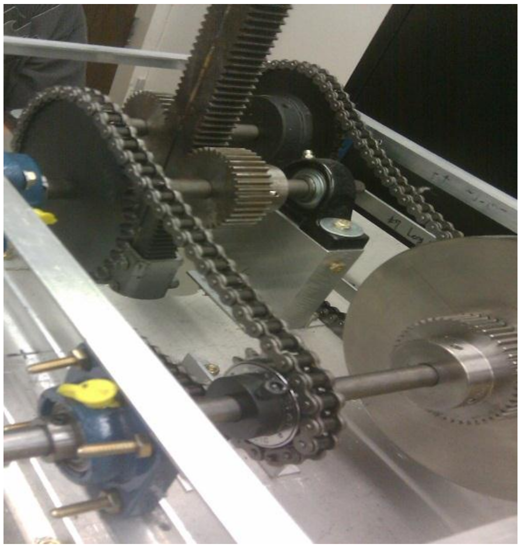

Fig. 9: Alternative Prototype 2

In addition to the prototype tests, the buoyancy force of the waves on a small buoy has been studied. For these experiments, the output of the force is recorded by a computer based data acquisition system and the

results help verify the computation fluid dynamics model used in the mathematical simulation and optimization model.

Wave Energy Conversion (WEC) system

A Wave Energy Conversion (WEC) simulation model (shown in Fig. 10) was built for stabilizing the variable frequency, variable voltage output and for satisfying the grid requirements of constant voltage, frequency, and power. Using experimental three-phrase AC voltage data of the generator, a three-phase breaker is turned on and off by the control system to output DC voltage shown in Fig. 11. The simulation is a stepping-stone to build a micro-controller that can run the buoy control system in the future. This work is for future preparation once the buoy power system is deployed in the ocean.

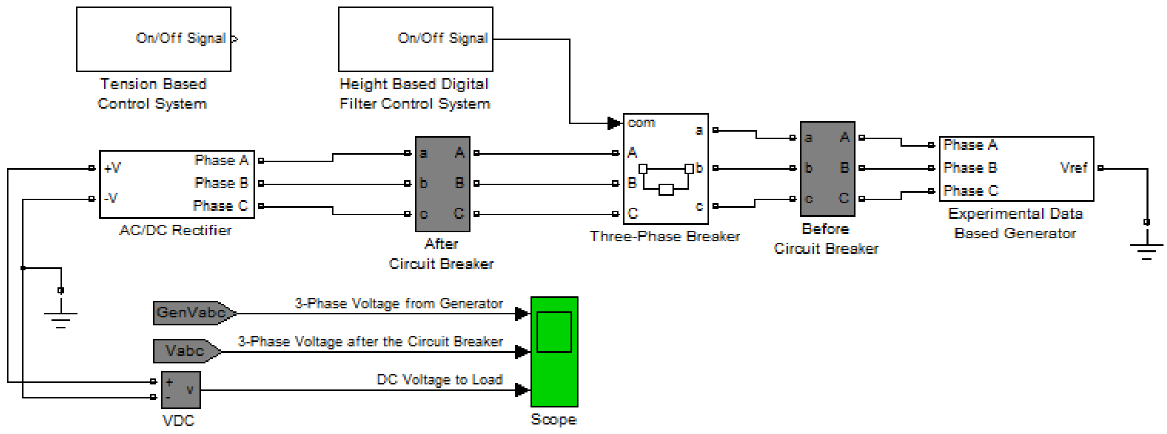

Fig. 10: Schematic for Wave Energy Conversion (WEC) system

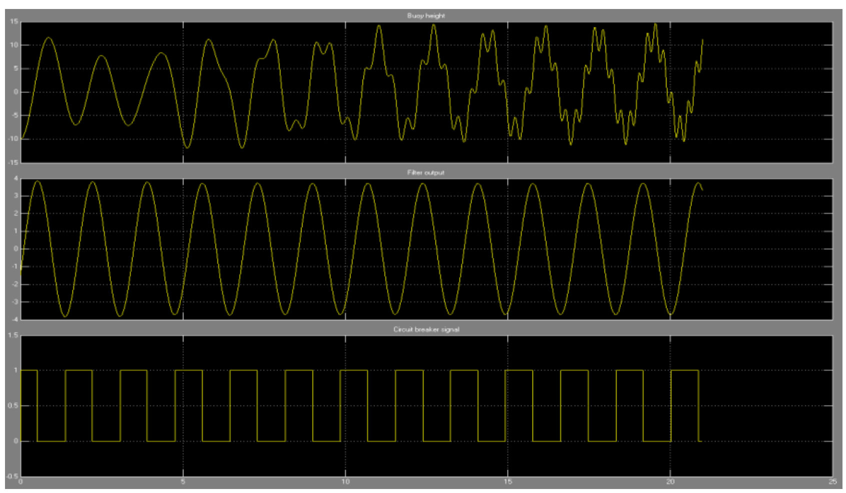

Fig. 11: Height-based control system output

System optimization

The power output of the system is dependent on several factors such as the radius of sprocket, the inertia of the flywheel(s), the ratio of the gear set, and the controlled electrical load added to the generator. An updated mathematical model was designed to optimize the system. The objective is to choose values for these parameters from their feasible ranges in an optimal way in order to get maximum power output. The power optimization model is designed based on the following criteria:

Flywheel inertia optimization: Without enough inertia on the shaft, the flywheel may not continuously spin throughout the wave cycle. With excessive inertia, on the other hand, the angular acceleration of the shaft will suffer as a result of increased chain tension. As such, the inertia of the shaft should be optimized so that the motion of the shaft is continuous while limiting the effect on the buoy motion.

Gear ratio optimization: A gear set can convert excess input torque into a greater RPM of the shaft, or yield a larger torque applied to the generator by sacrificing RPM. Both torque and shaft speed influence the power output for the system, and thus an optimum gear ratio should be found to balance these two inversely-proportional variables.

Electrical load control optimization: Keeping the electric load constantly applied will drastically slow the rotational speed of the shaft while no forcing input is applied. Intuition suggests that the load should be applied while the shaft RPM is high above some threshold, and it should be disconnected while it becomes low.

Optimization of the radius of sprocket: The radius of sprocket is directly related to the shaft RPM. The smaller the radius, the greater the RPM, but also the higher the cable tension.

This optimization method can be applied to a host of wave energy designs and obtain the most suitable parameters for higher efficiency and offer coupled optimization between a host of design parameters.

Bi-Directional Turbine Concept

Based on the finding of the experimental and analytical results of the mechanical design it was found that a different design concept would have more success in the field. Although the control systems were the main focus of this research a design to drive the generator was still lacking. Based on literature reviews the research decided that a turbine driven system would be best for successful wave energy extraction with least maintenance. The design chosen was a bi-directional impulse turbine which is commonly used in oscillating wave columns as it is able to convert bi-directional flow into uni-directional rotation. This is similar to the team's research in that bi-directional buoy motion is converted to uni-directional rotor rotation. The turbine design concept start when the research team began a new set of projects in collaboration with Harris Corp. Harris Company funded the work of four senior design teams involved in offshore structure projects. Two of these projects involved the design and testing of a uni-directional impulse turbine. An illustration of the turbine is shown below in Fig.12.

The research team began with CFD simulation to determine the major losses associated with the turbine design and began CFD and CAD optimization schemes to obtain the best design for increased efficiency. The simulation based results were in good agreement with the experimental results obtained by the senior design teams.

Currently, Harris Corporation is funding a second year of projects with an additional 10K support. This year three teams are sponsored to complete a phase II of the first years project with commercial involvement from local offshore companies.

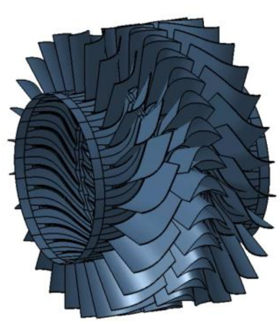

Figure 12: Bi-Directional Turbine

Experimental results

Experiment results show that the current laboratory prototype is capable of generating an average of 136W under the movement of a motion platform with 12cm in amplitude, 0.3Hz frequency, and 0.10kg-m^2 moment of inertia, and 206W with 10cm in amplitude, 0.3Hz frequency, and 0.25kg-m^2 moment of inertia.

The optimal power output depends on several factors. The radius of sprocket, the inertia of the flywheel(s), the ratio of the gear set used, and the controlled electrical load added to the generator, given a fixed wave amplitude and frequency. The overall optimized system parameters are as follows:

Inertia: 0.18 kg-m^2
Gear Ratio: 2.2
Load Control: 190 RPM

Figure 13 is the LabView measurement output when the electric load control is applied.

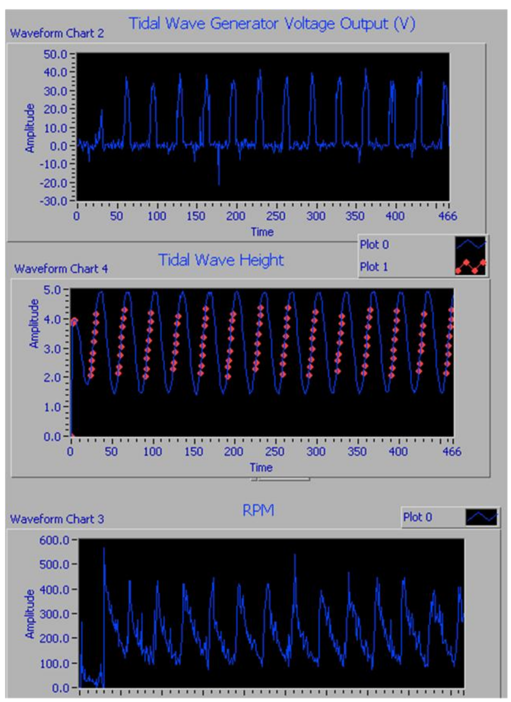

Figure 13: Voltage, RPM, and load control

Accomplishments

The research group spends great time and efforts in improving the research results, leveraging the funding, and commercializing the lab prototype, such as:

Cooperated with the Harris Corporation for the powering of a far offshore buoy system named OceanNet. The company is very interested in developing a clean energy supply local to these far offshore buoys which drastically lowers the expenses involved in traveling out the buoys and refueling. For this reason they have funded the work of 7 senior design teams in the process of two years and are continuing support with the research project to obtain a commercially viable design and the construction of an offshore wave energy converter.

Submitted a proposal with Rostech, Inc. Oviedo, FL, to apply for funding from the U.S. Department of Energy Phase I SBIR.

Designed built and tested 4 different wave energy extraction designs.

Developed analytical models, CFD simulations and experimental techniques pertinent to wave energy research.

Attended various national and international conferences to attract attention to the wave energy research work in the state of Florida.

Published two conference papers and submitted a journal paper based on the load control optimization scheme developed in this research.

Concluding Remarks

This project involves an innovative design, development, and laboratory prototype testing of a light-weight, low-cost, small size wave power generation system which includes a buoy, a set of mechanical devices, and a permanent magnetic generator. Prior to prototype setup, a hydrodynamic model, buoy model, and a generator model are analyzed and a Matlab simulation were conducted. The flywheel inertia, shaft rotation speed, and electrical load are optimized to maximize electricity production. The optimization method and results are helpful to the building of a functional prototype running in the ocean. The proposed bi-directional impulse turbine can be applied in oscillating wave columns to convert bi-directional flow into uni-directional rotation. Because of this project, a number of research projects involved by seven senior design teams at UCF have been funded by Harris Corporation, such as OceanNet, the powering of a far offshore buoy system in the process of two years. In addition, we believe our presentations and publications at national and international conferences have attracted attentions to the wave energy research in the state of Florida. The success of this system could provide clean, scalable, and supplementary electric power to Florida coastal communities with lower costs in the long term.

This project has been completed.