Project-Based Teaching: Wave to Water Technology

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Abstract

To connect theory and real-life application in the classroom, a team of students developed and optimized a simulation model for an oscillating surge wave energy converter (OSWEC) for seawater desalination. The developed model will be used in a project-based teaching approach that will enhance students' learning in the classroom by linking critical concepts learned in the classroom to a practical problem with seawater desalination using renewable energy. Using simulation software in the development process of an ocean wave energy converter (WEC) can help maximize its efficiency by optimizing converter design parameters. This work presents and analyzes the hydrodynamic coefficients and design parameters of an OSWEC for direct water desalination. The waves and their interactions with the OSWEC geometry are simulated, followed by the simulation of the WEC's response to the waves as a function of time. The goal of this project is to introduce students to the topic of renewable energy and bridge the gap between theory learned in a class setting and real-life application.

Keywords

Project-Based Learning, Design Project, Wave Energy Converter, Renewable Energy, Transfer Functions.

Introduction

Project-based learning is an important part of engineering education that focuses on self-directed learning.[1-3] Having the fundamental connections between concept and application will help students be more efficient by sharpening their problem-solving skills. The opportunity to work on research projects in an undergraduate course can help show students how the courses they take relate to real world applications[4-5]. This serves to enhance their curiosity and motivation[6-7]. The experience of working on a research project can allow students to work through the differences between problems on paper and solving real-life problems. Students who apply concepts to real-world problems will build an increasingly well-rounded understanding of those concepts and how they are applied to the world[8].

To strengthen the connection between theory and real-life application, a team of students developed a simulation model for an OSWEC. Renewable energy has been a focus of increasing attention due to its numerous environmental benefits, such as reduced greenhouse gas emissions and air pollution. A wave energy converter (WEC) is a device that harnesses the mechanical energy of ocean waves and converts it into other usable forms of energy. The WEC used in this project is a terminator type of WEC called an oscillating surge wave energy converter (OSWEC). Terminator WECs sit perpendicular to the waves to effectively absorb or terminate the mechanical energy of the wave. Typically, this conversion is facilitated by a rotating flap

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connected to a stationary base. The hydrodynamics of the WEC is simulated using a program called WAMIT. WEC-Sim is a MATLAB-based program that is used to simulate the system dynamics of the WEC. The system identification toolbox in MATLAB is then used to make open-loop transfer functions for the wave height and wave period using the wave conditions. The transfer functions are compared using the ramp response to determine their effects on the power output of the WEC. This project seeks to develop an engaging and enjoyable design project that will introduce students to the topic of renewable energy while simultaneously bridging the gap between theory and application.

Design Project

During the first step of this project students will model the geometry of the WEC using SolidWorks. The developed geometry model is converted into multiple file formats for further processing. A Stereolithography file, also known as an STL file, is required for visualization in WEC-Sim with the origin on the center of gravity for each part. STEP files are also required for use in the mesh software Rhinoceros 3D, which is also known as Rhino. The geometry of the STEP files needs to be below the origin for successful hydrodynamic diffraction. The flap is 1.235m tall, 1.50m wide, and 0.15m thick. The bottom is curved with a radius of 0.075m so that the edges do not hit the base when it rotates. There is a 0.01m gap between the two parts for the same purpose. The base is 1.5m long by 1.5m wide and 0.15m thick. Figure 1 shows the dimensions of the WEC.

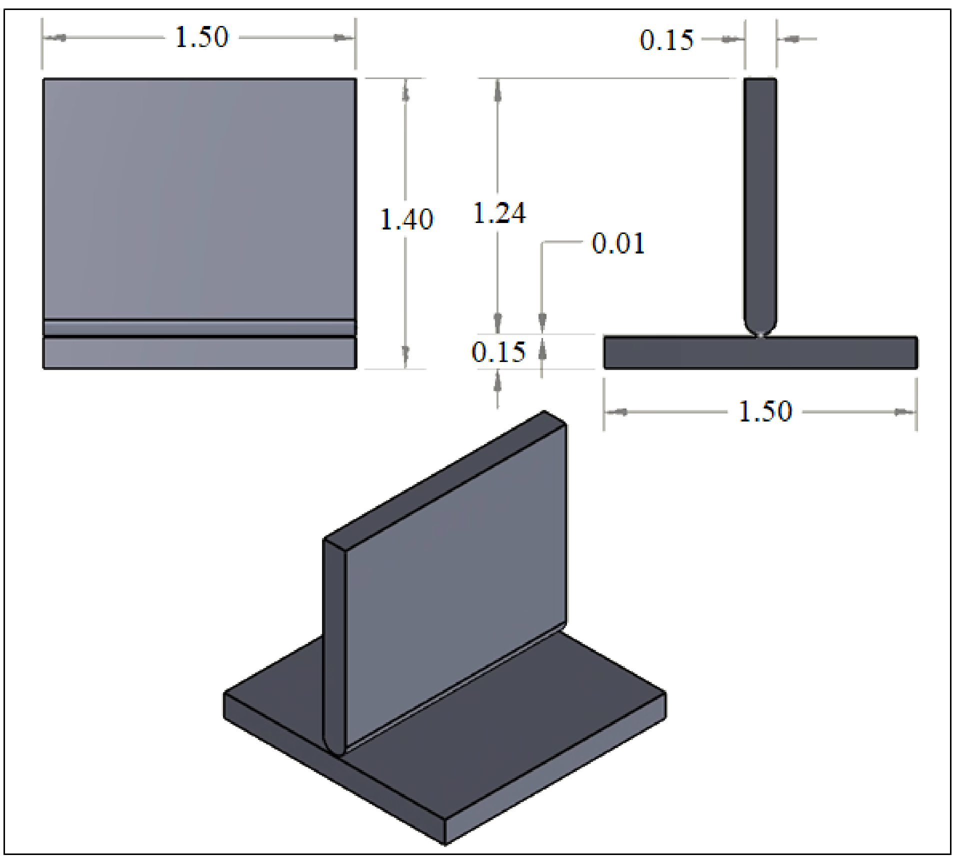

Figure 1: WEC Geometry

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Rhinoceros 3D is a computer-aided design software that specializes in producing a mathematically precise representation of curves and freeform surfaces. The STEP files for the flap and base were imported into Rhino and exported as a structured mesh. This is shown in Figure 2 below. Structured meshes mainly use quadrilateral panels but still have some triangular panels, usually near edges. SolidWorks was not used to generate the mesh because the supported file formats only create triangular panels, and there is less control over the mesh detail.

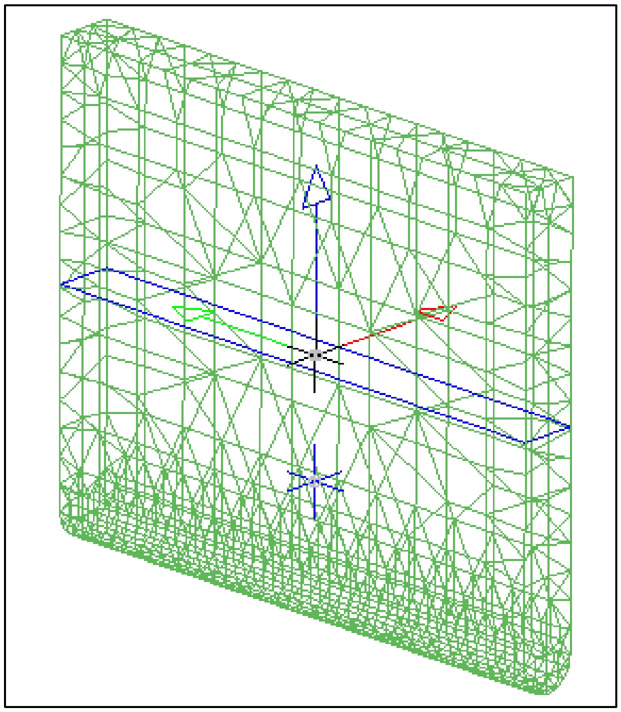

Figure 2: Mesh Created in Rhino

WAMIT is a wave analysis software that is used for hydrodynamic diffraction calculations. The WAMIT is a wave analysis software that is used for hydrodynamic diffraction calculations. The calculations require a potential control file (POT), a force control file (FRC), a configuration file (CFG), and a mesh file (GDF) to run. The POT, FRC, and CFG files are written by a MATLAB script that organize the parameters according to the wave analysis software. After writing these three files, the MATLAB code writes a file called "fnames.wam" that is required to run the wave analysis simulations. The simulation resulted in an output file (.OUT) that is used as an input for WEC-Sim.

WEC-Sim is an open-source MATLAB-based simulation tool developed by the National Renewable Energy Laboratory (NREL). This program is able to simulate WECs for varying wave conditions. WEC-Sim uses the STL file from SolidWorks and the output file from WAMIT. The hydrodynamic data from WAMIT is pre-processed using a function provided by WEC-Sim called Boundary Element Method Input/Output (BEMIO). BEMIO calculates the radiation and excitation impulse response functions, along with the state-space realization for the radiation impulse response function. It then saves the results in a Hierarchical Data Format 5 (HDF5)[9].

A simple MATLAB Simulink file is created by the students for WEC-Sim. For this Simulink file, two rigid body blocks, a rotational power take-off (PTO) block, a fixed constraint block, and a

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global reference frame are all added from the custom WEC-Sim Simulink Library. The rotational PTO is used to connect the two rigid body blocks. The fixed constraint block is used to connect one of the rigid body blocks to the global reference frame. Figure 3 shows the WEC-Sim Simulink model.

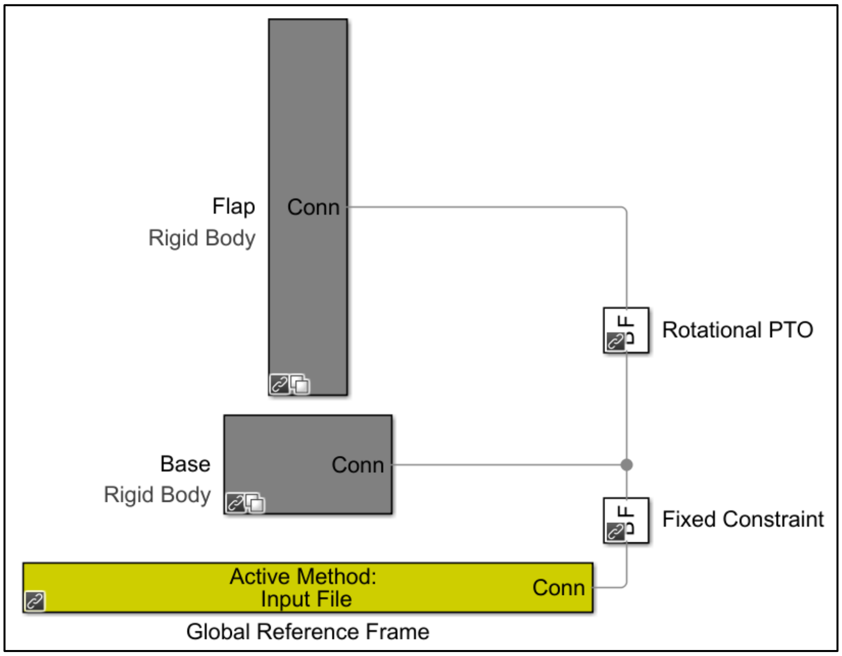

Figure 3: WEC-Sim Simulink Model

The students then create a WEC-Sim input file that defines the parameters for given application. The following list contains the information used in the input file.

- The simMechanicsFile variable is set as the Simulink file name
- The simulation start time is set as 0 seconds
- The simulation wave ramp time is set as 10 seconds, which is the time for waves to reach the specified wave height and period.
- The simulation end time is set as 150 seconds
- The simulation time step is set as 0.01 seconds
- The waves are set as regular waves by specifying the wave class as 'regular'
- The wave height is set to 0.2 meters, and the wave period is set to 1.1 seconds
- The body class for the flap and base are initialized using the BEMIO output file name
- The geometry file variable for the flap is set as the flap STL file name, and the geometry file variable for the base is set as the base STL file name
- The moment of inertia about each axis and the mass of the flap are obtained from SolidWorks and used to define the moment of inertia and mass variables of the flap in the WEC-Sim input file
- The mass of the base is set as 'fixed'
- A constraint class is set as 'Constraint1', and the location of the constraint is defined as [0,0,-1.3]. This constraint is where the base connects to seabed

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- A PTO class is defined as 'PTO1', and the location of the PTO is set as [0, 0, -1.1]. This location is where the flap and base are connected
- The final part of the input file is the PTO stiffness coefficient, K, and damping coefficient, C. These values will be defined and modified later to optimize the power output of the WEC

WEC-Sim allows for a user-defined output file to be made. For this project, a multiple condition run (MCR) user-defined output file is used. MCR makes it so WEC-Sim can run with multiple different PTO stiffness and damping coefficients and different wave periods and heights. For optimizing the WEC, an MCR is used with varying PTO stiffness and damping coefficients while the wave conditions are held constant. The user-defined output file would average the power output and store it in a structure along with the wave conditions and PTO stiffness and damping coefficients for each different case of the MCR. The next step for developing the simulation of this WEC is determining the optimum stiffness coefficient, K, and damping coefficient, C, for the PTO. These two values are set as arrays. The stiffness coefficient is set to be between 10000 N/m to 12000 N/m, using a step of 500 N/m. The damping coefficient is set to be between 2500 Ns/m to 4500 Ns/m using a step of 500 Ns/m. The simulation is ran using the wecSimMCR command provided by WEC-Sim. The simulation results show that the coefficients' optimal values are 11000 N/m and 3500 Ns/m for this WEC geometry and wave conditions. WEC-Sim provides a visualization of the simulated WEC, which can be seen in Figure 4.

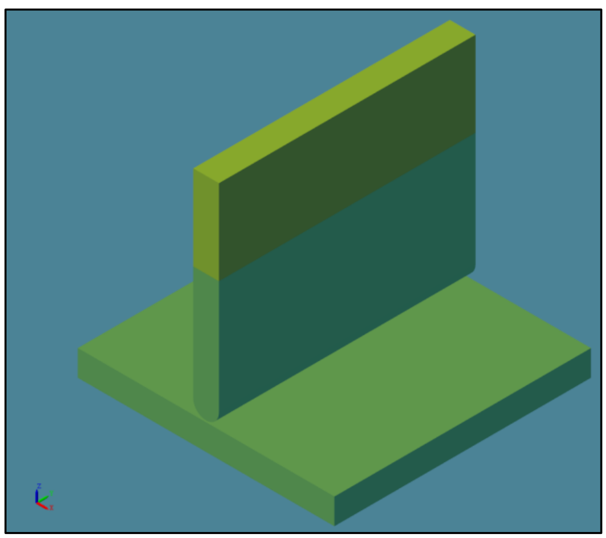

Figure 4: WEC-Sim Visualization

With the WEC optimized, the second part of the project begins. The determined coefficients replaced the array used to determine them at the end of the input file. The wave height is then switched to an array while the period is left constant. WEC-Sim then simulated the WEC for different wave heights. The resulting data for the power and wave height was then formatted using the iddata command provided by the System Identification Toolbox in MATLAB. The data that is formatted by this command is then used to make a transfer function using the tfest command. The tfest command lets the user specify the number of poles that are used to estimate the transfer function. Students can try different numbers to determine the number of poles that

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most accurately reflect the system. This process is repeated for a constant wave height and varying wave period.

From these simulations, two separate transfer functions were obtained for how the wave energy converter responds to different wave conditions. The transfer function based on the wave height had five poles and four zeros with a fit to the estimated data of 100%. The transfer function based on the wave period had three poles and two zeros with a fit to the estimated data of 91.6%. The transfer function based on the output power and input wave height can be seen in Figure 5. The transfer function based on the output power and input wave period can be seen in Figure 6.

```
  2127 s^4 + 6977 s^3 - 3.185e05 s^2 - 7.16e06 s - 7.953e06
  ----------------------------------------------------------
s^5 + 84.06 s^4 + 2353 s^3 + 1.839e04 s^2 + 1.853e04 s + 9.001
```

Figure 5: Wave Height Transfer Function

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 1384 s^2 + 1.178e04 s - 4.871e06
 ----------------------------------
s^3 + 127.9 s^2 + 1e04 s + 2.016e05
```

Figure 6: Wave Period Transfer Function

The transfer functions are tested under a ramp input to determine the magnitude of impact each variable has on the power output. This is done by integrating the transfer function and then plotting the step response. The transfer function is multiplied by (1/s) to integrate it. The step command is then used to plot the ramp response of the two integrated transfer functions. The ramp responses are plotted over the duration of the simulation, which is 150 seconds. The slopes of the functions are compared to see which has a more significant impact on the power output. The ramp response for the wave height can be seen in Figure 7, and the ramp response for the wave period can be seen in Figure 8.

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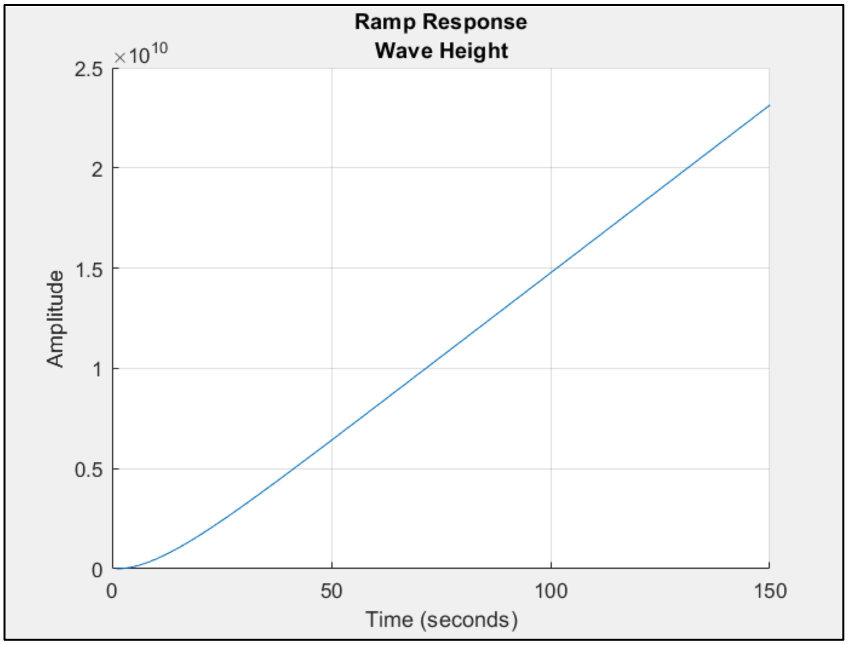

Figure 7: Ramp Response for the Wave Height Transfer Function

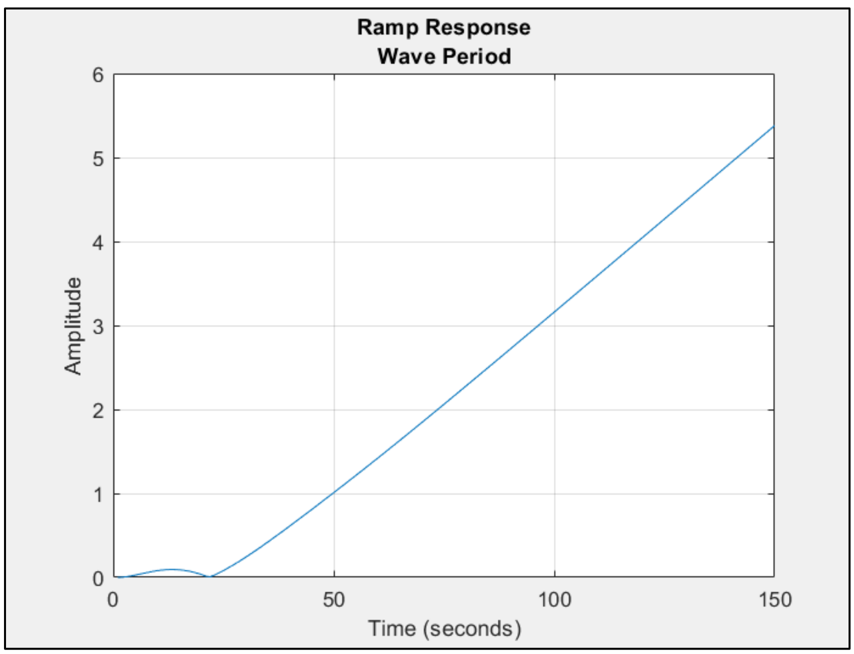

Figure 8: Ramp Response for the Wave Period Transfer Function

Discussion

Based on the ramp response graph results, the wave height has a significantly larger impact on the power output than the wave period. The slope of the wave height ramp response was 167320000, and the slope of the wave period ramp response was 0.04362. The magnitude of power output over time for different wave heights is 3.8 billion times larger than the magnitude of power output over time for different wave periods. This is reasonable since as the wave height

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grows more extensive than the WEC, the force will increasingly affect the WEC's motion and power output. As the wave period gets faster, the waves will hit the WEC before it finishes oscillating from the previous wave. This wastes energy and will cause the energy absorption to grow at a lower rate than that of the wave height. This means it is more important to optimize the factors affecting the wave height coming in contact with the WEC to maximize the power output. Students could repeat this analysis for different configurations of WEC devices out of a pool of variables.

This project could reinforce students' understanding by helping to create the fundamental connections between concept and application. This will help students be more efficient by sharpening their problem-solving skills. This project will also introduce students to renewable energy, which could inspire the students to work in this field. Renewable energy is an essential topic for the future because of the numerous environmental benefits, such as reduced greenhouse gas emissions and air pollution. The amount of non-renewable energy available is diminishing while the demand increases, raising the need for renewable energy.

Student Learning

This design project helped the students developing it gain a better understanding of many engineering theories and applications. This project demonstrated how much of an impact wave conditions have on the response of the WEC. Through completing this project, students learned about different types of meshes, such as unstructured and structured meshes. These meshes differ in the shapes of panels they use, triangular and rectangular, respectively, and the level of detail differs between them. Simulating the WEC system dynamics also showed the students how MATLAB can simulate the entire system, and it also introduced them to Simulink. This project introduced students to design approaches that can be optimized and how beneficial it can be to different systems. The students were also shown how a transfer function can be obtained from simulated or experimental data and how the function can numerically represent a physical system. The ramp response of the system showed the students how it can be used to demonstrate the impact that an input has on the output. This project was given to a small group of students to get initial feedback on how it could be improved and implemented further in the classroom. The main comments received were that the project was an effective aid to connect the understanding of control system theory to that of project implementation. The students also commented that it would be beneficial for the project to be altered to connect a wider variety of concepts learned in class to cement how it can be used in real world applications.

Strategy for Implementation

Before implementing this project into a classroom, the feedback received will be addressed and used to further improve it. Once improved, an instructional sheet will be created to help guide the students. Three separate surveys will also be created for students to take before, during, and at the end of the project. After taking the initial survey, students will be split into groups to help foster teamwork. Along with the project a report will also be required that will include students having to do some basic research on wave energy and its applications. The project will be given to the students at the beginning of the course, and they will be able to work through it as course progresses. Milestone due dates will also be created to help students progress throughout the semester and relate specific parts of the project to what is currently being learned in class.

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Conclusion

Renewable energy is the future of the world's energy as non-renewable sources are diminishing, and the effects on the environment are increasingly deleterious. In addition to reinforcing connections between concept and application to students, this project can help introduce change into the educational system as it has lacked innovation and has experienced very few changes for decades. Project-based teaching has been proposed to be most successful when it is used throughout a students' education[10-11].

This project seeks to engage students in a learning environment that is more applicable to the real world. Future research will seek to modify this project for use in a control system design course by incorporating more concepts and real-world data. The PTO for the project will be changed to a variable stiffness PTO and will be used as a control mechanism for the WEC. This will allow students to develop a closed-loop control system. The students will then be able to incorporate a controller to improve and help control the variable stiffness PTO's response to the wave conditions[12-13]. The students will also be able to apply various theories learned throughout a control system design course. Other theories that will be added to this project include plotting the root locus, checking the system stability, adding compensators, plotting the bode plot, and finding the phase margin and gain margin. Students will be presented this project and will have a chance to provide feedback before starting, during, and at the conclusion of the project. This feedback will be used to further improve the project and make it more enjoyable and engaging to the students.

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Biographical Information

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Gabriel Glosson is a senior at East Carolina University. Gabriel is in the process of earning his bachelor's degree in engineering with a concentration in electrical engineering. He is also a part of the accelerated program where he is working on earning his master's degree in mechanical engineering. Gabriel works under the supervision of Dr. Faete Filho as an undergraduate research assistant working on developing a simulation of a zero-waste wave-to-water desalination system.

Jason McMorris

Jason McMorris is a student at East Carolina University studying engineering with a concentration in electrical engineering for his bachelor's degree. He is also in the process of earning his master's degree in mechanical engineering through East Carolina's accelerated program. Jason is employed by Dr. Faete Filho as an undergraduate research assistant. Jason's work consists of developing simulations for hydrodynamic diffraction of a WEC.

Dr. Faete "JT" Filho

Dr. Faete 'JT' Filho (S'08–M'13–SM'20) received his Ph.D. degree from The University of Tennessee at Knoxville in 2012. In 2012, he joined Eaton Corporation medium voltage drive's

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power conversion laboratory as a power conversion scientist where he was working on high power medium voltage drives and subsea applications. He has extensive industrial experience in medium voltage drives, energy storage technologies and renewables. He is currently working in the areas of renewable energy, power systems, power electronics, smart systems, machine learning and desalination. In these research areas he has been leading several industrial and government projects and initiatives.

Dr. Tarek Abdel-Salam

Dr. Abdel-Salam is a professor of Mechanical Engineering at East Carolina University. His research is focused in two areas: technical research in thermo-fluids and engineering education. His technical research includes computational fluid dynamics methods related to combustion processes, fuel injection, fluid flow and micro mixers, energy efficiency, renewable energy, and environmental management. In engineering education, His research includes areas related to recruitment to STEM fields, virtual engineering laboratories, and distance education.

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Dr. Duba is a professor at East Carolina University. His teaching interest is in the areas Bioprocess, Environmental, and Thermal Engineering. His research interests are interdisciplinary and complementary with two primary focus areas (1) supercritical fluids based process development for the valorization, separation, and purification of bio-based products and byproducts from bio-botanical sources and (2) conversion of biomass to bioenergy using hydrothermal processes and upgrade bio-fuel using combined conventional and supercritical fluids techniques.

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