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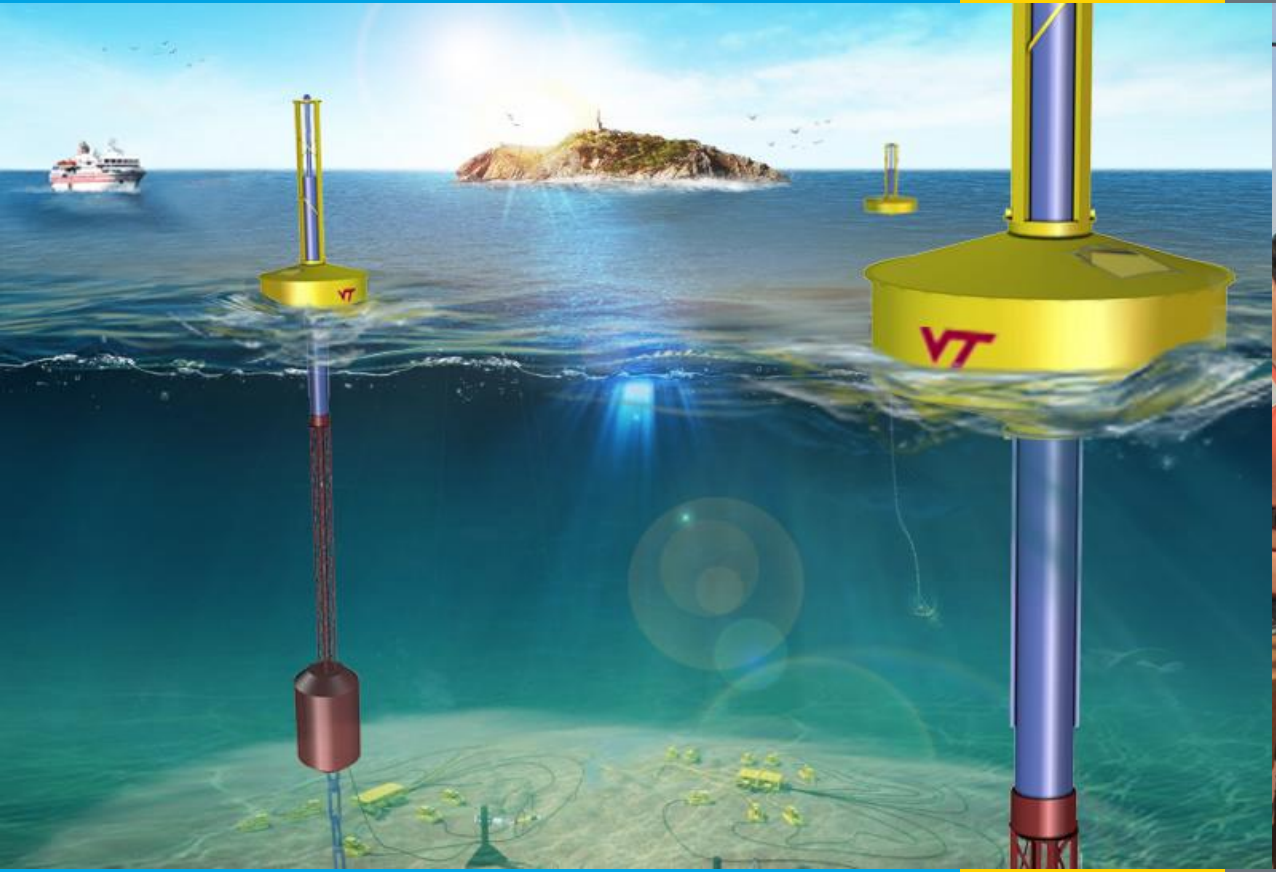

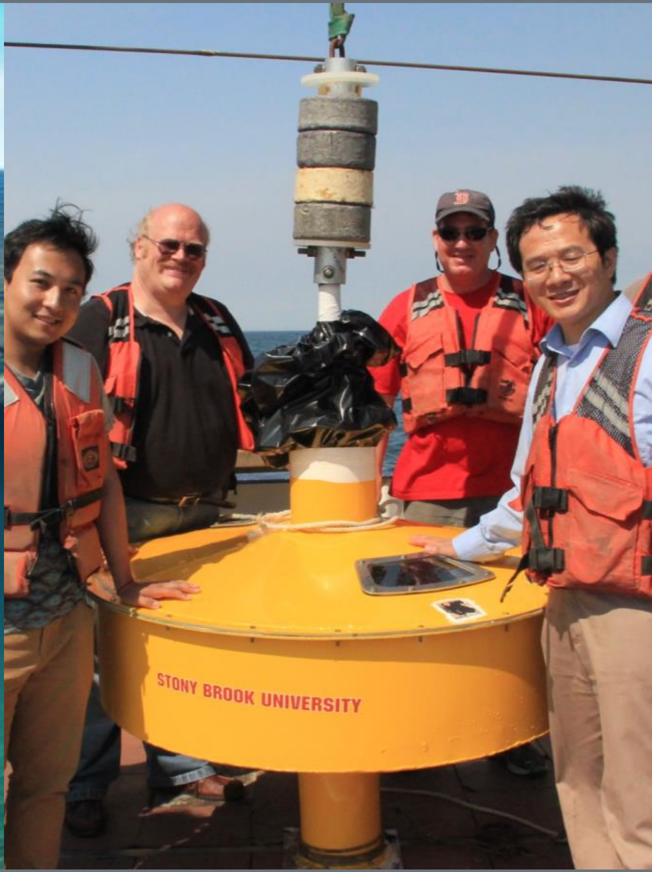

Efficient and Reliable Power Take-off for Ocean Wave Energy Harvesting

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Project Overview

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- This project seeks to improve the current ocean wave energy harvesting by designing, prototyping, and validating an innovative ocean wave power take-off based on a **mechanical motion rectifier (MMR)**.
- This MMR mechanism, invented by Lei Zuo, directly converts the irregular oscillatory wave motion into unidirectional generator rotation.

The Challenge

Solving the challenges caused by irregular, bi-directional, low frequency and low alternating velocity wave motions, the MMR will yield high-energy conversion efficiency, enhanced reliability, unmatched compactness, and optimal electrical grid integration.

The Partners

- National Renewable Energy Laboratory (NREL), CO: Al LiVecchi, Mark McDade, Ismael Mendoza, et al
- THK North America Inc, IL: James Matsunari and Evan Long
- Resolute Marine Energy Inc, MA: P. William Staby and Alan Chertok
- National Taiwan Ocean University: Jiahn-Horng Chen and Tai-Wen Hsu

Program Strategic Priorities

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Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- **Conduct R&D for innovative MHK systems & components**
- Develop tools to optimize device and array performance and reliability
- Develop and apply quantitative metrics to advance MHK technologies

Deployment Barriers

- Identify potential improvements to regulatory processes and requirements
- Support research focused on retiring or mitigating environmental risks and reducing costs
- Build awareness of MHK technologies
- Ensure MHK interests are considered in coastal and marine planning processes
- Evaluate deployment infrastructure needs and possible approaches to bridge gaps

Market Development

- Support project demonstrations to reduce risk and build investor confidence
- Assess and communicate potential MHK market opportunities, including off-grid and non-electric
- Inform incentives and policy measures
- Develop, maintain and communicate our national strategy
- Support development of standards
- Expand MHK technical and research community

Crosscutting Approaches

- Enable access to testing facilities that help accelerate the pace of technology development
- Improve resource characterization to optimize technologies, reduce deployment risks and identify promising markets
- Exchange of data information and expertise

Project Strategic Alignment

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Technology Maturity

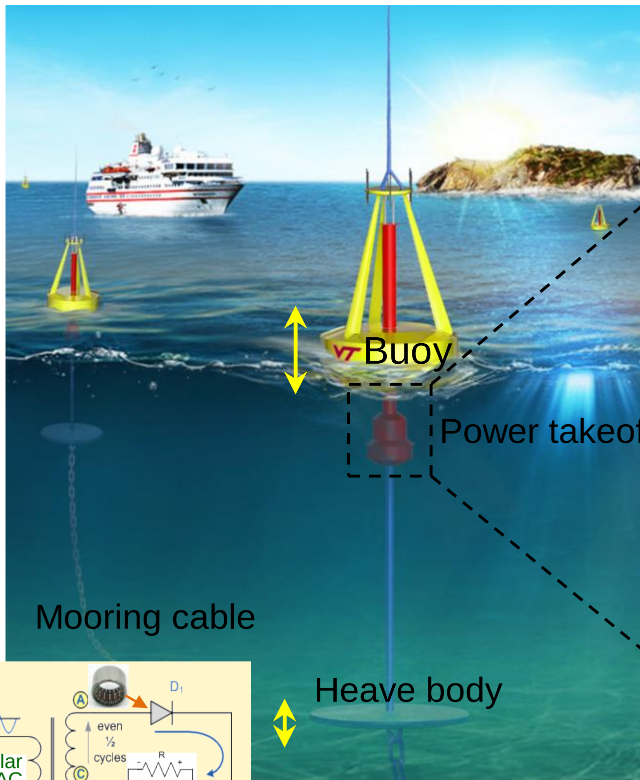
- Test and demonstrate prototypes at 500 W and 10 kW scales
- Develop cost effective design approaches for installation, grid integration, operations and maintenance
- **Conduct R&D for innovative MHK systems & components**
- Develop tools to optimize mechanical components and reliability
- Develop and apply quantitative metrics to advance MMR technologies

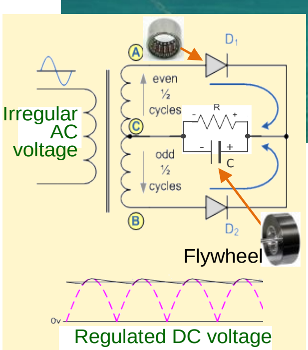
The Impact

- **METRIC I**: 25% increase of power generation per unit cost over the traditional power-take-offs (PTOs)
- **METRIC II**: 50% reduction of failure modes
- **Potential impact on the industry**: Our MMR system is highly scalable, either up (for electrical utilities) or down (for ocean sensing and surveillance, for example), which dramatically expands the range of commercial uses and potential industry and government partners.
- **The project's endpoint and final product**: A validated, industry-scalable PTO technology with high efficiency and reliability applicable to point absorber and wave surge types of wave energy converters (WECs).

Technical Approach

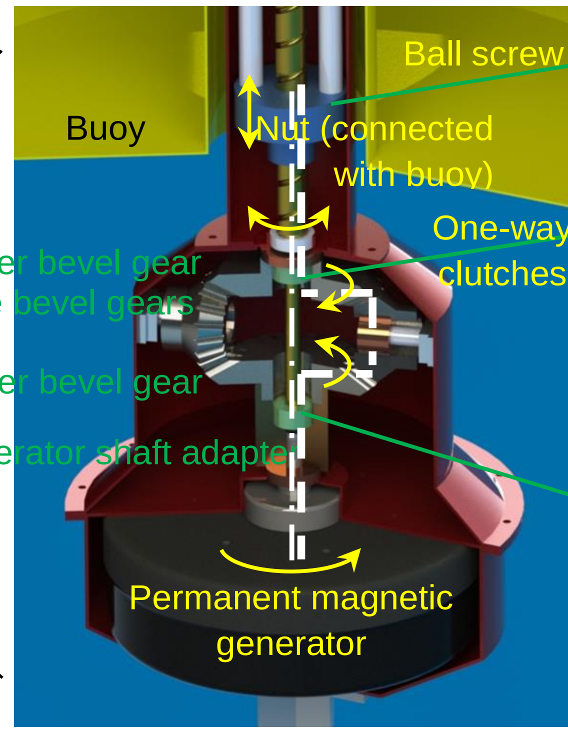
Mechanical Motion Rectifier Based Power Take-Off: to directly convert irregular oscillatory wave motions into unidirectional steady rotation of the generator.





Electrical Voltage Rectifier

MMR based power takeoff used ball screw



Ball screw and nut

One-way clutch between the ballscrew shaft and the upper bevel gears

Roller clutches and working principle

One-way clutch between the ballscrew shaft and the generator shaft adapter. (The lower bevel gear is rigidly mounted on the generator shaft adapter.)

Advantages: (1) high-energy conversion efficiency
(2) enhanced reliability
(3) unmatched compactness
(4) optimal electrical grid integration

Technical Approach

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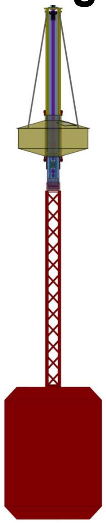
Design and Reliability of the PTO and WECs

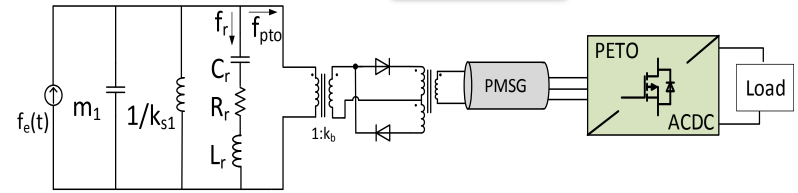


1:20 scale prototype (**500W**) for concept validation and testing at Virginia Tech and in the ocean

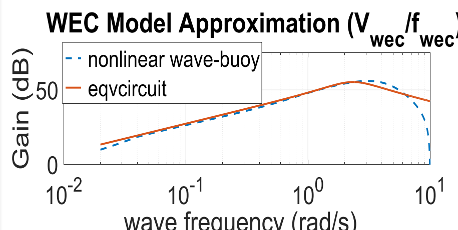
1:8-1:5 scale prototype (**10kW**) for testing in NREL testing and ocean

Power Electronics

Model

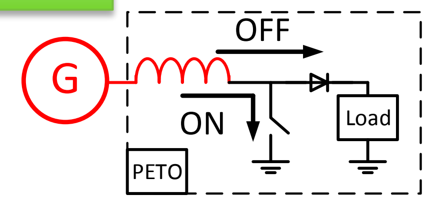


Brune's network synthesis

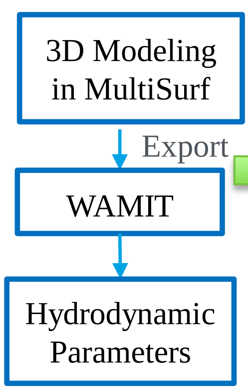


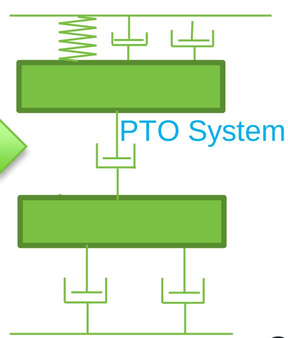
Control

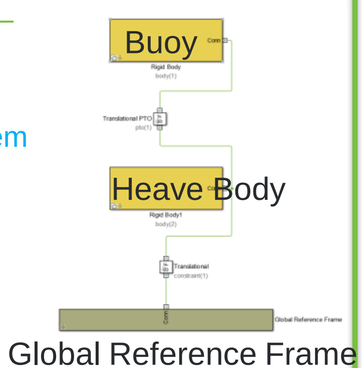
Pulse Energy Take-Off



Wave-WEC Dynamics and Optimization

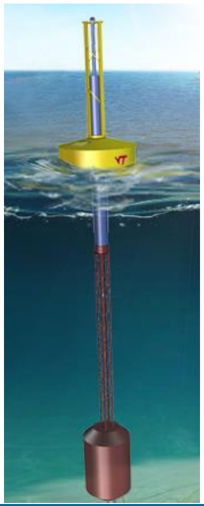






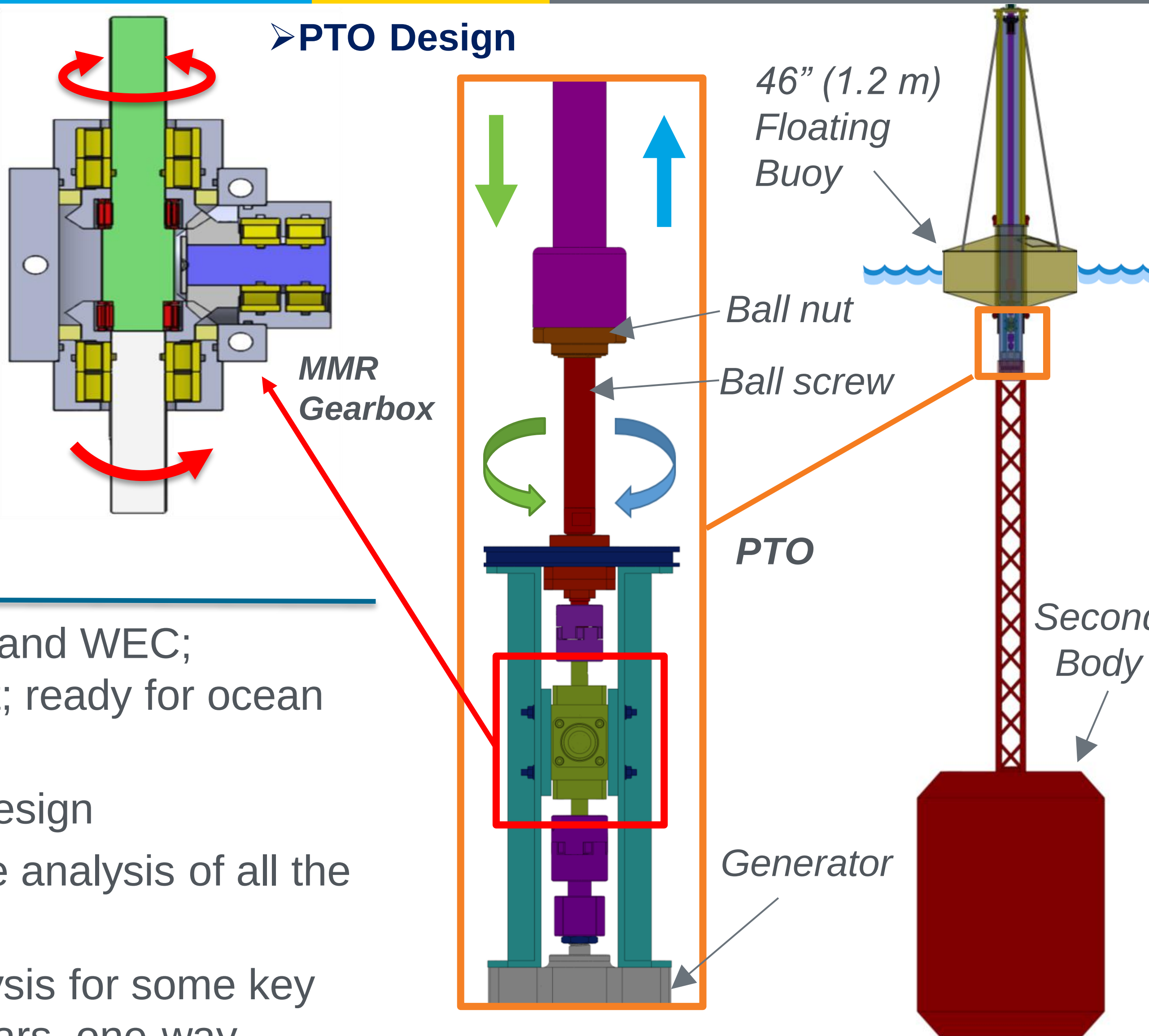
Hydrodynamics | Dynamic Model | WEC-Sim Model

PTO and WEC Testing in Lab and Ocean



Accomplishments and Progress (1): Design & Reliability

500W buoy and PTO prototype



- Prototyped 500W PTO and WEC; completed PTO lab test; ready for ocean test
- Finalizing 10kW PTO design
- Completed failure mode analysis of all the PTO components
- Pursuing in-depth analysis for some key comments including gears, one-way

Accomplishments and Progress (2): Hydrodynamics and Optimization

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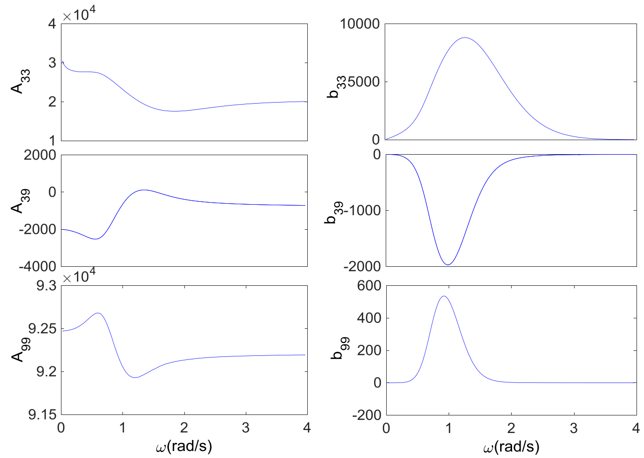
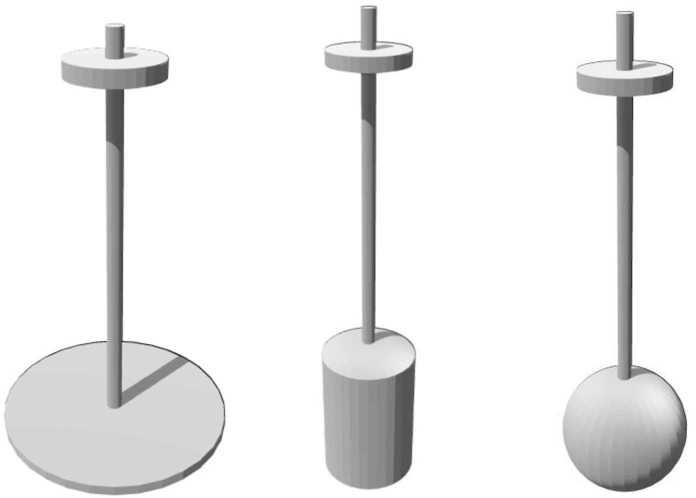
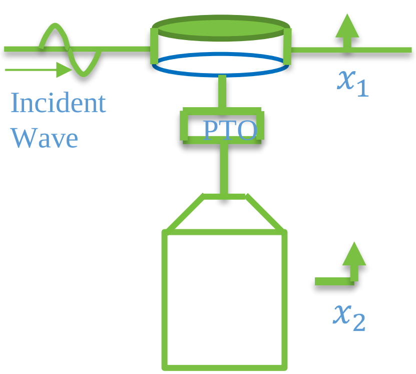
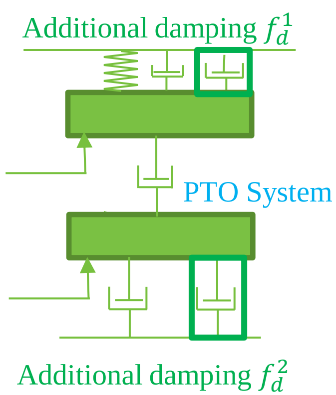


Hydrodynamics modeling and analysis with Multi-surf and WAMIT



Shape optimization of the submerged body with WEC-Sim





Dynamic modelling and PTO parameters optimization

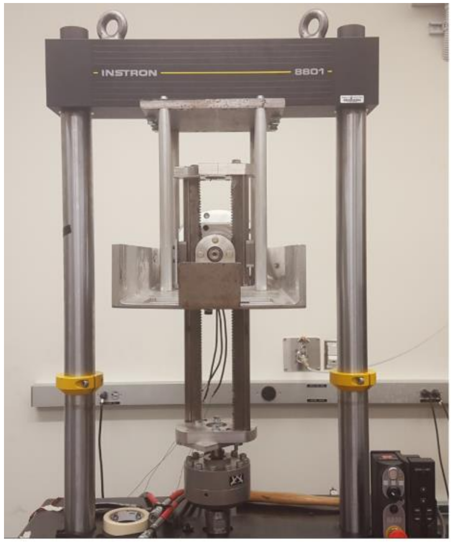
- Studied hydrodynamics with Multi-surf and WAMIT
- Conducted Shape optimization with WEC-Sim simulation. The submerged tank is considered to be the best.
- Conducted PTO optimization with the dynamic model

Accomplishments and Progress (3): Lab and Ocean Test

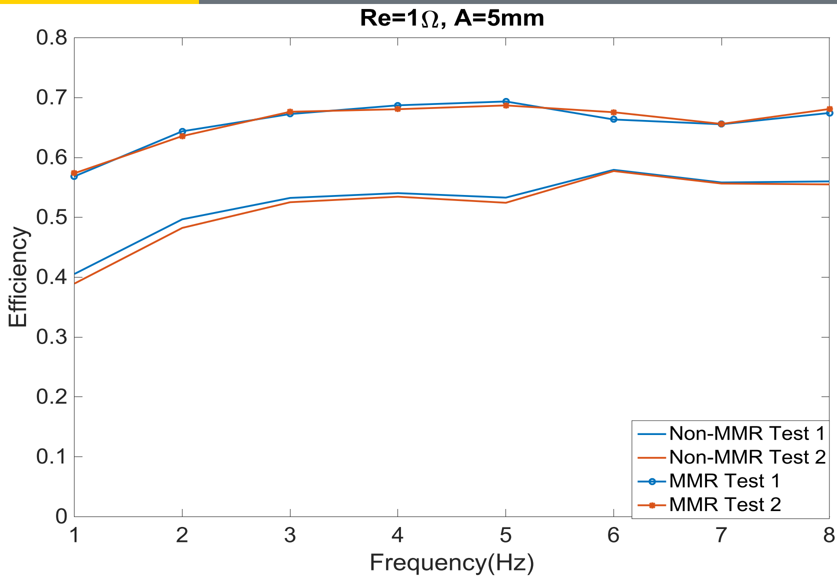
500W PTOs Lab Testing: Completed

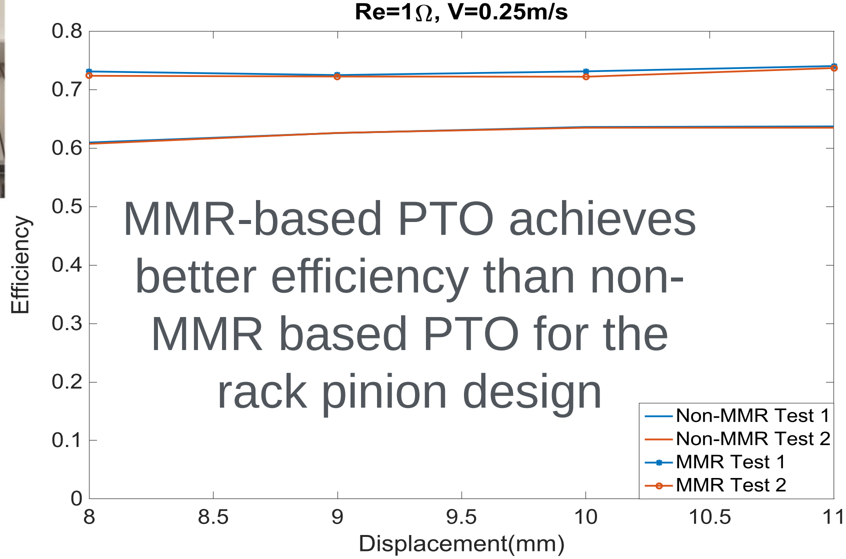
➢Prototyping and Lab Testing

New PTO



Baseline PTO



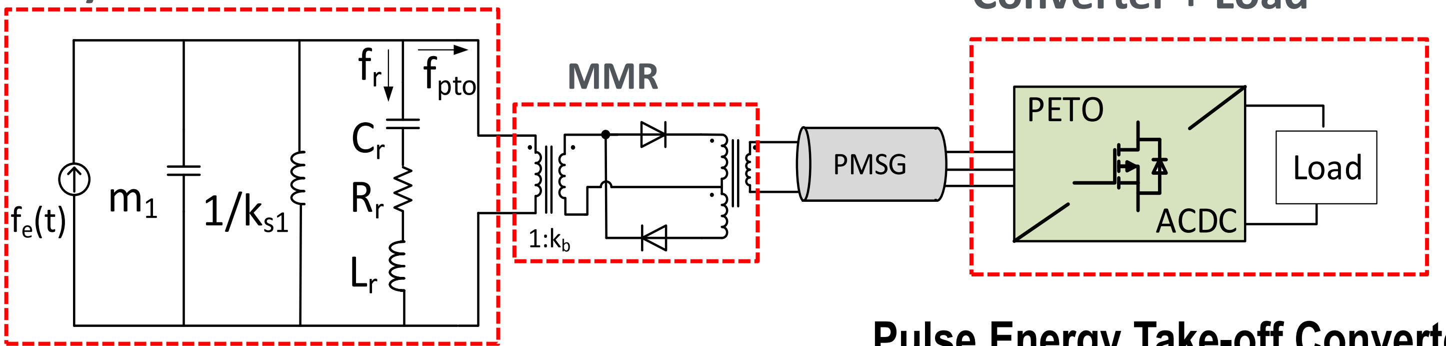


MMR-based PTO achieves better efficiency than non-MMR based PTO for the rack pinion design

500W WEC Ocean Test: in Process

Buoy and Wave Model

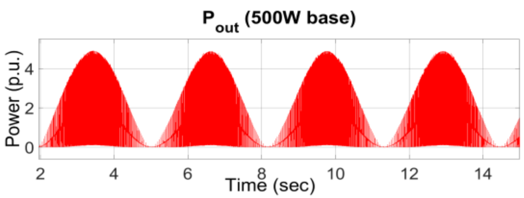
Converter + Load



Nonlinear approximated model for Buoy and Wave (Subtask 3.1)

Pulse Energy Take-off Converter (PETO) (Subtask 3.2/3.3)

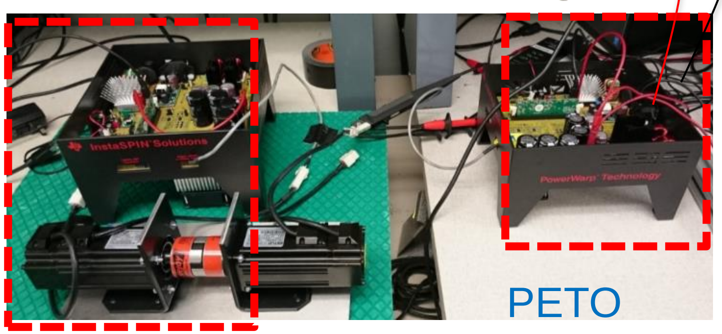
Regular wave cond.
H_s = 0.58 m , T_s = 6.3 s



Mean output power from **Simulink** model= **574** W

DC load 10A/100A, 150V/600V

Buoy and Wave (+MMR) Emulator

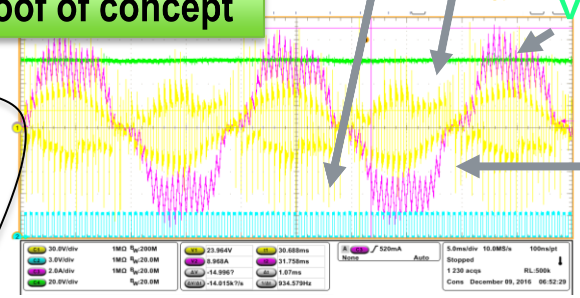


PMSG

PETO converter

Proof of concept

PWM (45%, 2kHz)



V_{in}* (vrms)	Sim. Power (W)	Exp. Power (W)	Error %
35	276	280	1.4 %
47.3	512	513	0.1 %

*Ratio between Speed(RPM) and Vin(vrms) is assumed to be 10:1.

Project Plan & Schedule

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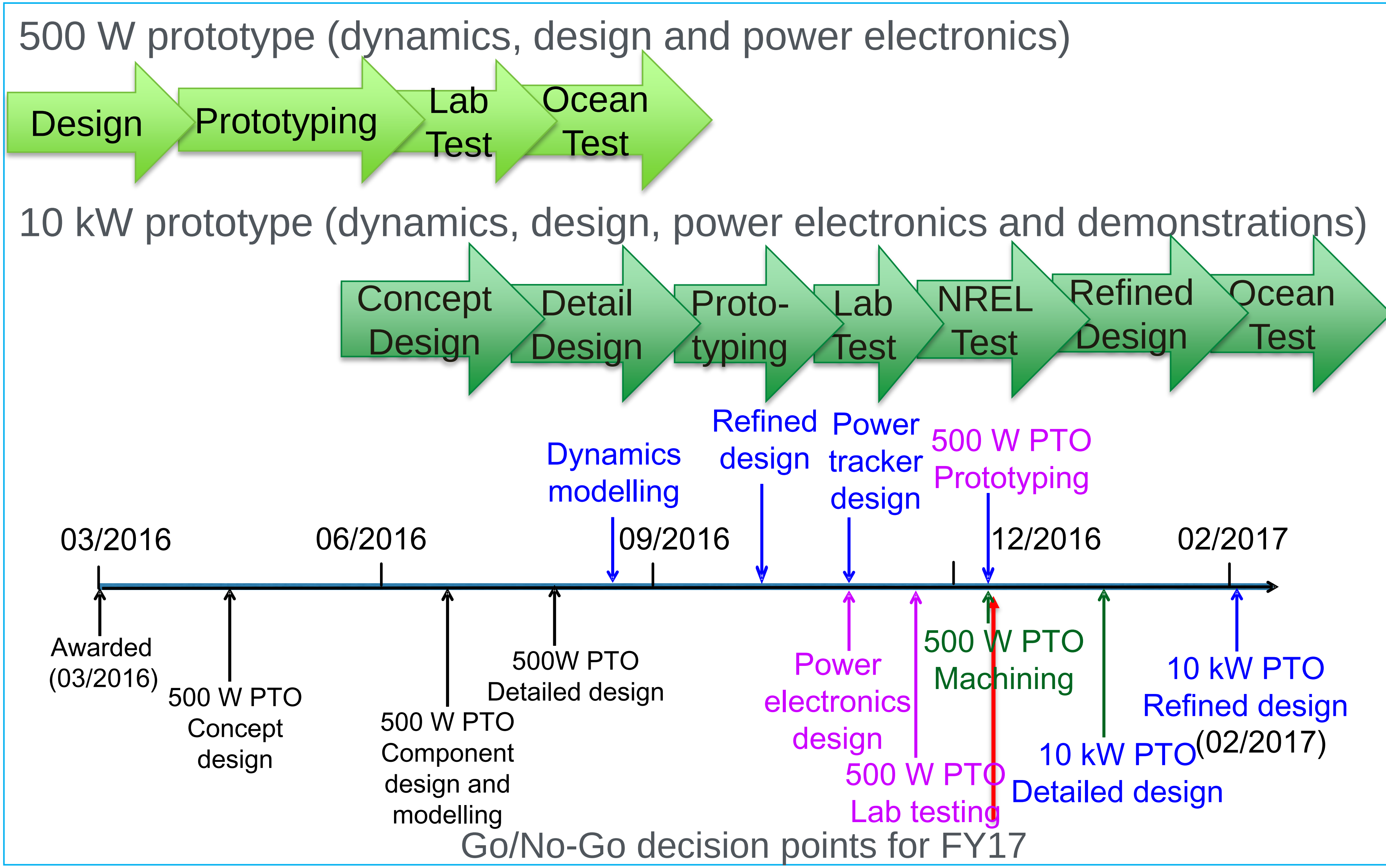

Project Budget

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Budget History					
FY2016		FY2017		FY2018	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$893.901	$223.476	$1,106k	$276.524		

The team obtained $100k from Virginia State Funding Agency Center for Innovative Technology (07/2017—12/2018)

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- NREL, CO
- THK North America Inc, IL
- Resolute Marine Energy Inc, MA
- Hawaii WETS, HI
- •National Taiwan Ocean University Ocean Energy Center, Taiwan

Communications and Technology Transfer:

- Seminars at and visit to universities (NTOU, National Taiwan University) and companies (Industrial Technology Research Institute, CSBC Corporation) in Taiwan, 06/2016
- Panelist of MHK in Hydrovision conference, 07/2016
- Paper in 2016 Motion and Vibration Control conference, 07/2016
- Paper and Presentation in ASME IDETC conference, 08/2016
- Presentation in Energy Harvesting Workshop, 09/2016
- Hosted visitors from NTOU (09/2016), National Chung Hsing University (09/2016), and National Sun Yat-sen University (11/2016)

Next Steps and Future Research

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FY17/Current research:

- Complete the ocean wave test of 500W WEC
- Prototype10 kW PTO (mechanical and electrical components), test the PTO in NREL
- Build the 10KW WEC, and conduct ocean test;

Proposed future research:

- Investigate the application of MMR-based PTO to wave surge converter.
- Scale-up study for utility scale WEC
- Scale-down study for ocean sensing applications
- Commercialization