System Modeling for Control Co-design of a Hybrid Marine Energy Converter

Wind & Wave

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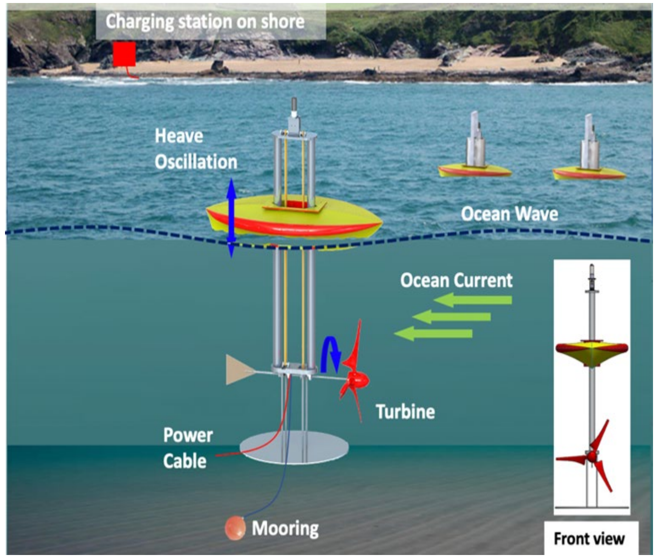
Wave & Current



Marine Renewable Innovations and Education Lab (MaRInE Lab)

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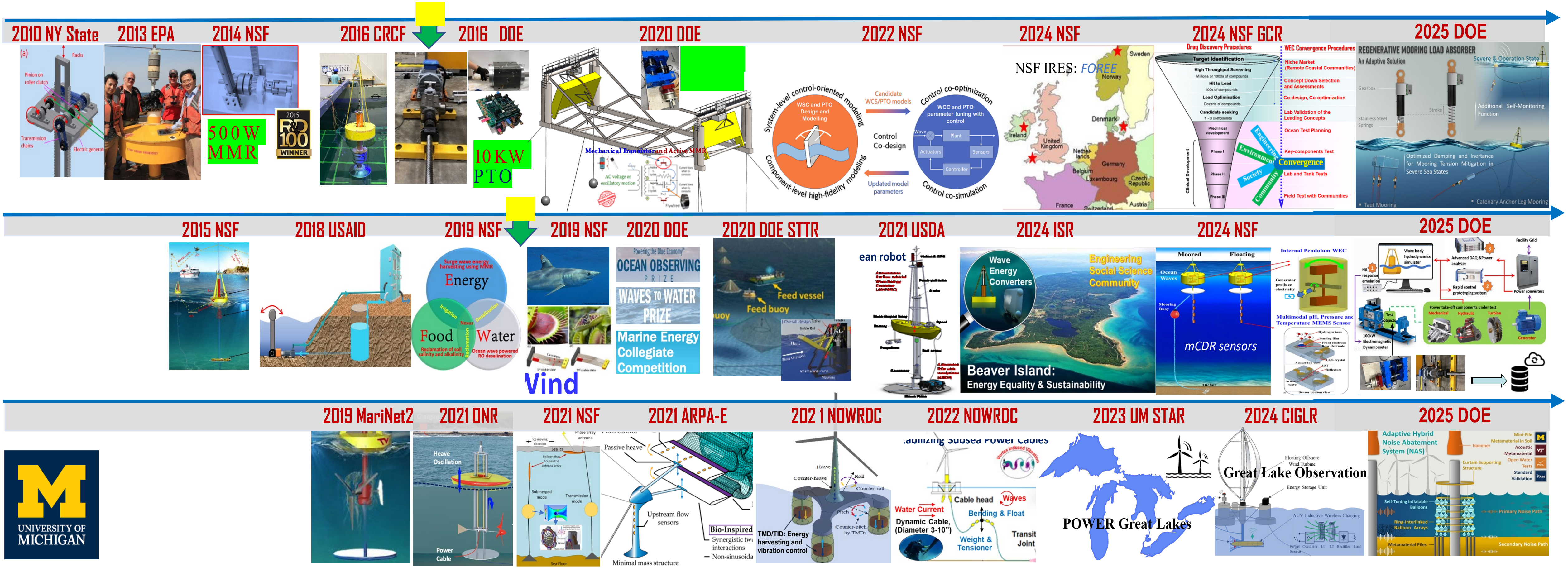
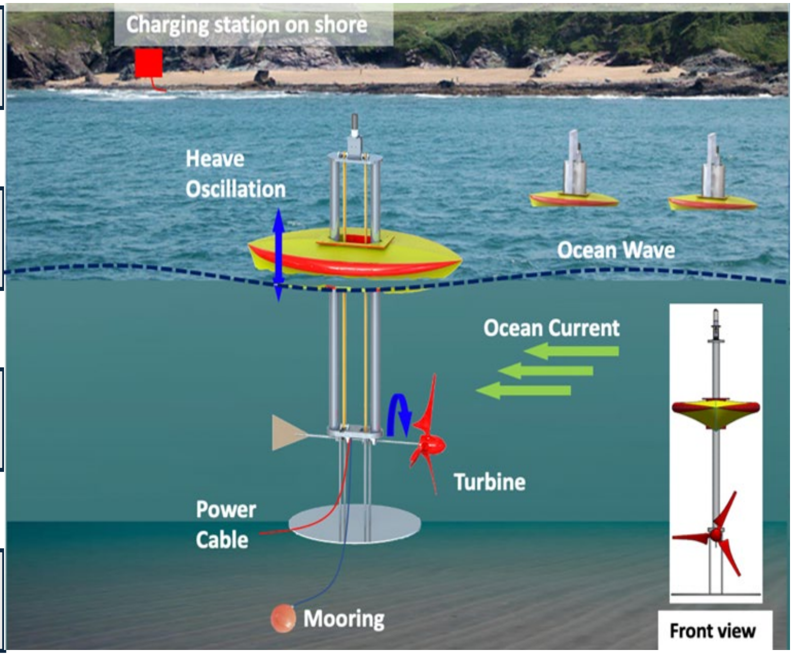


Marine Hydrodynamics	Power Takeoff	Dynamics and Control
Naval Structure Design	Power Electronics	Materials & Manufacturing
Environment Science	Economics and Business	Society and Policy

Outline

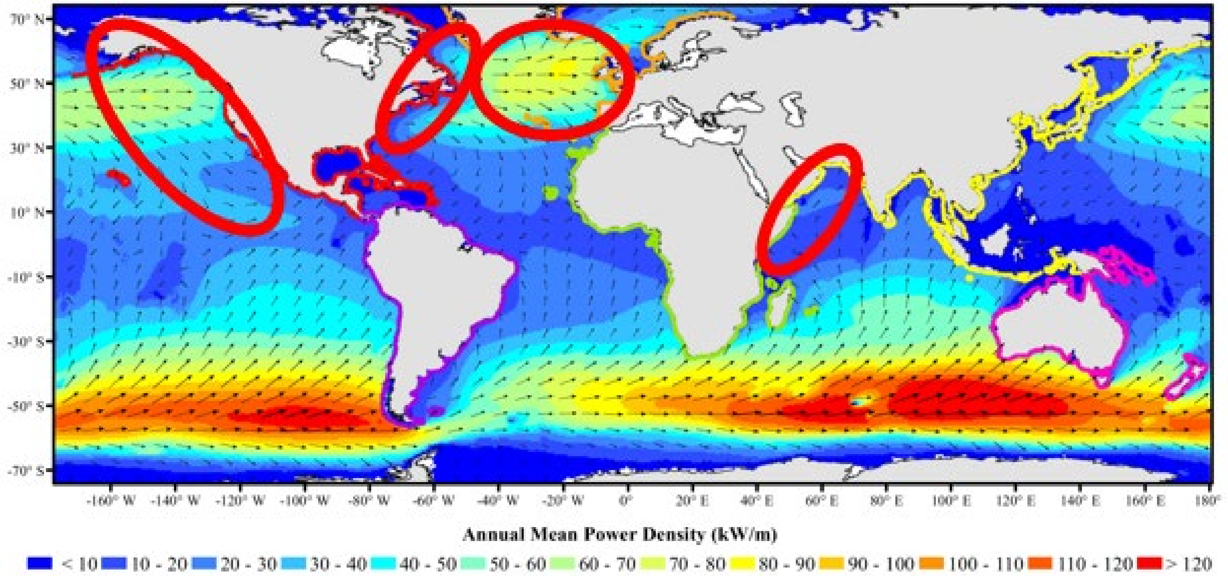


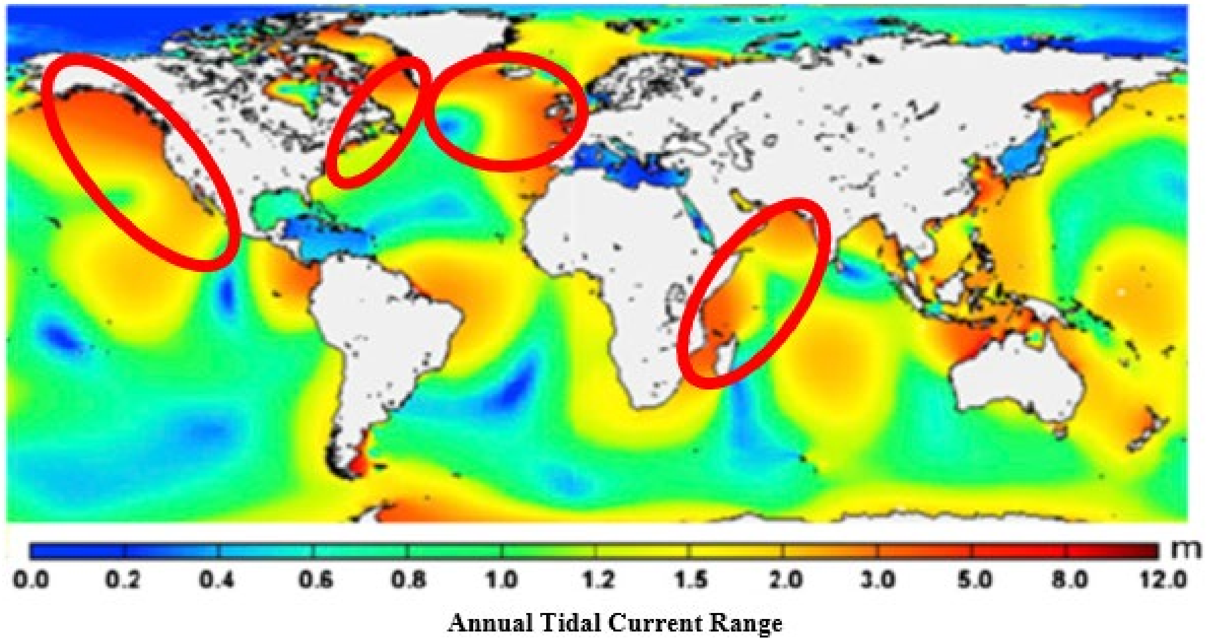
Charging station on shore
Heave
Oscillation
Ocean Wave
Ocean Current
Turbine
Power
Cable
Mooring
Front view

Background and Motivation

Collocated harvesting potential

- Wave and tidal current can **coexist**
- **Hybrid devices** shared structure for reduced cost





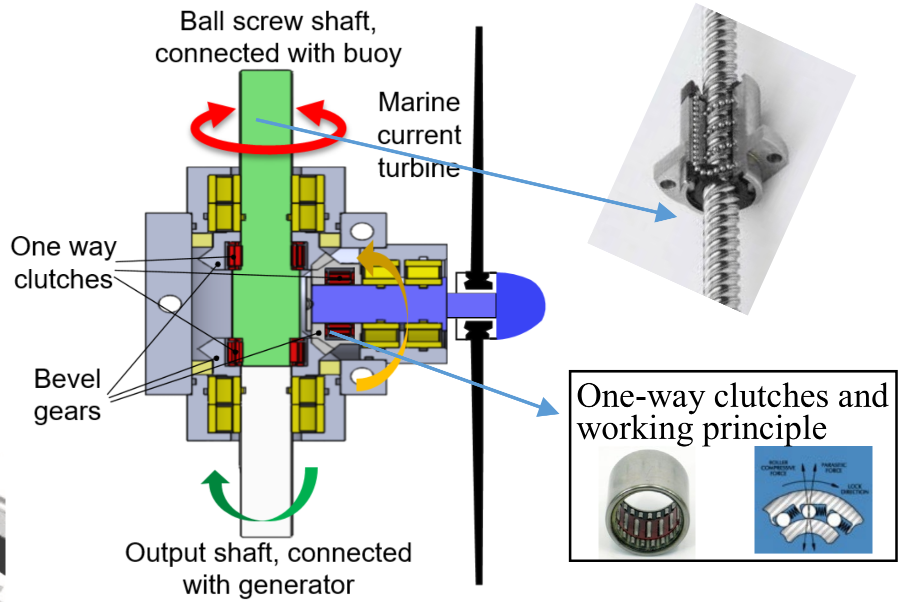
(Gunn, Kester, and Clym Stock-Williams. 2012)

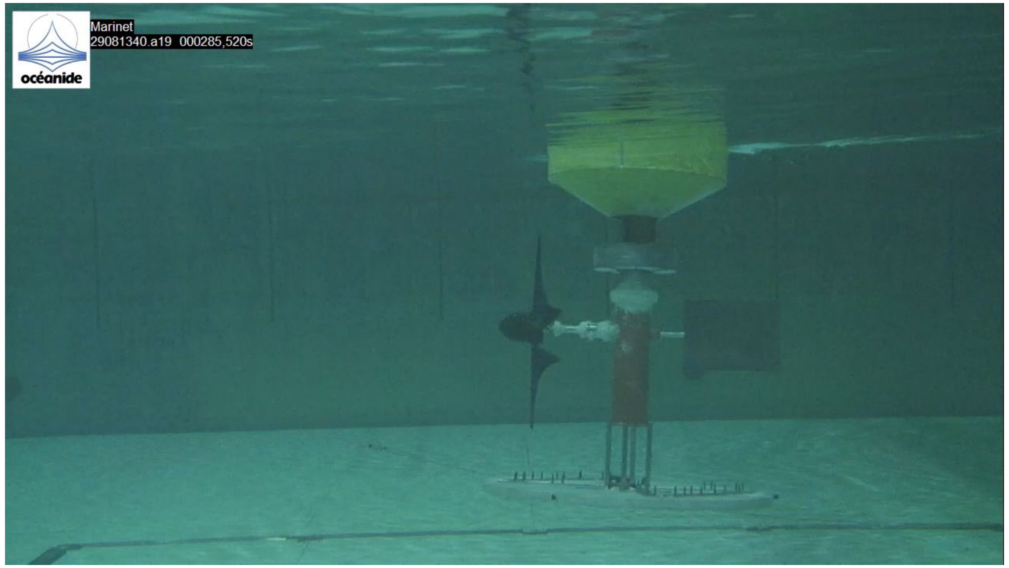
Background and Motivation - Previous Tank Test

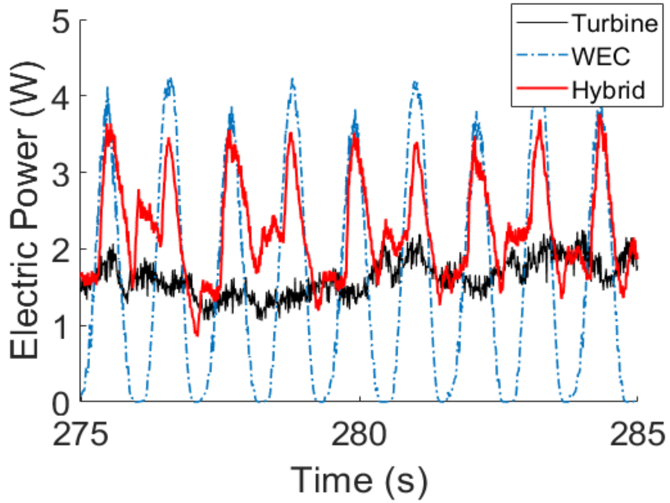
Test in France Oceanide's wave current basin, 09/2019

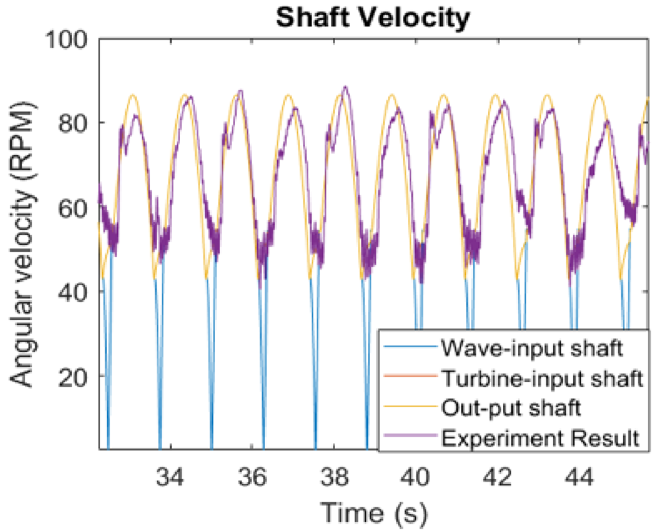
(Thanks to MARINET-2)

- Notice: both turbine and WEC shared one load for these studies
- The latest model allows us to find best loads for both system separately, and the best hydro geometry at the same time









Background and Motivation

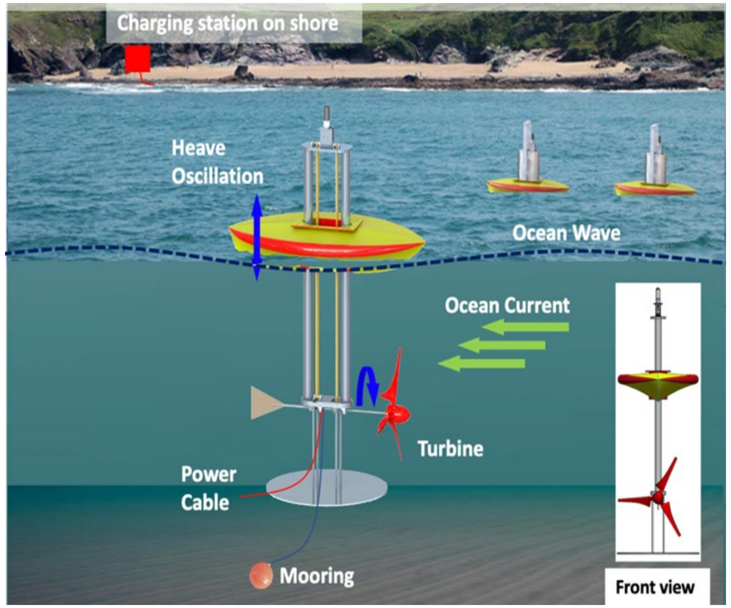
- U.S. Navy founded project
- All types of energy sources are required
- Solar energy limitations
  - Strongly **dependent on weather** and daylight
  - **Cannot deliver power 24/7**, especially during long periods of cloud cover or dust.
  - Low energy density. Systems are **heavy and take up large area** for modest power.
- Combining alternative renewable energy sources (e.g., **wave and current**) to provide steadier 24/7 power with more portable systems

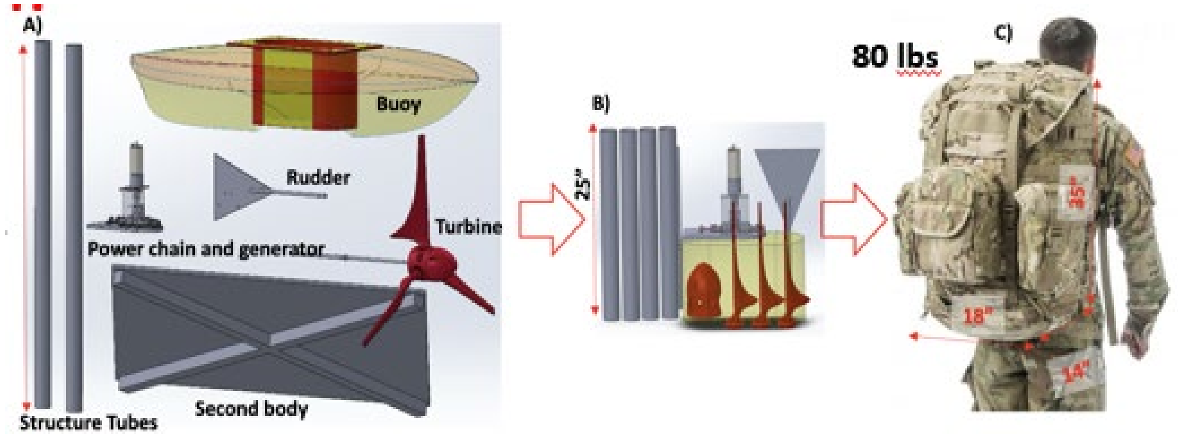
U.S. soldiers with the 2nd Cavalry Regiment march near Vilseck, Germany. (Pablo N. Piedra/U.S. Army)

Program Officer: Dr. Joseph F. Parker

Supported by the Office of Naval Research through grants #N00014-23-1-2100

Background and Motivation



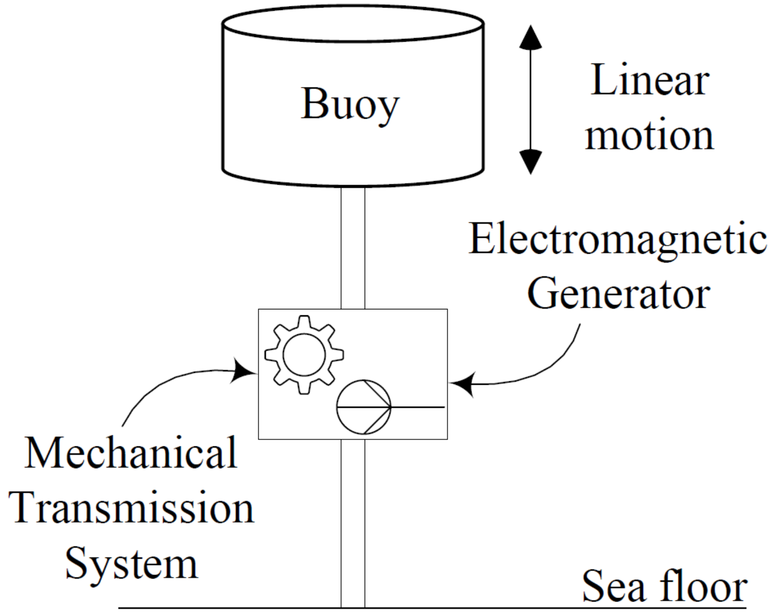


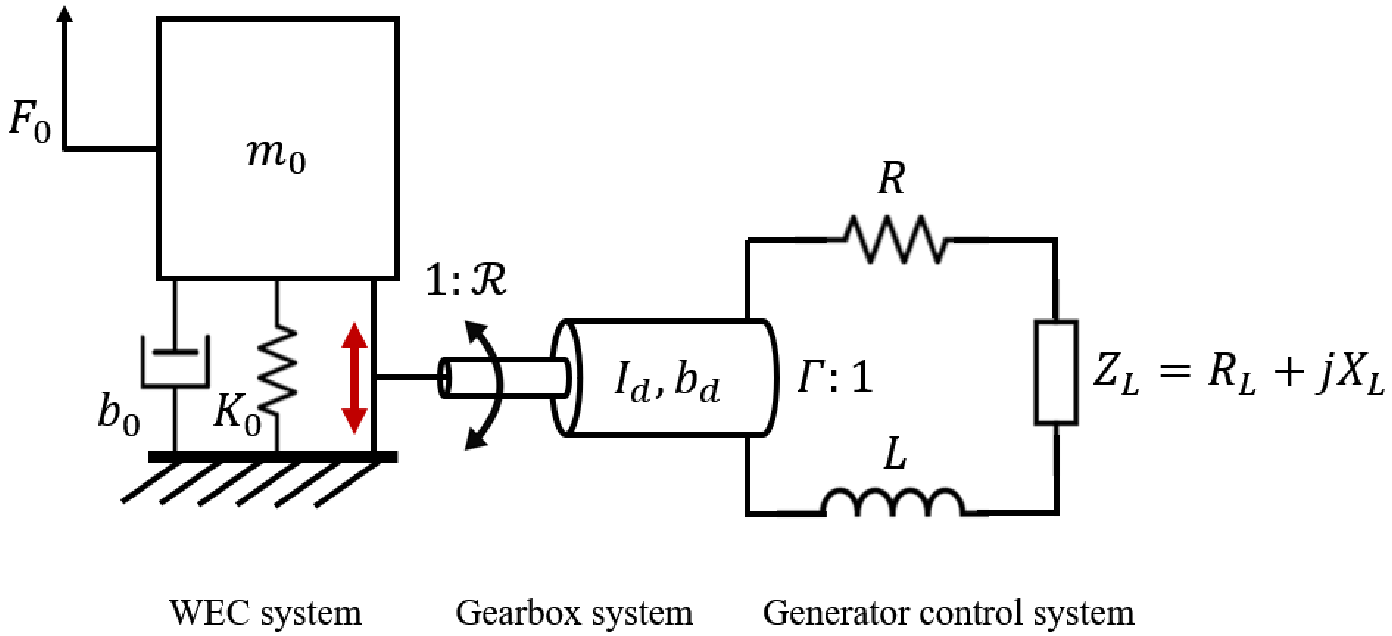
<u>Our focus</u>: Point Absorber Wave Energy Converter with Axial Turbine for Current Energy

From simple to comprehensive:

- **Single-body WEC → Two-body WEC with MMR → Portable Hybrid Wave & Current Energy Converter**

Single-body WEC Operation Principle and System Modeling



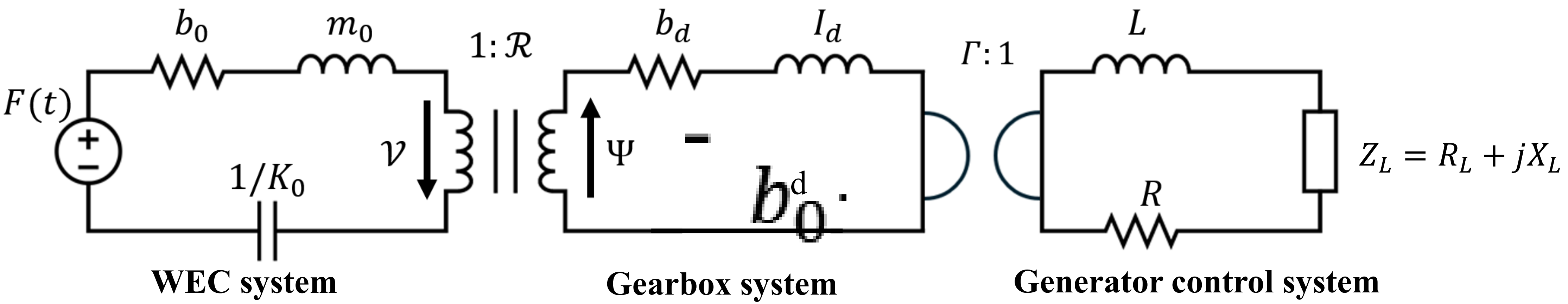


Concept of a single-body point absorber WEC using a floating buoy as the wave capture structure.

m_0 is the summation of **physical mass** and frequency dependent **added mass;**
b_0, F_0 are the frequency dependent **radiation damping** and **excitation force;**
K_0 is the **hydrostatic stiffness**;
I_d, b_d are the **inertia** and **friction damping** of the gearbox;
R *and* L are the internal **resistance** and internal **inductance** of the generator;
Z_L is the **external load** with real part resistance of R_L and imaginary part of jX_L;
$\mathcal{R}$ is **gear ratio**;
Γ is the electrodynamic **transduction factor** of the generator;

Lin, W., Huang, J., Truong, B., & Zuo, L. (2025). EWTEC

Single-body WEC Equivalent Circuit Model



This set of equations provides a comprehensive procedure to determine the generated power for any given set of system parameters.

Assuming: regular wave $F(t) = F_0 \cos(\omega t)$

Velocity: $\mathcal{V} = \frac{F_0}{b_0 + Z_{in}}, \Psi = \mathcal{V}/\mathcal{R}$

$$Z_{\mathrm{in}} = j\omega m_0 + \frac{K_0}{j\omega} + \frac{1}{\mathcal{R}^2}\left(b_{\mathrm{d}} + j\omega I_{\mathrm{d}} + \frac{K_{\mathrm{d}}}{j\omega} + \frac{\Gamma^2}{R + j\omega L + R_{\mathrm{L}} + jX_{\mathrm{L}}}\right)$$

Voltage across the real part of the load impedance and power output:

$$V_{\mathrm{L}} = \frac{\Psi\Gamma}{R + j\omega L + R_{\mathrm{L}} + jX_{\mathrm{L}}} R_{\mathrm{L}},$$

$$P_{\mathrm{L}} = \frac{1}{2}\frac{|V_{\mathrm{L}}|^2}{R_{\mathrm{L}}}.$$

→

$$\partial P_{\mathrm{L}} / \partial X_{\mathrm{L}} = 0$$

$$\partial P_{\mathrm{L}} / \partial R_{\mathrm{L}} = 0$$

→

$$P_{\mathrm{L}} = \frac{F_0^2 \Gamma_{\mathrm{e}}^2}{8[\Gamma_{\mathrm{e}}^2 b_{\mathrm{e}} + R(X_{\mathrm{e}}^2 + b_{\mathrm{e}}^2)]}$$

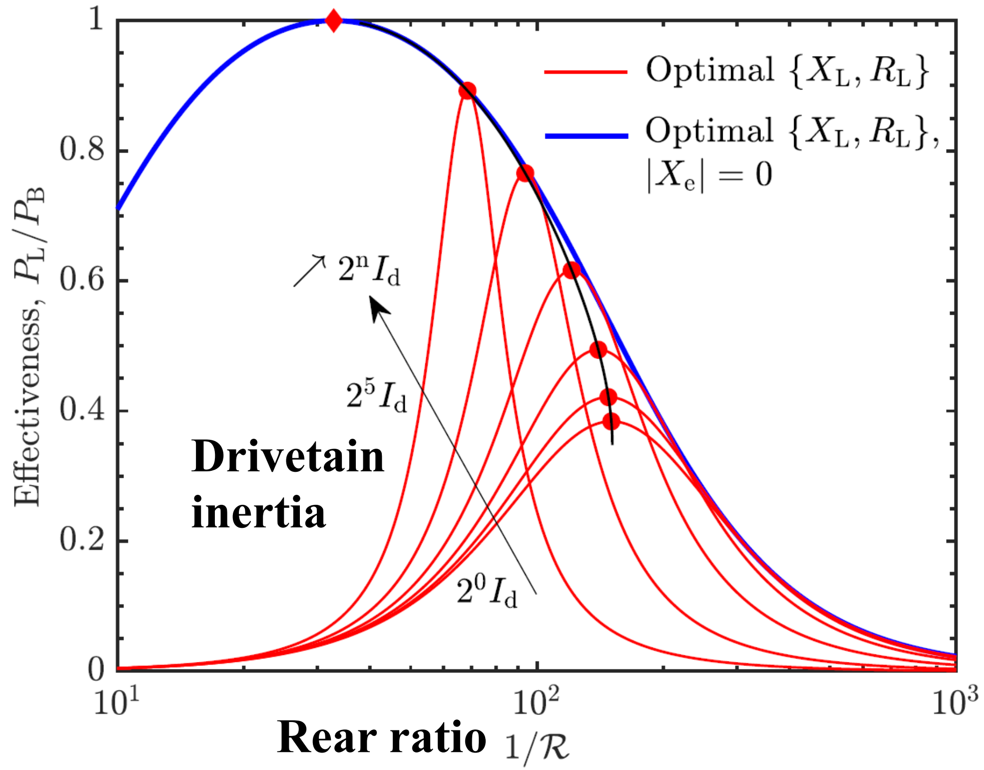
$$R_{\mathrm{L}} = R + \frac{\Gamma_{\mathrm{e}}^2 b_{\mathrm{e}}}{X_{\mathrm{e}}^2 + b_{\mathrm{e}}^2} \qquad X_{\mathrm{L}} = -X + \frac{\Gamma_{\mathrm{e}}^2 X_{\mathrm{e}}}{X_{\mathrm{e}}^2 + b_{\mathrm{e}}^2}$$

Where, $X = \omega L, b_{\mathrm{e}} = b_0 + b_{\mathrm{d}}/\mathcal{R}^2, X_{\mathrm{e}} = X_0 + \frac{X_{\mathrm{d}}}{\mathcal{R}^2} = \left(\omega m_0 - \frac{K_0}{\omega}\right) + \frac{1}{\mathcal{R}^2}\left(\omega I_{\mathrm{d}} - \frac{K_{\mathrm{d}}}{\omega}\right), \Gamma_{\mathrm{e}} = \Gamma/\mathcal{R}$

Single-body WEC Case Study

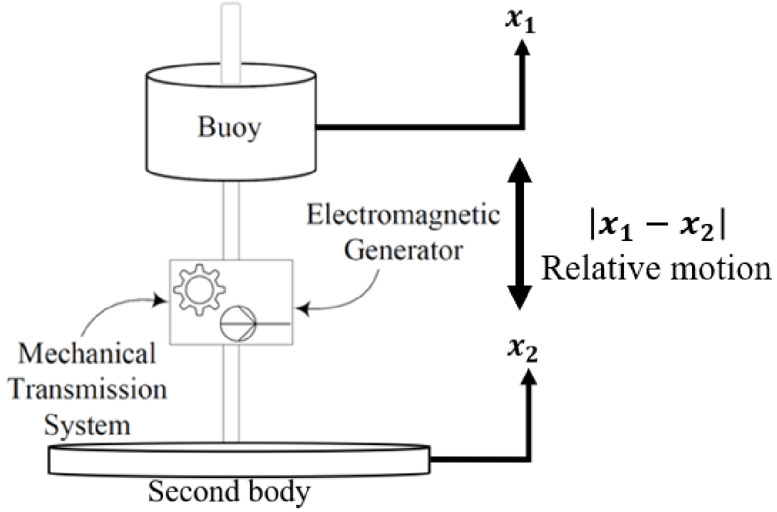
- Ideal case when $X_e = 0$, where resonance happens: $X_\mathrm{e} = X_0 + \frac{X_\mathrm{d}}{\mathcal{R}^2} = \left(\omega m_0 - \frac{K_0}{\omega}\right) + \frac{1}{\mathcal{R}^2}\left(\omega I_\mathrm{d} - \frac{K_\mathrm{d}}{\omega}\right)$
- More practical and higher upper power bound compared to using linear electric damping (detailed derivations are shown in the paper)
- As I_d(**drivetrain inertia**) increases, the optimal **gear ratio $1/\mathscr{R}$** decreases, leading to an increase in output power
- Beyond the optimal value, further increasing I_d results in a smaller optimal $1/\mathscr{R}$ and a reduction in output power

Parameters	**Value**
Wave frequency, f	0.1, Hz
Buoy structure	
Effective mechanical damping coefficient, b_0	42.11×10^3, Ns/m
Overall mass, m_0	5.61×10^5, kg
Mechanical stiffness, K_0	7.85×10^5, N/m
Mechanical transmission system (drivetrain) [21], [32]	
Effective mechanical damping coefficient, b_d	2, Nms
Moment of inertia, I_d	9.37, kgm^2
Mechanical stiffness, K_d	0, Nm/rad
Electromagnetic generator [33]	
Coil inductance, L	1.4, mH
Parasitic resistance, R	38, mΩ
Electromagnetic transduction factor, Γ	5.40, Nm/A

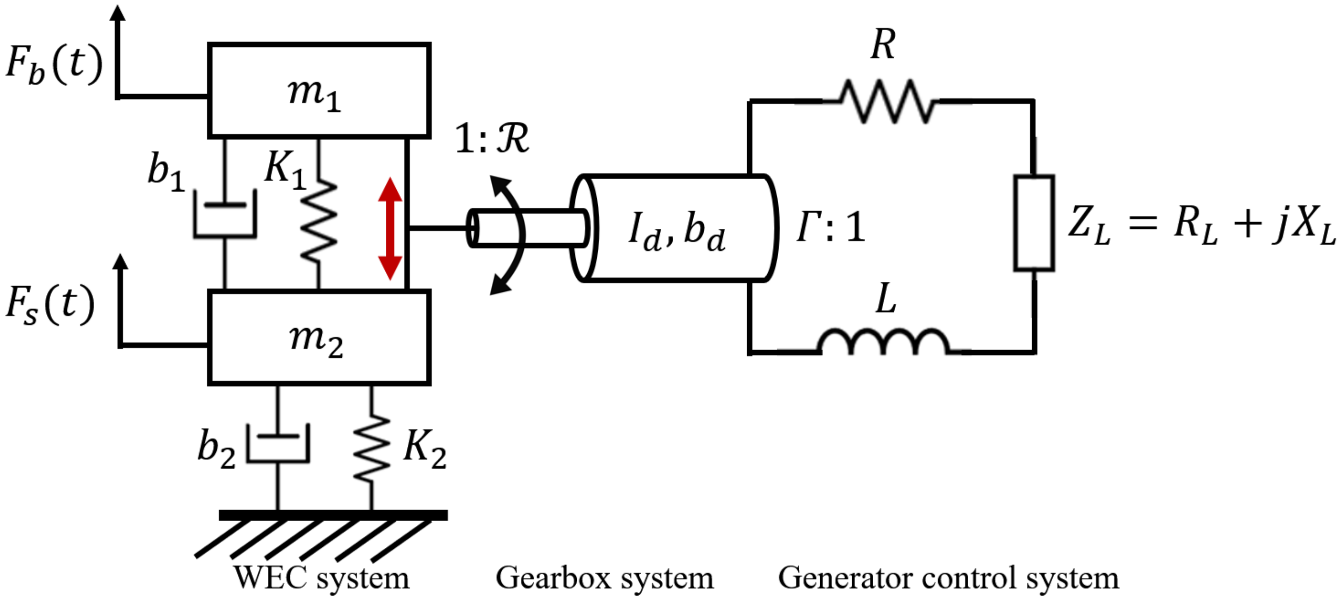


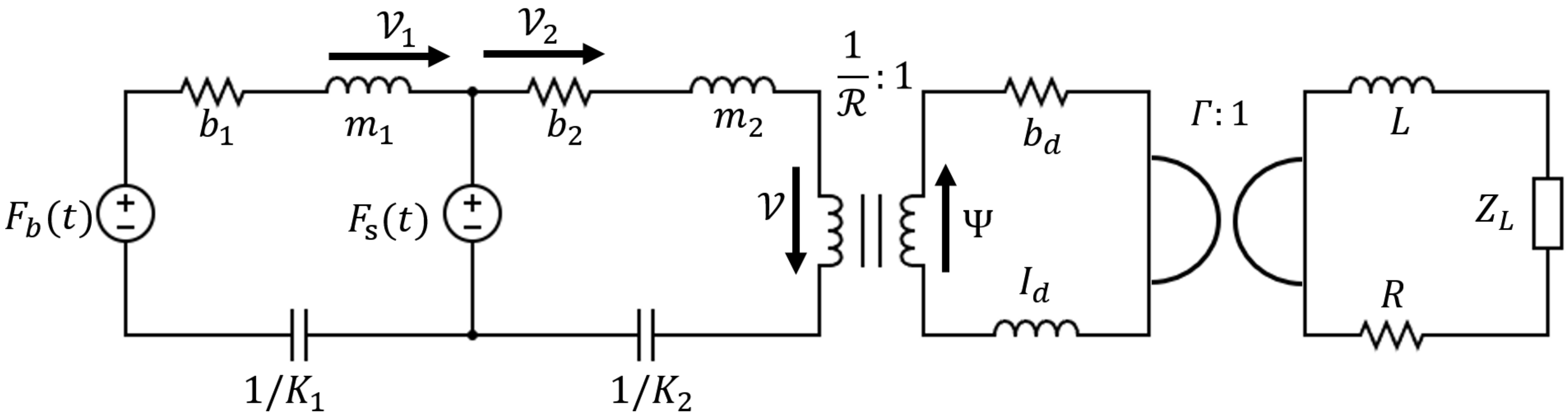
Lin, W., Huang, J., Truong, B., & Zuo, L. (2025). EWTEC

Two-body WEC Operation Principle and System Modeling



Concept of a two-body point absorber WEC

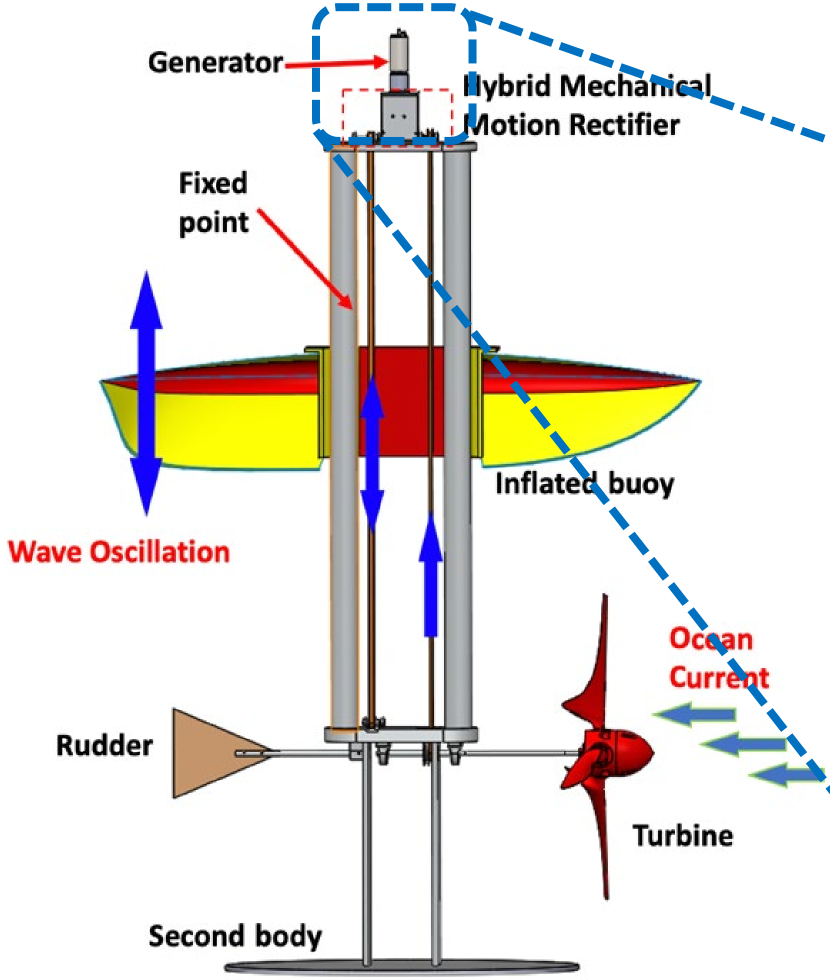


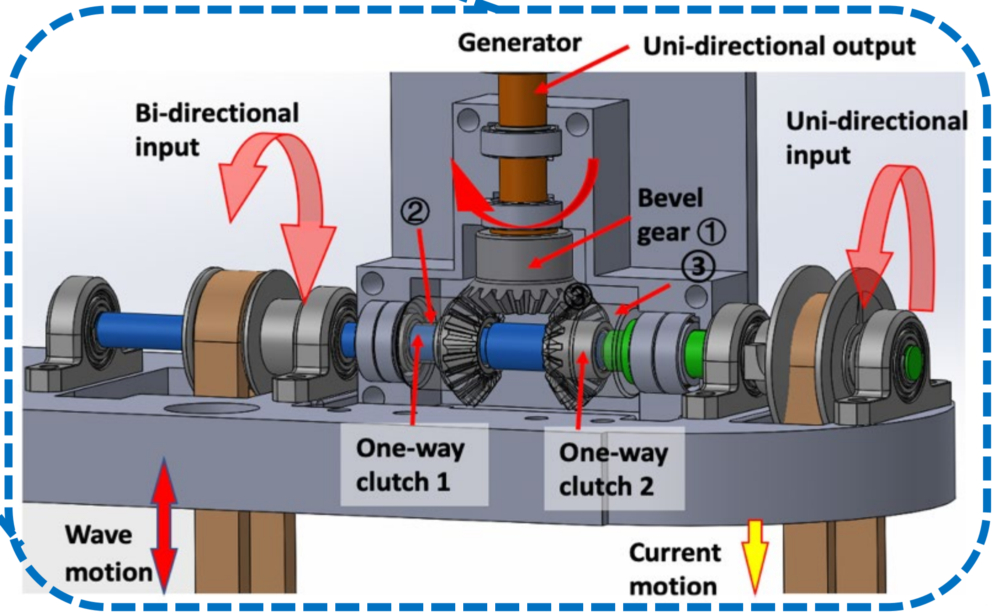


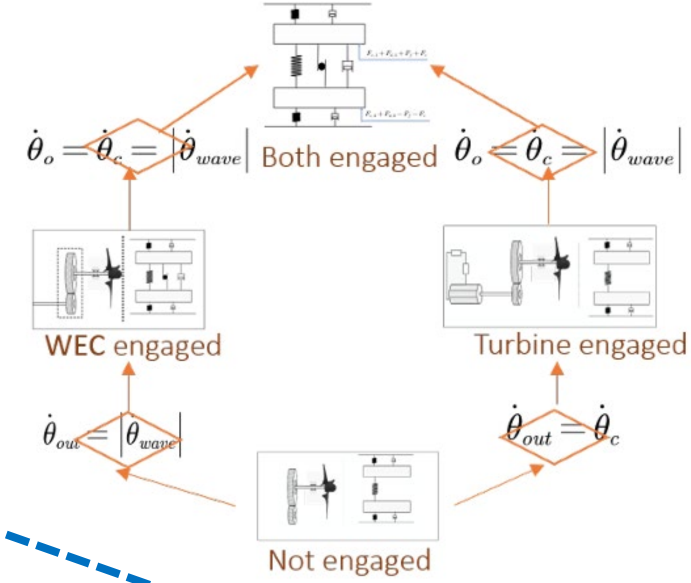
Similarly, we can solve for optimal power as two-body WEC

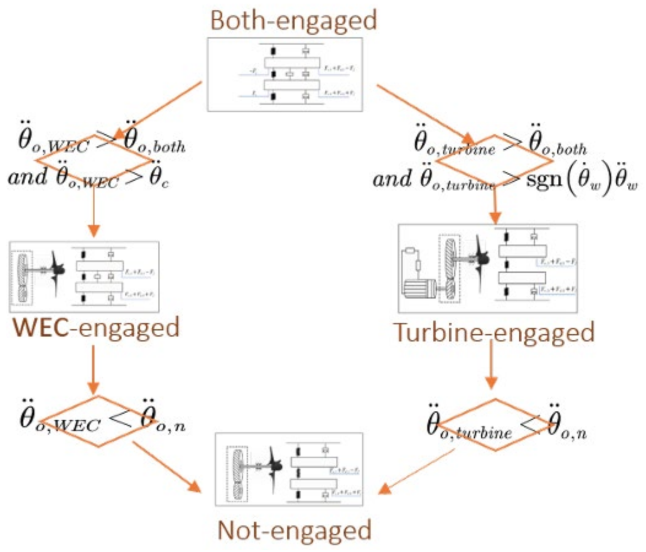
Hybrid Mechanical Motion Rectifier

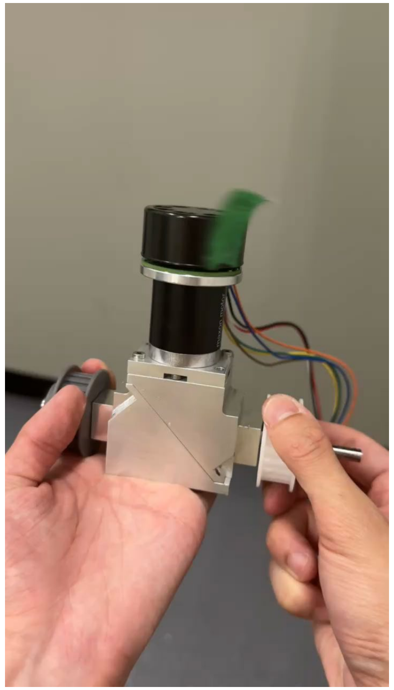
- HMMR combines **bi-directional** wave motion and **unidirectional** current motion into **one unidirectional** motion



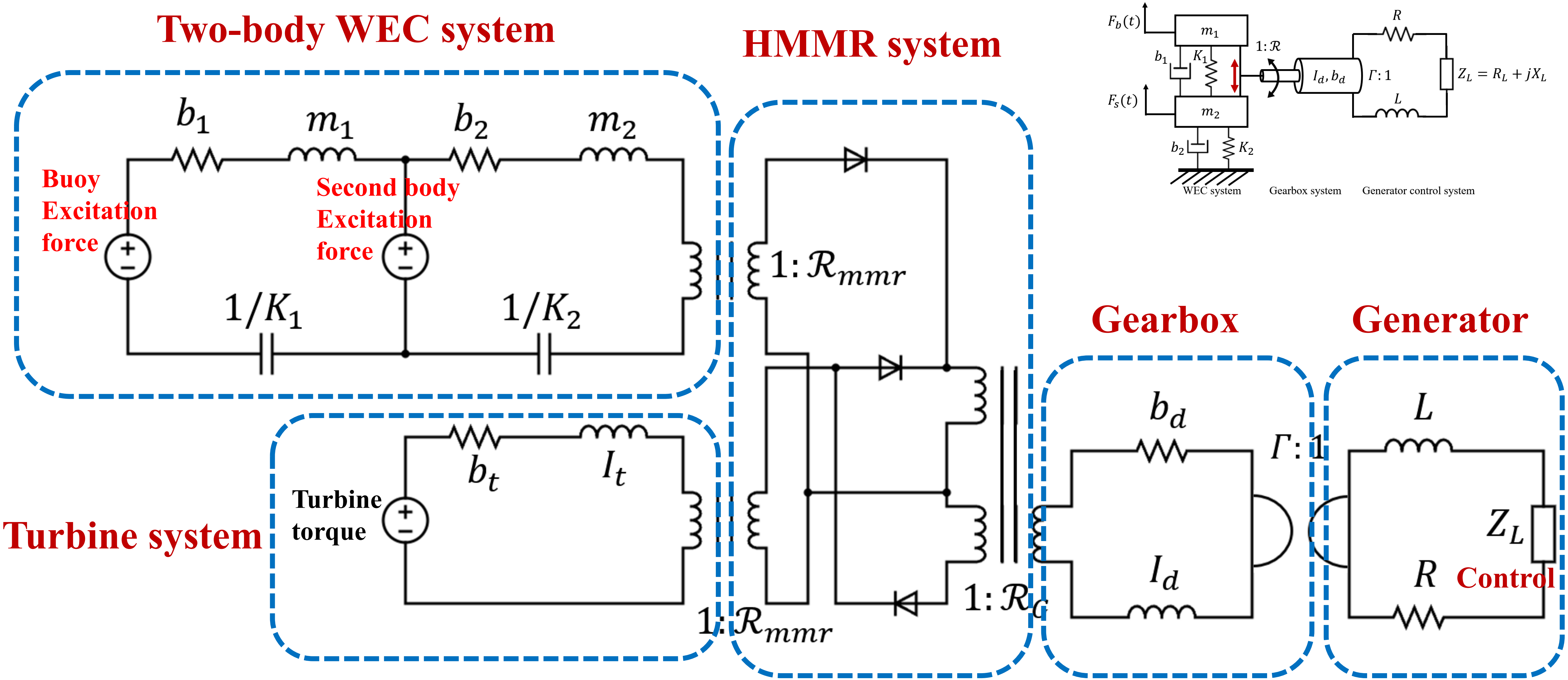








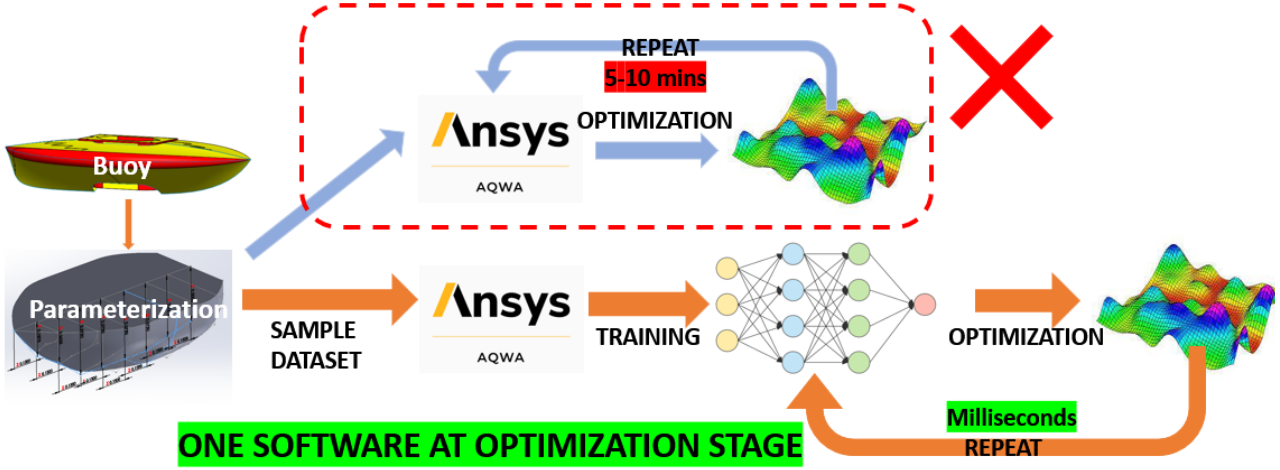
HWCEC Equivalent Circuit Model

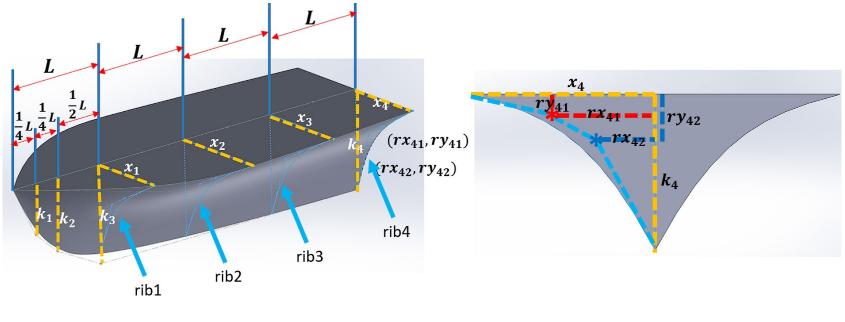


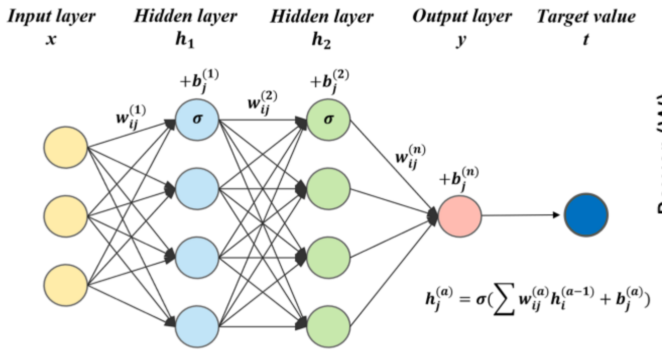
A framework of co-design and optimization of all components

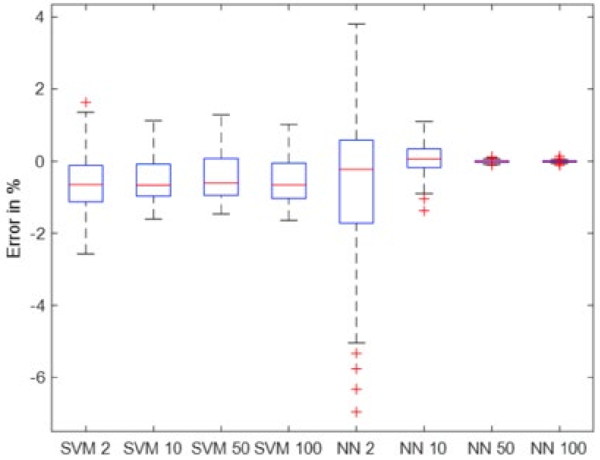
A Machine Learning Based Buoy Hull Optimization

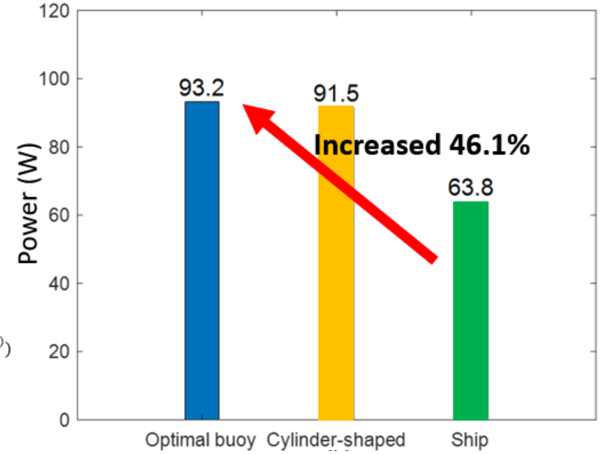
- We've built a **machine learning model** to simulate the **hydrodynamic parameters**, including added mass, radiation damping and excitation force, with error less than 1%
- Goal: find the optimal buoy hull that **maximize the wave energy** output and **minimize the current drag** force.
- This model **linked the buoy geometry with those hydrodynamic parameters**, and can be further combined with the HWCEC model for control co-design purpose.

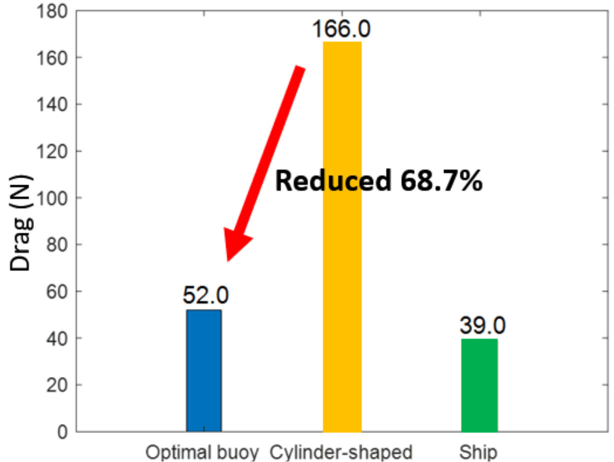












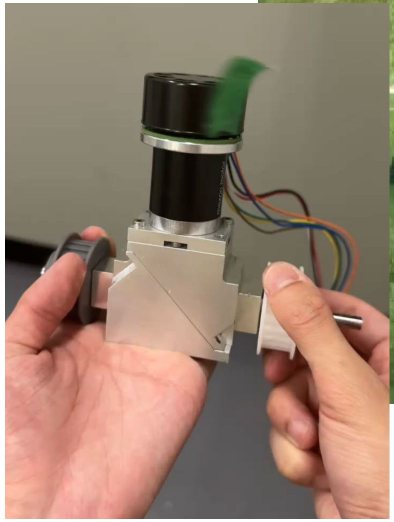
Lin, W., Li, X., & Zuo, L. (2024). IEEE Transactions on Sustainable Energy.

WEC-Sim Modeling of HWCEC with HMMR– Case Study

Case Study for H=0.1m, T=2s

Buoy mass = 25kg
Second body mass = 5.3kg
Pulley radius = 0.01756m
Gear ratio = 14:1
Lumped gear inertia = 3.1260e-6 kgm^2
Drivetrain inertia = 0.8e-7 kgm^2
Drivetrain friction = 3e-4 Nms/rad

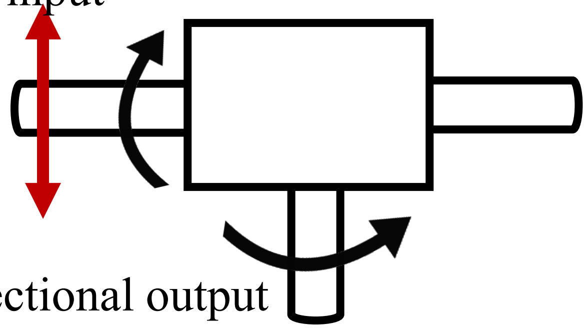
Generator:
Speed constant = 1/24.7 V/rpm
Torque constant = 0.0404 Nm/A
Internal resistance = 0.573 Ohm
Internal impendence = 0.3 mH
Rotor inertia = 1.81e-5 kgm^2



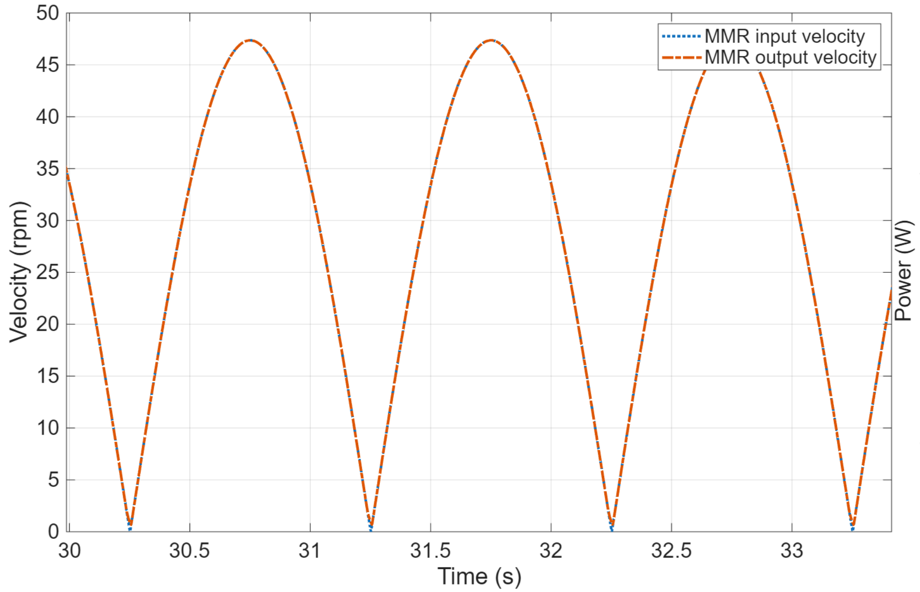
WEC-Sim Modeling of HWCEC with HMMR – Compared to Two-body WEC

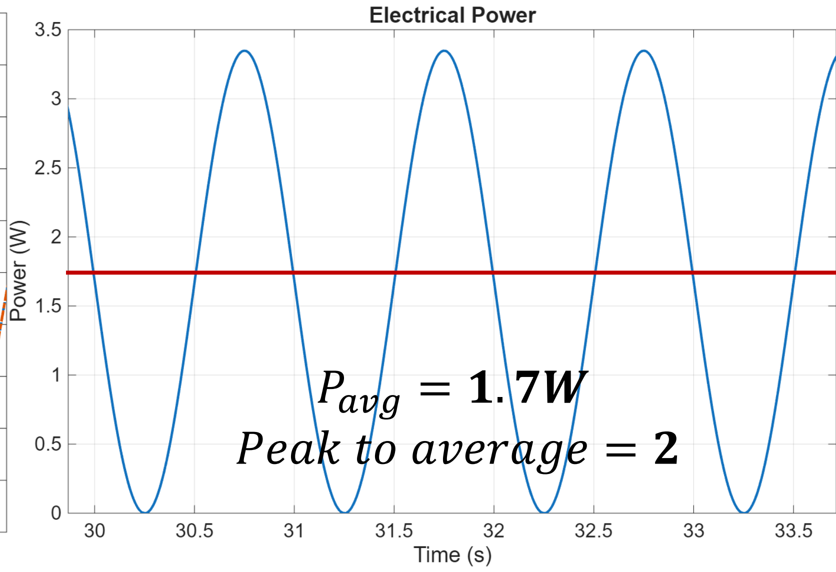
Two-body WEC with MMR: load 1 Ohm

Bi-directional wave input



unidirectional output



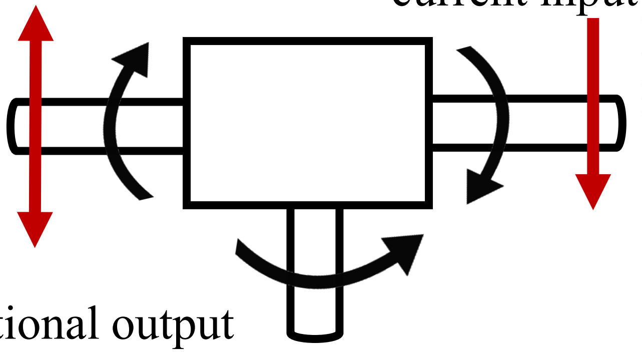


HWCEC: load 1 Ohm,

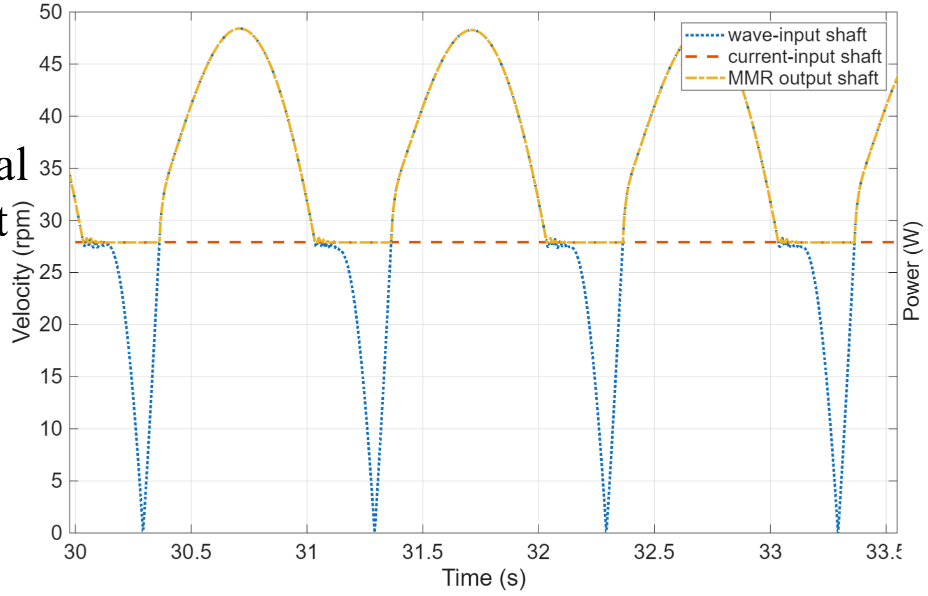
Current speed **0.75 m/s**

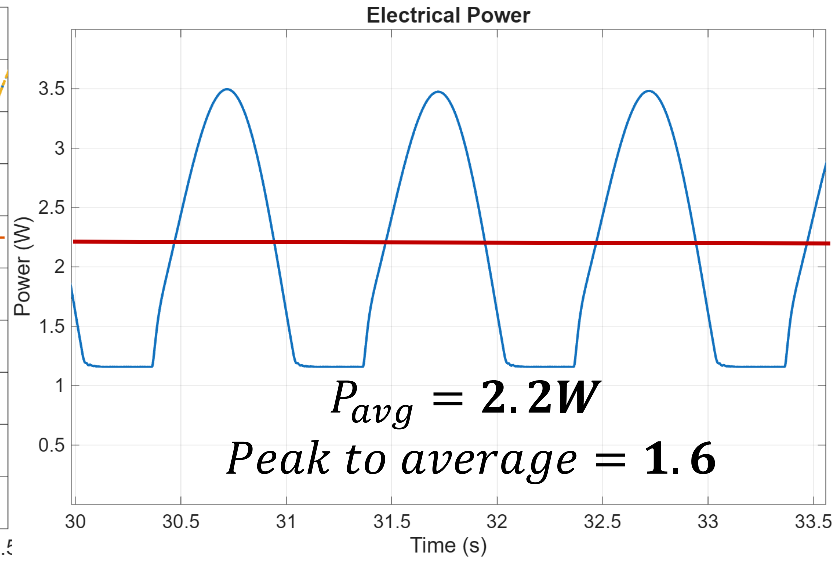
Bi-directional wave input

unidirectional current input



unidirectional output

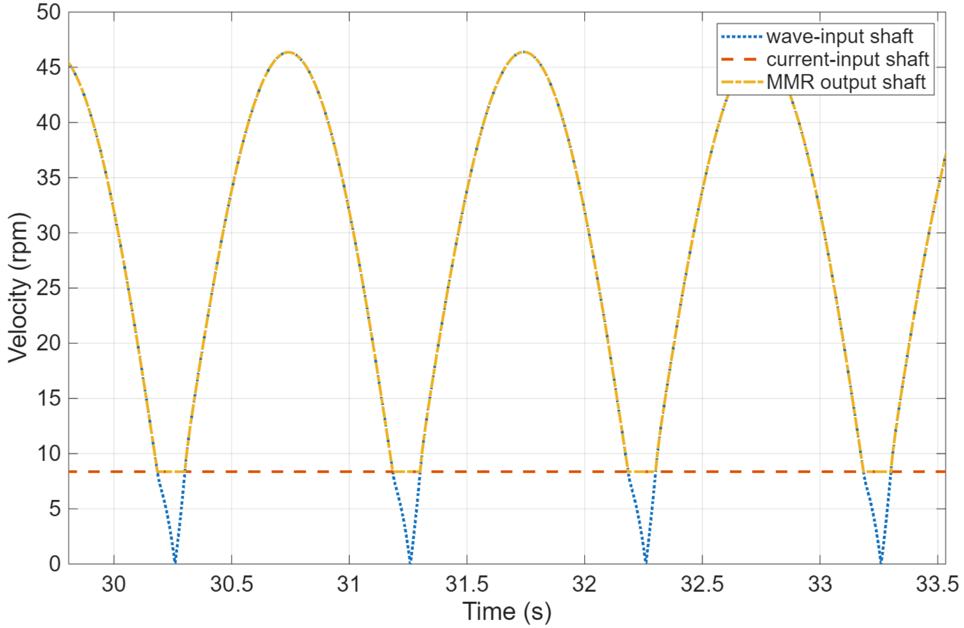


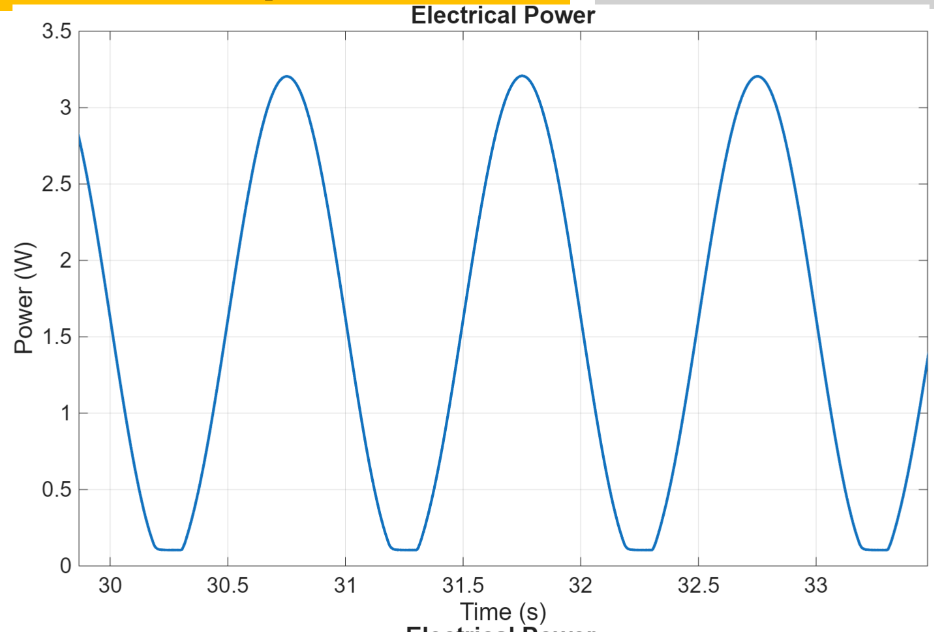


WEC-Sim Modeling of HWCEC with HMMR – Current Speed Study

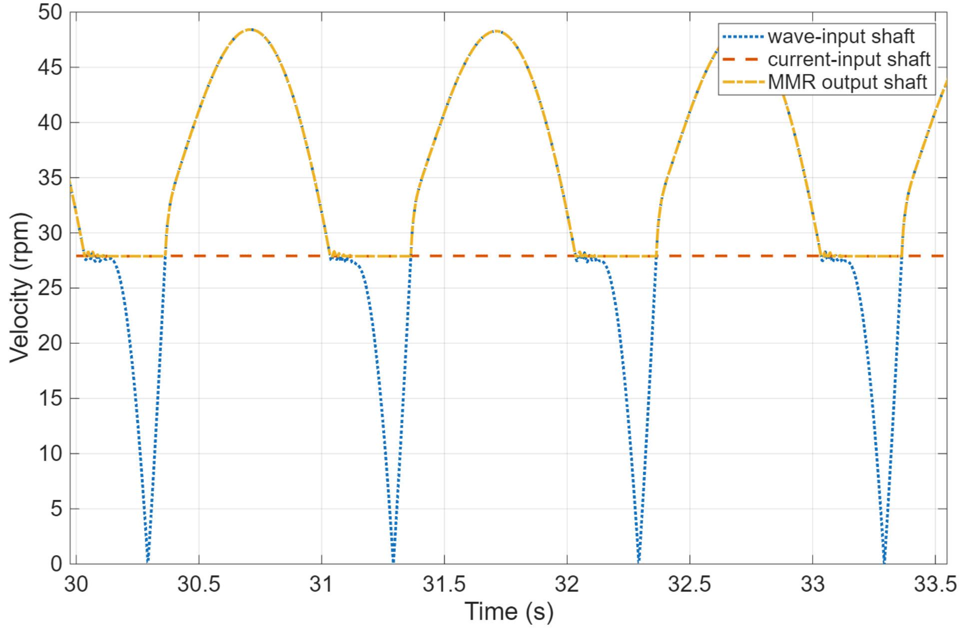
Different current speed

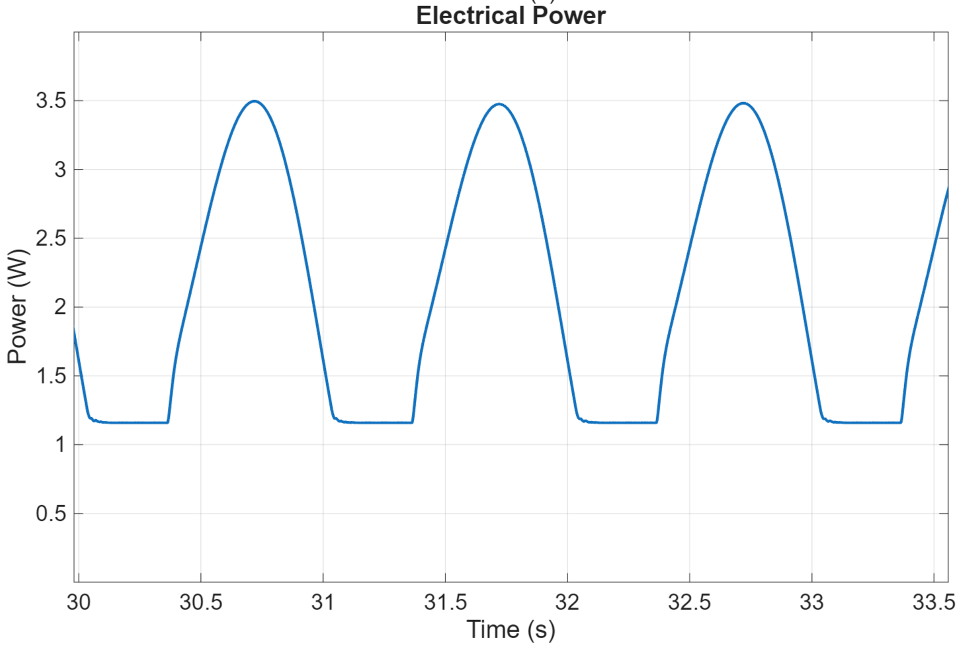
HWCEC
External load 1 Ohm:
Current speed **0.5 m/s**





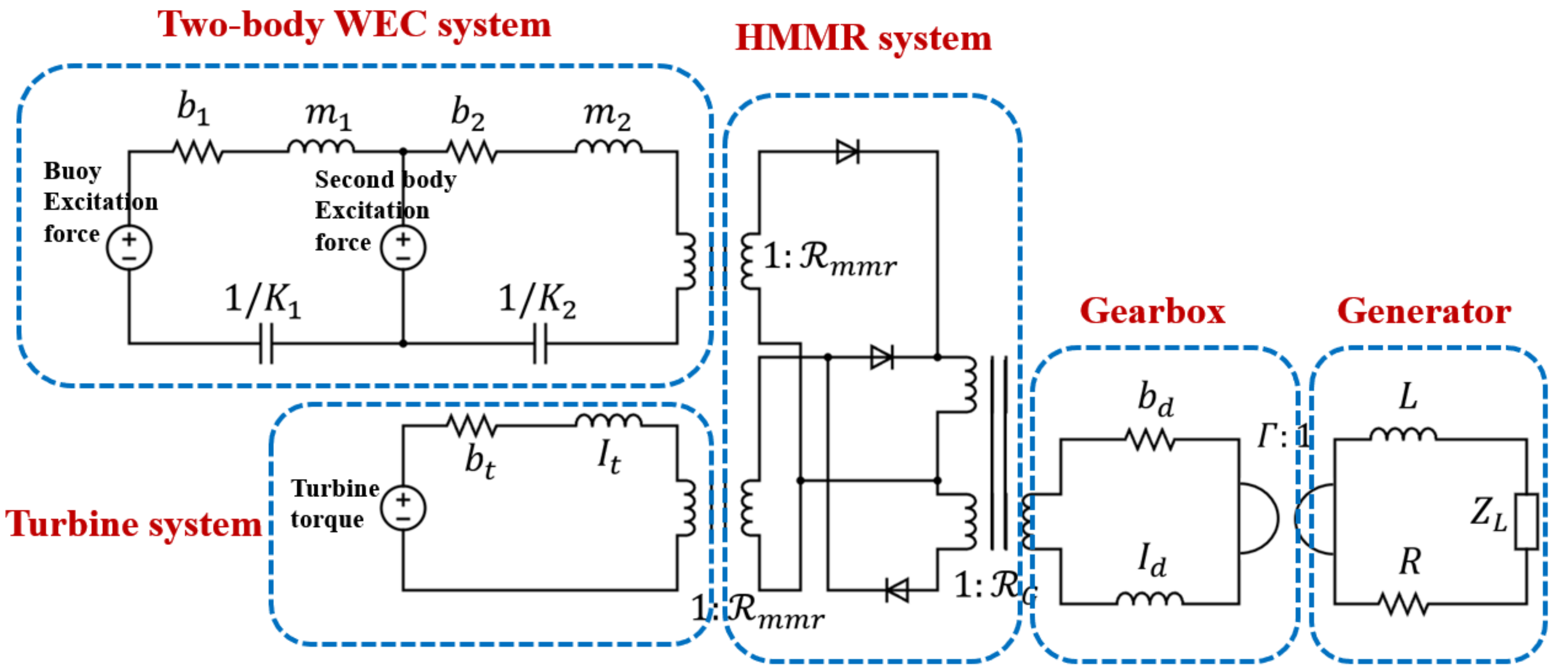
HWCEC
External load 1 Ohm:
Current speed **0.75 m/s**



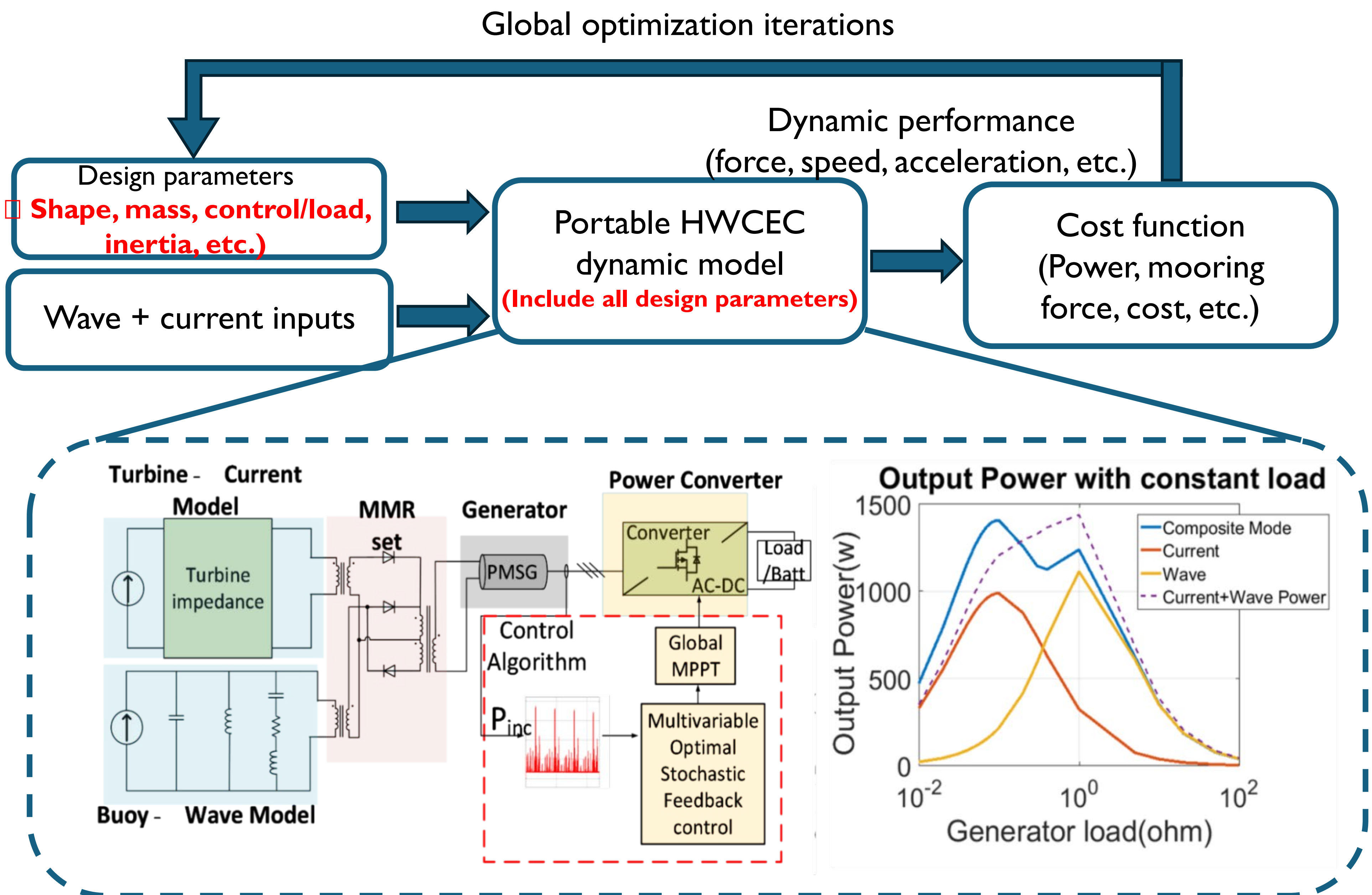


WEC-Sim Modeling of HWCEC with HMMR – On Going Work

- HWCEC can highly increase the bottom line of power generation, leading to a **higher average power** output and **smaller peak to average ratio**.
- Considering **electric load** and **flywheel inert**ia effects is our ongoing work
- We will conduct **control co-design** for the HWCEC system very soon.
- Modeling needs tank test for validation



Co-design and System Optimization

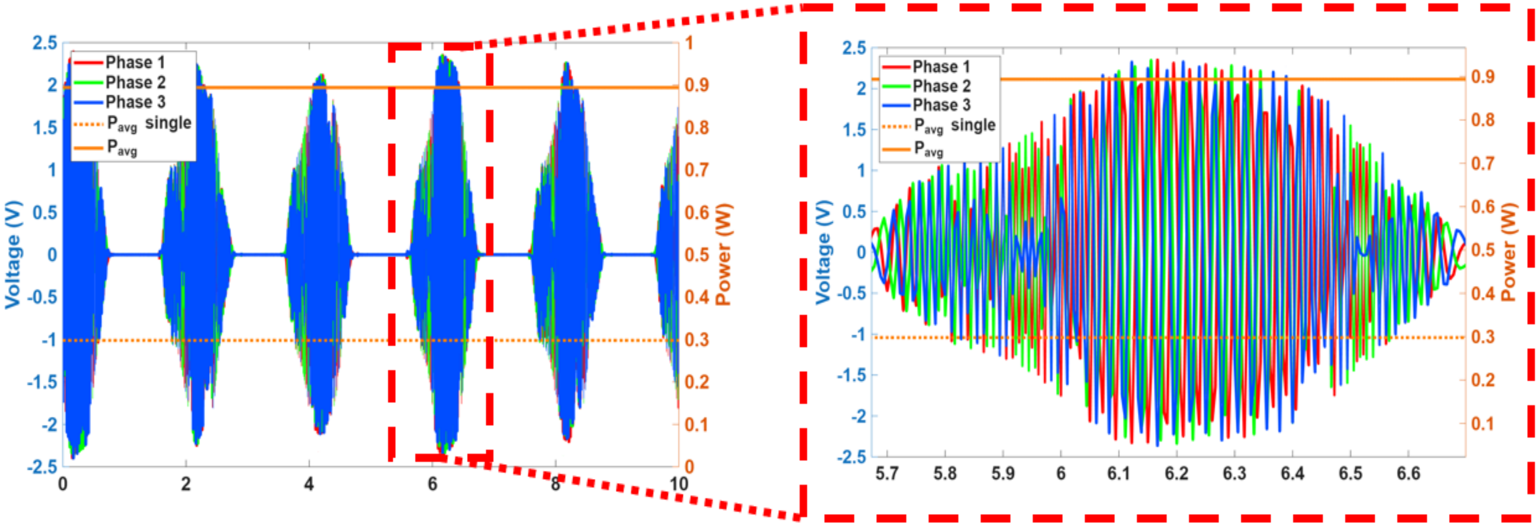


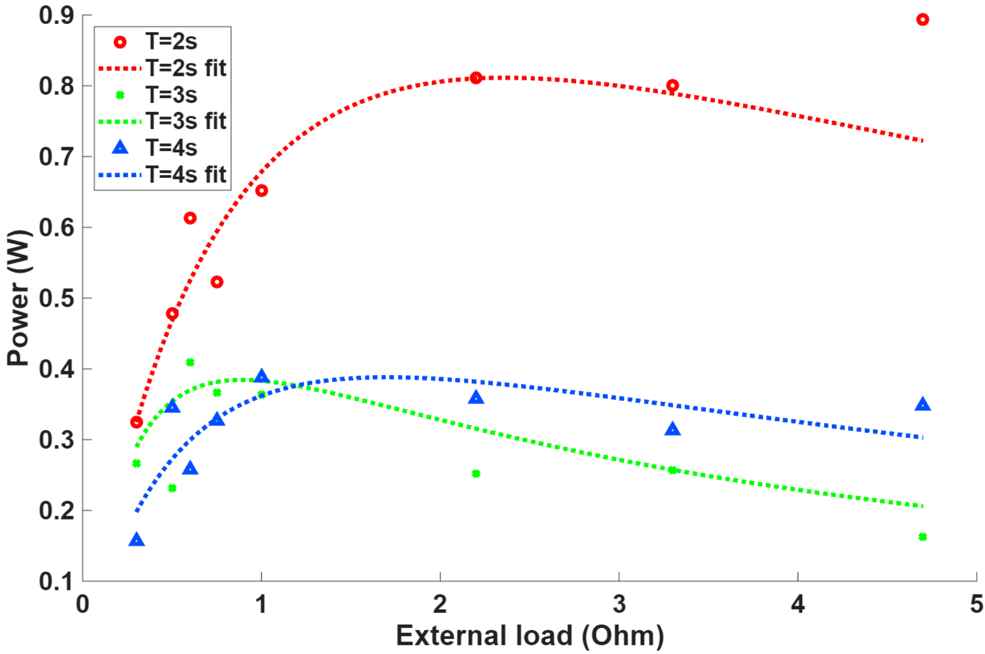
Preliminary Tank Test of HWCEC with HMMR

- **Tank test videos**

Preliminary Tank Test of HWCEC with HMMR

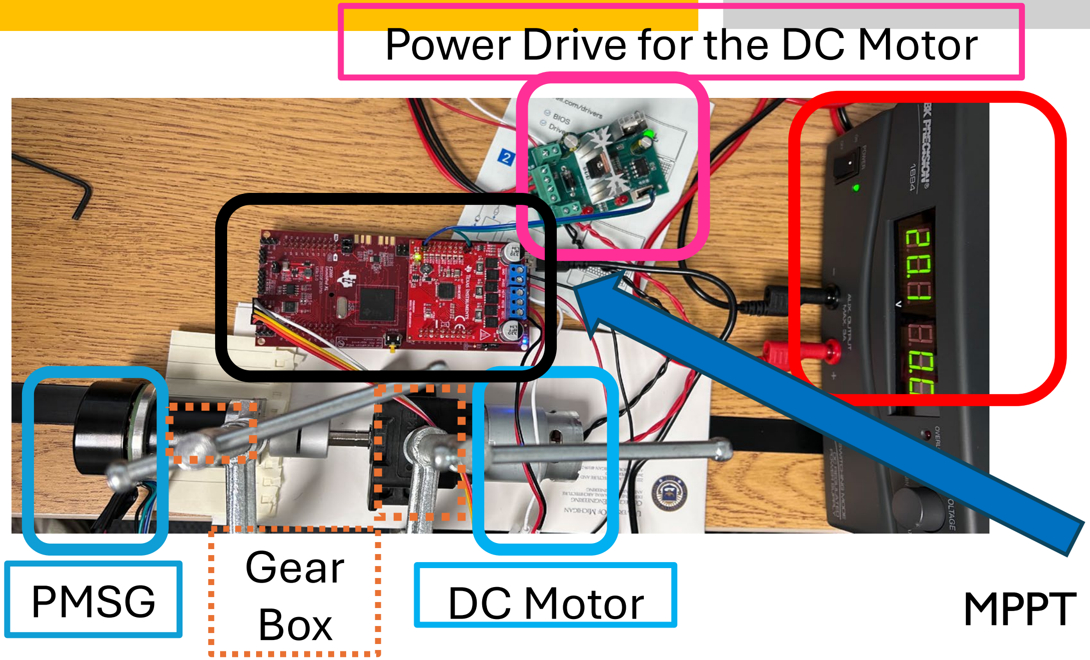
- Wave energy for H=0.1m, T=2 – 4sec is 10 – 20 W/m
- For small scaled system, wave to wire efficiency is less than10-30% because of friction
- Free-decay test is necessary to configure hydrodynamic parameters of the system
- However, due to unexpected damage on the one-way clutch, the friction was too large to complete the free-decay test.

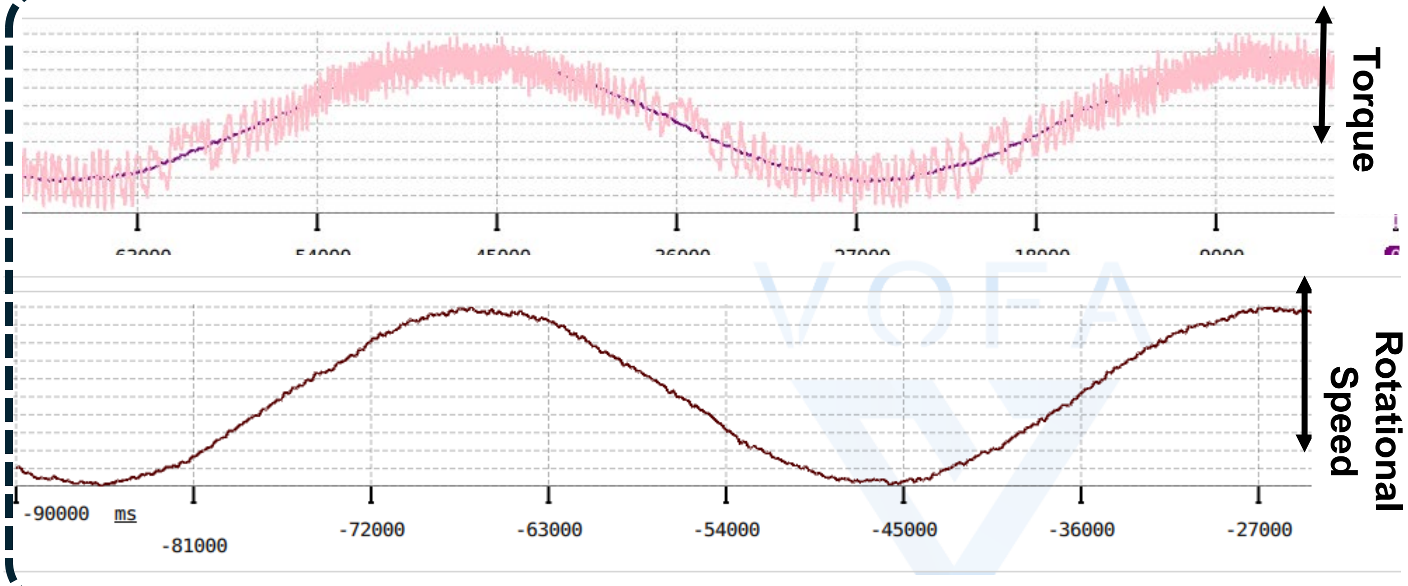


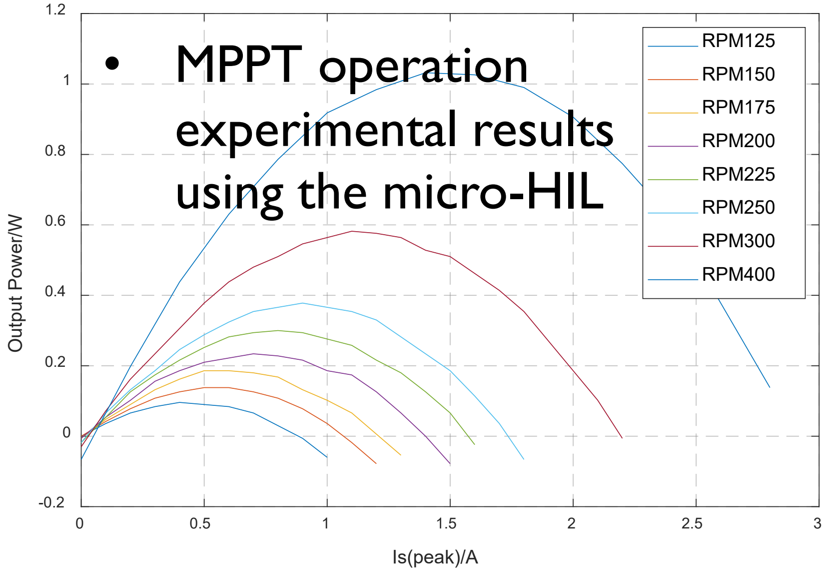


Electrical Subsystem

- MPPT has been done for wave inputs
- Next step:
  - Integrate current input
  - For both inputs
  - Tank tests



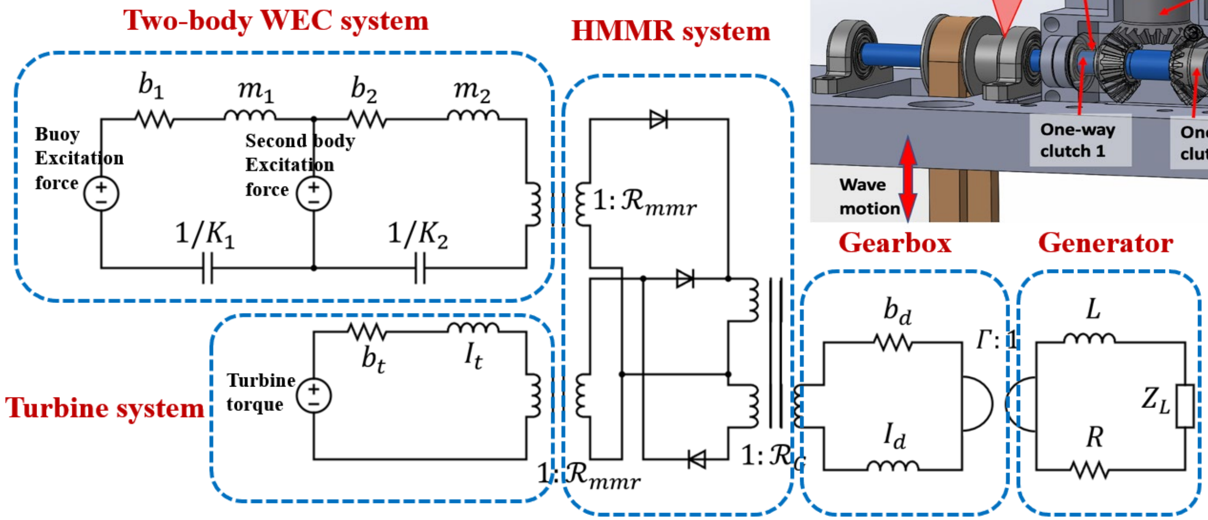


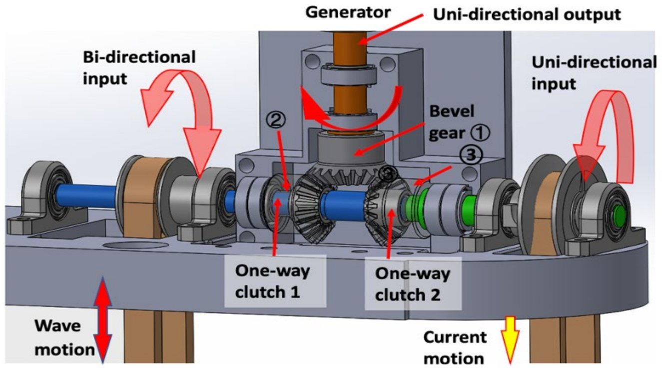


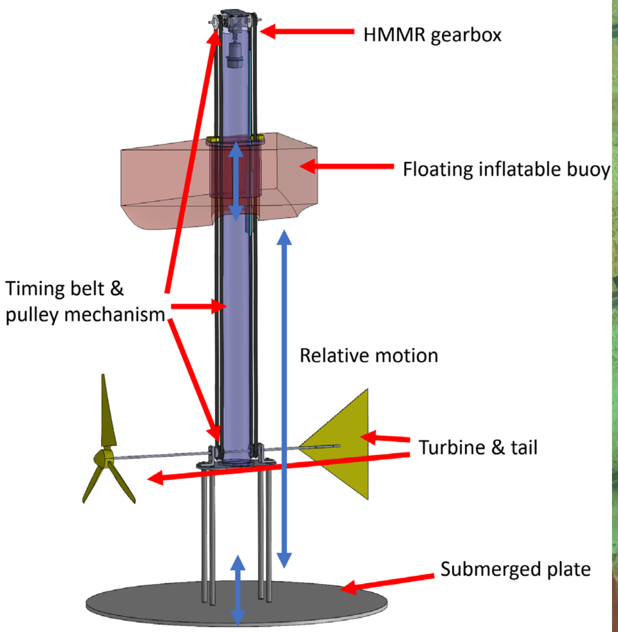
- MPPT operation experimental results using the micro-HIL

Conclusion

- We present **a comprehensive model** that accounts for the complex interactions among the various components of a HWCEC with HMMR, so that we can find the optimal solution by considering all parameters simultaneously.
- For the single-body and two-body WEC, we analytically solve for the **highest possible power** delivered to the load under regular waves.
- We further build a WEC-Sim Simulink model for HWCEC system with **case studies and preliminary tank test** validation.
- **Further validation of tank test** is necessary to calibrate the modeling parameters.
- **Control co-design** of the HWCEC system will be done in next couple months.







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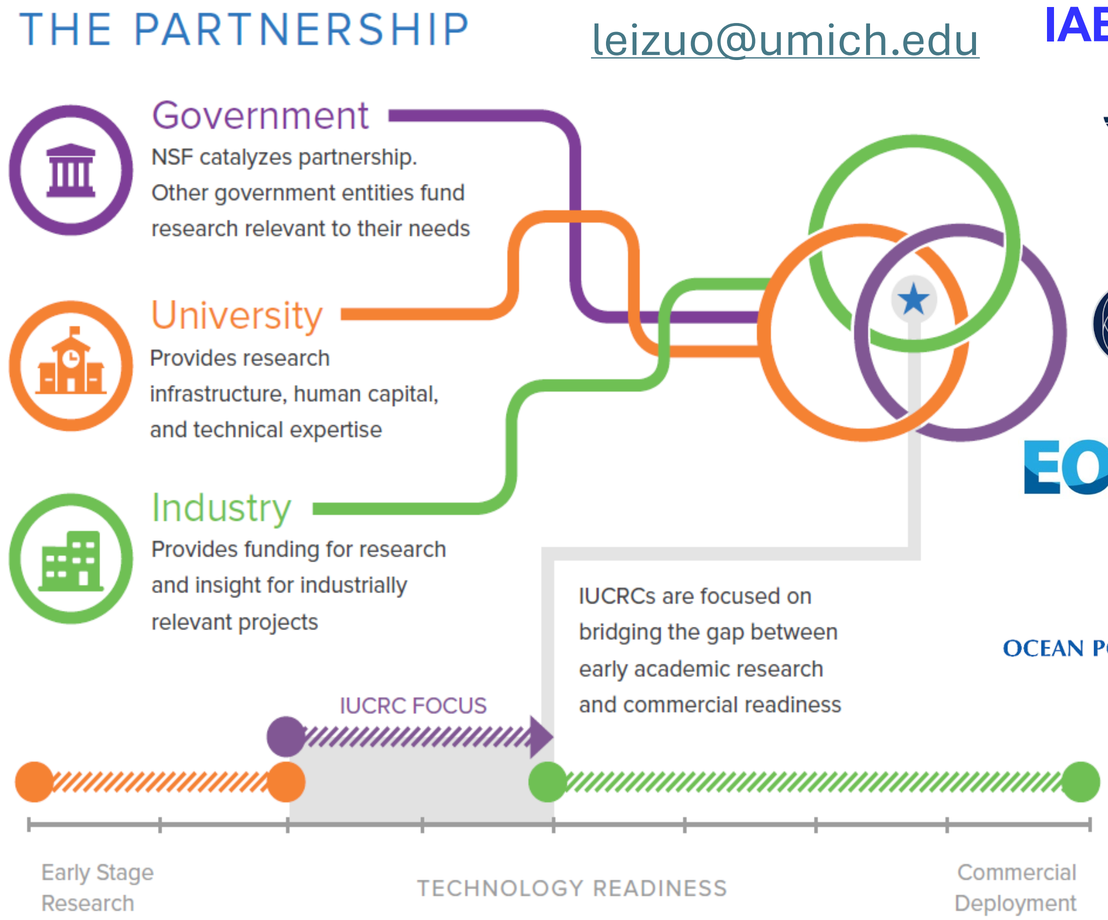

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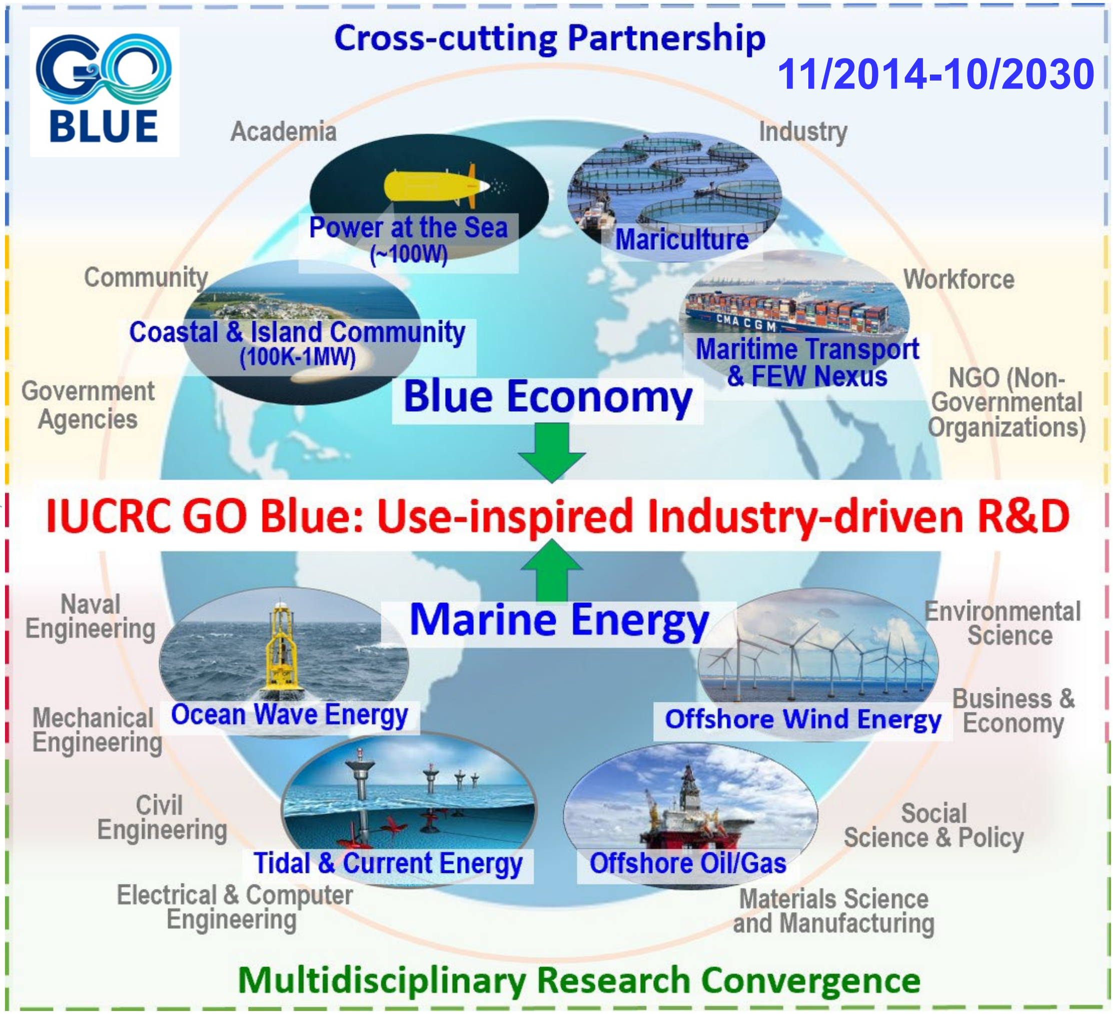

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