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Atlantic Marine Energy Center

Control Framework Design for WECs with Direct Drive Linear Generator-Based Power Take Off Systems

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OUTLINE

- Motivation

- Multi Level Control framework for Wave Energy Converter (WEC)

- WEC and Permanent Magner Linear Synchronous Generator (PMLSG) Model

- Sliding Mode Control Formulation

- Simulation Setup

- Simulation Results

- Conclusion and Future Works

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MOTIVATION

- **Higher Power Density,** Reliable , Forecastable and minimal environmental impact compared to wind and solar.

- Advanced control strategies for the WECS can **increase energy absorption** compared to **passive** or **non-optimized** systems

- By adapting to constantly changing wave conditions, control systems **extract more energy per wave**, maximizing efficiency over time.

- Higher energy capture leads to **lower LCOE**, making wave energy more competitive with other renewable sources

Effect of Advanced Control on WEC Energy Absorption
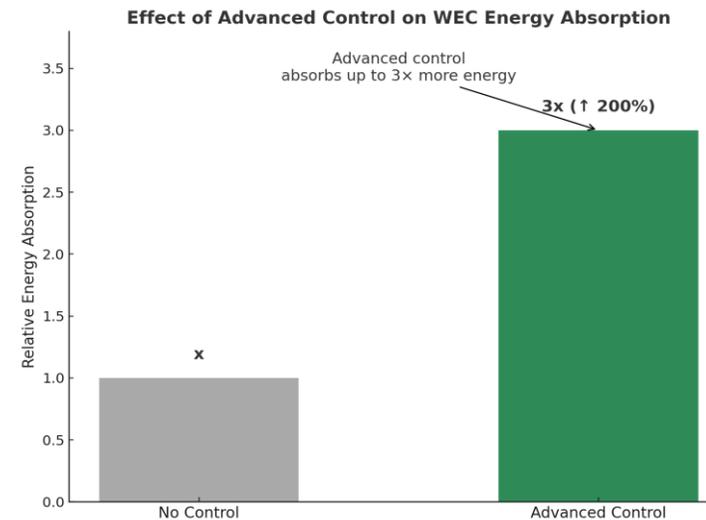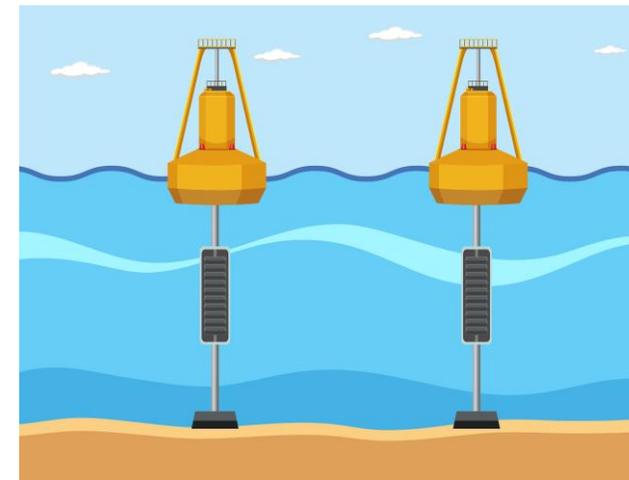
WEC Multi level control framework

- **Wave Energy Absorption (first Stage)**
  - The buoy converts ocean wave motion into mechanical energy.
  - Control is required to optimize energy capture efficiency based on sea conditions
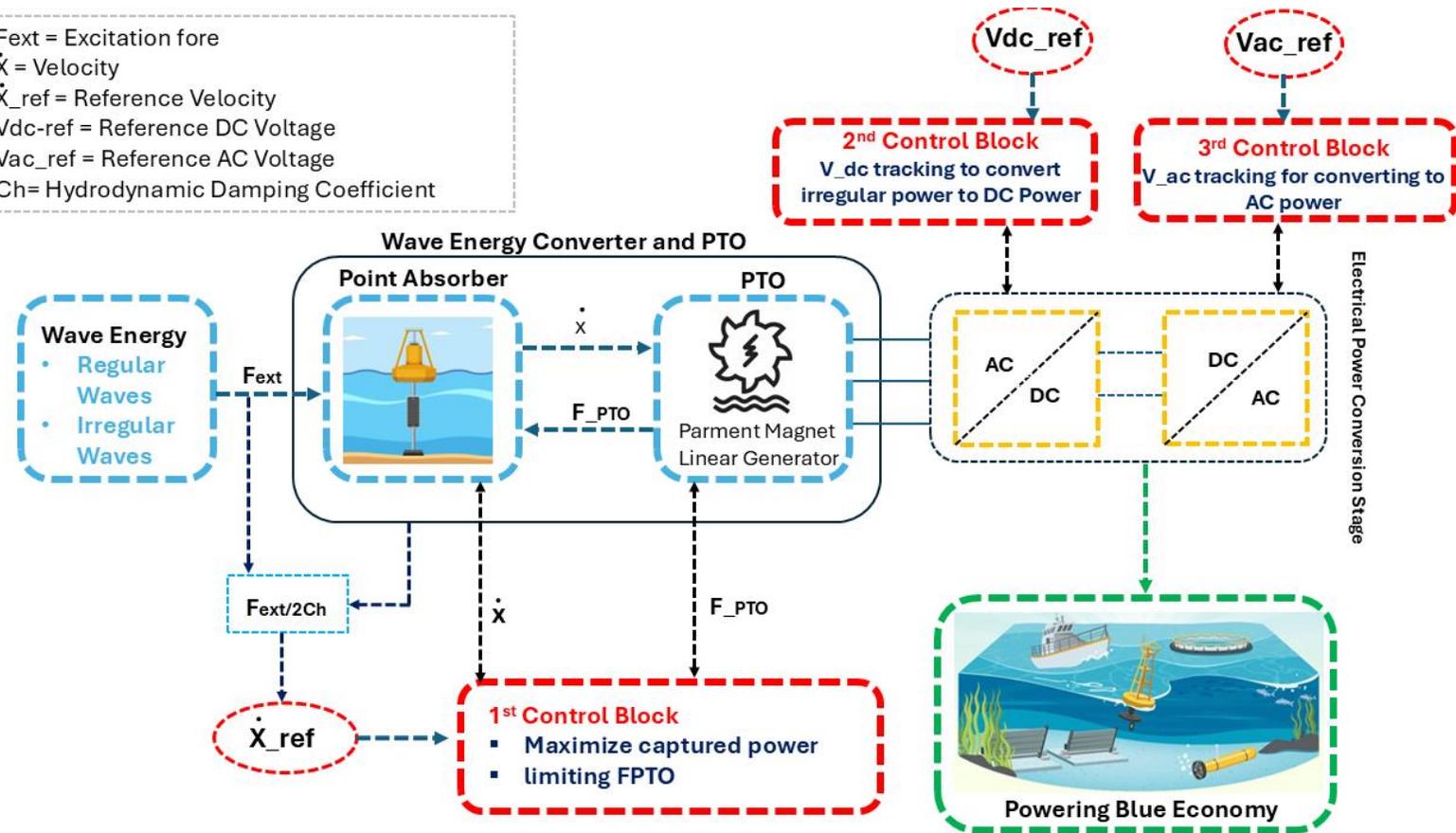 - PTO converts captured mechanical energy into Electrical Energy
- **Direct Current (DC) Stage (second stage)**
  - Irregular and Raw power is converted to DC, by DC voltage Tracking
- **Grid Integration and PBE (Third Stage)**
  - This stage converters DC to AC for grid integration and to convert to suitable power for PBE Application.

Fext = Excitation fore
$\dot{X}$ = Velocity
$\dot{X}$_ref = Reference Velocity
Vdc-ref = Reference DC Voltage
Vac-ref = Reference AC Voltage
Ch= Hydrodynamic Damping Coefficient

Vdc_ref   Vac_ref

2ⁿᵈ Control Block
V_dc tracking to convert irregular power to DC Power

3ʳᵈ Control Block
V_ac tracking for converting to AC power

Wave Energy Converter and PTO

Point Absorber   PTO

Wave Energy
- Regular Waves
- Irregular Waves

Fext

Parment Magnet Linear Generator

Electrical Power Conversion Stage

AC / DC   DC / AC

Fext/2Ch

$\dot{X}$ F_PTO

$\dot{X}$_ref

1ˢᵗ Control Block
- Maximize captured power
- limiting FPTO

Powering Blue Economy

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WEC and Permanent Magnet Linear Synchronous generator (PMLSG)

WEC Model:

F_e = Excitation Force [N], F_D = Diffraction Force [N], u = Control Force [N]

F_{FKdy} = Froude– Krylov Hydro Dynamic Force [N]

F_{FKst} = Froude– Krylov Hydro Static Force [N]

F_{hs} = Hydrostatic Restoring Force [N]

F_r = Radiation Force approximated by using sate space model[N]

C= Damping Coefficient [Ns/m]

PMLSG Model:
K_E = Generator Constant [Vs/m]
scales the velocity-to-voltage transformation
z = translator displacement [m]
v(t) = instantaneous velocity of translator [m/s]

Heave dynamics of a single degree of freedom (DOF) point absorber

$$x_1 = \text{displacement}, \quad x_2 = \dot{x}_1 = \text{velocity}$$
$$\dot{x}_2 = \ddot{x}_1 = \frac{1}{M}(F_e - F_r - F_{hs} - u)$$
$$F_e = F_{FKdy} + F_{FKst}$$
$$x_{2\text{ref}} = \frac{F_e}{2C}$$
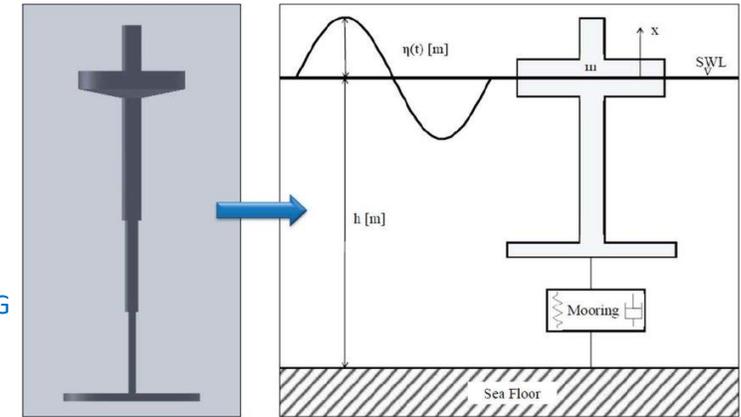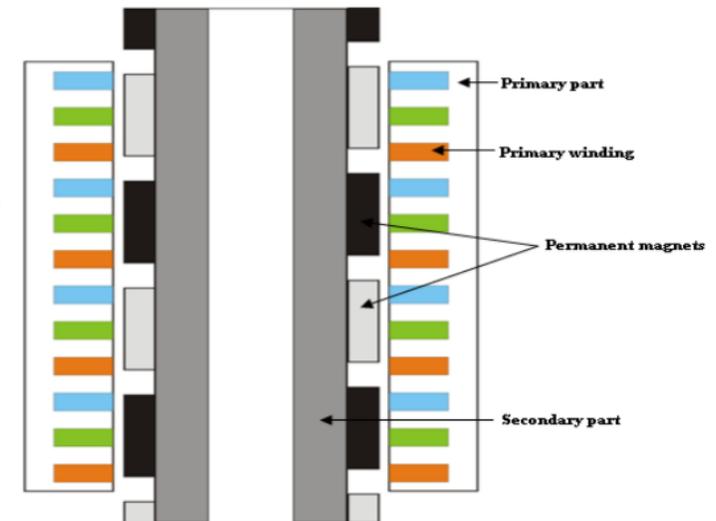
Model the EMF generated in each of the three phases in PMLSG

$$e_1 = K_E * \cos\left(\left(\frac{\pi}{\tau}\right) * z\right) * v(t)$$
$$e_2 = K_E * \cos\left(\left(\frac{\pi}{\tau} - \frac{2\pi}{3}\right) * z\right) * v(t)$$
$$e_3 = K_E * \cos\left(\left(\frac{\pi}{\tau} - \frac{4\pi}{3}\right) * z\right) * v(t)$$

Differential equations describe the rate of change of current in each phase

$$\frac{d}{dt} i_1 = \frac{(e_1 - v_1 - i_1 * R_a)}{L_s}$$
$$\frac{d}{dt} i_2 = \frac{(e_2 - v_2 - i_2 * R_a)}{L_s}$$
$$\frac{d}{dt} i_3 = \frac{(e_3 - v_3 - i_3 * R_a)}{L_s}$$

PMLSG

Figure WEC: Neely, Jason. (2013). Electromechanical emulation of hydrokinetic generators for renewable energy research.

Niu, Xin. "Modeling and design analysis of a permanent magnet linear synchronous generator." (2013).

Zou, S., Song, J., & Abdelkhalik, O. (2023). A sliding mode control for wave energy converters in presence of unknown noise and nonlinearities. *Renewable Energy*, *202*, 432-441.

Sliding Mode Control Formulation

- **Sliding Mode Control (SMC)** is a nonlinear control method that forces the system state to reach and stay on a predefined surface (called the *sliding surface*) in the state space.
- Once on this surface, the system dynamics become insensitive to disturbances and uncertainties
- RM is reaching mode
- SM is sliding mode

Model of WEC

$$\dot{x}_2 = \ddot{x}_1 = \frac{1}{M}(F_e - F_r - F_{hs} - u)$$

$$x_{2\text{ref}} = \frac{F_e}{2C}$$

Defining Error:

$$e = x_2 - x_{2\text{ref}}$$

$$\dot{e} = \dot{x}_2 - \dot{x}_{2\text{ref}}$$

Defining sliding Surface:

$$s = ae = a(x_2 - x_{2\text{ref}})$$

$$\dot{s} = a\dot{e}$$

$$\dot{s} = a\left[\frac{1}{m}(F_{\text{ext}} + F_r - u) - \dot{x}_{2\text{ref}}\right]$$
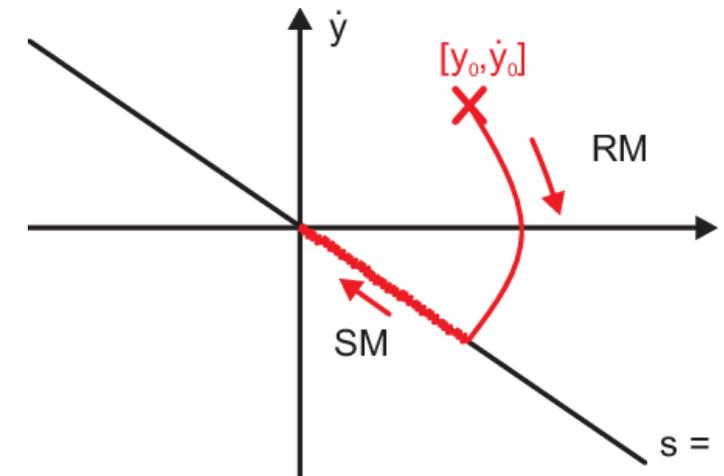
$$\dot{s} = -l\,\text{sgn}(s)$$

Control Law

$$u = F_e - F_r - F_{hs} - m\left(\dot{x}_{2ref} - \frac{l}{a}\,\text{sign}(s)\right)$$

Applying Control Force Limit

$$|u| = F_e - F_r - F_{hs} - m\left(\dot{x}_{2ref} - \frac{l}{a}\,\text{sign}(s)\right)$$

Control force Limit (CFL) = –4e5 [N] to 4e5 [N]

Dannehl, J., & Fuchs, F. W. (2009, September). Discrete sliding mode current control of three-phase grid-connected PWM converters. In *2009 13th European Conference on Power Electronics and Applications* (pp. 1-10). IEEE.
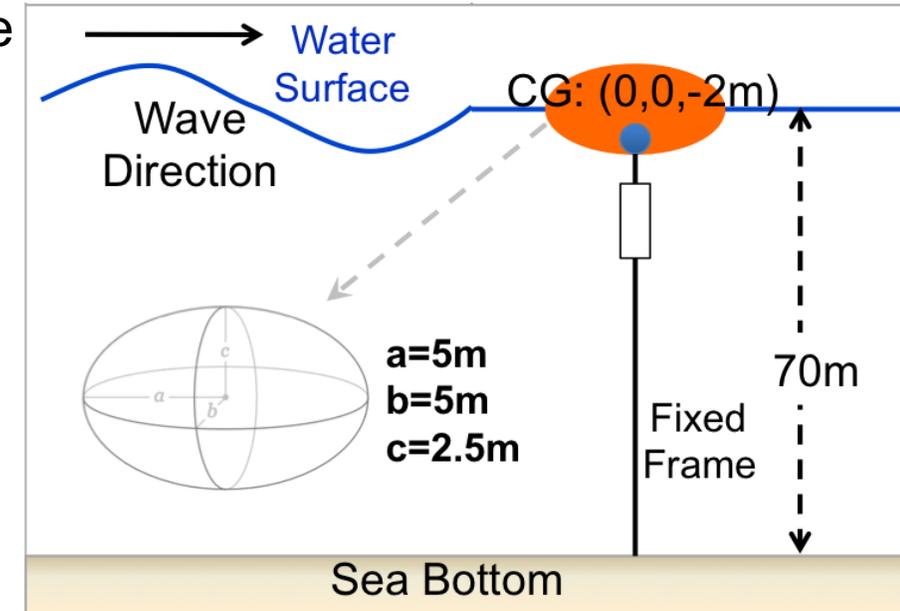
Simulation Setup

- **Simulation Setup:**

  MATLAB/Simulink WECSIM

Details of Simulation

- Benchmarking SMC with PI
- Elipsoid buoy: Dimensions [m] in figure
- Wave Type: Regular
- Forces: Nonlinear
- Times Step = 0.01[s]
- Wave Perio= 6 [s]
- Wave height= 0.822 [m]
- Simulation time = 350 [s]
- With quadratic drag
- With and Without Control Force Limit
- Control force Limit (CFL) = -4e5 [N] to 4e5 [N]

Simulation Results

- **Absorbed Energy:**

- It can be observed the Control Force Limit (CFL) did not impact the energy absorbed.

- Energy absorbed is11.2 [MJ] in case PI and 12.4 [MJ] in case of SMC.
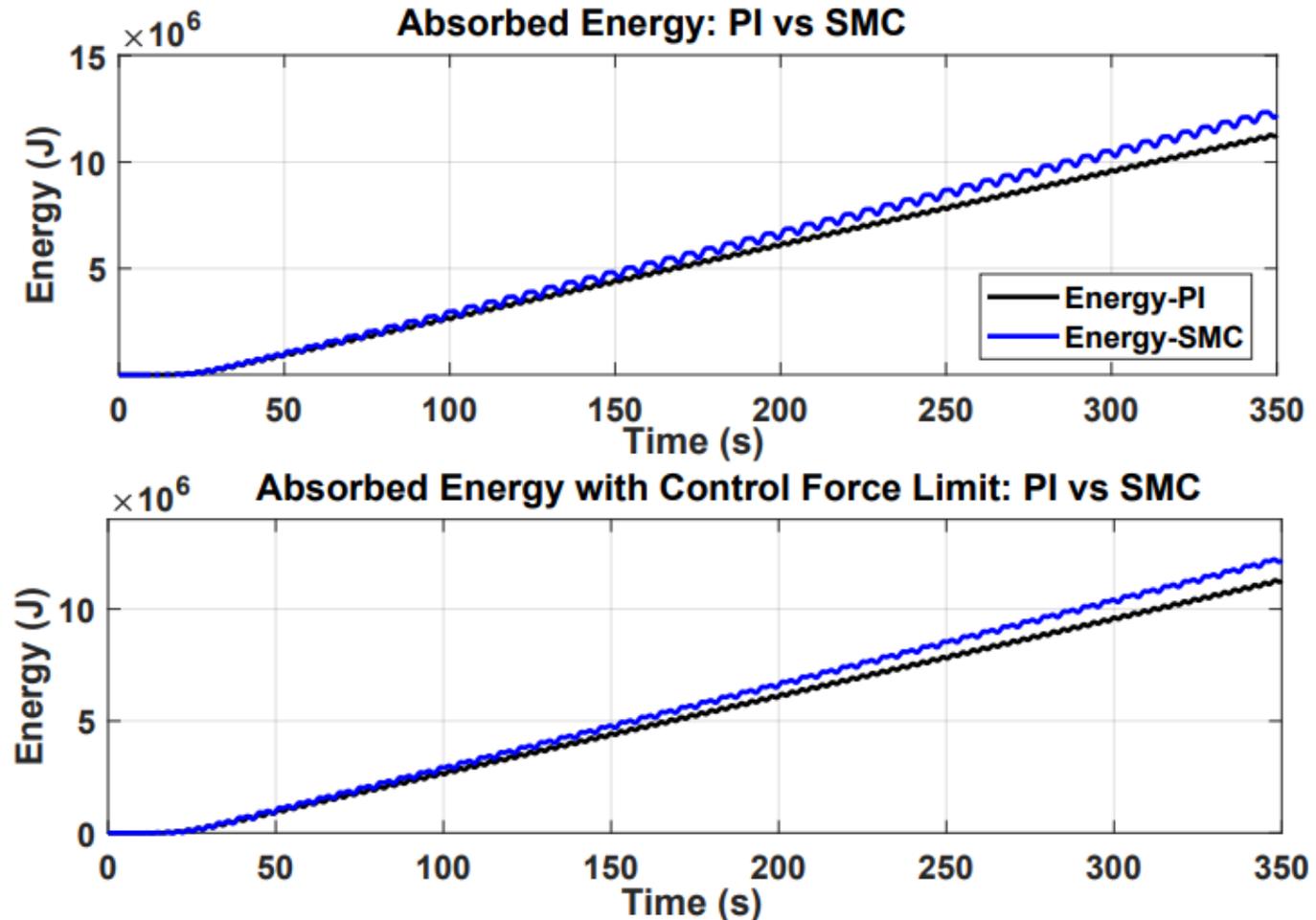
Figure: Comparison of Harvested Energy using PI and SMC with and without Control Force Limit

Simulation Results

- **Velocity Tracking:**

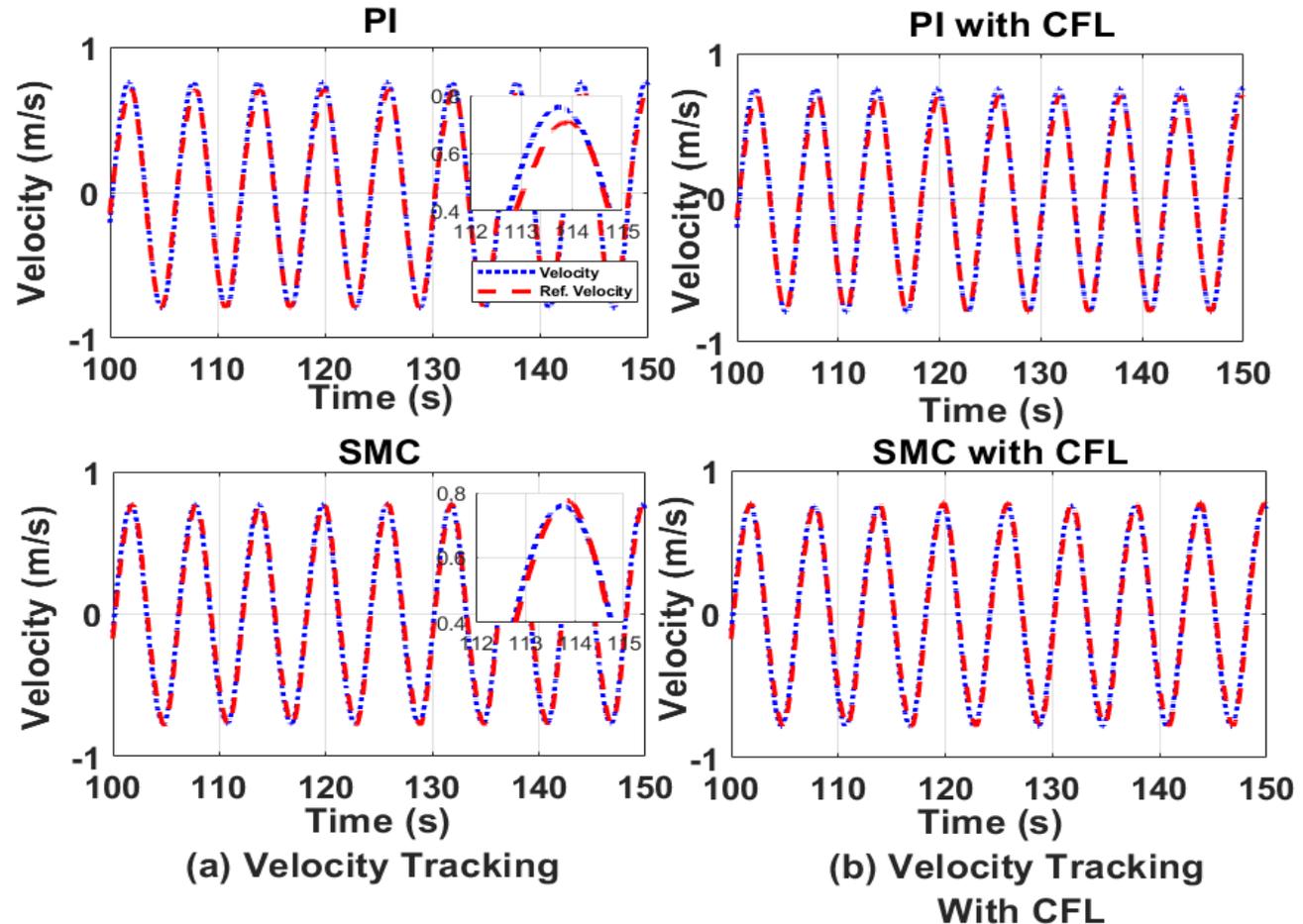- Better performance of SMC can be observed, Where SMC tracks reference velocity better than PI

Figure: Comparison of Reference Velocity Tracking using PI and SMC with and without Control Force Limit

Simulation Results

- **Control Force:**

- Figure shows the control force comparison where chattering phenomena can be observed in case of SMC due to signum function and nonlinearity and magnitude of control force is slightly higher than PI, when control force limit is applied, SMC hits the Control force limit
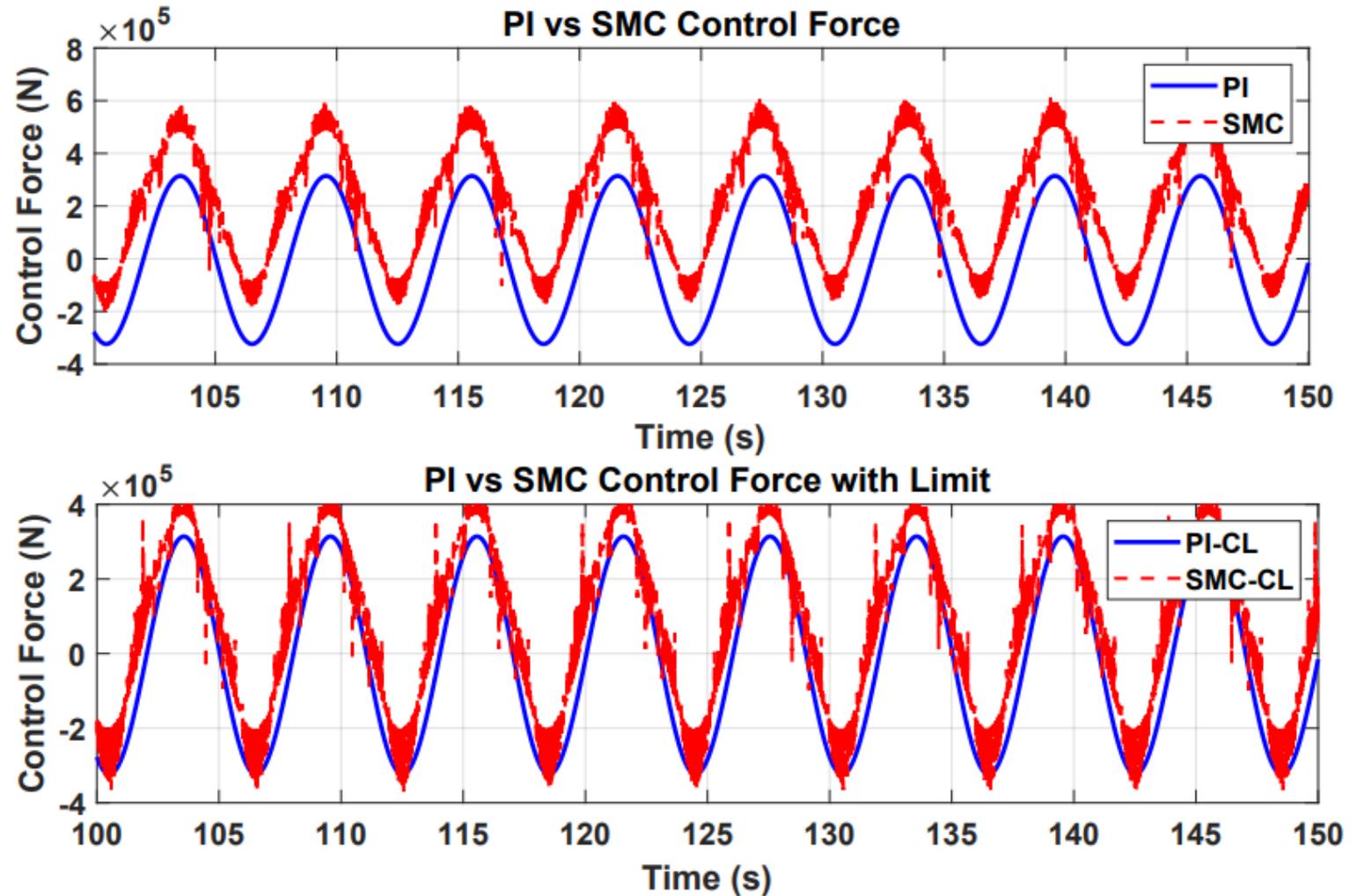

Figure : Comparison of Control Force using PI and SMC with and without Control Force Limit

Simulation Results

- **Heave:**

- The SMC exhibits slightly higher heave than PI due to the influence of the control force. Control force limit reduces the offset in the SMC response but also helps regulate the buoy's heave motion.

- Notably, potential stroke issues can be mitigated by applying an appropriate Control force limit

- Stroke is the maximum relative motion allowed between a WEC's buoy and its reference structure.

- Beyond which damage or efficiency loss can occur. Managing stroke is critical to ensure safe, efficient, and controlled energy extraction, especially under large wave conditions.
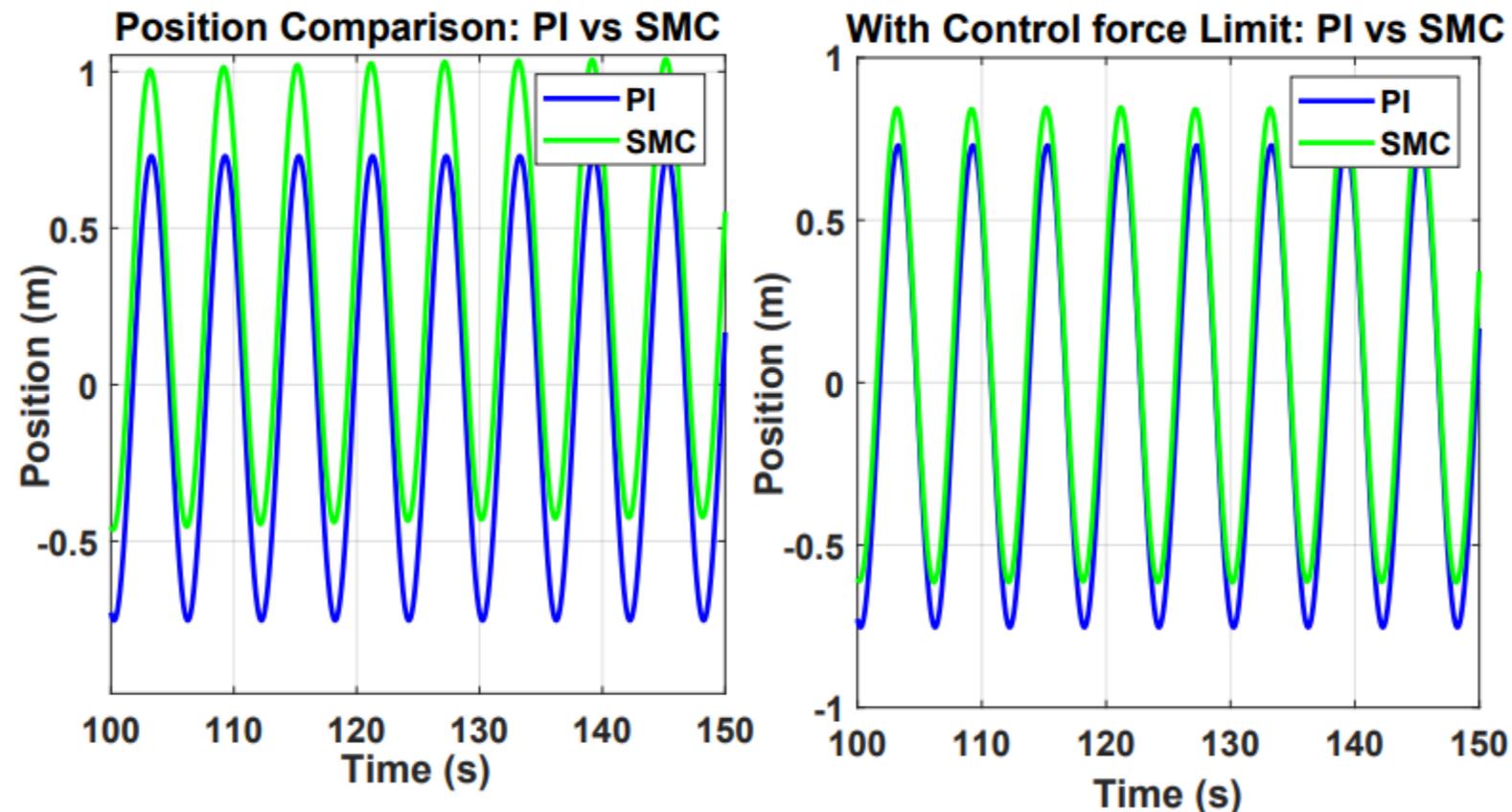

Figure: Comparison of Heave using PI and SMC with and without CFL

Simulation Results

- **Generated Power:**

- Figure shows the current waveforms i1, i2, and i3, demonstrating balanced three-phase sinusoidal behavior under regular wave excitation. The consistent amplitudes indicate stable generator operation

- The currents are presented for one period of regular waves, illustrating the system's power output scaled to a single period under regular and linear model conditions.
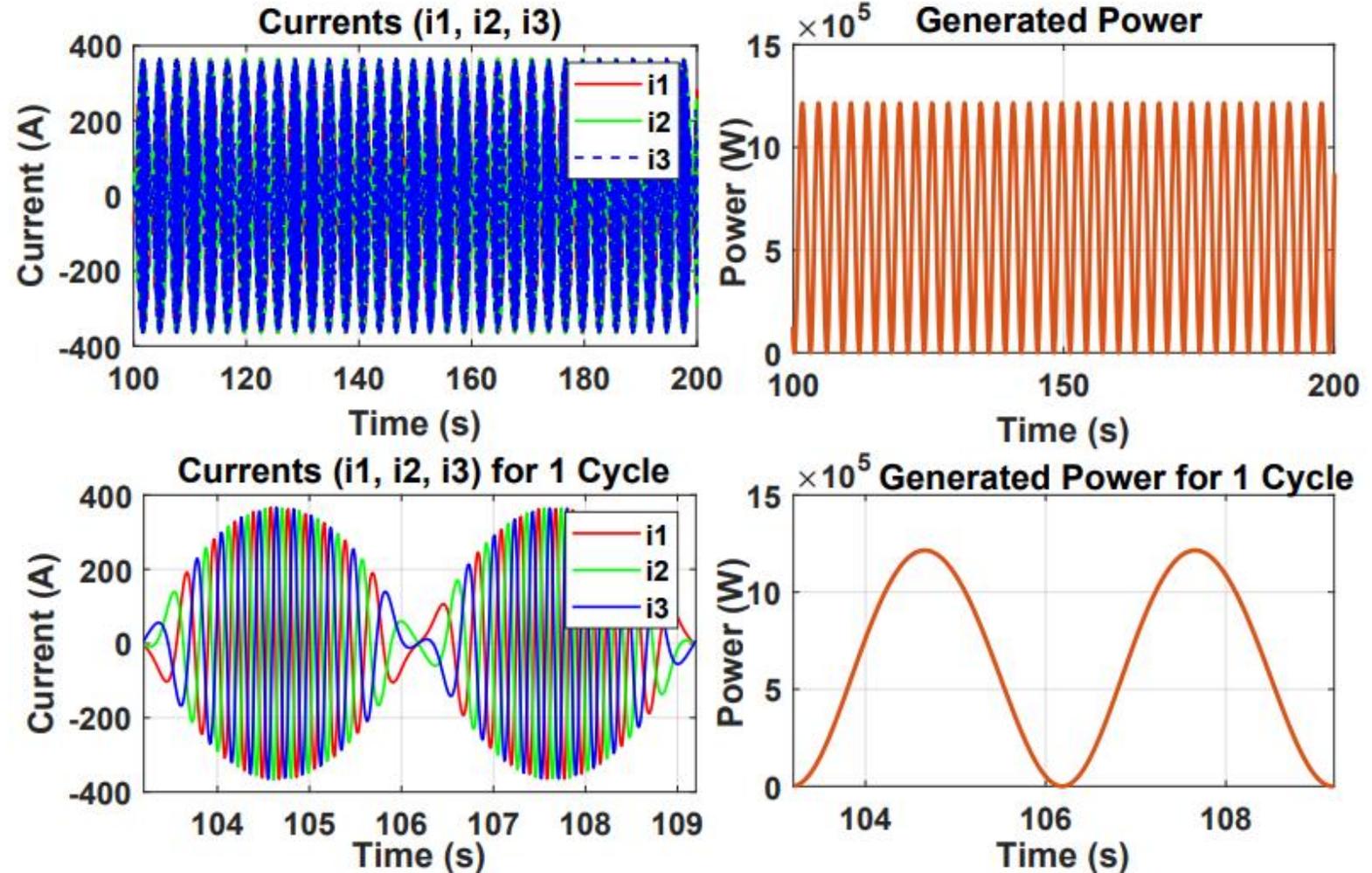
Figure: Generated Power from PMLSG using linear waves and linear forces

Conclusion

- System Setup: A nonlinear wave energy conversion (WEC) system was modeled and simulated using WEC-Sim. Used an ellipsoidal buoy model and a Permanent Magnet Linear Synchronous Generator (PMLSG) model.

- Control Approaches Compared: Sliding Mode Control (SMC) Proportional-Integral (PI) Control

- Performance Outcomes :Energy Absorption: SMC: 12.4 MJPI: 11.2 MJ SMC absorbed ~9.7% more energy

- Velocity Tracking :SMC: Accurate reference tracking PI: Tracking errors observed

- Stable generator operation with clean, balanced three-phase sinusoidal currents has been observed in linear case.

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Future work

- Designing Optimal Velocity Profiles:

  Develop velocity trajectories that maximize energy absorption while maintaining safe and efficient PTO operation.

- Incorporating Electromagnetic Force in the Model:
  Integrate detailed electromagnetic force modeling of the linear generator to improve simulation accuracy and control performance.

- Implementing Reinforcement Learning-Based Control:
  Explore the use of reinforcement learning algorithms to adaptively control the WEC under varying sea states and environmental uncertainties.

- Testing Controllers with Hardware-in-the-Loop (HIL):
  Validate the designed control strategies using real-time HIL simulations to bridge the gap between simulation and practical deployment.

- Applying Advanced Nonlinear Control Techniques:
  Investigate and implement robust nonlinear control methods (e.g., adaptive, predictive, or optimal control) to enhance system performance under dynamic ocean conditions.

Thank you!

Any Questions?
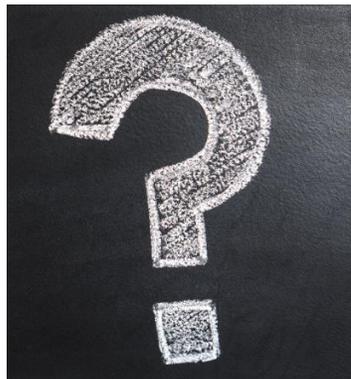
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https://github.com/Energy-Control-and-Optimization-Lab/Control-codesign-of-wave-energy-converters.git