Comparison of Hydraulic Power Take-Offs With and Without Continuous Control Force Capabilities

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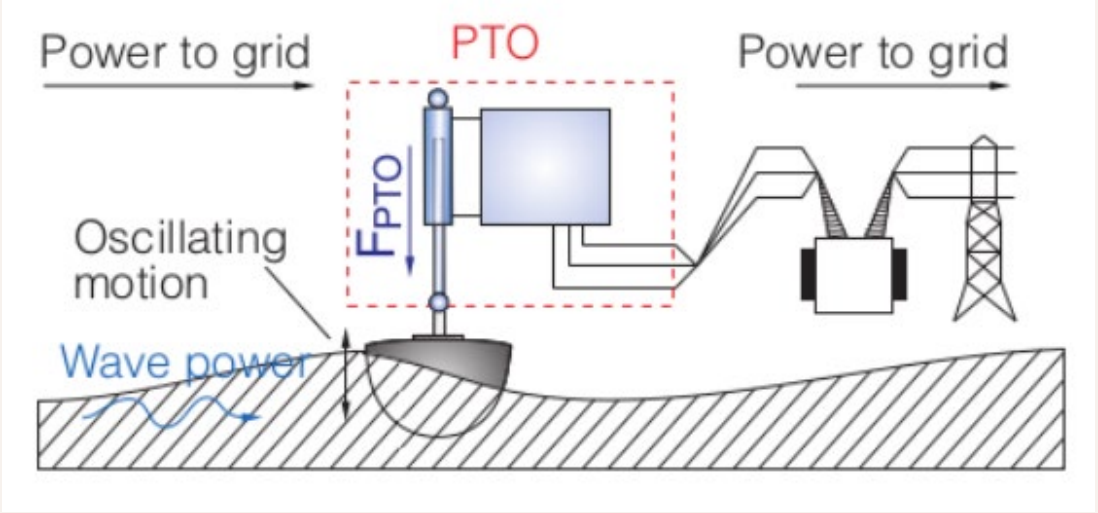
Power Take-Off

The Three Qualities of Highly Effective PTOs

1. Controllability
2. High efficiency
3. Low capital costs

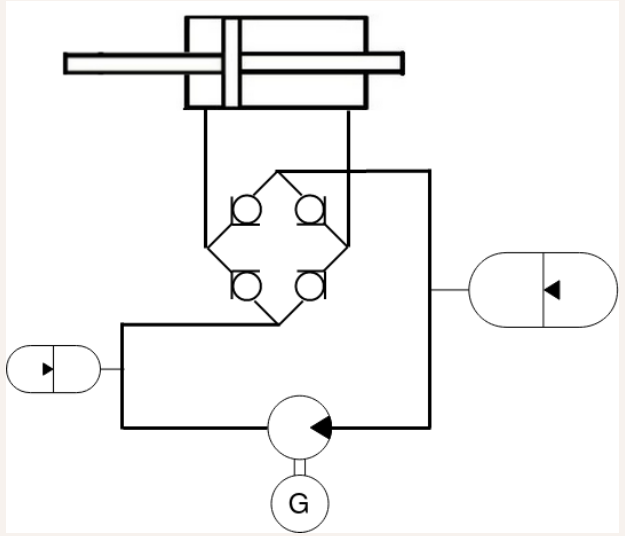


Hansen, R. H., 2013. "Design and control of the powertake-off system for a wave energy converter with multiple absorbers". PhD thesis, Department of Energy Technology, Aalborg University.

Common Hydraulic Power Take-Offs

Check valve PTO (or rectifying circuit)

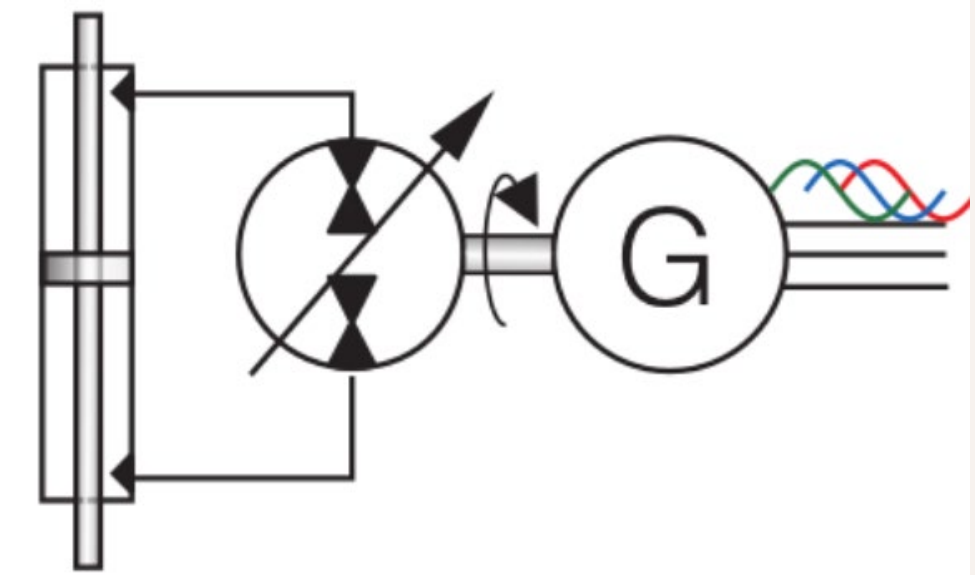
- Not actively controllable
- Power smoothing
- Efficient



Common Hydraulic Power Take-Offs

Electro-hydraulic actuator (EHA)

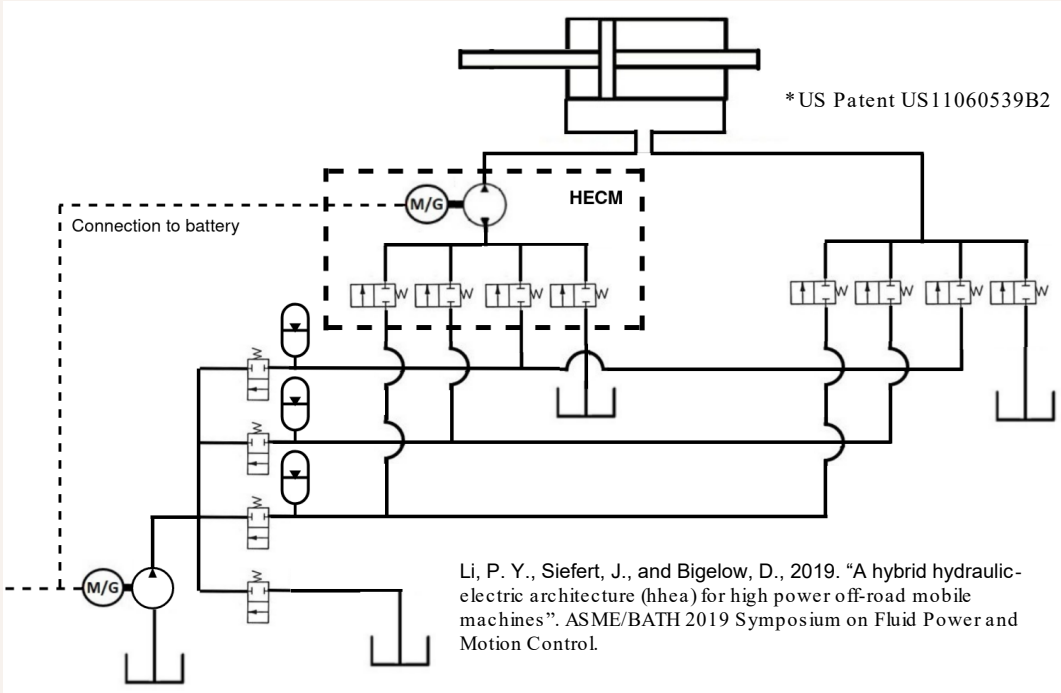
- Actively controllable
- No power smoothing



Hybrid Hydraulic-Electric Architecture (HHEA)

- Originally proposed for mobile machines
- Continuous control capability

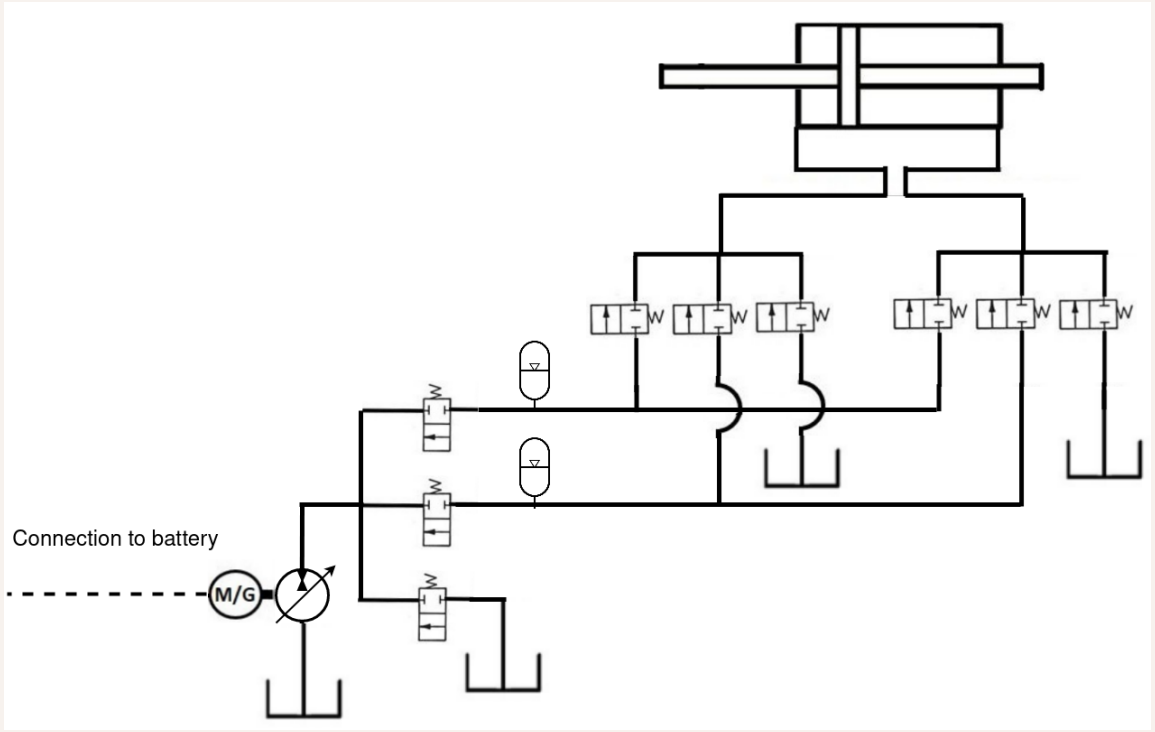
$$\underbrace{(P_A A_{cap} - P_B A_{rod})}_{F_{rails}(p_A, p_B)} + F_{elect} = F_{PTO}$$



Li, P. Y., Siefert, J., and Bigelow, D., 2019. "A hybrid hydraulic-electric architecture (hhea) for high power off-road mobile machines". ASME/BATH 2019 Symposium on Fluid Power and Motion Control.

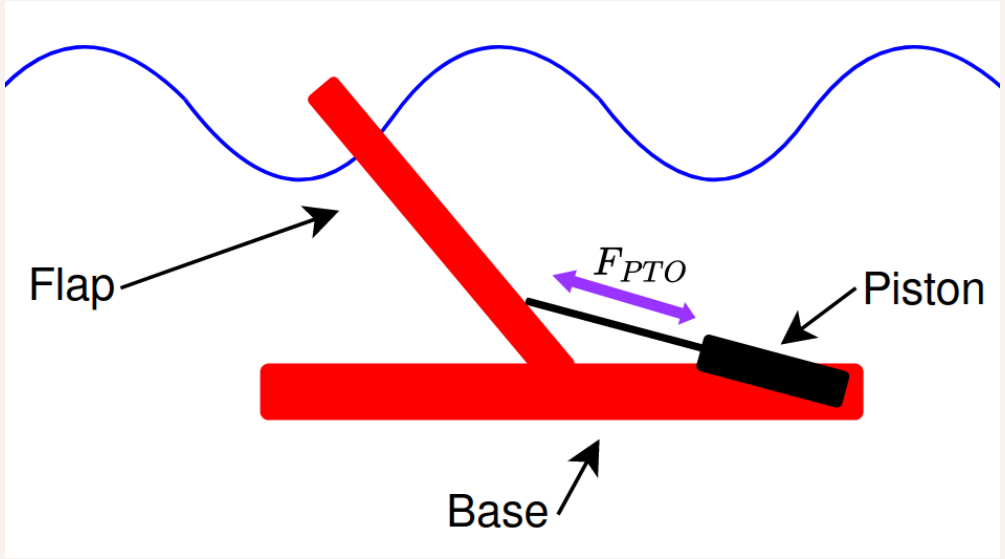
Discrete HHEA

- Controllable discrete forces
- Energy efficient
  - Energy storage
- Simple and cheap



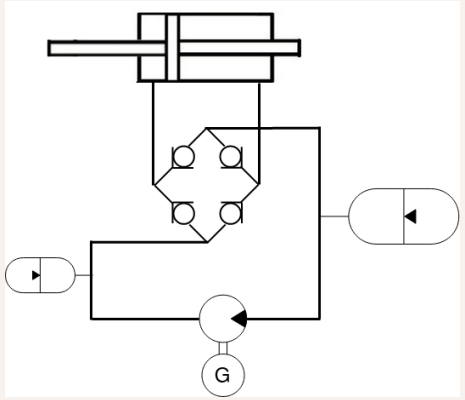
Comparison of PTO Architectures

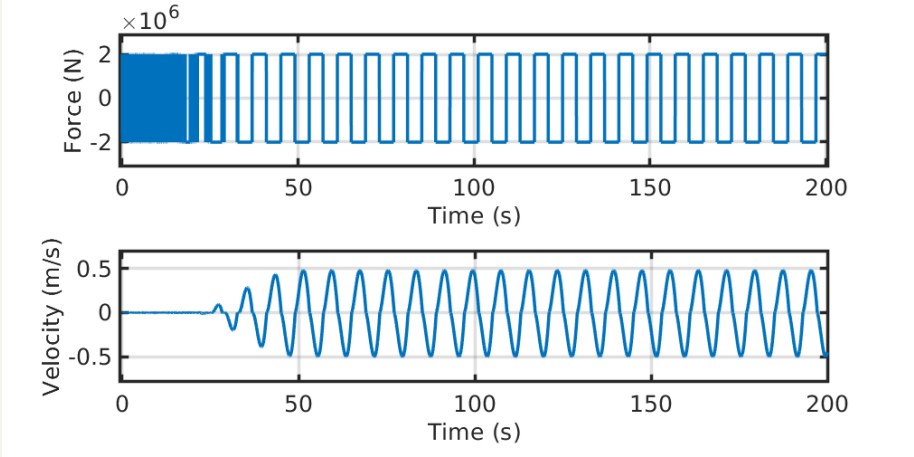
- Oscillating surge wave energy converter (OSWEC)
  - Simulated in WEC-Sim
- 4 PTOs simulated
  - Check valve PTO
  - Electro-hydraulic actuator
  - Hybrid Hydraulic Electric Architecture (HHEA)
  - Discrete Hybrid Hydraulic Electric Architecture (Discrete HHEA)

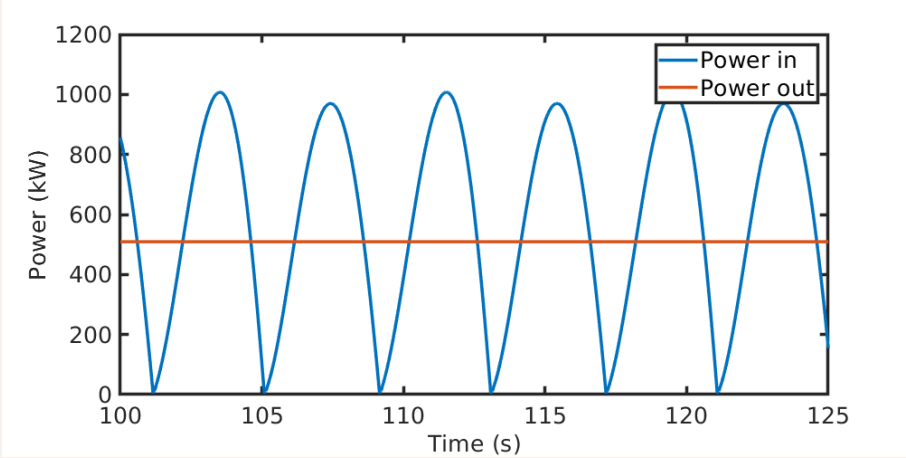


Control Algorithms - Check Valve PTO

- Check valve PTO enacts coulomb damping control



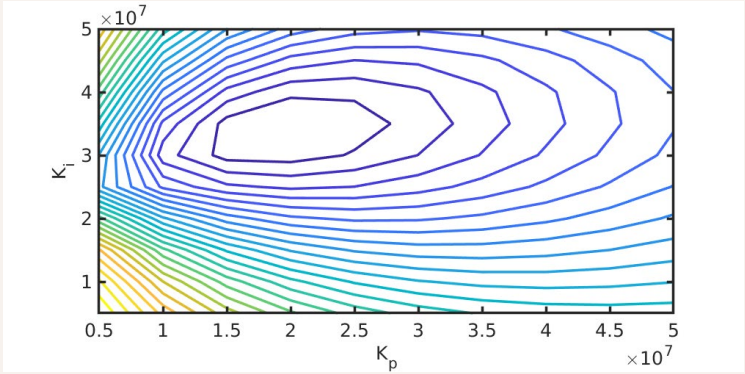


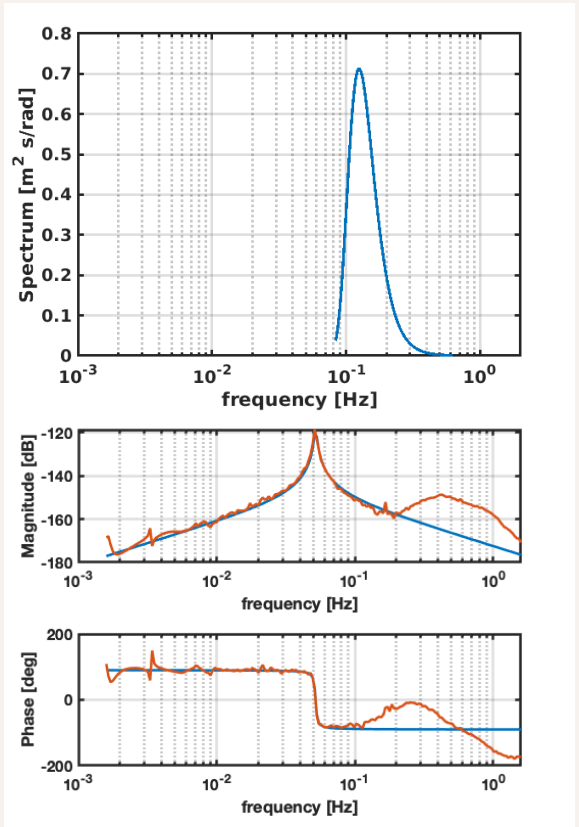


Control Algorithms - Continuous Control

- Frequency of waves do not match the natural frequency of the WEC
  - Control required to achieve resonance
  - PI control used
    - Grid search for gains
    - Cost function: mechanical power (force x velocity)

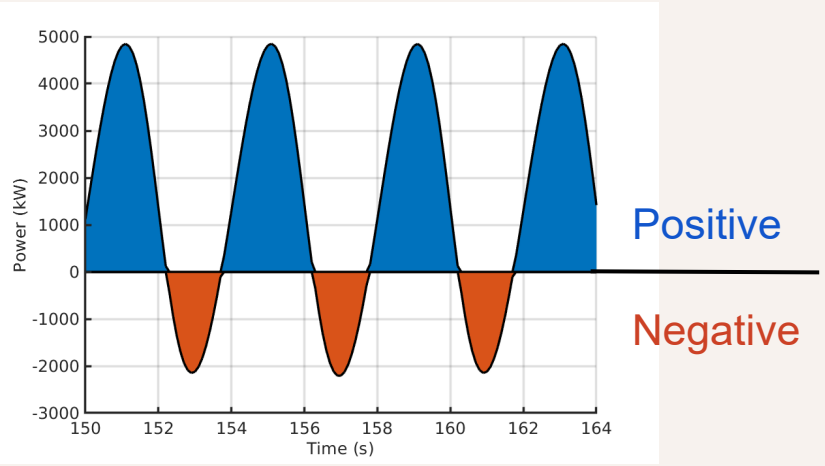
$$F_{PTO}(s) = \frac{K_p s + K_i}{s} v(s)$$





Bidirectional Power

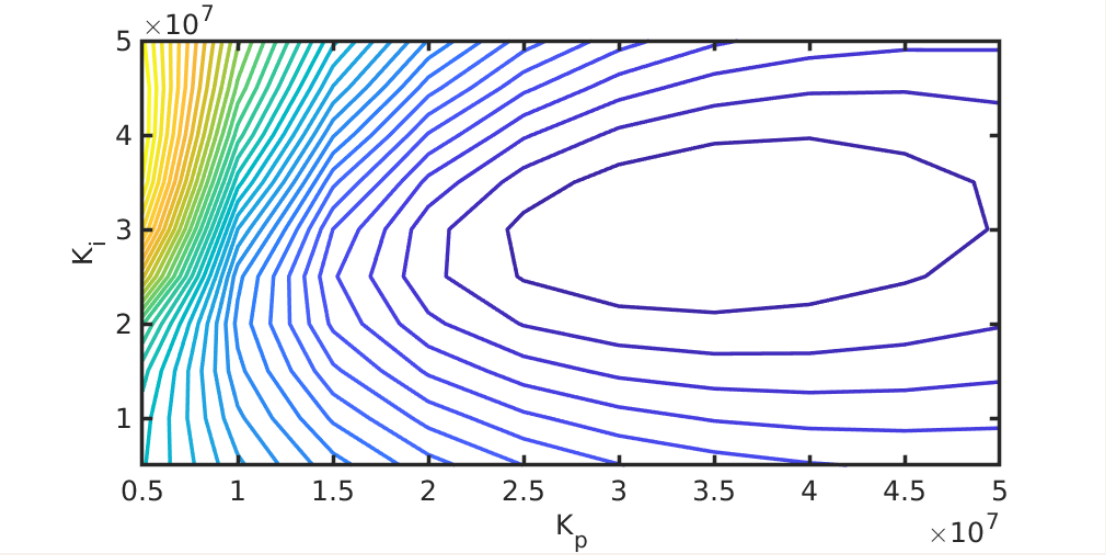
- PTOs with no power smoothing (Electro-hydraulic actuator) must have all power go all the way to electricity and back again
- Example:
  - Average instantaneous eff: 60%
  - 5 units positive energy : 1 unit negative energy
  - 5*0.6 = 3 units positive electric energy absorbed
  - 1/0.6 = 1.67 units electric energy released
  - 3-1.67 = 1.33 units net electric energy absorbed
    - Out of 4 units available
  - 1.33/4 = 0.33 > 0.6



Codesign of EHA

- Design control along-side the architecture
  - Design a new controller for each architecture, including the losses of the PTO
- Redo grid search for electrical energy

$$F_{PTO}(s) = \frac{K_p s + K_i}{s} v(s)$$

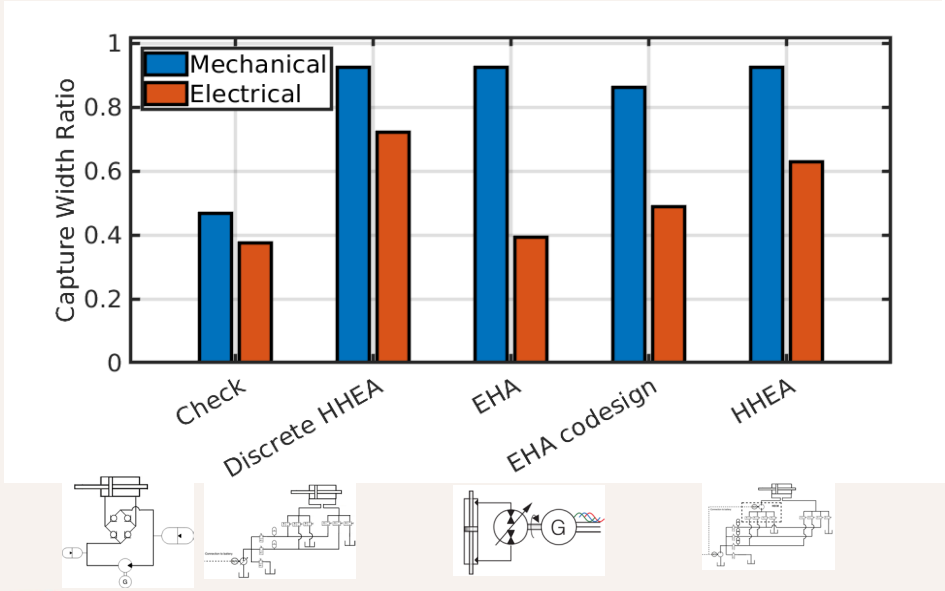


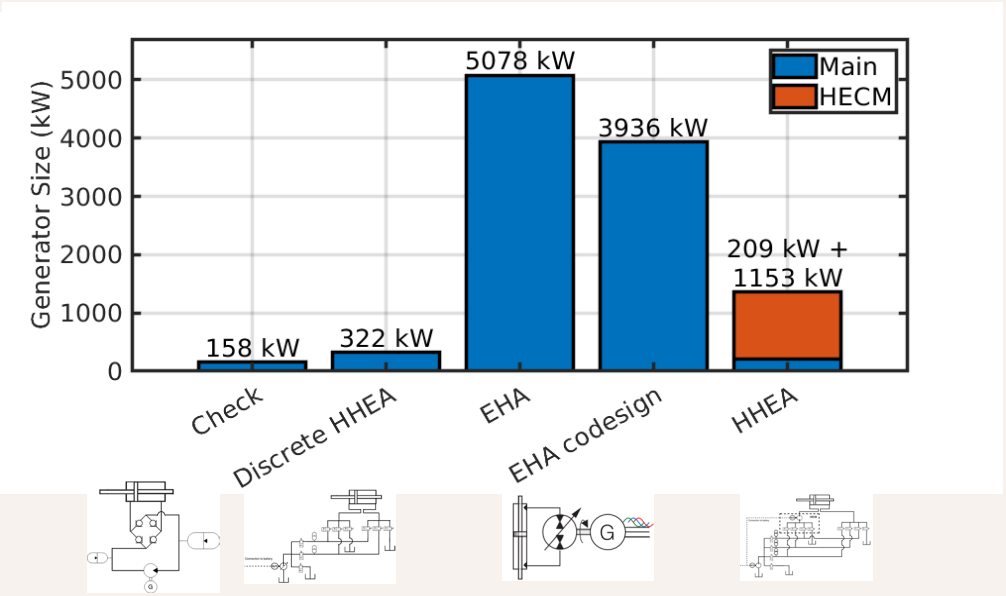
Results

$$CW = \frac{\text{Average absorbed power}}{\text{Wave resource per wave front width}}$$

$$CWR = \frac{CW}{\text{Width of WEC}}$$

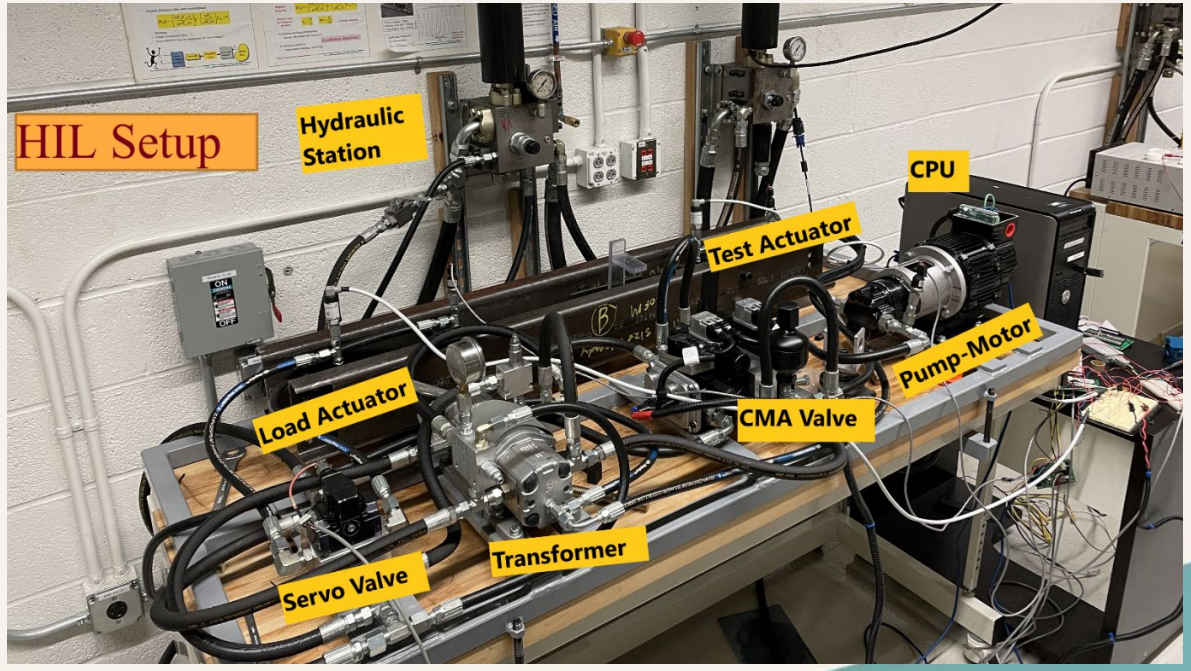
- Comparison of capture width ratio (CWR)
- Generator sized by peak power



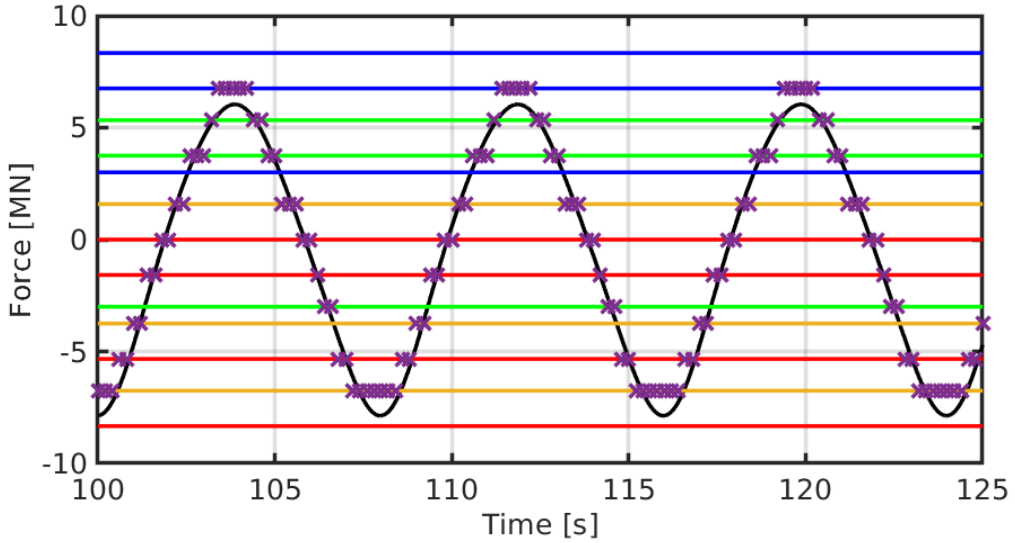


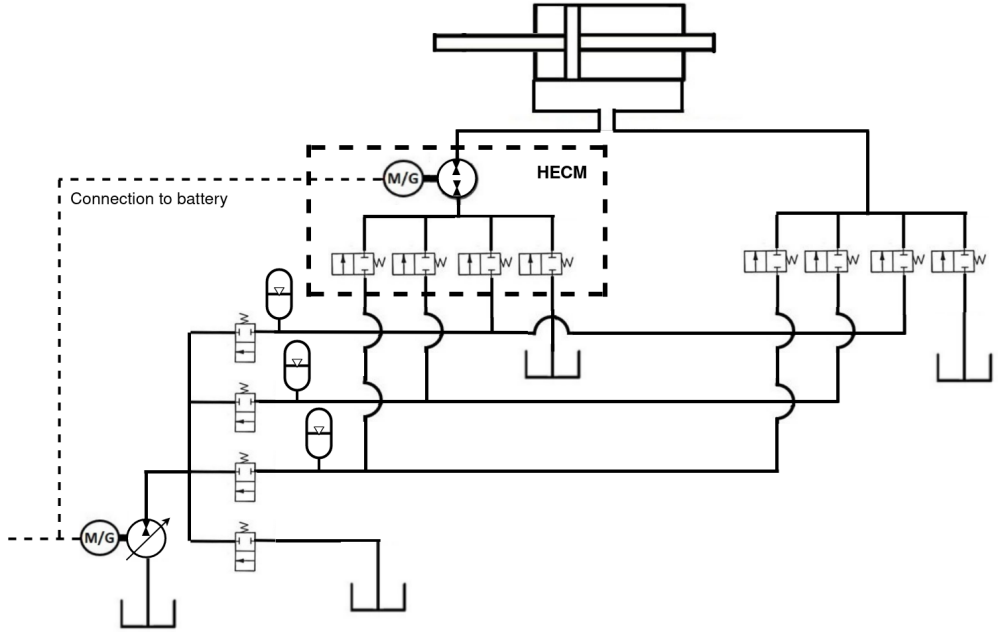
Conclusion

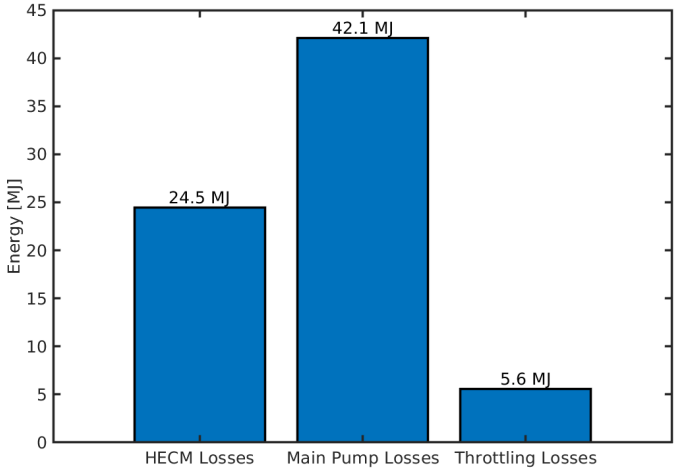
- Control is important - at least when waves are away from device natural frequency
  - The problem with the check valve PTO
- Power smoothing is important because power profile is bidirectional
  - The problem with the EHA PTO
- Discrete control does not significantly decrease mechanical energy capture
  - HHEA is overkill
- Discrete HHEA is a promising option
  - **Validate results on hardware-in-the-loop teststand**

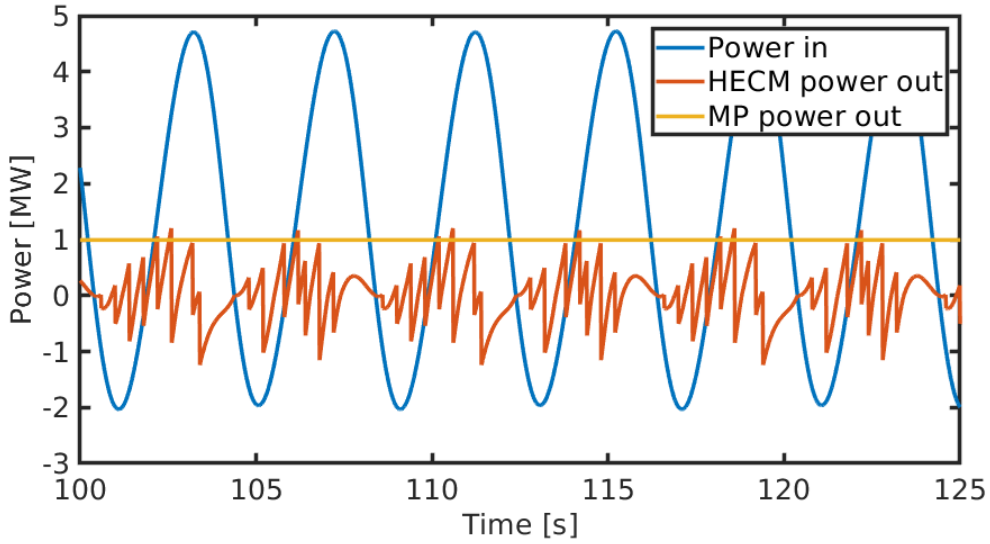


HHEA Results









Removal of Force Modulation System