SSM
SECURE SCALABLE MICROGRIDS
It's the end of the grid as we know it

SAND2013-8123C

Electromechanical Emulation of Hydrokinetic Generators for Renewable Energy Research

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Sandia National Laboratories

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Renewable Energy Integration

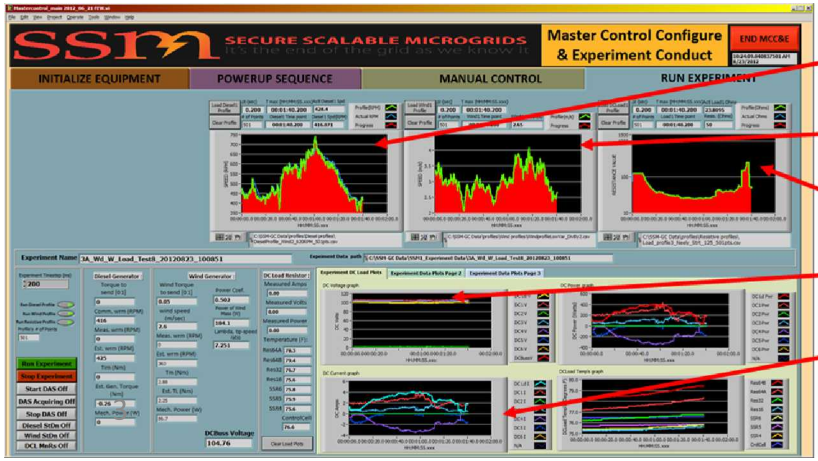
- Stochastic/variable generation is integral to Microgrid research

- Advancing the technology readiness of new and advanced controls requires results in hardware

- Unfortunately … hydrokinetic (and other renewable) generators don't fit in a conventional laboratory

Hydrokinetic Emulators are Key Components of the Secure Scalable Microgrid (SSM) Testbed

- **Testbed includes**
  - Programmable Loads
  - Programmable Generators/Emulators
  - Reconfigurable Bus
  - Power Electronic Converters
  - Networked Control
  - Automated Experiment Orchestration



Emulator Profile 1

Emulator Profile 2 (m/s)

Digital Resistor (Ω)

Bus voltage (V)

Currents into bus (A)

- **Master Controller controls load profiles, system settings and the "weather"**

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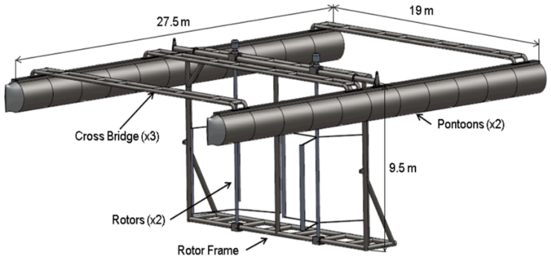
System Presented Herein can Emulate two Types of Hydrokinetic Generation

– Emulator Hardware and Software Description

– River Turbine Emulation

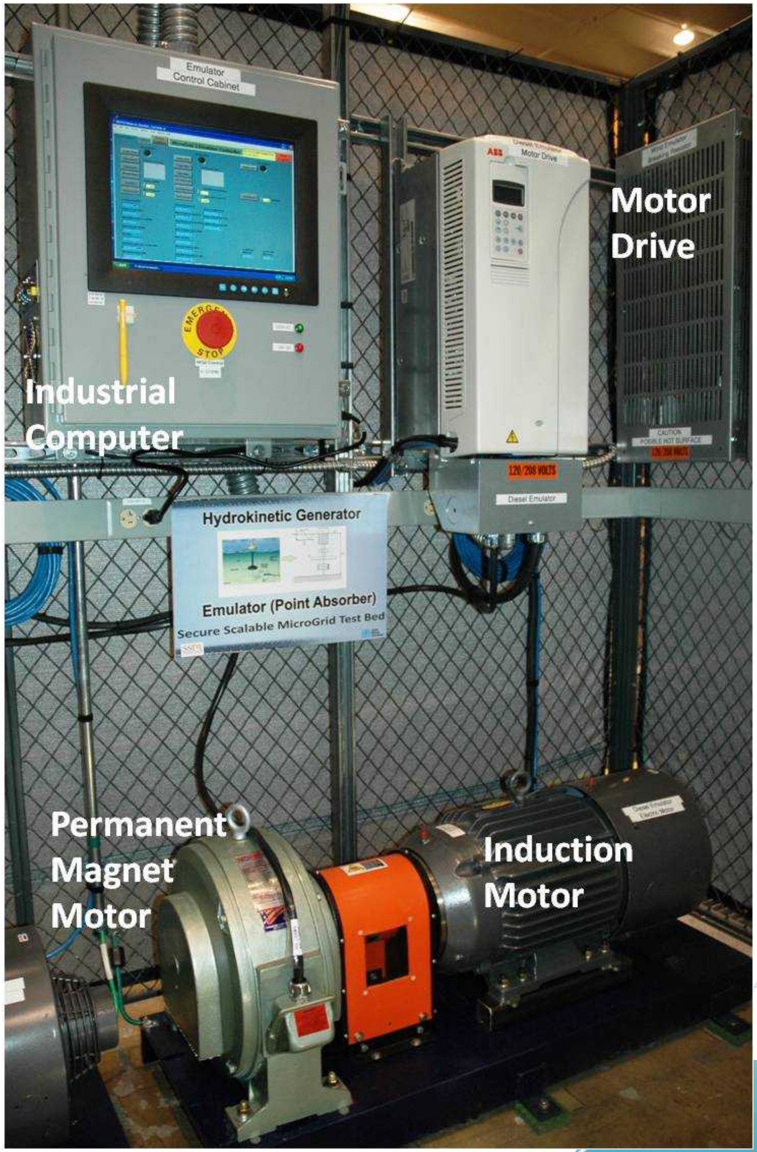


– Wave Energy Converter (Point Absorber) Emulation

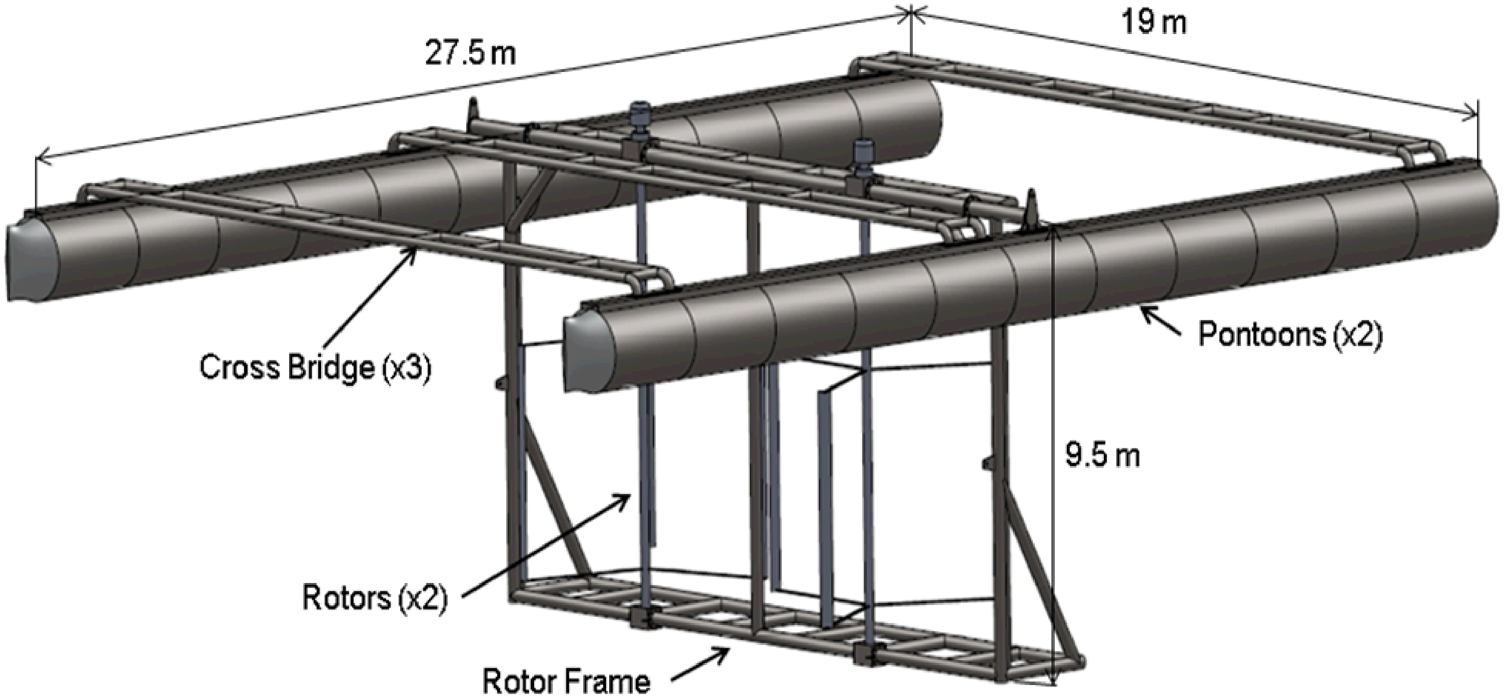
– Conclusions

The Emulator is Constructed of Commercial Hardware

- Baldor 15 HP Induction Motor with speed encoder
- ACS800 30HP ABB drive
  - DTC with 1% error when used with speed encoder
  - 24 msec timestep
  - 5 msec delay after register read
  - Brake Resistor
- 10 kW Georator 36-013-1 Permanent magnet alternator
- Computer runs LabVIEW 2011 with Mathscript RT toolkit



River Turbine Emulator



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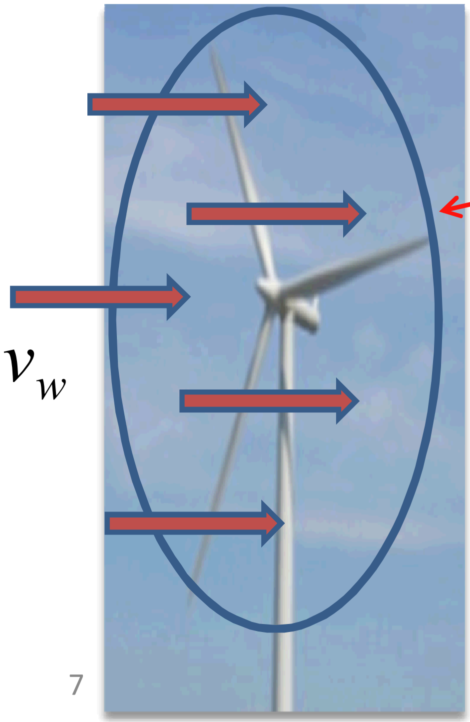
The River Turbine Mechanical Power Calculation is Equivalent to that of the Wind Turbine

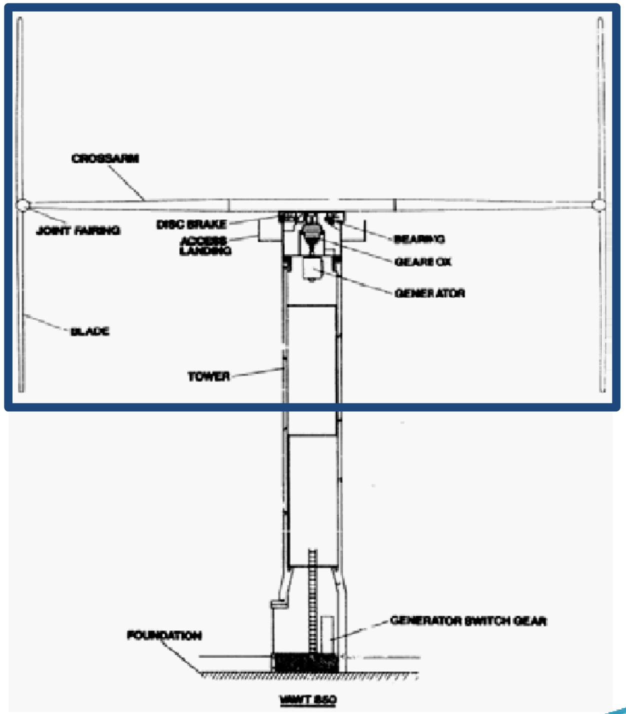
- **Average Power Equation is derived from the kinetic energy of the fluid flow and the power coefficient of the turbine**

$$P_{turb} = \frac{1}{2} C_p(\lambda) \rho_w A_r v_w^3$$

v_w



A_r



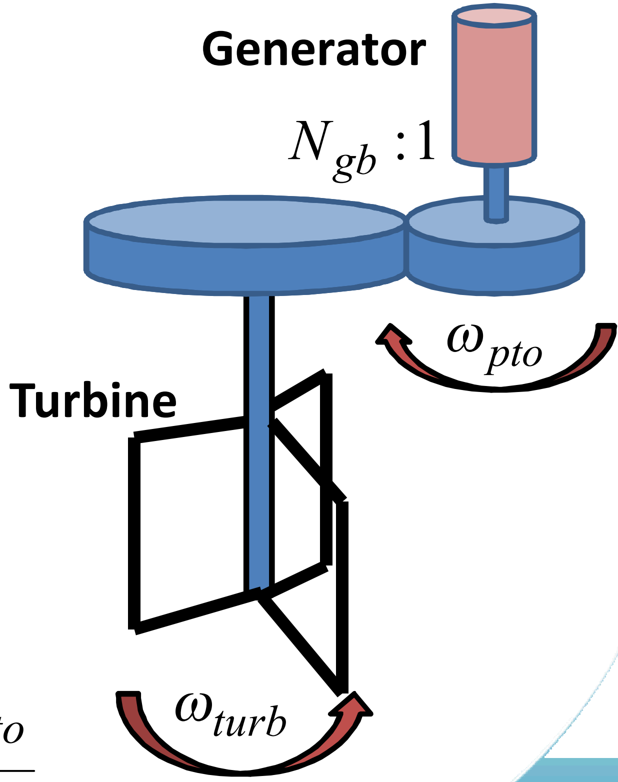
River Turbine Dynamical Model requires Greater Detail about System Components

- **Dynamic response of the turbine depends on the inertias gearbox ratios and damping coefficients of the mechanical components**

$$T_{turb} = \frac{P_{turb}}{\omega_{turb}} = \frac{C_p(\lambda)\rho_w A_r v_w^3}{2\omega_{turb}}$$

$$\frac{d}{dt}\omega_{turb} = \frac{T_{turb} - N_{gb}T_{pto} - B_{gb}\omega_{turb}}{J_{turb} + N_{gb}^2 J_{pto}}$$

$$\frac{d}{dt}\omega_{pto} = \frac{\left(1/N_{gb}\right)T_{turb} - T_{pto} - \left(1/N_{gb}^2\right)B_{gb}\omega_{pto}}{(1/N_{gb}^2)J_{turb} + J_{pto}}$$



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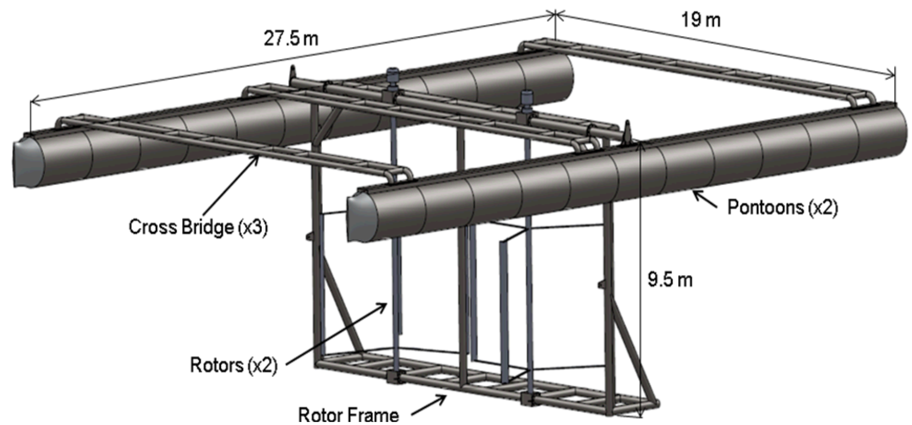
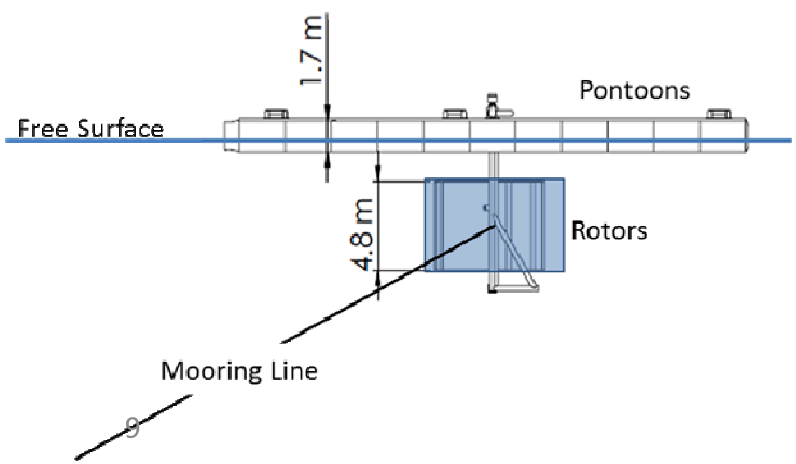
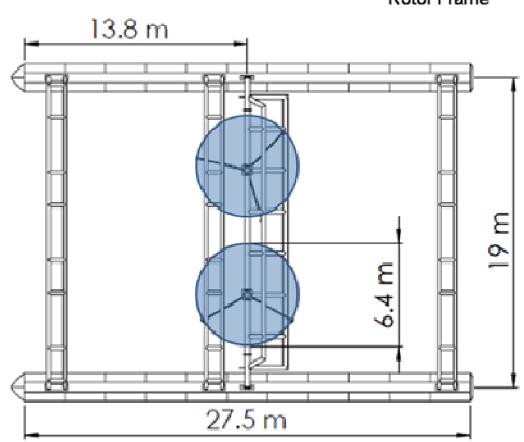
River Turbine Model Parameters were Established from System Design

- **Reference Model 2, Cross-Flow River Turbine**
  - Two 50 kW cross-flow turbines
  - Each turbine is connected through a gearbox to a permanent magnet generator
  - Turbine mass and dimensions used to estimate turbine inertia
  - Gearbox published data used to determine inertia and damping

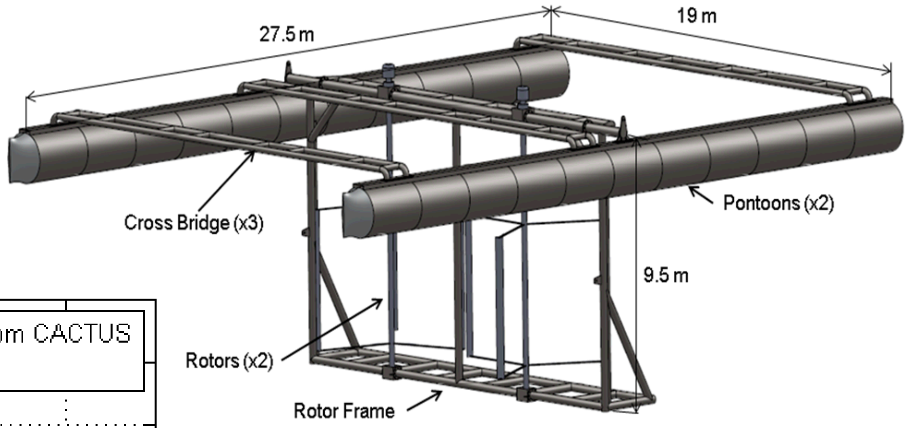


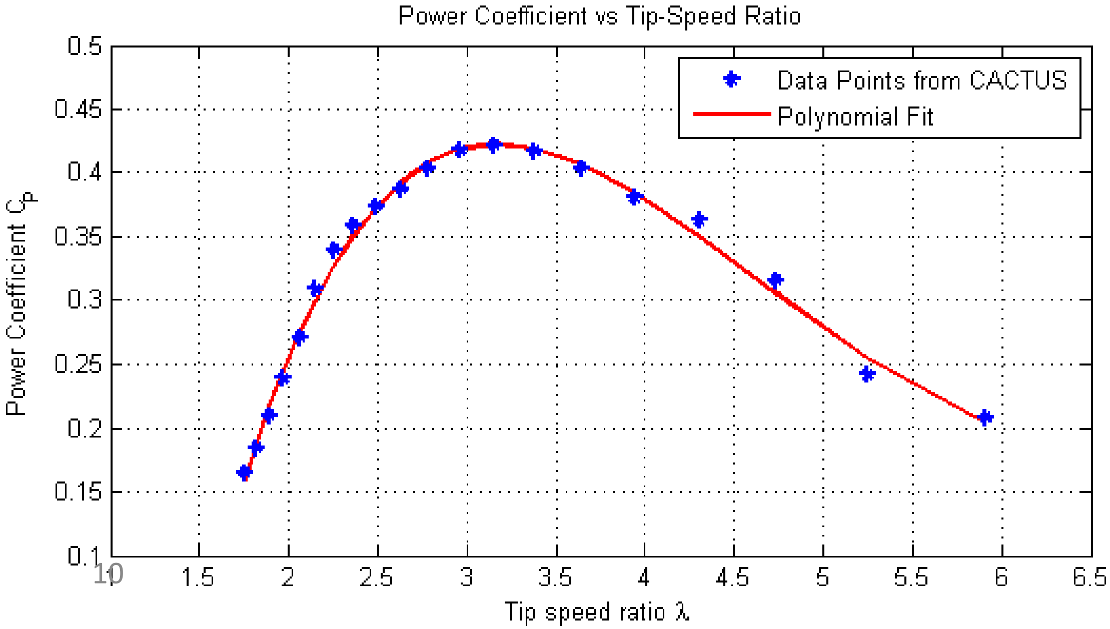




River Turbine Model Parameters were Established from System Design

- **Reference Model 2, Cross-Flow River Turbine**
  - The power coefficient was determined by performing CACTUS (Code for the Analysis of Cross- and axial-flow TUrbine Simulation) simulations





Emulator Dynamics must "Match" River Turbine Dynamics

- **Emulator Dynamics are given by**

$$\frac{d}{dt}\omega_{em} = \frac{T_{im} - T_{gen} - B_{em}\omega_{em}}{J_{em}}$$

- **Two scale factors are defined**

$$P_{em} = k_{sc}P_{turb} \;, \qquad n_{em} = \frac{n_{pto}R_{turb}\max(\omega_{em})}{N_{gb}\lambda^{*}\max(v_w)}$$

- **To avoid the use of a torque sensor, a generator torque estimator is developed using the measured shaft speed**

$$\frac{d}{dt}\begin{bmatrix}\hat{\omega}_{em}\\ \hat{T}_{gen}\end{bmatrix} = \begin{bmatrix}\frac{-B_{em}}{J_{em}} & \frac{-1}{J_{em}}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\hat{\omega}_{em}\\ \hat{T}_{gen}\end{bmatrix} + \begin{bmatrix}\frac{1}{J_{em}}\\ 0\end{bmatrix}T_{im} + \begin{bmatrix}\kappa_{\omega}\\ \kappa_{T}\end{bmatrix}\Delta\omega_{em}$$

Emulator Dynamics must "Match" River Turbine Dynamics

- **Emulator Parameters, Turbine Parameters, estimated generator torque and two scale factors are used to compute the torque command**
- **However, key system characteristics, including time constants are preserved**

$$
\begin{aligned}
T_{im}^{*} = & \left(\frac{n_{em}}{n_{pto}} \cdot \frac{\left(1/N_{gb}\right) J_{em}}{\left(1/N_{gb}^{2}\right) J_{turb} + J_{pto}} \right) T_{turb} \\
& + \left(1 - \left(\frac{n_{em}}{n_{pto}} \right)^{2} \frac{J_{em}}{k_{sc}\left(\left(1/N_{gb}^{2}\right) J_{turb} + J_{pto} \right)} \right) \hat{T}_{gen} \\
& + \left(B_{em} - \frac{\left(1/N_{gb}^{2}\right) B_{gb} J_{em}}{\left(1/N_{gb}^{2}\right) J_{turb} + J_{pto}} \right) \omega_{em}
\end{aligned}
$$

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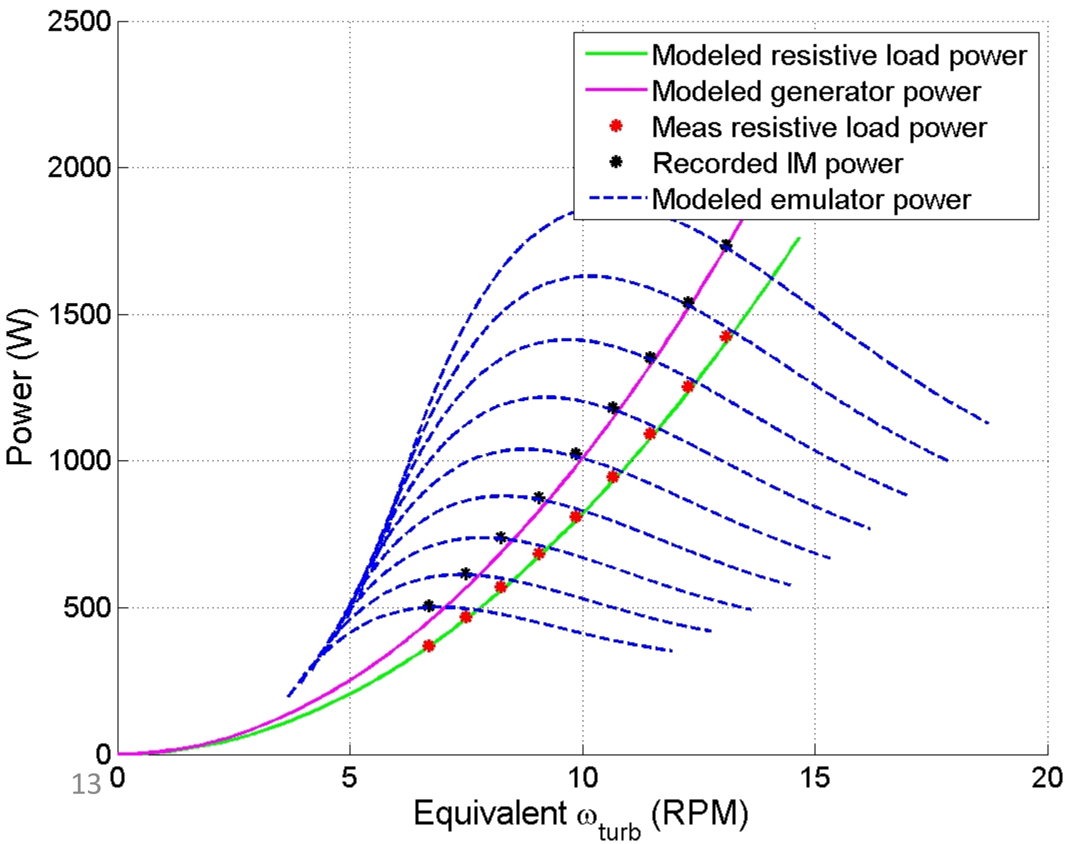
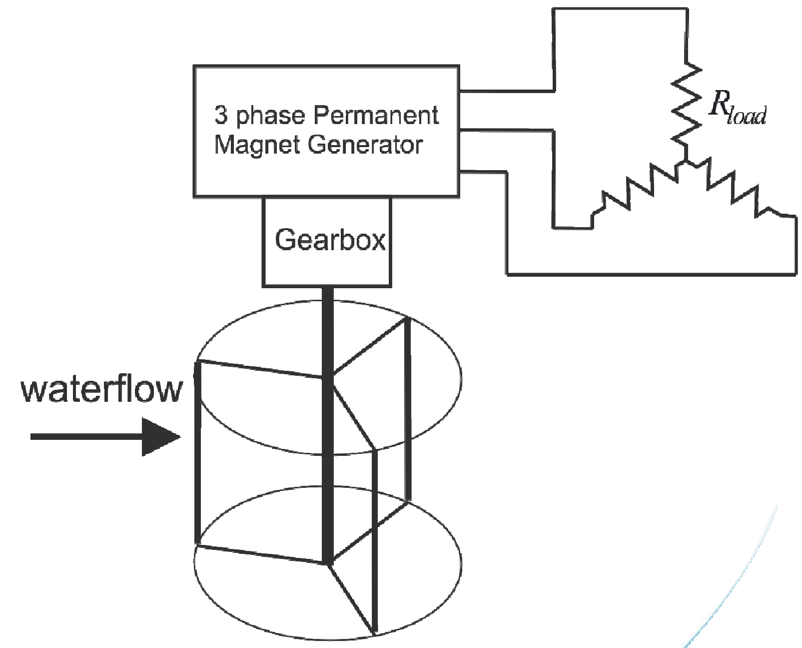
River Turbine Emulator Static Hardware Test Agrees with Analysis

- The 3-Φ load resistance is fixed, and the emulator is allowed to reach steady-state for several water velocities between 0.7 and 1.1 m/sec
- The mechanical power reported by the drive and the measured electrical power are compared to those predicted in analysis





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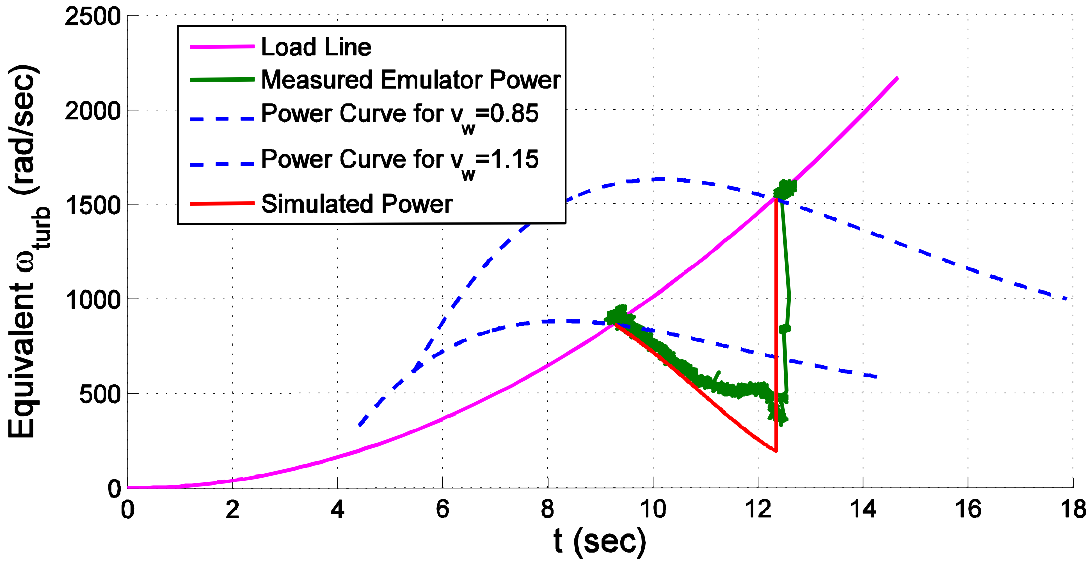
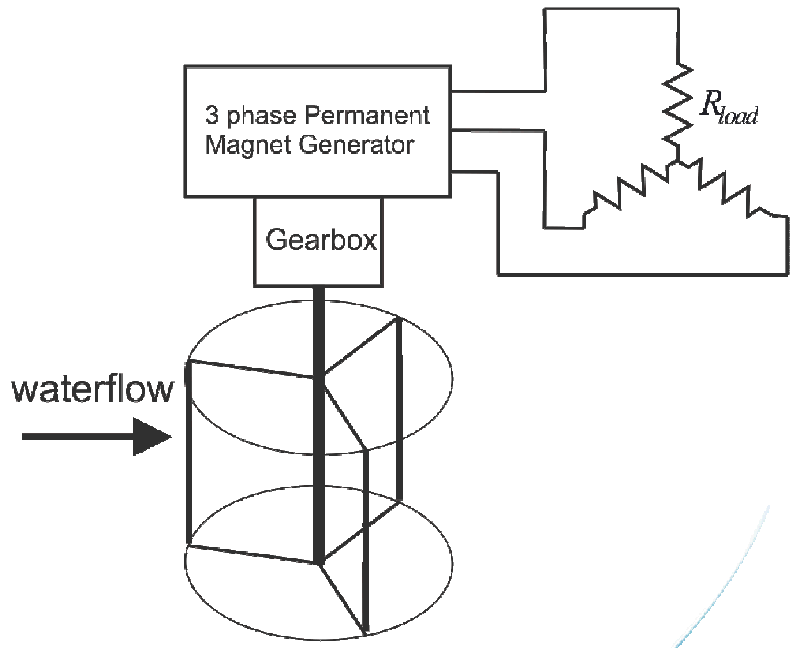
River Turbine Emulator Dynamic Hardware Test Agrees with Simulation

- The 3-Φ load resistance is fixed, and the water velocity is stepped from 1.15 to 0.85 m/sec
- The rotor speed and measured mechanical power are compared to that predicted in Matlab simulation





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Point Absorber (WEC) Emulator

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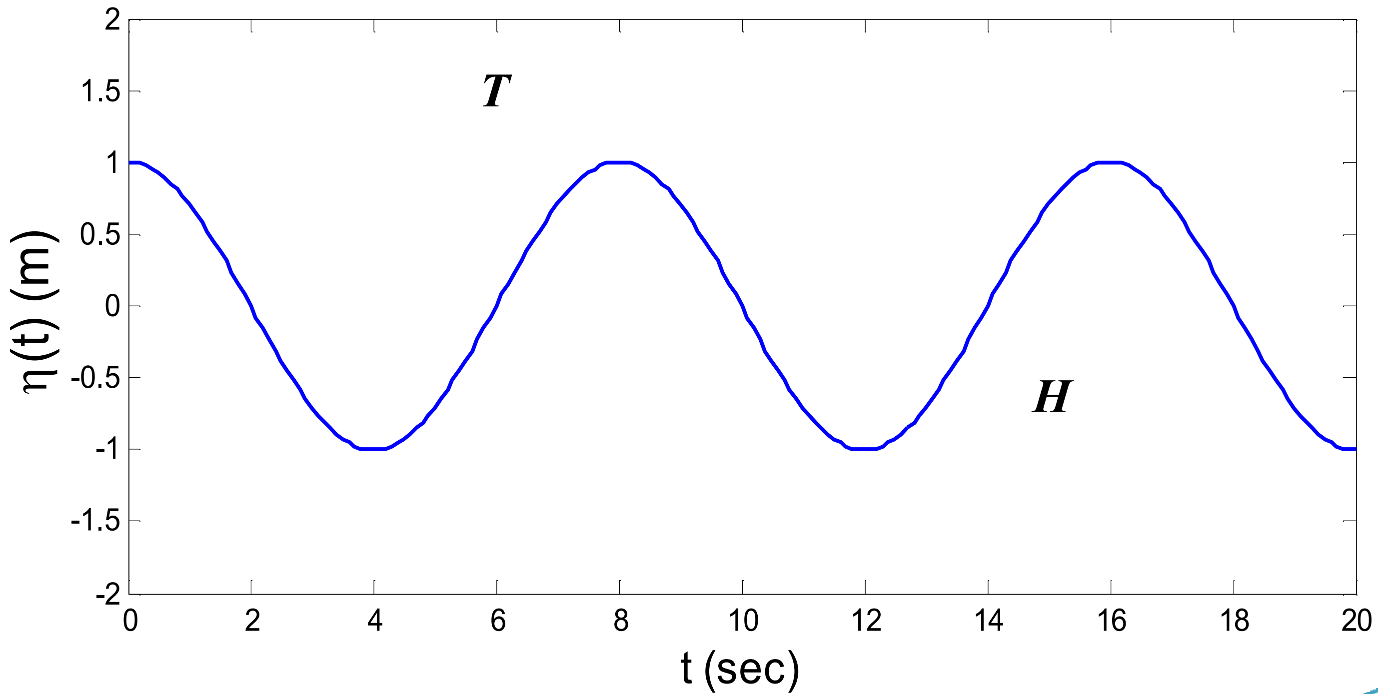
Ocean Wave Energy Depends on both the Potential and Kinetic Energy of the Water

- **Power is given by the product of the wave energy flux and the capture width**

$$P_{wave} = \frac{\rho_{sw} g^2 H^2 T}{32\pi} CW$$



The Point Absorber Dynamical Model Resembles a Mass-Spring-Damper system

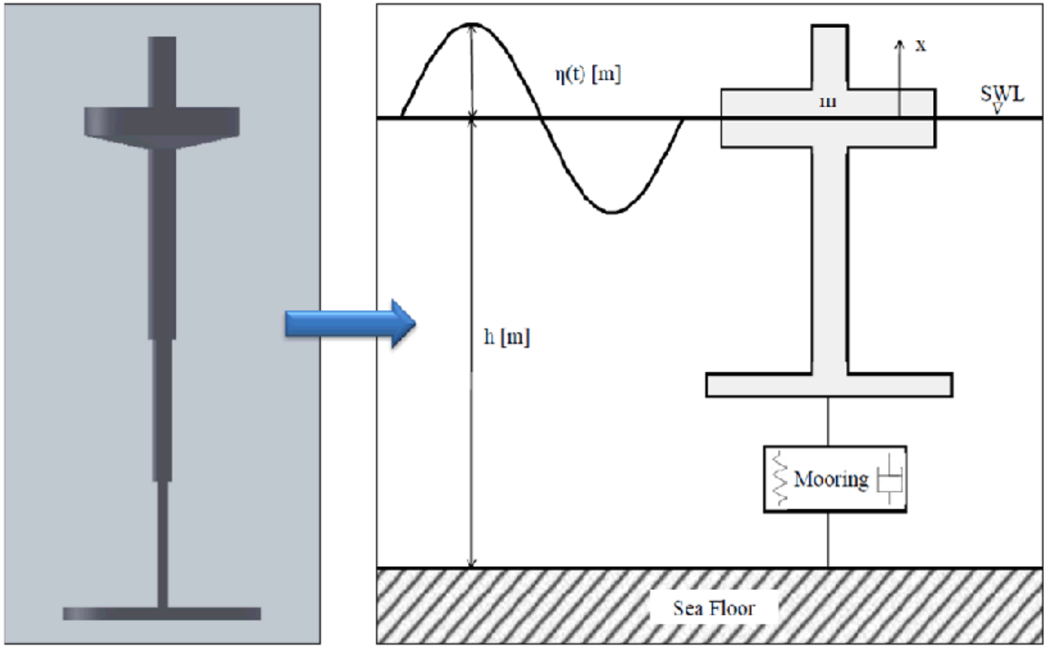
- **Single Body Point Absorber is represented as a second order nonlinear noncausal system**

$$\left(m + A(\infty)\right)\ddot{x} = -B_{pto}\dot{x} - K_{hs}x + F_e - F_r - F_m$$

$$F_e(t) = \int_{-\infty}^{\infty} \eta(\tau) f_e(t-\tau)\, d\tau$$

$$F_r(t) = \int_{-\infty}^{t} \dot{x}(\tau) f_r(t-\tau)\, d\tau$$

$$F_m(t) = 8k_m x\left(1 - \frac{l_m}{\left(l_m^2 + x^2\right)^{1/2}}\right)$$



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The Point Absorber Dynamical Model Resembles a Mass-Spring-Damper system

- **Impulse Response is identified experimentally using wave tank testing**

$$\left(m + A(\infty)\right)\ddot{x} = -B_{pto}\dot{x} - K_{hs}x + F_e - F_r - F_m$$

$$F_e(t) = \int_{-\infty}^{\infty} \eta(\tau) f_e(t-\tau)\, d\tau$$

$$F_r(t) = \int_{-\infty}^{t} \dot{x}(\tau) f_r(t-\tau)\, d\tau$$

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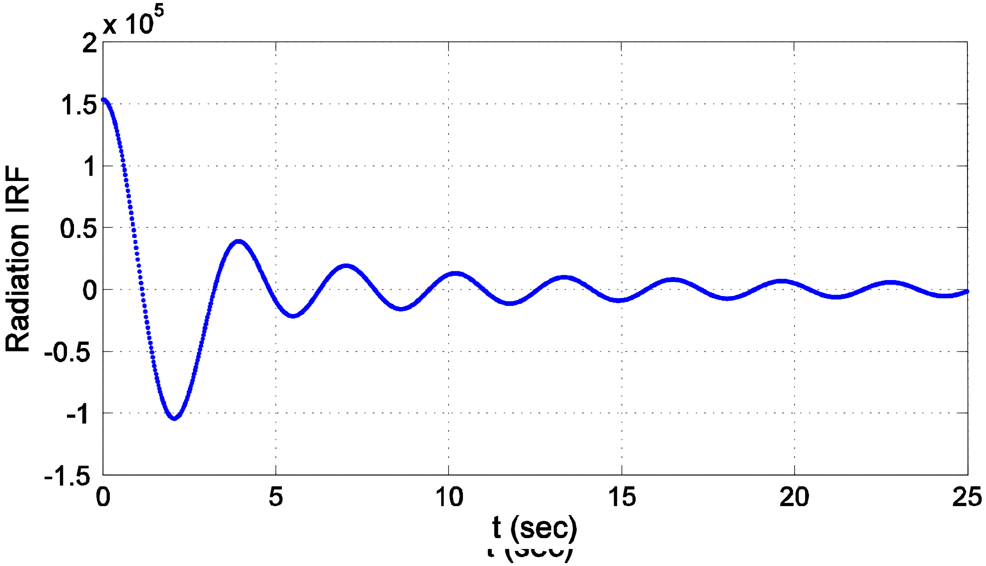


The Point Absorber Linear Motion must be Converted to Rotational Power

- The equations of motion are expressed as two ODEs and solved numerically using trapezoidal integration (Mooring force neglected)

$$\frac{d}{dt}v_m = -\frac{B_{pto}}{\left(m + A(\infty)\right)}v_m - \frac{K_{hs}}{\left(m + A(\infty)\right)}x + \frac{F_e - F_r - F_m}{\left(m + A(\infty)\right)}$$

$$\frac{d}{dt}x = v_m$$

- An idealized (loss-less) power take-off is considered that appears as additional viscous damping to the point absorber

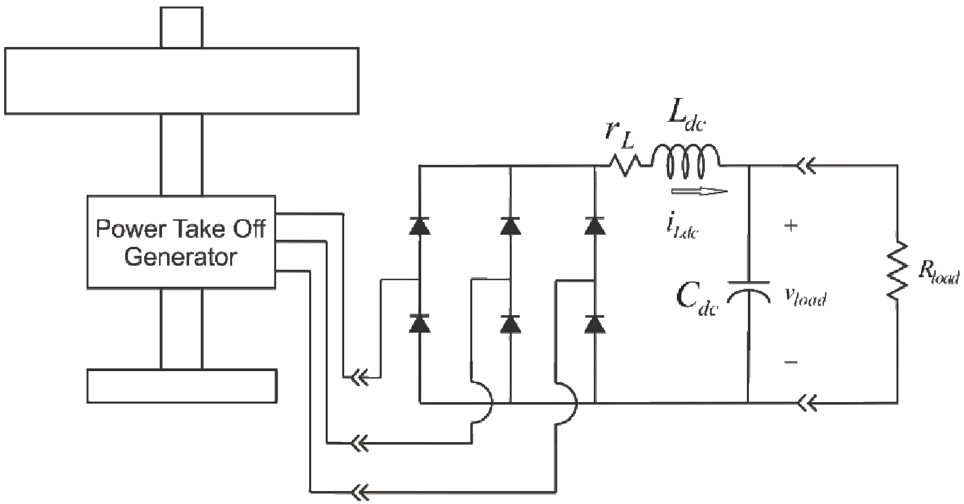
$$T_{im}^{*} = k_{sc}\frac{B_{pto}v_m^2}{\omega_{em} + \varepsilon}$$

Point Absorber Emulator Hardware Tests Agree with Simulation

- The emulator generator is connected to a rectifier with LC output filter and DC resistive load

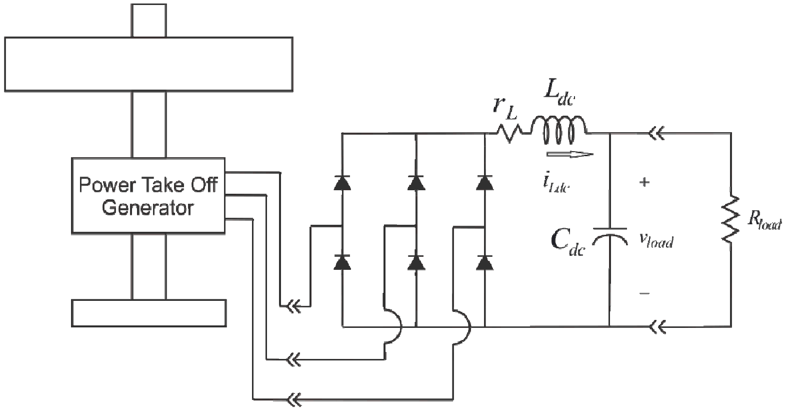
- Measured electrical output power was compared to that obtained in Simulink simulation

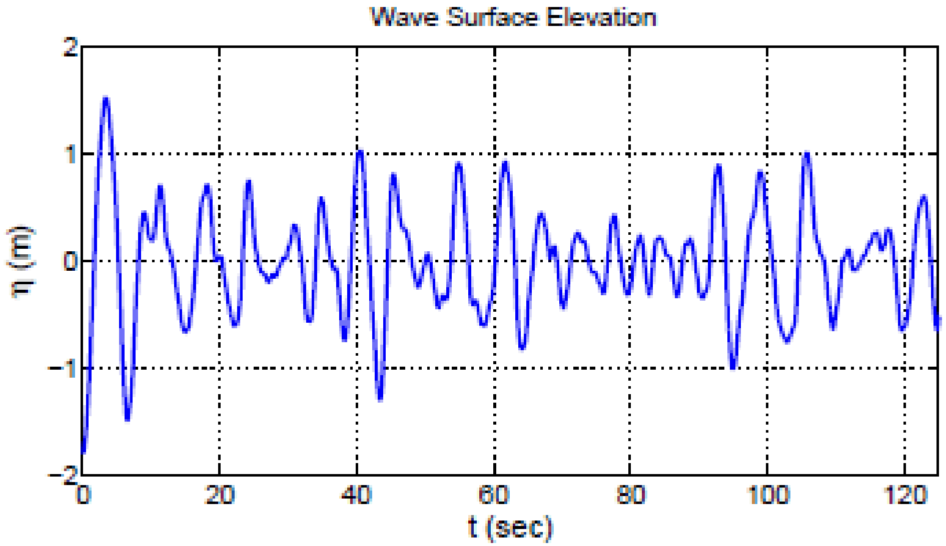
- A 125 second wave profile was needed for a 100 second experiment due to the non-causal FIR filter

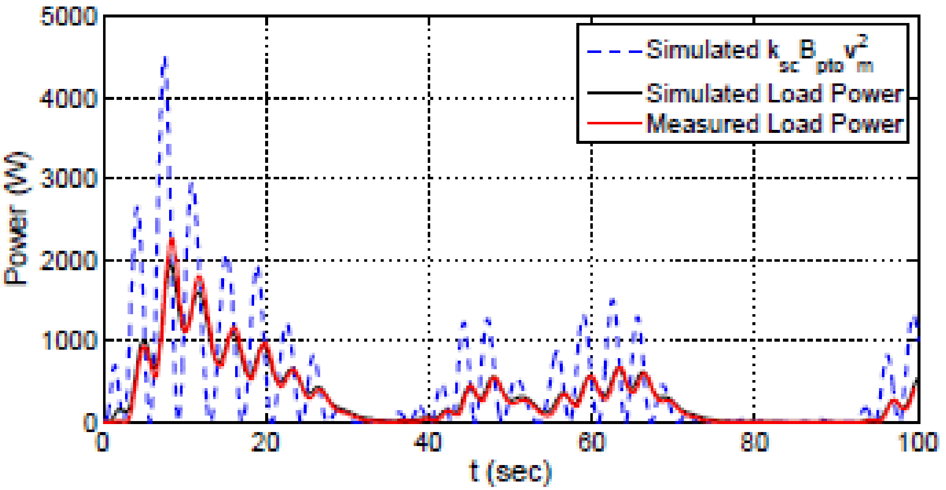


Point Absorber Emulator Hardware Tests Agree with Simulation

- **The emulator is tested for an irregular wave profile recorded from a data buoy time-series from Umpqua 46229 in June 2008**







Conclusions and Future Work

- A river turbine and a wave energy converter (point absorber) were emulated dynamically using a commercial motor drive
- These emulators are incorporated into a microgrid testbed that includes power converters, loads
- A patent application has been filed for this emulator method

- Future Work will includes
  - Implementation of a two-body WEC model
  - Incorporation of a detailed hydraulic power take-off model
  - Testing of hydrokinetic control methods using the testbed

BACK UP SLIDES

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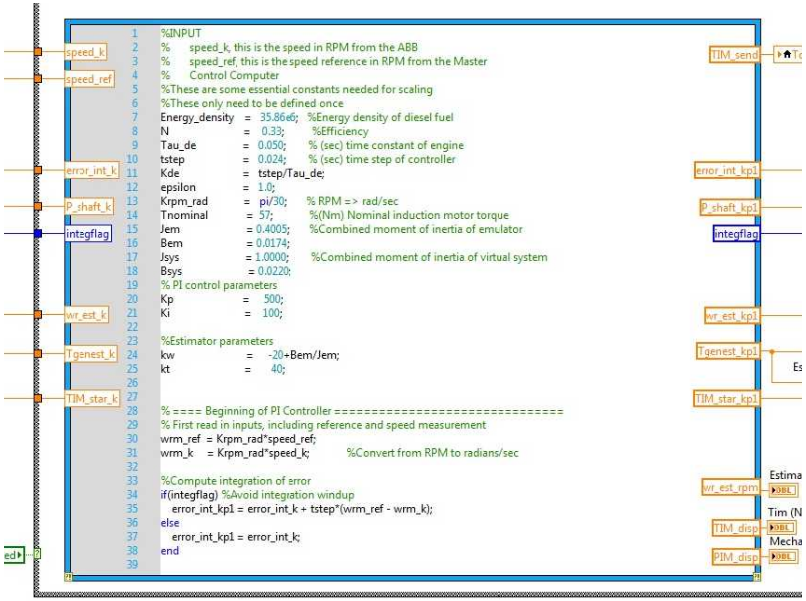
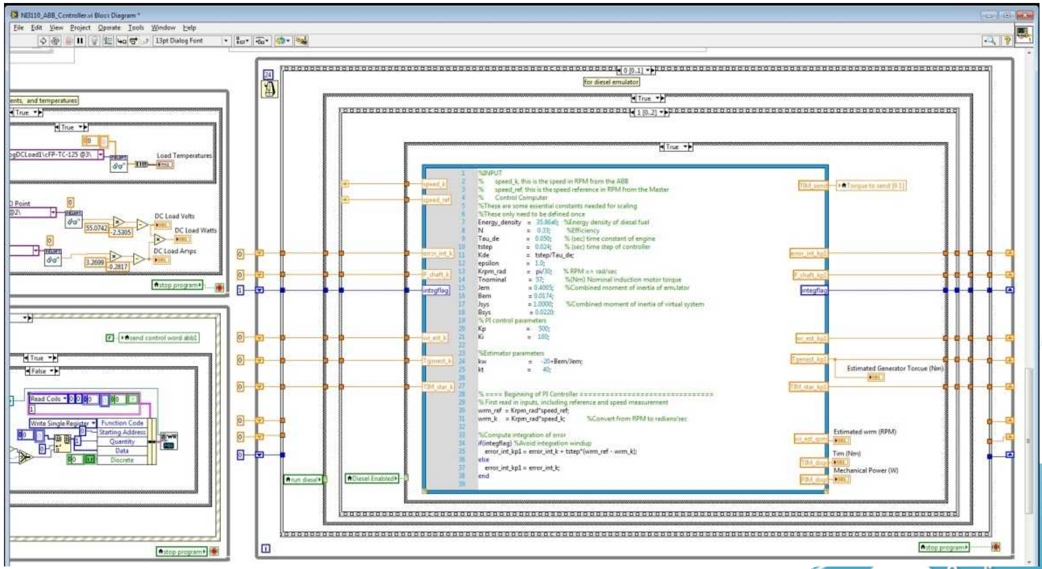
Emulator Control Software is Developed using LabVIEW and Matlab

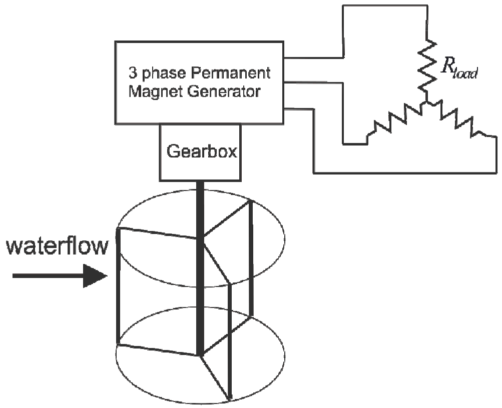
- LabVIEW 2011 with Mathscript RT toolkit
- River Turbine Emulator coded in Matlab
- Point Absorber Emulator implemented using Matlab and LabVIEW FIR filters
- LabVIEW manages the network interface with the ABB drive

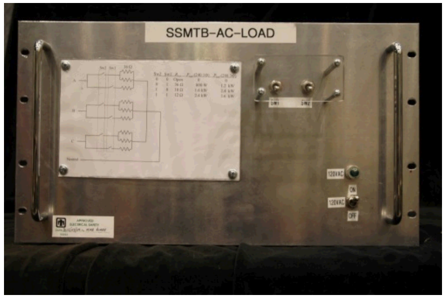


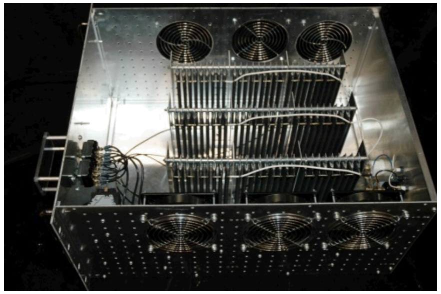


Additional Testbed Components were Used

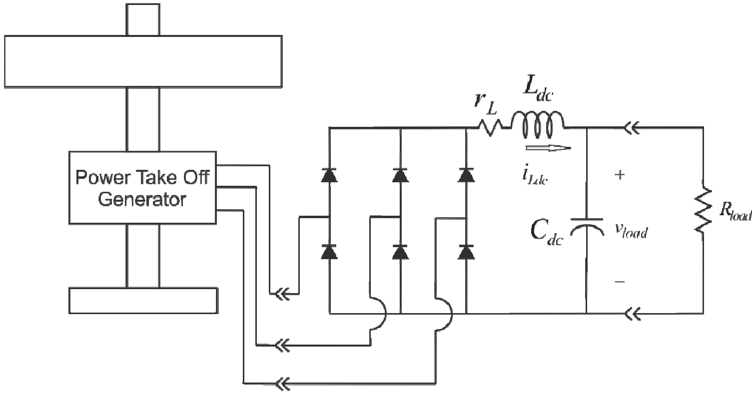
- **3 Phase Wye-Connected Resistive Load**

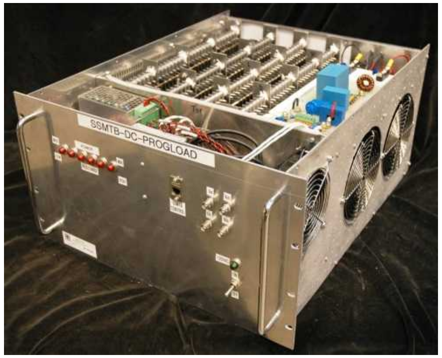


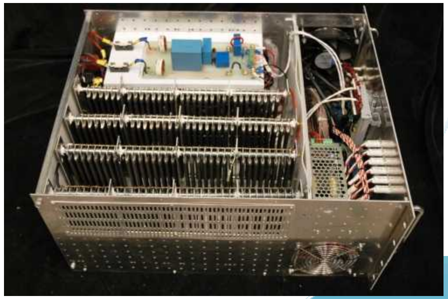




- **Rectifier with LC filter**

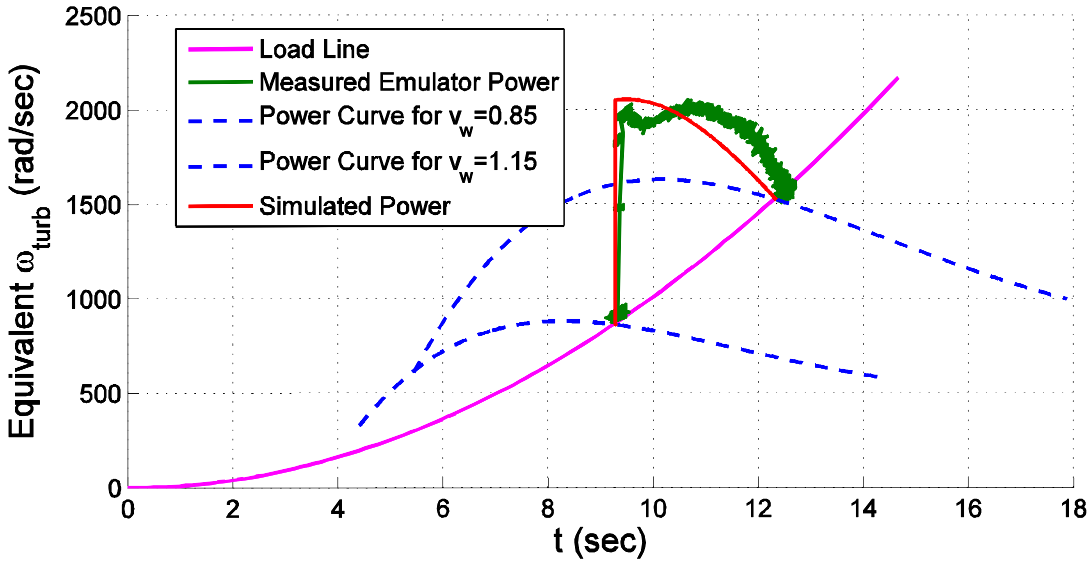


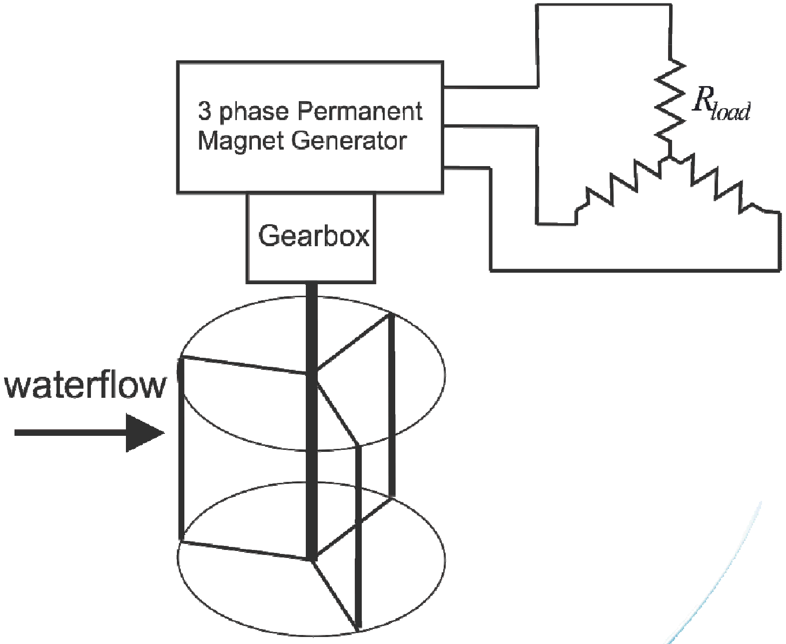




River Turbine Emulator Dynamic Hardware Test Agrees with Simulation

- The 3-Φ load resistance is fixed, and the water velocity is stepped from 0.85 to 1.15 m/sec
- The rotor speed and measured mechanical power are compared to that predicted in Matlab simulation





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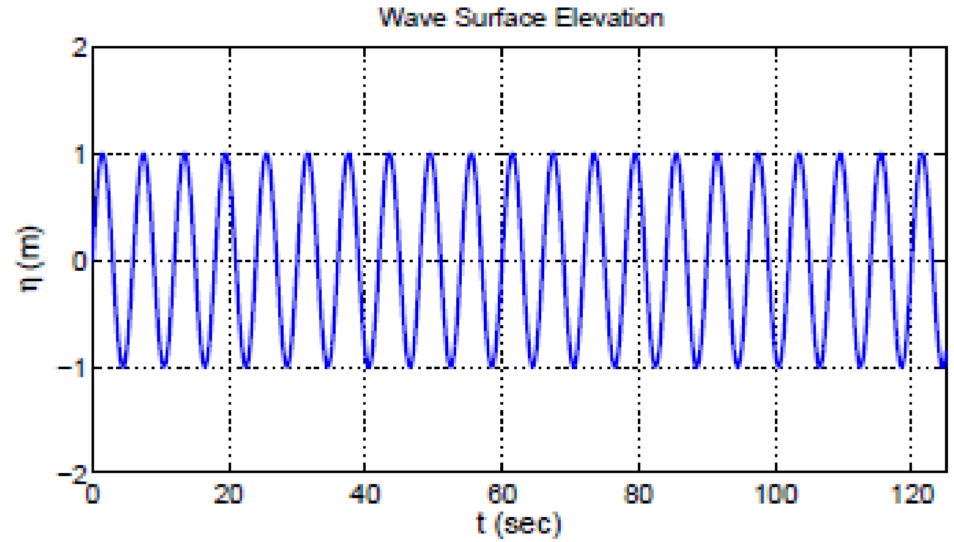
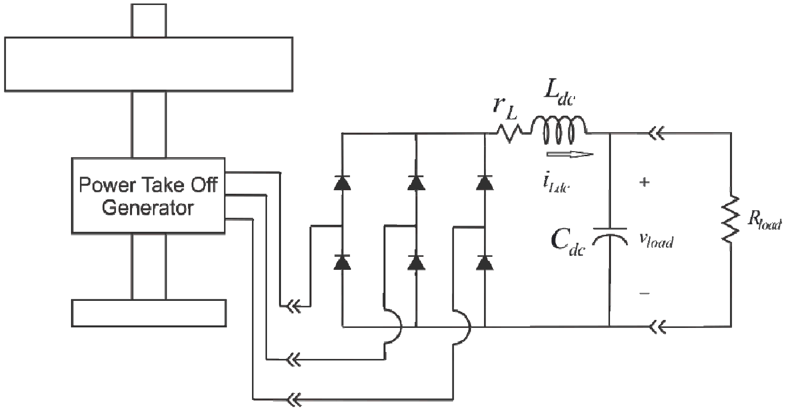
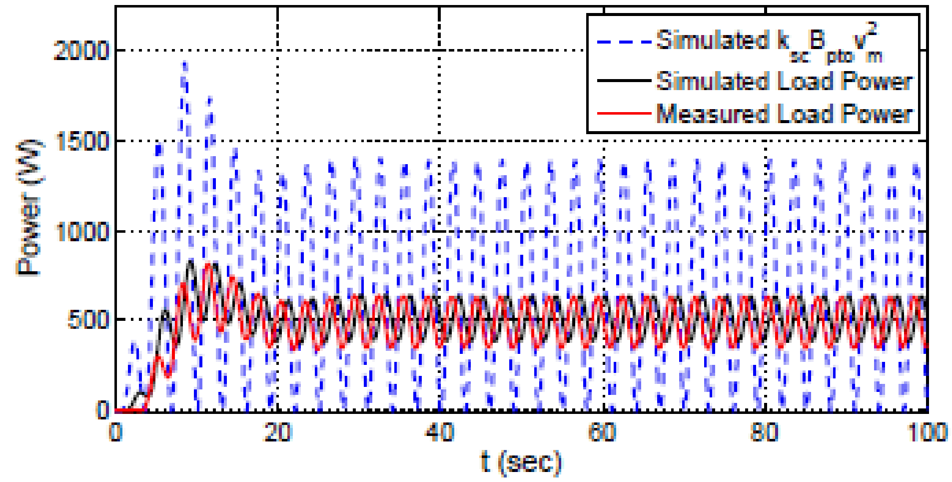
Point Absorber Emulator Hardware Tests Agree with Simulation

- **The emulator is tested for a regular wave with a wave period of 6 seconds and a peak wave height of 1 meter**







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