PHIL Validation of Ultracapacitor Storage for Black Start Application*

*National laboratory contributions were funded by the U.S. Department of Energy’s Water Power Technologies Office as part of the HydroWIRES Initiative.
DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.
Idaho Falls Power is municipal utility with five ROR hydropower plants on upper Snake River

- Plants all connected to city’s distribution and sub-transmission system.
- Under normal conditions, plants are operated for maximum efficiency. Balancing is performed by Rocky Mountain Power.
  - 8.9 MVA Upper Plant (ROR, Horizontal Kaplan Bulb)
  - 8.9 MVA City Plant (ROR, Horizontal Kaplan Bulb)
  - 8.9 MVA Lower Plant (ROR, Horizontal Kaplan Bulb)
  - 2 x 1.8 MVA Old Lower Plant (ROR, Vertical Francis)
  - 22.6 MVA Gem State Plant, (Vertical Kaplan)

Additional Info: [https://www.ifpower.org/](https://www.ifpower.org/)
Islanded Distribution Grid Black start: Successful Field Demonstration with Idaho Falls Power

Idaho Falls Power, with Idaho National Lab, tests small hydro’s black start capabilities
Islanded black start with ROR hydropower

From the December 2017 Field Test

- Load stepping causes frequency stability issues
  - Potential trip off during black start
  - Critical load carrying capability is limited
- Hydrogovernor and frequency protection settings need adjustment

Can energy storage integration demonstrate improvement?
Energy Storage

- Ultracapacitor
  - High power density
  - Small form factor
  - Enables mobility

Steps to de-risk the field demonstration

**Modeling**
- Collect hydrogovernor data in grid connected mode of operation
- Develop hydrogovernor model for ROR hydropower on Simulink

**Simulation**
- Set hydrogovernor in islanded mode
- Analyze response to load step change on Simulink
  - Without UCAP
  - With UCAP

**Test**
- Develop RSCAD model for digital real-time simulation (DRTS)
- Conduct power hardware-in-the-loop (PHIL) test
RSCAD modeling for digital real-time simulation

- Grid Following Inverter
- 480 VAC Bus
- Ultracapacitor (UCAP) system
- Bulb-style hydropower plant
- Critical loads on Idaho Falls Power system
AMETEK 540 kVA Grid Emulator
Tektronix Current Probing Assembly

[Image of Tektronix Current Probing Assembly]

Current Probe

To GTAII
“Closed-loop” Power Hardware In-the-Loop Testing

What capacitance does the grid emulator see?

How to calibrate?

710 – 1000 VDC,
Trips at 650 VDC
Ultracapacitor Characterization

\[ C_{480VAC} = \frac{2 \times 1000}{N_c(950^2 - 750^2)} \sum_{n=1}^{N_c} P_n [\text{kW}] \times \Delta t_n \]

- \( C_{480VAC} = 6.7 \, \text{F} \)
How to set DRL, $K_v$, and $K_i$?
Analyze DRL Sensitivity through f-Watt Responsive Current Synthesis
Set DRL

\[ RS = 100 \times \left( 1 - \frac{I_{\text{Ref}}}{I_{\text{Branch}}} \right) \]
Set $K_v$

- Peak analog input to AMETEK grid emulator: 10 V
- Grid emulator’s line-to-neutral amplification factor: 40
- Line-to-neutral peak value at 480 VAC bus $\approx 0.4$ kV
- $0.4 \times K_v = 10$
- $K_v = 25$
Set $K_i$

$K_i = 78$ from

$$K_i = \frac{1}{N_L} \sum_{n=1}^{N_L} \frac{I_{\text{Emulator}}}{I_{RSCAD}}$$
<table>
<thead>
<tr>
<th>Event Number</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>UCAP ESS: Disable inverter operation. Current injection model: 'Disable'</td>
</tr>
<tr>
<td>E2</td>
<td>“Lower Bulb” Unit: Set “Initial Mode of Lock/FreeSwitch” to “Lock” under “Mechanical Data and Configuration”.</td>
</tr>
<tr>
<td>E3</td>
<td>Dynamic Load Bank”: Set the desired value for steady-state load.</td>
</tr>
<tr>
<td>E4</td>
<td>Run load flow and initialize hydrgovernor turbine settings according to [6], [7]. This step must be repeated for each steady-state electric loading and prior to stepload change.</td>
</tr>
<tr>
<td>E5</td>
<td>Compile the draft file and load to RUNTIME.</td>
</tr>
<tr>
<td>E6</td>
<td>Start simulation and “unlock” the “Lower Bulb Unit” from E2.</td>
</tr>
<tr>
<td>E7</td>
<td>Apply a desired step load change on the “Dynamic Load Bank” and observe frequency and other variables of interest.</td>
</tr>
<tr>
<td>E8</td>
<td>Stop the simulation.</td>
</tr>
<tr>
<td>E9</td>
<td>EPC converter: Load the desired f-Watt setting via the EPyQ GUI. Enable inverter operation and current injection system from E1. Repeat E2 - E8.</td>
</tr>
</tbody>
</table>
Test UCAP system injection rates

3 MW initial load, 375 kW step load up

Ultracapacitor (45/50/55)

Ultracapacitor (35/40/45)

No ultracapacitor

Time (s)

Frequency (Hz)

Ultracap Injection (%)
Observe UCAP response

Power Injection from UCAP

Instantaneous Current Injection at 480 VAC Bus
Test maximum step load size

2 MW initial load, testing response to varying step load ups

Time (s)

*Graph showing response to varying step load ups for different kW values: 300 kW, 350 kW, 375 kW, 400 kW.*
Conclusions

• RSCAD Model is Publicly Available on GitHub
  - https://github.com/IdahoLabResearch/Hydropower_Unit_Models

• Key findings
  - Pre-characterization of energy storage response drives the inverter control design.
  - A systematic approach to real-time simulation model calibration with hardware response can reduce effort and cost for PHIL preparation.

• Next steps
  - Develop operational-mode-aware-coordination scheme between hydrogovernor and inverter control for transient stability.
  - Explore inverter integration beyond grid following mode operation and frequency droop-based control to further improve islanded operation stability (e.g., lower the ROCOF, dampen oscillation).
Reference: Alam et al. 2022 “Enhancing Local Grid Resilience with Small Hydropower Hybrids: Proving the concept through demonstration, simulation, and analysis with Idaho Falls Power”, INL/RPT-22-69038. DOI: https://doi.org/10.2172/1891110

Reference: Alam et al. 2022 “Power Hardware-In-the-Loop Hydropower and Ultracapacitor Hybrid Testbed”, IEEE PES GM 2022. DOI: https://doi.org/10.1109/PESGM48719.2022.9917167