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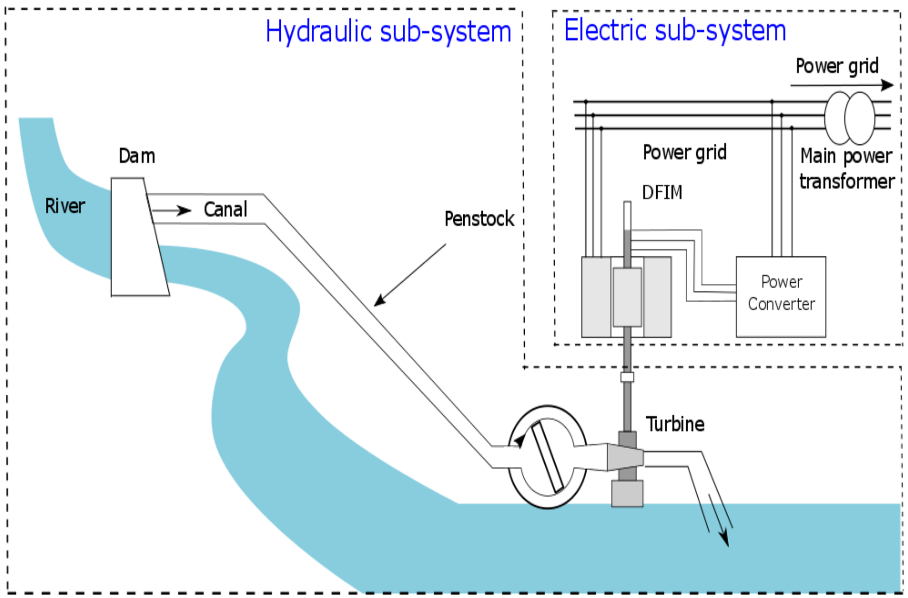
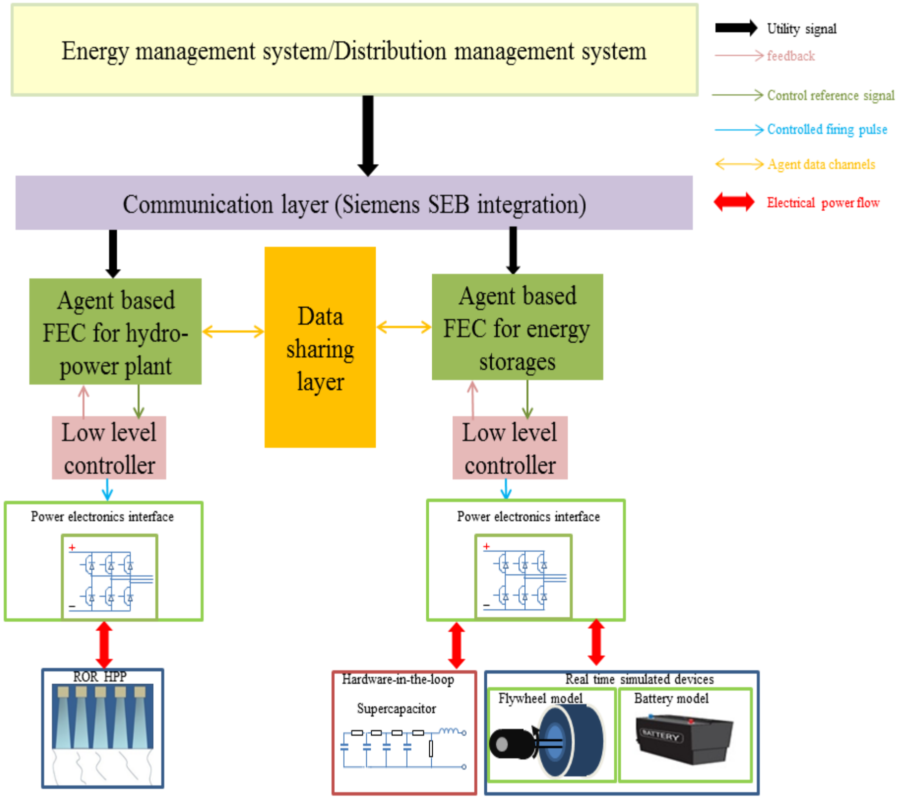


Run-Of-the-River Hydro Power Plant



Integrated Hydropower and Storage Systems Operation for Enhanced Grid Services

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February 2017

Project Overview

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Run-Of-the-River Hydropower Plant and Energy Storage: Develop integration strategies for Run-Of-the-River (ROR) Hydropower Plant (HPP) and energy storage to provide ancillary services and enhance revenue streams. Control and integration of Energy Storage Systems (ESS), cohesive response to network events, interaction of multiple ROR HPPs with grid, and its equivalence to a large HPP are other objectives of this proposal.

The Challenge: Constructing a new, large hydropower plant is a challenging proposition with multiple dimensions. Additionally, a significant (~65 GW) untapped, small head, hydro resource exists in the US. Grand challenge of emulating the behavior of a large hydropower plant by combining and cohesively controlling multiple, small ROR HPP with energy storage.

Partners:

- ANL is assessing the potential ancillary service market avenues
- INL is performing the real-time modeling of ESS and Hardware-In-the-Loop (HIL) and ROR HPP modeling and system level integration
- NREL is performing the machine modeling and gap analysis for ROR HPPs
- Siemens and INL are implementing controls and communications to control all the ROR HPP and ESS

Next Generation Hydropower (HydroNEXT)

Optimization

- Optimize technical, environmental, and water-use efficiency of existing fleet
- Collect and disseminate data on new and existing assets
- Facilitate interagency collaboration to increase regulatory process efficiency
- Identify revenue streams for ancillary services

Growth

- Lower costs of hydropower components and civil works
- Increase power train efficiency for low-head, variable flow applications
- Facilitate mechanisms for testing and advancing new hydropower systems and components
- Reduce costs and deployment timelines of new PSH plants
- Prepare the incoming hydropower workforce

Sustainability

- Design new hydropower systems that minimize or avoid environmental impacts
- Support development of new fish passage technologies and approaches
- Develop technologies, tools, and strategies to evaluate and address environmental impacts
- Increase resilience to climate change

Next Generation Hydropower (HydroNEXT)

Optimization

- Optimize technical, environmental, and water-use efficiency of existing fleet
- Collect and disseminate data on new and existing assets
- Facilitate interagency collaboration to increase regulatory process efficiency
- Identify revenue streams for ancillary services

The Impact

- Multiple ROR HPPs can provide larger cumulative rating of the unit and hence wider avenues
- Some impacts, such as the inertial response, are expected to contribute to greater stability of power systems with high penetration of renewable energy generation.
- These tools will facilitate the development of control algorithms customized to specific ROR HPPs and suitable ESS in order to achieve better operational responses.
- First real-time co-simulation between electrical and hydrodynamic circuits along with the HIL of ESS is being performed
- New control and optimization techniques of cohesively operating unique assets (ROR and ESS) will be studied and implemented

Next Generation Hydropower (HydroNEXT)

Growth

- Lower costs of hydropower components and civil works
- Increase power train efficiency for low-head, variable flow applications
- Facilitate mechanisms for testing and advancing new hydropower systems and components
- Reduce costs and deployment timelines of new PSH plants
- Prepare the incoming hydropower workforce

The Impact

- The project will provide the industry and power system operators with the tools to perform simulations and modeling of ROR HPP and integrate unique storage technologies, allowing for better understanding of their impacts on the stability of power systems.
- This project features a unique real-time integration of hydropower generators and multi-scale energy storage systems as HIL with an aim of providing responses of varying magnitudes at desired rates
- The control topologies developed and implemented in this project (on an open platform - SEB), in collaboration with a vendor will demonstrate both lab-based as well practical implementation in the field
- Modeling and testing of hydrodynamics, power systems, thermal management, with HIL of supercapacitors and batteries is a unique experimentation to achieve V&V

Technical Approach – Ancillary Services

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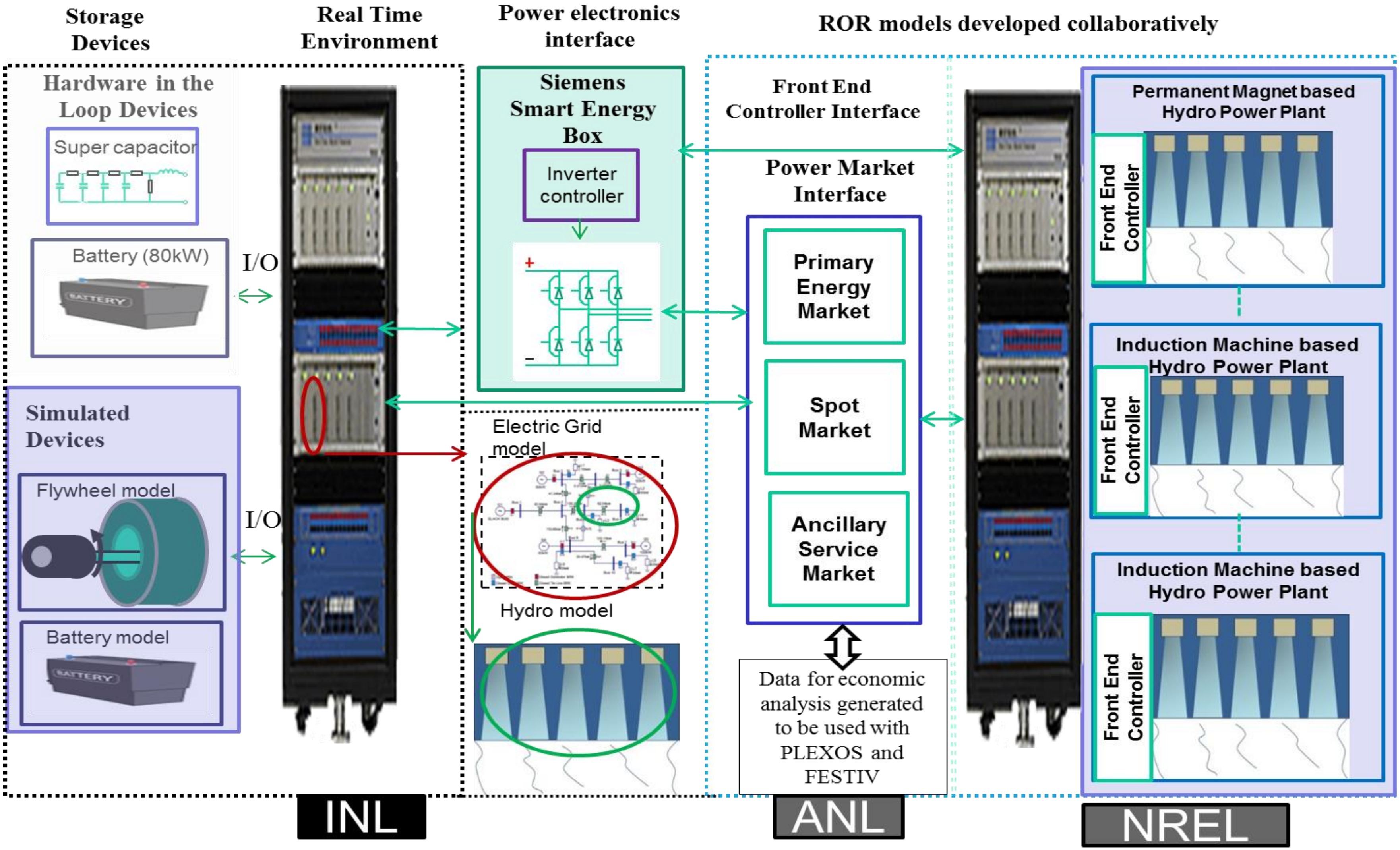
- Cohesive response of multiple ROR HPPs and ESS to provide ancillary services with a specific focus shown below:

Market description	Proposed	Primary	Secondary	Tertiary
Reserve type	**Power electronically interfaced**	Spinning	Spinning	Non-spinning
Timescale of response	**Smaller (µs – ms)**	Medium (ms – s)	Longer (s – minutes)	Longer (minutes – hours)
Timescale of discharge	**µs – minutes**	several minutes	30 minutes – 2 hours	several hours
Application	**Transient stability, power quality corrections**	Operating reserve for regulation, fault recovery, power quality	Operating reserve for slow dynamics, voltage support, contingency	Load leveling, energy arbitrage, firming, contingency
Example technologies	**Supercapacitors, flywheels**	Synchronous generators, batteries	Synchronous generators, batteries	Pumped hydro, gas turbines

Technical Approach – System Architecture

- Overall project implementation of simulations and hardware



Technical Approach – Summary

- A cohesive operation of multiple ROR hydropower plants and ESS
- ESS comprises of multiple time-scale systems such as supercapacitors, flywheels, and batteries
- ESS is capable of short to long term support based on ROR power output and response requests
- Coordination and controls between the components is based on ‘Siemens Smart Energy Box (SEB)’ which is an open platform developed by Siemens
- ROR does not have the inherent storage flexibility therefore it can only participate in the primary energy market
- Real-time ROR models with ESS & SEB hardware will be tested in real-time grid models to register responses to dynamic conditions
- Economic analysis based on the cohesive response under different dynamic market conditions will be generated and analyzed

Technical Approach – Frond End Controller

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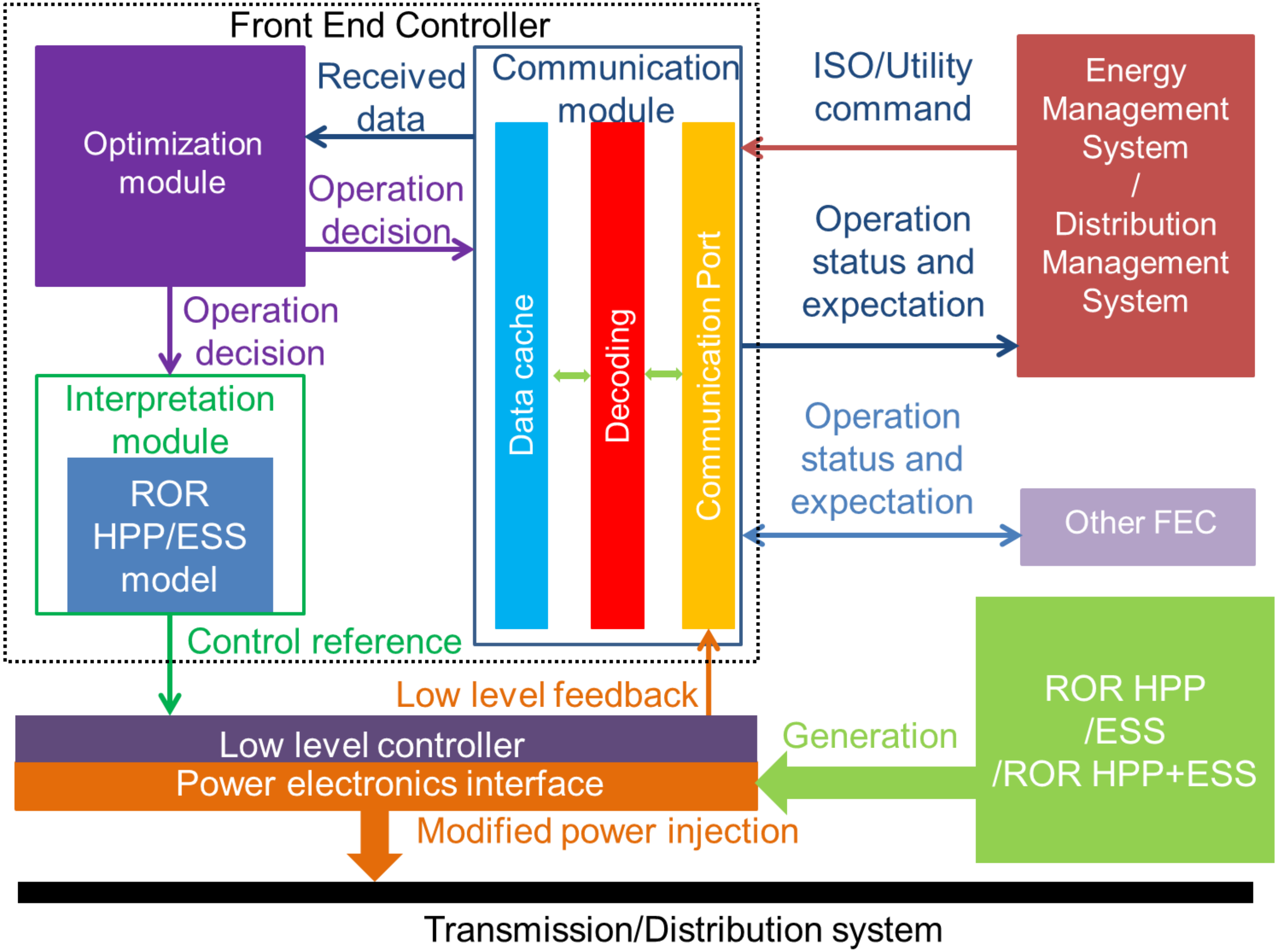
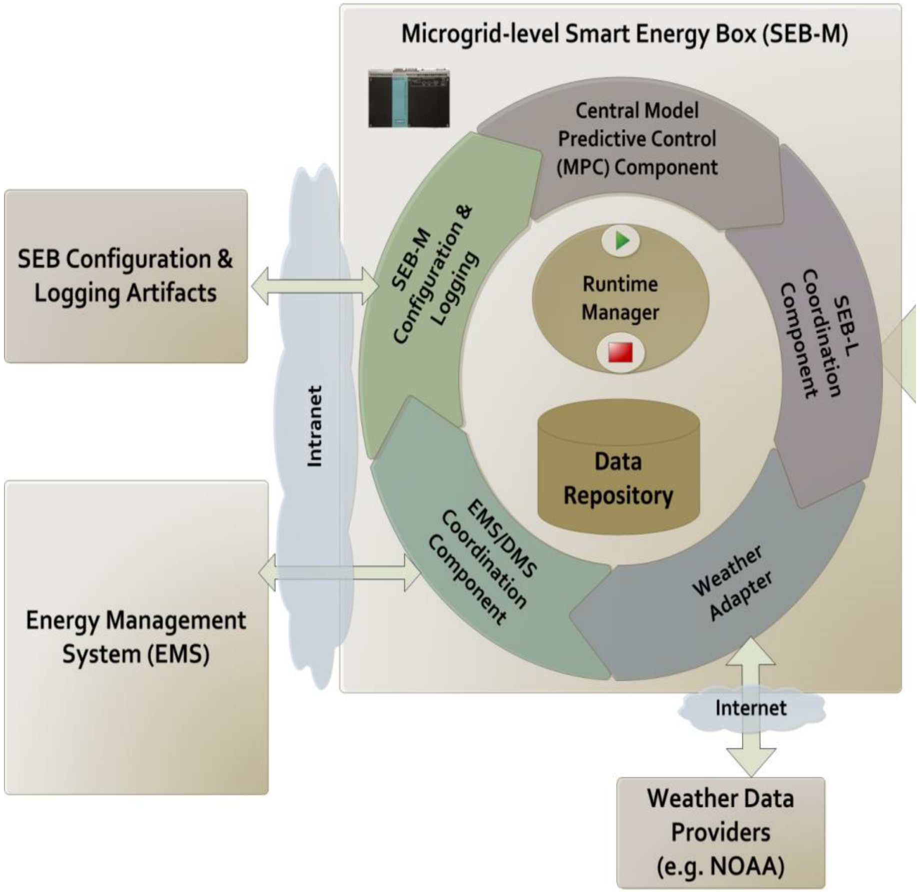
- System operators should be able to communicate optimal dispatch generation tasks to each ROR HPP
- A local control center is required to aggregate information from multiple ROR HPPs and communicate with upper level system operators
- The communication network is required to provide low-latency, high-reliability, and high availability communications
- Control system of ROR HPP should be capable of reading interpreting and forwarding received operator commands to the Low Level Controller (LLC)
- Combine multiple ROR HPP locating within the same distribution network, coordinating their operation so that the total generation output can approach a conventional HPP

Technical Approach – FEC Architecture



Functions of Siemens SEB



- Optimization
- Decentralized control
- Agent based asset management
- Grid integration and interface
- Communications (local and global)
- Data and event logging

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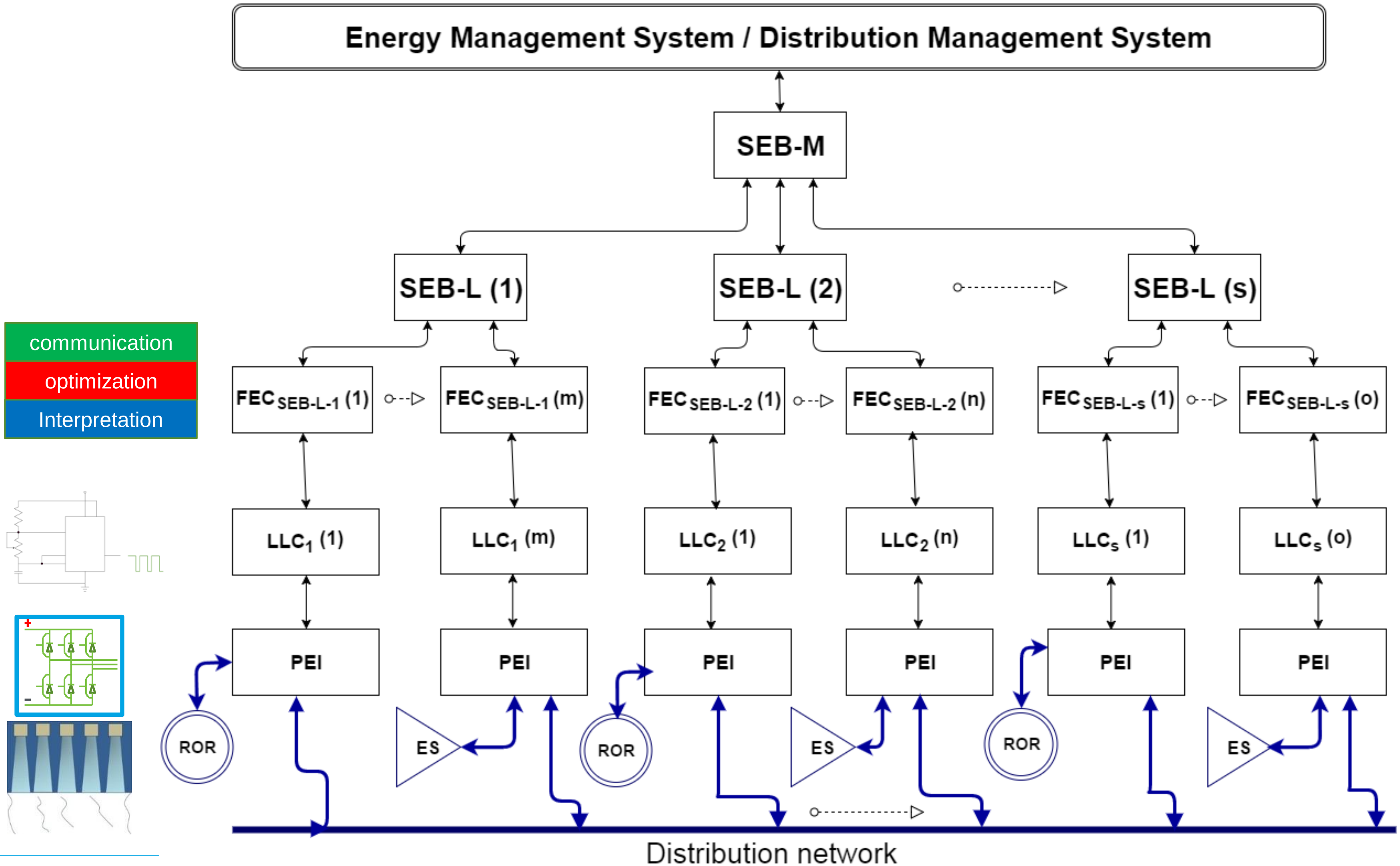
- Control Architecture for integrating ROR HPP with ESS and power grid



Accomplishments

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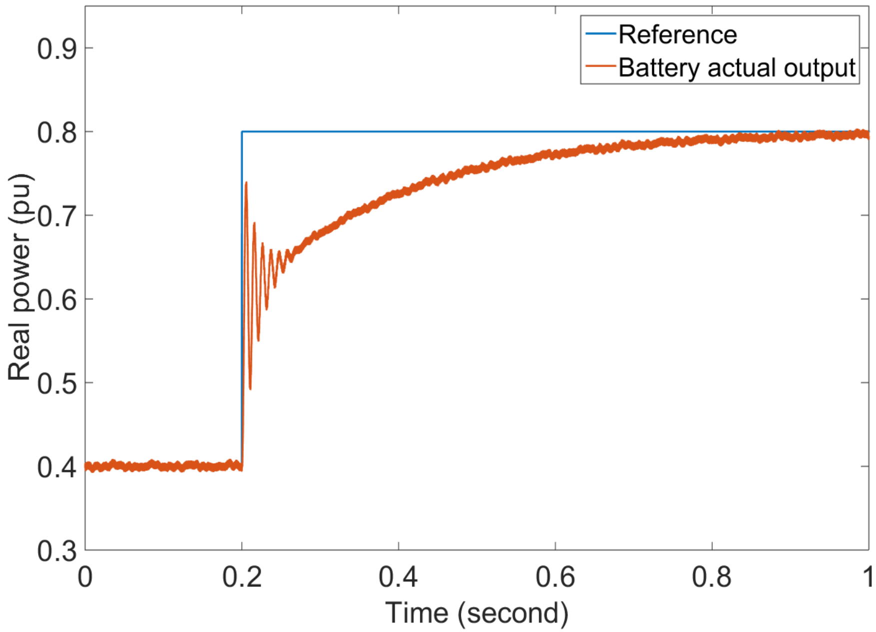
- ROR HPP generation topology has been analyzed and modeled by NREL
- Analysis on market level and water flow data has been conducted by ANL
- Literature review on ESS is concluded and a hybrid ESS solution has been selected and progressively implemented in INL
- Several ESS models have been jointly developed by INL and NREL
- ESS hardware has been installed and commissioned at INL
- Distribution system integrating ROP HPP and ESS has been built in INL's DRTS
- FEC's function development has been completed with three modules proposed: communication module, optimization module, and interpretation module
- Real time simulation test is being performed to test FEC's functionalities

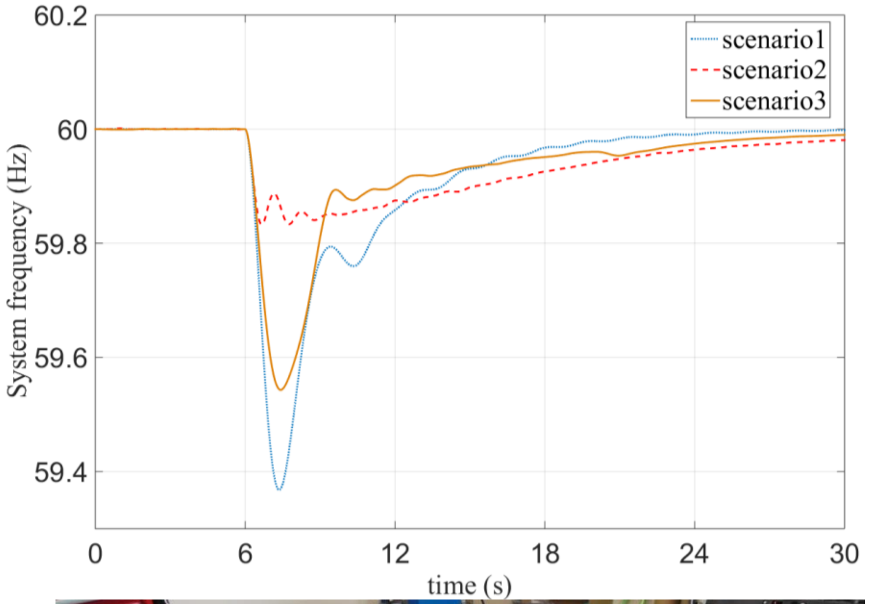
Accomplishments and Progress – Battery as Hardware-In-the-Loop

- Battery storage is used to provide steady long term energy support
- Commissioned 128 kW flow battery system is capable of storing 320 kWh energy
- Test result shows when reference signal step up from 0.4 p.u. to 0.8 p.u., it takes 0.8 seconds to finish the step response

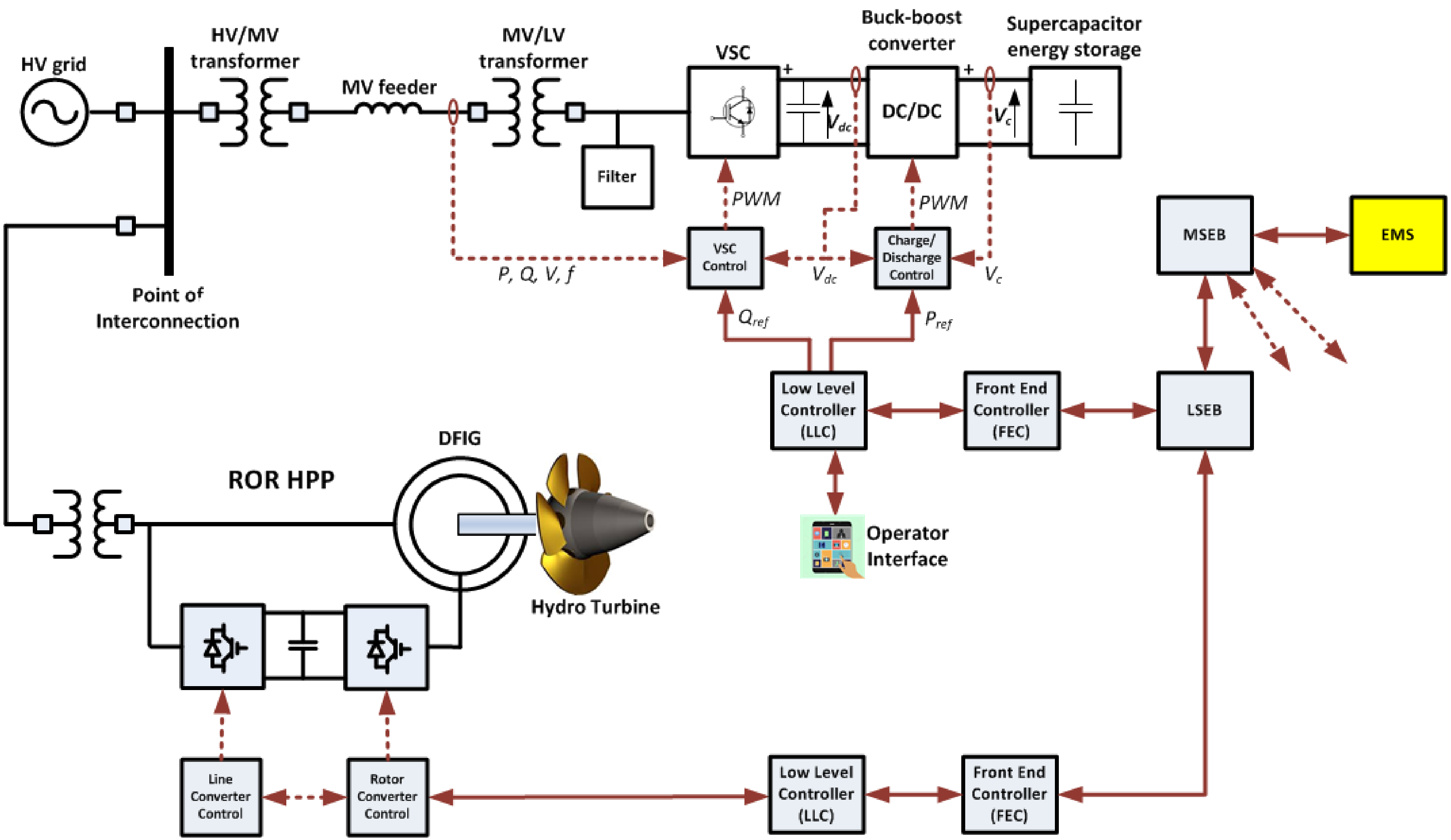


Accomplishments and Progress – Supercapacitor as Hardware-In-the-Loop

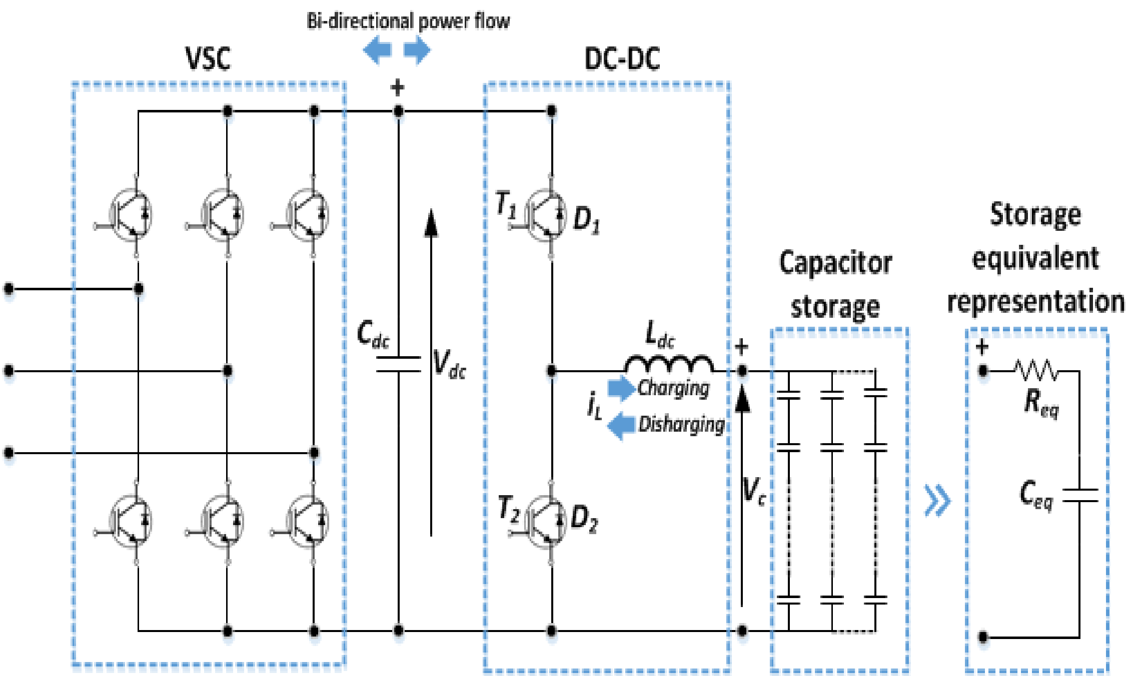
- Supercapacitors provide instantaneous high power support with advanced thermal management
- 4F supercapacitor energy storage system initial stores 4 kV voltage and responds to load increase from 10 MW to 19 MW
  - ➢ Scenario1: Synchronized generator functions to restore frequency
  - ➢ Scenario2: Supercapacitors without and with thermal management support frequency restoration
  - ➢ Scenario3: Supercapacitors with and with thermal management support frequency restoration



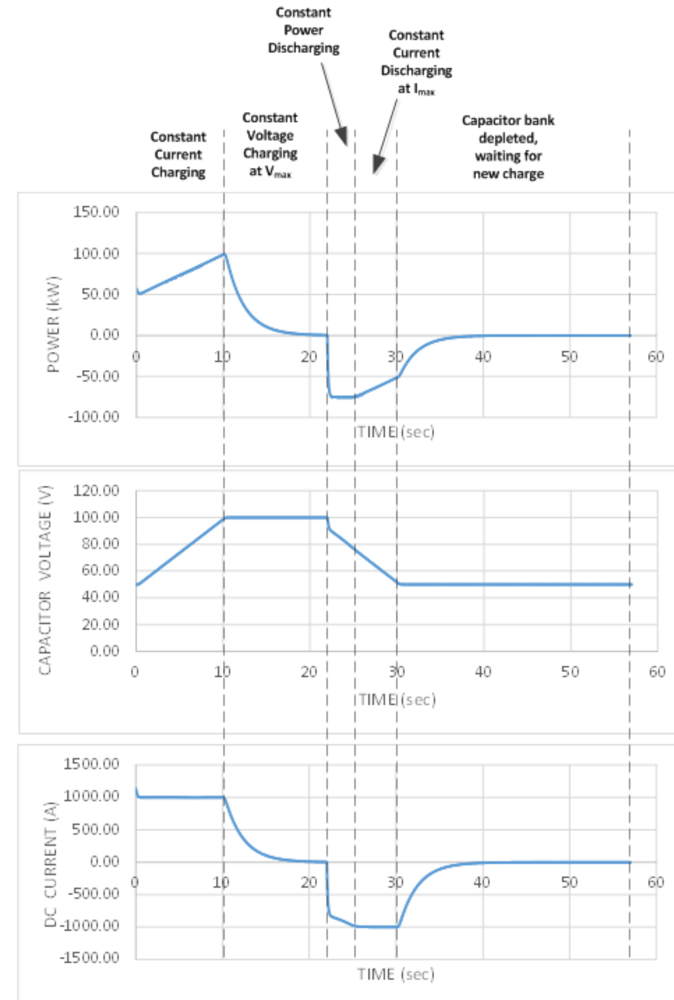
Accomplishments and Progress - Supercapacitor Storage Coupled with ROR



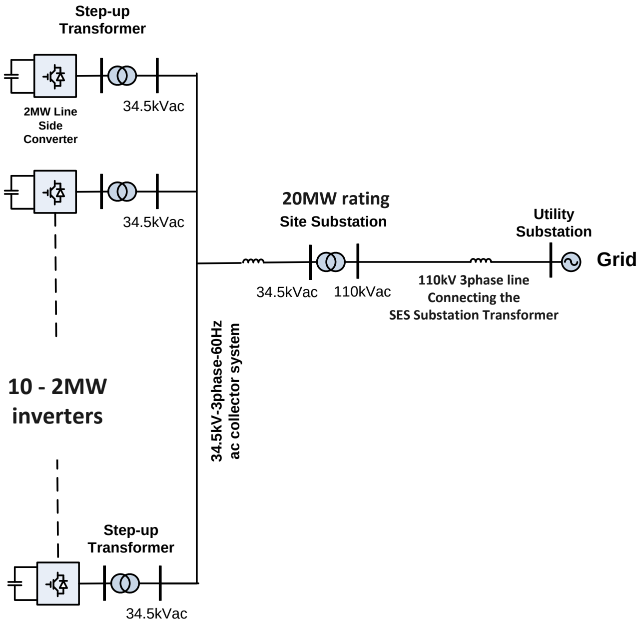
Electric topology of supercapacitor energy storage



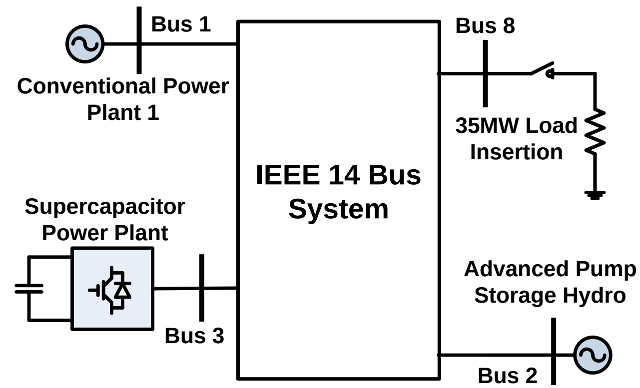
Supercapacitor charge/discharge control



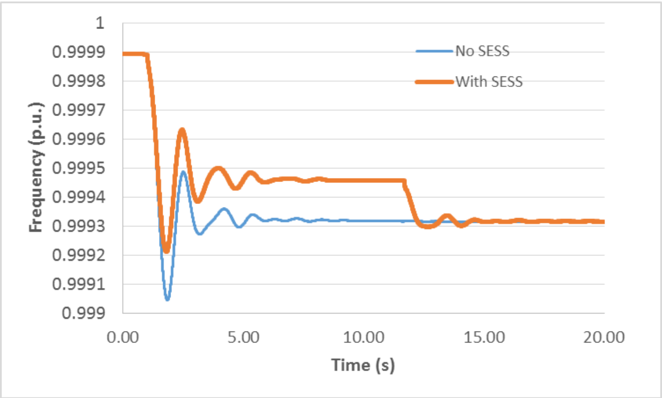
Single line diagram of 20 MW supercapacitor storage plant model



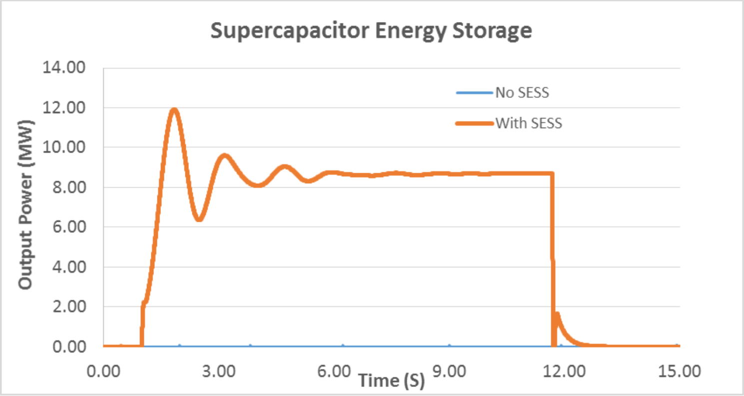
20 MW supercapacitor storage plant model connected to IEEE 14-bus test system's PSCAD model



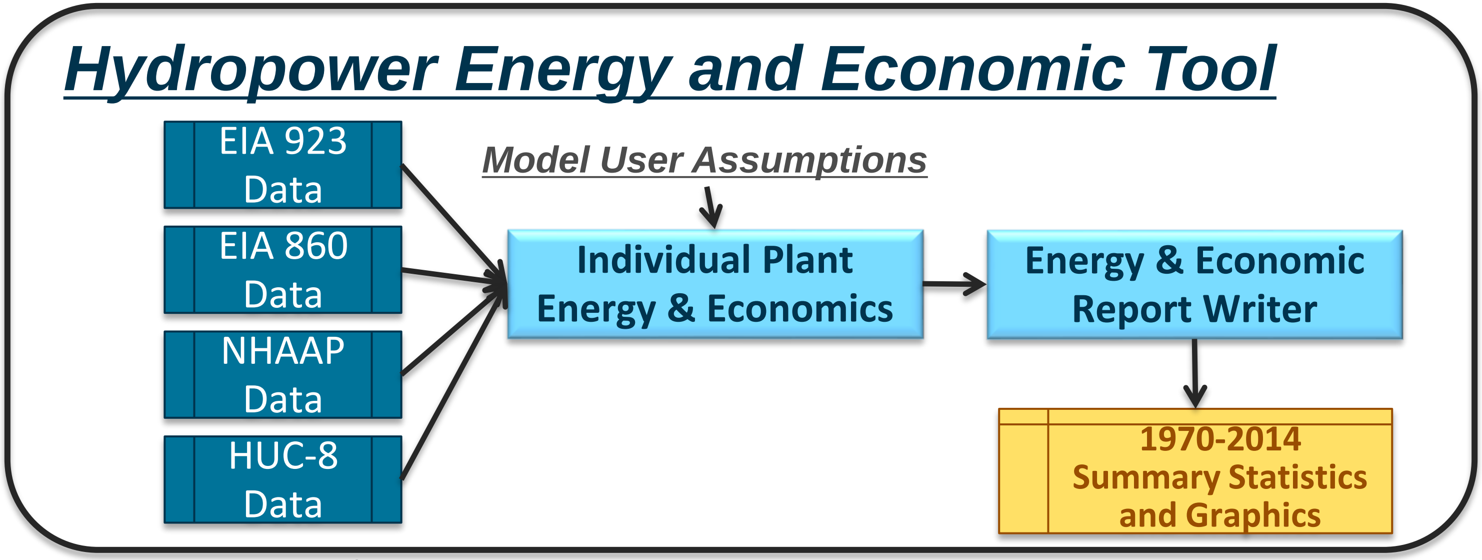
Grid frequency comparison between system with and without Supercapacitor Energy Storage System



Output power from a Supercapacitor Energy Storage System delivered with governor control scheme.



- The hydropower energy and economic evaluation toolkit assesses and displays historical monthly generation and economic values
  - Based on user defines assumptions about operational flexibility and market participation
  - *Energy Economics:* Uses generation profiles and market prices
  - *Capacity Economics:* Based on maximum output during month(s) of peak demand, risk preference, and replacement of market value (e.g., CONE[1])



[1] *Cost of New Entry Used by PJM for Capacity Market Price Caps*

Currently Running Number ID: 5

RUN

Percent of real-time sales: 90

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
% above ave. gen.	5	5	5	5	5	5	5	5	5	5	5	5
Season	Winter	Winter	Winter	Winter	Summer	Summer	Summer	Summer	Summer	Summer	Winter	Winter

Run ID #	Perform Run	Hyrdropower Plant Name	EIA Plant Code	HU[illegible]8	Start Time	Stop Time	Run Time
1	TRUE	Ban[illegible]head Dam	2	03[illegible]	07/11 20:59:14	07/11 20:59:15	[illegible]:01
2	TRUE	Walter Bo[illegible]lin Dam	4	0[illegible]	07/11 20:59:15	07/11 20:59:16	[illegible]
3	TRUE	H Neely Hen[illegible]	11	[illegible]	[illegible]20:59:16	07/11 20:59:17	00:0[illegible]
4	TRUE	Holt Dam	[illegible]	[illegible]	[illegible]9:17	07/11 20:59:18	00:01
5	TRUE	Jordan Da[illegible]	[illegible]	[illegible]	[illegible]9:18	07/11 20:59:19	00:01
6	TRUE	Logan Ma[illegible]	[illegible]	[illegible]	[illegible]9:19	07/11 20:59:20	00:01
7	TRUE	Lay Dam	[illegible]	[illegible]	[illegible]9:20	07/11 20:59:21	00:01
8	TRUE	Martin Da[illegible]	[illegible]	[illegible]	[illegible]9:21	07/11 20:59:22	00:01
9	TRUE	Mitchell D[illegible]	[illegible]	[illegible]	[illegible]9:22	07/11 20:59:23	00:01
10	TRUE	Lewis Smith Dam	18	03160110	07/11 20:59:23	07/11 20:59:24	00:01
11	TRUE	Thurlow Dam	19	03150110	07/11 20:59:24	07/11 20:59:25	00:01
12	TRUE	Weiss Dam	20	03150105	07/11 20:59:25	07/11 20:59:26	00:01
13	TRUE	Yates Dam	21	03150110	07/11 20:59:26	07/11 20:59:27	00:01
14	TRUE	Rollins	34	18020126	07/11 20:59:27	07/11 20:59:28	00:01
15	TRUE	Millers Ferry	38	03150203	07/11 20:59:28	07/11 20:59:29	00:01
16	TRUE	Guntersville	48	06030002	07/11 20:59:29	07/11 20:59:30	00:01
17	TRUE	Wheeler Dam	49	06030005	07/11 20:59:30	07/11 20:59:31	00:01
18	TRUE	Gantt	53	03140301	07/11 20:59:31	07/11 20:59:32	00:01
19	TRUE	Point A	55	03140301	07/11 20:59:32	07/11 20:59:33	00:01
20	TRUE	Annex Creek	62	19010301	07/11 20:59:33	07/11 20:59:34	00:01
21	TRUE	Gold Creek	63	19010301	07/11 20:59:34	07/11 20:59:35	00:01
22	TRUE	Salmon Creek 1	65	19010301	07/11 20:59:35	07/11 20:59:36	00:01

One Button Click Evaluates all User Selected Plants

Monthly Generation Profiles Are Based on Operational Flexibility Assumptions

User Defined Splits of Energy Sales Between Real-time & Day-ahead Markets

Each Selected Plant Is Evaluated in about 1 second

Market	LMP Bus/Zon	Year	Month	PeakCat	Price.m	Price.s	Price.max	Price.min
DA	AECO	2000	6	Off-Peak	12.41	6.37	38.56	-0.23
DA	AECO	2000	6	Peak	42.01	21.56	102.22	12.00
DA	AECO	2000	7	Off-Peak	11.74	3.72	21.00	0.10
DA	AECO	2000	7	Peak	33.09	16.60	100.00	10.86
DA	AECO	2000	8	Off-Peak	14.43	6.66	50.00	0.10
DA	AECO	2000	8	Peak	41.34	23.16	140.00	0.10

A Plant Is Linked to a Specific Bus, Zone, or Region that Contains Energy Market Price Profiles

Accomplishments and Progress – Statistics and Results from Economic Assessment

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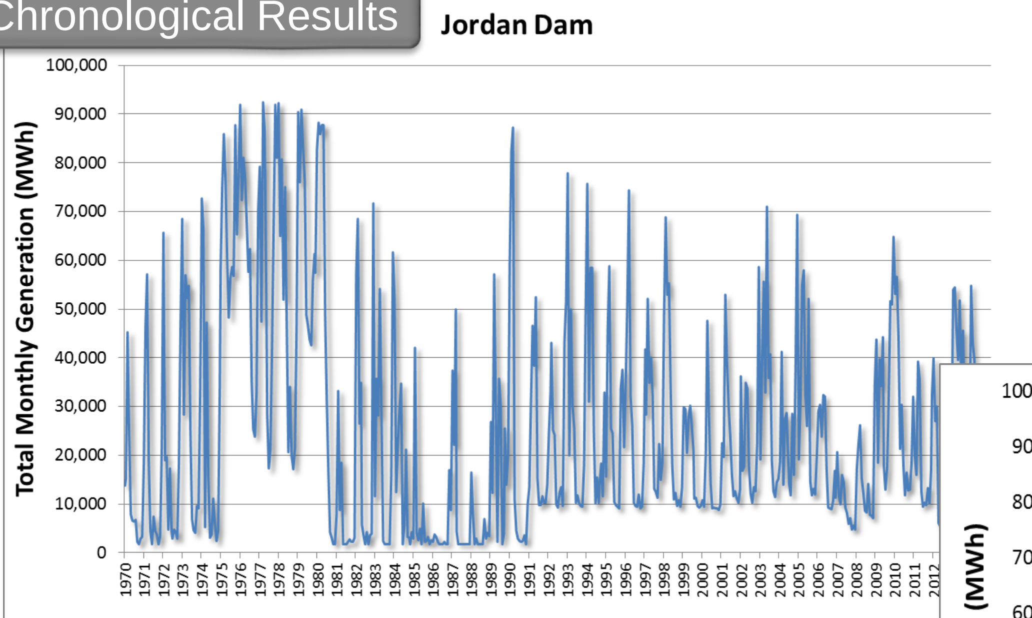
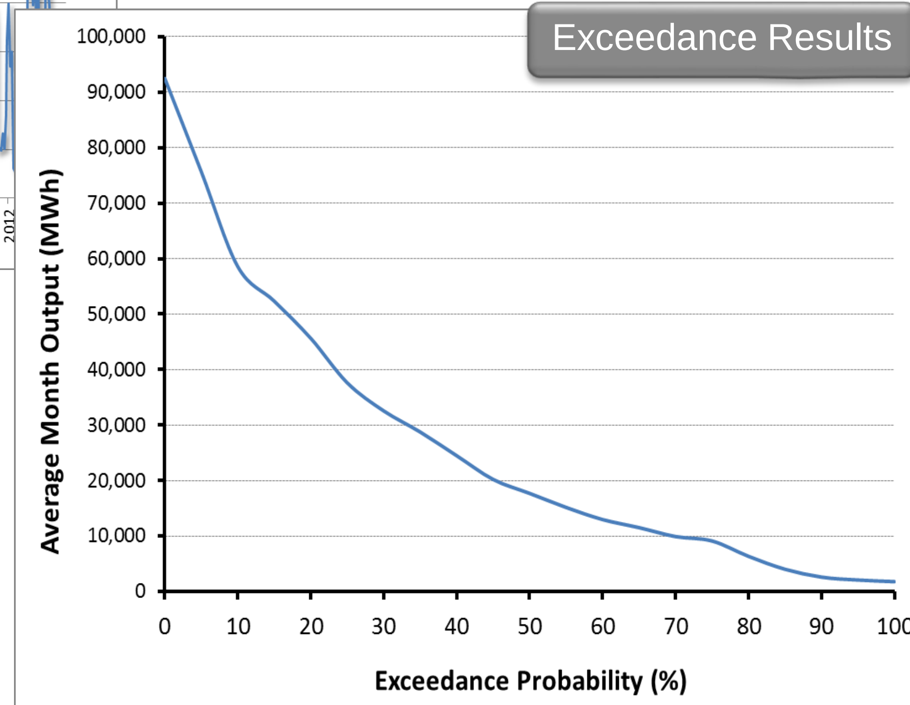
Chronological Results



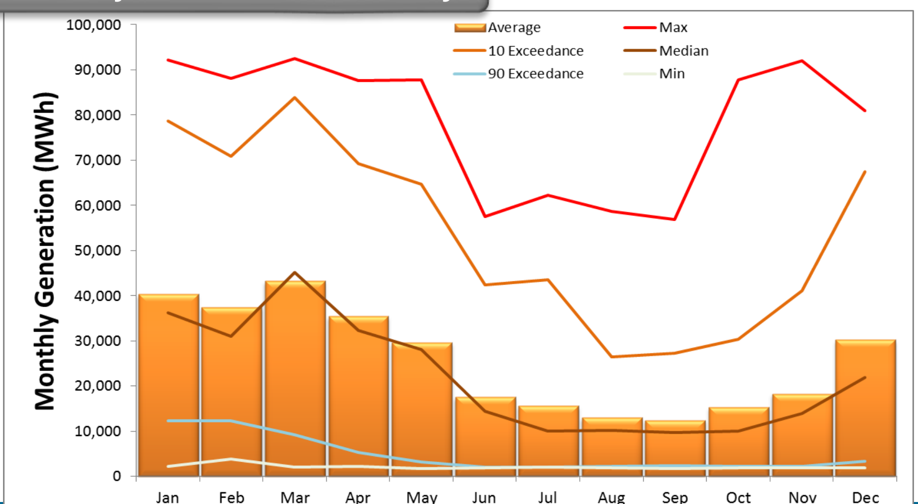
Results can be summarized by:

- Power plant
- Area (State, market, region, etc.)
- Plant type
- For selected month and periods

Exceedance Results

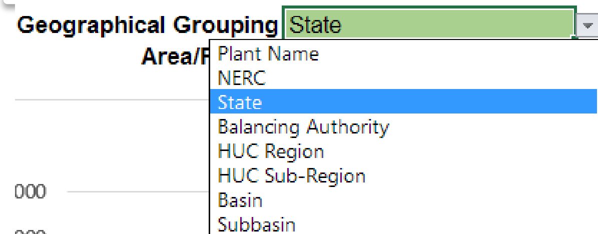


Monthly Trends & Variability

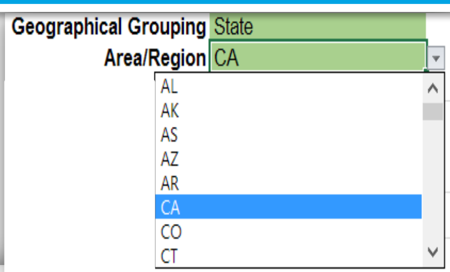


Accomplishments and Progress - EZMT Displays ROR Data and Analysis Results

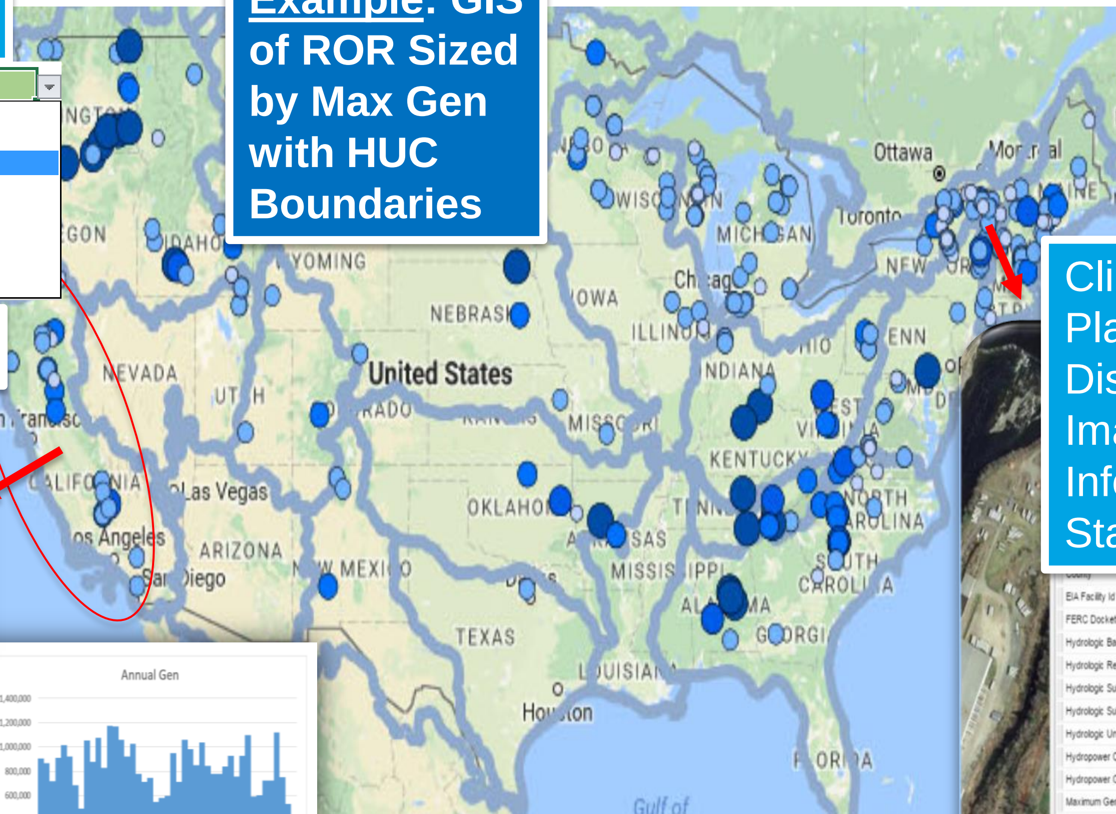
Geographical Selection



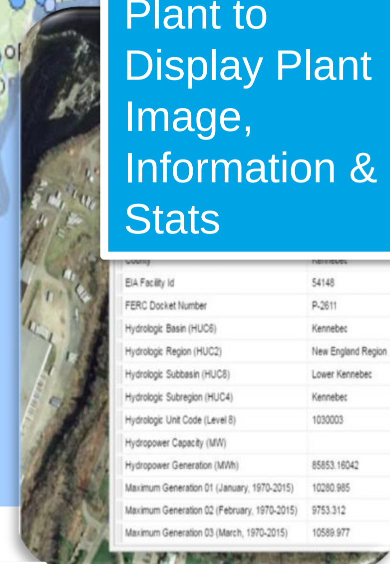
Plant/Region Selection

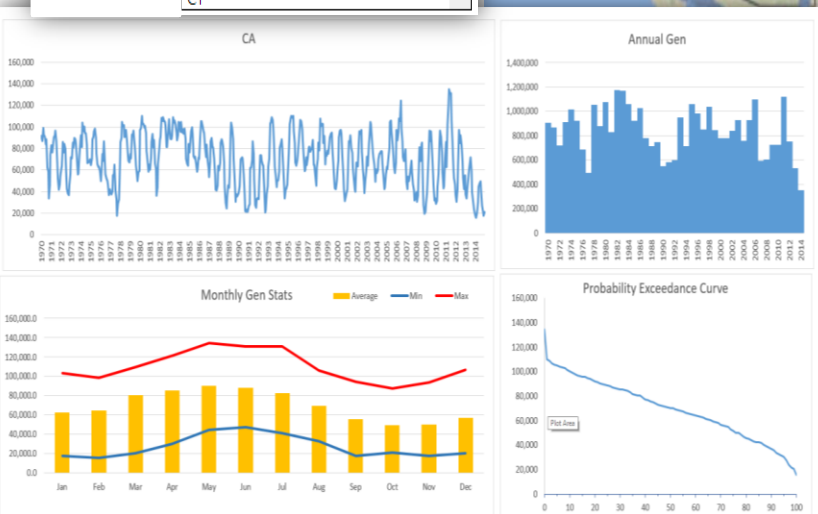


<u>Example</u>: GIS of ROR Sized by Max Gen with HUC Boundaries



Click on a ROR Plant to Display Plant Image, Information & Stats





RGE Result Writer Linked to EZMT

EZMT – Energy Zones Mapping Tool (https://ezmt.anl.gov)

Project Plan & Schedule

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- This project is funded for three years
- Initiation date – October 2015
- Completion date – September 2018

Project Budget

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Budget History (INL)					
FY2016		FY2017		FY2018	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$350K	N/A	$325K	N/A	$300K	N/A
Budget History (NREL)					
$200K	N/A	$275K	N/A	$200K	N/A
Budget History (ANL)					
$200K	N/A	$200K	N/A	$200K	N/A
Budget History (Siemens)					
$150K	$50K	$150K	$150K	$175K	N/A

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- ANL is assessing the potential ancillary service market avenues
- INL is performing the real-time modeling of ESS and Hardware-In-the-Loop (HIL) and ROR HPP modeling and system level integration
- NREL is performing the machine modeling and gap analysis for ROR HPPs
- Siemens and INL is implementing controls and communications to control all the ROR HPP and ESS
- Collaboration with GMLC 1.3.9: Smart Reconfiguration of Idaho Falls Power Distribution Network for Enhanced Quality of Service
  - Integration of 3 ROR plants to provide generation for an islanded city grid to enhance resilience
  - Provides reliable supply to the critical loads during transmission level outages

Communications and Technology Transfer:

- "Novel Control Strategy for Multiple Run-of- the-River Hydro Power Plants to Provide Grid Ancillary Services," Submitted to HydroVision, Denver, CO, 2017.

Next Steps and Future Research

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FY17/Current research:

- Siemens SEB will be used to develop the hardware implementation of the FEC that will be used with the RTDS as a Controller-Hardware-In-the-Loop (CHIL). This will serve to verify the design performance of FEC based on actual hardware. The integration of SEB with the RTDS will be performed to ensure real time connectivity between the two.
- INL and NREL will perform a ‘one-of-a-kind’ distributed real-time simulation using real-time simulators and controllable grid interface (CGI) to perform verification of control algorithms
- ANL will optimize single project ROR HPP/EES operations under different plausible power sector futures. Create cascaded systems and estimate aggregate value streams. Analyze, summarize, and document results.

Proposed future research:

- Team will analyze, document, and disseminate the results of ROR HPP/storage values to the hydropower industry. A document describing project methods and results will be completed and published as an INL technical report. A combination of the potential energy to deliver primary and secondary frequency response, and a capability to deliver a large inertial response will significantly improve the AS-PSH system to become the clearing house of the fast frequency response provider. Economic assessment of the overall system will be performed in CHEERS software and its details will be included in the report.