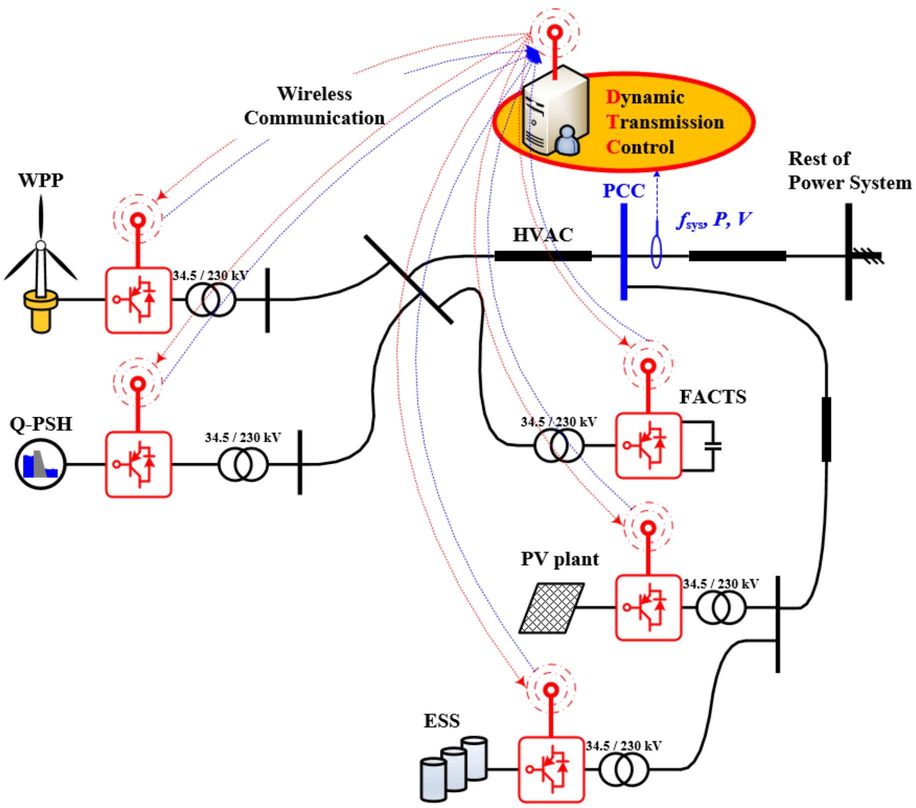

Transforming the U.S. Market with a New Application of T-PSH Technology

WBS#: 02.02.03.00.404

Hydropower Program

October 9, 2019

Mark Jacobson

NREL

Project Overview

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Project Summary

- Problem: The U.S. electrical grid is seeing a huge increase in new renewable energy (RE) generation and at the same time, a huge amount of thermal generation retirements. This dynamic is changing the traditional operation of the grid and is placing a premium on assets that can provide fast-ramping flexible capacity.
- Solution: Addressing this need, the study goals, were to assess & quantify how innovative, fast-acting advanced pumped-storage hydro (PSH) systems can economically solve these grid integration challenges during future high RE contribution scenarios. Project focused on ternary PSH (T-PSH) and quaternary PSH (Q-PSH), coupling them with sophisticated transmission monitoring/control equipment (i.e., dynamic transmission) as a proposed solution.

Project Objective & Impact

- Conduct feasibility studies on these cutting-edge technologies and compare to traditional PSH; Demonstrate how development timelines can be reduced in U.S.
- Evaluate how these technologies would perform in other markets (focused on the Northwest Power Pool, CAISO, and ISO-NE).
- Project Impact elevates U.S. knowledge in commercial/system benefits; compares/quantifies benefits for investors/regulators of spec. technologies

Project Information

Project Principal Investigator(s)

Mark Jacobson

WPTO Lead

Rajesh Dham

Project Partners/Subs

Absaroka Energy
GE Renewables
Grid Dynamics
Auburn University

Project Duration

- Project Start Date: 10/1/17
- Project End Date: 9/30/19

Alignment with the Program

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Hydropower Program Strategic Priorities

Environmental R&D and Hydrologic Systems Science

Big-Data Access and Analysis

Technology R&D for Low-Impact Hydropower Growth	R&D to Support Modernization, Upgrades and Security for Existing Hydropower Fleet	Understand, Enable, and Improve Hydropower's Contributions to Grid Reliability, Resilience, and Integration

Alignment with the Hydro Program

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Understand, Enable, and Improve Hydropower's Contributions to Grid Reliability, Resilience, and Integration

- Understand the needs of the rapidly evolving grid and how they create opportunities for hydropower and PSH.
- Investigate the full range of hydropower's capabilities to provide grid services, as well as the machine, hydrologic, and institutional constraints to fully utilizing those capabilities.
- Optimize hydropower operations and planning—alongside other resources—to best utilize hydropower's capabilities to provide grid services.
- Invest in innovative technologies that improve hydropower capabilities to provide grid services

<u>Explanation:</u> The team conducted concept feasibility studies using cutting-edge T-PSH systems paired with RE generation and dynamically integrated into the transmission grid and energy markets through optimized control systems using synchrophasors (along with other grid-edge infrastructure—hardware, software, and business innovations) and FACTS (Flexible Alternating Current Transmission System) devices. The combined impact includes situational awareness of system stability margin and potential revenue forecast from ancillary services. The first FERC-designated power market studied was the Northwest Power Pool, then CAISO and NE Power Pool.

<u>Explanation:</u> This project investigates the best options to implement control coordination between PSH and the FACTS devices implemented on the grid and quantify the benefits of dynamic transmission (modernized controls and communication systems) when paired with advanced fast-acting PSH.

Project Budget

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Total Project Budget – Award Information				
DOE	Cost-share	Total		
$1,250K	$250K	$1,500K		
FY17	FY18	FY19 (Q1 & Q2 Only)	Total Project Budget FY17–FY19 Q1 & Q2 (October 2016 – March 2019)	
Costed	Costed	Costed	Total Costed	Total Authorized
$32K	$583K	$212K	$827K	$1,250K

Management and Technical Approach

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Management Approach:

- Assembled diverse project team
- Encouraged strong communication and cooperation—Bi-weekly meetings over 2 years experienced near 100% attendance.
- Reported all milestone and budget information to DOE on a quarterly basis.
- The project stayed under budget and on schedule

Technical Approach:

- Assessment of Technical Concept Feasibility, siting, sizing, design/configuration, and specs.
- Assessment of Technical Aspects of the Market, including the use of power flow and transient dynamics (on common Positive Sequence Load Flow (PSLF) platform.
- Assessment of Economic and Non-Economic Benefits within the Market, which required documentation of full system costs. A reference site was used to access up-to-date costs and performance data for a T-PSH/Q-PSH system.

Challenges encountered and overcome: completing development of new HSC model, obtaining cost data, adding new technology (quaternary) to the comparison mix. Key aspect--valuing fast transition times. Industry standard PLEXOS modeling is limited to evaluating at 5 minutes. The market indicates there will be future economic value inside of 5 minutes. So a price-taker model was used to better understand the value coming from a fast-acting PSH system. It was determined that there are a number of predictable and unpredictable revenue streams that need to be considered to make advanced PSH economically viable.

End-User Engagement and Dissemination Strategy

- Overall: Investors, utility ISOs, and policymakers will benefit from this increased knowledge. DOE's funding allowed analyses to be shared more broadly across the nation to break through current limitations in this market—real or perceived—related to high capital costs, lack of understood revenue streams in existing market structures, and uncertain regulatory/permitting time frames. These audiences are the primary attendees at conferences we have and will be attending.
- We engaged the industry directly by including them on our project team. GE, Absaroka Energy, and Grid Dynamics provided real-time feedback on siting, equipment costs, performance data, power marketing updates, and grid integration strategies.
  - Results are more credible with updated costs, performance data and marketing info
- Additionally, (if budget allows) adding a new engagement scope item: hold an utility red team review. Constructive critiques will be solicited and recorded for the published report.
- Presented preliminary results at three hydro conferences soliciting feedback from and incorporating ideas (where budgets allow).
- Submitted eight journal/conference papers (winning "best paper" at one) and was presented at two hydro conferences and two poster sessions in 2018/2019. Intend to generate five more journal articles and two to three more conference presentations in 2020.
- Submitted Draft Report to DOE.
- The report will be published after incorporating input/review comments.

Technical Accomplishments

Summary of Accomplishments:

- A new NREL hydraulic short circuit model (in PSLF) has been developed and used to more accurately quantify the dynamic benefits of fast-acting PSH on the grid.
- Preliminary wide area controls paired with advanced PSH have been demonstrated to increase the dynamic benefits to the grid.
- Economic production cost modeling and price-taker modeling has been completed for two markets
- The most updated installation costs (in the United States) have been received and analyzed for both T-PSH and Q-PSH.
- PSH siting guide has been developed.
- PSH FERC licensing lessons learned have been incorporated into report.
- A full value stream matrix has been developed to further the understanding of predictable and unpredictable revenue streams needed to make advanced PSH economically viable

Technical Accomplishments (Cont.)

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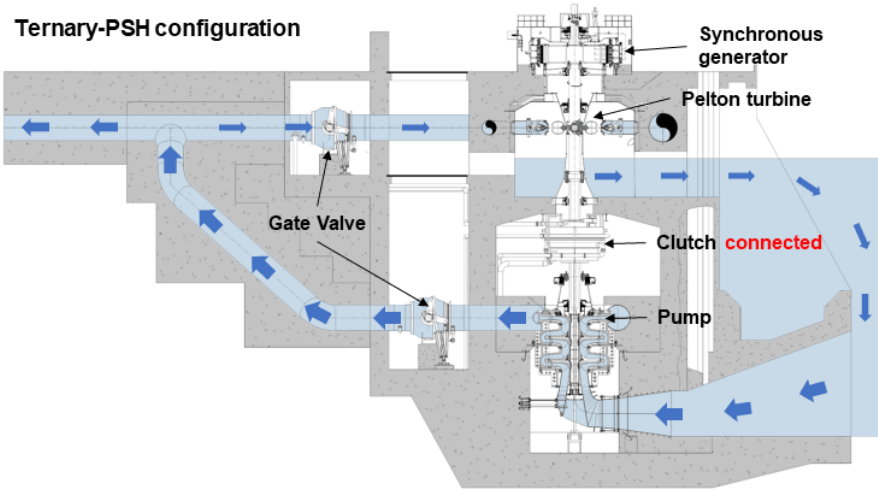
T-PSH Technology Overview

Advantages of T-PSH:

- Fast dynamic power response
- Primary frequency control is possible in both turbine and pump mode
- Possible to provide virtual inertia
- Fast mode switching

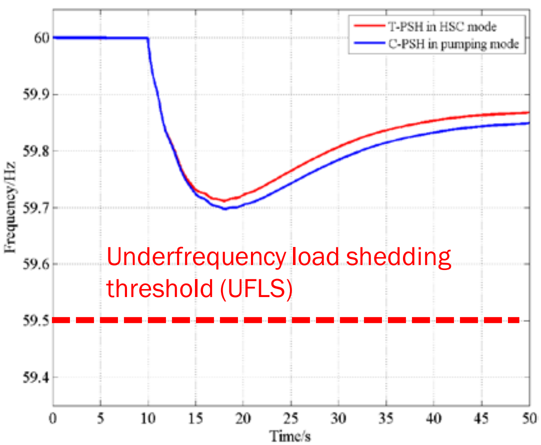


Hydraulic-short circuit mode (HSC)

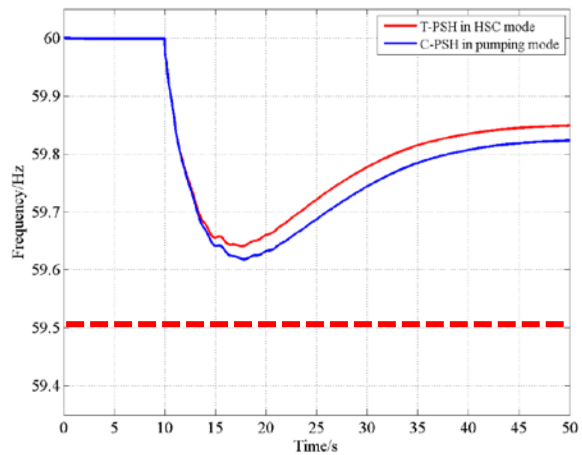
Source: GE Renewable Energy

Impact of T-PSH on Frequency Response in Western Electric Coordinating Counsel (WECC) when 2% of WECC generation is theoretically converted to T-PSH

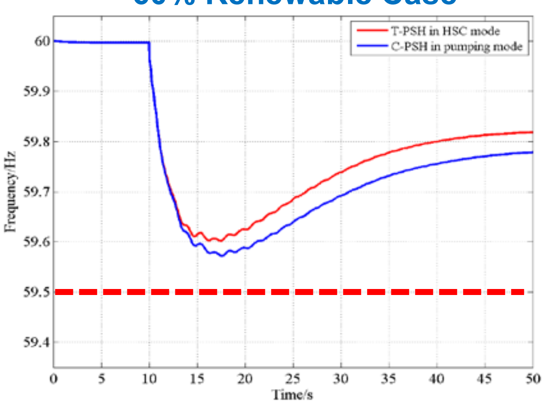
20% Renewable Case



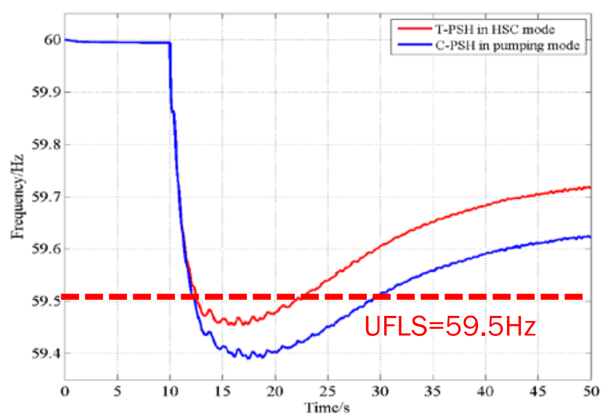
40% Renewable Case



60% Renewable Case



80% Renewable Case



Renewable Increase

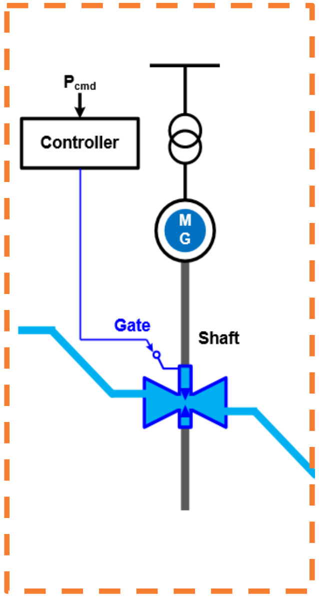
- ☹ Rate of change of frequency (ROCOF) ↑
- ☹ Frequency nadir ↓
- ☹ Settling frequency ↓

Replace C-PSH with T-PSH

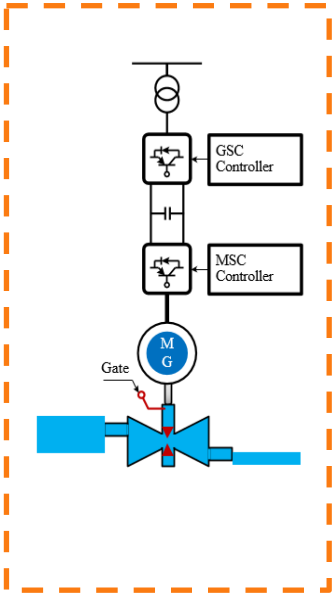
- ☺ Frequency nadir ↑
- ☺ Settling frequency ↑
- 😐 ROCOF

Technical Accomplishments (Cont.)

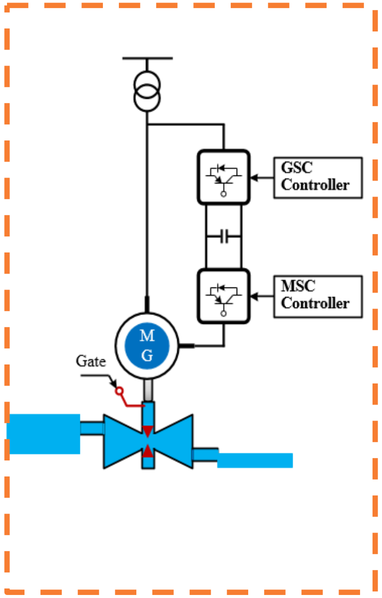
Comparison's of Pumped Storage Power Plants



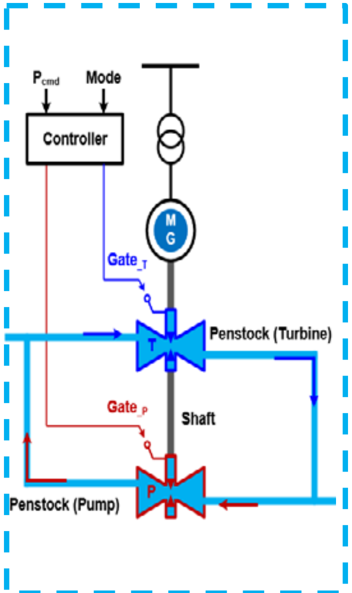
Conventional/ Fixed Speed Turbine



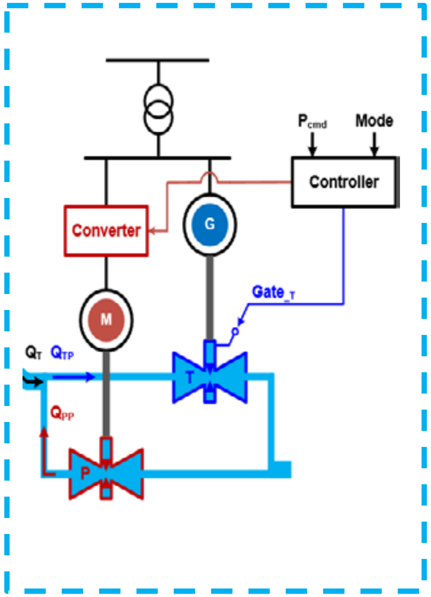
Adjustable Speed Full Converter



Adjustable Speed (Doubly-Fed Motor Generator)



Ternary



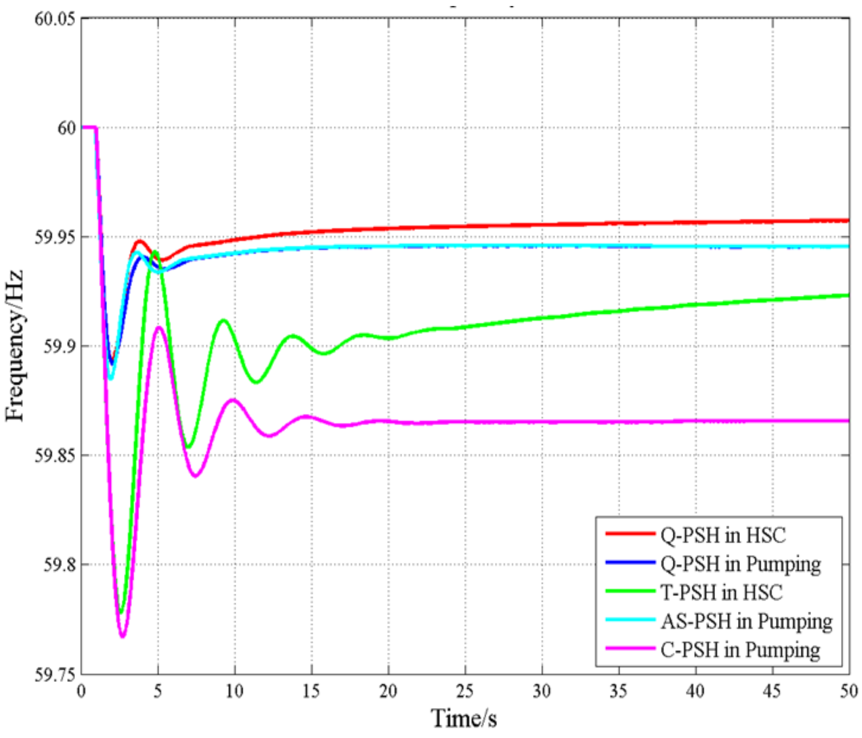
Quaternary

C-PSH = Conventional PSH (*Fixed speed*)
AS-PSH = Adjustable Speed PSH

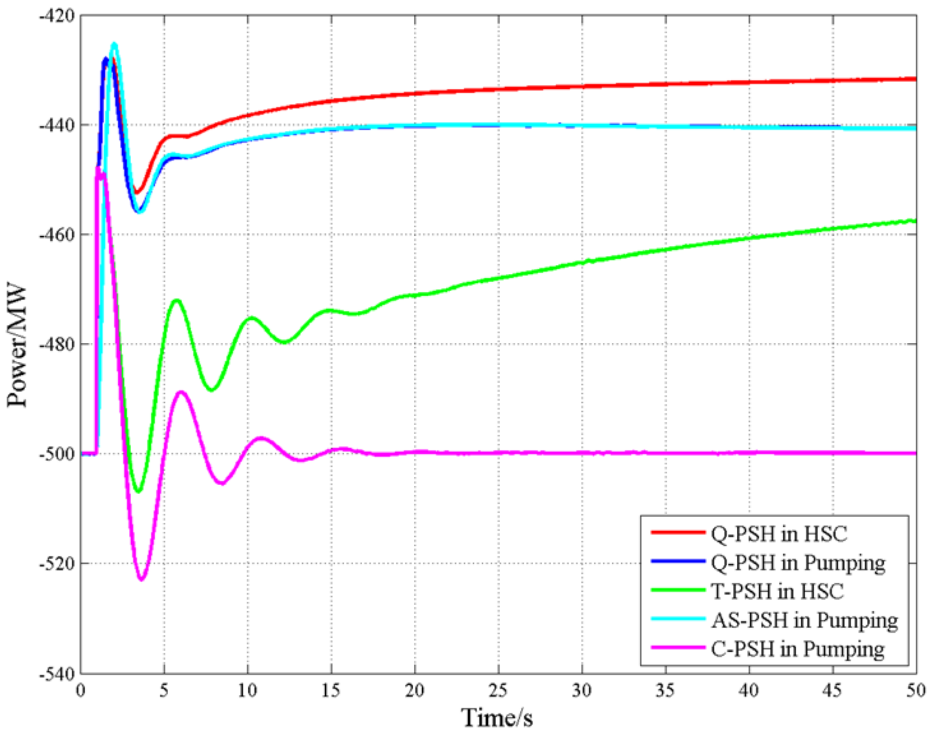
T-PSH = Ternary PSH
Q-PSH = Quaternary PSH

Comparison study of different types of PSH

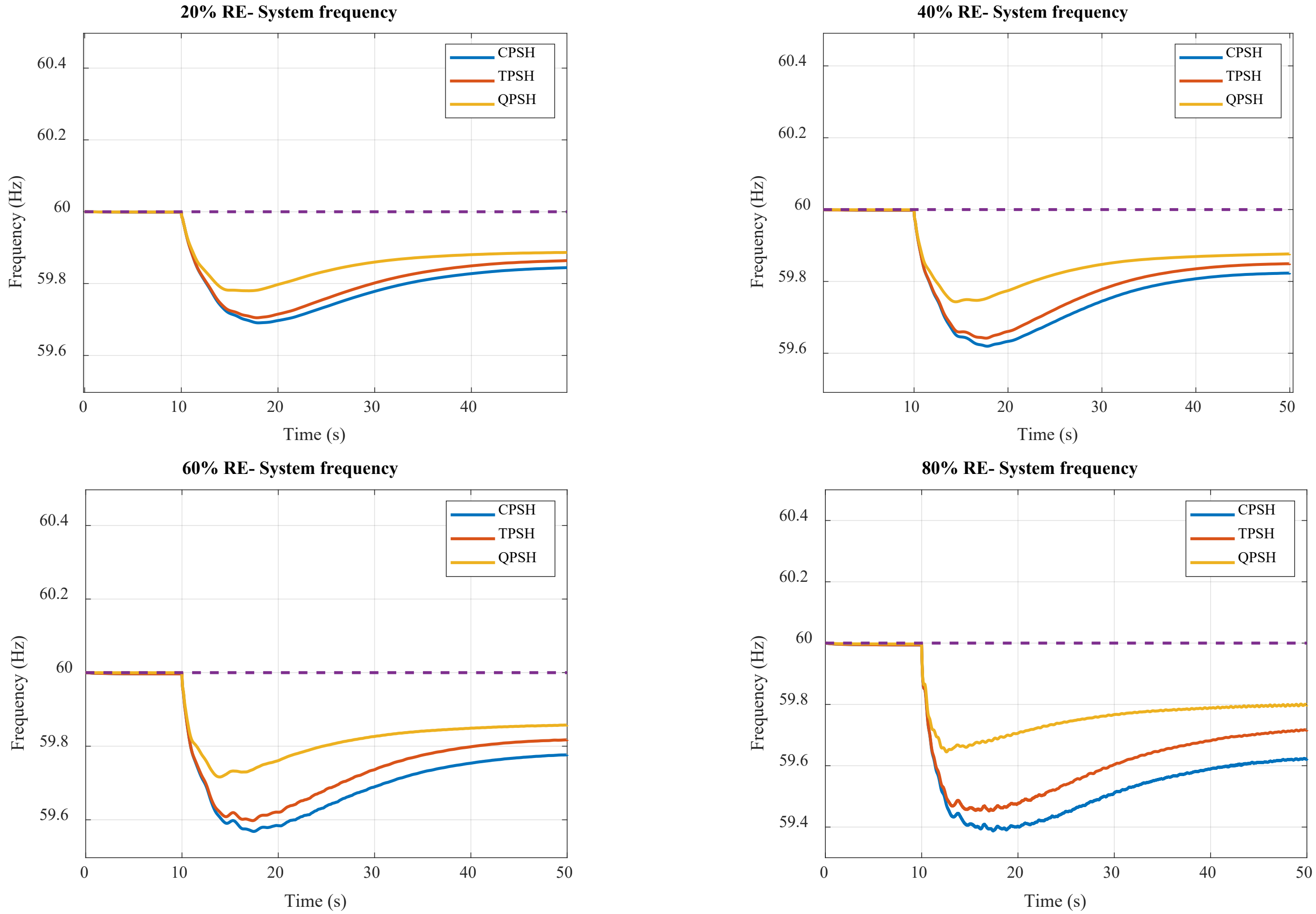
Frequency response



Output power from PSH



Frequency responses of advanced-PSH technologies in WECC



Technical Accomplishments (Cont.)

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Wide-Area Control Strategy

Question: How do we maximize the benefit of T-PSH in term of the following characteristics:

- Shorter transition time
- Large capacity
- Large flexibility range

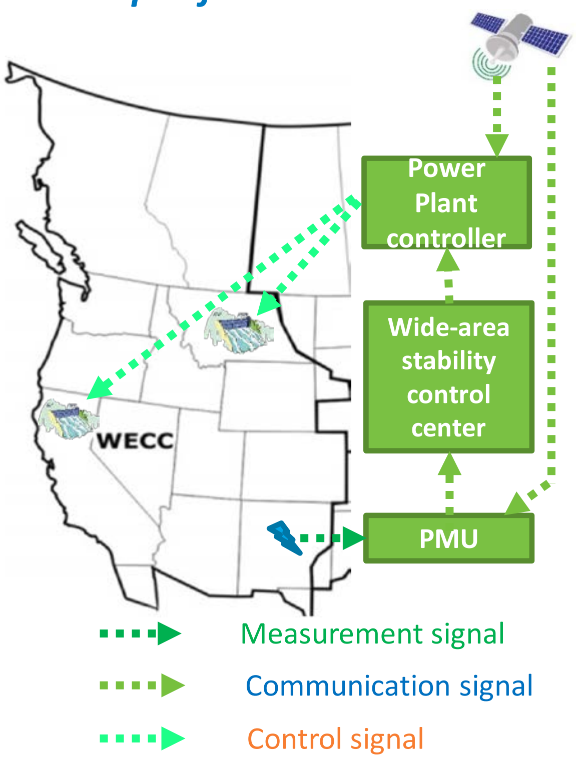
Problem:

- A sudden generation trip
- Wind generation trip caused by the thunderstorm

Solution: Wide-area control for T-PSH

- Propose a control strategy for T-PSH based on wide-area frequency monitoring
- Improve the awareness of T-PSH

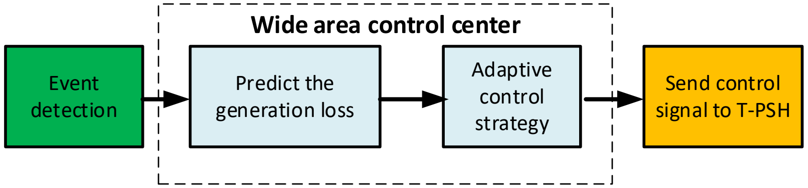
Concept of Wide-Area Control



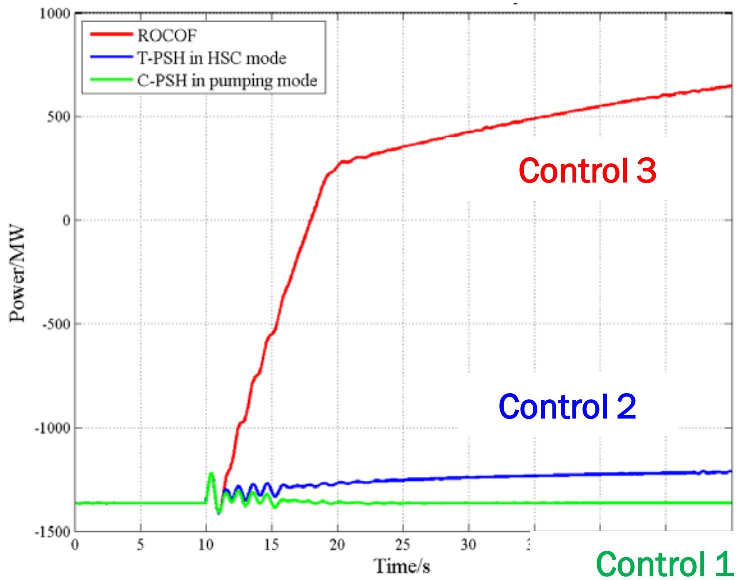
Technical Accomplishments (Cont.)

Capability of Control Strategies

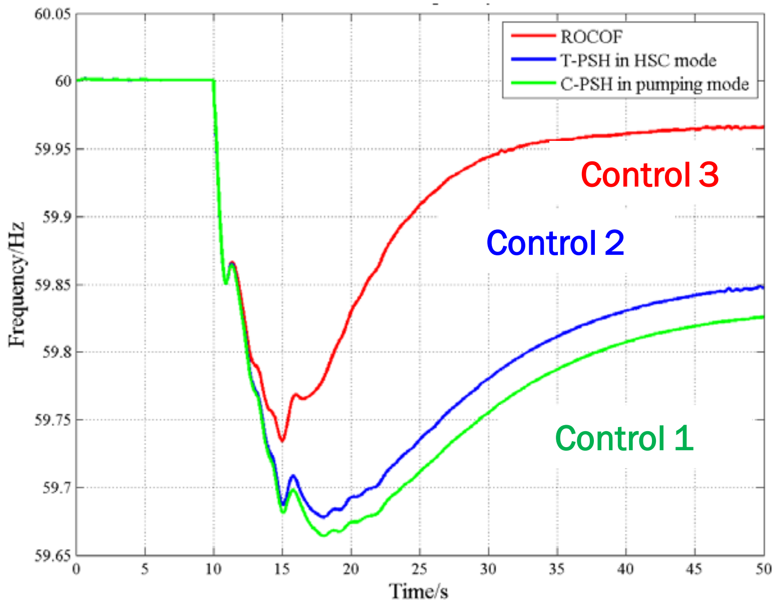
- Control 1: C-PSH in pumping mode
- Control 2: T-PSH in HSC mode
- Control 3: T-PSH with wide-area controls –Rate of Change of Freq. (ROCOF)



Total Output Power of PSH



Grid frequency



T-PSH with Wide Area Controls (based on ROCOF) provides much greater generation and frequency support

Technical Accomplishments (Cont.)

Comparison of Feasibility for Different Services

Pumping mode of different PSH technologies

Type of Services		C-PSH	AS-PSH DFIG	AS-PSH Full Conv.	T-PSH	Q-PSH
Ancillary Services	Inertial Response	green	yellow	yellow	green	green
	Primary Frequency Response	red	yellow	yellow	green	green
	Frequency Regulation	red	yellow	yellow	green	green
	Load Following	red	green	green	green	green
	Spinning Reserve	red	green	green	green	green
Others	Start-up (s)	300	280	40	120	
	Pump*-Generating(s)	190	190	190	25	
	Synchronous Condenser-Generating (s)	100	100	100	20	
Flexibility	Pumping	100%	60%-100%	60%-100%	0%-100%	0%-100%

T-PSH vs C-PSH

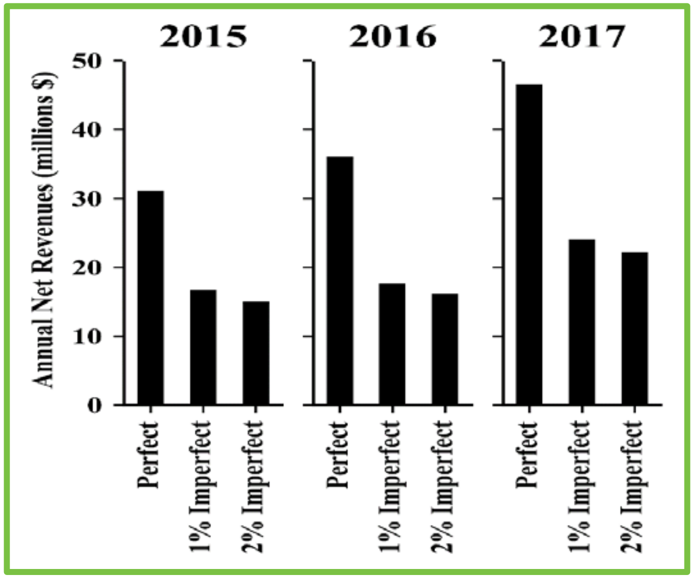
☺Fast frequency/power support ☺Flexibility in pumping

T-PSH vs A-PSH

☺ Natural inertia, Fast mode switching, Less harmonics

Technical Accomplishments (Cont.)

Price Taker model:



PLEXOS model (2024):

Turbine Type	CAISO Energy Arbitrage Revenue Potential, $million	
	Day-Ahead	Real-Time
AS-PSH	7.7	50.4

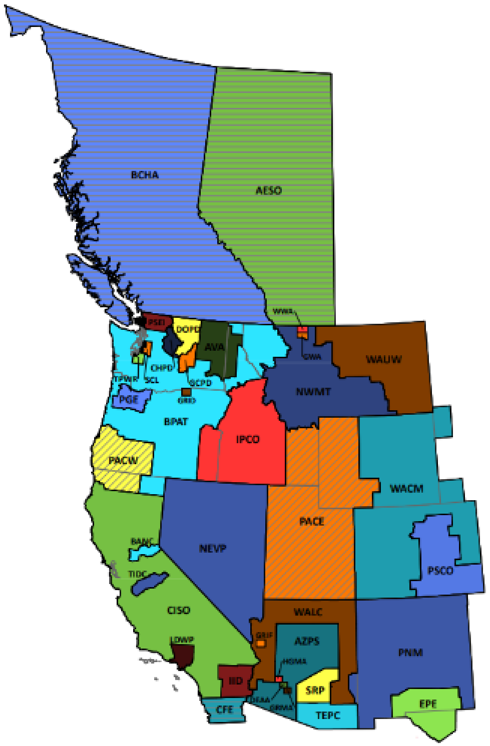
- Modeling focused on Energy Arbitrage/Regulation Reserves
- PLEXOS limitations: 5 min. resolution; assume perfect market foresight

Economic Analysis

Benefits / Services	North West Power Pool	CAISO	North East Power Pool
Capacity			
ENERGY (Day Ahead)			
Energy 2 (Real Time)			
Regulation Reserve			
Flexibility Reserve			
Spinning Reserve			
Contingency Reserve			
Voltage Support			
Frequency Support			
Inertia			
Integration Services			
Peaker Deferral			
GHG Emissions			
Transmission Utilization/Optimization			
Forecast Error			
Energy Price Impact to Load			
Capacity Price Impact to Load			
Ancillary Service Price Impact to Load			

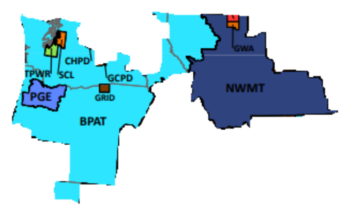
Methodology

1 Linear run of WECC Day step-size



2 MIP – Day Ahead

Non-focus regions take generation and inter-regional transmission flows from step 1

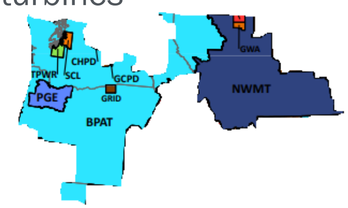


Day step-size with 1 day look-ahead of 4 hour resolution

Day ahead wind and solar forecasts

3 MIP – Real Time

Unit Commitment taken from the day ahead for all generation, except for solar, wind and combustion turbines



5 minute step-size with 1 hour look-ahead, or 1 hour step-size

Real time wind and solar profiles

First time using geographic decomposition to reduce the resolution requirement of MIP gap

Future Work

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- **Industry Red-Team review**
- **AS-PSH WECC model run**
- **Proposing:**
  - Develop an Integrated Model: stitching together an economic model with a dynamic model. Benefit will be that dynamic inputs to new model will generate preliminary economic results.
  - Analysis: Proposing a detailed Advanced PSH comparison to the latest Battery technology focusing on lifecycle costs and examining deterioration levels during various cycling scenarios.
  - Demonstrating additional modeling in other markets

Supplemental slides

Progress Since Project Summary Submittal

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- Dynamic transmission use cases were completed