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U.S. Department Of Energy

SAPPHIRE: Stability-Augmented Optimal Control of Hybrid PV Plants with Very High Penetration of Inverter-based Resources

Principal Investigator:

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National Renewable Energy Laboratory

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NREL Transforming ENERGY · The University of Tennessee Knoxville · EPRI Electric Power Research Institute · Temple University · AES Distributed Energy · Hawaiian Electric · KIUC

Team

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- DOE SETO funded
- 3 years
- 7 partners+ 3 ISOs
- April 2021 – March 2024

National Lab

NREL Transforming ENERGY

Research Institute

EPRI ELECTRIC POWER RESEARCH INSTITUTE

University

THE UNIVERSITY OF TENNESSEE KNOXVILLE

TEMPLE UNIVERSITY

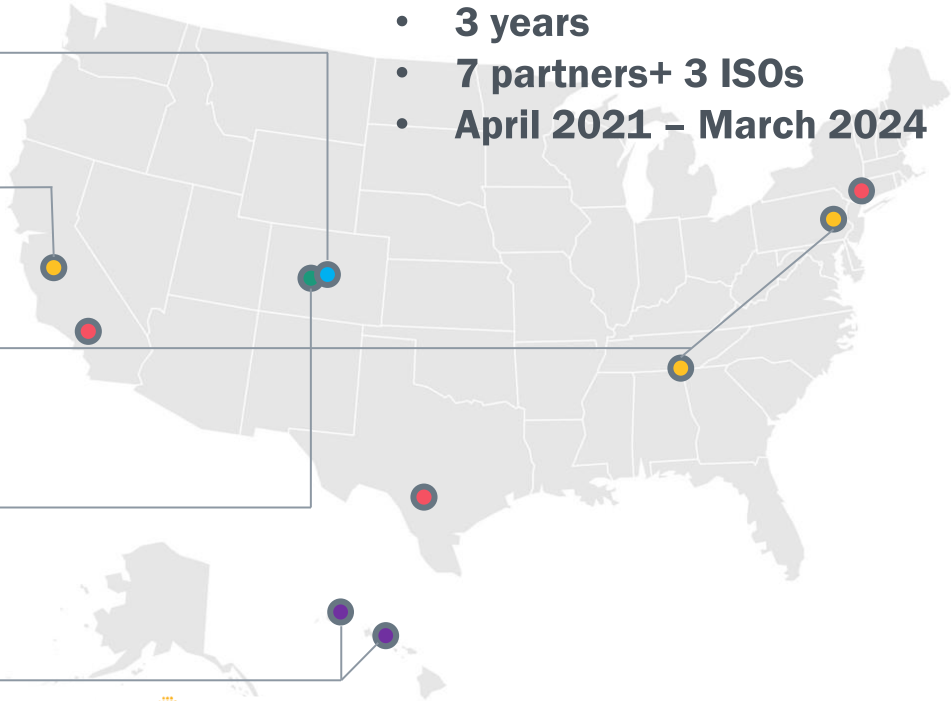
Vendor

AES Distributed Energy

ISO and Utility

Hawaiian Electric

KIUC Your Touchstone Energy Cooperative The power of human connections



California ISO Shaping a Renewed Future

ercot

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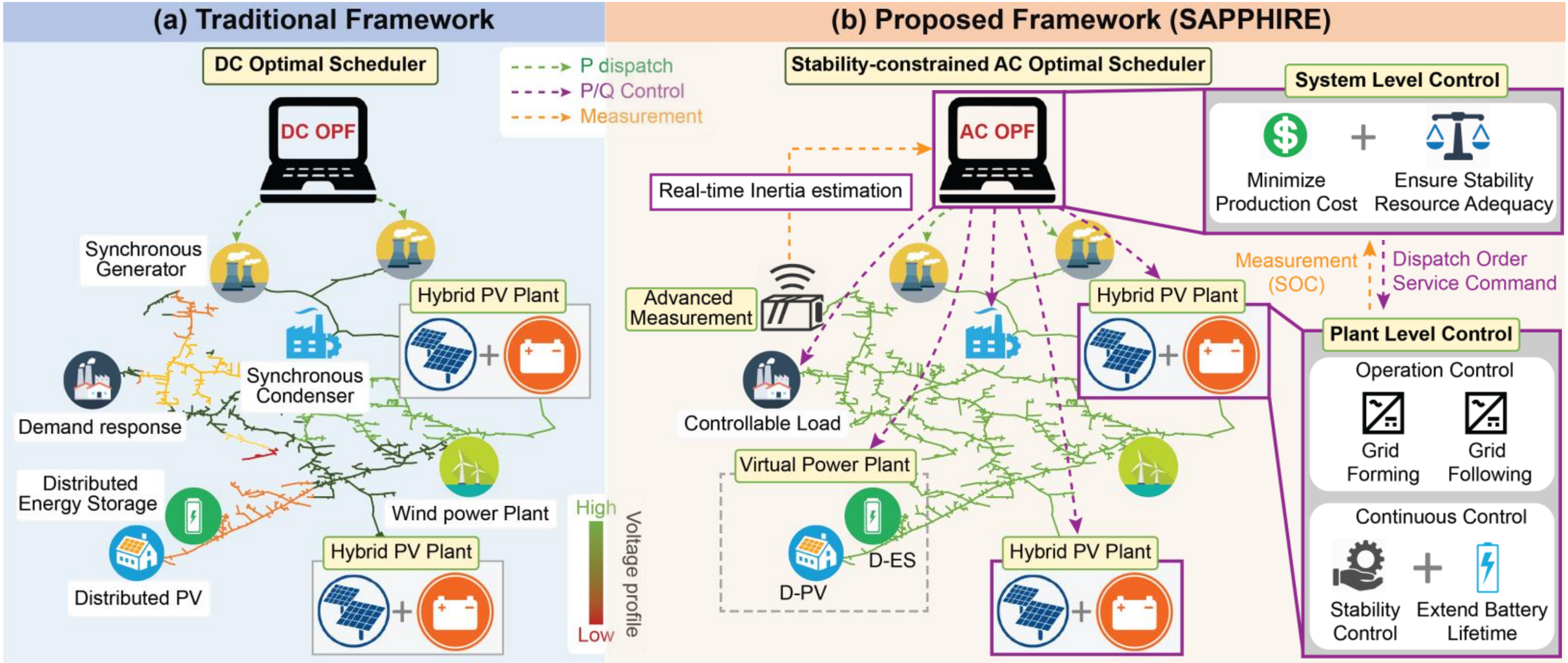
Project Introduction



The proposed solution can simultaneously ensure **system stability** at the transmission system level, **optimize the provision of multiple services**, and **realize GFM operation of individual HPPs in coordination with PVs and BESS at the plant level**.

Project Approach

Task 1
System-level scheduling & modeling

- HPP Modeling
- FFR quantification from IBRs
- Stability-constrained scheduling
- AC-OPF formulation

Task 2&4
Real-time monitoring

- Real-time inertia estimation
- Frequency measurement
- HPP operational data analysis

Task 3
Plant/device level Stability analysis & control

- Stability issues related to Grid-forming control
- Advanced control of HPP
- Optimal control of PV and battery

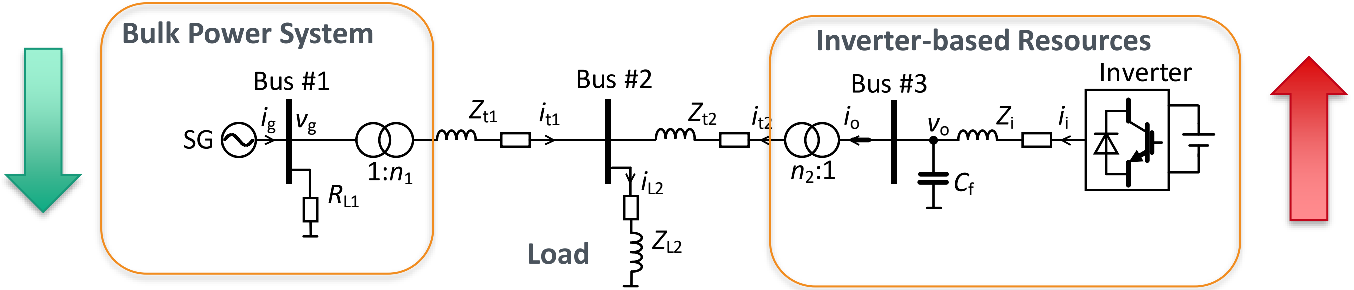
Task 5
PHIL validation

- Grid services provision
- GFM operation
- inertia estimation using HPP

Task 6
Field demonstration

- Grid services
- Probing-based inertia estimation using HPP
- 100% Renewable operation with HPP

Fundamental Questions

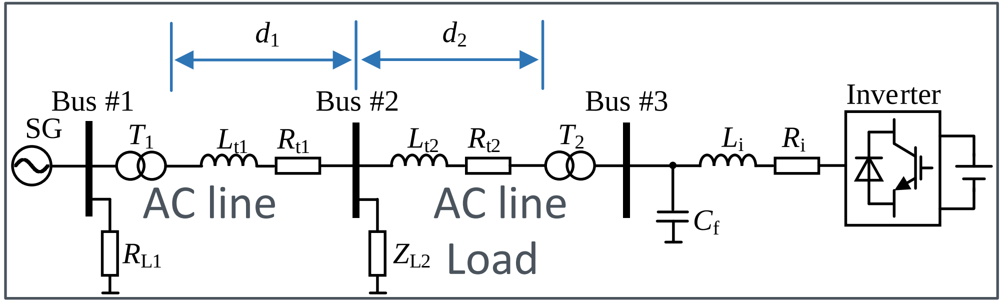


- What are the fundamental dynamic stability impact and characteristics when the IBR penetration level increases in a large-scale bulk grid?
  - Will IBRs introduce any new system-level stability issue?
  - How do they interact with the rest of SGs?
  - What are the critical/key parameters for the new stability issues, if there is any?
  - How do we determine the generation mix of GFL and GFM to mitigate stability issues for a given grid?

Lack of the theoretical analysis to understand the reason behind it!

Approach for Small Signal Stability

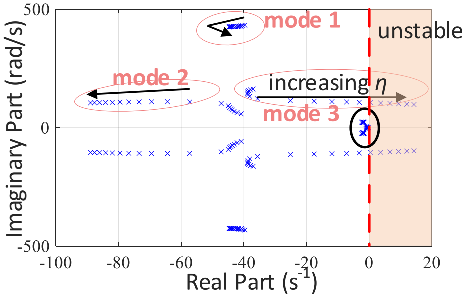
Transmission System Representation



- State-space model

$$\begin{bmatrix} \Delta\dot{X}_{Gen} \\ \Delta\dot{X}_{Inv} \\ \Delta\dot{X}_{Load} \\ \Delta\dot{X}_{Net} \end{bmatrix} = A_{sys} \begin{bmatrix} \Delta X_{Gen} \\ \Delta X_{Inv} \\ \Delta X_{Load} \\ \Delta X_{Net} \end{bmatrix}$$

- Eigenvalue analysis



Case1.1 Eigenvalue trajectory plots when IBR penetration level changes (d_1 = 400 km)

- Four dimensions
  - Control technology
  - Grid topology
  - Grid strength
  - Renewable penetration level

Scenario		GFL Inverter w/o Droop	GFL Inverter w/ Droop	GFM Inverter
Scenario 1 **d_1 = 50 km, d_2 = 1 km**	IBRS are located in the load center	Case 1.1	Case 1.2	Case 1.3
Scenario 2 **d_1 = 1 km, d_2 = 50 km**	IBRS are far away the load center	Case 2.1	Case 2.2	Case 2.3

Control Technology Comparison

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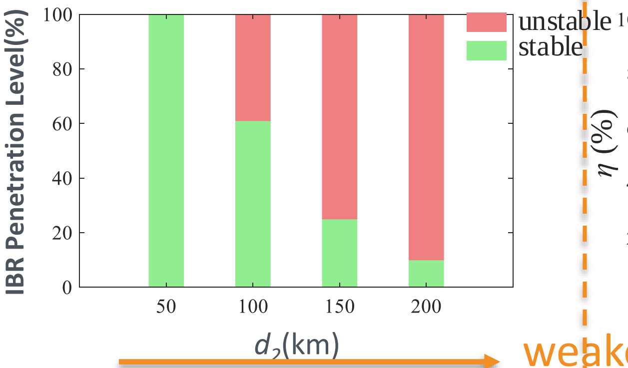
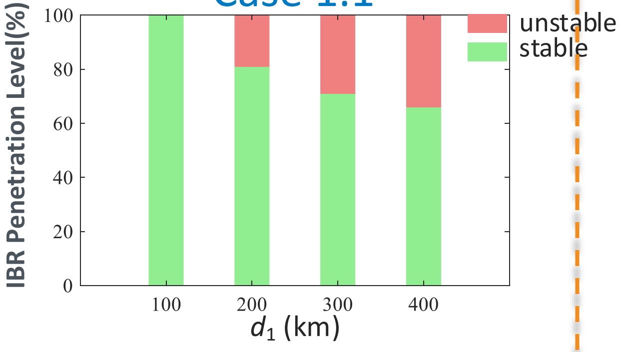
GFL Inverter w/o Droop

Case 2.1



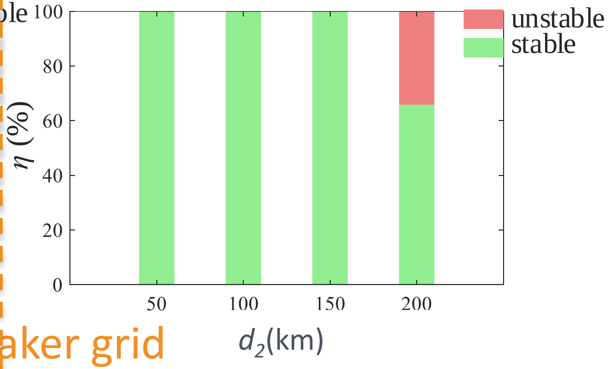
weaker grid

Case 1.1

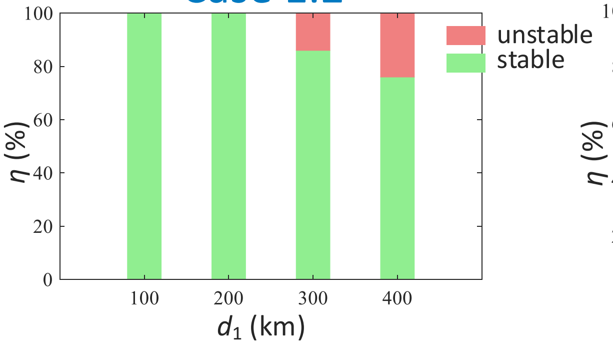


GFL Inverter with Droop

Case 2.2

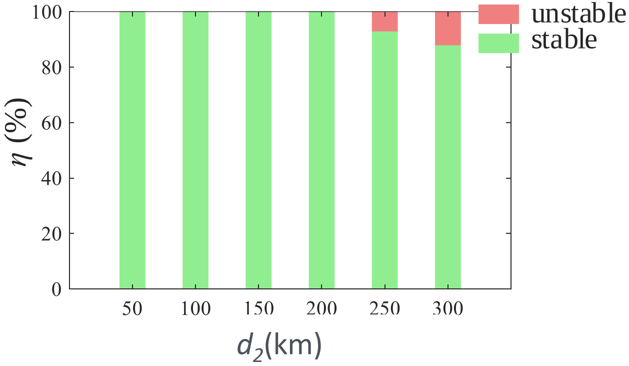


Case 1.2

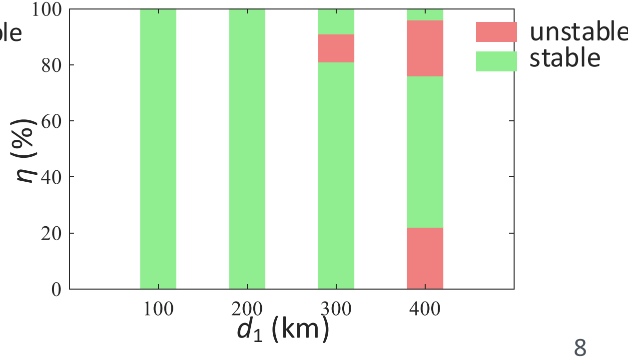


GFM Inverter

Case 2.3

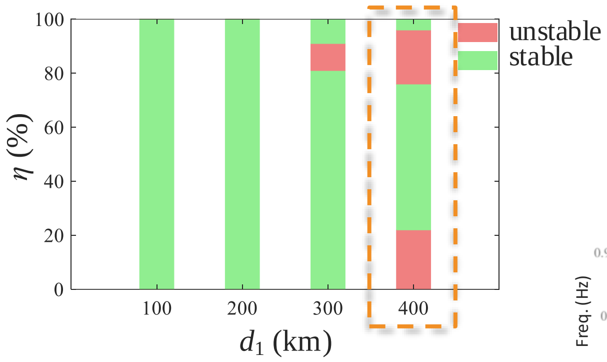


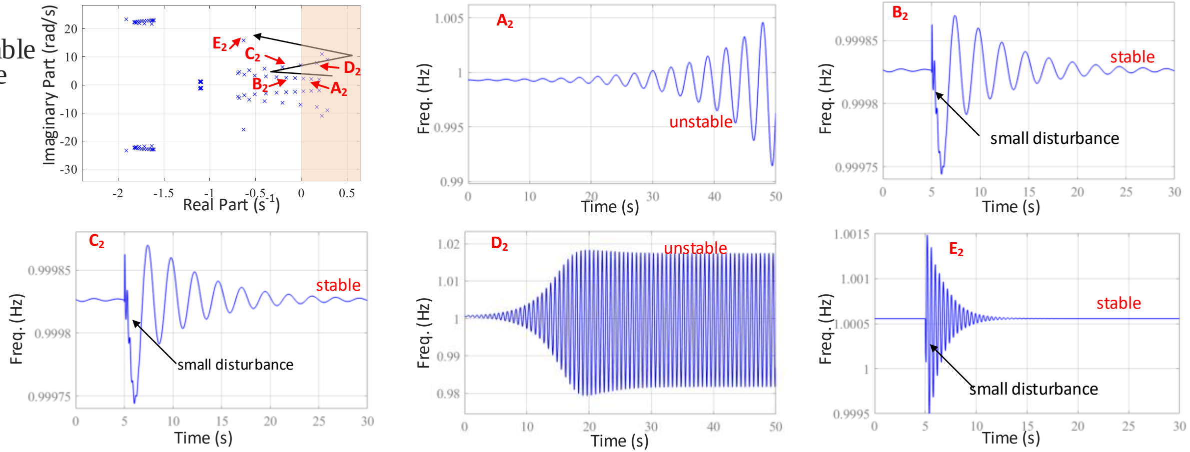
Case 1.3

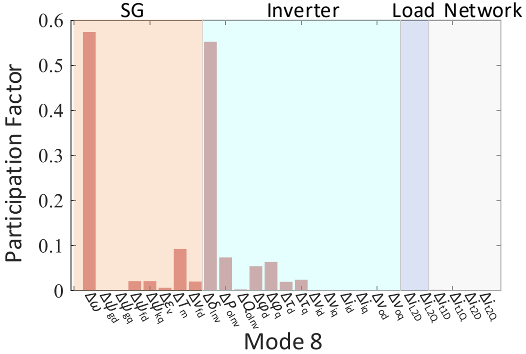


New interactive mode between GFM and Grid

Case 1.3





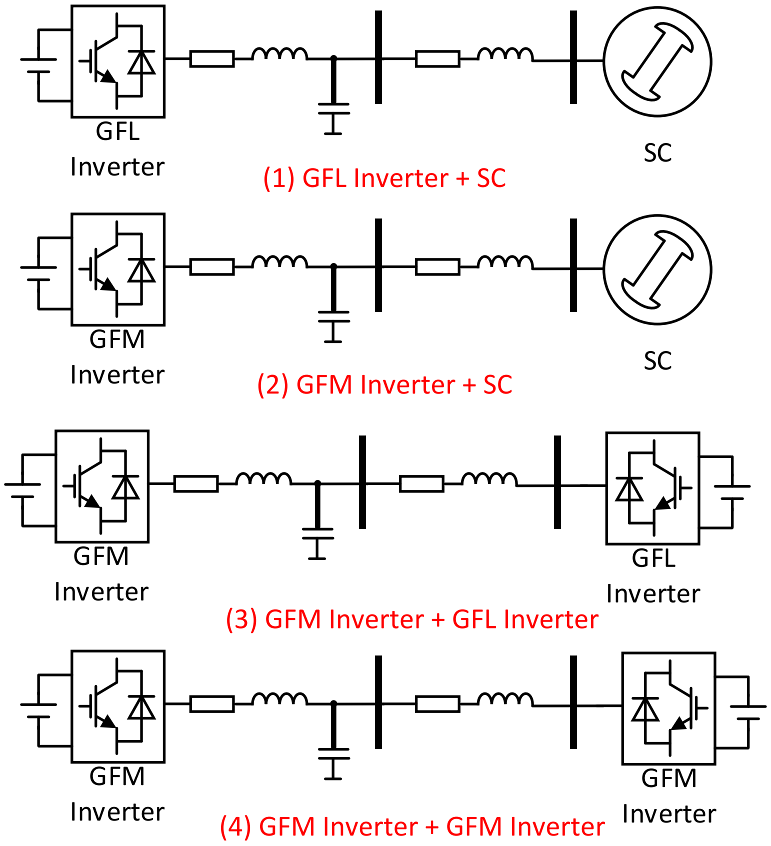


0.93 Hz coupling mode
(IBR Penetration=75%)

The new coupling oscillation mode between SG and GFM (Mode 8) has the dominant impact on stability when penetration level changes

L. Ding, X. Lu, J. Tan,” Comparative Small-Signal Stability Analysis of Grid-Forming and Grid-Following Inverters in Low-Inertia Power Systems” accepted by IEEE IECON 2021

Towards 100% Penetration of IBRs



L. Ding, X. Lu, J. Tan, "Small-Signal Stability of Low-Inertia Power Grids with Inverter-Based Resources and Synchronous Condensers" accepted by ISGT 2022

100% GFL is different from 100% GFM

- Transient stability

  Preliminary data shows

  - with the same small signal stability margin, the transient stability margins for different inverters are different.
  - GFM may improve transient stability margin, comparing to GFL.

…many questions remain

Summary

- All the control technologies are sensitive to grid strength. Compared to GFL with or w/o droop, GFM has the largest stability margin, but it still can have small-signal instability when we further push the envelop of the grid strength.
- Both GFL and GFM can achieve 100% renewable under some specific hypothesis in terms of small signal stability.
- Modal analysis reveals that unlike the **GFL** that a **PLL-related medium-frequency oscillation mode** could become the troublemaker for grid stability, the **GFM** can introduce a low-frequency oscillation mode that shows a strong interaction between the SGs, network and inverter controls.
- Compared to **GFL** with and w/o droop, **GFM** has the largest small signal stability margin, but it still can have small-signal instability when we further reduce the grid strength.
- When **GFM** is located at/near load center and SG is far away, it is easier to achieve 100% renewable than relatively high renewable. The instability is mainly caused by the new coupling oscillation modes that are introduced by GFM.

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Thank you

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Project Introduction

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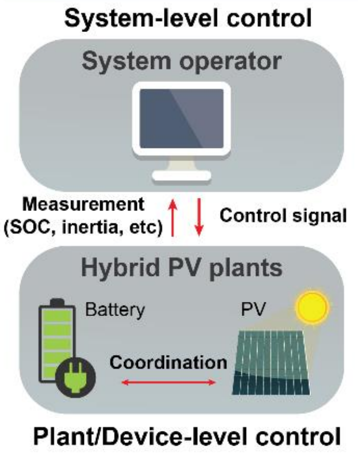
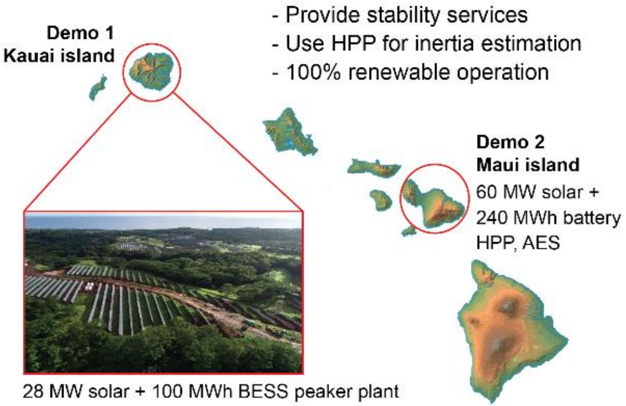
Hierarchical Control Framework: SAPPHIRE



Stability-constrained AC OPF
- Minimize production cost
- Ensure adequacy of stability resources

Coordinated optimal control
- Fulfill system-level requirements
- Operate in grid-forming mode
- Provide multiple stability services
- Extend battery lifetime

Field Demonstration in Hawaii Grids

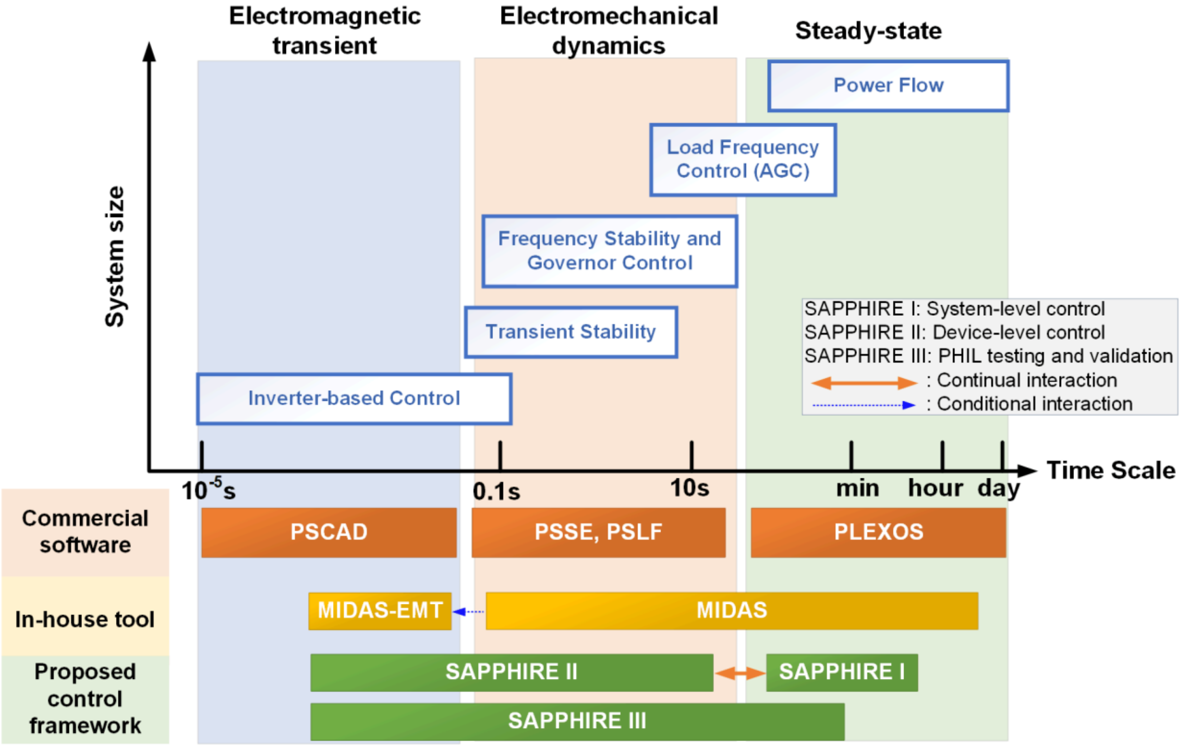


28 MW solar + 100 MWh BESS peaker plant
HPP, AES Corporation 2019

To improve the performance of HPPs in supporting the stability of grid operations:

- Unlock the capability of **HPPs to provide essential stability services**
- Bridge **the gaps between system-level and plant-/device-level control** of HPPs
- **Help the power industry achieve high renewable grids** by demonstrating the use of HPPs as the backbone of extremely high inverter-based resource(IBR) grids

Timescales of SAPPHIRE



Problems and solutions

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Challenges

System level

- Lack of a unified framework and systematic method to consider the fast response capability of HPPs for **grid stabilization**

Plant level

- GFM control of HPP is not mature
- Sub-optimal coordination of PV and BESS

Move forward to practice

- Lack of actual field demonstration of advanced stability-related HPP controls

Solutions

Hierarchical HPP control framework

- Develop **stability-constrained AC-power-flow-based optimal control**
- Develop **measurement-based real-time inertia estimation**

Plant-level stabilization

- Develop **versatile GFM controls**
- Develop **optimal coordinated control of PV and battery**

First-of-its-kind field test in Hawaii

- Develop a "**no-harm to grid**" field test plan to demonstrate 100% renewable operation for hours