SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Modeling and Control of Solar PVs for Large Grid Disturbances and Weak Grids

DE-FOA-1987 SETO Advanced System Integration for Solar Technology (**ASSIST**) Program

Award # DE-EE-0008771

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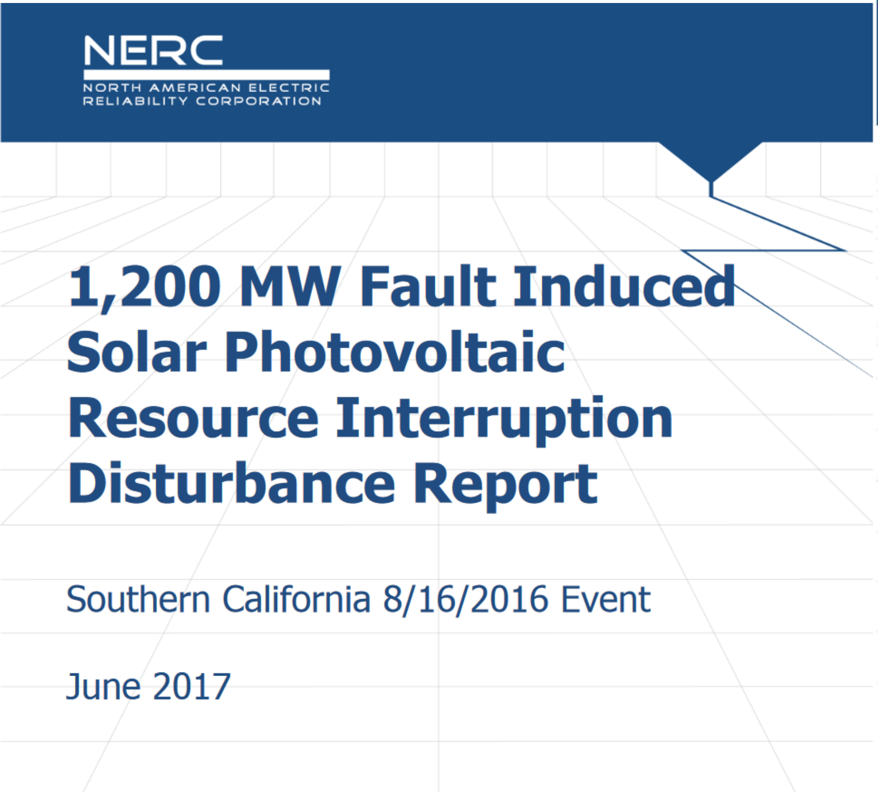
Team: University of South Florida

National Renewable Energy Laboratory

Background: Industry Needs

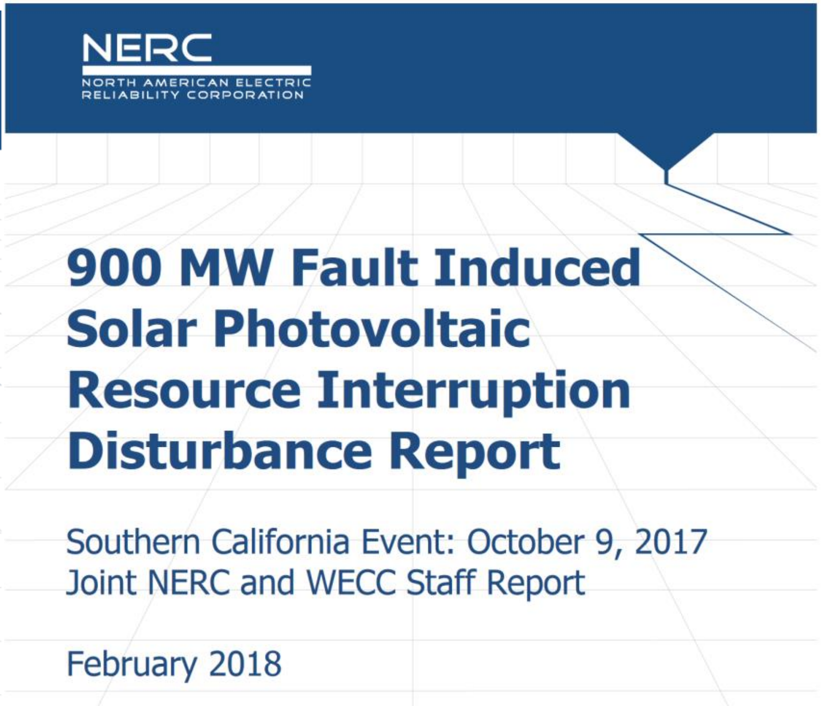


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California 8/16/2016 Event

June 2017

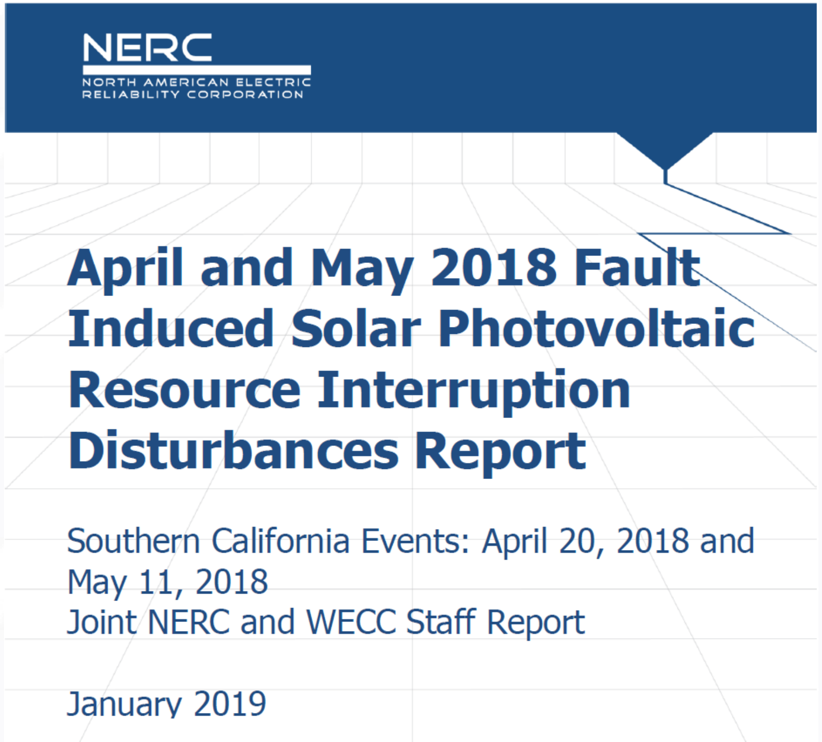


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California Event: October 9, 2017
Joint NERC and WECC Staff Report

February 2018



NERC
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April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report

Southern California Events: April 20, 2018 and May 11, 2018
Joint NERC and WECC Staff Report

January 2019

What the grid industry wants:

1. NERC Mod-033 event replication;
2. Predict PV behavior under extreme grid conditions at the planning stage.

Background: Industry Needs

- Event 1 (Aug 2016): 1200 MW PV tripping. Causes: **erroneous frequency measurement** by inverters during grid disturbances [1].
- Event 2 (Oct 2017): 900 MW PV tripping. Causes: **sub-cycle overvoltage**, dc reverse current due to grid disturbances [2].
- Events 3 &4 [3]: PV tripping. Causes: **sub-cycle overvoltage**, undervoltage, overcurrent, dc reverse current.
- Potential events of PV in weak grids: **7 Hz oscillations** observed in real-world PV farms when transmission system had a line tripping according to First Solar [4].

Figure 1.1: Map of the Affected Area and Blue Cut Fire Location

From [1]

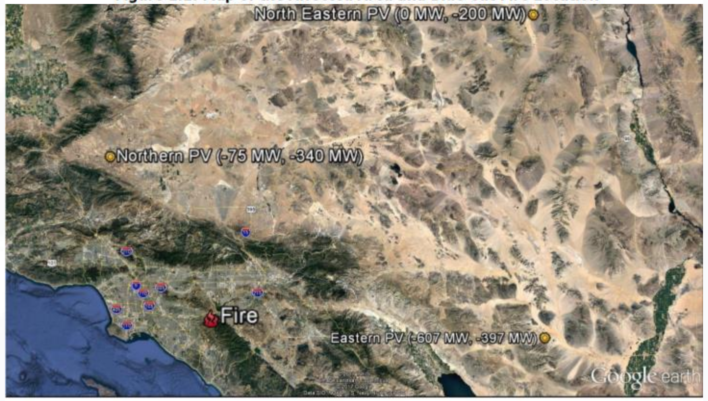


Figure 1.1: Map of the Affected Area and Canyon 2 Fire Location[7]

From [2]

[1] "1200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report: Southern California 8/16/2016 Event," NERC, Tech. Rep., 06 2017.

[2] "900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report: Southern California Event: October 9, 2017," NERC, Tech. Rep., 02 2018.

[3] "April and May 2018 Fault induced Solar Photovoltaic Resource Interruption Disturbances Report," NERC, Tech. Rep., 01 2019

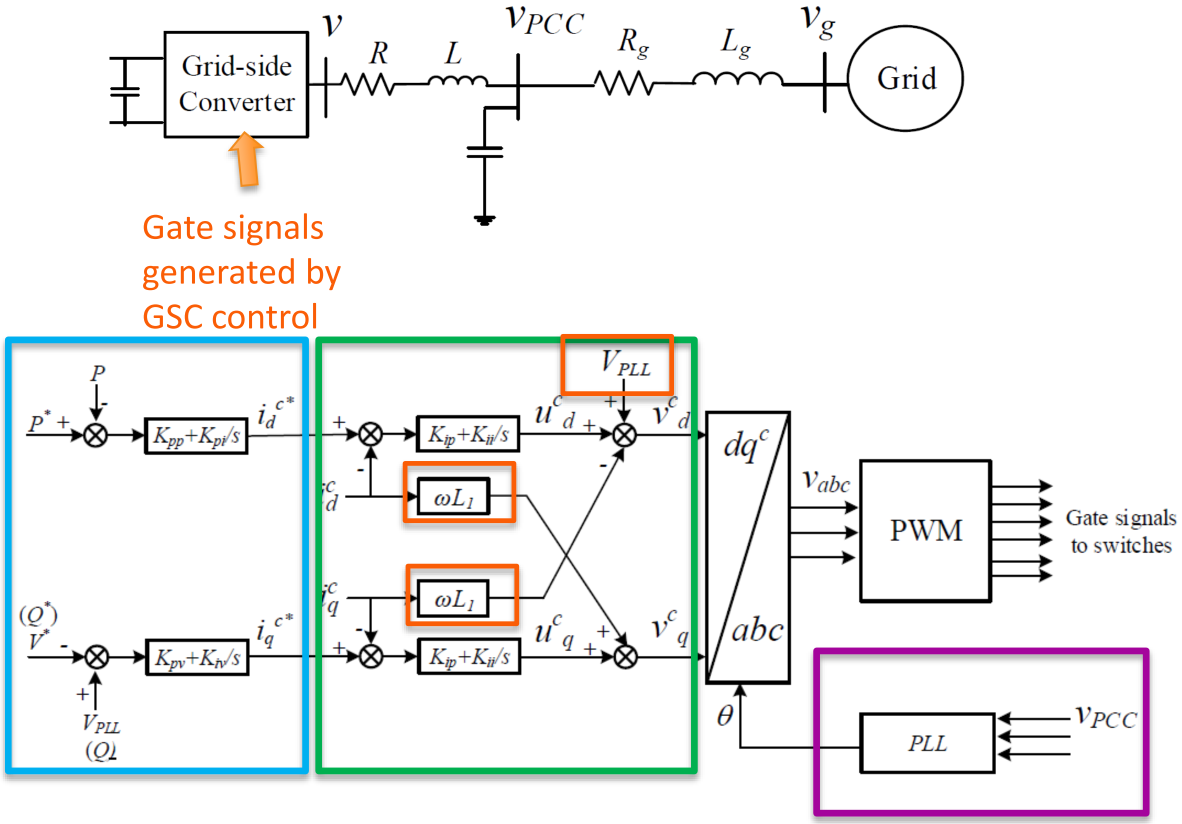
[4] First Solar, "Deploying utility-scale PV power plants in weak grids," IEEE PESGM July 2017 panel presentation.

An urgent issue:

Lack of adequate PV models for large disturbances and weak grids

Background: PV inverter control

- Grid-following inverters (voltage source converters) have standard control structure. Several textbooks are available [5][6].
  - PCC voltage oriented vector control: **decoupled PQ control:** d-axis for P regulation, q-axis for Q regulation, d-axis aligned with the PCC voltage
  - Vector control consists of outer power/voltage control and **fast inner dq-axis current controls**
  - Vector control relies on phase-locked-loop (**PLL**) to sense PCC voltage frequency and angle for synchronization.
  - Decoupled from grid relying on **voltage feedforward and cross-coupling**



[5] Yazdani, Amirnaser, and Reza Iravani. Voltage-sourced converters in power systems. John Wiley & Sons, 2010.
[6] R. Teodorescu, M. Liserre, and P. Rodriguez, Grid Converters for Photovoltaic and Wind Power Systems, Joh Wiley & son, 2011.

Technical Objectives: modeling, coordination, stability enhancement

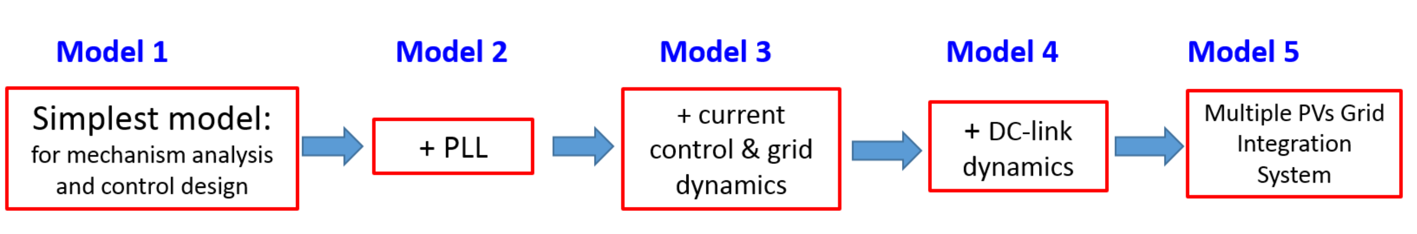
- **Modeling Gaps**: Large-scale grid analysis adopts simplified models for inverter-based resources. Currently many converter controls are ignored, including current control loops, voltage feedforward, phase-locked-loop (PLL).
  - Cannot replicate real-world inverter trip event due to **sub-cycle overvoltage** (*fast converter control: e.g., current control, feedforward, PLL, plays a role*)
  - Cannot replicate real-world inverter trip event due to **synchronization issues** (*PLL*)
  - Cannot replicate **7 Hz oscillation** due to PV in weak grid (*PLL, voltage feedforward, slow converter control all play roles*)
- **Goals:**
  - Analytical model design of PV systems with grid-following inverters
    - Capable of capturing essential dynamics, small-signal analysis and scalable computing
  - Detect and mitigate multiple IBR interaction
  - Stability enhancement module design & hardware prototyping for PV inverters

Project Plan: Goal 1 & BP1

- **Goal 1: Adequate modeling of PV systems**
- **Approaches**:
  - Develop adequate simplified models suitable for the application scopes
  - **Validation** against EMT testbeds and Physical Hardware-In-the-Loop (PHIL) tests, including comparison of frequency-domain responses, time-domain responses under various grid disturbance scenarios and weak grid conditions.
- **Outcomes:**
  - Analytical models of PVs with essential dynamics suitable for large grid disturbance study and weak grid condition
  - Real-world events study:
    - **PLL reaction to transmission grid phase-to-phase fault;**
    - **PV inverter sub-cycle overvoltage due to grid voltage dip;**
    - **7 Hz oscillations due to transmission line tripping**

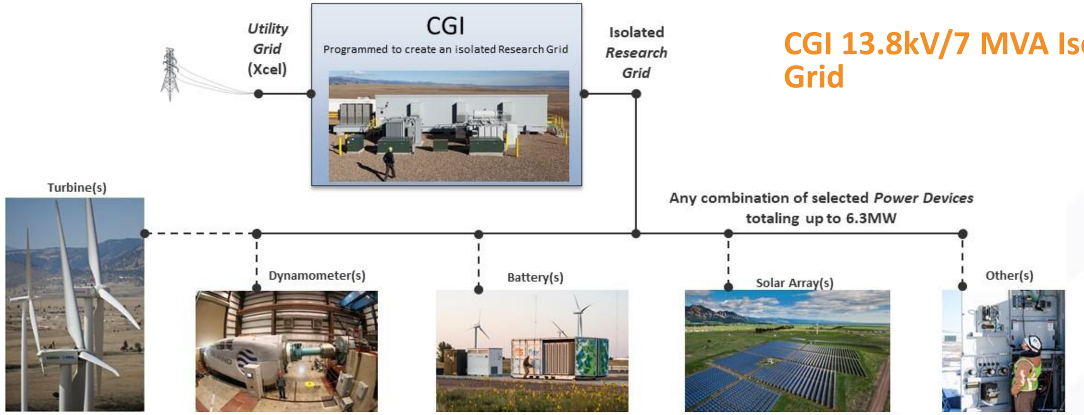
Project Plan: BP1

- In BP1, we focus on single PV system analytical model design

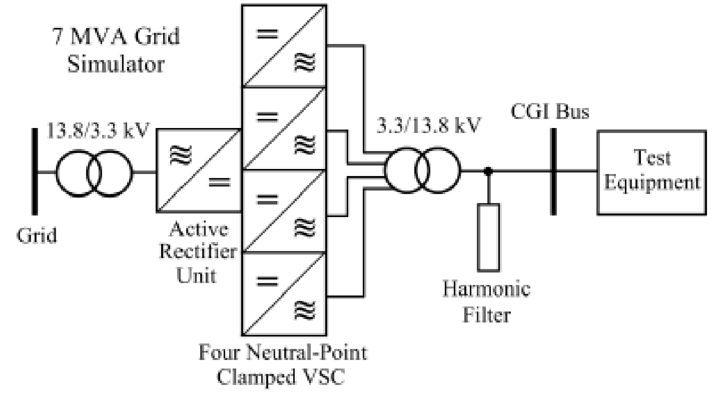


- The set of models will be **compared** with validation testbeds on:
  - **Time-domain** responses (Event replication)
  - **Frequency-domain** responses (Impedance/admittance measurement)
- Two types of validation testbeds will be used:
  - Electromagnetic Transient (**EMT**) simulation testbeds in (PSCAD, RT-Lab, or MATLAB/SimPowerSystemes)
  - **1-MW commercial inverter** at NREL: measurement data of time-, frequency-domain will be obtained relying on NREL's physical Hardware-in-the-loop (**PHIL**) setup.

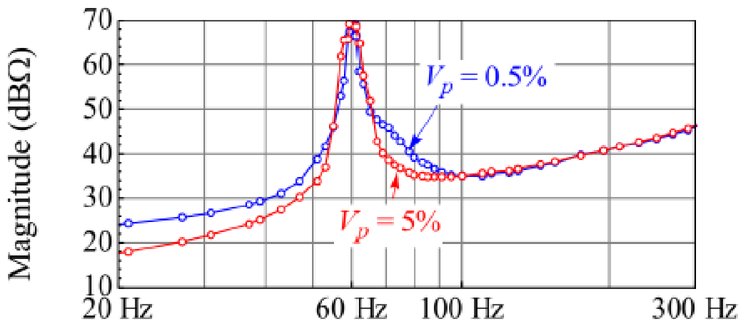
Project Plan: BP1
PHIL experiments for analytical model validation



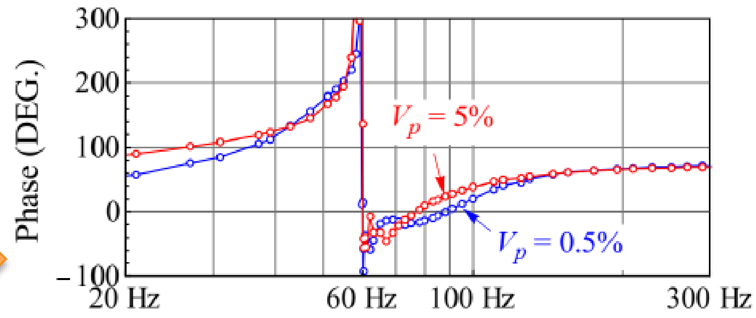
CGI 13.8kV/7 MVA Isolated Research Grid



The CGI can be configured by NREL researchers to create an isolated *Research Grid*. NREL researchers can selectively connect any combination of *Power Devices* to the *Research Grid.*

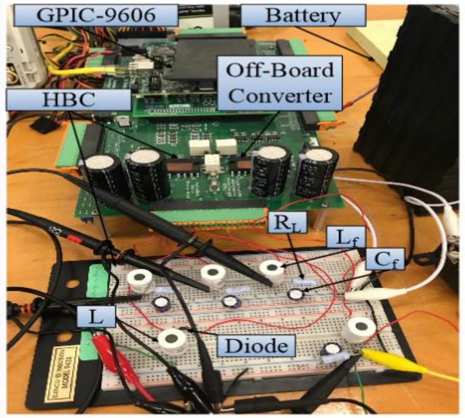


- Major challenges
  - How to tune/adjust analytical models to fit the measurement data of the real-world 1-MW inverter. This is essentially a **black-box** with no control parameters disclosed.
  - We are working on **data-driven tools** to identify parameters using time-domain and frequency-domain measurements.

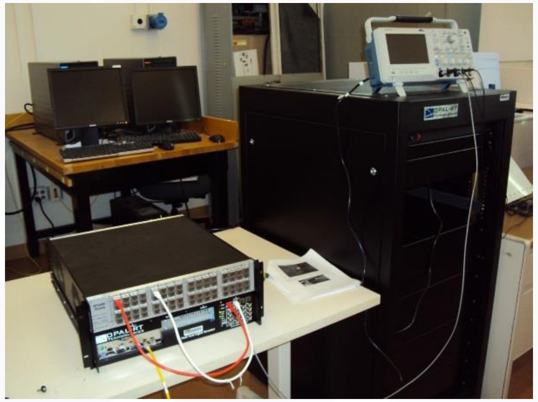


Project Plan: BP2 and BP3

- In BP2, we will use the designed model for multiple IBR interaction analysis.
  - The **goal** is to identify and mitigate potential interactions among IBRs from different vendors.
  - A powerful **modular small-signal analysis tool** will be designed to accommodate admittance models of various IBRs and synchronous generators.
    - The tool is scalable and easy to accommodate new devices.
- In BP3, we will conduct **control hardware prototyping** for stability enhancement module of PV inverters.
  - HIL testbeds will be built to show single-inverter grid integration operation and multiple inverter grid integration operation.



National Instrument sbRIO enabled hardware prototyping



RT-Lab enables HIL

Project Plan: Overview

BP1:

Task 1: Stakeholder engagement

Task 2: EMT models of PV systems → **Task 3:** Analytical models of PV systems. → **Task 4:** PHIL-based characterization of utility-scale 1 MW inverter

BP2:

Task 5: Stakeholder engagement

Task 6: EMT and analytical models for PV systems with grid interactions → **Task 7:** Coordination strategy of multiple PVs and DERs.

BP3:

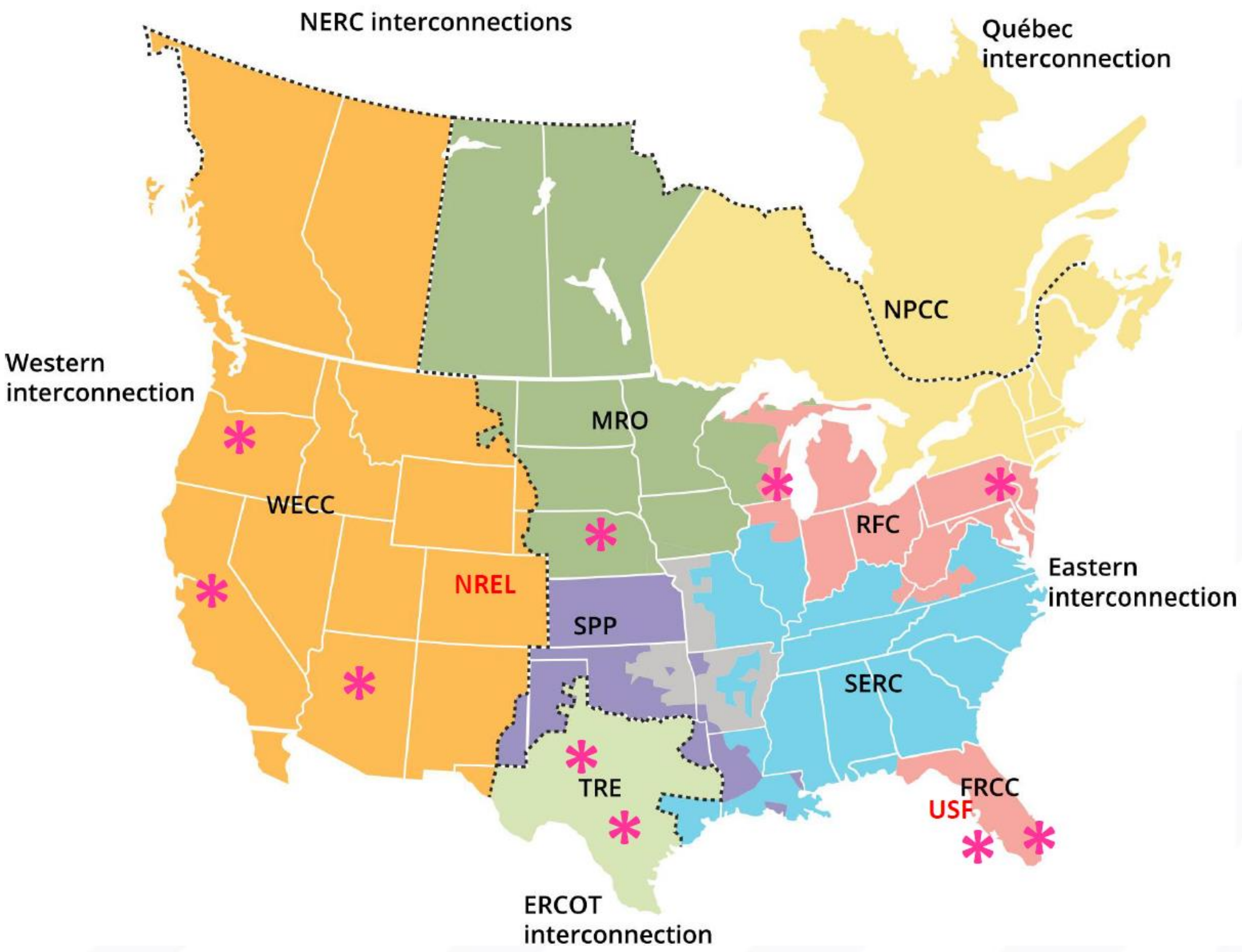
Task 8: Stakeholder engagement

Task 9: Stability enhance module for PV inverters → **Task 10:** Control hardware implementation → **Task 11:** Inverter coordination hardware implementation

BP1 focuses on single PV infinite bus system: **subcycle overvoltage, low-frequency oscillations**
BP2 focuses on multiple IBR + grid topology: **potential interactions**
BP3 focuses on converter control: **power system stabilizer for VSC**

Tasks 1-4 focus on computer-based platforms.
Tasks 5-8 focus on hardware experiment platforms.

Industry Advisory board



Electric Utility Industry

WECC:

California ISO: **Songzhe Zhu**

PacifiCorp: **Song Wang**

Arizona Public Service: **Akhil Mandadi**

Texas:

ERCOT: **Yunzhi Cheng**

ONCOR: **Haiping Yin**

Midwest:

Omaha Public Power District (OPPD): **Joshua Verzal, Courtney Kennedy**

Florida:

NextEra Energy: **Edina Bajrektarevic**

Solar Farm Owner: EON (Headquarter at Chicago)

Feng Li

Manufacturers:

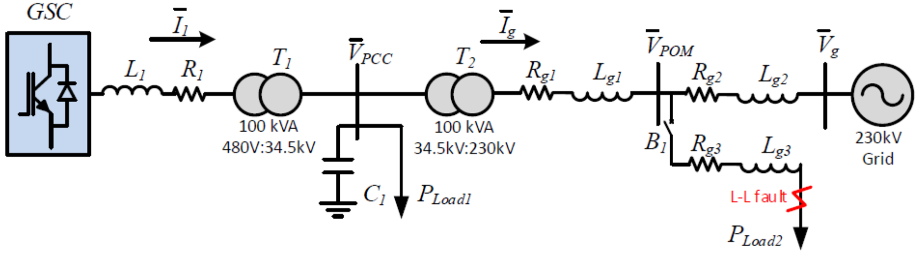
GE Energy Consulting (NY): **Ling Xu**

Jabil Circuit (Tampa Bay): **Mohammad Tamimi**

Current project status and outcomes

- Aug. 2019: Overview of the project at WECC; Kickoff meeting with stakeholders
- Q1, Q2 reports have been submitted. Two GNG Milestones have been achieved (total there are three GNG milestones in BP1).
  - **Event Replication**: Developed EMT testbeds and replicated dynamic phenomena observed in real-world.:(1) Low frequency sensed by inverter due to grid side L-L fault; (2) subcycle over-voltage at inverter due to momentary cessation; (3) 7 Hz oscillations in weak grid.
  - **Analytical Model Design**: Designed analytical models that replicate event 2 and event 3, with frequency-domain responses closely-matching those from the validation testbeds. Root causes of the dynamics have been identified.

Event replication: Erroneous frequency measurement at L-L fault

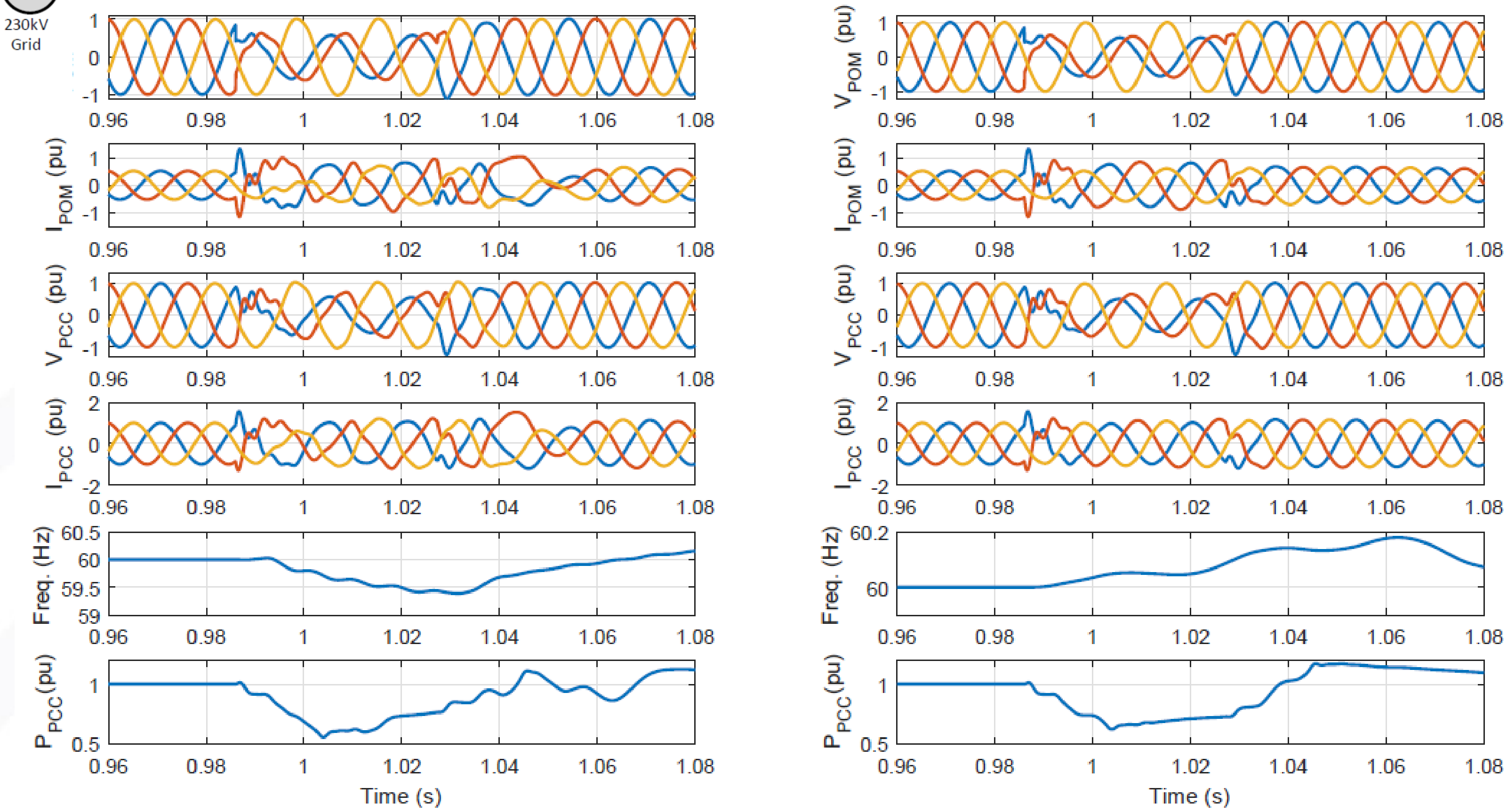


L-L fault:

Single-phase PLL observes frequency dip while three-phase PLL observes frequency increase.

Low-frequency was detected by PV inverters in 2016 during the Blue Fire event that tripped 1200 MW PV.

EMT Validation Testbed



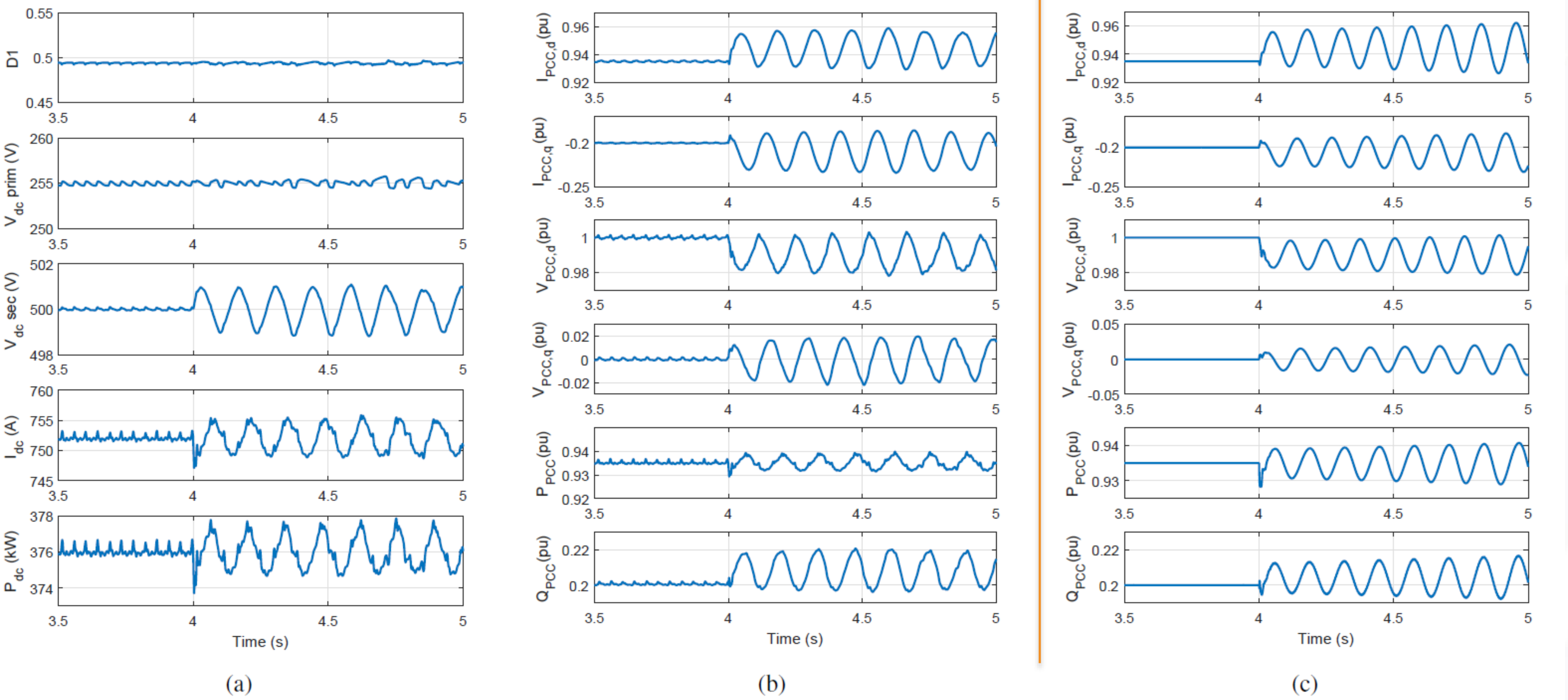
(a) Jovcic PLL.

(b) SRF PLL.

Event replication: Low-frequency oscillations

EMT Validation Testbed: with full details: inverter, dc/dc converter, MPPT.

Analytical model: inverter only, dc-side dynamics ignored.

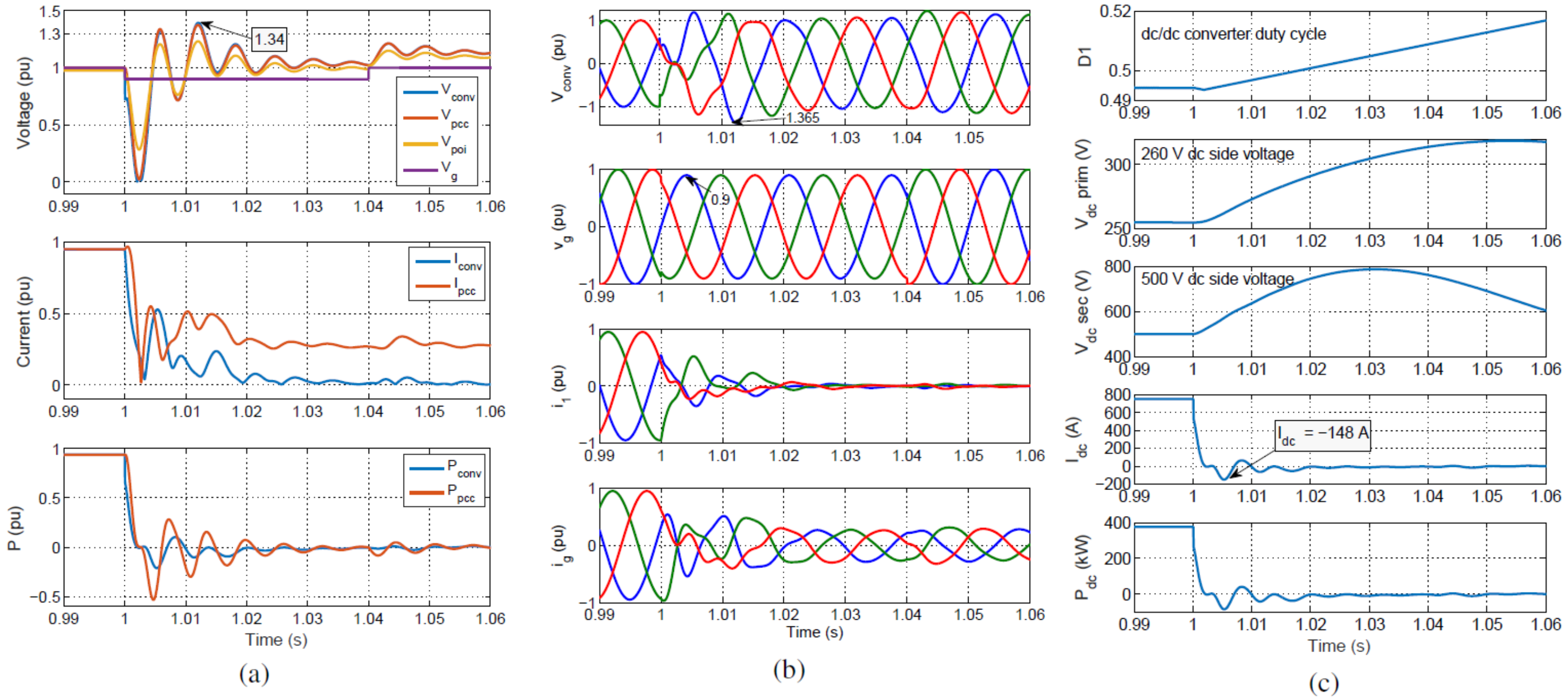


- Low-frequency oscillations are demonstrated using analytical model with low order and EMT validation testbed

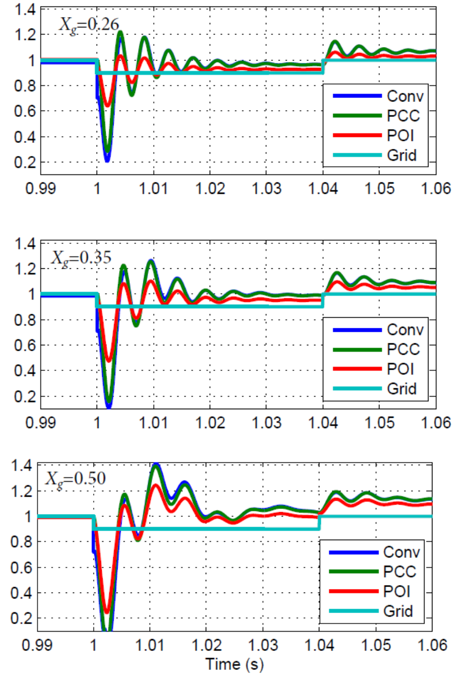
AC Voltage order steps from 1.0 to 0.99 at t = 4 s.
(a) Detailed testbed: dc side variables (duty cycle of the dc/dc boost converter, PV side voltage, boost converter output voltage, dc side current and dc side power). (b) Detailed testbed: ac side variables (dq-axis GSC current to the PCC bus, dq-axis PCC bus voltage, and real and reactive power to PCC bus); (c) Simplified model: ac side variables (dq-axis GSC current to the PCC bus, dq-axis PCC bus voltage, and real and reactive power to PCC bus).

Event replication: subcycle overvoltage

EMT Validation Testbed: with full details: inverter, dc/dc converter, MPPT.



Analytical model: inverter only. DC side dynamics ignored.



Grid voltage dips to 90%. PV enters **momentary cessation after 1 second**. (a) GSC ac side voltage magnitudes, current magnitudes and real power. (b) GSC ac side three-phase converter voltage, grid voltage, converter current, and grid current. (c) dc/dc converter duty cycle, 260 V dc-side voltage, 500 V dc side voltage, dc current, and dc power to the grid from the converter.

Research outcomes

1. A. Almunif, L. Fan, and Z. Miao, "**A tutorial on data-driven eigenvalue identification: Prony analysis, Matrix Pencil, and Eigensystem Realization Algorithm**," *International trans. on Electrical Energy Systems*, 2020.
2. L. Fan and Z. Miao, "**Admittance-base stability analysis: Bode Plots, Nyquist Diagrams, or Eigenvalue Analysis**?" *submitted, IEEE Power Engineering Letters*.
3. L. Fan and Z. Miao, "**Admittance model identification of inverter-based resources using time-domain signals**," *submitted, IEEE trans. Power Systems*.
4. M. Zhang, Z. Miao, and L. Fan, "**Low-frequency oscillations in solar PV farms in weak grids**," *submitted, IEEE trans. Energy Conversion*.
5. A. Alassaf and L. Fan, "**Randomized dynamic mode decomposition for oscillational modal analysis**," *submitted, IEEE trans. Smart Grid*.

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