DOE 10658 Project
Sensitivity-Driven Wide Area Protection (SWAP) Coordination Tools for IBRs

Ajmal Saeed
Pacific Gas & Electric Co.

PG&E

We are focused on providing safe, reliable, clean and affordable natural gas and electricity to our customers.

141,215 Circuit miles of electric distribution lines

Service Area **70,000** SQUARE MILES

Service area population **16 million** CALIFORNIANS (That's 1 in 20 Americans!)

25,000 EMPLOYEES WHO LIVE AND WORK in the communities we serve

67 Hydroelectric powerhouses

MORE THAN **715,000** SOLAR CUSTOMERS representing **>6,900 MW** of solar energy generated

NEARLY **500,000** ELECTRIC VEHICLES registered in our service area

18,616 Circuit miles of electric transmission lines

PG&E System Wide

8,440 MW of Distributed Generation
10,376 MW of Transmission Connected Inverter based generation.

95% greenhouse gas-free energy in 2022

NEARLY **40%** renewable energy in 2022

On track to meet California's goal:
60% renewable energy by 2030

2022 Power Mix*
PG&E-owned generation and power purchases

- 38% Renewable**
- 8% Large Hydro**
- 5% Fossil Fuel
- 49% Nuclear**
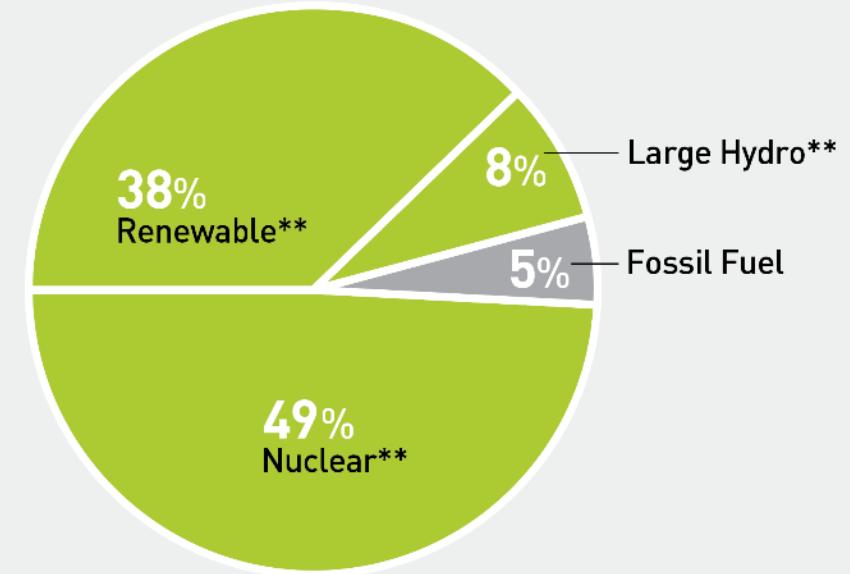
*Numbers are rounded for presentation
**Greenhouse gas free and/or renewable resources

PG&E delivers a range of clean energy resources, such as solar, wind, hydropower and nuclear and is also integrating innovative technology to make the power grid smarter and more resilient.

Drivers for Renewable Energy California Legislation

❑ *Reduce Greenhouse gas emissions by 40% from 1990 levels via:*

    ❑ *Senate Bill SB 32*

    ❑ *AB 197*

❑ *Increase Energy Derived from Renewable Energy Sources to 100% by 2045 via:*

    ❑ *Senate Bill SB 350*

    ❑ *Senate Bill SB 100*

    ❑ *Renewable Portfolio Standard (RPS) Targets*

        ❑ *40% by the end of 2024*

        ❑ *45% by the end of 2027*

        ❑ *60% by the end of 2030*

        ❑ *100% by the end of 2045*

- CAISO High Penetration Renewables

- April 30, 2024
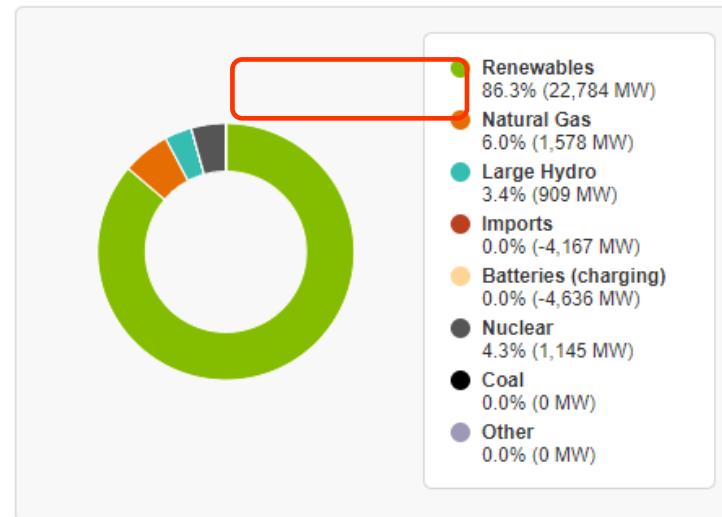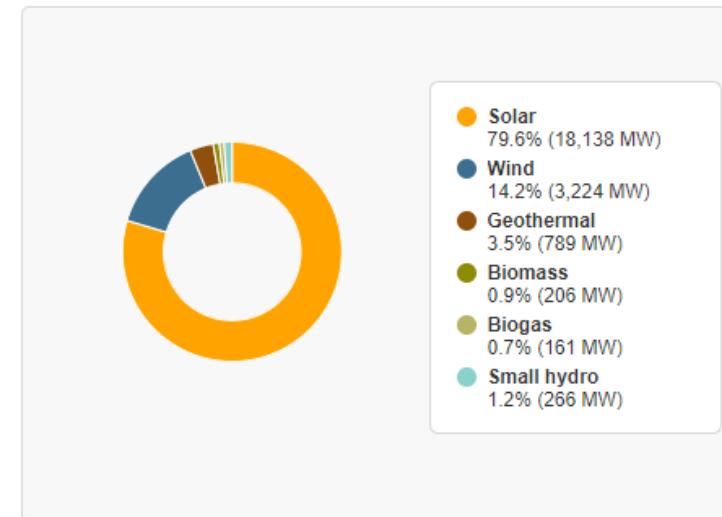
Project Objectives

- **Objective 1:** Improve IBR models used in short circuit programs to accurately capture the response of IBR at the Bulk Power System (BPS) level for fault and protection studies.

- **Objective 2:** Develop an automation tool that allows engineers to identify protection coordination and sensitivity issues by performing short-circuit and protection coordination studies in an IBR-penetrated grid by applying variations to the IBR models, faults, contingencies, etc.

- **Objective 3:** Develop new protection mitigation solutions schemes that complements the existing protection systems to ensure safe operation of the BPS with higher IBR penetration levels. Protection systems will include different types of line, bus, and transformer protection schemes.

Team Members & Key Personnel

Team Members

Supporting Organizations

Mike Jensen (PI)
Ajmal Saeed

Electric Utility (Prime)

Amin Zamani
Omid Alizadeh

Consultant & Tool Developer

Mohammad Zadeh

Short-Circuit Software Developer

Inverter Manufacturer

Taylor Raffi
Huimin Li
Electric Utility

Mathew Reno

Consultant & National Laboratory

Ali Bidram

University Partner

Relay Manufacturer

Key Milestones & Deliverables

Year 1
- All the protection data is gathered and reviewed.
- First version of the IBR model is developed.
- The modeling specification document is ready.

Year 2
- IBR short-circuit model is verified and integrated.
- The SWAP coordination tool is ready.
- Wide-area coordination results are ready.

Year 3
- Protection solutions are developed
- Testing and validation of solution(s) completed.

Overview of Proposed Approach
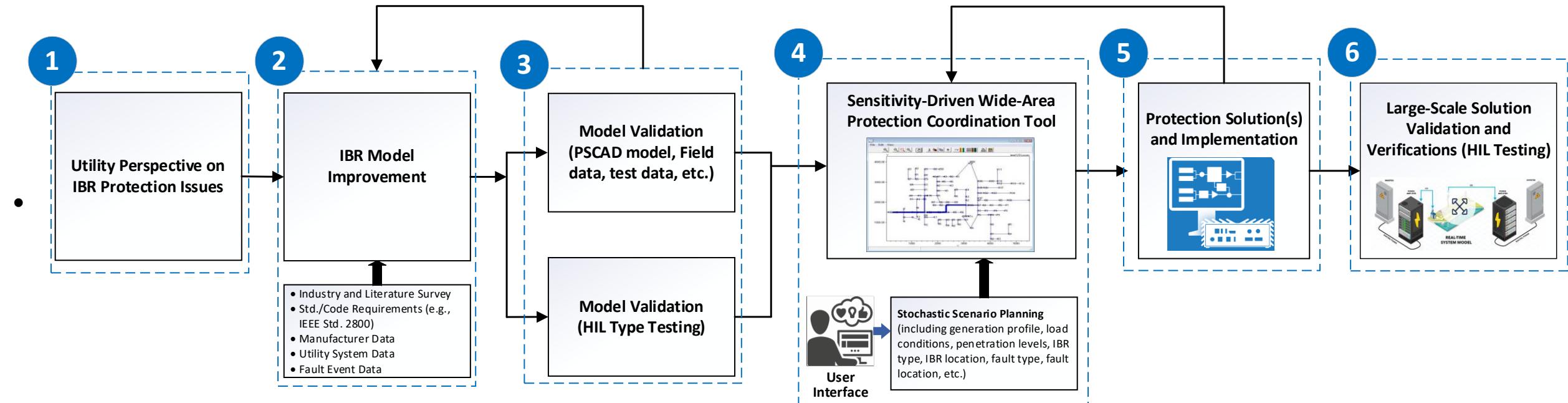
Utility Perspective

Modeling Challenges

- Fault simulation software vendors do not have a comprehensive IBR model.
    - The "Voltage Controlled Current Source" (VCCS) model has limitations.

- The current IBR models are removed when reducing the network

- Convergence issues with VCCS IBR models.

- It's difficult to get modeling data in a timely manner from manufacturers. Manufacturers may want to sign non-disclosure agreements (NDA) that take months to finalize.

- Time domain analysis (using EMTP and PSCAD) is not practical.

- Most of the utilities are still modeling IBRs as synchronous machines.

Utility Perspective

Protection issues due to low inertia

- Low fault current presents challenges to set the element low enough.

- Rapid frequency changes can be attributed to low inertia of IBRs resulting in several issues:
    - ROCOF
    - low memory polarization
    - frequency tracking issues
    - unstable I2 phasors

- Fault ride through issues causes loss of generation for external faults

- IBRs affect rate of change of swing impedance and can impact operation of power swing blocking.

- IBRs can cease to energize (momentary cessation) which will delay protection relay to respond.

- Lack of zero sequence current from IBRs may prevent the ground overcurrent relay to operate.

Utility perspective

Protection issues with low negative sequence

- **Directional Element Performance issues.** Lack of negative sequence current or unstable negative sequence current prevents the relay to determine the directionality of faulted event.

- **Distance Element Performance.** Inconsistent expansion of mho circle due to non-homogeneous phase angle relationship cause overreach or underreach.

- **Faulted Phase Identification Logic issues.** Inconsistent relationship between I2 and I0 prevents the relay from accurately identifying the faulted phase.

- Directional element performance causes **issues with POTT & Blocking schemes operating correctly**

- **Possible overvoltage issues.** Lack of negative sequence and zero sequence current can cause transmission line overvoltages.

Utility Perspective

A questionnaire was initiated to validate the protection issues, the following are the responses from AEP, SMUD, SDGE, Southern Company, TEPCO

- Utilities are concerned about protection challenges due to low fault current, low negative sequence current, islanding, voltage ride through.

- Commercialized short circuit software programs such as CAPE and Aspen lack a comprehensive IBR model.

- Utilities are not receiving model information like (EMT model) from the manufacturers

- Utilities have begun to analyze the IBR events and are becoming aware of the protection challenges with IBRs

Utility Perspective

Research areas that utilities want to focus for IBRs

- Develop accurate and efficient short circuit models for IBRs.

- Develop advanced protection schemes tailored to ensure grid stability and reliability.

- Research on backup protection elements during communication failures and fault conditions.

- Negative sequence current injection during fault conditions

- Research and development on Grid Forming Inverters

- IBR Fault Events

- PG&E Area PV Fault Events – Momentary Cessation
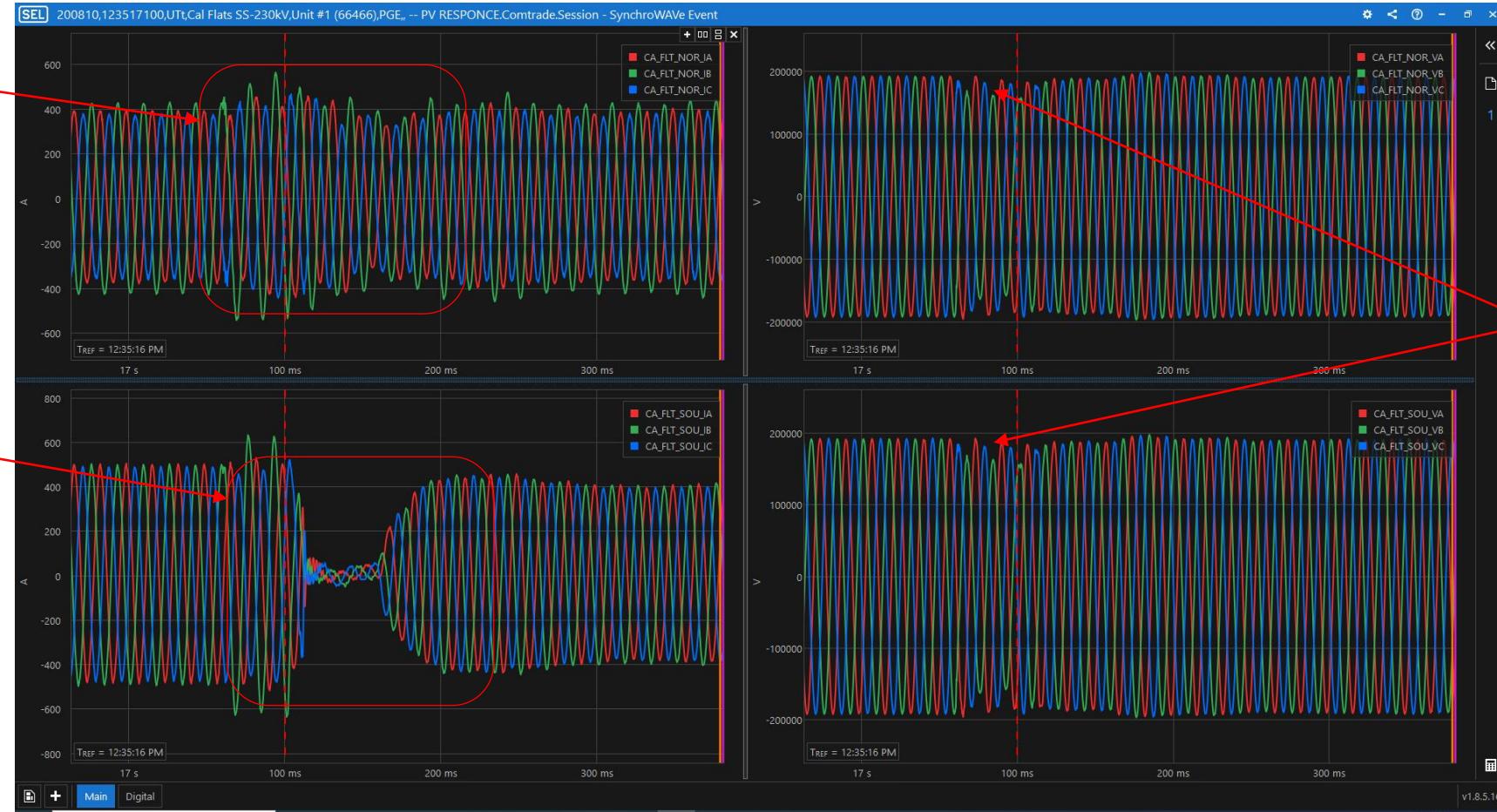
- IBR Fault Events

- 160MW Solar Facility Event
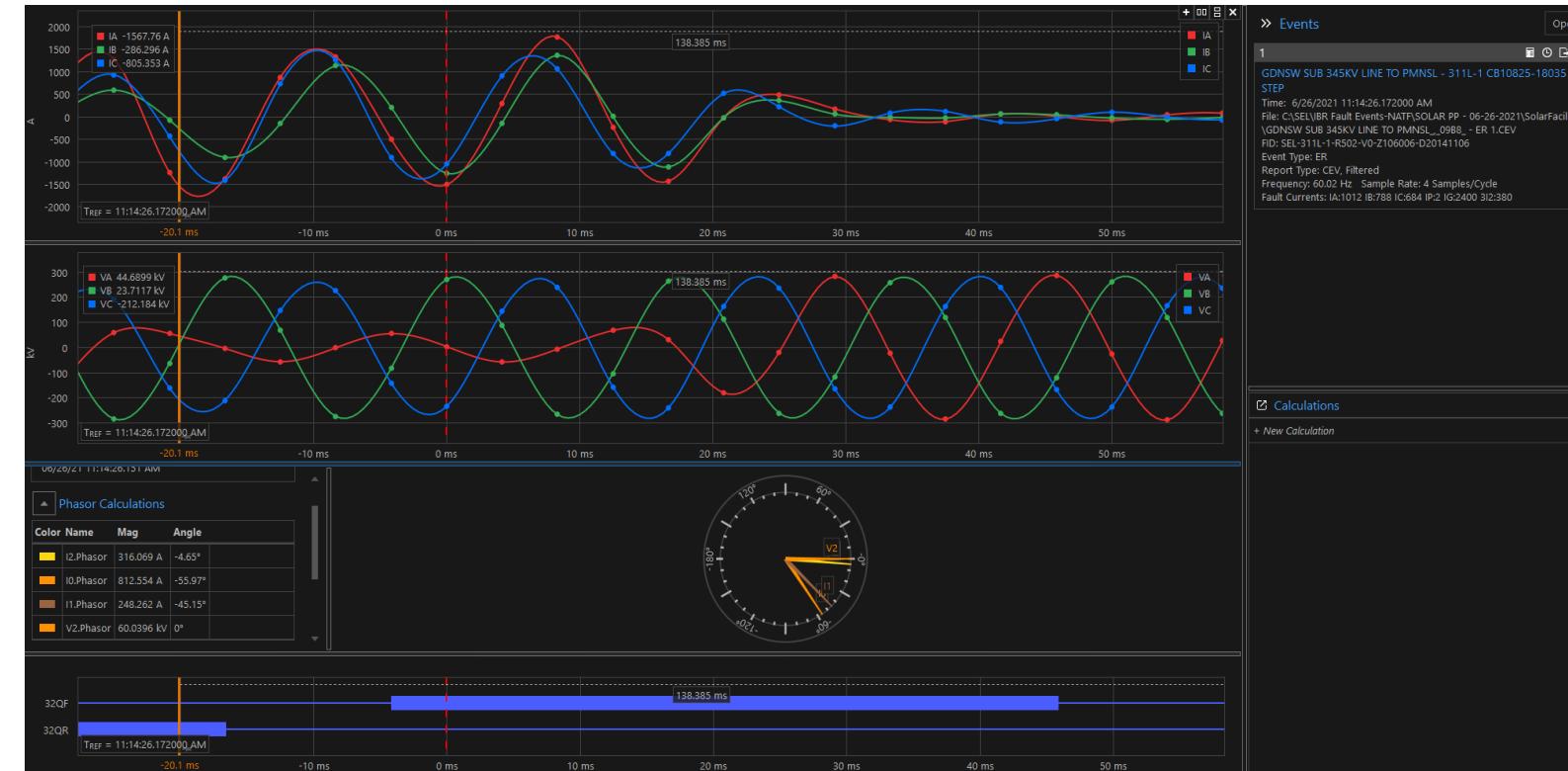
- **Relay momentarily shows forward fault for out of section reverse fault**

- **Relay does not determine the faulted phase correctly**
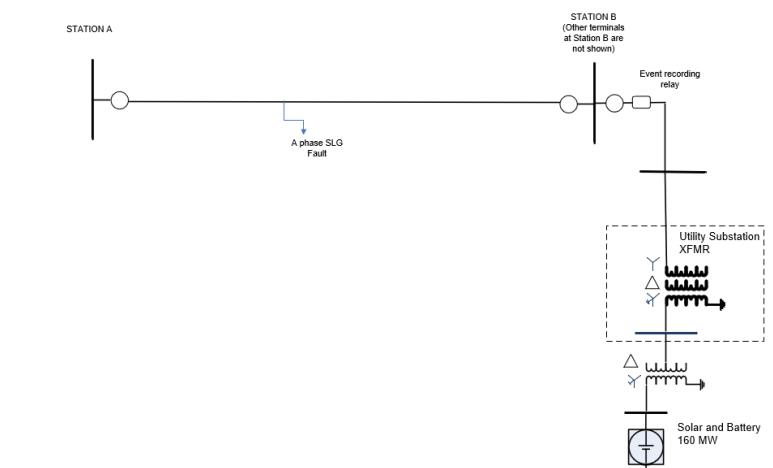
- 160MW Solar Facility Event

- Inconsistent V2 and I2 phasors

32QF = Asserted

32QR = Asserted

If protection scheme is using negative Sequence for polarization, then microprocessor relay uses the Relationship between V2 and I2 to determine if the fault is forward or reverse

I2 and V2 relationship at different time during the fault

- IBR Fault Events

- 40MW Wind Turbine Type III

- **Relay overreached and tripped by Zone 1**

- **This is the case where impedance was oscillating due to an oscillating I2 phasor**
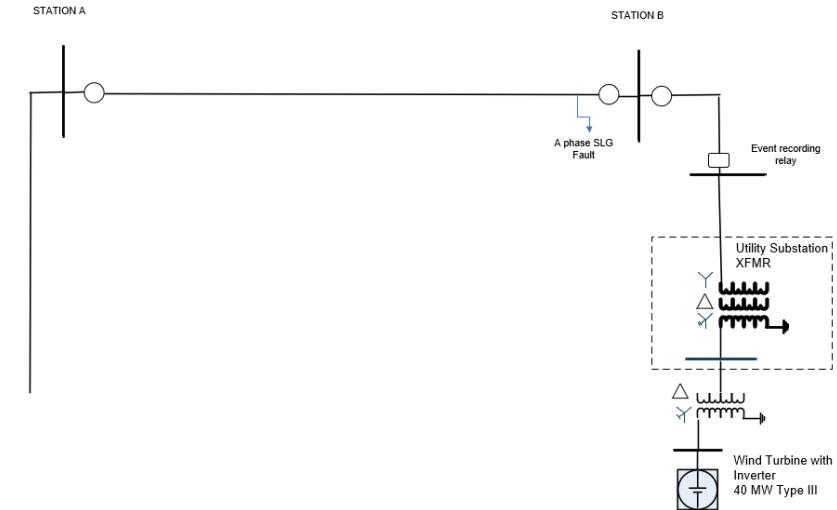
- IBR Fault Events

- 145MW Wind Turbine Type IV

- **Relay incorrectly reported CG fault for AG fault.**

- **This is due to inconsistent relationship between I2 and I0 phasors during the fault. Microprocessor relays use I2 and I0 phasors for fault identification selection (FIDs) logic**

- IBR Fault Events

- Wind Turbine Type IV

I0 and I2 phasor at fault inception

I0 and I2 phasor at later stage of fault
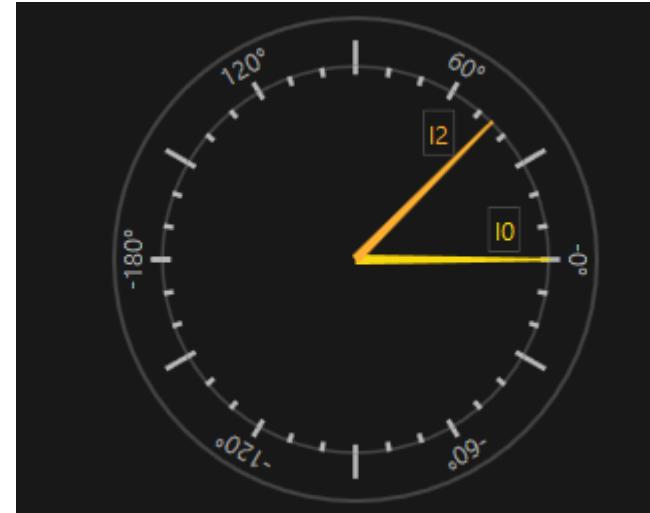
Microprocessor relays use the angular relationship between I2 and I0 to determine the faulted phase.

During the event, I2 has unstable behavior shown in the figures in this slide.

First figure on left side shows CG fault, whereas second figure shows AG fault.

Frequency Tracking Issues

- PG&E event, DERs back feeding into transmission
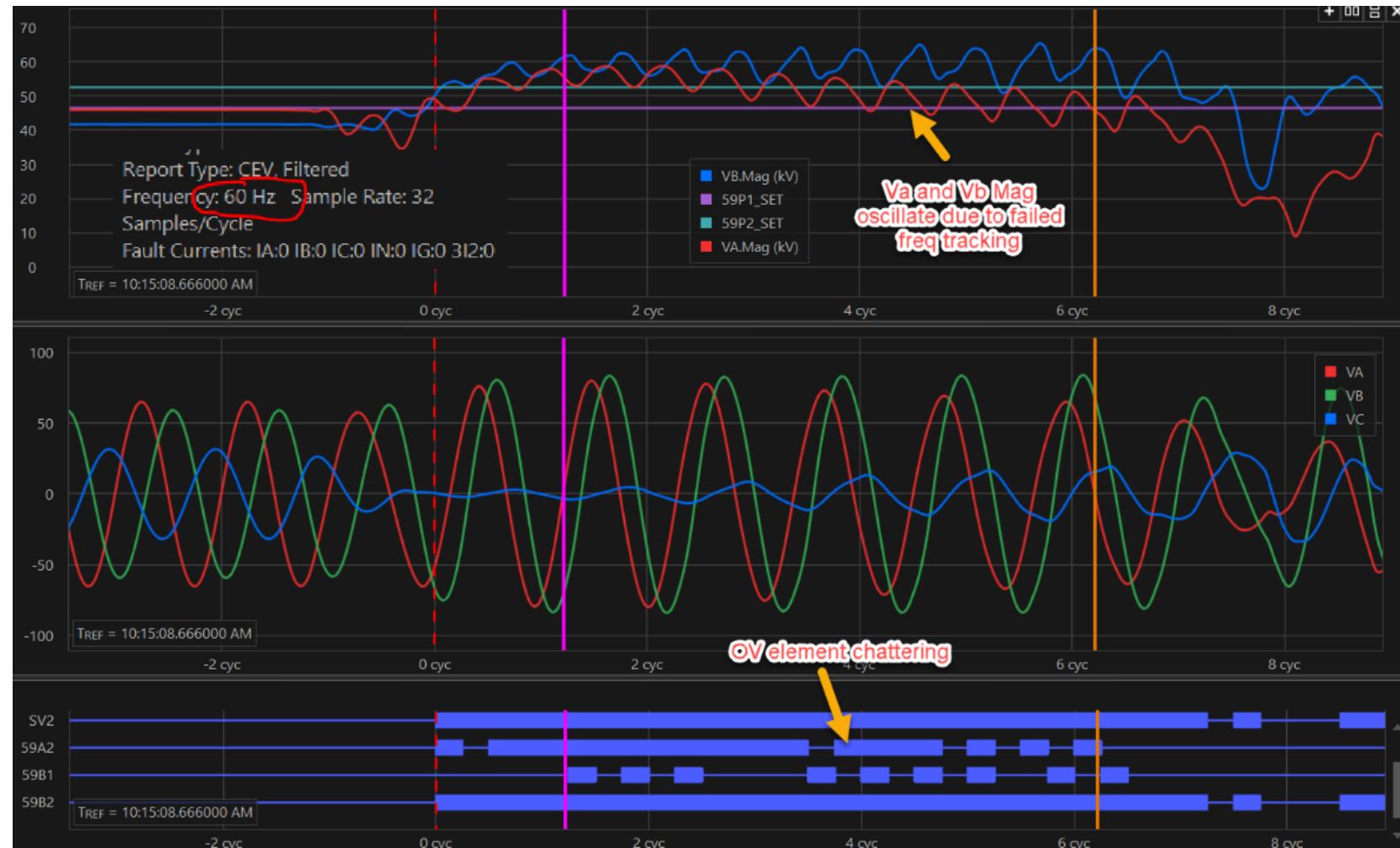
Sudden frequency shift exceeded relay's frequency tracking limit. Voltage oscillated leading the relay failure to operate

Frequency Tracking Issues

- PG&E event, DERs back feeding into transmission

Event at 70kV PG&E substation, where microprocessor relay failed to trip, because of the inverter sudden frequency shift (from 60Hz to 55Hz in very short time). This sudden frequency shift exceeded relay's frequency tracking limit. The voltage magnitude oscillated, which led to the relay failure to operate.
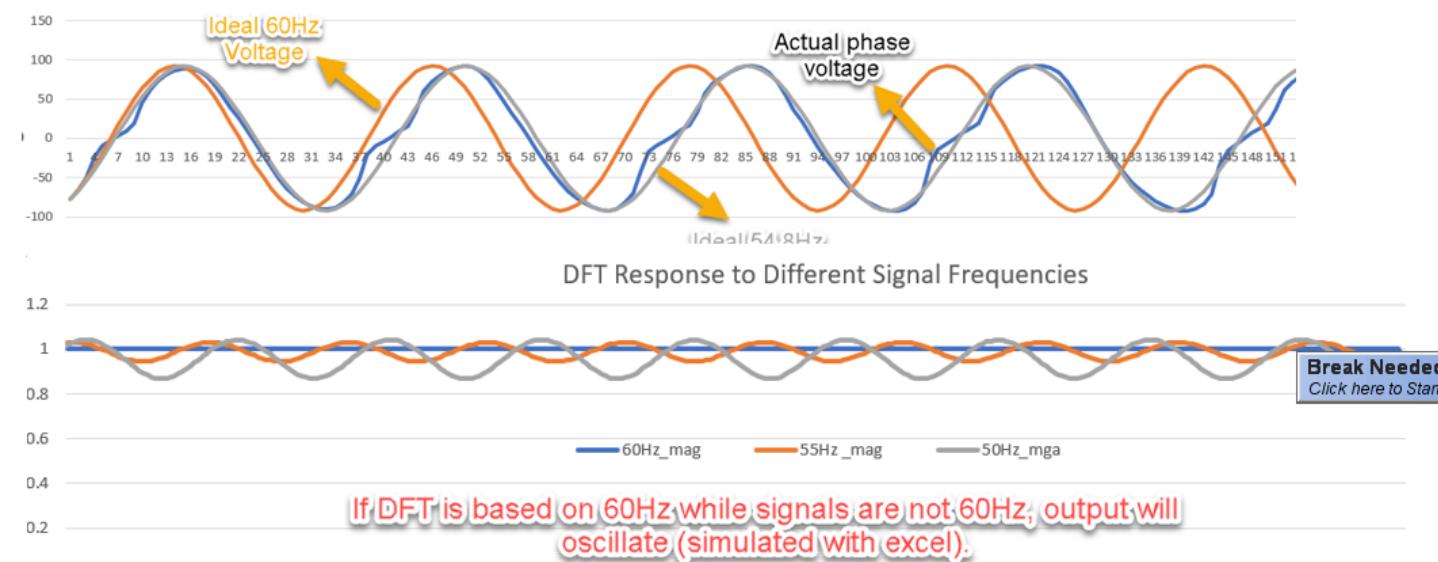
IBR Fault Events

PG&E Area BESS Event

- BESS was in charge mode initially

- Faulted phase BESS current contribution dropped

- Fault current magnitudes changed multiple times
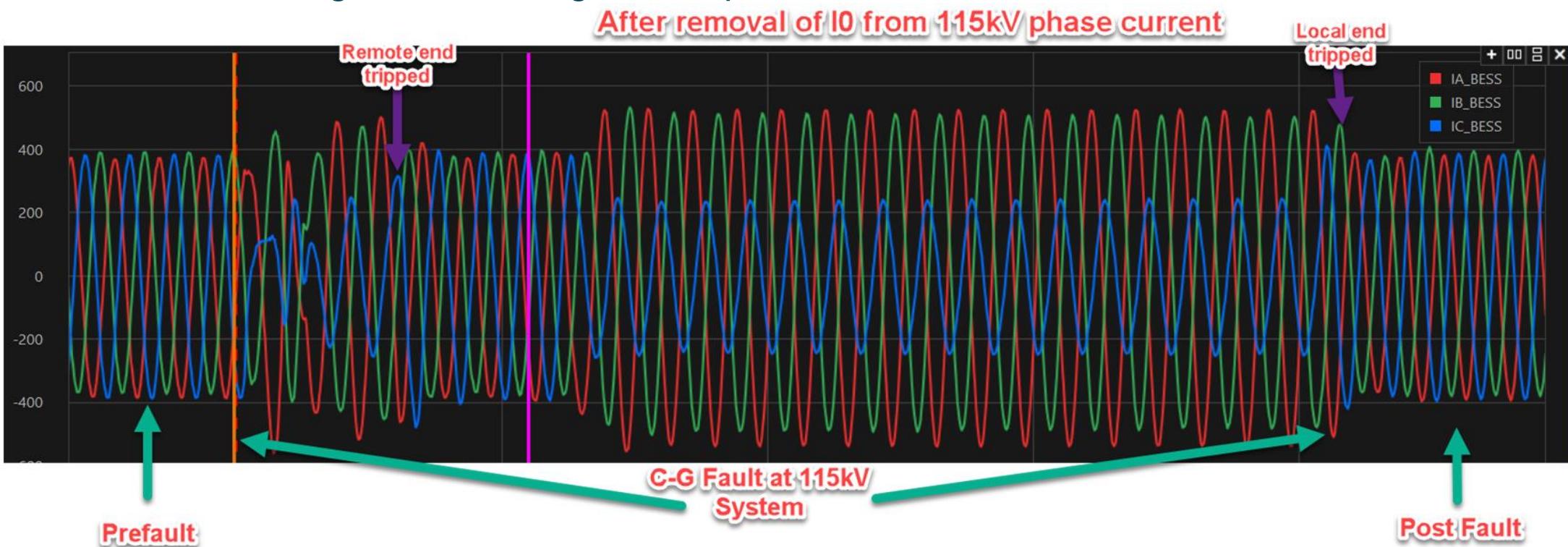
IBR Fault Events

PG&E Area PV Event
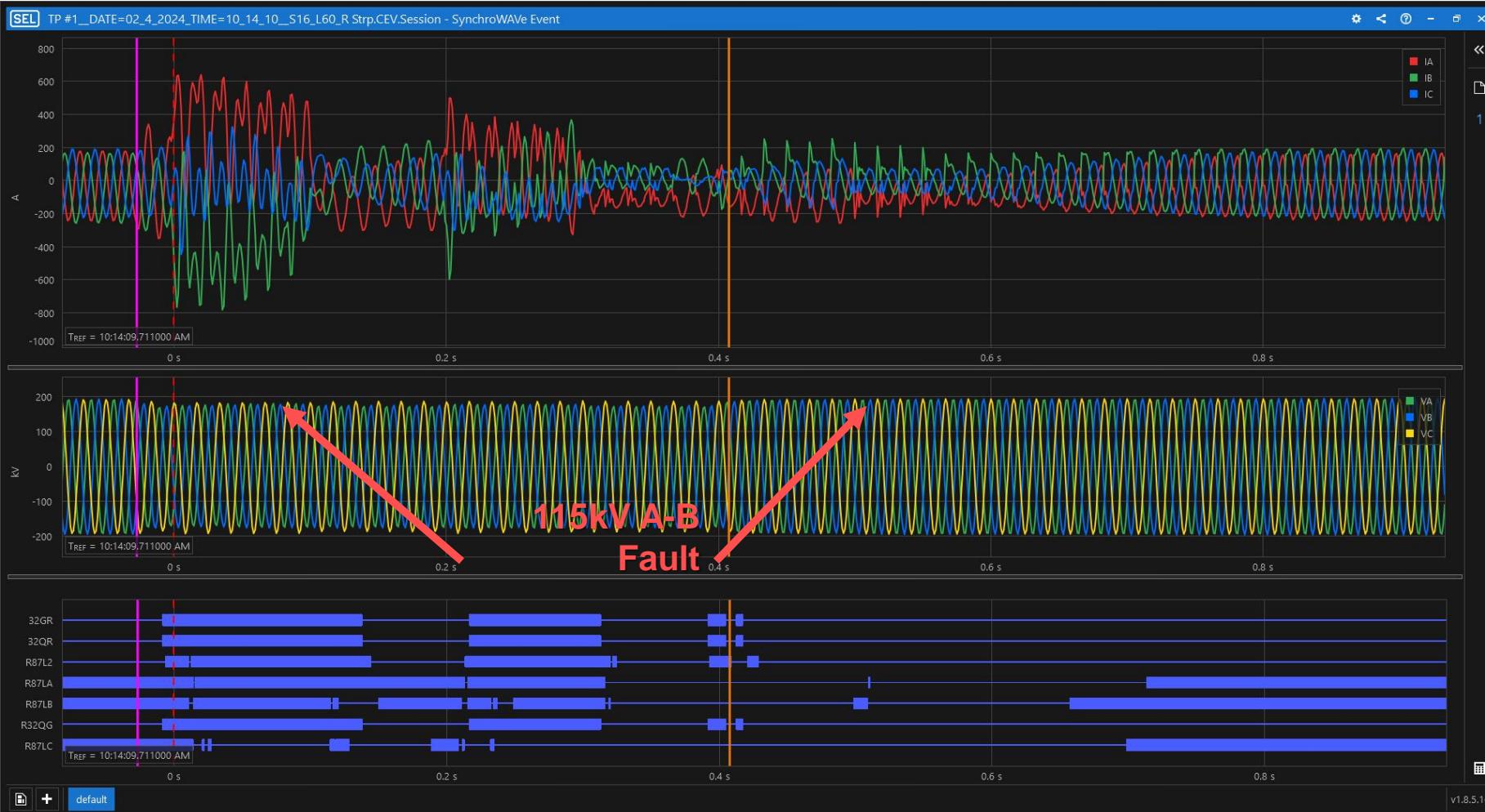
- **230kV 225MW solar facility response to a 115kV LL fault.**

- **Large DC offset and second harmonic.**

- **Current oscillation is approx. 100 msec.**

- **230kV Voltage dropped to approx 0.9 Vpu.**

- Major observation in modeling reactive power support during fault

- In WECC model
  - The curve is not continuous by nature
  - It is forced to be continuous within a time frame (default: 100 msec)
  - For K = 2, and dV1max= (0.1+ε) pu, there will be a sudden 0.2 pu current injection. This is a non-uniform response.

(a) Positive Seq.　　(b) Negative Seq.
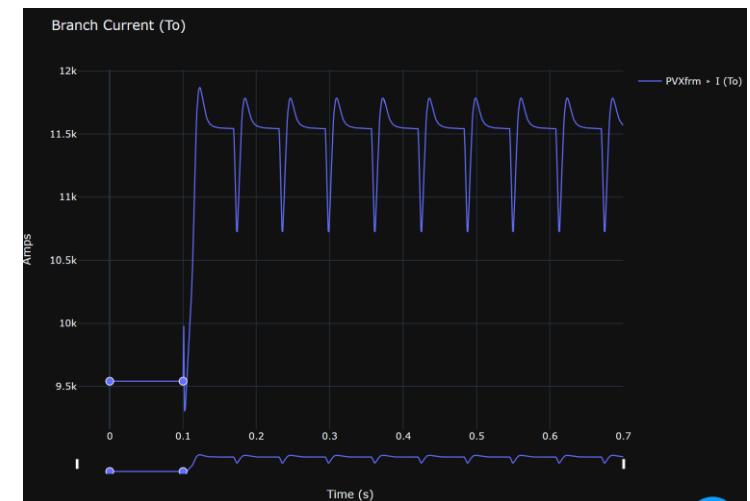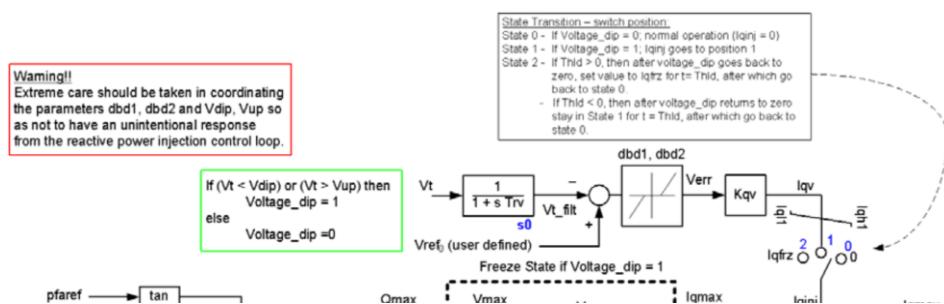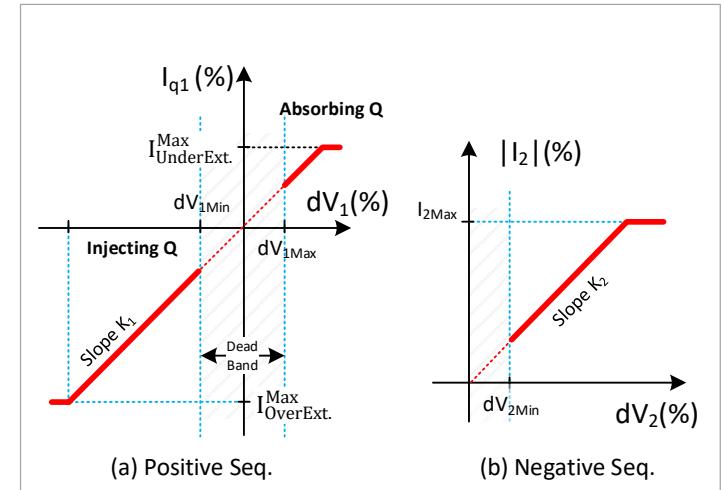
- ## **Development of Dynamic Phasor-based model**
  - Major observation in modeling reactive power support during fault

(a) Positive Seq.
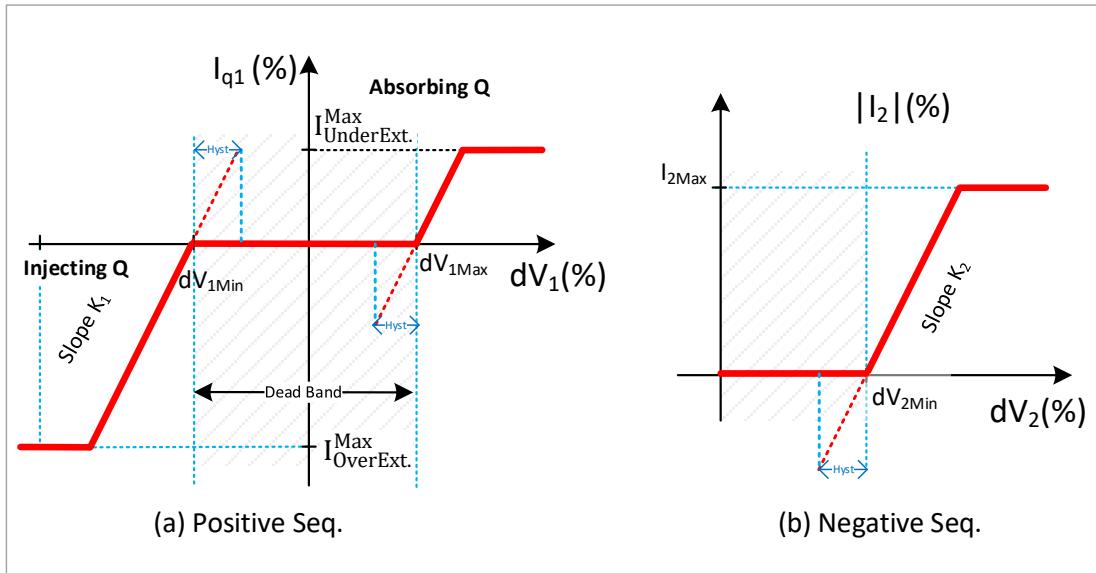
(b) Negative Seq.

One of the Manufacturer's Default

Mohammad
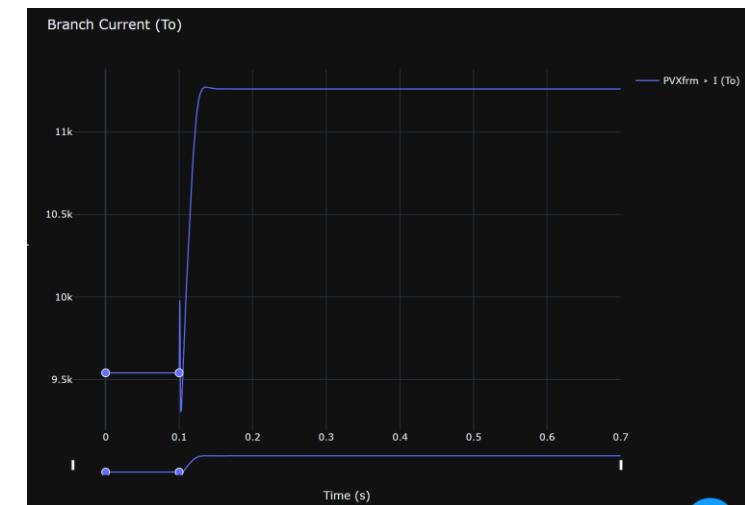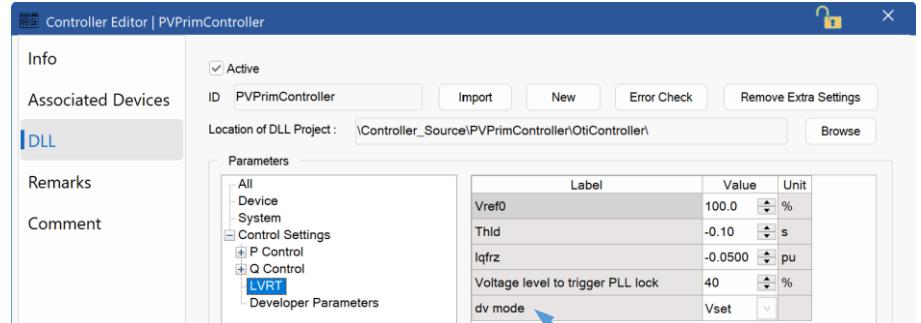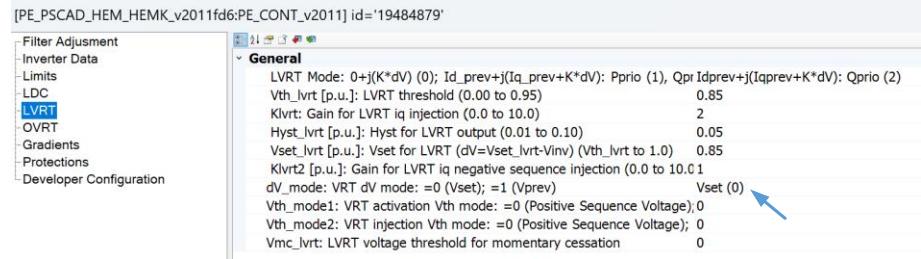
- DOE Project – SWAP Tool for IBRs

- IBR Model Improvement

Development of Dynamic Phasor-based model
WECC 2nd generation model (extended to include
negative sequence)

- DOE Project – SWAP Tool for IBRs

- IBR Model Development

- **Development of Steady-State Short-Circuit (SC) Model**
  − Investigate the importance of modeling IBR equivalent shunt impedance on SC convergence. Writeup submitted to IEEE PSRC C45.
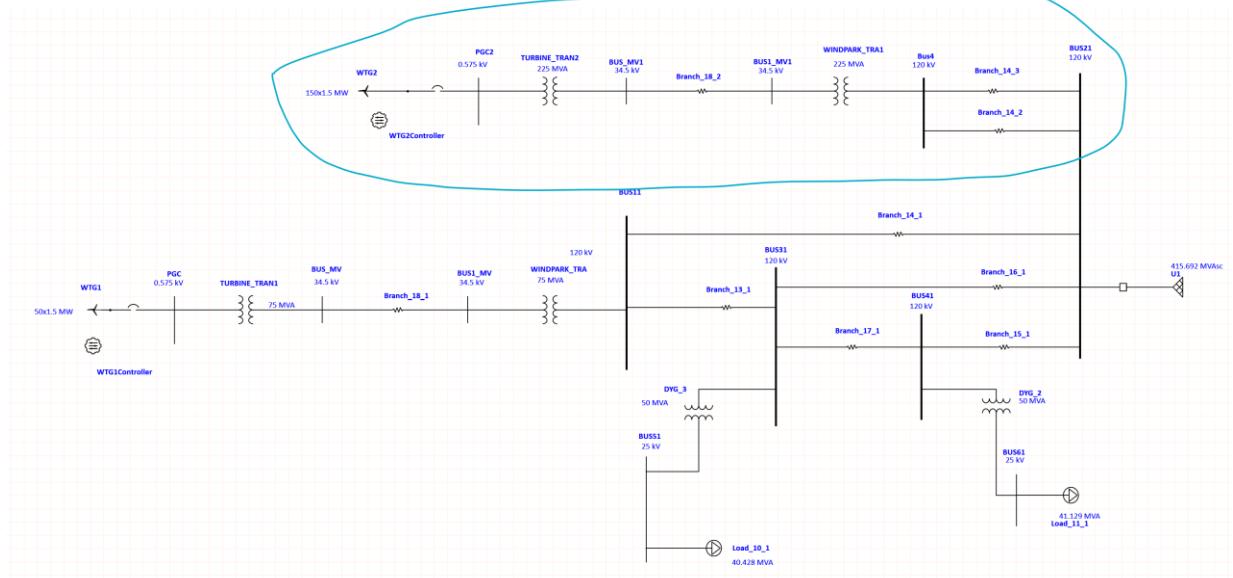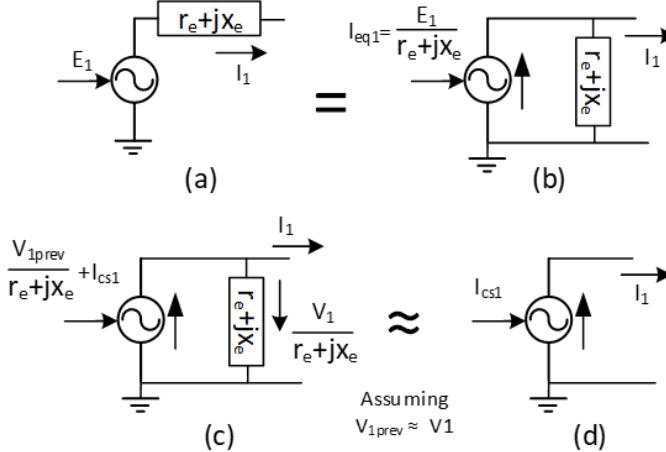
Evaluation Using EMT Models:

▪ Several scenarios will be run in ETAP to compare the fault response of the IBR model concerning the industry standards and grid codes.

▪ Vendor PSCAD models will be compared against the ETAP-created model.

▪ The ETAP models will be calibrated and fine-tuned based on the comparison with the detailed PSCAD vendor models.

Evaluation Using HIL Testing:

A high-level schematic of the HIL testbed for IBR model validation

Inverter Control Digital Twin

Inverter Control Board

Standard Interface

V_{DC} & I_{DC}

Switching Signal

Vac & Iac

DC SW, BRK, etc.

Analog and Digital IO Cards (or Comm Cards)

IBR Model

PV or Battery

Inverter

LV

HV

Bulk Power System (BPS)

Real-Time Simulation Platform
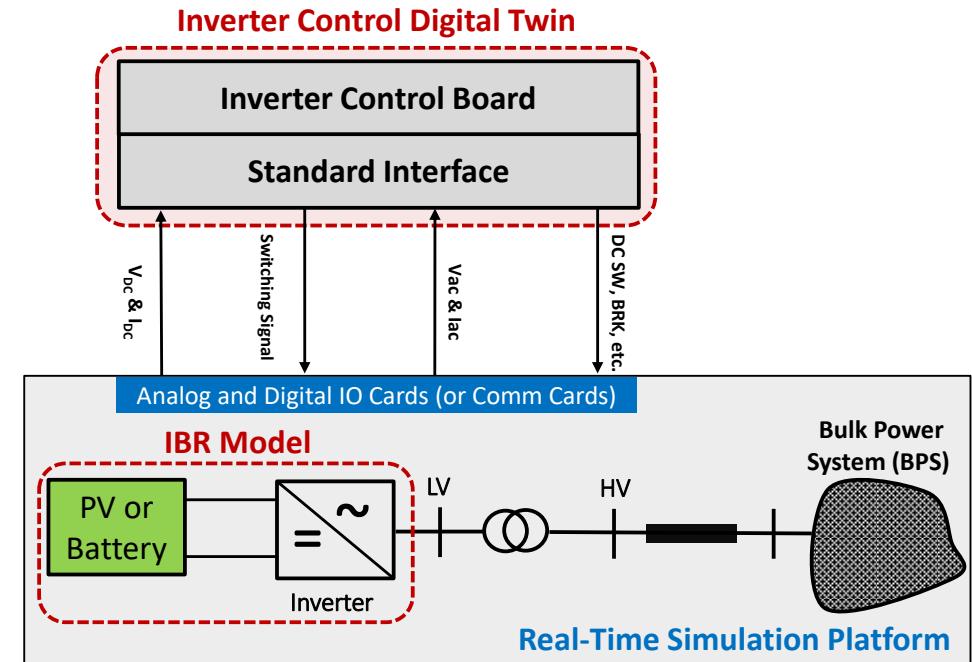
SWAP Tool Specification Document

Commenced work Specification
Document Development

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- Questions

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