Utility Perspective on Protection Challenges with High IBR Penetration

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This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE00010658.

Pacific Gas and Electric (PG&E): About us

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 2022 Power Mix

PG&E System Wide

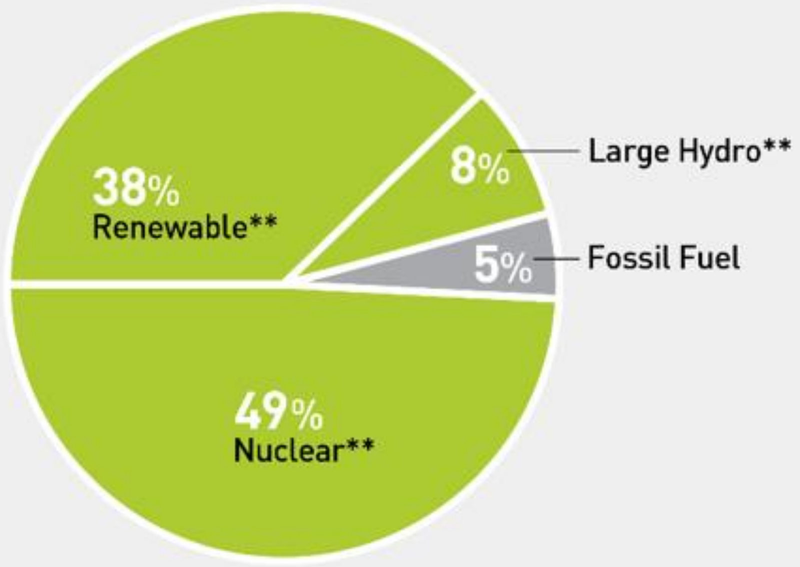
8,440 MW of Distributed Generation
10,376 MW of Transmission Connected Inverter based generation.

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

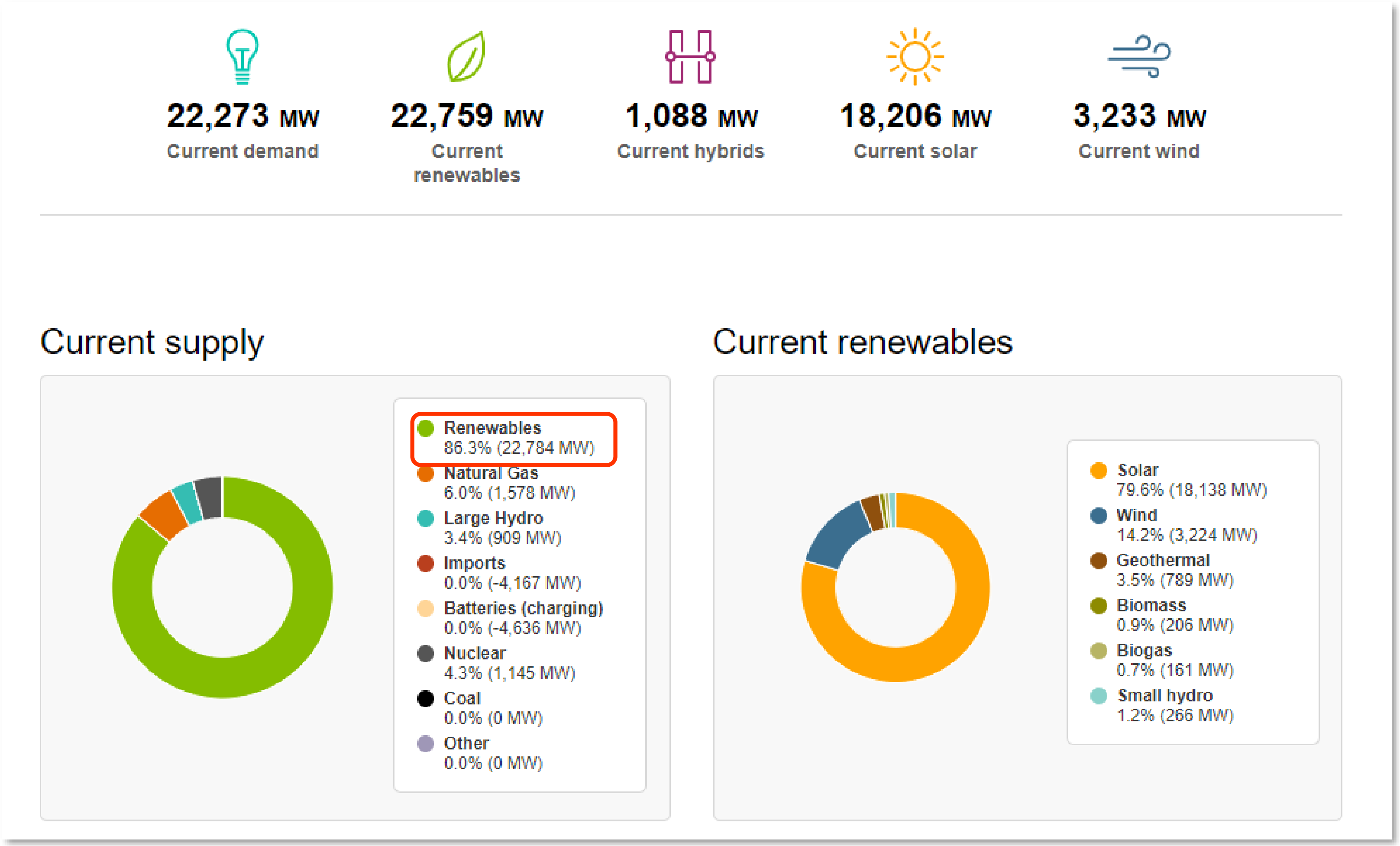


*Numbers are rounded for presentation
**Greenhouse gas free and/or renewable resources

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.

CAISO High Penetration Renewables

- April 30, 2024



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*

DOE Project – SWAP Tool for IBRs

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 complement 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

Pacific Gas & Electric

Mike Jensen (PI)
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Mathew Reno

Consultant & National Laboratory

University of New Mexico

Ali Bidram

University Partner

Supporting Organizations

EPC Power

Inverter Manufacturer

SEL

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.

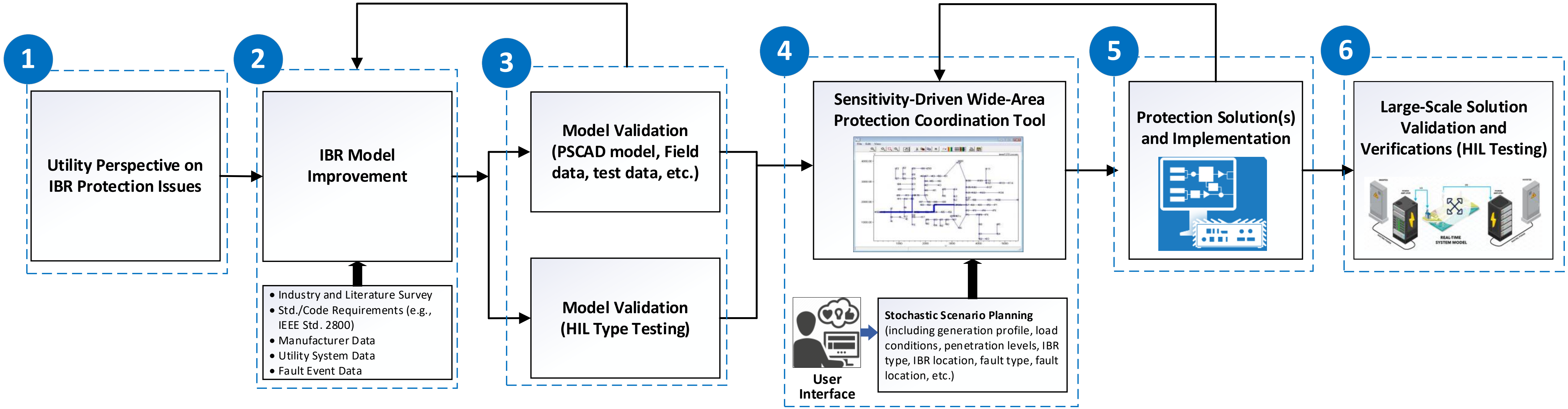
Year 2

- 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



PG&E	ETAP	Sandia National Lab	Quanta Technology	Quanta Technology	PG&E
Duke Energy		UNM	PG&E	PG&E	Sandia National Lab
		epcpower	Duke Energy	SEL	Quanta Technology

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 issue 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 causes 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. 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 on for IBRs

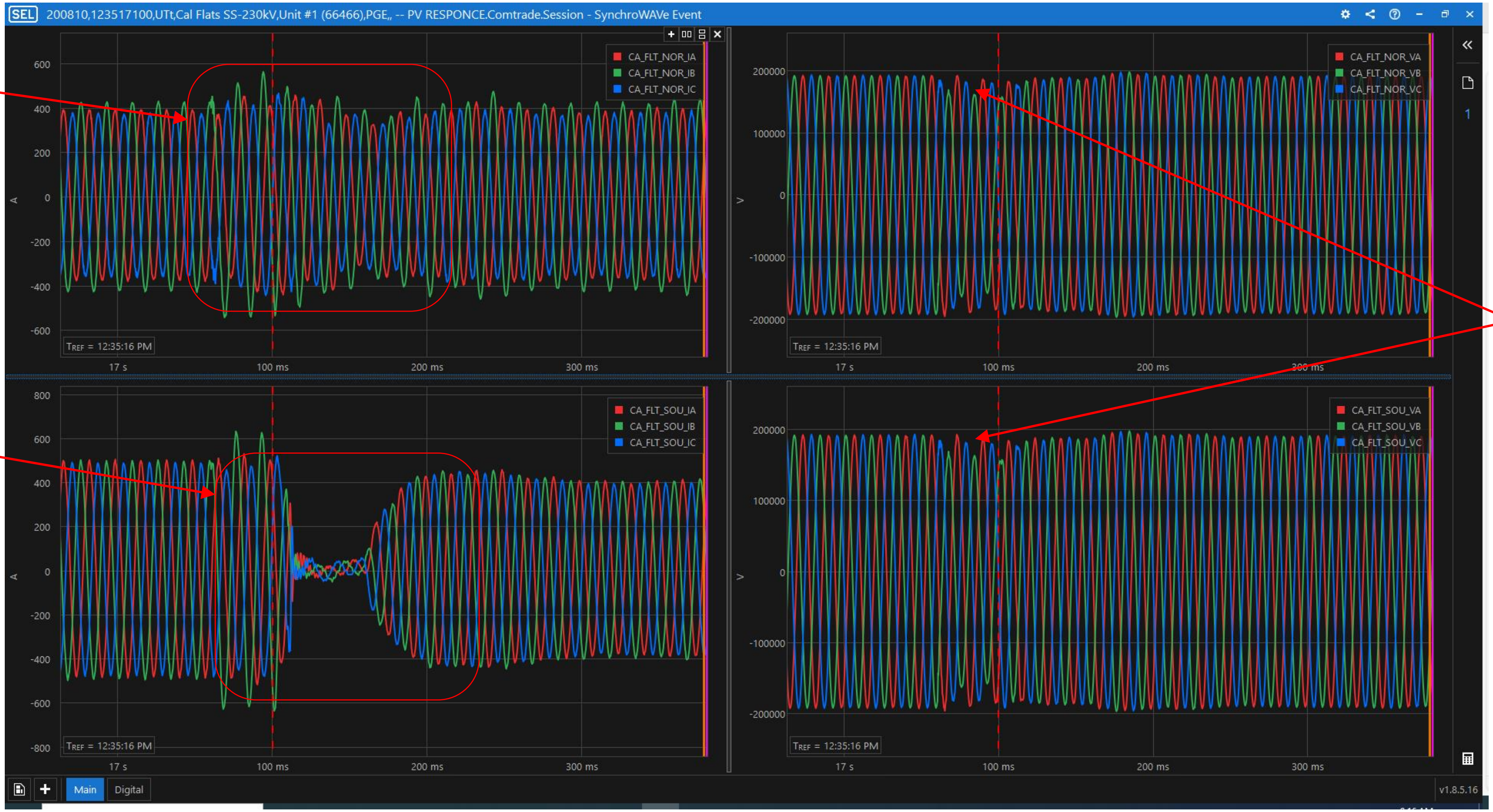
- Develop accurate and efficient short circuit models for IBRs.
- Develop advanced protection schemes tailored to ensure grid stability and reliability.
- Research on backup protection elements during communication failures and fault conditions.
- Negative sequence current injection during fault conditions
- Research and development on Grid Forming Inverters

IBR Fault Events

- PG&E Area PV Fault Events – Momentary Cessation

IBR fault current response for manufacturer 1

IBR fault current response for manufacturer 2



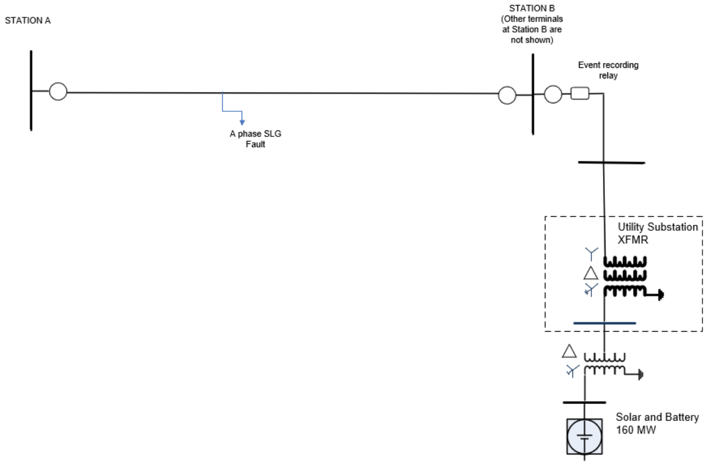
Voltage dip seen by the IBRs

IBR Fault Events

- 160MW Solar Facility Event

- **Relay momentarily shows forward fault for out of section reverse fault**

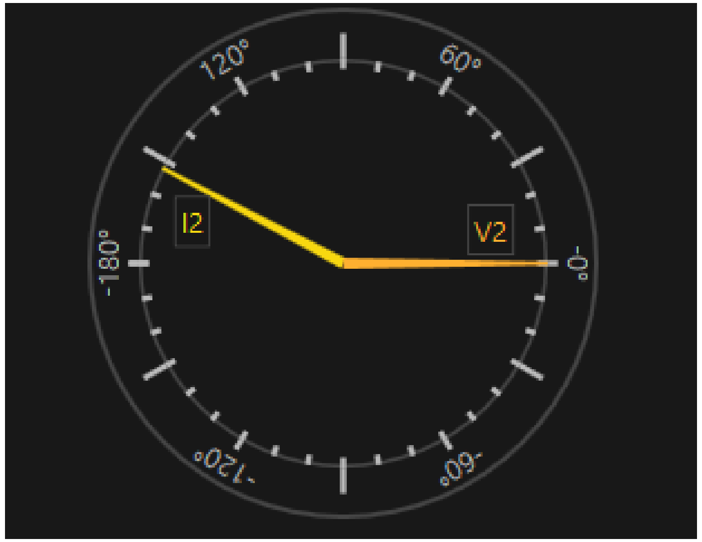
- **Relay does not determine the faulted phase correctly**



160MW Solar Facility Event

- Inconsistent V2 and I2 phasors

32QF = Asserted



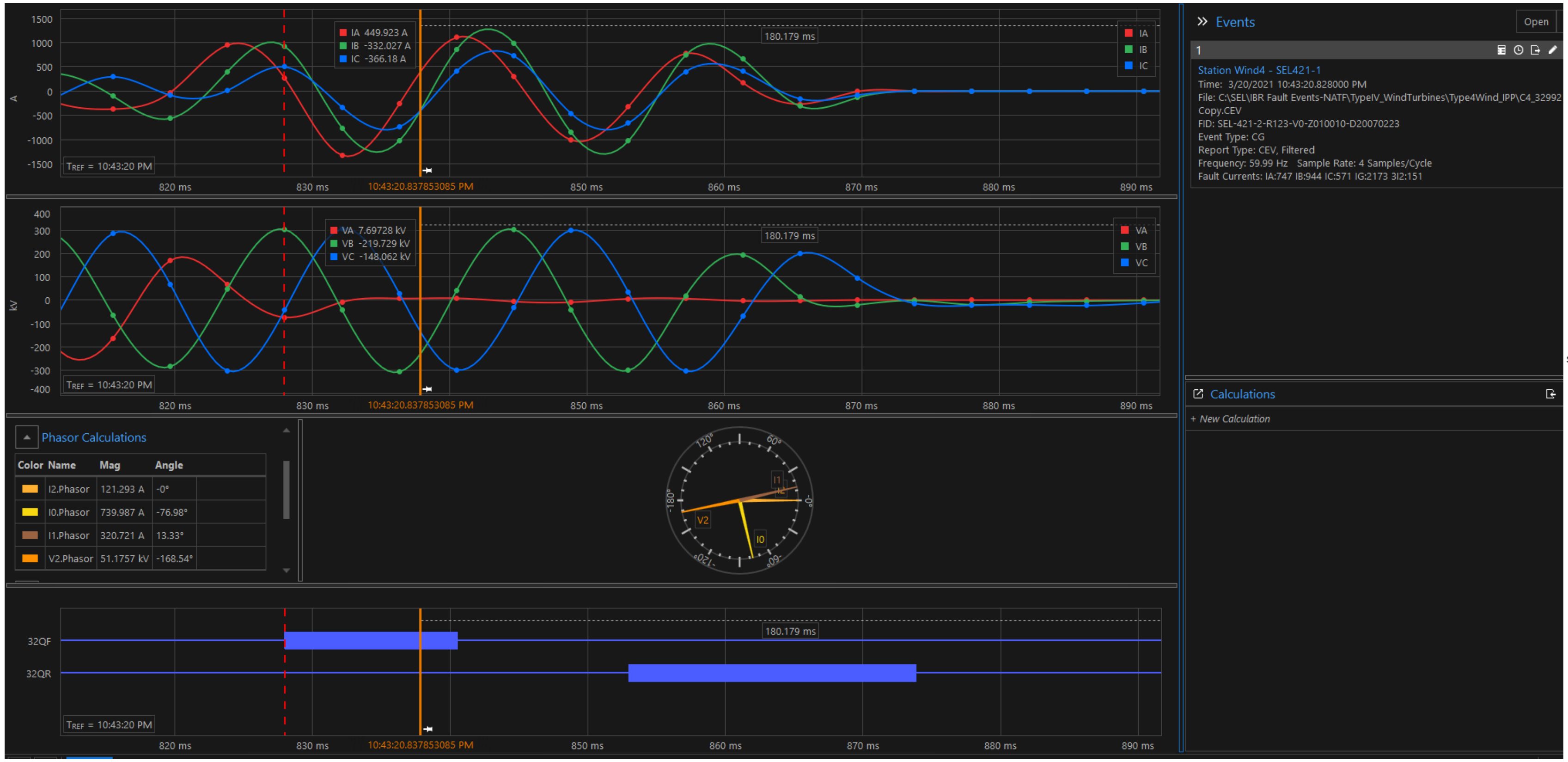
32QR = Asserted

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

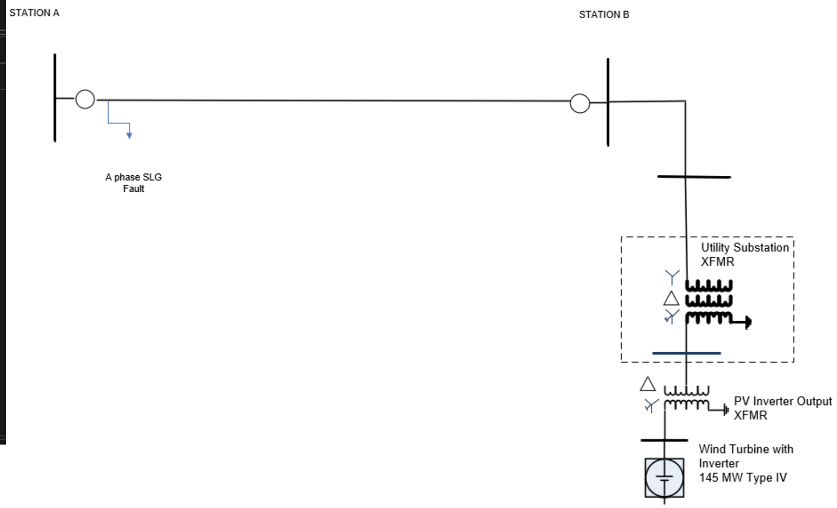
I2 and V2 relationship at different time during the fault

IBR Fault Events

- 145MW Wind Turbine Type IV



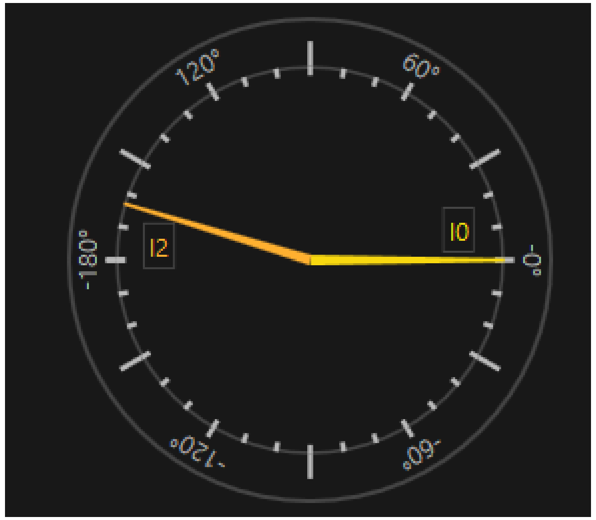
- **Relay incorrectly reported CG fault for AG fault.**
- **This is due to inconsistent relationship between I2 and I0 phasors during the fault. Microprocessor relays use I2 and I0 phasors for fault identification selection (FIDs) logic**



IBR Fault Events

- Wind Turbine Type IV

I0 and I2 phasor at fault inception



I0 and I2 phasor at later stage of fault

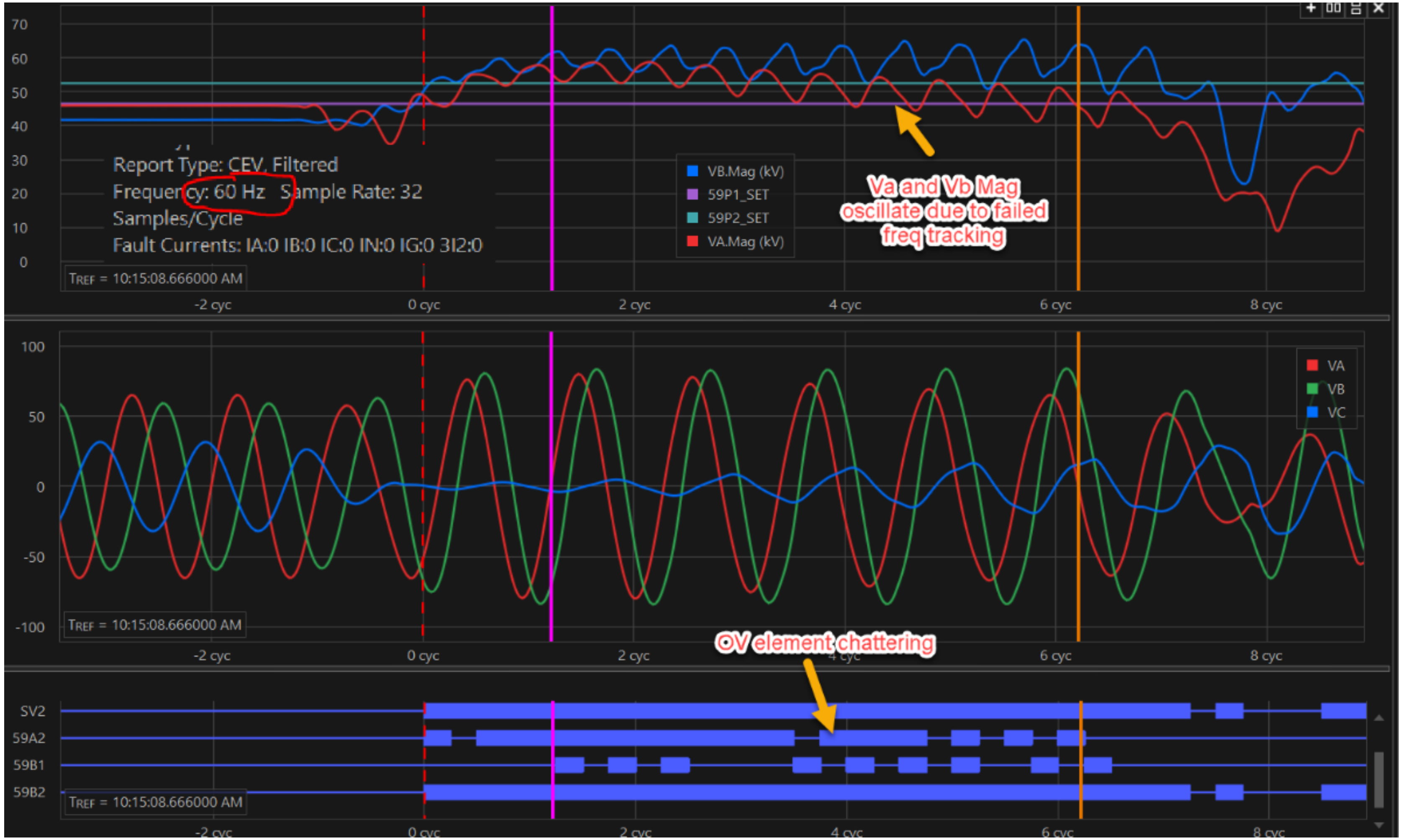
Microprocessor relays use the angular relationship between I2 and I0 to determine the faulted phase.

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

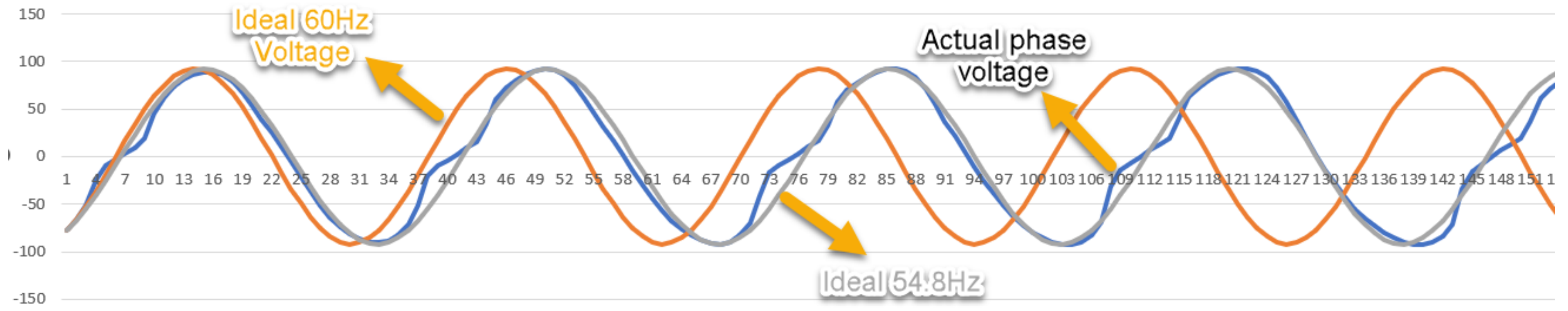


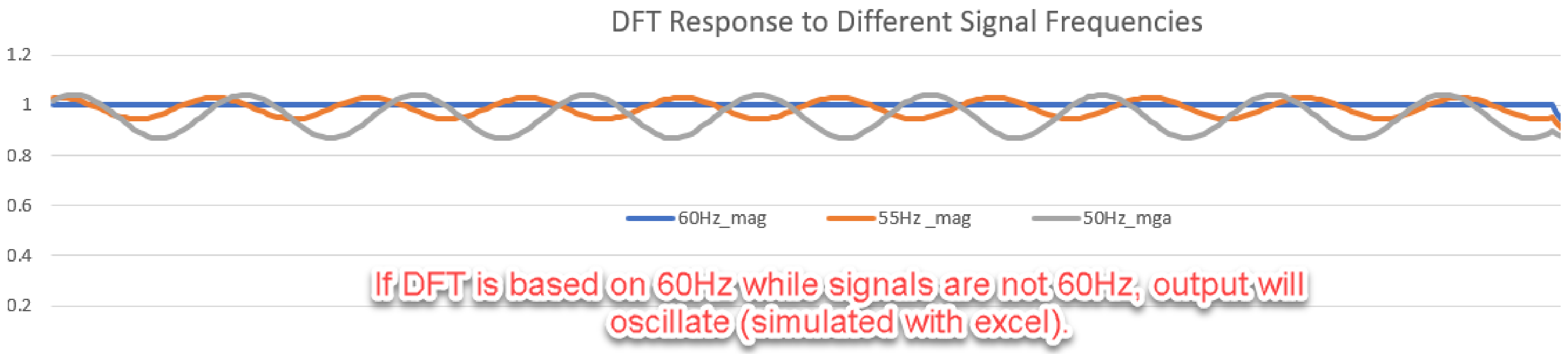
Sudden frequency shift exceeded relay's frequency tracking limit. Voltage oscillated leading the relay failure to operate

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.

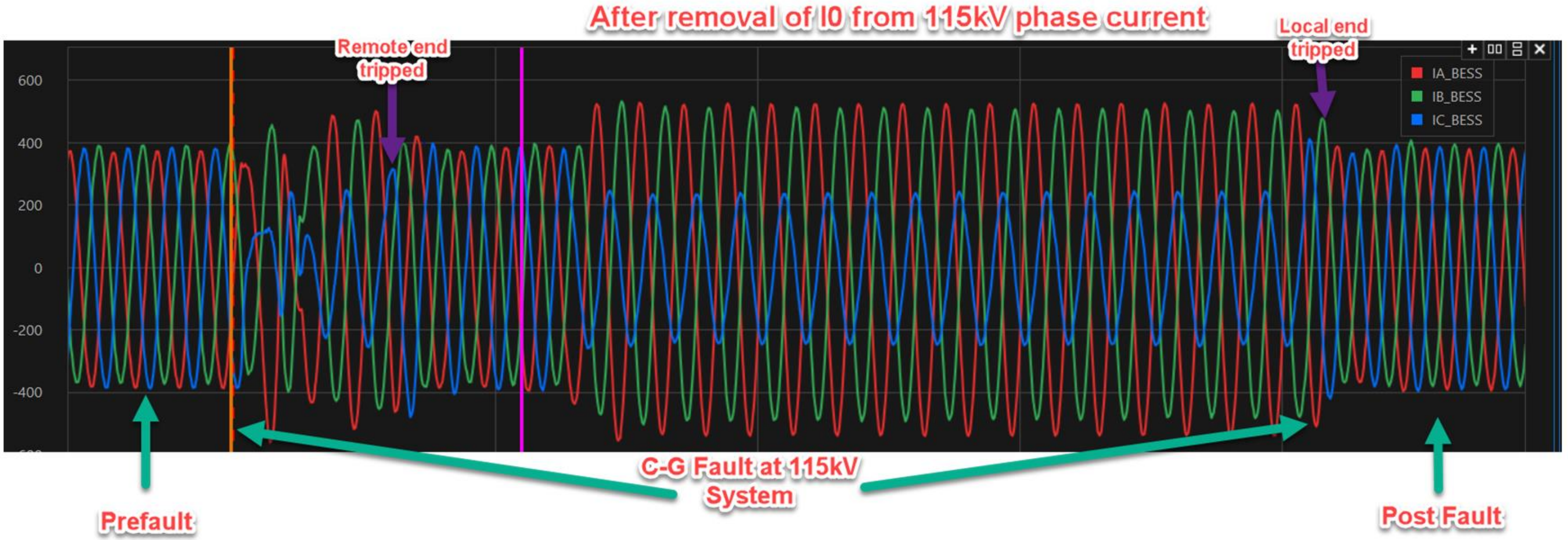




IBR Fault Events

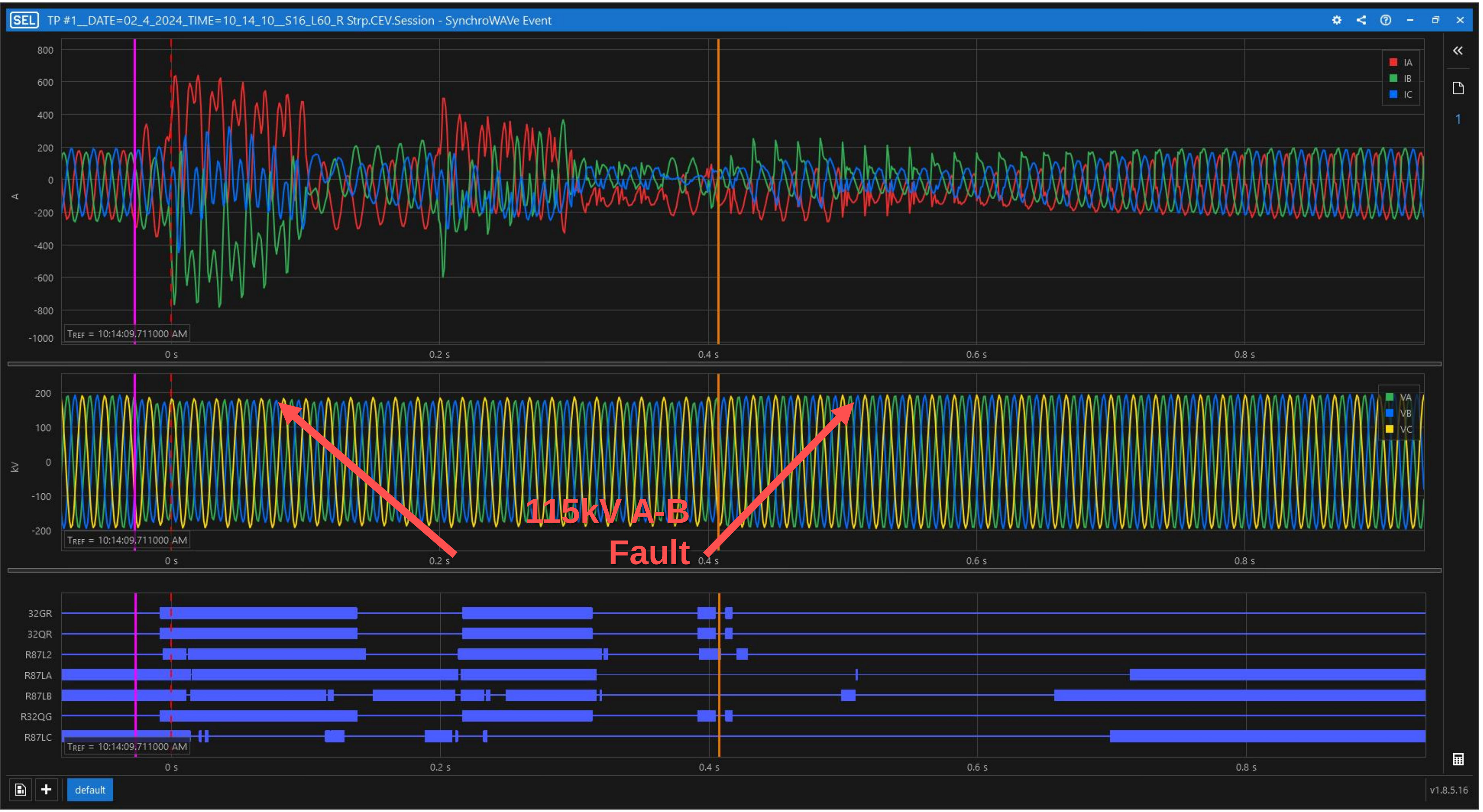
PG&E Area BESS (Battery Energy Storage System) Event

- BESS was in charge mode initially
- Faulted phase BESS current contribution dropped
- Fault current magnitudes changed multiple times



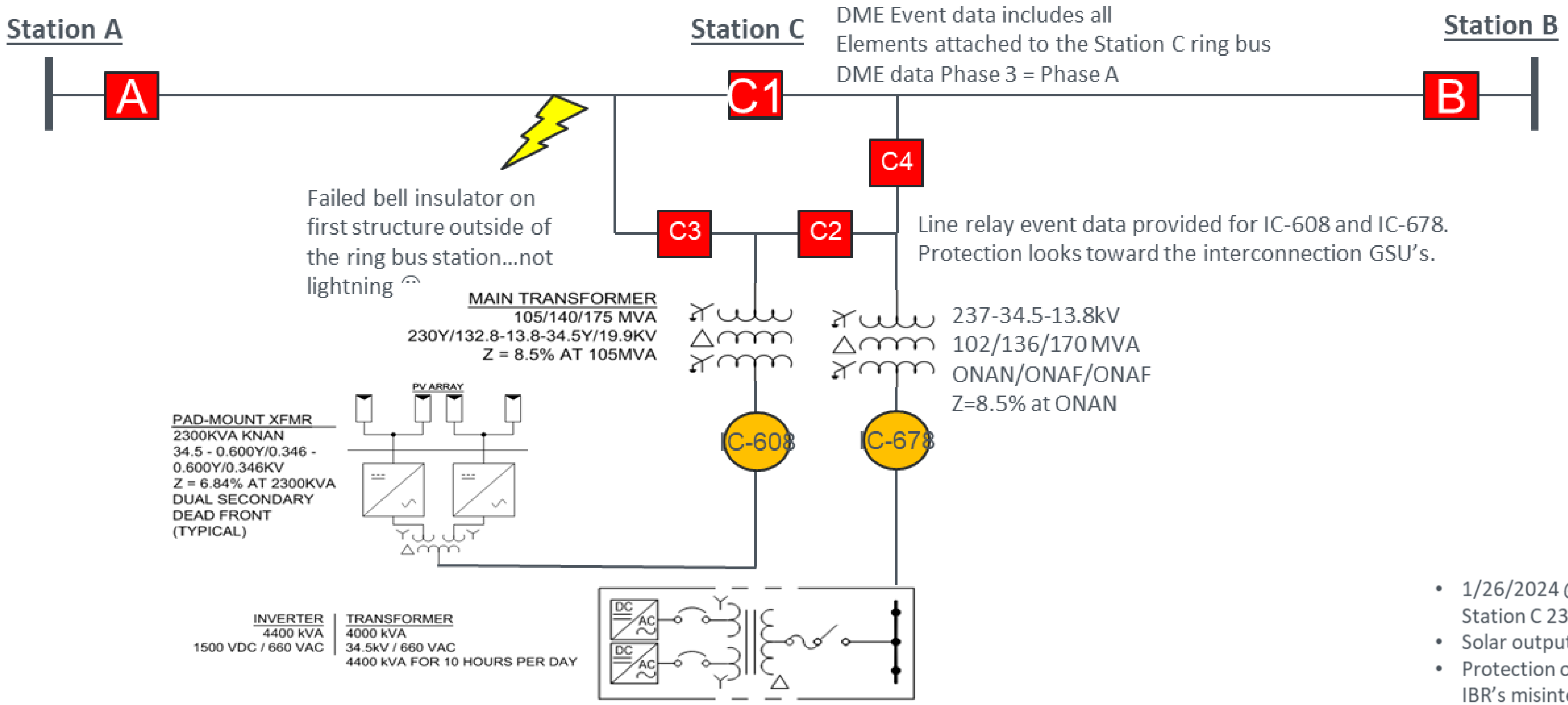
IBR Fault Events

PG&E Area PV Event



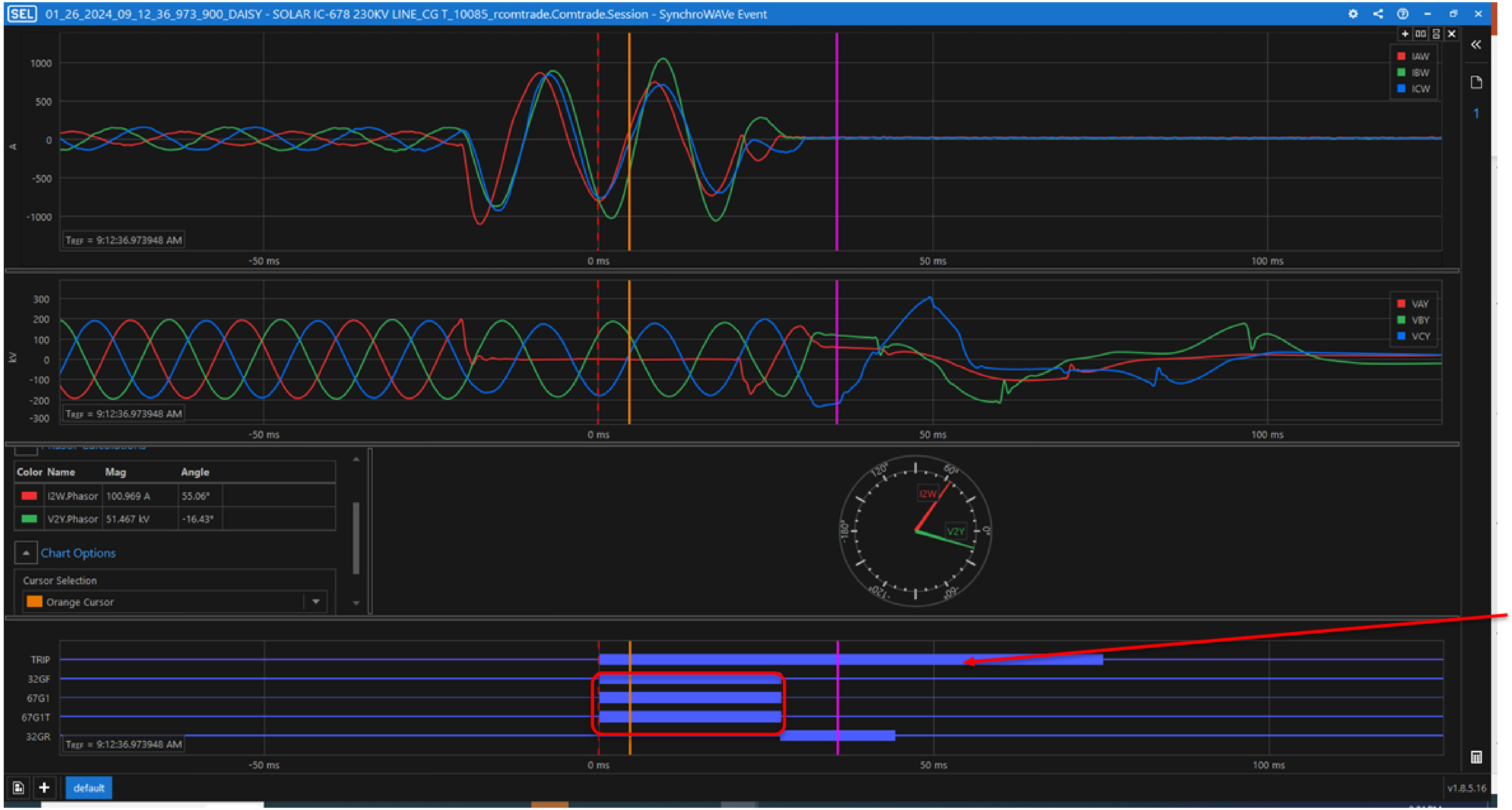
- **230kV 225MW solar facility response to a 115kV LL fault.**
- **Large DC offset and second harmonic.**
- **Current oscillation is approx. 100 msec.**
- **230kV Voltage dropped to approx 0.9 Vpu.**

IBR Events (Recent Southern Co Fault)



- 1/26/2024 @ 1012 EST, A-G fault on Station A – Station C 230kV line 0.07 mi from Station C.
- Solar output was approx. 35MW.
- Protection on the 2 interconnection lines to the Solar IBR's misinterpreted fault as forward direction
- IBR contribution to the A-G fault lasted 3 cycles
- Protection on Station C – Station A operated correctly
- The misoperation of the interconnection line protection resulted in all four breakers at Station C to open, which activated the Anti-Island trip scheme

IBR Faults (Southern Co Event)

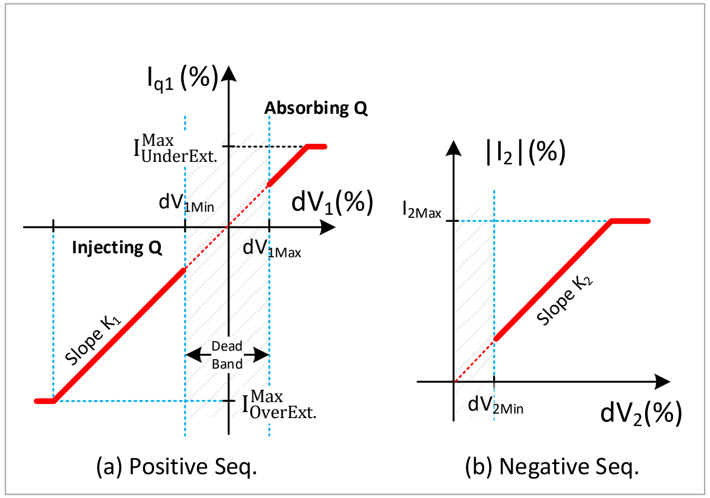


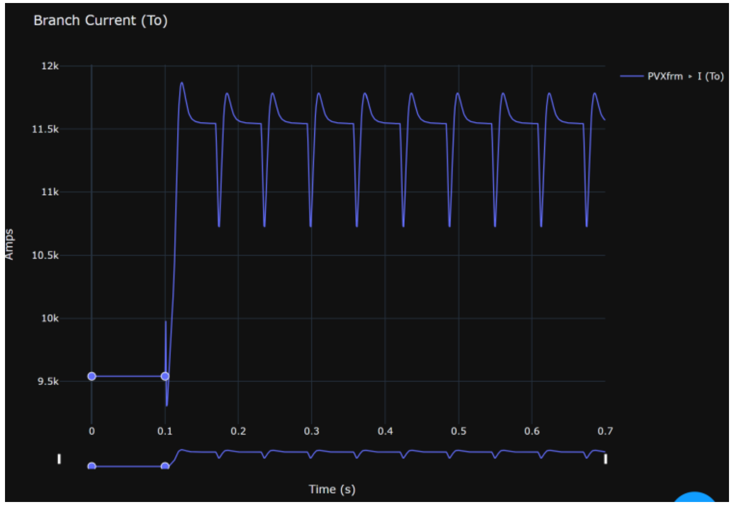
- The ground directional element was not picked up initially.
- During the second cycle the 32GF element picked up.

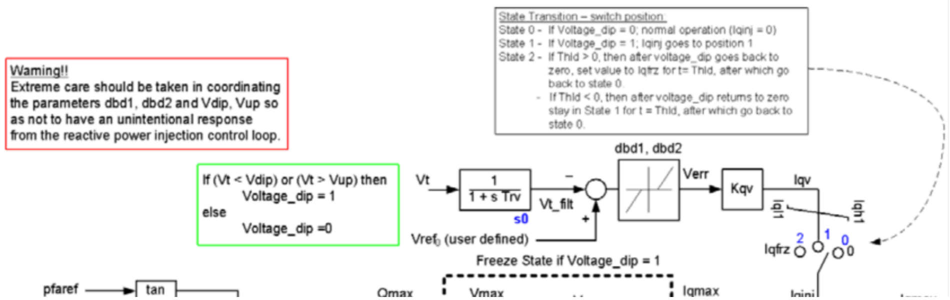
Relay incorrectly determined the fault was in the forward direction and tripped on 67G

IBR Model Development (ETAP)

- 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.

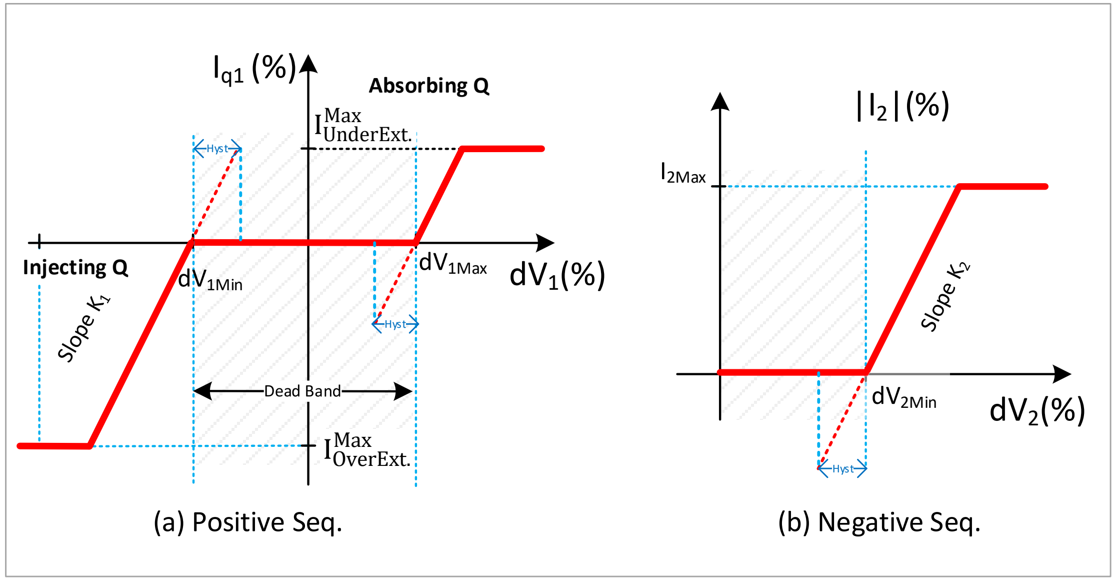




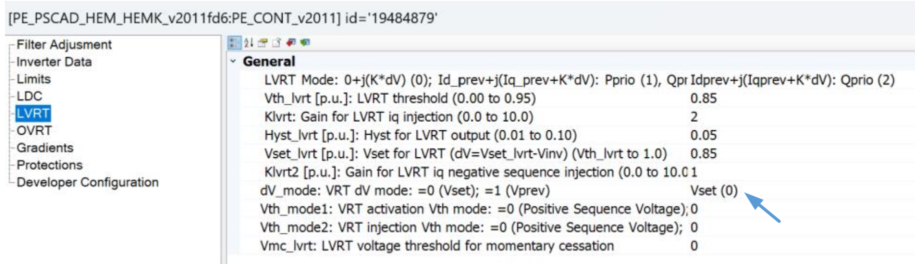


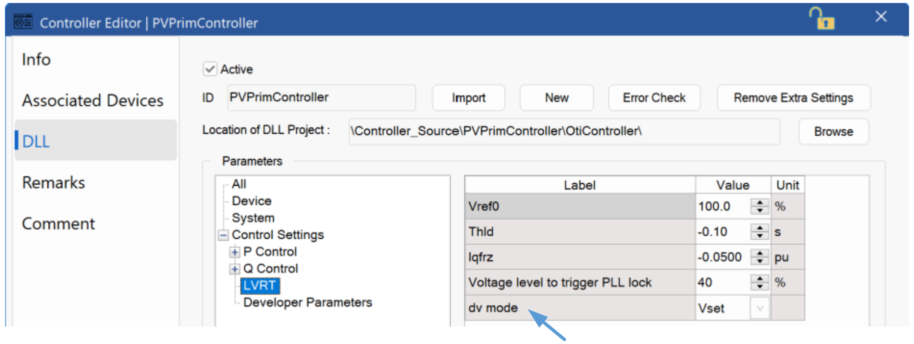
IBR Model Development (ETAP)

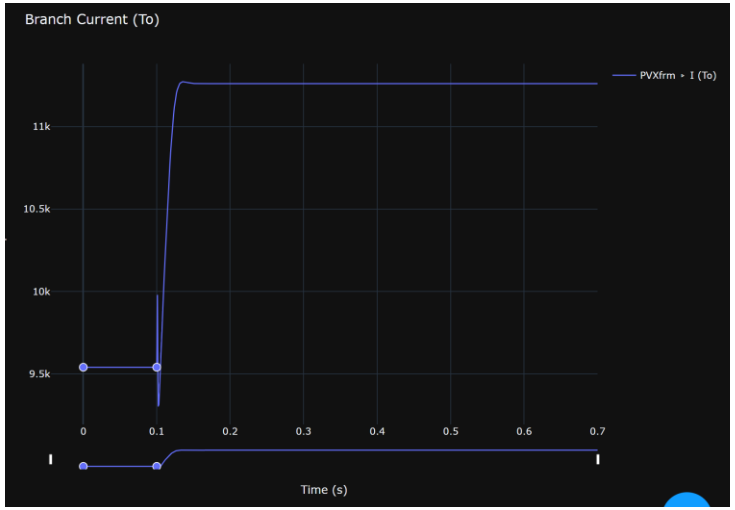
- **Development of Dynamic Phasor-based model**
  - Major observation in modeling reactive power support during fault



One of the Manufacturer's Default







DOE Project – IBR Model Development

IBR Model Development

- Part of DOE project “Award Number DE-EE00010658”
  - Plan to develop SC Blackbox models for four vendors.
  - Three already completed.
- Modeling Approach
  - Use an agreed interface between short circuit simulation software vendors
  - Received EMT Blackbox models from three vendors so far
  - No detailed information provided by vendors about the control logic
  - Guess control logic related to short circuit based on settings and EMT studies

Result Comparison with EMT

Vendor 1

Errors for Remote Faults

	$\lvert V_1 \rvert$ (%)	$\angle V_1$ (°)	$\lvert I_1 \rvert$ (%)	$\angle I_1$ (°)	$\lvert V_2 \rvert$ (%)	$\angle V_2$ (°)	$\lvert I_2 \rvert$ (%)	$\angle I_2$ (°)
3Ph	0.0	0.07	0.0	0.16	---	---	---	---
LG	0.1	0.06	0.2	0.0	0.0	0.35	0.1	0.38
LLG	0.1	0.14	0.1	0.18	0.0	0.03	0.1	0.61
LL	0.5	1.87	0.1	1.13	0.4	3.5	0.5	4.0

Max Error

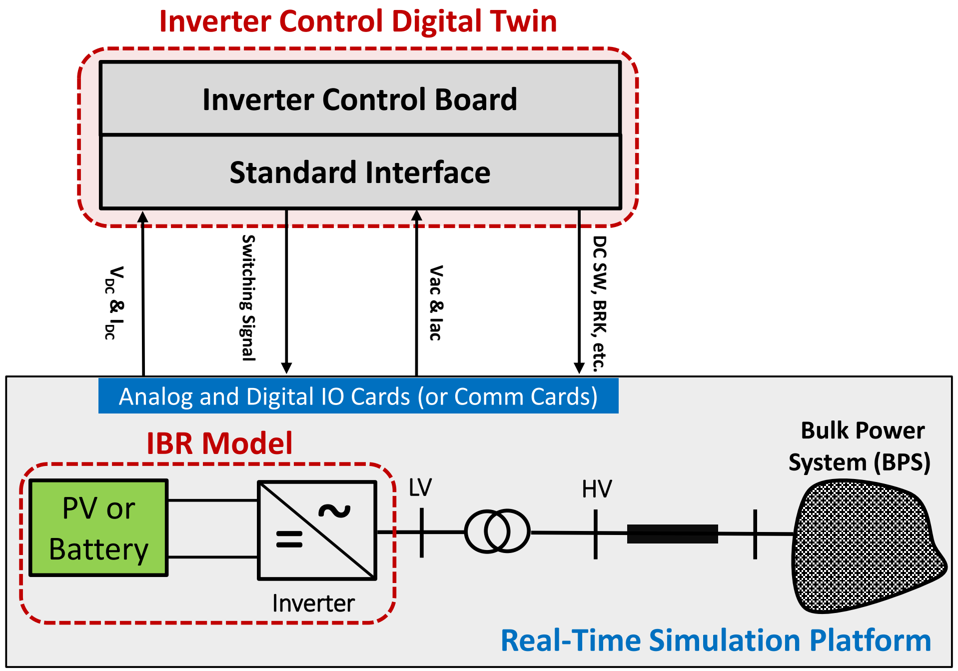
- Mag: 1.4%
- Angle: 4.2°

Overview of IBR Model Validation Task

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

SWAP Tool Specification Document

Commenced work Specification Document Development

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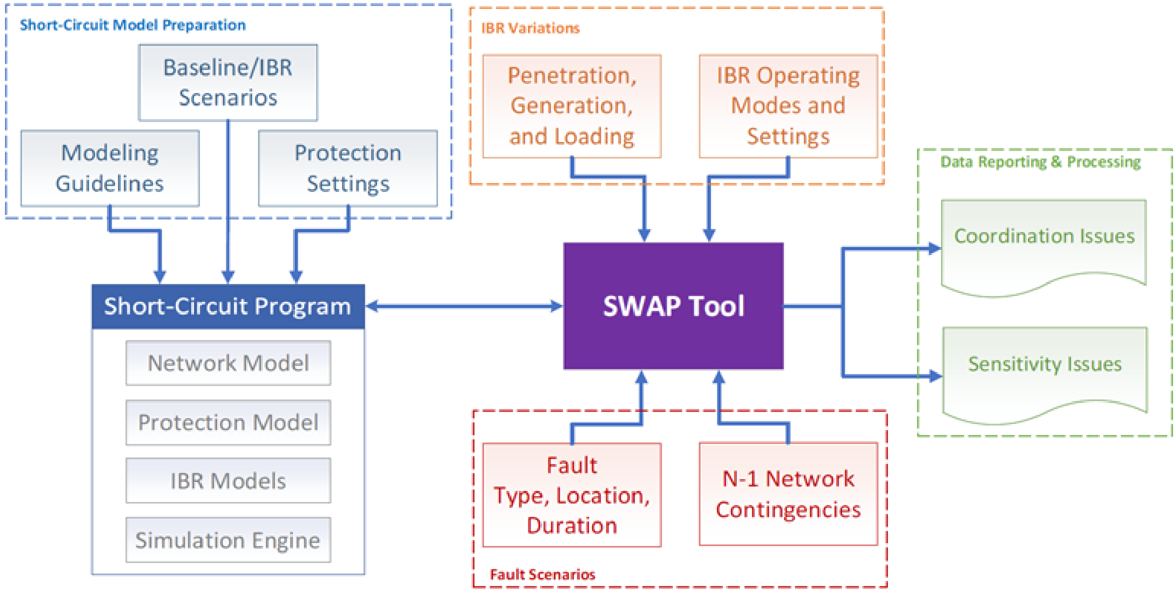

Questions

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