A Power Hardware-in-the-Loop (PHIL) Test Bed for Inverter Testing in Southern California Edison (SCE)

6th International Workshop on Grid Simulator Testing of Wind Turbine Power Trains and Other Renewable Technologies

Arifujjaman, PhD
Grid Technology Innovation
Southern California Edison

November 9 - 10, 2022
Golden, CO

SOUTHERN CALIFORNIA EDISON®

Outline

- Introduction
- Power Hardware-in-the-Loop (PHIL) Test Bed
- RSCAD Model and Scenarios
- Results
- Conclusions

Introduction

Energy for What's Ahead[SM]

SOUTHERN CALIFORNIA
EDISON®

SCE Activities and Need

- ❑ The Distributed Energy Resource (DER) technologies are emerging as one of the most prominent solutions for Southern California Edison (SCE) to augment California's Green House Gas (GHG) reduction goals.

- ❑ The adoption of such technologies in the existing grid is also encouraged by the California Public Utilities Commission (CPUC) through numerous avenues. Such as the Electric Program Investment Charge (EPIC) program.

- ❑ Rule 21 compliant Smart Inverter (SI), which is a mandatory requirement for the interconnection of inverter-based DER technologies.

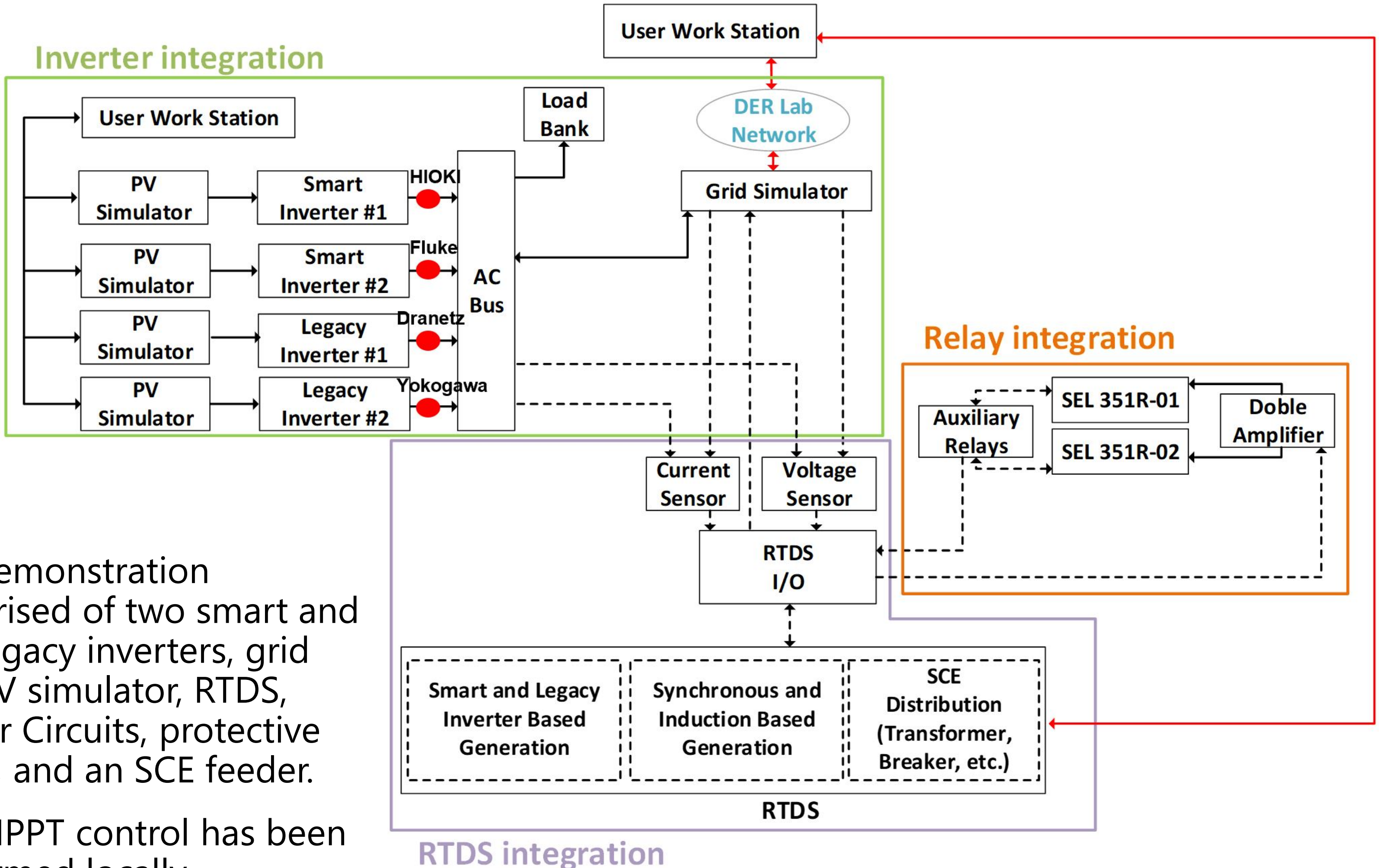
- ❑ The installed Legacy Inverters (LIs) are capable of performing certain functions, but in sharp contrast, SIs offer unique and advanced control capabilities when integrated with DER technology.

Aim of the Applied Research

- ❑ An organizational, vendor-agnostic PHIL test bed to enhance the ease of DER into the SCE grid. The testbed can enable SCE, stakeholders, national labs, vendors, and university researchers to evaluate existing and future use cases in a test set that provides a realistic combination of multiple utility management systems and field equipment
- ❑ Verify the Rule 21 advanced functions for smart inverters
- ❑ Analyze results and determine what could be the potential impact on the feeder protection system

Power Hardware-in-the-Loop (PHIL) Test Bed

PHIL Testbed Architecture



- The demonstration comprised of two smart and two legacy inverters, grid and PV simulator, RTDS, Sensor Circuits, protective relays, and an SCE feeder.
- The MPPT control has been performed locally

PHIL Testbed Pictures

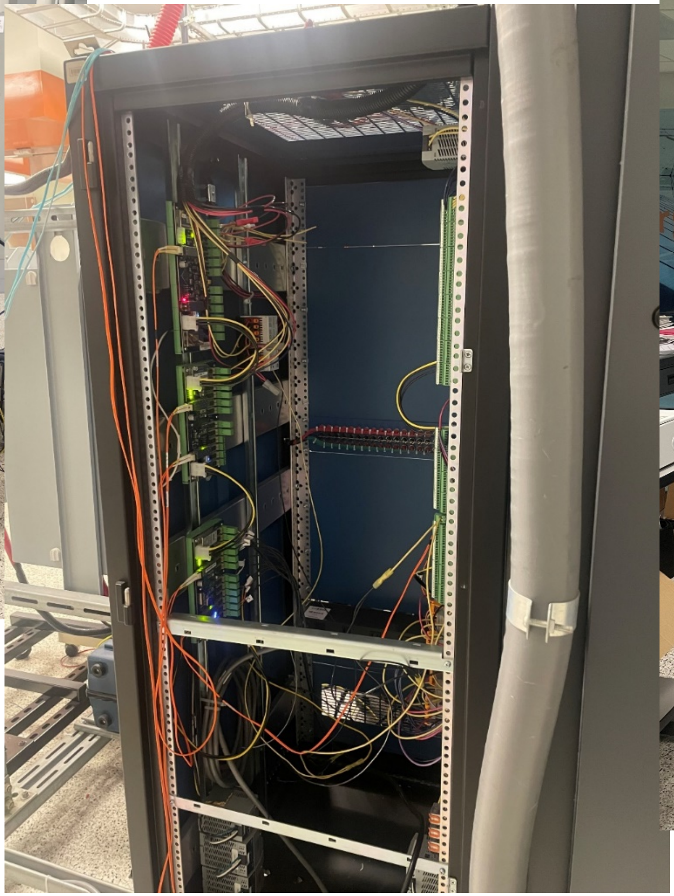
Grid Simulator

Relay

PV Simulator

PHIL Testbed Pictures

RTDS

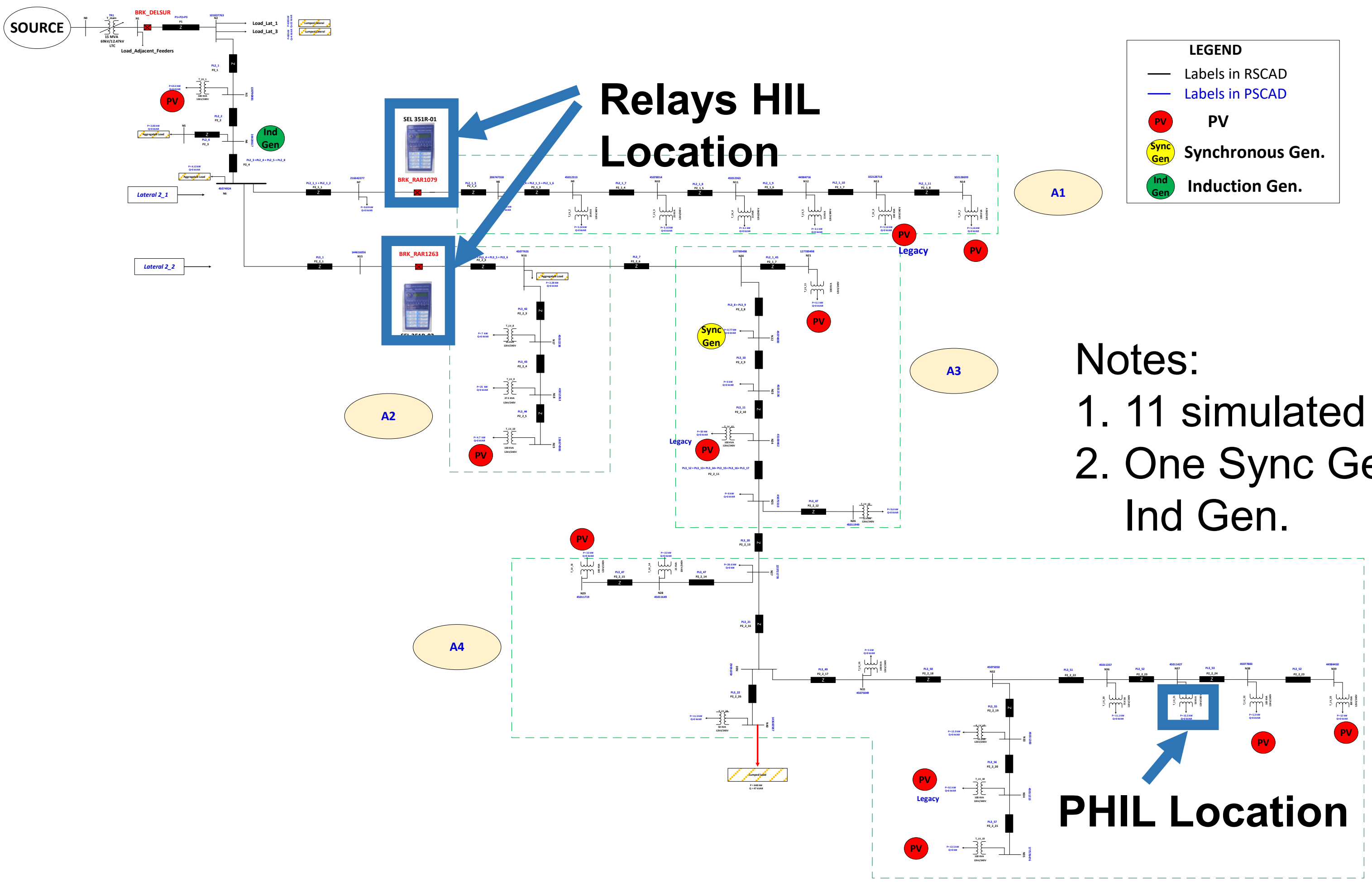


Sensor Circuits

Smart and Legacy Inverters

RSCAD Model and Scenarios

RSCAD Model for Feeder



Notes:

1. 11 simulated PV models.
2. One Sync Gen. plus one Ind Gen.

Different Scenarios For Volt/VAR use case

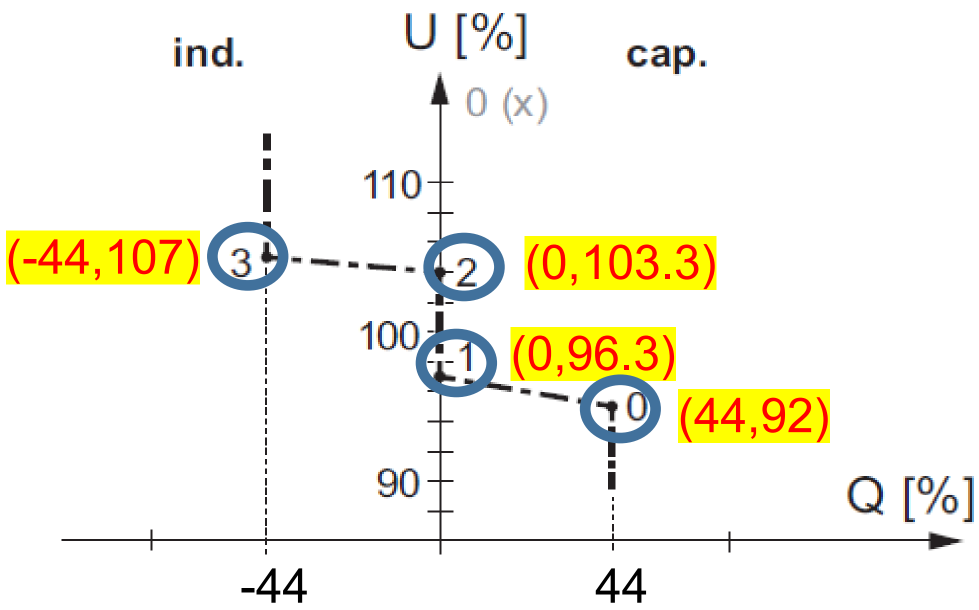
Scenario NO.	Inverter (Hardware) in the loop	Simulated DER type	DER penetration level	Event
I	1 Smart	• All PV inverters are **legacy** • Sync and induction generation units are **off**	60	Voltage variation
II	2 Smart	• All PV inverters are **legacy** • Sync and induction generation units are **off**	60	Voltage variation
III	2 Smart	• All PV inverters are **smart** • Sync and induction generation units are **off**	60	Voltage variation
IV	2 Smart	• All PV inverters are **smart** • Sync and induction generation units are **off**	120	Voltage variation
V	2 Smart 2 Legacy	• All PV inverters are **legacy** • Sync and induction generation units are **off**	60	Voltage variation
VI	2 Smart 2 Legacy	•**66% smart inverters** •**34% legacy inverters** • Sync and induction generation units **are off**	60	Voltage variation
VII	2 Smart 2 Legacy	•**66% smart inverters** •**34% legacy inverters** • Sync and induction generation units **are off**	120	Voltage variation
VIII	2 Smart 2 Legacy	•**66% smart inverters** •**34% legacy inverters** • Sync and induction generation units **are on**	60	Voltage variation
IX	2 Smart 2 Legacy	•**66% smart inverters** •**34% legacy inverters** • Sync and induction generation units **are on**	120	Voltage variation

Results

Energy for What's Ahead[SM]

SOUTHERN CALIFORNIA EDISON®

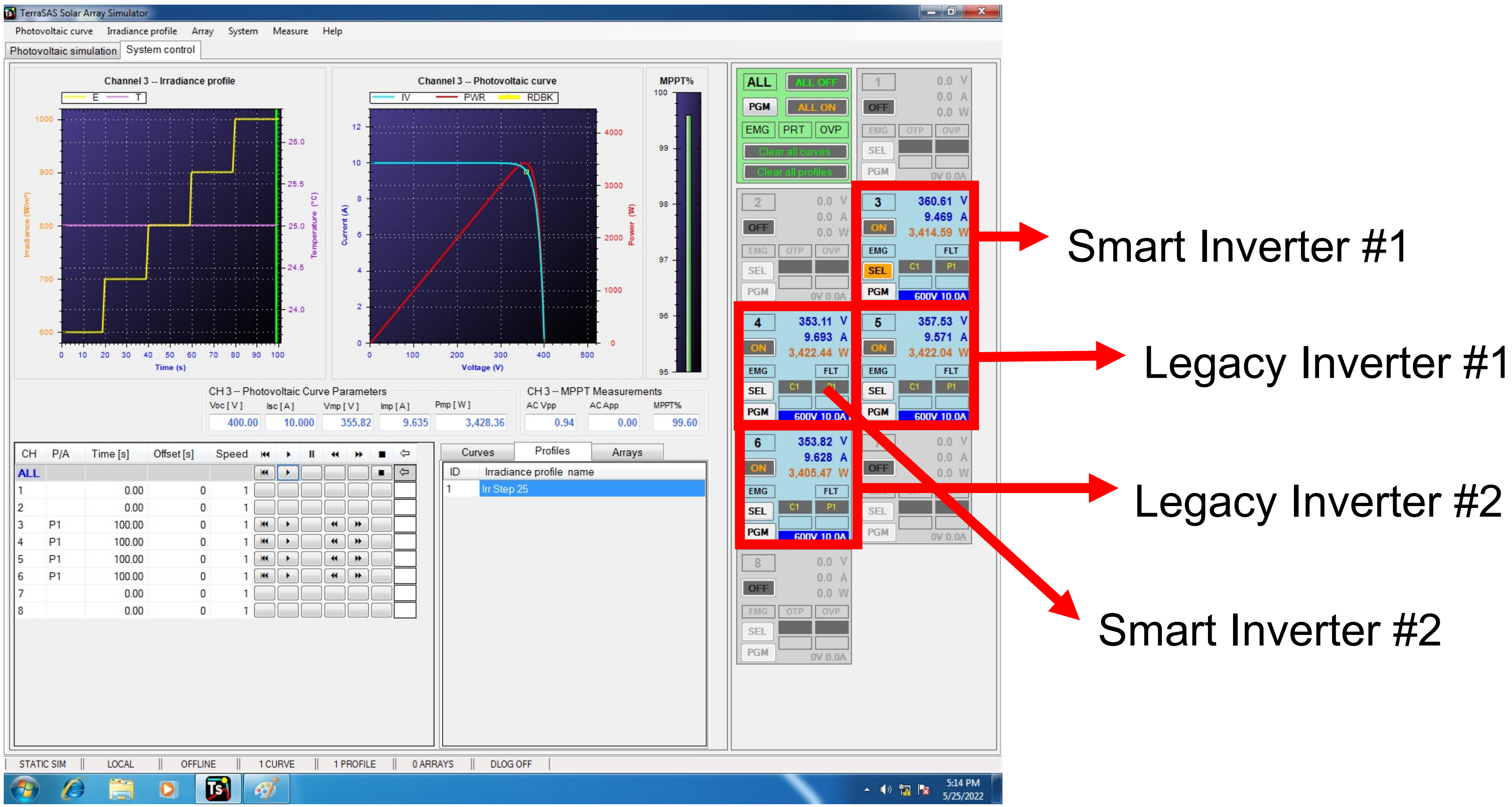
Volt/VAR Curve of Smart Inverters for IEEE 1547-2018



✓ Verify this curve for smart inverters in Scenario VII

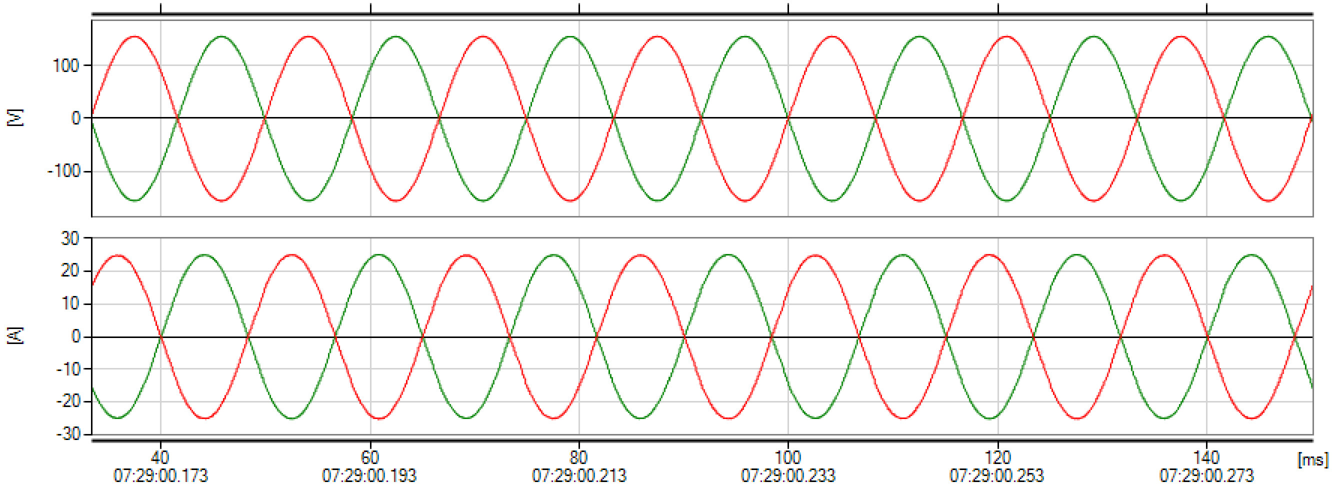
Inverters DC Measurements for Operational Point #0 (+44,92)

- Running the RSCAD model and vary main source voltage to have **0.92 pu** voltage at PV.



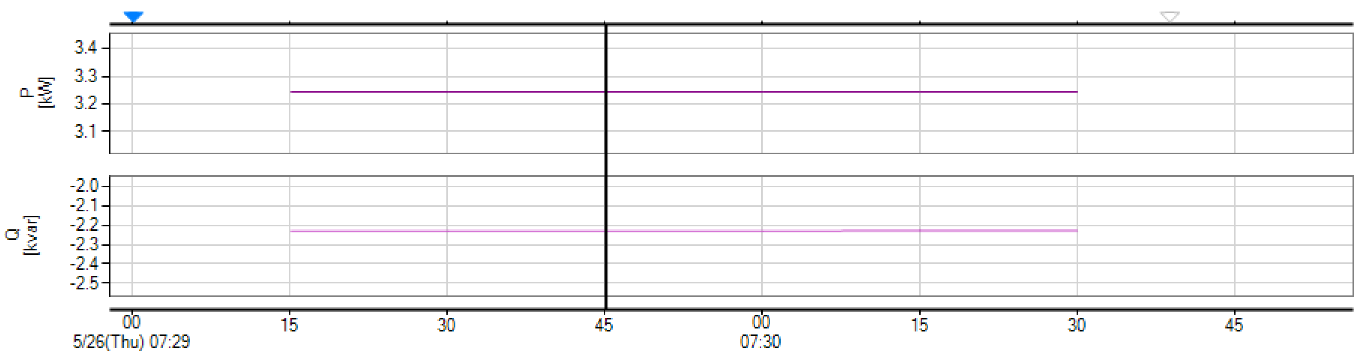
Smart Inverter#1 Results for Operational Point #0 (+44,92)

- Running the RSCAD model and vary main source voltage to have **0.92 pu** voltage at PVHIL.



5/26/2022 07:29:45.134

U1 rms AVG	**110.33**	V
U2 rms AVG	**110.25**	V
I1 rms AVG	**17.84**	A
I2 rms AVG	**17.85**	A



5/26/2022 07:29:45.134

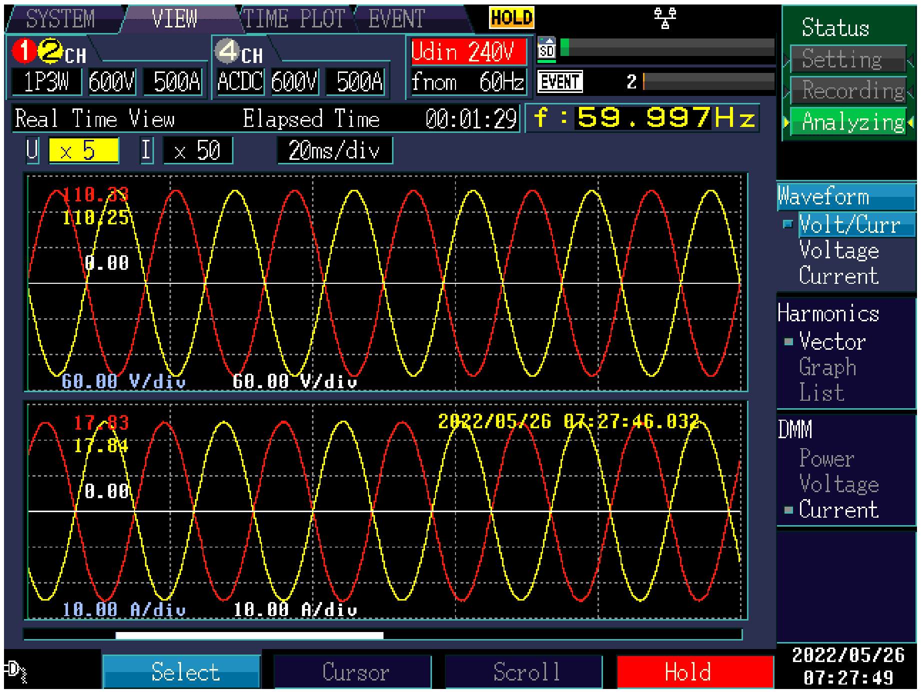
P sum AVG	**3.24**	kW
Q sum AVG	**-2.23**	kvar

S_{max} = 5050 KVA

$$\frac{-2.23}{S_{max}} = 44.15\%$$

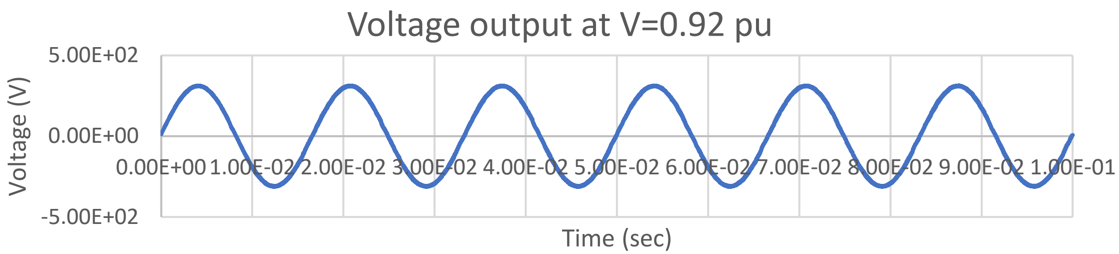
Smart Inverter #1 Results for Operational Point #0 (+44,92)

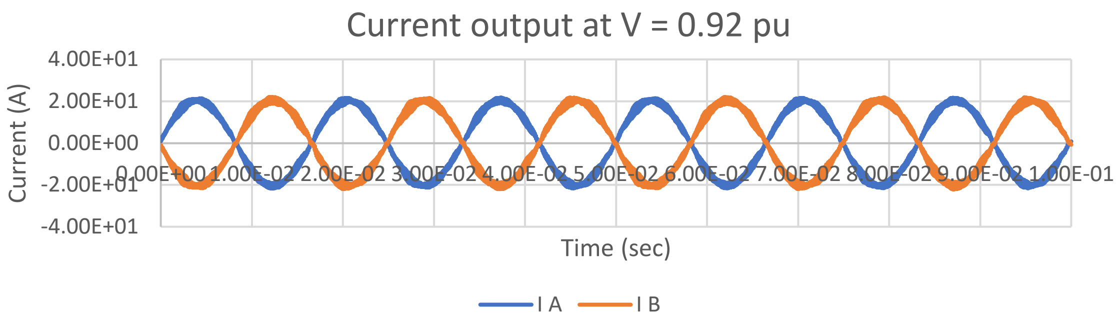
- Running the RSCAD model and vary main source voltage to have **0.92 pu** voltage at PVHIL.

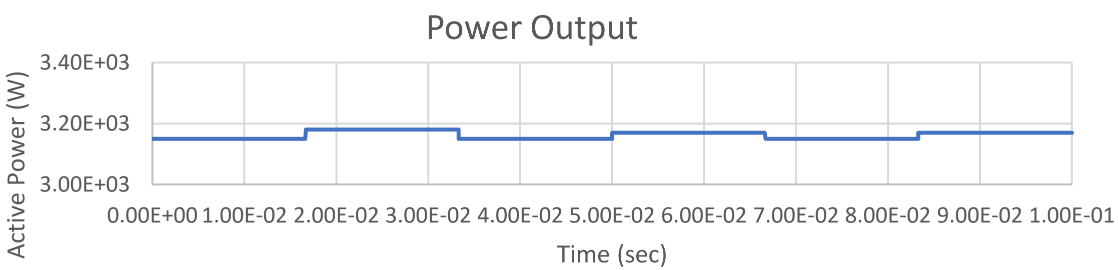


Legacy Inverter#1 Results for Operational Point #0 (+44,92)

- Running the RSCAD model and vary main source voltage to have **0.92 pu** voltage at PVHIL.







V_{LL} rms = 219.24 V
I_A rms = 14.44 A
I_B rms = 14.48 A
P = 3.16 kW

Inverter #2 and #3 Results for Operational Point #0 (+44,92)

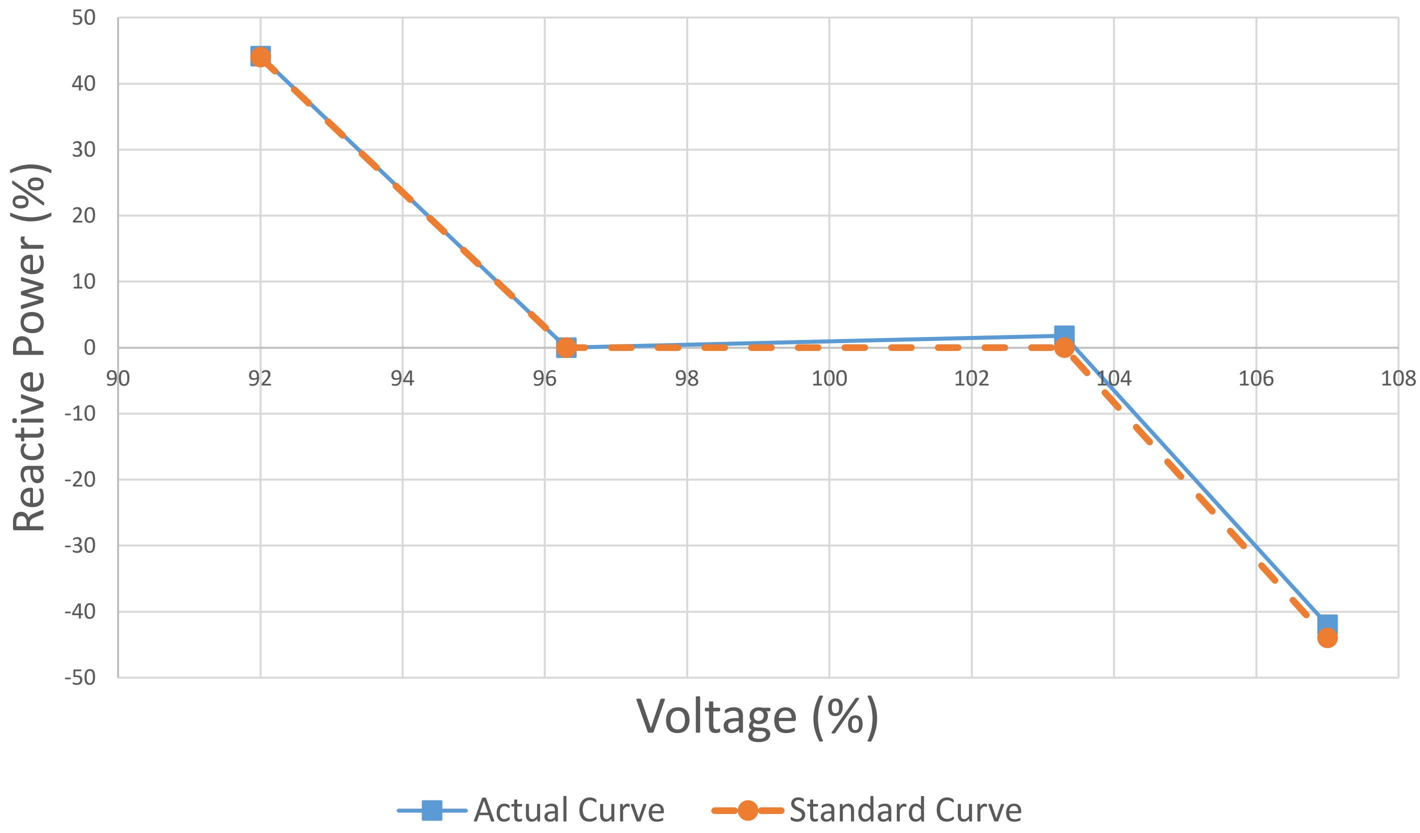
- Running the RSCAD model and vary main source voltage to have **0.92 pu** voltage at PHIL.

Measurement Parameters	#2 (Smart)	#3 (Legacy)
V_A	**110.3 V**	**110.3 V**
V_B	**110.2 V**	**110.2 V**
I_A	**17.75 A**	**14.41 A**
I_B	**18.04 A**	**14.45 A**
S	**3.94 KVA**	**3.16 KVA**
P	**3.28 kW**	**3.16 kW**
Q	**2.16 lead kVAR**	**0**

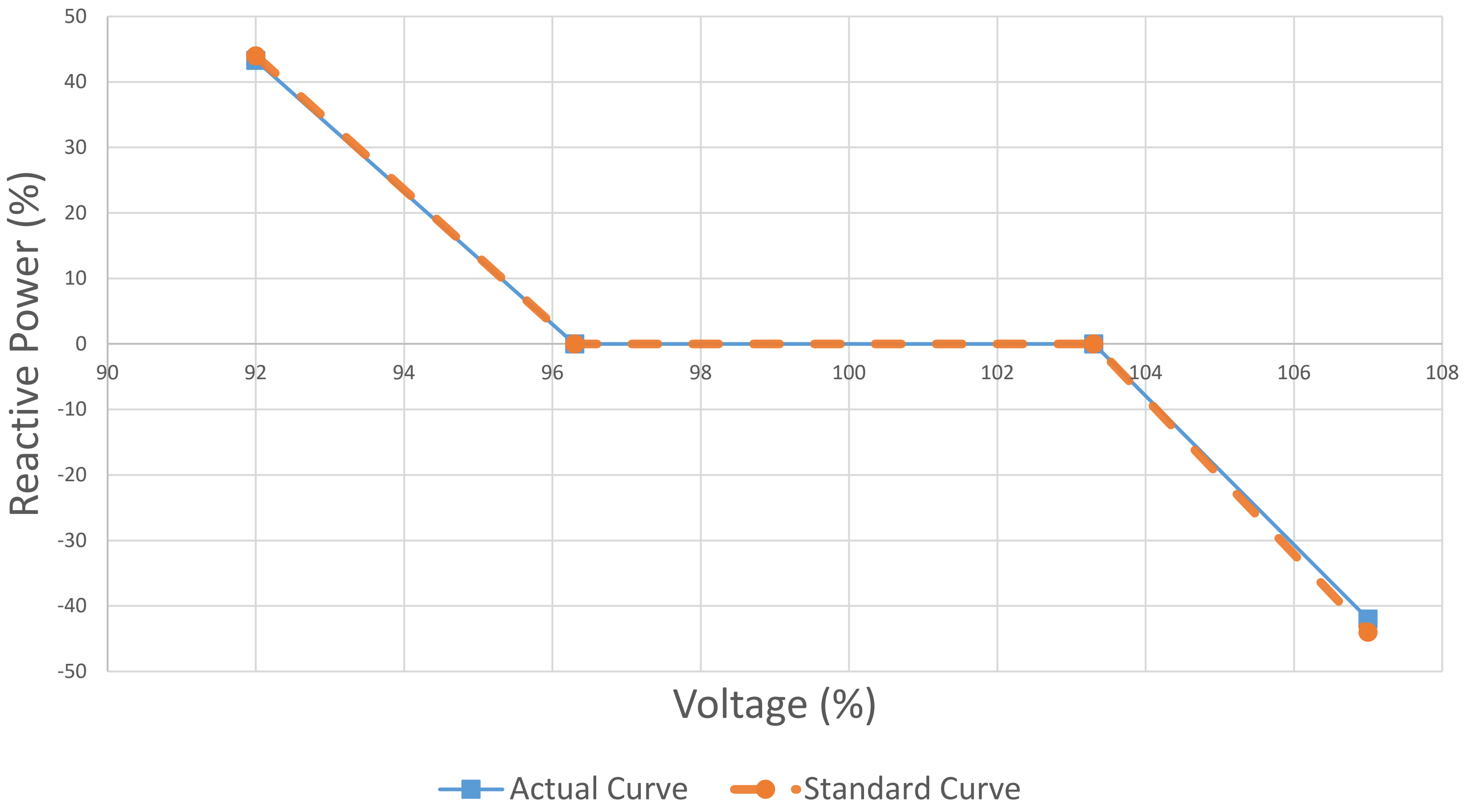
S_{max} = 5000 KVA

2.16 = 43.3% S_{max}

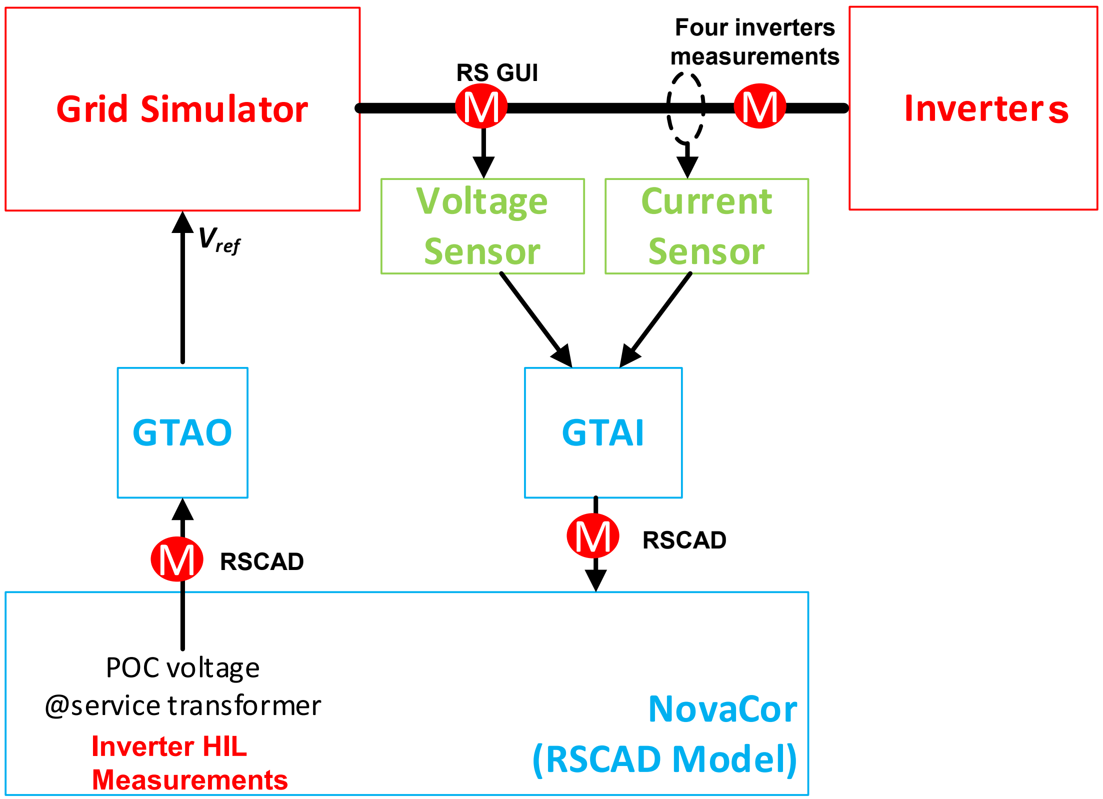
Volt/VAR Curve of Smart Inverter#1



Volt/VAR Curve of Smart Inverter#2



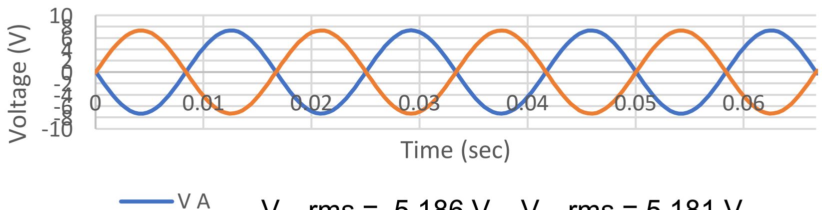
Inverters Verification for Operational Point #0 (+44,92)



RSCAD Results for Operational Point #0 (+44,92)

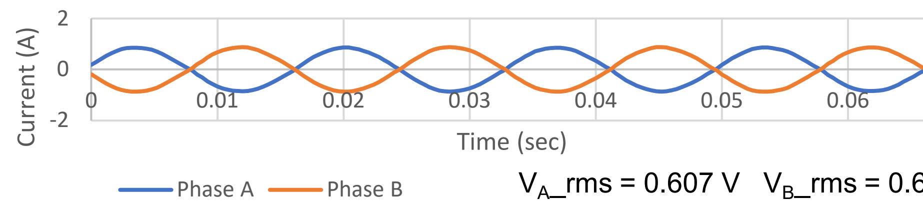
- Running the RSCAD model and vary main source voltage to have **0.92 pu** voltage at PVHIL.

GTAO Voltage/ Grid Simulator Input from RSCAD



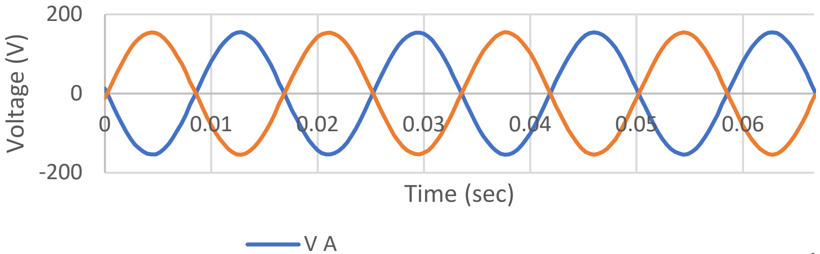
V_A_rms = 5.186 V V_B_rms = 5.181 V

GTAI Voltage/Current sensor output as input to RSCAD



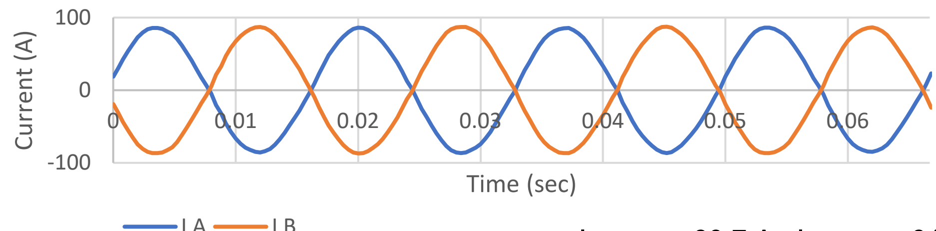
V_A_rms = 0.607 V V_B_rms = 0.617 V
sensor gain is **100 mV/A**

GTAI Voltage/Volatge sensor output to RSCAD



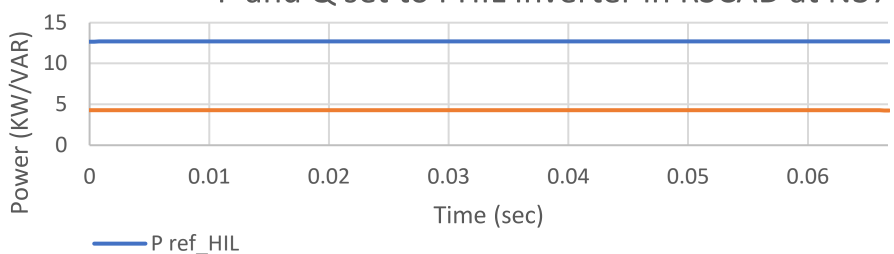
V_A_rms = 5.186 * 21. 2132 = 110.02 V
V_B_rms = 5.181* 21.2132 = 109.9 V

GTAI Actual Current to RSCAD



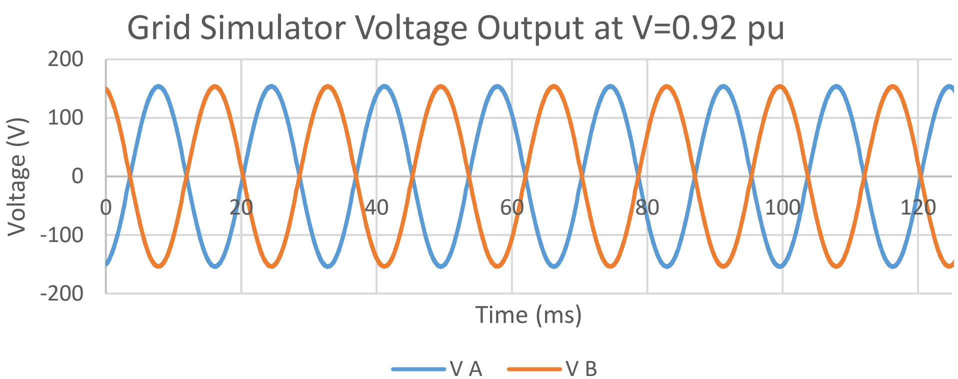
I_A_rms = 60.7 A I_B_rms = 61.7 A

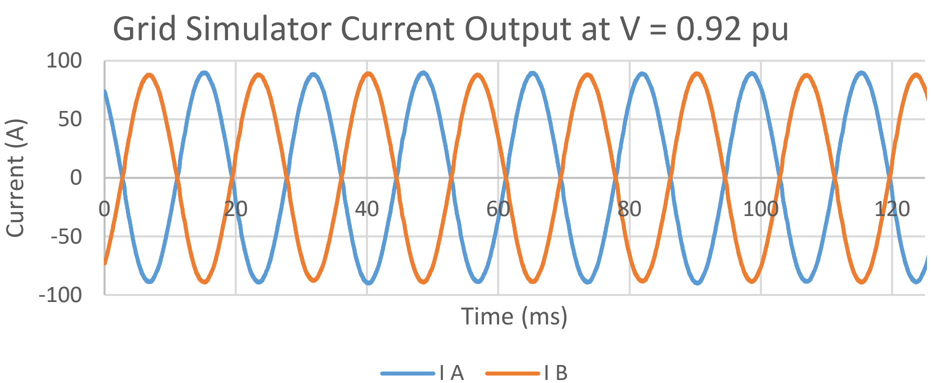
P and Q set to PHIL Inverter in RSCAD at N37

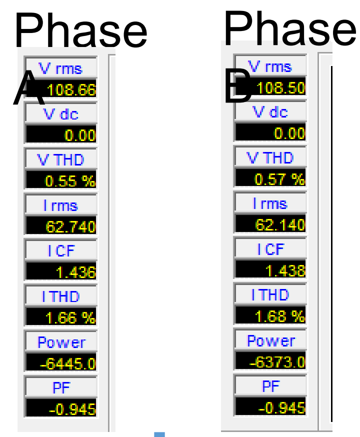


P = 12.7 kW Q = +4.3 kVAR

Grid Simulator Results for Operational Point #0 (+44,92)

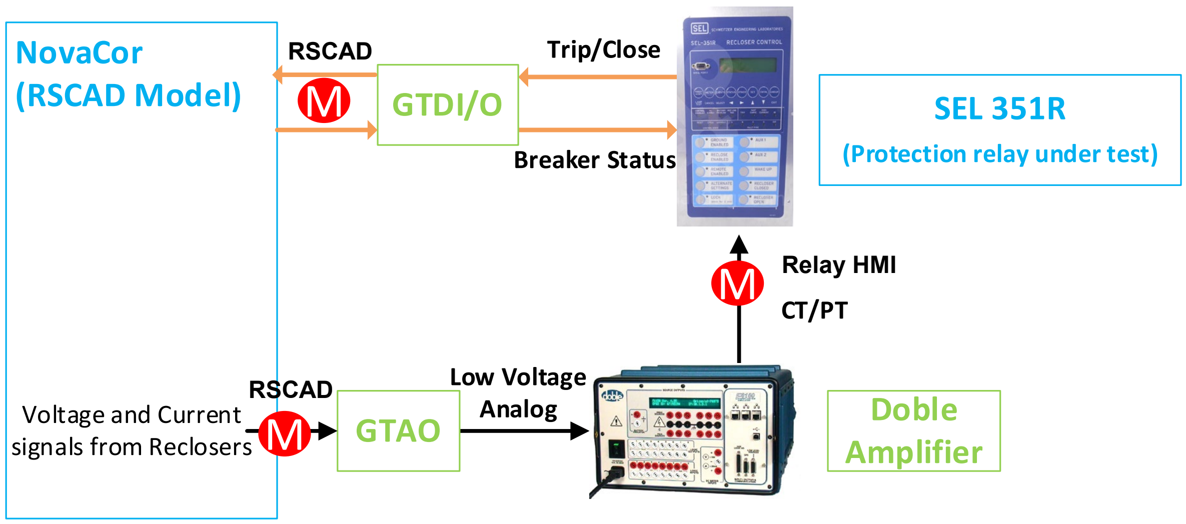






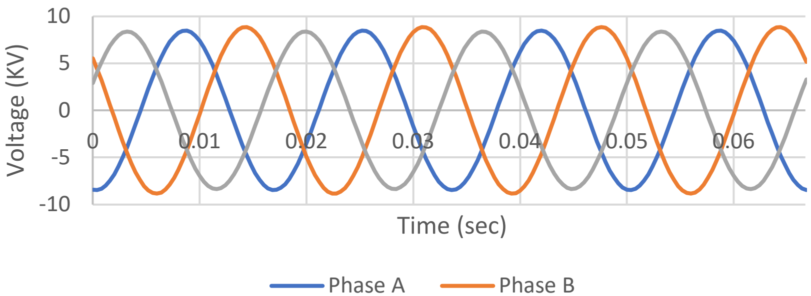
P_{tot} = 12.82
Q_{tot} = 4.4363 kVAR

Relays Verification for Operational Point #0 (+44,92)

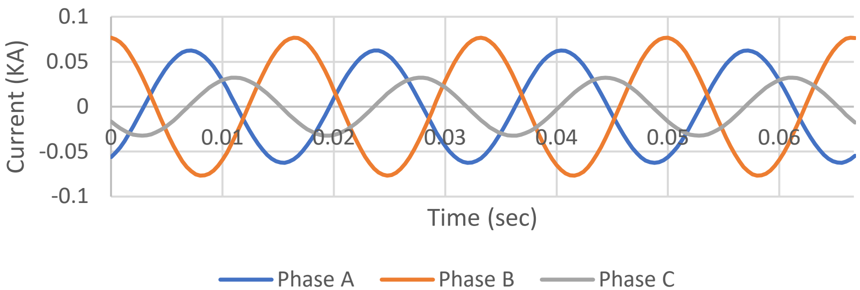


Relays Results for Operational Point #0 (+44,92)

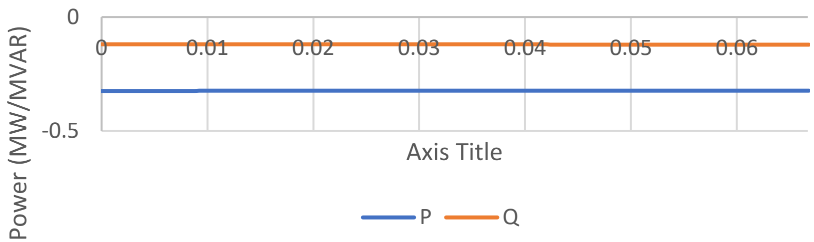
Voltage in RSCAD



Current output in RSCAD



P and Q measurement in RSCAD



Relay HMI

Instantaneous

Date: 05/25/22 Time: 15:08:24.544

	A	B	C	N	G
I MAG (A)	44.212	53.912	22.006	4.020	3.578
I ANG (DEG)	-144.92	12.33	130.53	77.32	52.29

	A	B	C	S
V MAG (KV)	5.957	6.223	5.883	0.002
V ANG (DEG)	0.00	-121.93	116.86	-88.19

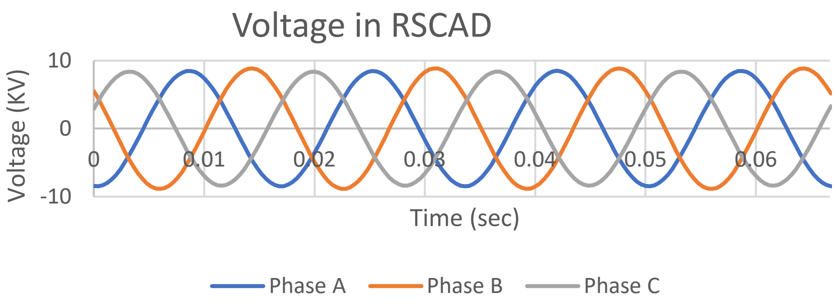
	AB	BC	CA
V MAG (KV)	10.650	10.549	10.088
V ANG (DEG)	29.73	-93.44	148.65

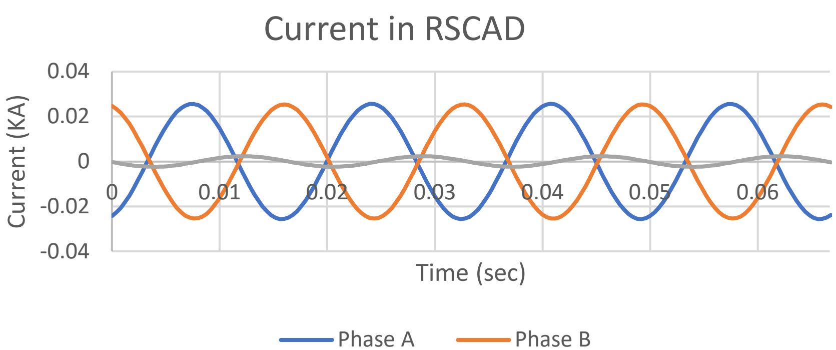
	A	B	C	3P
MW	-0.216	-0.234	0.126	-0.324
MVAR	0.151	-0.240	-0.031	-0.119
PF	-0.818	-0.698	0.972	-0.938
	LEAD	LAG	LEAD	LAG

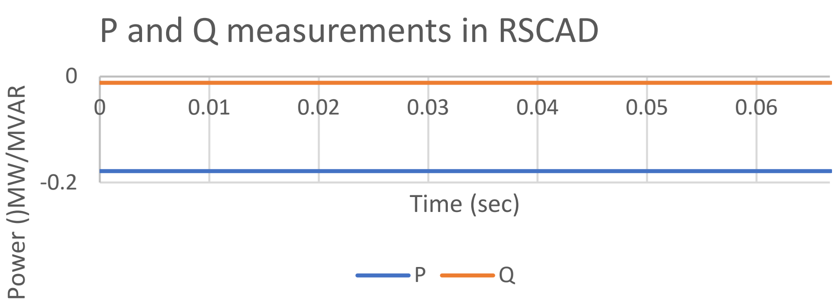
	I1	3I2	3I0	V1	V2	3V0
MAG	38.147	54.097	3.578	0.199	6.020	0.035
ANG (DEG)	-121.55	160.05	52.29	108.37	-1.69	-76.07

FREQ (Hz) 60.00

Relays Results for Operational Point #0 (+44,92)







Relay HMI

Instantaneous

Date: 05/25/22 Time: 15:16:56.940

	A	B	C	N	G
I MAG (A)	18.086	17.270	0.470	0.788	0.979
I ANG (DEG)	-150.90	25.23	88.61	-158.66	-99.93

	A	B	C	S
V MAG (KV)	5.955	6.222	5.882	0.002
V ANG (DEG)	0.00	-121.80	116.96	-75.62

	AB	BC	CA
V MAG (KV)	10.641	10.549	10.091
V ANG (DEG)	29.80	-93.33	148.69

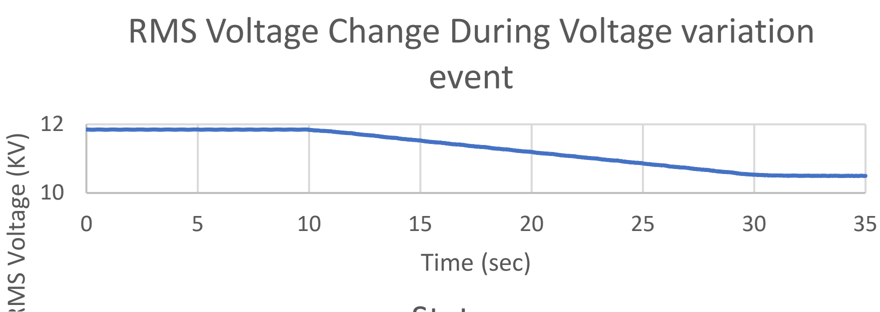
	A	B	C	3P
MW	-0.094	-0.090	0.002	-0.182
MVAR	0.052	-0.058	0.001	-0.005
PF	-0.874	-0.839	0.880	-1.000
	LEAD	LAG	LAG	LAG

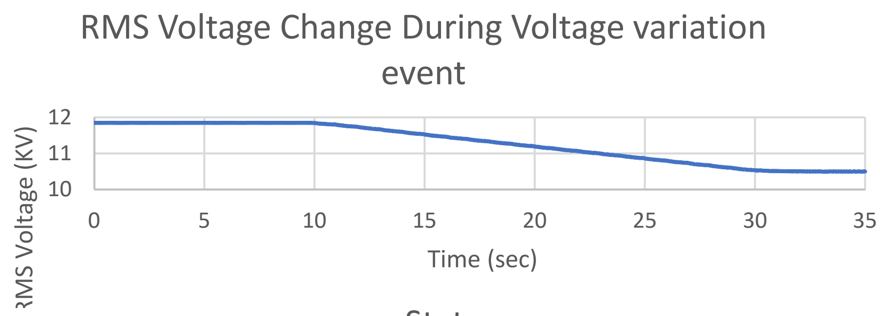
	I1	3I2	3I0	V1	V2	3V0
MAG	10.539	29.600	0.979	0.195	6.018	0.045
ANG (DEG)	-123.94	178.44	-99.93	109.18	-1.61	-77.35

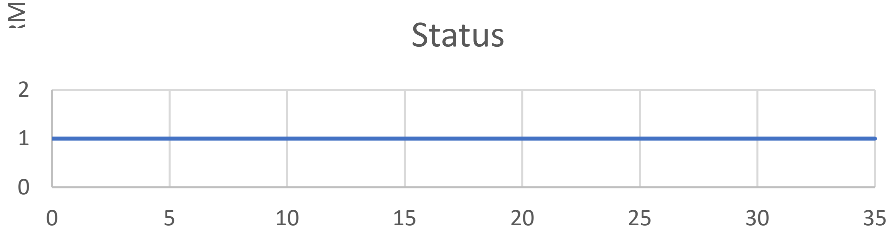
FREQ (Hz) 60.00

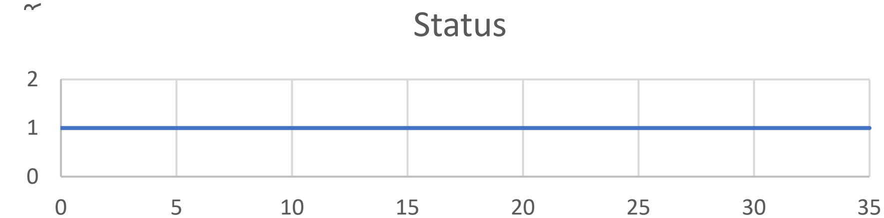
Impact on Relays For Scenario VII

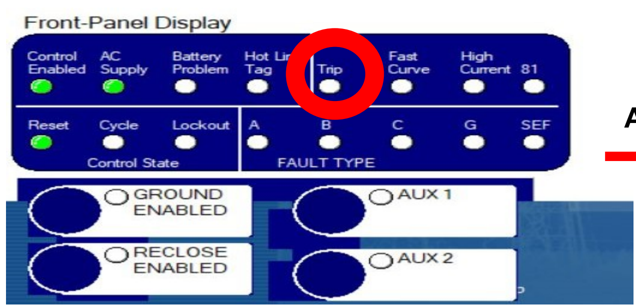
- ✓ During voltage variation event in which the voltage drops, breaker status is closed.
- ✓ No trips command for relays.



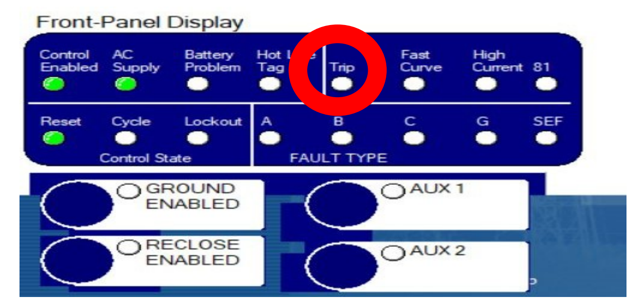






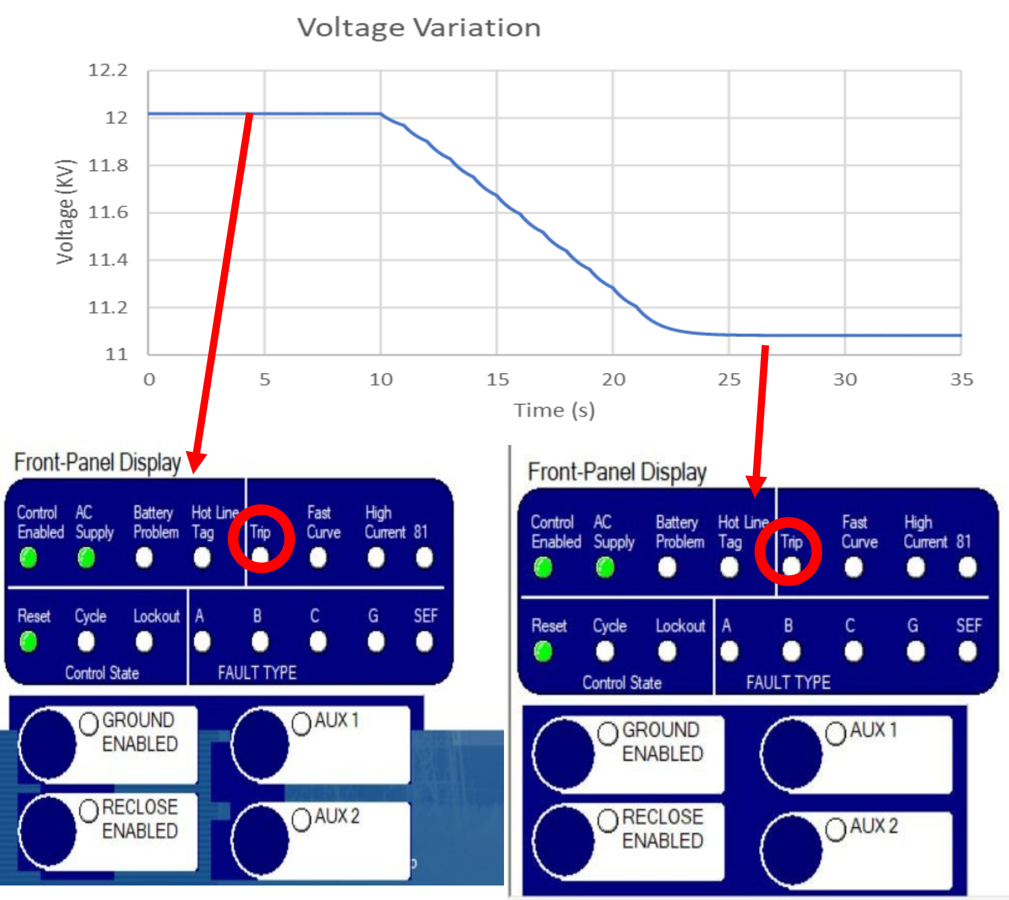


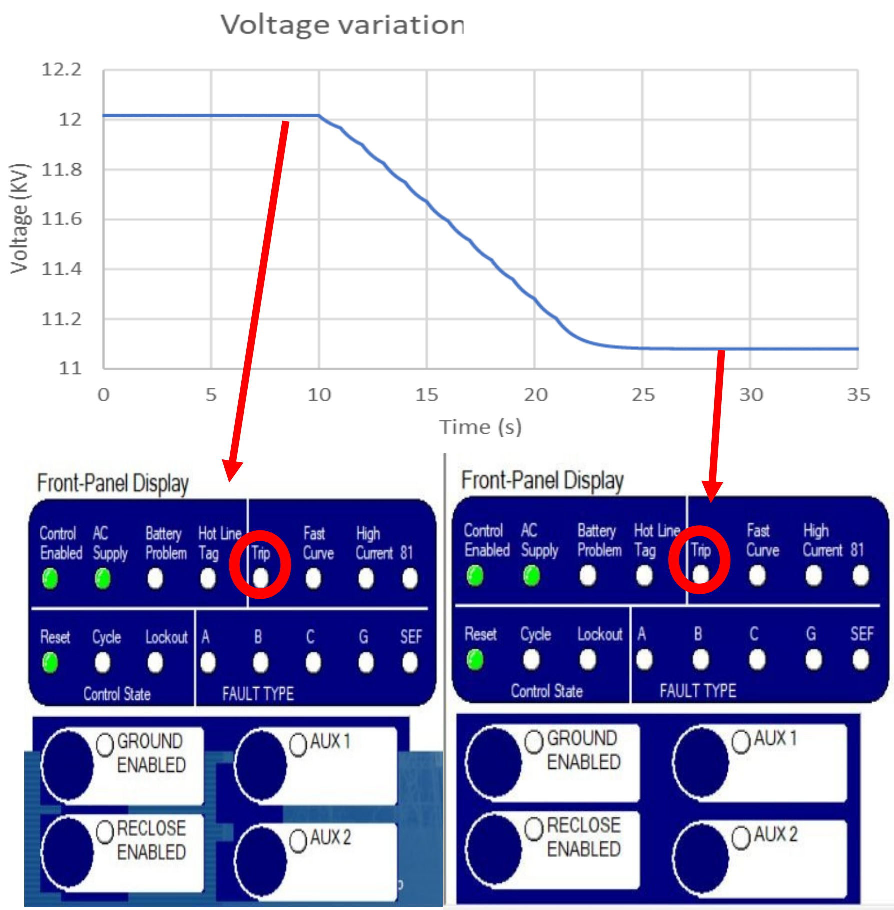
After Voltage variation event



Impact on Relays for Scenario I

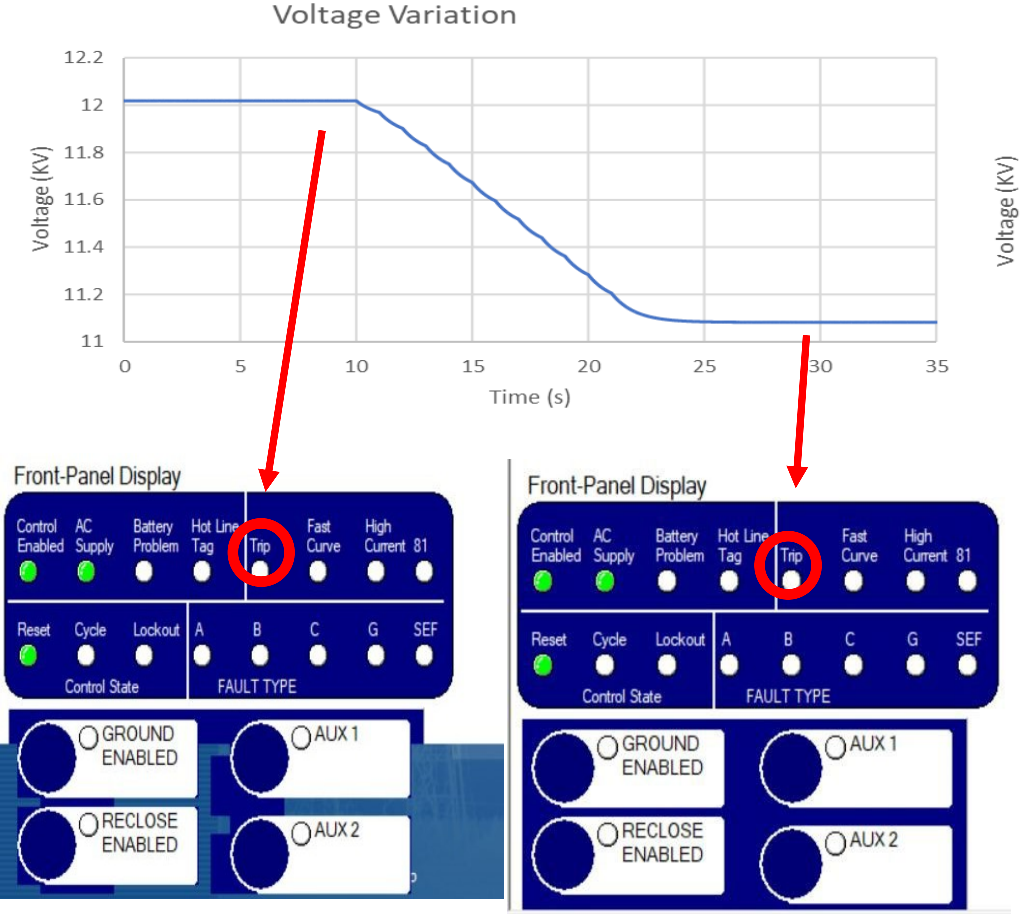
✓ No trips command for relays.

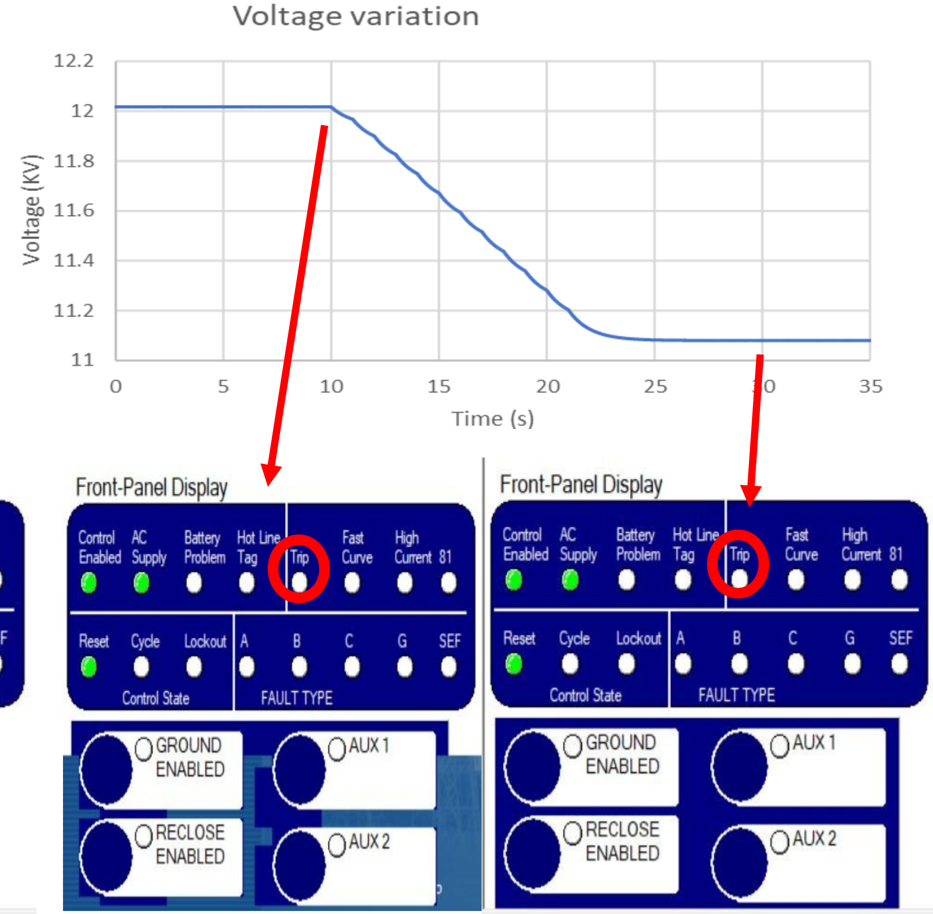




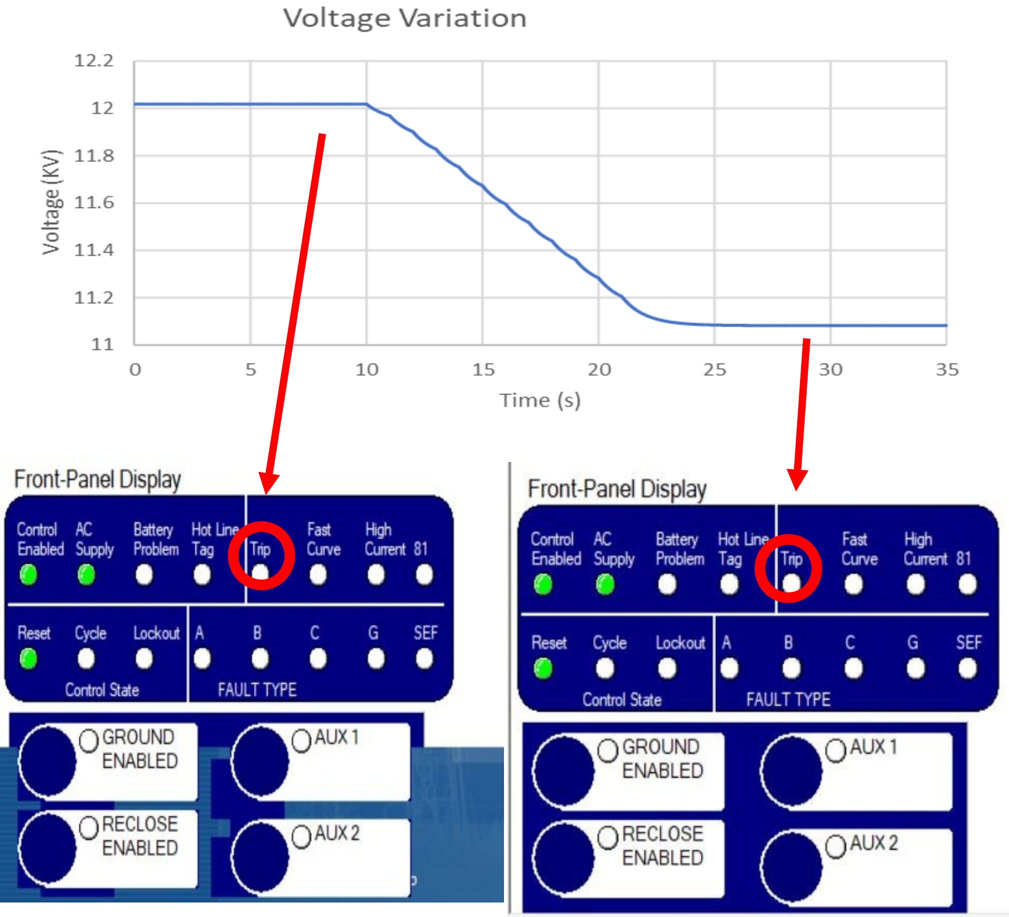
Impact on Relays for Scenario II

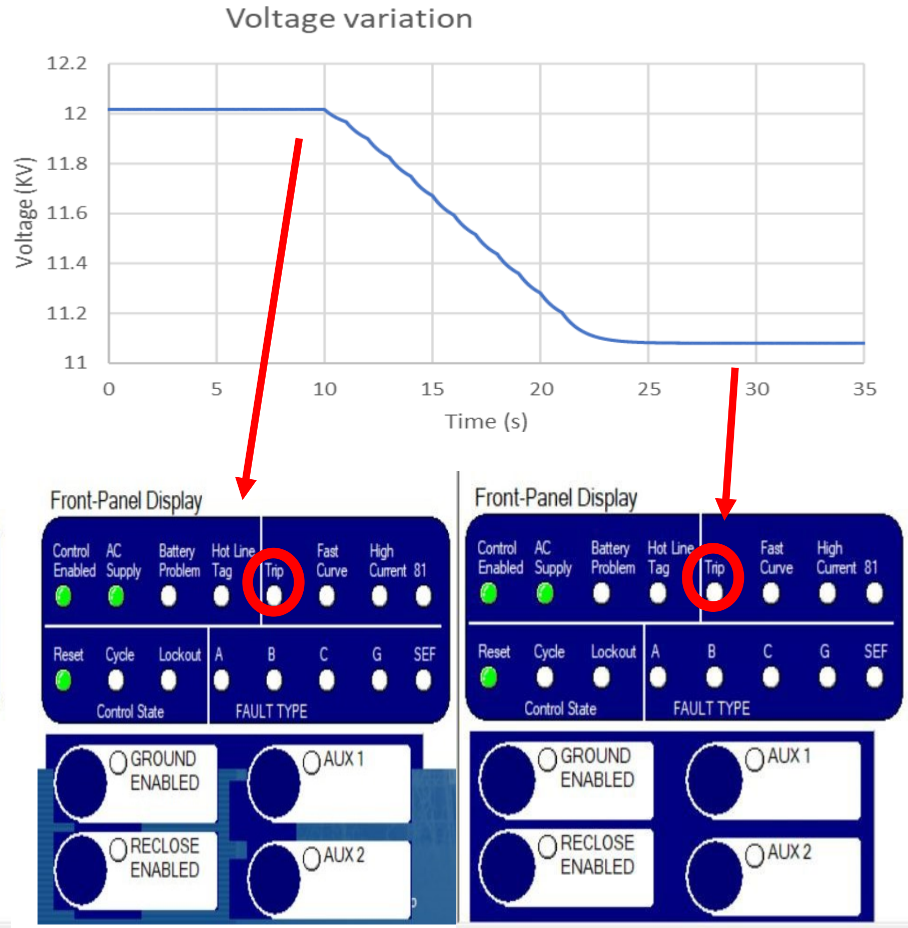
✓ No trips command for relays.





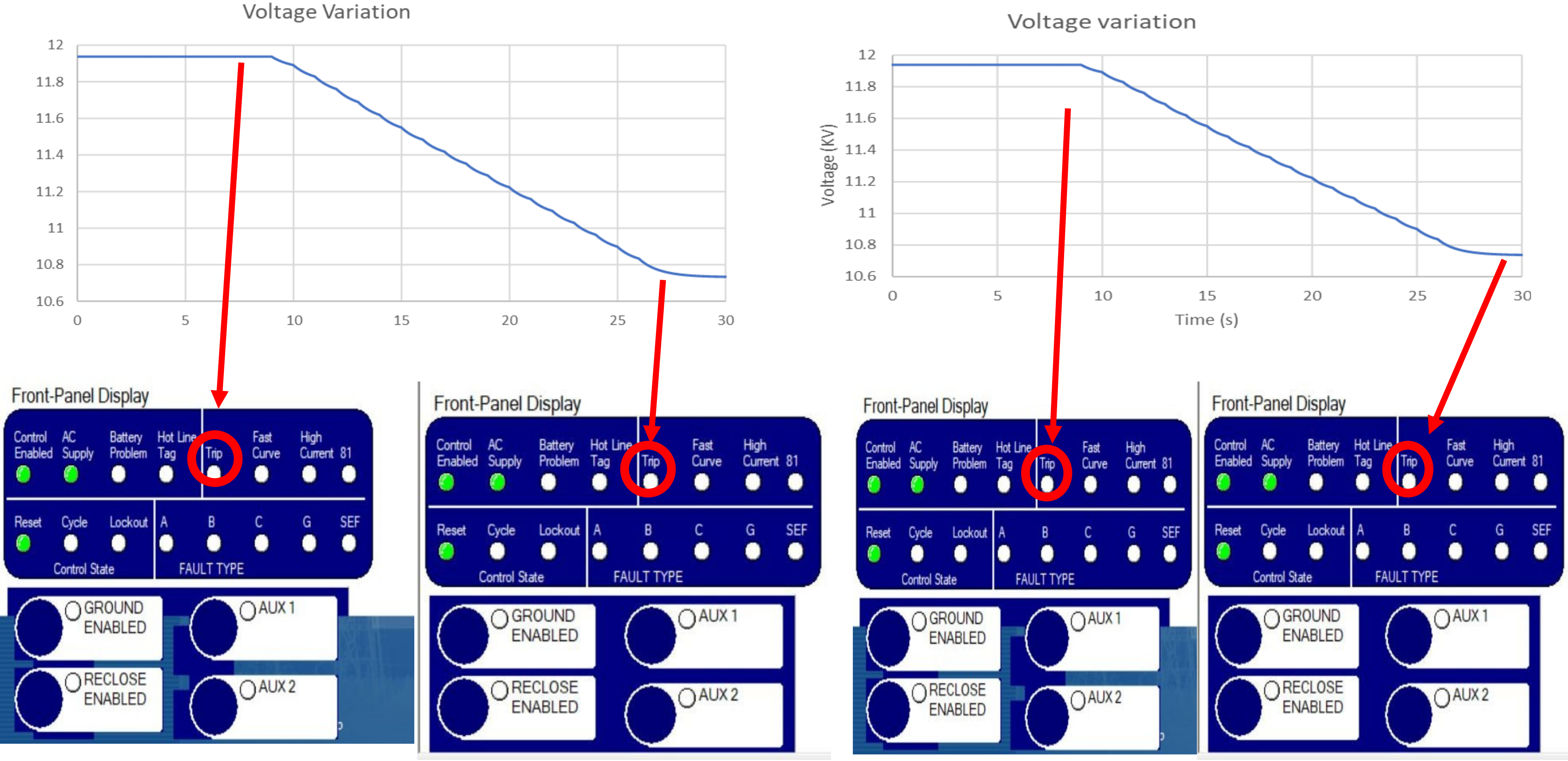
✓ No trips command for relays.





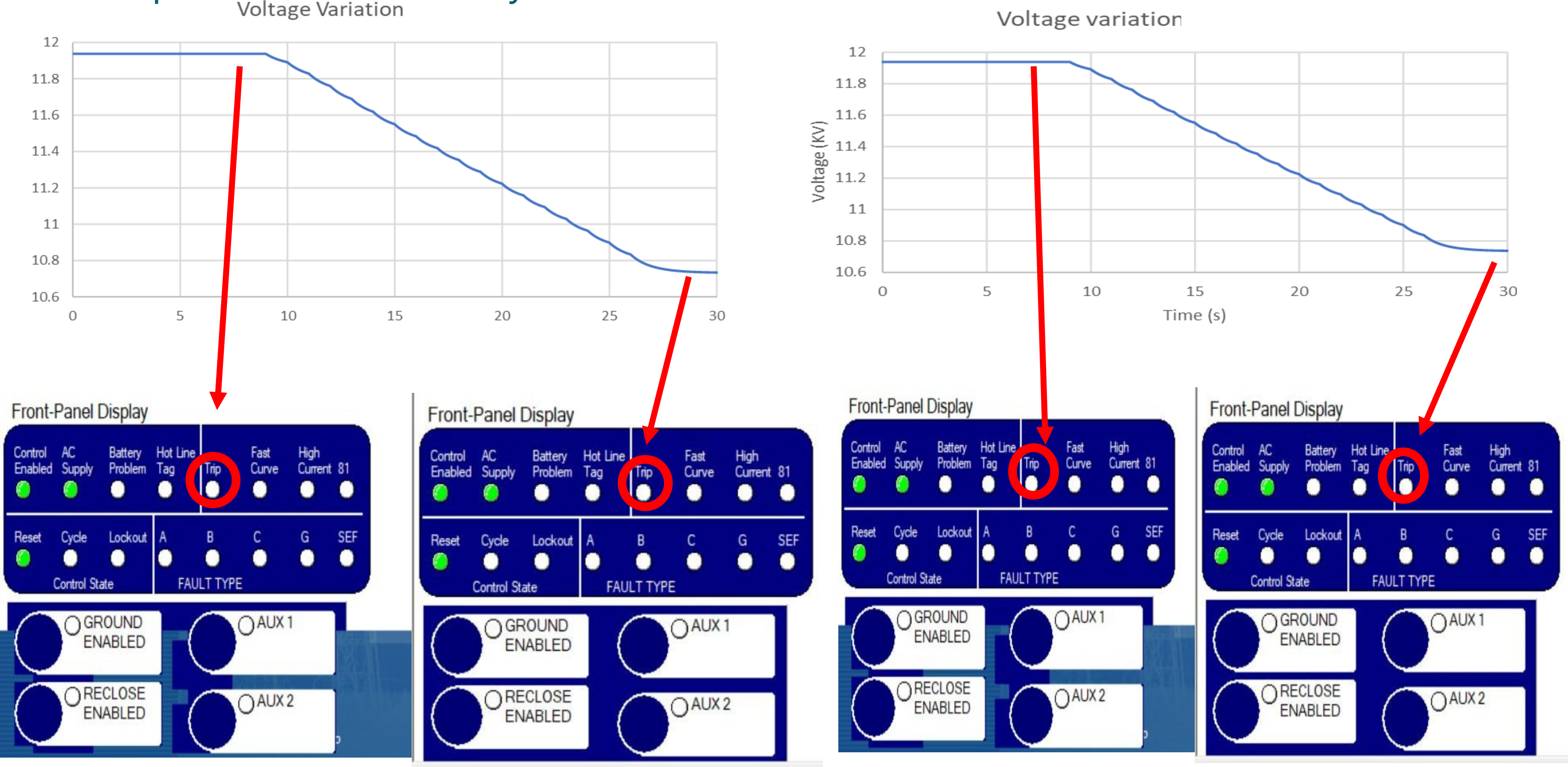
Impact on Relays for Scenario IV

✓ No trips command for relays.



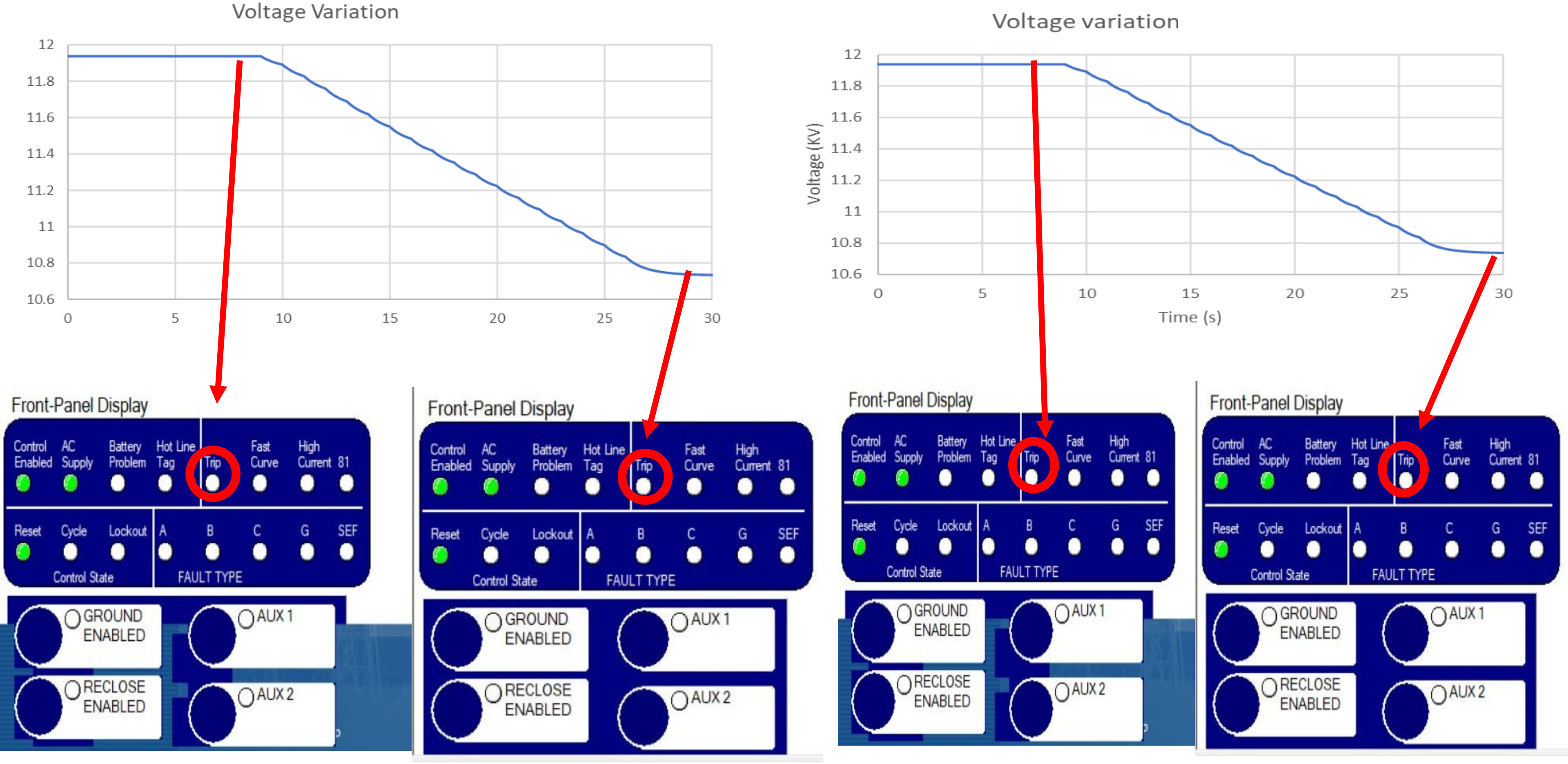
Impact on Relays for Scenario V

✓ No trips command for relays.



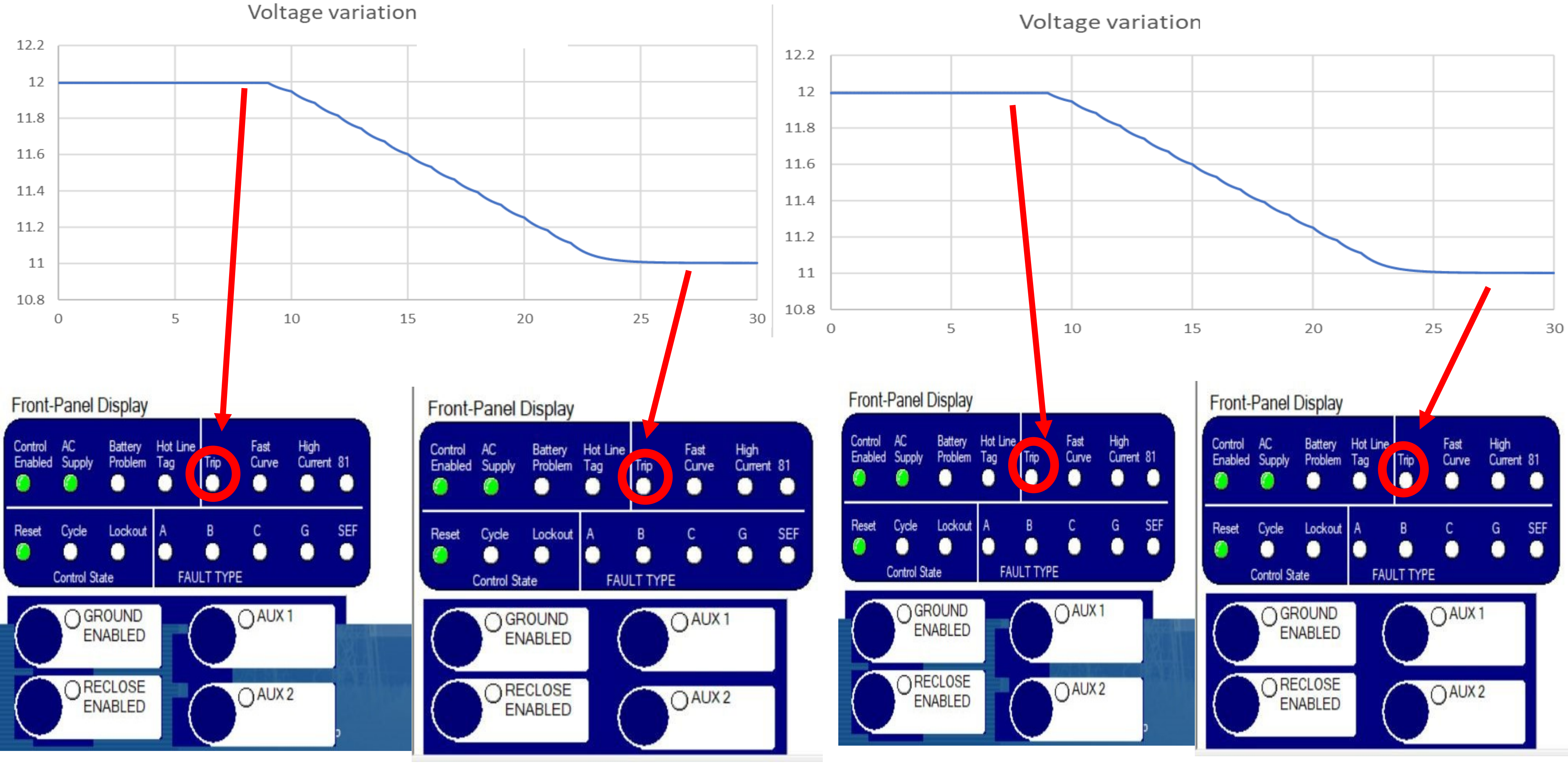
Impact on Relays for Scenario VI

✓ No trips command for relays.



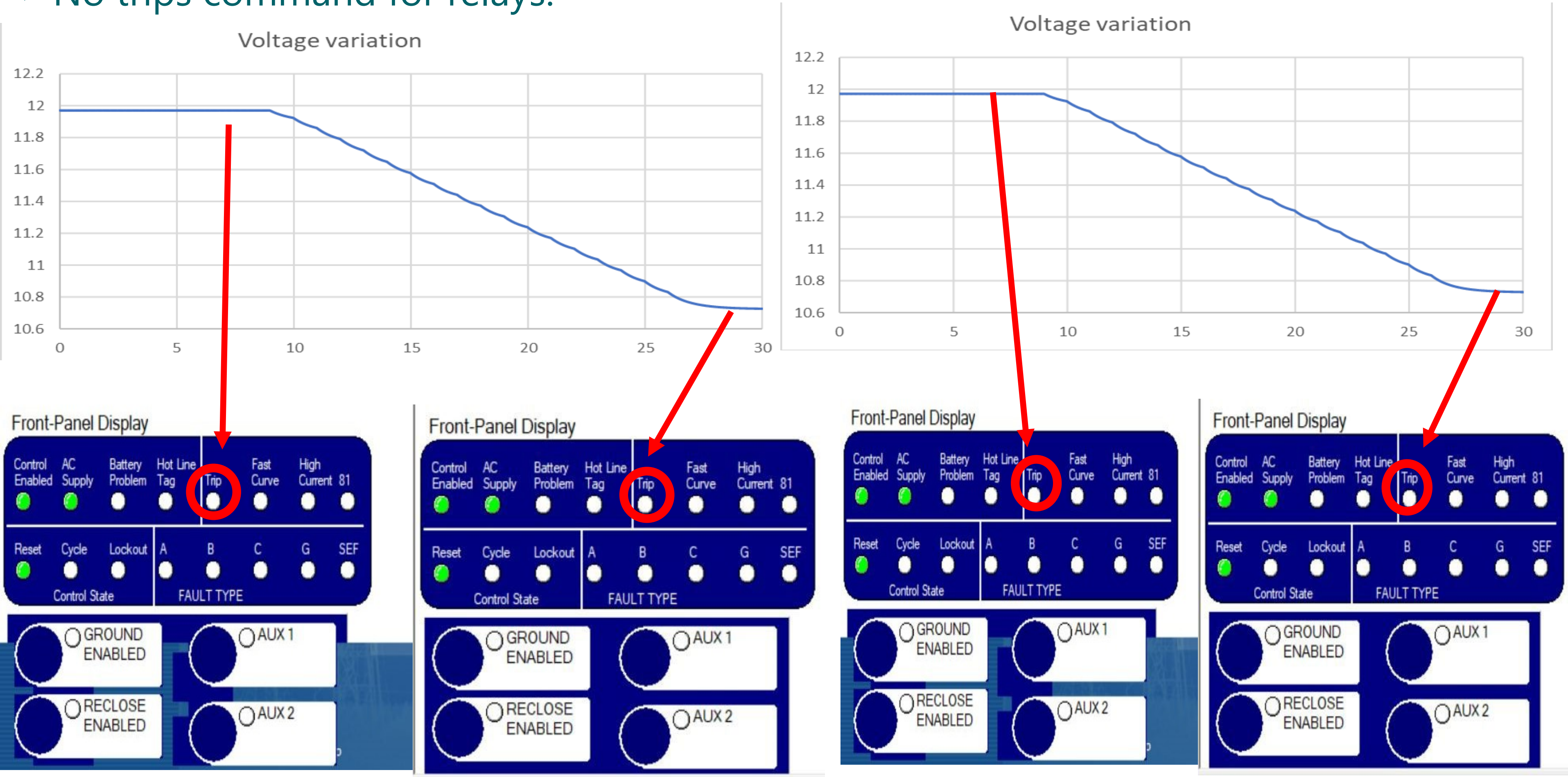
Impact on Relays for Scenario VIII

✓ No trips command for relays.



Impact on Relays for Scenario IX

✓ No trips command for relays.



Conclusions

- The development of a Power Hardware-in-the-Loop (PHIL) testbed at Southern California Edison (SCE)'s Distributed Energy Resource (DER) Laboratory is described

- The volt/var use case results are verified by experimentation and found that there would be no impact on the feeder protection given the current protection setting.

- This testbed can benefit SCE to study the emerging technologies without the need to conduct in-field trials

Q & A