Impact Analysis of High PV Penetration on Protection of Distribution Systems Using Real-Time Simulation and Testing – A Utility Case Study

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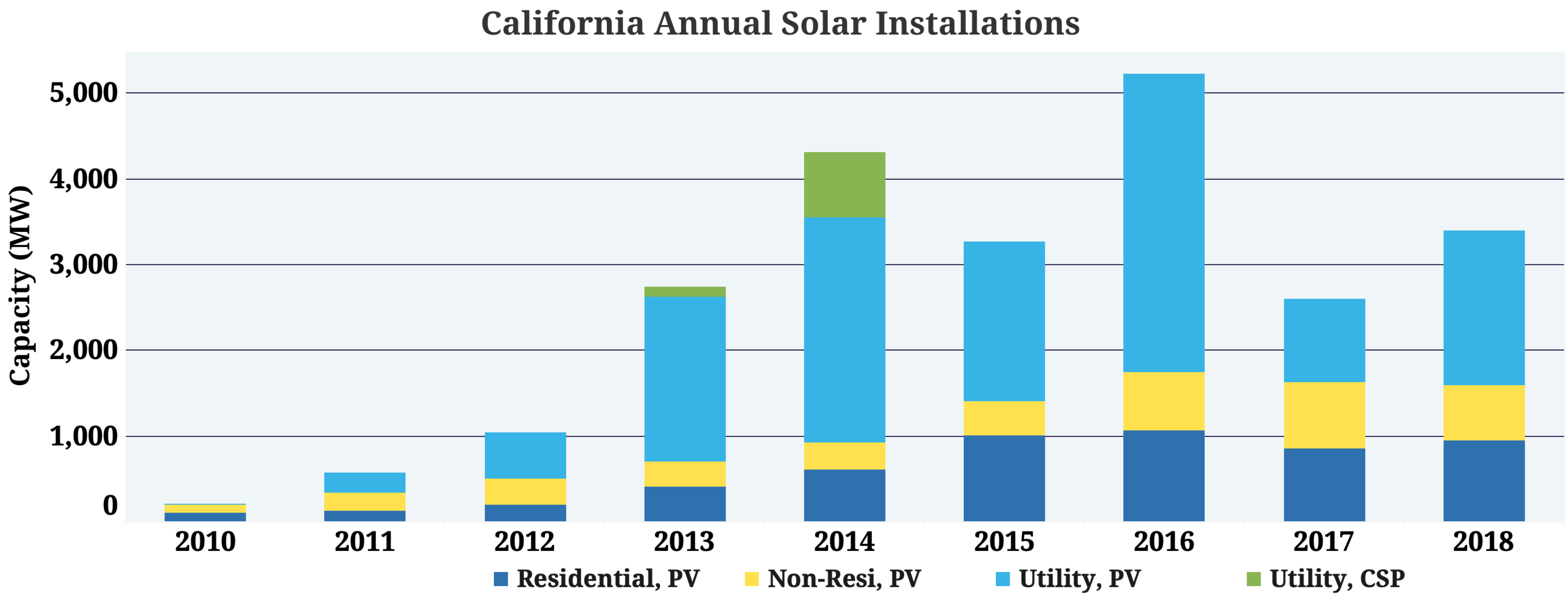
Introduction



from: https://www.seia.org/state-solar-policy/california-solar

Introduction

- Several utilities across North America are experiencing increased penetration of Distributed Energy Resources (DERs) within their service territories.
- Some risks posed by increased DER adoption:
  - sympathetic tripping,
  - coordination loss,
  - protection blinding,
  - failed auto-reclosing.

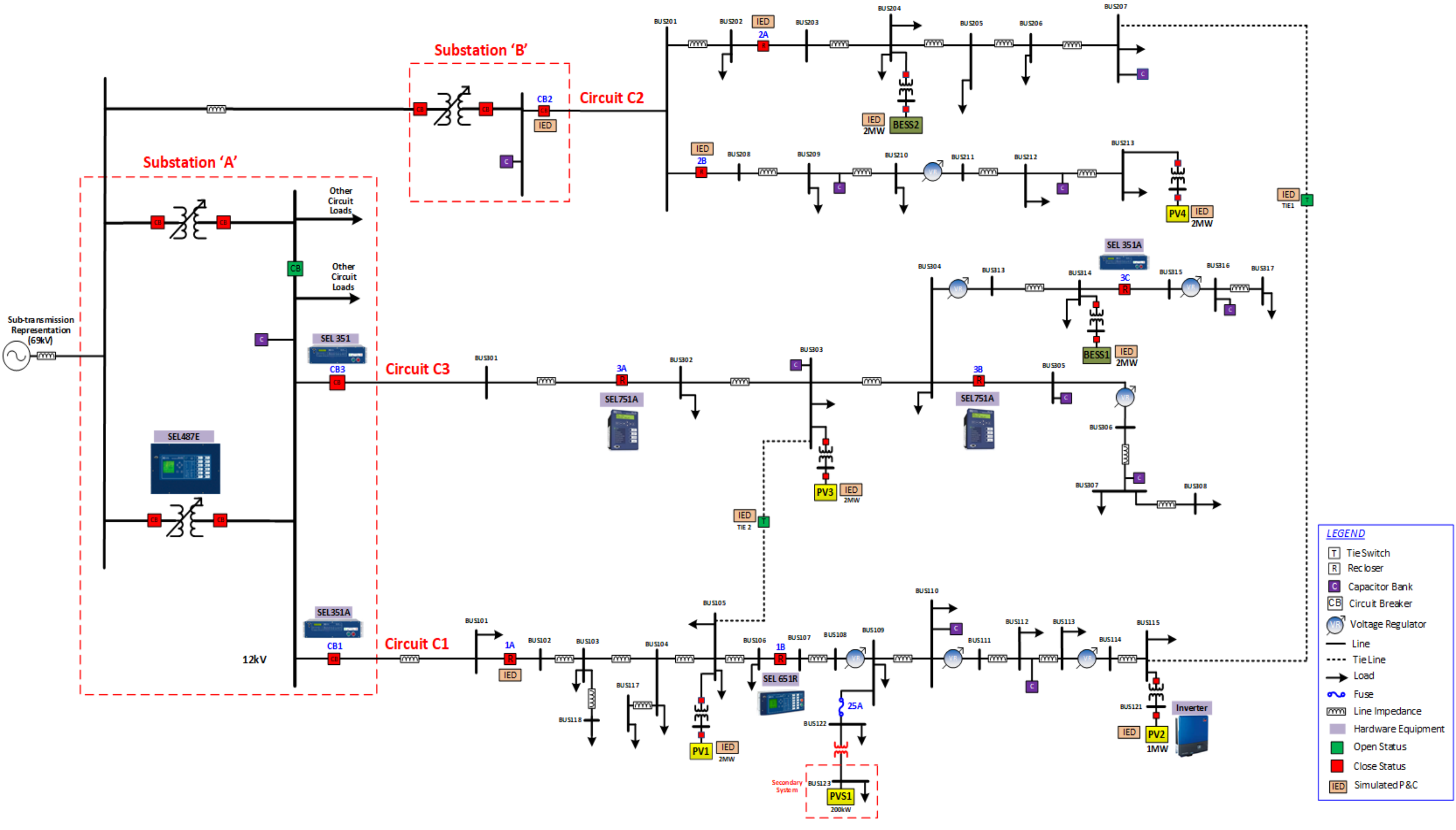
Study Objectives

- Hosting capacity studies using planning tools used to identify the maximum PV integration level in distribution system.

- Impact of high PV penetration on conventional distribution-level protection and automation schemes needs a more detailed investigation.

- Study Objective: Identifying and resolving protection issues for typical San Diego Gas & Electric® (SDG&E) distribution systems with high penetration of PV, using a Hardware In-the-Loop testing platform.

Studied System

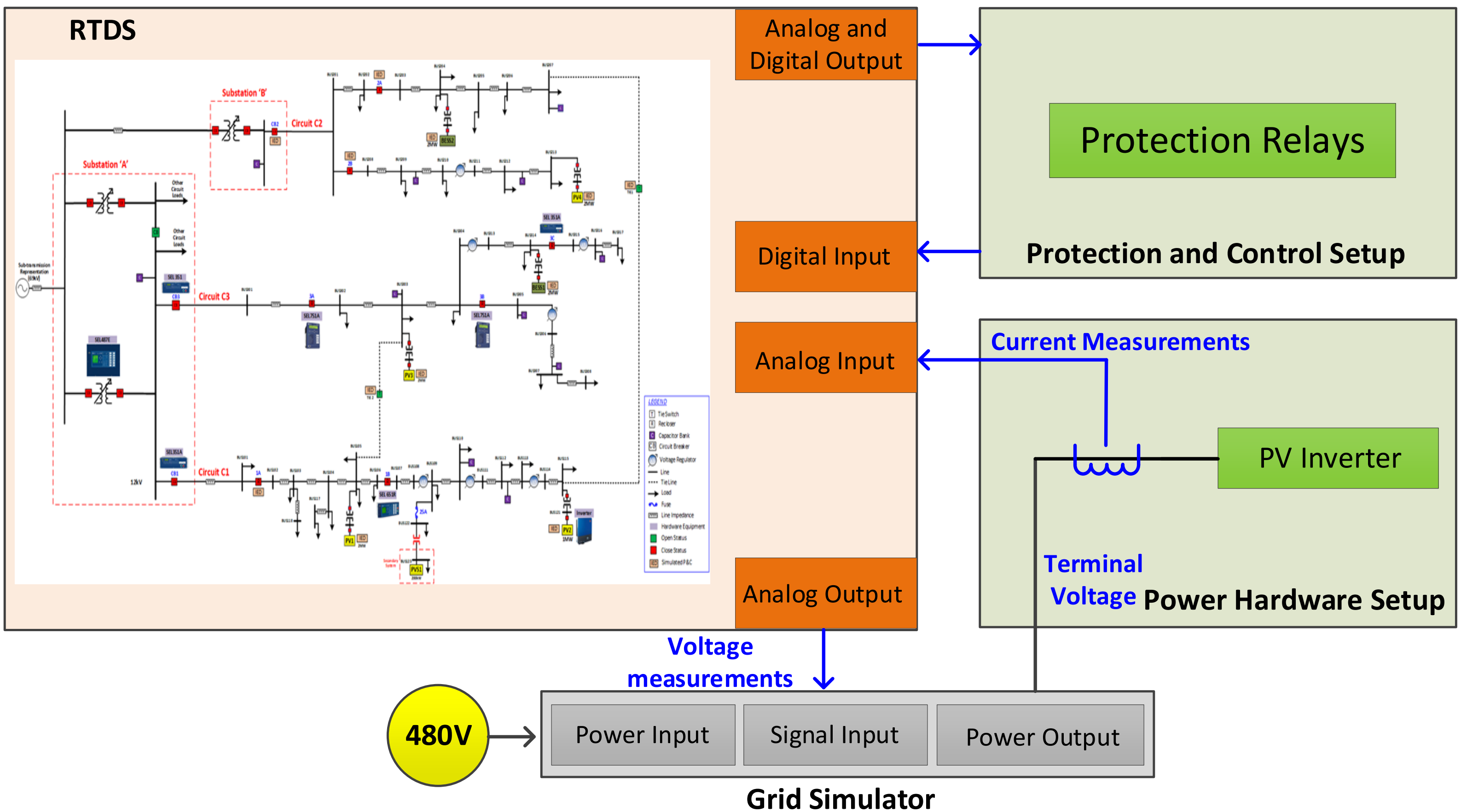


Baseline System Analysis

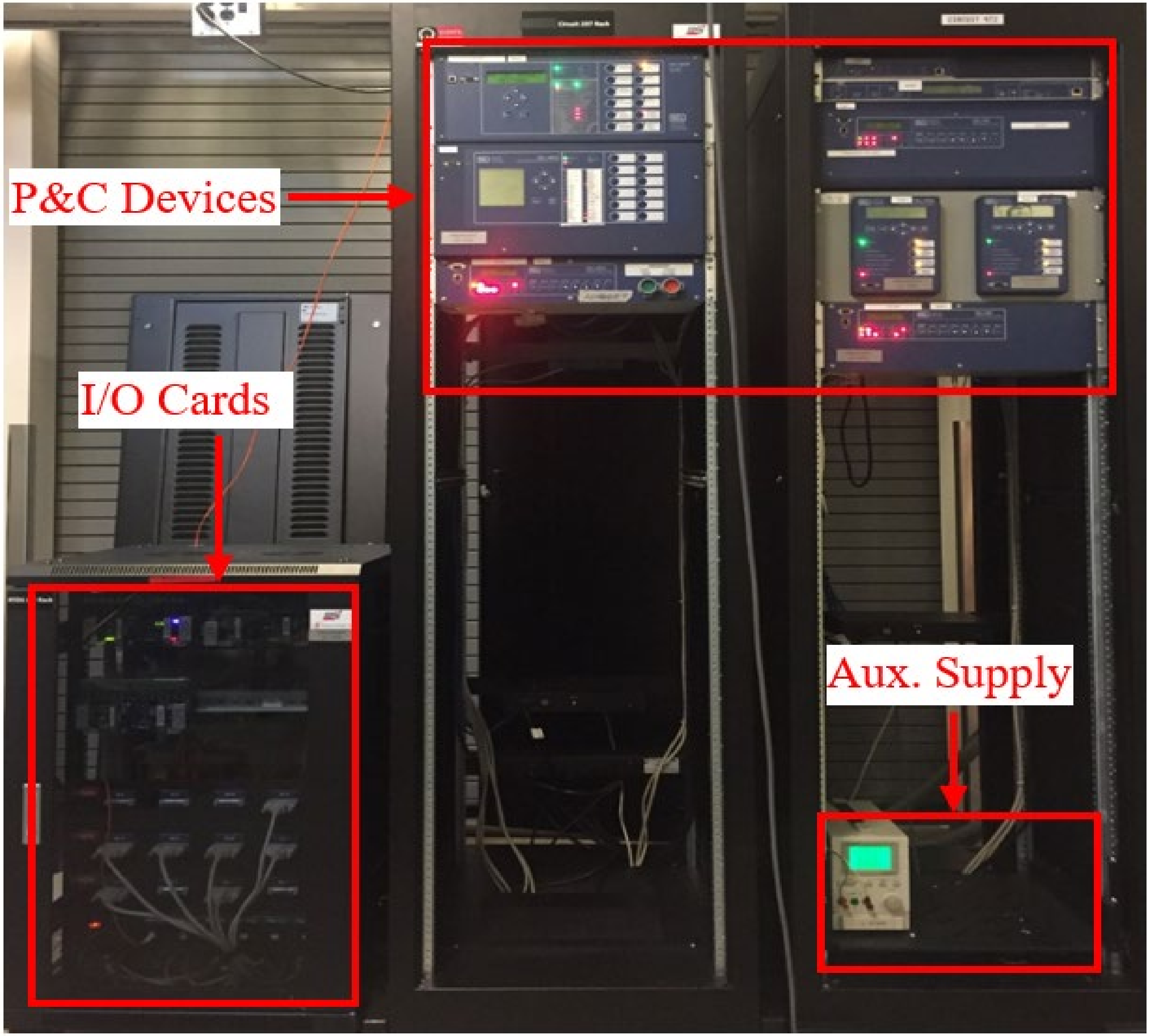
CIR	Flt. Loc.	Flt. Current (kA)		Operating Time (Sec)							
				TPH Fault				SLG Fault			
		TPH	SLG	CB1	R1A	R1B	Fuse	CB1	R1A	R1B	Fuse
C1	101	13.30	8.10	0.018	NO*	NO*	NO*	0.678	NO*	NO*	NO*
	104	5.20	4.00	0.832	0.012	NO	NO	0.824	0.015	NO	NO
	107	2.50	1.97	2.086	1.529	0.077	NO	1.196	0.541	0.087	NO
	122	2.15	1.60	2.799	2.065	1.510	NO	1.393	0.708	0.082	NO
	110	1.17	0.86	8.387	6.265	3.823	NO	3.615	2.727	1.771	NO
	115	0.57	0.50	NO*	NO	18.881	NO	23.740	18.630	8.903	NO
				CB2	R2A	R2B		CB2	R2A	R2B	
C2	201	5.17	5.50	0.009	NO	NO		0.014	NO	NO	
	203	4.50	4.20	0.013	0.007	NO		0.015	0.008	NO	
	207	1.05	0.85	1.005	0.622	NO		1.693	1.014	NO	
	208	5.20	5.50	0.009	NO	0.007		0.013	NO	0.006	
	213	1.16	0.92	0.767	NO	0.630		1.272	NO	1.091	
				CB3	R3A	R3B	R3C	CB3	R3A	R3B	R3C
C3	301	12.4	8.5	0.020	NO	NO	NO	0.018	NO	NO	NO
	302	9.10	6.9	0.021	0.061	NO	NO	0.019	0.058	NO	NO
	305	2.60	1.78	1.863	1.043	0.085	NO	1.504	1.004	0.084	NO
	308	1.71	1.3	2.910	1.616	1.145	NO	2.078	1.383	1.024	NO
	315	1.10	0.8	3.962	2.203	NO	0.072	3.173	2.101	NO	0.072
	317	0.82	0.64	5.877	3.253	NO	2.320	4.840	3.124	NO	2.670

Impact Analysis Methodology

In this study, a real-time simulation platform with power and control hardware in-the-loop was used to evaluate PV impacts on distribution automation and protection.



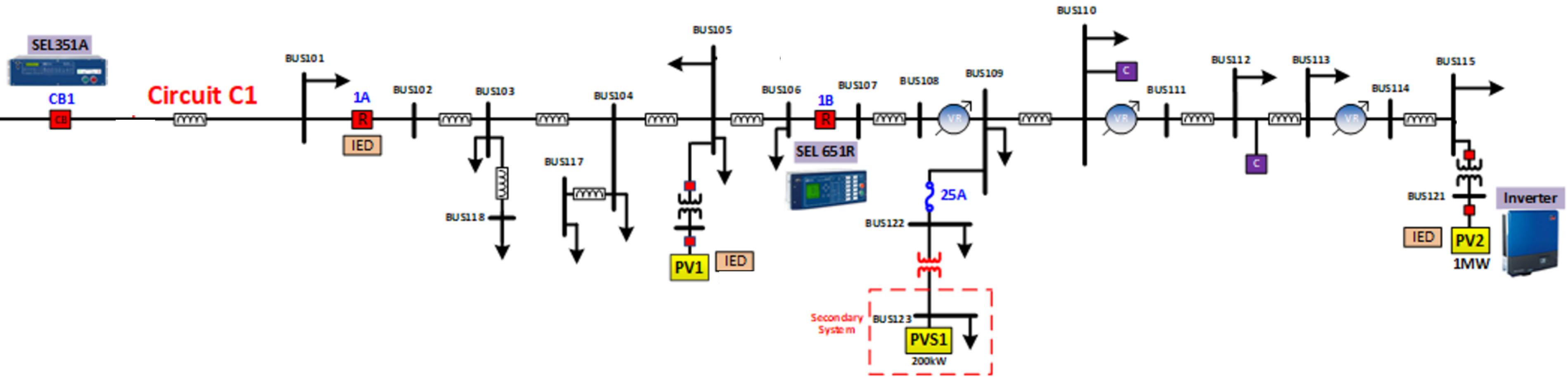
HIL Testbed



Test Cases

- Location of the PV system (beginning, middle, end)
- PV penetration level (low, medium, high)
- PV control mode (droop or constant power factor)
- Various ride-through capability of simulated inverters
- PV fault current capacity (1.1pu – 1.4pu)
- Status of other DERs (ON/OFF)
- Load profiles (low/winter or high/summer)
- Circuit Configuration
- Fault location
- Fault type (balanced vs unbalanced)

Circuit C1 Test Results (P1/3)



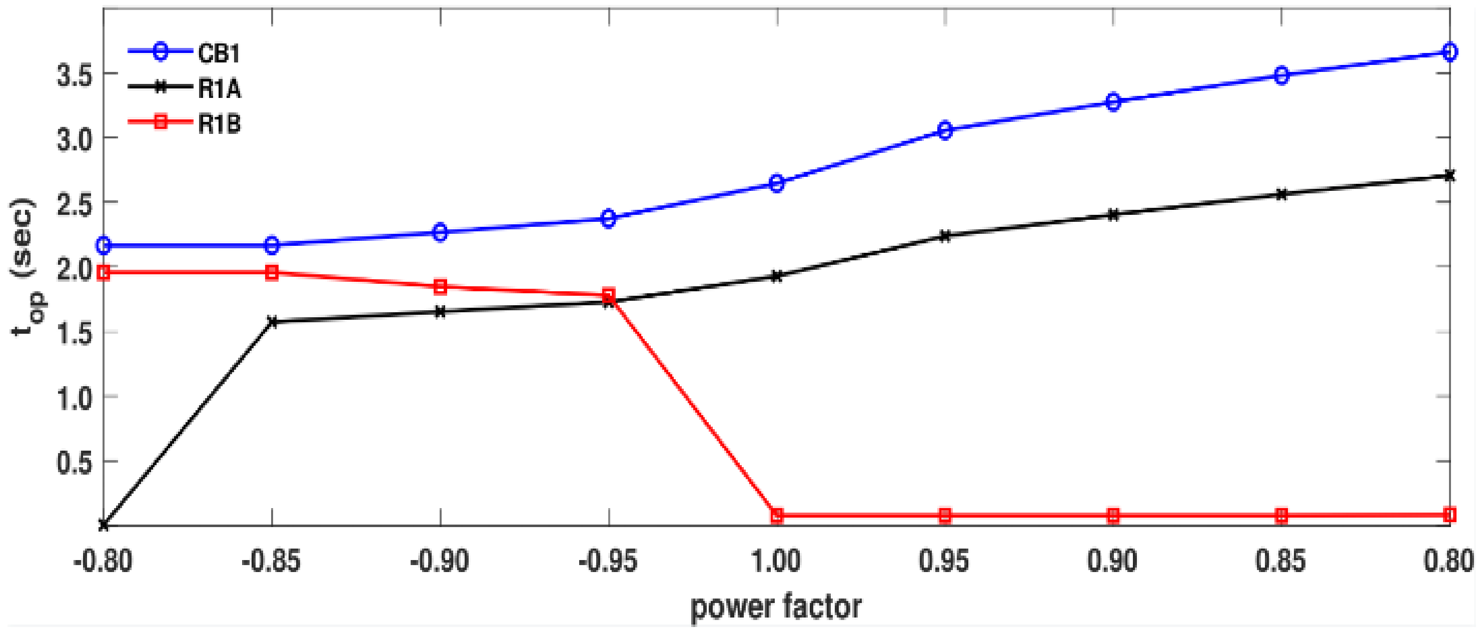
- 10 MW of PV is connected to Bus 105.
- PV penetration is kept constant (at 100%), while power factor setpoint is changed from 0.8 (Q injection) to – 0.8 (Q absorption) with steps of 0.05.
- Fault is applied at Bus 109.

Circuit C1 Test Results (P2/3)

Percentage change in relay operating times (with respect to the baseline protection) for a fault at bus 109

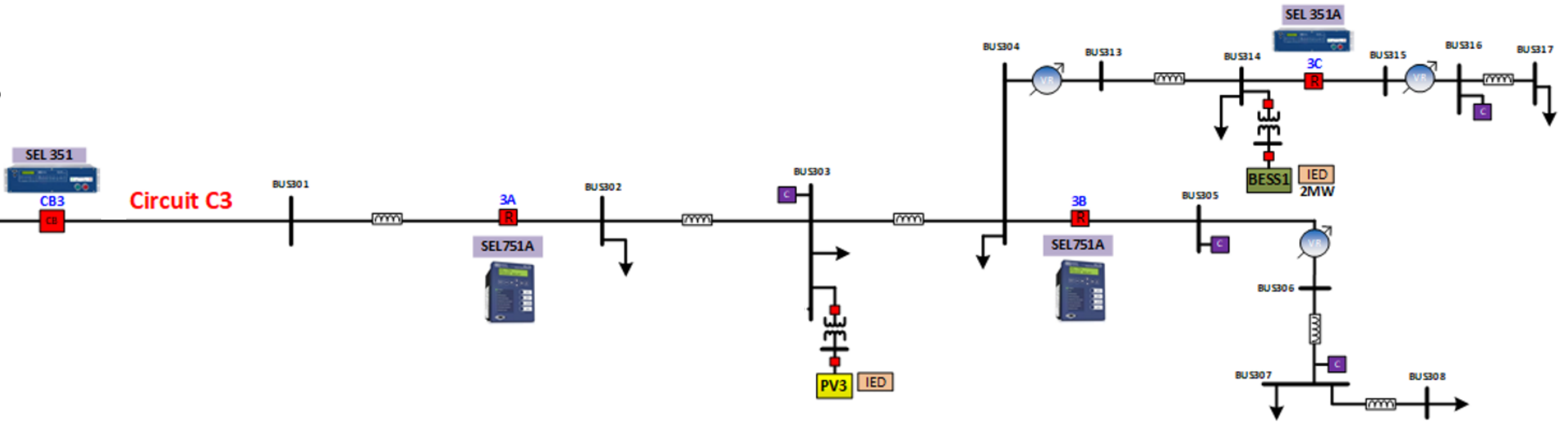
PF	TPH Fault				SLG Fault			
	Protective Devices				Protective Devices			
	CB1	R1A	R1B	Fuse	CB1	R1A	R1B	Fuse
0.80	30.8	31.1	–94.5	NO	1.4	4.9	–4.1	NO
0.85	24.3	24.0	–94.8	NO	2.0	6.0	–5.2	NO
0.90	17.0	16.4	–94.8	NO	4.8	10.0	–3.7	NO
0.95	9.2	8.4	–94.8	NO	5.2	10.7	–0.9	NO
1.00	–5.5	–6.6	–94.8	NO	6.1	13.7	–1.2	NO
–0.95	–15.2	–16.3	17.8	NO	9.7	19.4	–1.4	NO
–0.90	–19.0	–19.9	22.3	NO	11.1	21.4	–3.6	NO
–0.85	–22.6	–23.8	29.6	NO	11.1	21.4	17.4	NO
–0.80	–22.6	–99.8	29.6	NO	11.1	–97.4	25.9	NO

Circuit C1 Test Results (P3/3)



Relay operating time vs inverter power factor (THP fault at Bus 109)

Circuit C3 Test Results (P1/3)



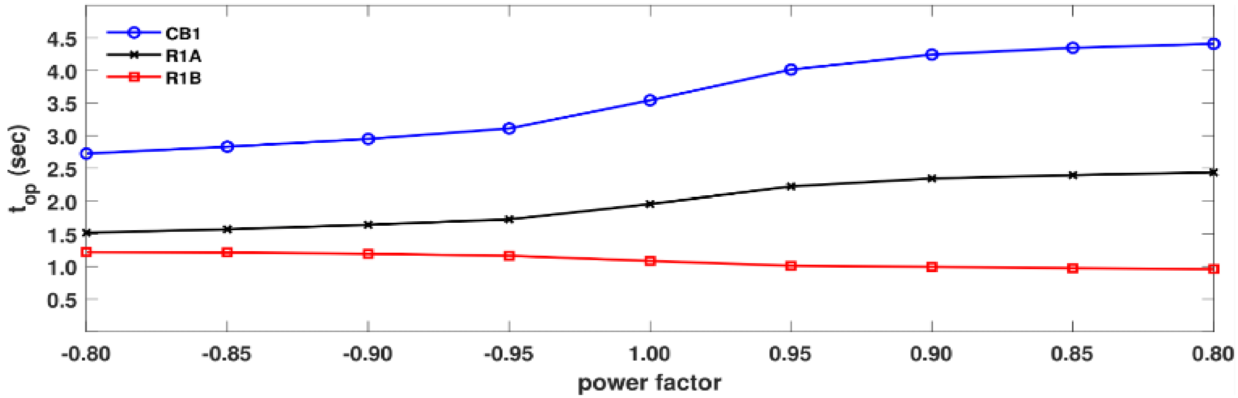
- PV connected to Bus 303 downstream of Recloser 3A (middle of the circuit) @ penetration of 100% (10MVA).
- PV penetration kept constant (at 100%), while power factor setpoint is changed from 0.8 (Q injection) to – 0.8 (Q absorption) with steps of 0.05.

Circuit C3 Test Results (P2/3)

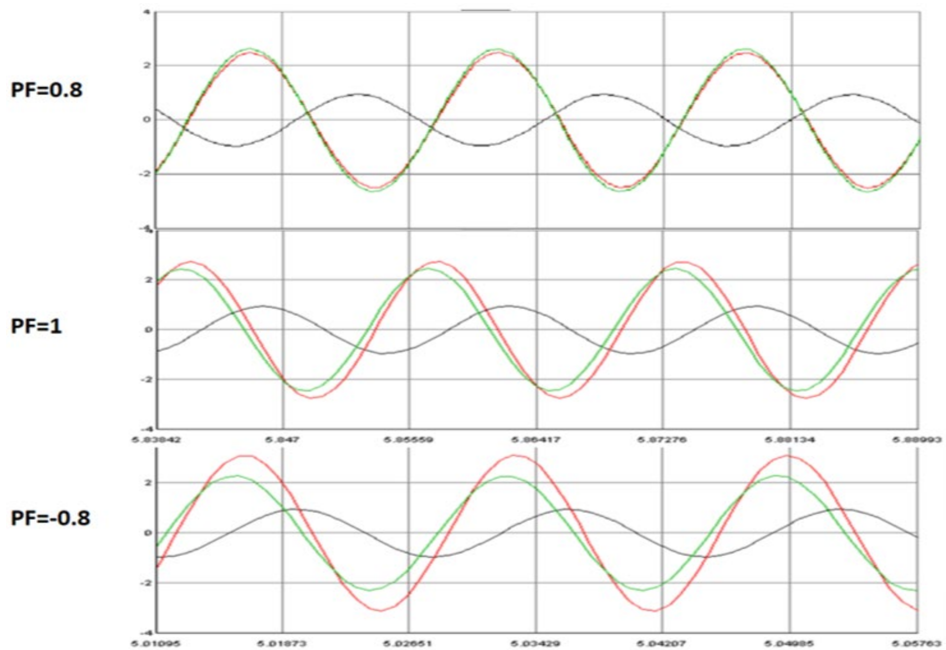
Percentage change in relay operating times (with respect to the baseline protection) for a fault at bus 308

PF	TPH Fault				SLG Fault			
	Protective Devices				Protective Devices			
	CB3	R3A	R3B	R3C	CB3	R3A	R3B	R3C
0.80	51.5	50.9	–15.9	NO	9.4	23.6	–16.5	NO
0.85	49.5	48.3	–14.8	NO	9.4	23.6	–16.5	NO
0.90	45.9	45.1	–13.0	NO	4.3	3.7	–14.7	NO
0.95	38.0	37.6	–11.5	NO	4.9	4.6	–13.3	NO
1.00	21.8	21.2	–5.1	NO	5.9	5.6	–9.1	NO
–0.95	6.9	6.7	1.9	NO	5.5	6.1	–3.4	NO
–0.90	1.4	1.6	4.5	NO	5.2	6.2	–2.2	NO
–0.85	–2.7	–2.7	6.5	NO	6.3	7.7	–1.3	NO
–0.80	–6.3	–5.9	6.9	NO	5.2	6.6	0.9	NO

Circuit C3 Test Results (P3/3)



Relay operating time vs inverter power factor (THP fault at Bus 308)



Currents of PV3 (black), R3A (red), and R3B (green) during the fault for positive (VAr injection), unity, and negative (VAr absorbtion) power factors

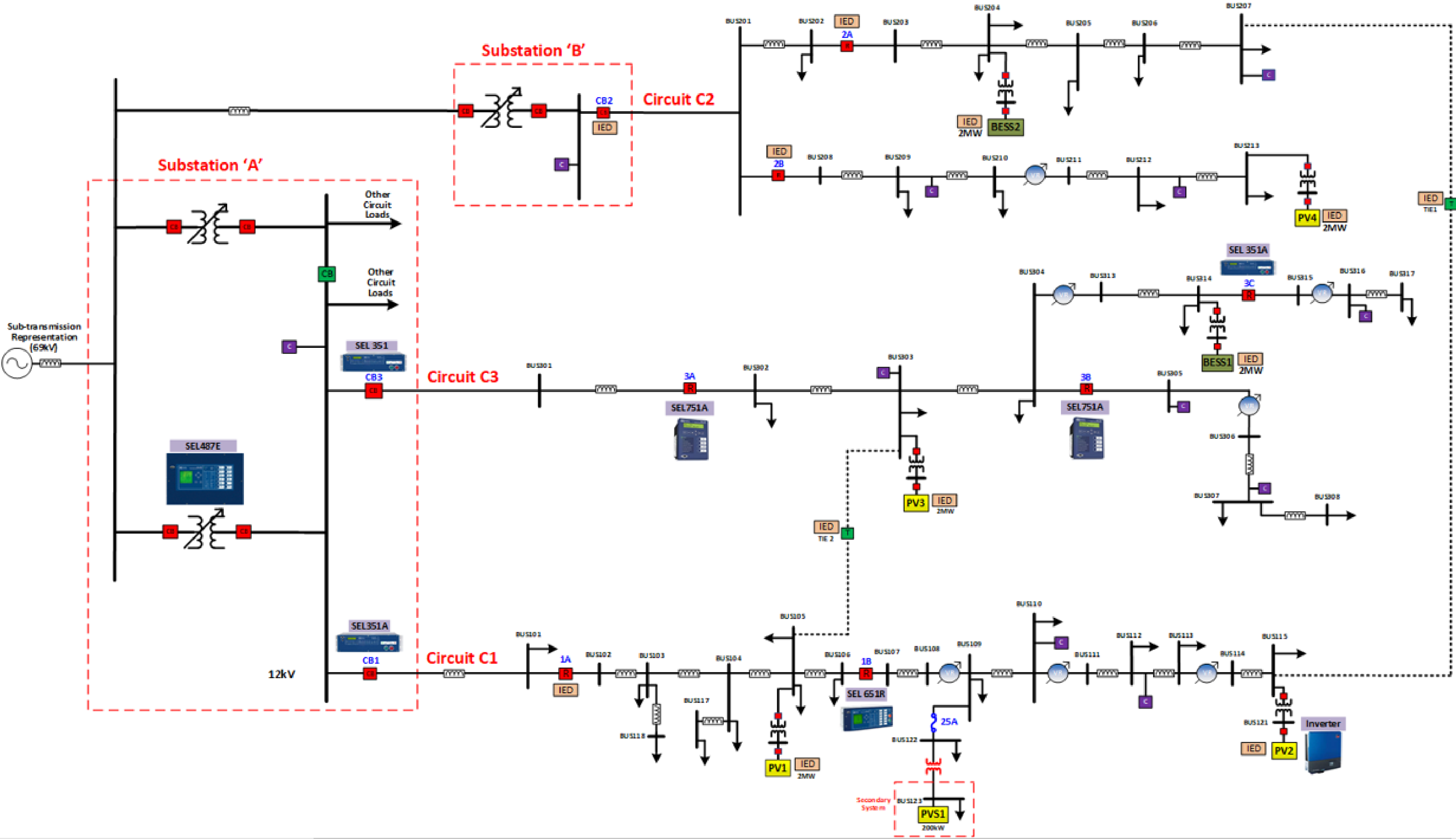
Circuit Reconfiguration (P1/3)

- High PV penetration can affect distribution automation processes.
- Many utilities perform distribution circuit reconfiguration through a close transition, without any synchronization check prior to the process.
- However, with high PV penetration level, the synchronization between the two adjacent circuits from two different substations may be compromised.
- It will be essential to revisit conventional circuit reconfiguration procedures, e.g., for load transfer.

Circuit Reconfiguration (P1/3) cont'd

- To perform circuit reconfiguration in this study, the tie between Circuit C2 and Circuit C1 (TIE1) is closed,
- Then some loads were transferred from Circuit C1 (Substation 'A') to Circuit C2 (Substation 'B') by opening Recloser R1B.
- In addition to loads, the plant connected to Bus 115 (PV2) is transferred to Circuit C2.

Circuit Reconfiguration (P2/3)



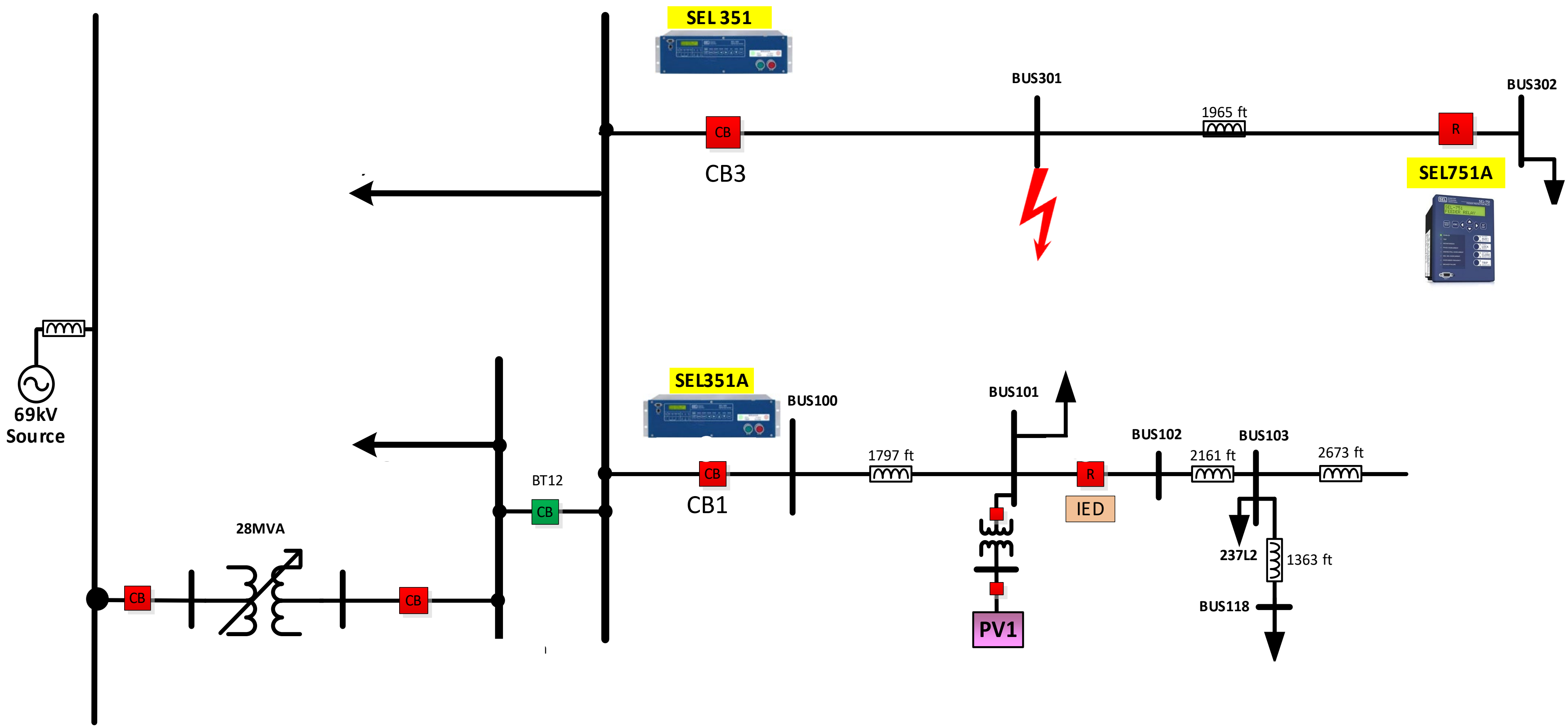
Circuit Reconfiguration (P3/3)

- Operating time of circuit-c2 relays, before and after circuit reconfiguration

Circuit	Fault Loc.	TPH Fault Protective Devices			SLG Fault Protective Devices		
		CB2	R2A	R2B	CB2	R2A	R2B
Without PV2							
C2	107	8.415	3.107	NO	20.980	6.095	NO
	109	7.826	2.965	NO	19.360	5.764	NO
	111	4.968	2.110	NO	10.950	3.796	NO
	113	2.236	1.088	NO	3.847	1.645	NO
With PV2							
		CB2	R2A	R2B	CB2	R2A	R2B
C2	107	NO	7.042	NO	39.870	28.250	NO
	109	NO	8.049	NO	32.130	15.080	NO
	111	17.450	4.319	NO	17.550	12.130	NO
	113	2.257	1.229	NO	5.586	2.940	NO
Percentage Change							
C2	107	NO	126.6	NO	90.0	363.5	NO
	109	NO	171.5	NO	65.9	161.6	NO
	111	251.2	104.7	NO	60.2	219.5	NO

- Test results show that the transfer of PV2 has generally increased Circuit-C2 relays operating times because PV2 is added to circuit end, resulting to the reduced grid fault current.
- But, the addition of PV2 did not cause any major protection miscoordination.

Sympathetic Tripping (P1/2)



Sympathetic Tripping (P2/2)

		Operation Time (sec)			
		3-Ph Fault		SLG Fault	
		Protective Devices		Protective Devices	
PV Gen	PF	CB3	CB1	CB3	CB1
3MVA	1	0.0182	25	0.0194	1.678
15MVA	0.8	0.0187	26.3	0.0181	3.034
15MVA	1	0.0181	23.5	0.0172	2.164
15MVA	-0.8	0.0176	21.75	0.0177	2.402

- False tripping can be a potential challenge in presence of rotating machines
- Inverters have limited fault contribution due to the presence of current limiters.
- Didn’t trigger the TOC elements and not IOC elements on neighboring circuits

Summary and Recommendations

- Due to the limited fault current capacity of PV inverters, major protection issues in SDG&E circuits occurred for very high PV penetration levels (> 50%).
- The presence of PV systems reduces the grid fault current, leading to the delayed (or non-operation) operation of the substation circuit breaker (revised setting is recommended).
- The grid fault current reduction in the presence of PV systems is a function of the size, location, fault current capacity, and control (ride-through) of the PV.

Summary and Recommendations…Cont'd

- Since SDG&E uses fuse-blowing scheme, no recloser-fuse miscoordination was identified in this study. However, fuse-fuse miscoordination were observed in high PV penetration levels (> 50%).
- The results showed that reactive power support of PV systems during the fault increases the chance of protection failure.
- The impact of PV systems on protection is minimized when the power factor of the plant remain unity during the fault. Thus, protection engineers need to study DER ride-through capabilities.
- Coordination between the PV protection system (usually owner responsibility) and utility protection system must be analyzed to avoid issues such as failed auto-reclosing.