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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Project Team

- San Diego Gas & Electric (SDG&E)
- Electric Power Research Institute (EPRI)
- Quanta Technology

Introduction

- Increase in penetration of Photovoltaic (PV) systems introduces new challenges to the protection and automation of distribution grids.
- The objective was to identify these impacts on SDG&E distribution circuits, using power and control Hardware In-the-Loop (HIL) testing.
- Hosting capacity studies are normally done by planning study tools, which do not provide precise modelling of DERs as well as various aspects of protection and automation schemes.
- The HIL testing also enables incorporation of actual inverter fault current characteristics into the study.

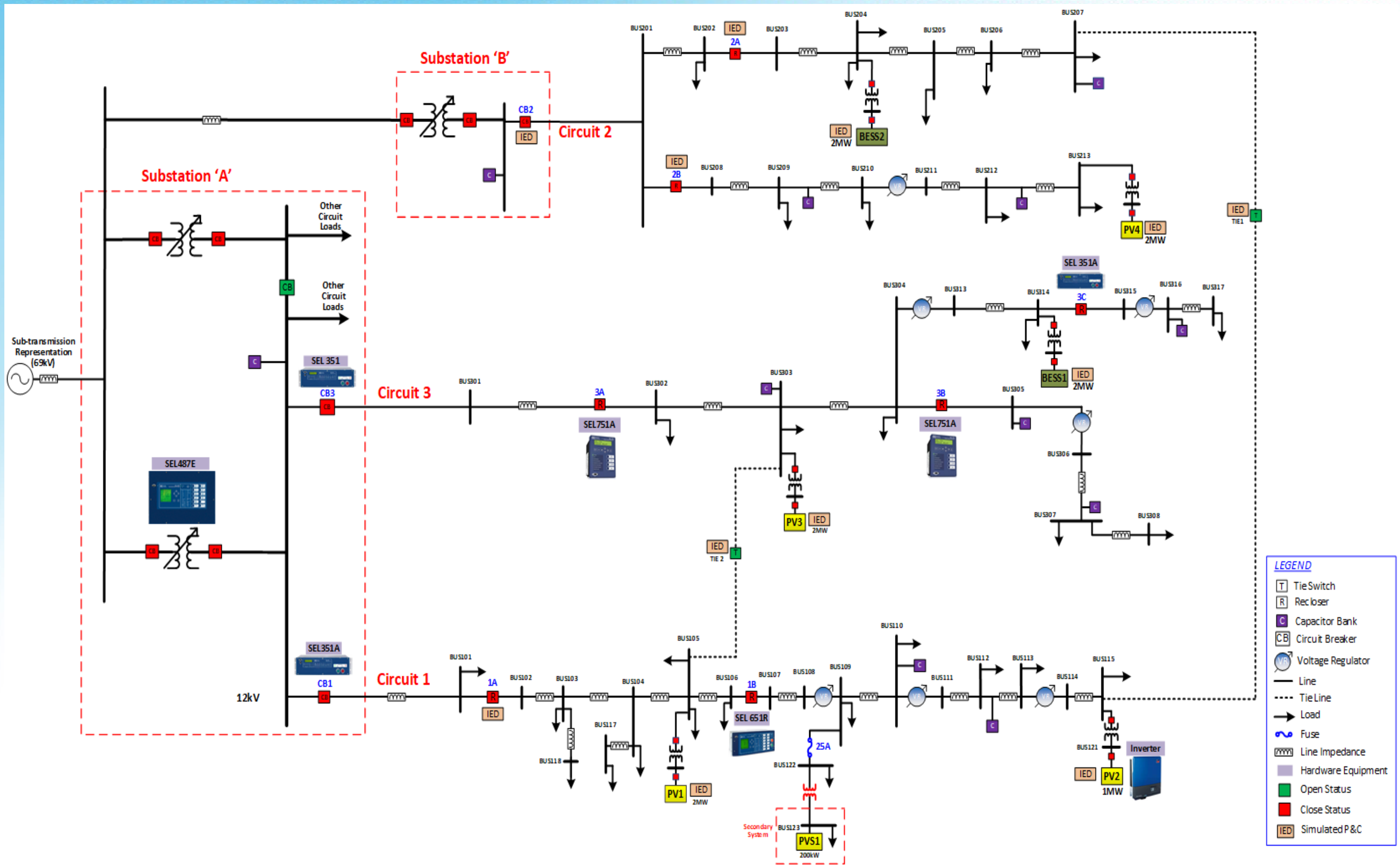
Introduction

- The results of this study aimed at defining the following:
  - The PV penetration levels at which distribution protection system is compromised.
  - Protection and automation challenges in the SDG&E distribution system with high-penetration PV integration.
  - The impact of various PV fault current capacity and ride-through capability on the protection coordination.
  - Impact of circuit reconfigurations on the protection coordination in the presence of PV systems.
  - Potential solution to major distribution-level protection issues.

Study System Selection

- Real-time simulation with hardware equipment in-the-loop allows limited numbers of circuits to be modeled/studied.
- A study was conducted to select circuits that are best representative of the SDG&E's distribution system:
    - Two substations with electrical connection to enable circuit reconfiguration
    - Circuits with existing/expected high penetration levels
    - Circuits that embed other DER types/technologies
    - Circuits with lower-than-average reliability indices
    - More than one circuit from one substation to be studies
- 3 circuits from 2 different substations were selected.

Study System Selection (cont.)

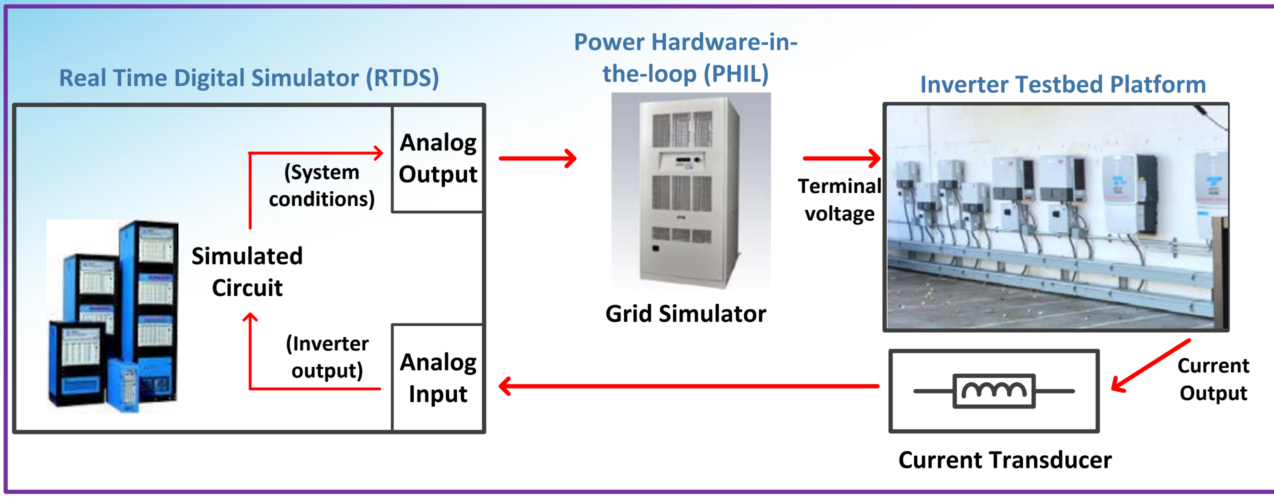


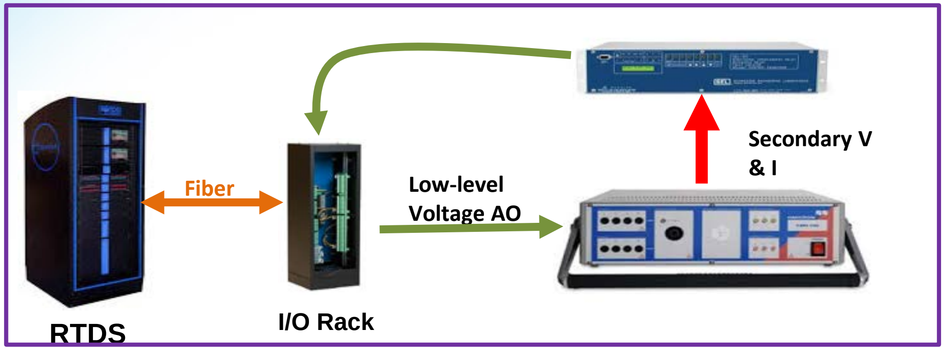
Model Verification and Assumptions Made

- The simplified RTDS model was verified and checked against the planning (SynerGi) model.
  - The PV inverters are modeled as voltage-controlled current source, with limited fault current capacity (1.1pu – 1.4pu)
  - An average model was used for inverter models to enable incorporating more PVs
  - The PV model was verified through comparison with fault current characteristics of the actual inverter
  - The focus was on the utility protection, assuming that PV protection is the owner responsibility (and operates as expected)
  - Maximum fault current contribution from the PV system was considered
  - It is assumed that high PV penetration does not significantly impact the fault current level of the grid

Hardware In-the-Loop (HIL) Testing

Power Hardware In-the-Loop (PHIL)

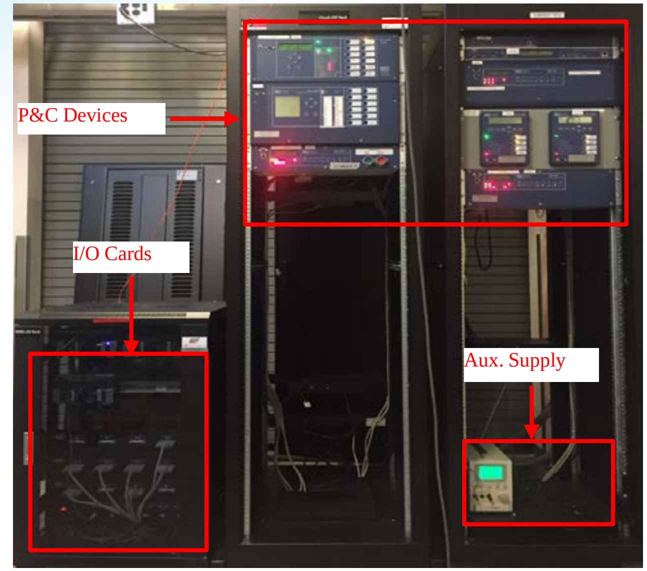




Control Hardware In-the-Loop (CHIL)

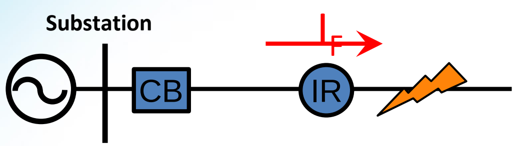
HIL Test Setup

- HIL testbed was developed in SD&GE Integration Testing Facility.
- Power and Control hardware (Inverter, relays, and voltage regulators) were interfaced with the RTDS model.
- Low-Energy Analog (LEA) inputs of relays were utilized to minimize the number of amplifiers required for this testing.



Impact Analysis Approach – Baseline Protection

- Operation times of the protection relays were studied for selected number of faults at different locations.
- Analyzing the results for existing system showed some protection mis-coordination issues.



- IOC (50) elements of substation relay and Sub-IR operate for close-in faults.

CIR	Flt. Loc.	Flt. Current (kA) TPH	Flt. Current (kA) SLG	Operating Time (Sec) TPH Fault CB273	237-17R	237-2R	Fuse	SLG Fault CB273	237-17R	237-2R	Fuse
Circuit 1	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
				CB222	222-1370R	222-1364R		CB222	222-1370R	222-1364R	
Circuit 2	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	
				CB972	972-26R	972-32R	972-30R	CB972	972-26R	972-32R	972-30R
Circuit 3	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

* 'NO' denotes that the relay has not operated

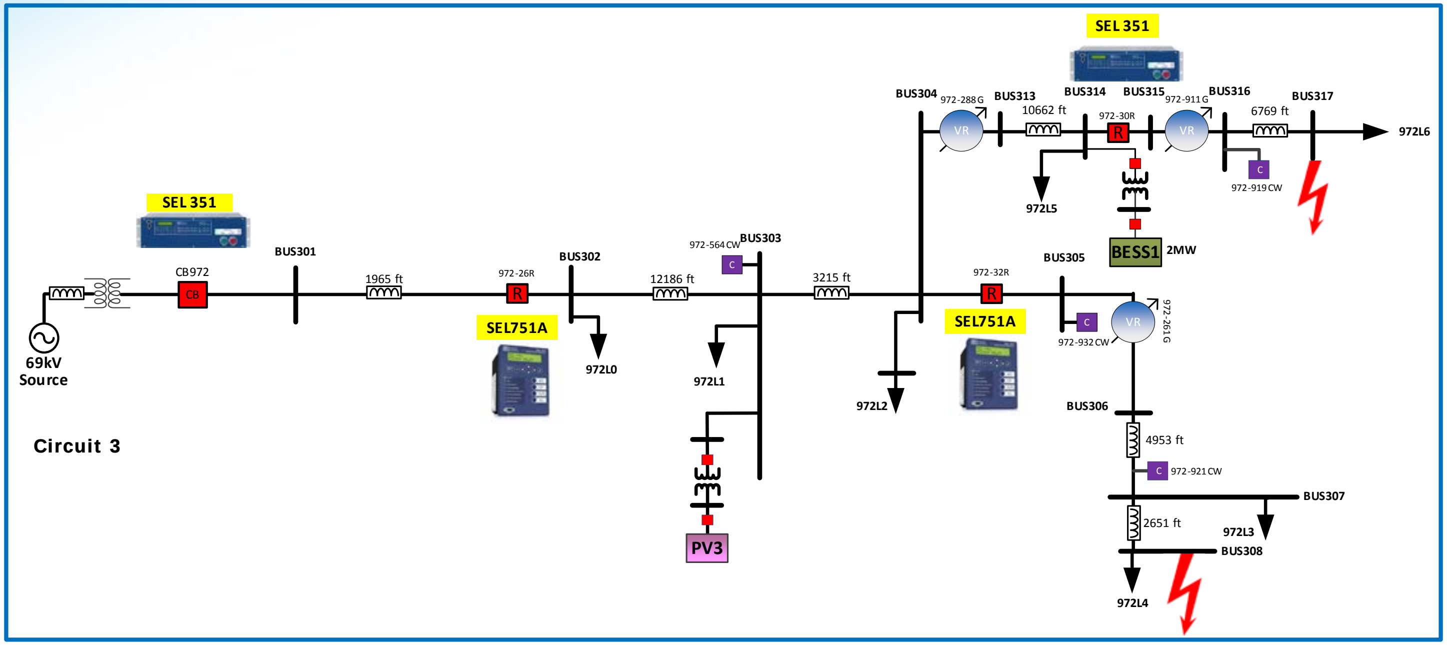
Impact Analysis Approach – Test Cases

In the preparation of the test plan, various factors that can potentially affect protection system were considered:

- 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 or unbalanced)

Test Results and Analysis (C 3)

- Let us assume that a 7.5-MW PV system (100% penetration) is connected to Bus 303 on Circuit 3
- Various reactive power support during the fault (power factor ranging from +0.8 leading/Injecting to –0.8 lagging/absorbing)



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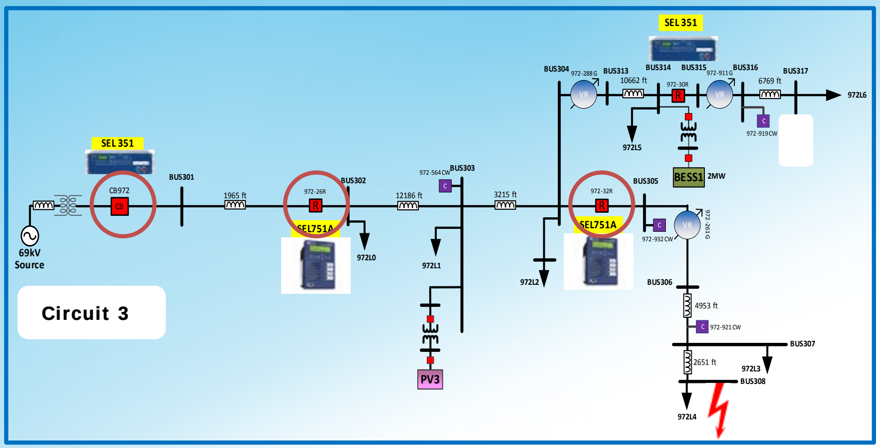
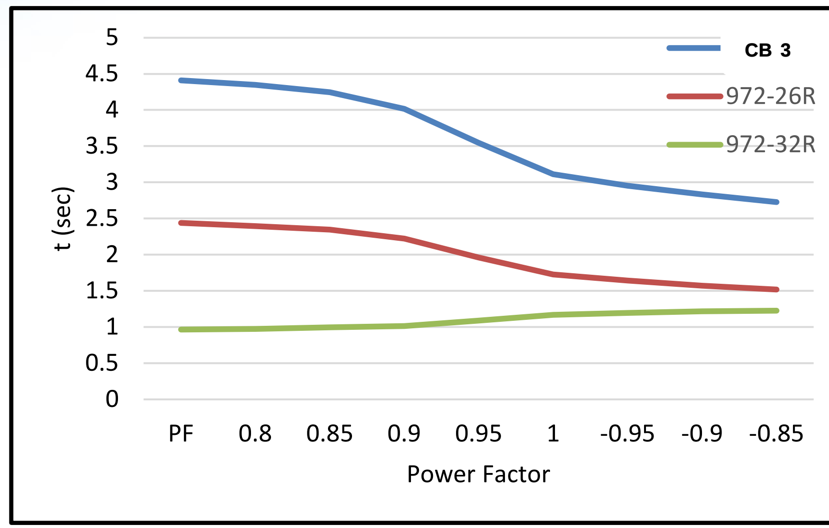
Test Results and Analysis (C 3) – Fault @ Bus 308



PF	TPH Fault				SLG Fault			
	Protective Devices				Protective Devices			
	CB972	972-26R	972-32R	972-30R	CB972	972-26R	972-32R	972-30R
0.80	4.410	2.439	0.963	NO	4.274	1.710	0.857	NO
0.85	4.349	2.396	0.975	NO	3.807	1.710	0.857	NO
0.90	4.246	2.345	0.997	NO	3.668	1.434	0.873	NO
0.95	4.015	2.223	1.013	NO	3.179	1.447	0.887	NO
1.00	3.544	1.959	1.087	NO	2.200	1.460	0.931	NO
–0.95	3.112	1.725	1.167	NO	2.192	1.468	0.989	NO
–0.90	2.951	1.642	1.196	NO	2.187	1.469	1.001	NO
–0.85	2.832	1.573	1.219	NO	2.208	1.489	1.011	NO
–0.80	2.726	1.520	1.224	NO	2.187	1.474	1.033	NO

Relay operation time (sec) for a TPH & SLG faults at Bus 308



Relay operation time (sec) for a TPH fault at Bus 308

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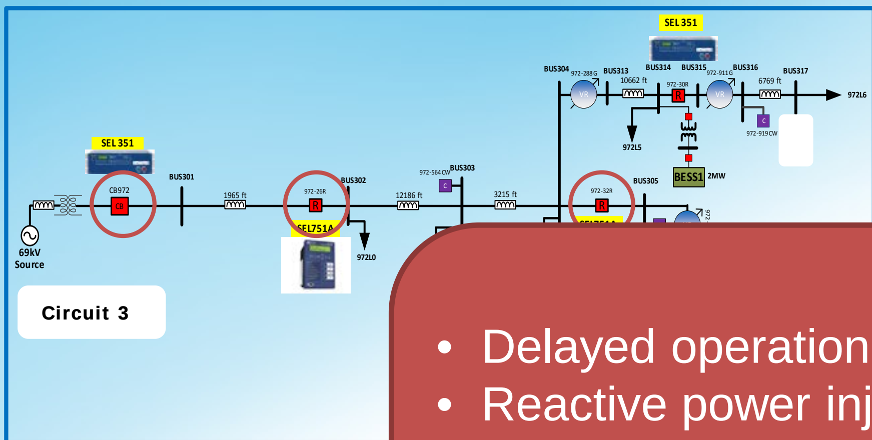
Test Results and Analysis (C 3) – Fault @ Bus 308



- Delayed operation of upstream relays
- Reactive power injection during the fault will intensify the situation.
- The results for TPH and SLG faults follow the same trend.
- No major mis-coordination was observed.

PF	TPH Fault							
	Protective Devices							
	CB972	972-26R	972-32R					
0.80	4.410	2.439	0.963					
0.85	4.349	2.396	0.975					
0.90	4.246	2.345	0.997					
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–0.95	3.112	1.725	1.167					
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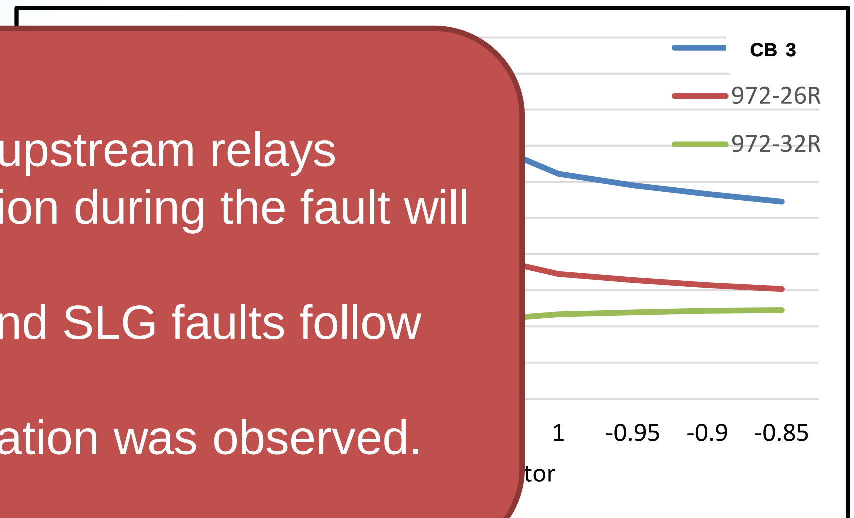
–0.85	2.832	1.573	1.219	NO	2.208	1.489	1.011	NO
–0.80	2.726	1.520	1.224	NO	2.187	1.474	1.033	NO

Relay operation time (sec) for a TPH & SLG faults at Bus 308



a TPH fault at Bus 308

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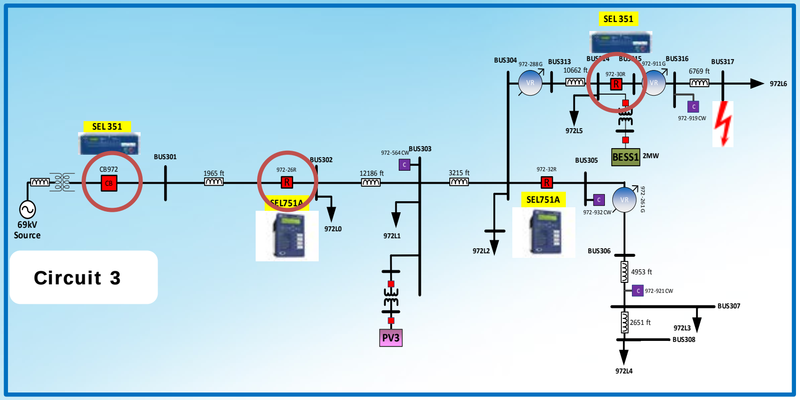
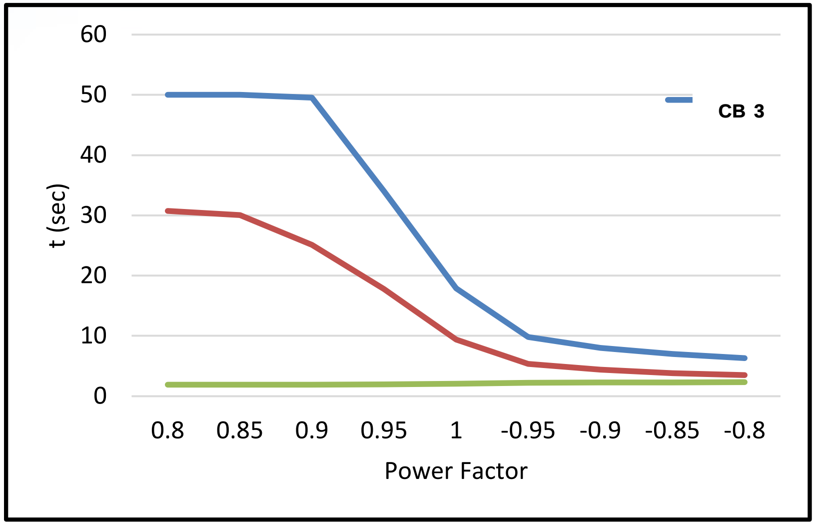
Test Results and Analysis (C 3) – Fault @ Bus 317



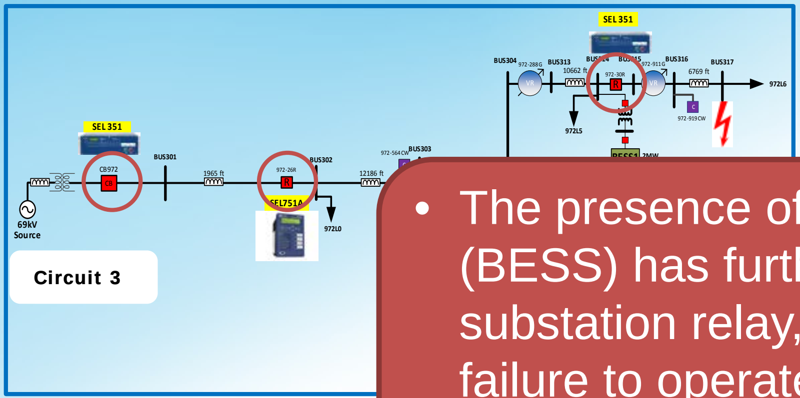
PF	TPH Fault				SLG Fault			
	Protective Devices				Protective Devices			
	CB972	972-26R	972-32R	972-30R	CB972	972-26R	972-32R	972-30R
0.80	NO	30.710	NO	1.874	16.377	4.072	NO	2.283
0.85	NO	30.070	NO	1.883	12.332	4.039	NO	2.271
0.90	49.520	25.120	NO	1.916	9.524	4.178	NO	2.337
0.95	34.010	17.780	NO	1.948	6.435	4.128	NO	2.361
1.00	17.890	9.368	NO	2.056	6.271	4.016	NO	2.436
–0.95	9.809	5.332	NO	2.221	5.714	3.717	NO	2.622
–0.90	8.032	4.382	NO	2.288	5.526	3.665	NO	2.698
–0.85	7.021	3.826	NO	2.280	5.336	3.567	NO	2.671
–0.80	6.321	3.475	NO	3.321	5.248	3.536	NO	2.747

Relay operation time (sec) for a TPH & SLG faults at Bus 317

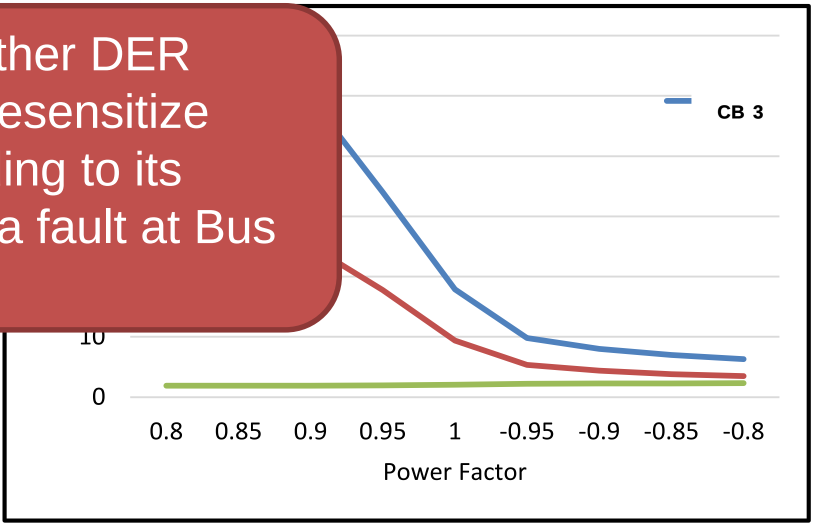


Relay operation time (sec) for a TPH fault at Bus 317

Test Results and Analysis (C 3) – Fault @ Bus 317



- The presence of another DER (BESS) has further desensitize substation relay, leading to its failure to operate for a fault at Bus 317.



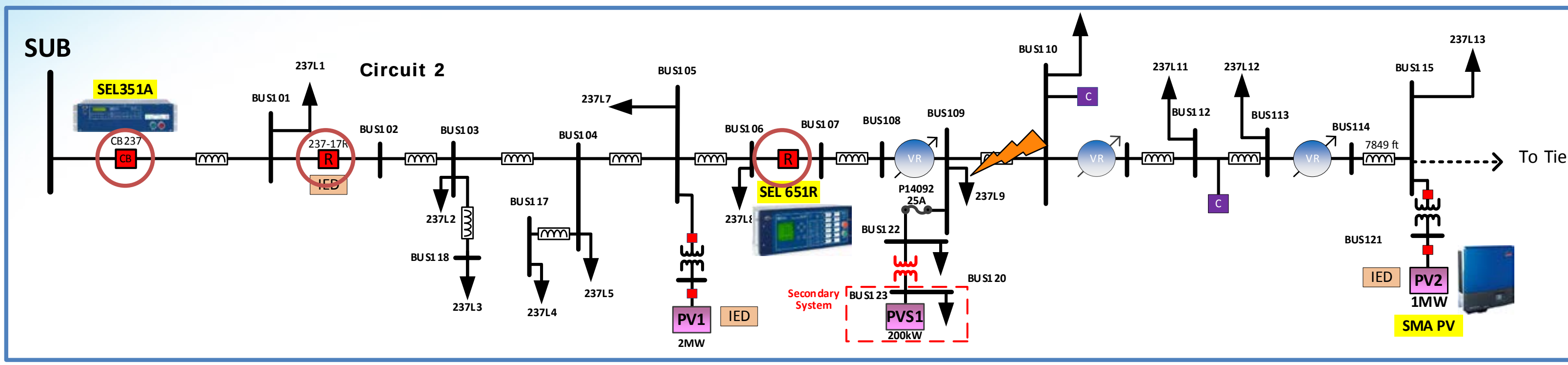
Relay operation time (sec) for a TPH fault at Bus 317

PF	TPH Fault							
	Protective Devices							
	CB972	972-26R	972-32R	972-30R	CB972	972-26R	972-32R	972-30R
0.80	NO	30.710	NO	1.874	16.377	4.072	NO	2.283
0.85	NO	30.070	NO	1.883	12.332	4.039	NO	2.271
0.90	49.520	25.120	NO	1.916	9.524	4.178	NO	2.337
0.95	34.010	17.780	NO	1.948	6.435	4.128	NO	2.361
1.00	17.890	9.368	NO	2.056	6.271	4.016	NO	2.436
–0.95	9.809	5.332	NO	2.221	5.714	3.717	NO	2.622
–0.90	8.032	4.382	NO	2.288	5.526	3.665	NO	2.698
–0.85	7.021	3.826	NO	2.280	5.336	3.567	NO	2.671
–0.80	6.321	3.475	NO	3.321	5.248	3.536	NO	2.747

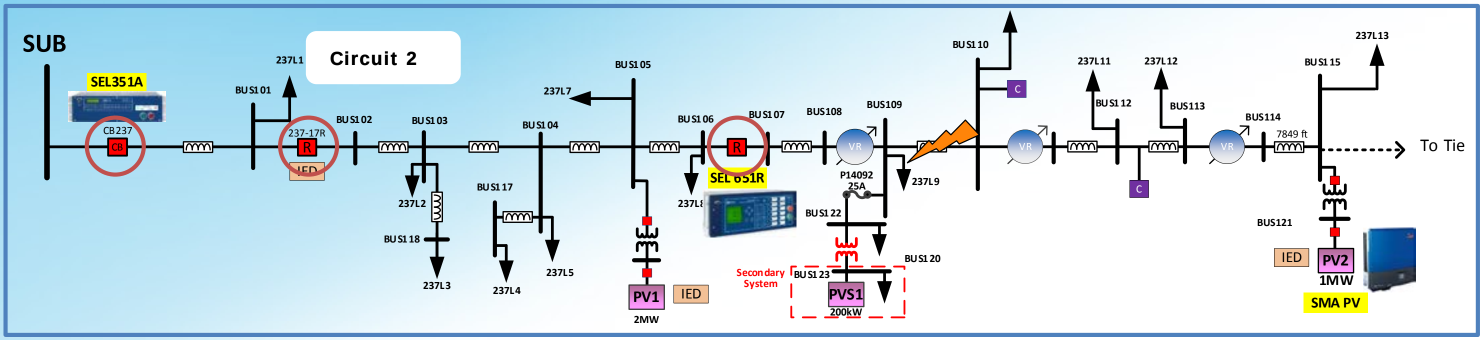
Relay operation time (sec) for a TPH & SLG faults at Bus 317

Test Results and Analysis (C 2) – Fault @ Bus109

- Let us assume that a 10-MW PV system (>100% penetration) is connected to Bus 105 on Circuit 2
- Various reactive power support during the fault (power factor ranging from +0.8 leading/Injecting to –0.8 lagging/absorbing)

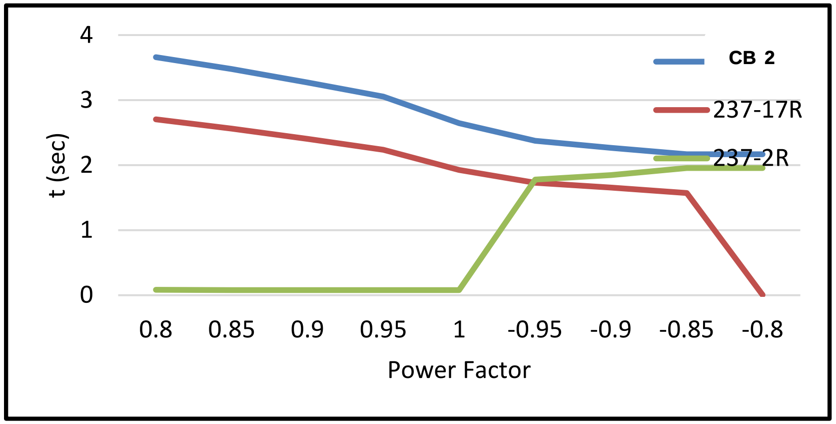


Test Results and Analysis (C 2) – Fault @ Bus 109



<table>
<tr><th rowspan="3">PF</th><th colspan="4">TPH Fault</th><th colspan="4">SLG Fault</th></tr>
<tr><th colspan="4">Protective Devices</th><th colspan="4">Protective Devices</th></tr>
<tr><th>CB273</th><th>237-17R</th><th>237-2R</th><th>Fuse</th><th>CB273</th><th>237-17R</th><th>237-2R</th><th>Fuse</th></tr>
<tr><td>0.80</td><td>3.662</td><td>2.706</td><td>0.083</td><td>NO</td><td>2.412</td><td>0.743</td><td>0.078</td><td>NO</td></tr>
<tr><td>0.85</td><td>3.480</td><td>2.561</td><td>0.077</td><td>NO</td><td>2.421</td><td>0.750</td><td>0.077</td><td>NO</td></tr>
<tr><td>0.90</td><td>3.275</td><td>2.403</td><td>0.077</td><td>NO</td><td>2.460</td><td>0.779</td><td>0.079</td><td>NO</td></tr>
<tr><td>0.95</td><td>3.055</td><td>2.238</td><td>0.077</td><td>NO</td><td>2.465</td><td>0.783</td><td>0.081</td><td>NO</td></tr>
<tr><td>1.00</td><td>2.646</td><td>1.928</td><td>0.077</td><td>NO</td><td>2.478</td><td>0.805</td><td>0.081</td><td>NO</td></tr>
<tr><td>–0.95</td><td>2.373</td><td>1.728</td><td>1.779</td><td>NO</td><td>2.628</td><td>0.845</td><td>0.081</td><td>NO</td></tr>
<tr><td>–0.90</td><td>2.266</td><td>1.653</td><td>1.847</td><td>NO</td><td>2.748</td><td>0.859</td><td>0.079</td><td>NO</td></tr>
<tr><td>–0.85</td><td>2.166</td><td>1.573</td><td>1.957</td><td>NO</td><td>2.748</td><td>0.859</td><td>0.096</td><td>NO</td></tr>
<tr><td>-0.80</td><td>2.166</td><td>0.004</td><td>1.957</td><td>NO</td><td>2.748</td><td>0.008</td><td>0.286</td><td>NO</td></tr>
</table>

Relay operation time (sec) for a TPH & SLG faults at Bus 109



Relay operation time (sec) for a TPH fault at Bus 109

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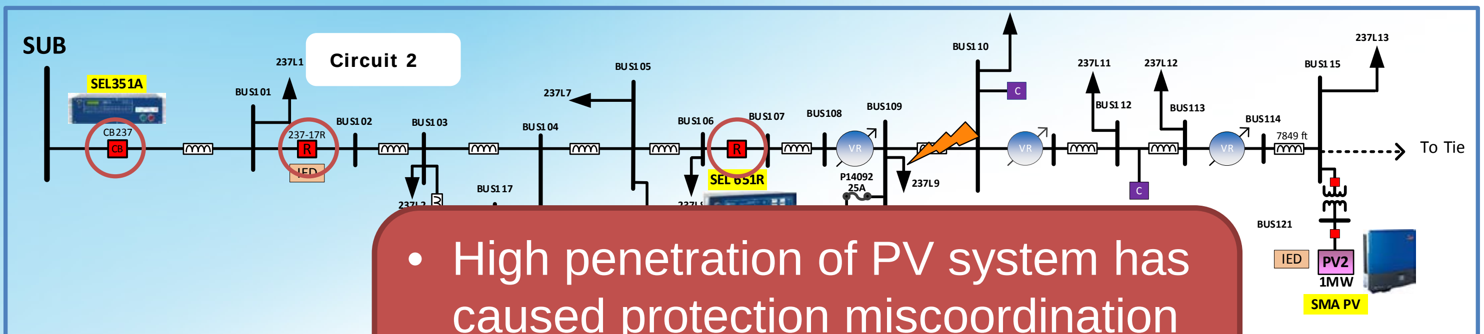
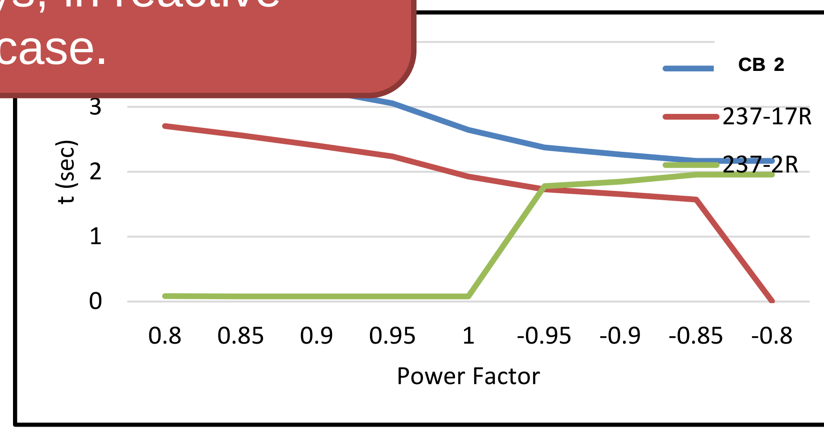
Test Results and Analysis (C 2) – Fault @ Bus 109



- High penetration of PV system has caused protection miscoordination between two relays, in reactive power absorbing case.

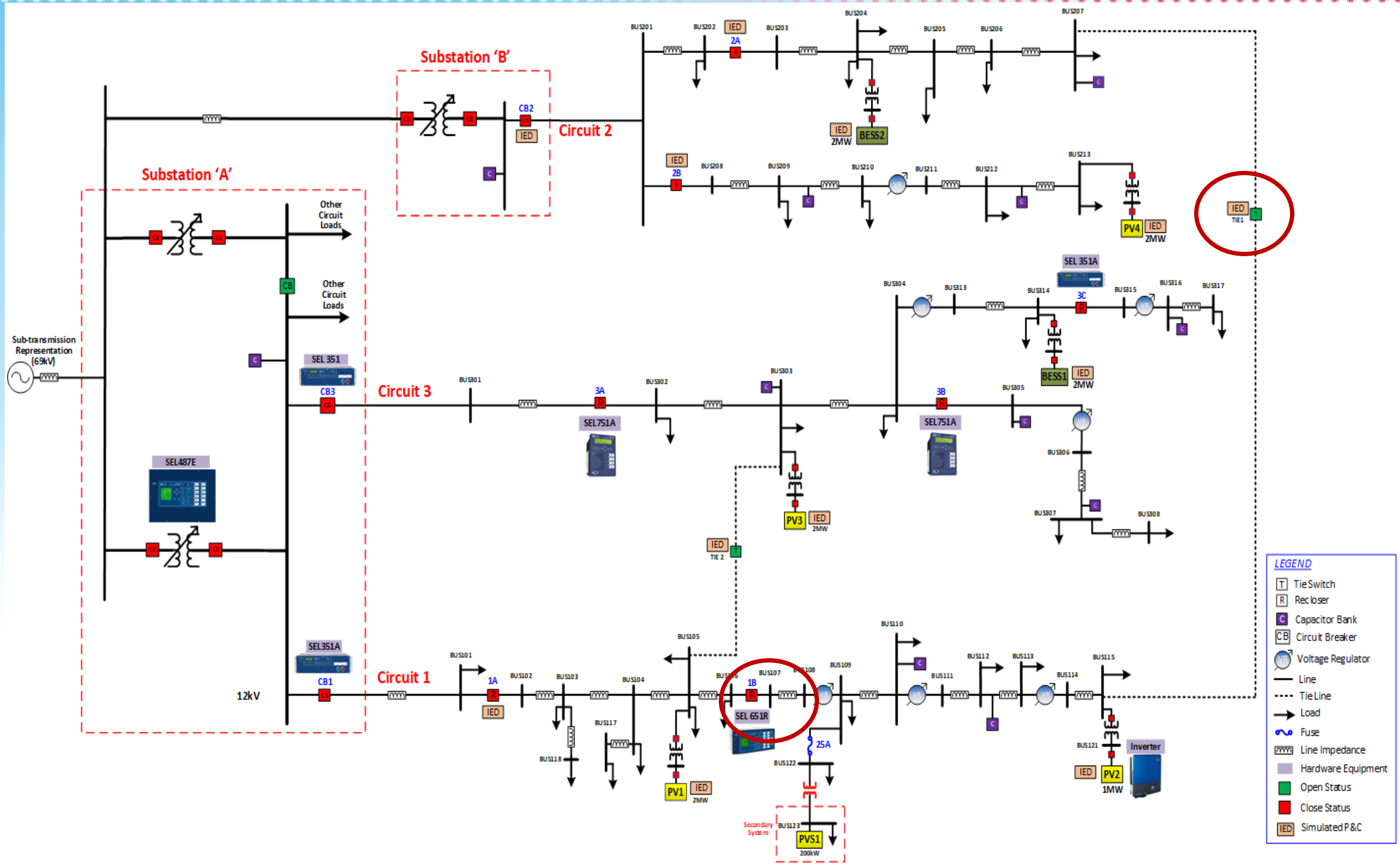
PF	TPH Fault							
	Protective Devices							
	CB273	237-17R	237-2R	Fuse	CB273	237-17R	237-2R	Fuse
0.80	3.662	2.706	0.083	NO	2.412	0.743	0.078	NO
0.85	3.480	2.561	0.077	NO	2.421	0.750	0.077	NO
0.90	3.275	2.403	0.077	NO	2.460	0.779	0.079	NO
0.95	3.055	2.238	0.077	NO	2.465	0.783	0.081	NO
1.00	2.646	1.928	0.077	NO	2.478	0.805	0.081	NO
–0.95	2.373	1.728	1.779	NO	2.628	0.845	0.081	NO
–0.90	2.266	1.653	1.847	NO	2.748	0.859	0.079	NO
–0.85	2.166	1.573	1.957	NO	2.748	0.859	0.096	NO
-0.80	2.166	0.004	1.957	NO	2.748	0.008	0.286	NO

Relay operation time (sec) for a TPH & SLG faults at Bus 109



Relay operation time (sec) for a TPH fault at Bus 109

Test Results and Analysis (circuit reconfiguration)



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Test Results and Analysis (circuit reconfiguration)

Circuit	Fault Loc.	TPH Fault			SLG Fault		
		Protective Devices			Protective Devices		
		CB222	**222-1370R**	**222-1364R**	**CB222**	**222-1370R**	**222-1364R**
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							
		CB222	**222-1370R**	**222-1364R**	**CB222**	**222-1370R**	**222-1364R**
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
	113	1.0	13.0	NO	45.2	78.7	NO

Test Results and Analysis (circuit reconfiguration)

Circuit	Fault Loc	TPH Fault			SLG Fault		
							1364R
C2	107						NO
	109						NO
	111						NO
	113						NO
							1364R
C2	107						NO
	109						NO
	111						NO
	113						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
	113	1.0	13.0	NO	45.2	78.7	NO

- Transfer of PV system (caused by circuit reconfiguration) has increased relay operating times (but no major mis-coordination case).
- All possible configuration needs to be studied.
- High PV penetration may necessitate revisiting existing utility automation practices.

Summaries and Recommendations

- For practical penetration limits of PV penetration (<50%), no significant impacts on the protection coordination of SDG&E distribution system were observed.
- The presence of a PV system on a feeder reduces the fault current contribution at the head end of the feeder , leading to the delayed operation of the substation circuit breaker.
- The grid fault current contribution is a function of the PV size, PV location, PV fault current capacity, and PV control modes.
- Analysis of test results shows that reactive power support of the inverter (during the fault) plays a role in the relay operating time.
- The impact of PV systems on protection coordination is minimized when the pre-fault inverter power factor setpoint is unity.

Summaries and Recommendations

- Performance of the SDG&E protection system is not likely to be significantly impacted after circuit reconfigurations.
- Delayed operation of PV protection system can cause automatic reclosing failure as well as miscoordination for faults within the PV protection zone.
- More to consider protection and automation design of circuits with high DER penetration:
  - Inverter Ride-Through Capability and Control
  - Reverse Fault Current
  - Protection Desensitization
  - Out-of-Phase Reclosing
  - Distribution Automation Considerations with PV Systems
  - Adaptive Settings

Thank you for your attention!

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