Model-Based Integrated High Penetration Renewables Planning and Control Analysis

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- Model-Based Integrated High Penetration Renewables Planning and Control Analysis
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- Contributors
  - Pepco Holdings, Inc
  - Electrical Distribution Design, Inc
  - Clean Power Research
  - Center for Energy, Economic & Environmental Policy (CEEEP), Rutgers University
  - New Jersey Board of Public Utilities

SunShot U.S. Department of Energy

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Introduction

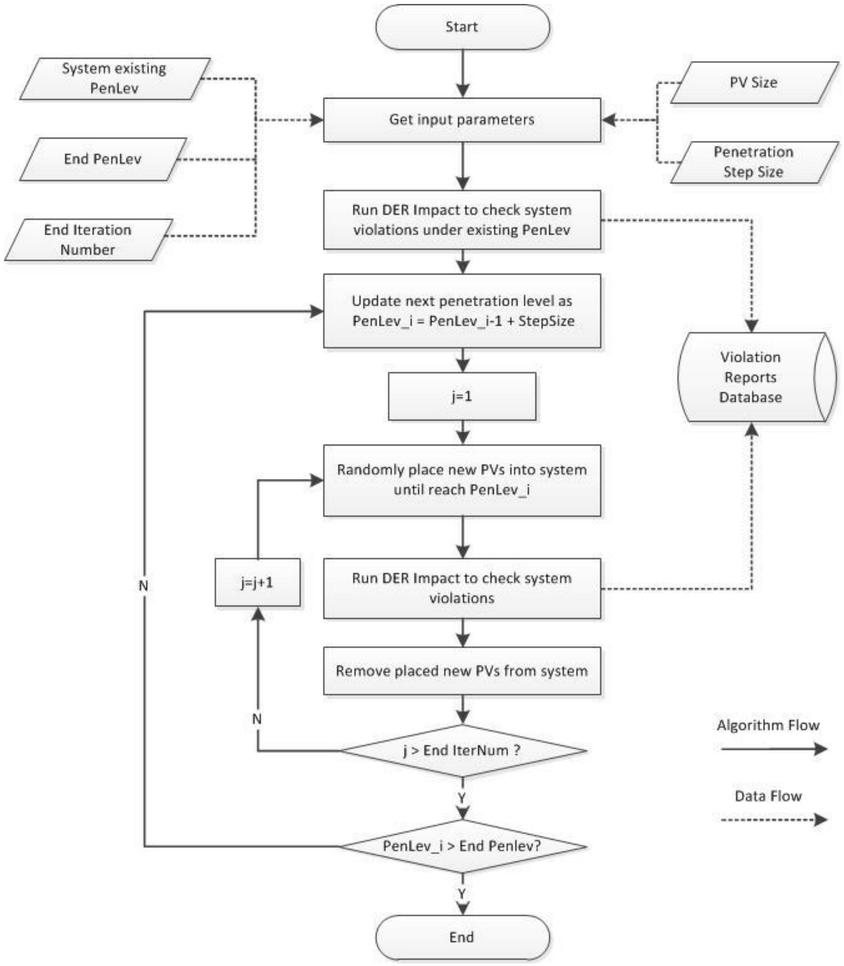
- The proposal was put together to address several identified industry needs :
  - Many customers with PV, tend to export during times of low native load and can raise voltage at their premise, sometimes over 126V on a 120V base, and now need “Voltage Headroom”
  - High penetration feeders and feeder sections are starting to exhibit violations such as high voltage. There are a number of optimization and control setting changes that could provide the means to increase hosting capacity at a reasonable cost. These needed to be studied and the cost/benefit of using these approaches published
  - Real time optimized control of feeder equipment can impact Hosting Capacity, so one goal was to test dynamically adjusting Voltage Regulator and Inverter settings to see the impact on Hosting Capacity
  - A voltage drop/rise tool is needed for reviewing voltage rise between the feeder and meter, especially when multiple PV systems are attached to a single line transformer.

Hosting Capacity Study Overview

- Twenty distribution feeders selected from PEPCO's service territory
- A hosting capacity study was performed on each feeder to determine how much additional PV it could support in its current configuration
- Several improvements were performed on these circuits. After each one the hosting capacity of the circuit was reevaluated in order to determine the impact on the amount of PV that could be hosted
- A cost benefit analysis was performed in order to evaluate the expected costs of each feeder improvement and how each one was able to increase the hosting capacity of each feeder
- It is hoped that these results can be generalized by PEPCO and other distribution utilities in order to understand how they can improve the hosting capacity of their feeders and facilitate the deployment of more PV generation at the distribution level

Hosting Capacity Analysis

- Place new PV sites at randomly selected customers on the circuit in order to satisfy the PV Penetration level under test.
- Once the PV is placed the circuit is tested for violations such as over/under voltage and overloads, flicker sensitivity, reverse flows (see table on next slide for full list of violations tested).
- This random placement process is repeated a number of times for each penetration level in order to build a stochastic set of results.
- Steps to the next PV Penetration Level and repeats the random placement and violation testing process
- The user is able to specify PV penetration levels to test, the size of the placed PV sites, the violations to check for and the number of placement iterations.



Hosting Capacity Violations

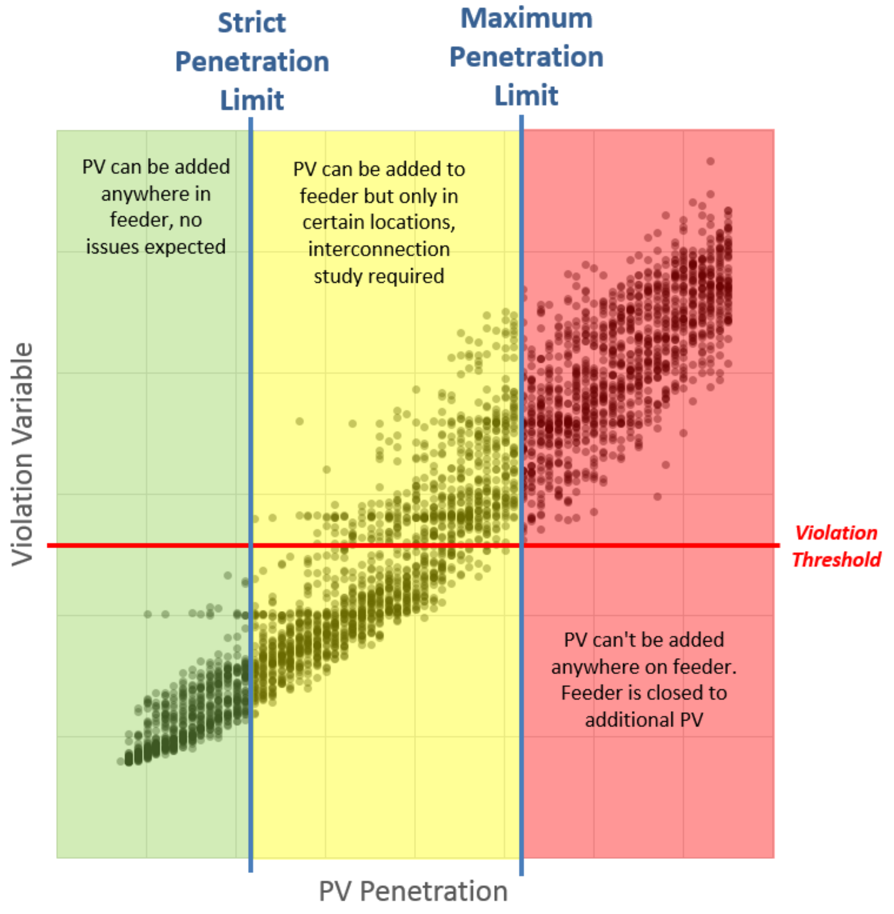
Violation Variable	Comparison	Threshold	Units	Comment
Customer Level Overvoltage (Steady-State)	>	123.5	Volts	Secondary
Customer Level Undervoltage (Steady-State)	<	116.5	Volts	Secondary
Line Transformer Overvoltage (Steady-State)	>	123.5	Volts	Primary
Line Transformer Undervoltage (Steady-State)	<	116.5	Volts	Primary
Line Transformer Temporary Overvoltage (During PV output Change)	>	126	Volts	Primary
Line Transformer Temporary Undervoltage (During PV output Change)	<	114	Volts	Primary
Generator POI Overvoltage (Steady-State)	>	126	Volts	at POI
Generator POI Undervoltage (Steady-State)	<	114	Volts	at POI
Generator POI Temporary Overvoltage (During PV output Change)	>	126	Volts	at POI
Generator POI Temporary Undervoltage (During PV output Change)	<	114	Volts	at POI
Generator POI Flicker Sensitivity (Irritability - PV Step Up)	>	2	Volts	at POI
Generator POI Flicker Sensitivity (Irritability - PV Step Down)	>	2	Volts	at POI
Voltage Change at Voltage Controller (During PV output Change)	>	1/2 BW	Volts	at Vreg or Cap
Voltage Regulator Reverse Flow	<	-0.1	kW	Reverse Power
Protective Device Reverse Flow	<	-0.1	kW	Reverse Power
Feeder Reverse Flow	<	-0.1	kW	Reverse Power
Feeder Current Imbalance	>	20	%	
Component Voltage Imbalance	>	3	%	
Component Overload	>	100	%	

PV output step change used for analysis: 100% - 20% on all PV sites (% of clear sky output)

Analysis performed at time point with maximum generation / load ratio

PV Penetration Limits

- Each point corresponds to one random placement of PV satisfying the PV Penetration on the Horizontal axis
- Vertical position of each point is the highest observed violation value for that placement of PV
- If the point falls above the violation threshold it represents a placement of PV which results in an issue on the circuit
- The ***Strict Penetration Limit*** occurs at the point below which all tested random placements are under the violation threshold
- The ***Maximum Penetration Limit*** occurs at the point past which all tested random placements are above the violation threshold



Feeder Improvements

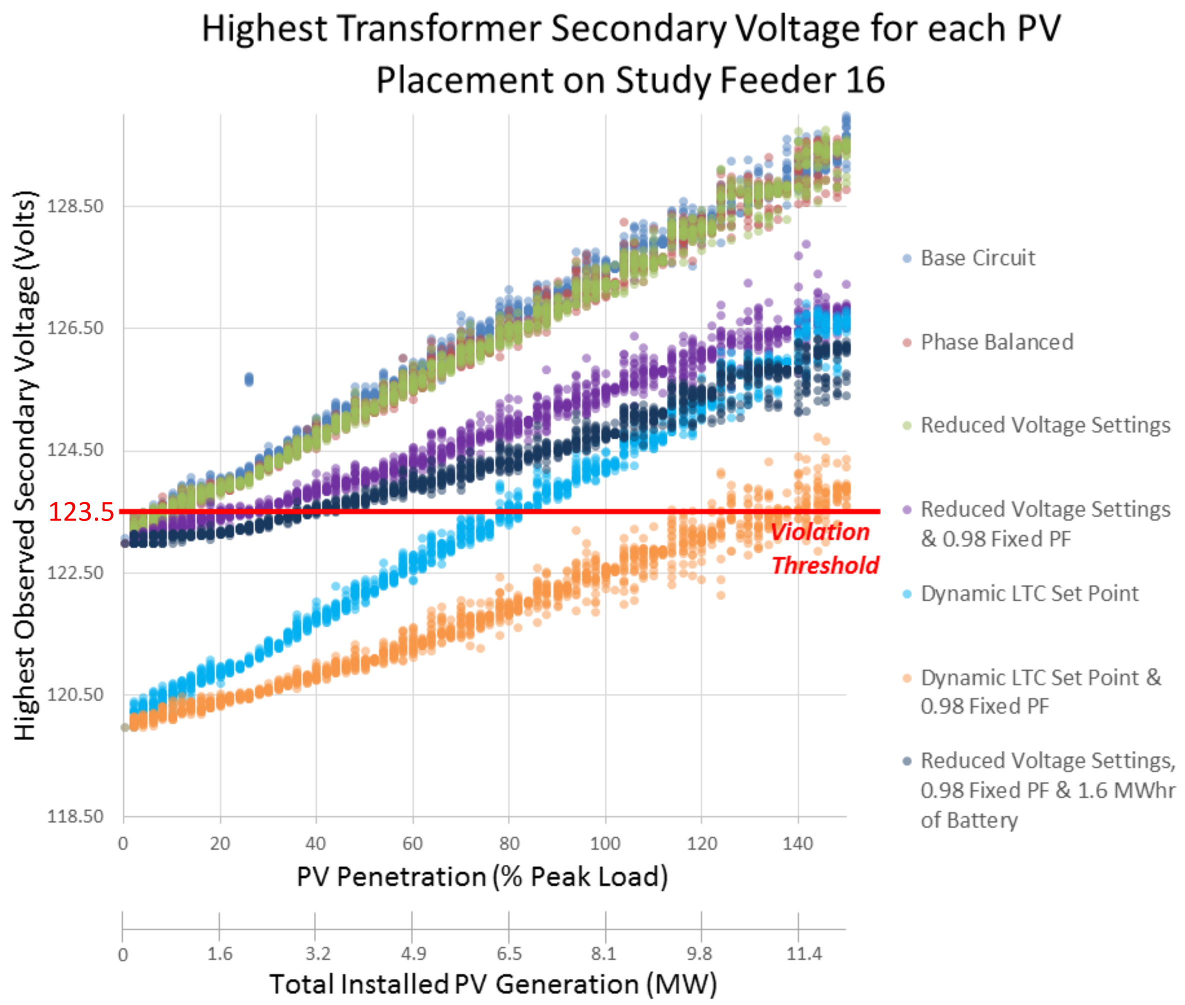
- ***Base***: circuit as-is (existing PV included)
- ***Balanced***: phase balancing performed on the base case
- ***Capacitor Design***: moves existing or places additional capacitors in order to flatten feeder voltage profile and optimize the capacitor placement
- ***Reduced Voltage Settings***: voltage regulation and LTC set-points lowered as far as possible while still maintaining acceptable customer voltages at peak load.
- ***Dynamic Voltage Control***: voltage regulation and LTC set-points are adjusted over time to be as low as possible while still maintaining acceptable customer voltages at each time point (i.e. using FSMA tool to determine optimal Vreg settings over time).
- ***Fixed PF***: power factor of randomly placed inverters are set to a fixed, absorbing power factor of 0.98. Existing PV sites are unmodified (i.e. all new PV on feeder required to operate at 0.98 absorbing).
- ***Battery Storage***: battery storage in a daily charge/discharge schedule is added to circuit in order to add effective load at peak PV production times.

Example Feeder (Study Feeder 16)

- Contains newer 34.5 kV primary out of sub and on most of backbone, also has several areas of older 4.15 kV primary connected through step transformers
- One of the longer feeders in the study, three voltage regulation zones (plus sub LTC), four voltage controlled switched cap banks, one fixed cap bank
- Poor voltage regulation on the 4.15 kV sections and phase imbalances limit the PV penetration of base circuit to about **6%**, limited by customer steady-state high voltages

Study Feeder 16 Summary	
Feeder Type	Res
Primary Voltage	34.5 kV Y-G and 4.15 kV Y-G
Feeder Length (total circuit miles)	64 mi
Distance from Sub to Furthest Load	12.8 mi
Peak Load (SCADA)	8.1 MW
Minimum Daytime Load (SCADA)	2.4 MW
Number of Distribution Transformers	331
Connected KVA (total xfrmr rating)	65 MVA
Number of Capacitor Banks	5
Total Capacitor Bank Rating	7.8 MVAR
Number of Voltage Regulation Zones	3
Number of Existing PV Sites	2
Total Existing PV Generation	15 kW
Existing PV Penetration	< 1%

Example Feeder (Study Feeder 16)



Example Feeder (Study Feeder 16)

Study Feeder 16 Hosting Capacity Violations Summary

Violation Type	Base Circuit		Phase Balanced		Phase Balanced & Reduced Voltage Settings		Phase Balanced, Reduced Voltage Settings & Fixed PF		Phase Balanced & Dynamic Voltage Control		Phase Balanced, Dynamic Voltage Control & Fixed PF		Phase Balanced, Reduced Voltage Settings, Fixed PF & Battery Storage	
	Strict Pen Limit	Max Pen Limit	Strict Pen Limit	Max Pen Limit	Strict Pen Limit	Max Pen Limit	Strict Pen Limit	Max Pen Limit	Strict Pen Limit	Max Pen Limit	Strict Pen Limit	Max Pen Limit	Strict Pen Limit	Max Pen Limit
Line Xfrm Steady-State Overvoltage	25.9	41.9	35.9	41.9	40.0	47.9	60.0	75.8	119.7	135.7	171.9	217.8	85.8	111.9
Line Xfrm Steady-State Undervoltage														
Customer Steady-State Overvoltage	5.9	12.0	5.9	14.0	3.9	14.0	17.9	30.0	78.0	83.8	113.7	135.7	35.9	52.0
Customer Steady-State Undervoltage									269.7					
Voltage Regulator Reverse Flow	2.0	12.0	2.0	8.0	2.0	10.0	2.0	10.0	2.0	8.0	2.0	10.0	2.0	10.0
Feeder Reverse Flow	22.0	24.0	25.9	28.0	25.9	28.0	25.9	28.0	25.9	28.0	25.9	28.0	30.0	31.9
Protective Device Reverse Flow	3.9	12.0	2.0	14.0	2.0	14.0	2.0	12.0	2.0	12.0	2.0	12.0	3.9	14.0
Feeder Imbalance	0.2	2.0	8.0	22.0	8.0	24.0	8.0	20.0	8.0	22.0	5.9	20.0	14.0	24.0
Gen POI Steady-State Overvoltage	70.0	87.7	78.0	97.7	70.0	91.9	105.8	153.8	153.8	179.5	229.4	259.5	149.8	179.5
Gen POI Steady-State Undervoltage														
Gen POI Step Change Temp Overvoltage														
Gen POI Step Change Temp Undervoltage														
Generator POI Flicker Sensitivity (Irritability - Step Change)	53.9	61.9	47.9	57.9	47.9	52.0	63.9	73.9	47.9	52.0	63.9	75.8	57.9	75.8
Line Xfrm Temp Overvoltage Gen Step Change														
Line Xfrm Temp Undervoltage Gen Step Change														
Controller Temp % Bandwidth Change	103.7	121.9	116.0	133.7	113.7	135.7	181.9	239.6	113.7	135.7	181.9	239.6	185.5	261.9
Imbalance of Any Bus (CustVImbal%Max)	199.4	239.6	265.3		293.7		243.6		269.7		209.9		297.6	
Overload	85.8	90.0	85.8	91.9	85.8	91.9	85.8	91.9	85.8	91.9	78.0	83.8	85.8	91.9

Improvement Cost (k$)	0	5	7	7	85	85	451
Vreg Upgrade Cost (k$)	60	60	60	60	82	82	60

*** The capacitor design improvement was not implemented on this feeder as the existing capacitor placement was near optimal*

Penetration Limit Increase Realized by Each Feeder Improvement

Study Feeder	Base Strict Pen Limit (%)	Phase Balancing		Capacitor Redesign		Reduced Voltage		Dynamic Voltage Control		Fixed PF (with Reduced Voltage)		Fixed PF (with Dynamic Voltage)		Battery Storage	
		Strict Limit Inc. (%)	Cost (k$)	Strict Limit Inc. (%)	Cost (k$)	Strict Limit Inc. (%)	Cost (k$)	Strict Limit Inc. (%)	Cost (k$)	Strict Limit Inc. (%)	Cost (k$)	Strict Limit Inc. (%)	Cost (k$)	Strict Limit Inc. (%)	Cost (k$)
1	29.7	0	1.5			64	1.5	138	60	75	0	0	0	0	184
2	27.9	0	2.5	0	10.0	16	0.5	86	20	92	0	83	0	22	283
3	53.6	0	2.0			50	2.0	211	80	10	0	-2	0	0	220
4	34.9	-6	2.0			20	0.5	106	20	4	0	0	0	0	186
5	43.7	0	2.0	0	25.5	18	2.0	79	80	132	0	71	0	0	239
6	38.9	6	1.5	0	57.0	0	0.5	119	20	76	0	56	0	34	358
7	36.9	8	4.0			22	3.0	26	120	26	0	16	0	4	289
8	23.8	0	1.5			38	0.5	73	20	68	0	20	0	12	318
9	1.9	2	1.0			24	0.5	108	20	24	0	49	0	9	270
10	12.8	12	7.5			24	0.5	38	20	4	0	0	0	14	132
11	39	0	2.5	0	28.5	0	1.5	14	80	18	0	8	0	2	275
12	8	0	5.5	0	35.5	0	3.5	0	140	4	0	2	0	0	463
13	2.9	0	3.0			28	2.0	42	80	56	0	60	0	18	298
14	15.9	-1	5.5	0	25.5	3	2.0	1	140	-2	0	0	0		
15	20	2	1.5			18	0.5	46	20	6	0	8	0	20	442
16	5.9	0	5.0			-2	2.0	42	80	14	0	16	0	32	444
17	17	0	2.0	0	28.5	24	0.5	70	20	64	0	4	0	22	558
18	42.9	2	5.0			40	0.5	122	20	90	0	170	0	24	356
19	25.9	2	4.5			24	1.5	30	60	16	0	10	0	6	327
20	44.9	0	2.0			0	0.5	82	20	140	0	-28	0	30	442
Average	26.3	1	3.1	0	30.1	21	1	72	56	46	0	27	0	13	320

Protection and Coordination

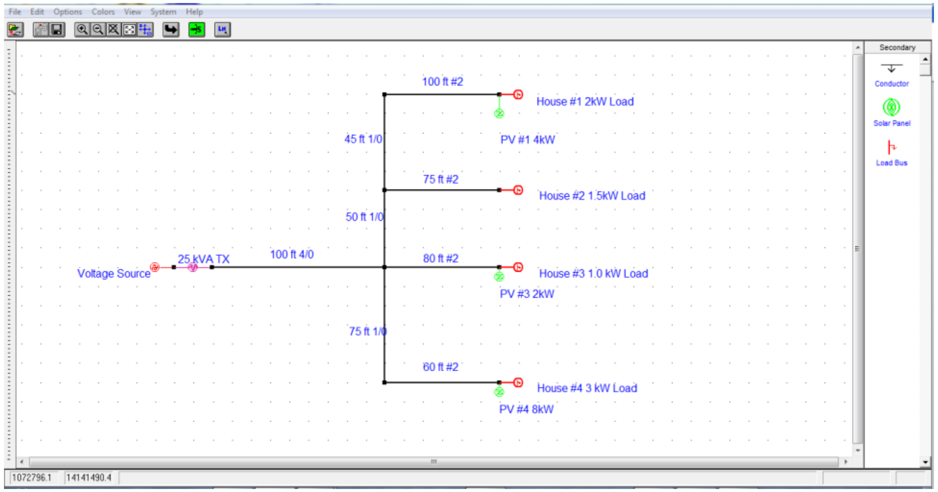
- Protection and coordination studies were performed on feeders 6 and 13
- These studies were performed at the ***maximum*** penetration limit for the battery storage cases, representing worst case scenarios for inverter fault contributions (maximum amount of allowable PV and inverter battery storage)
- Even at these worst case scenarios the inverter fault current was not enough to interfere with existing protection. From these results it can be expected that protection issues will not limit PV deployment lower than the penetration levels determined in the hosting capacity studies.

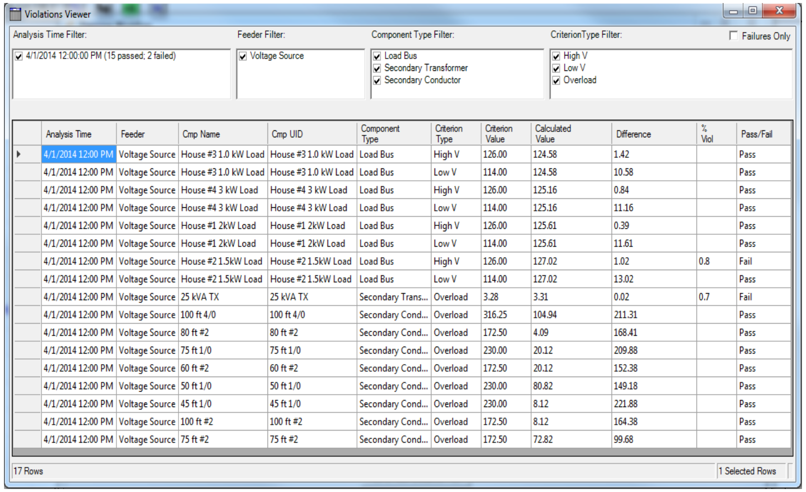
Study Feeder 6 - Maximum Fault Currents

	3PhZ0FA (A)	3PhZ0FA (B)	3PhZ0FA (C)	1PhZ0FA (A)	1PhZ0FA (B)	1PhZ0FA (C)
PV off	9327	9327	9327	9159	9159	9159
PV on	9431	9461	9446	9265	9294	9277
Change	104	134	119	106	135	118
%	1.1	1.4	1.3	1.2	1.5	1.3

Secondary Design Tool

- Standalone application that utilizes a simplified version of EDD's DEW modelling software package. Designed to be used by engineers, technicians, or PV contractors to identify any violations created by attaching PV systems to the secondary/services fed by a single phase distribution transformer.
- The user can modify components in the model such as transformer size, conductor size and length, and PV size to mitigate violations created by adding PV sites at selected locations
- The application is designed to check for the following types of violations:
  - High Voltage – customer voltages greater than 126 volts
  - Low Voltage – customer voltages lower than 114 volts
  - Overload – current flow (amps) in excess of component rating for conductors and transformers





Violations Viewer

Analysis Time Filter: 4/1/2014 12:00:00 PM (15 passed; 2 failed)

Feeder Filter: Voltage Source

Component Type Filter: Load Bus; Secondary Transformer; Secondary Conductor

CriterionType Filter: High V; Low V; Overload

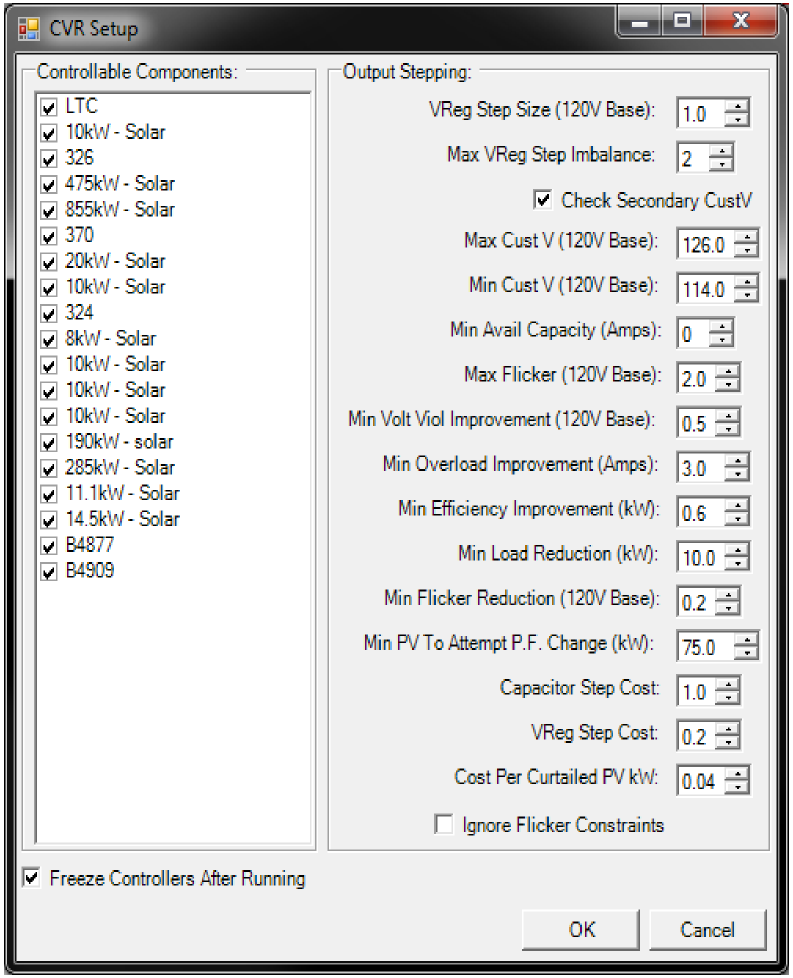
Failures Only

Analysis Time	Feeder	Cmp Name	Cmp UID	Component Type	Criterion Type	Criterion Value	Calculated Value	Difference	% Viol	Pass/Fail
4/1/2014 12:00 PM	Voltage Source	House #3 1.0 kW Load	House #3 1.0 kW Load	Load Bus	High V	126.00	124.58	1.42		Pass
4/1/2014 12:00 PM	Voltage Source	House #3 1.0 kW Load	House #3 1.0 kW Load	Load Bus	Low V	114.00	124.58	10.58		Pass
4/1/2014 12:00 PM	Voltage Source	House #4 3 kW Load	House #4 3 kW Load	Load Bus	High V	126.00	125.16	0.84		Pass
4/1/2014 12:00 PM	Voltage Source	House #4 3 kW Load	House #4 3 kW Load	Load Bus	Low V	114.00	125.16	11.16		Pass
4/1/2014 12:00 PM	Voltage Source	House #1 2kW Load	House #1 2kW Load	Load Bus	High V	126.00	125.61	0.39		Pass
4/1/2014 12:00 PM	Voltage Source	House #1 2kW Load	House #1 2kW Load	Load Bus	Low V	114.00	125.61	11.61		Pass
4/1/2014 12:00 PM	Voltage Source	House #2 1.5kW Load	House #2 1.5kW Load	Load Bus	High V	126.00	127.02	1.02	0.8	Fail
4/1/2014 12:00 PM	Voltage Source	House #2 1.5kW Load	House #2 1.5kW Load	Load Bus	Low V	114.00	127.02	13.02		Pass
4/1/2014 12:00 PM	Voltage Source	25 kVA TX	25 kVA TX	Secondary Trans...	Overload	3.28	3.31	0.02	0.7	Fail
4/1/2014 12:00 PM	Voltage Source	100 ft 4/0	100 ft 4/0	Secondary Cond...	Overload	316.25	104.94	211.31		Pass
4/1/2014 12:00 PM	Voltage Source	80 ft #2	80 ft #2	Secondary Cond...	Overload	172.50	4.09	168.41		Pass
4/1/2014 12:00 PM	Voltage Source	75 ft 1/0	75 ft 1/0	Secondary Cond...	Overload	230.00	20.12	209.88		Pass
4/1/2014 12:00 PM	Voltage Source	60 ft #2	60 ft #2	Secondary Cond...	Overload	172.50	20.12	152.38		Pass
4/1/2014 12:00 PM	Voltage Source	50 ft 1/0	50 ft 1/0	Secondary Cond...	Overload	230.00	80.82	149.18		Pass
4/1/2014 12:00 PM	Voltage Source	45 ft 1/0	45 ft 1/0	Secondary Cond...	Overload	230.00	8.12	221.88		Pass
4/1/2014 12:00 PM	Voltage Source	100 ft #2	100 ft #2	Secondary Cond...	Overload	172.50	8.12	164.38		Pass
4/1/2014 12:00 PM	Voltage Source	75 ft #2	75 ft #2	Secondary Cond...	Overload	172.50	72.82	99.68		Pass

17 Rows — 1 Selected Rows

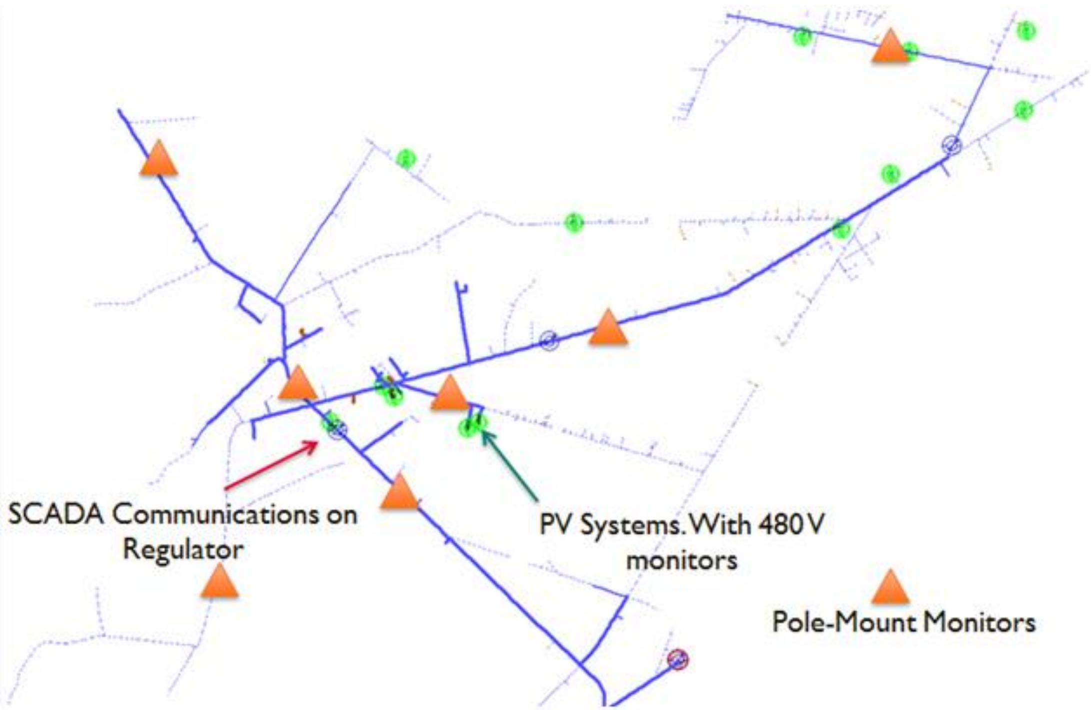
Forecast, Schedule, Monitor, Adjust (FSMA) Tool

- Application within EDD's DEW modelling software package, it is designed to be used for operations monitoring using real-time measurements
- Also can be used for detailed planning analysis using time step simulation that will allow planners to evaluate control device interactions with PV and load changes using historical load measurements, historical PV output data from CPR and NREL, and historical measurements from SCADA
- Inputs all of these measurement sources, attaches the measurement values to a distribution feeder model and to determines optimal voltage regulator, capacitor bank and inverter controller settings in order to maximize a set of user defined objectives while minimizing control costs
- Uses a tabular search to determine the optimal control positions for capacitors, voltage regulating transformers, and solar panel supplying inverters with user-configurable weighting factors

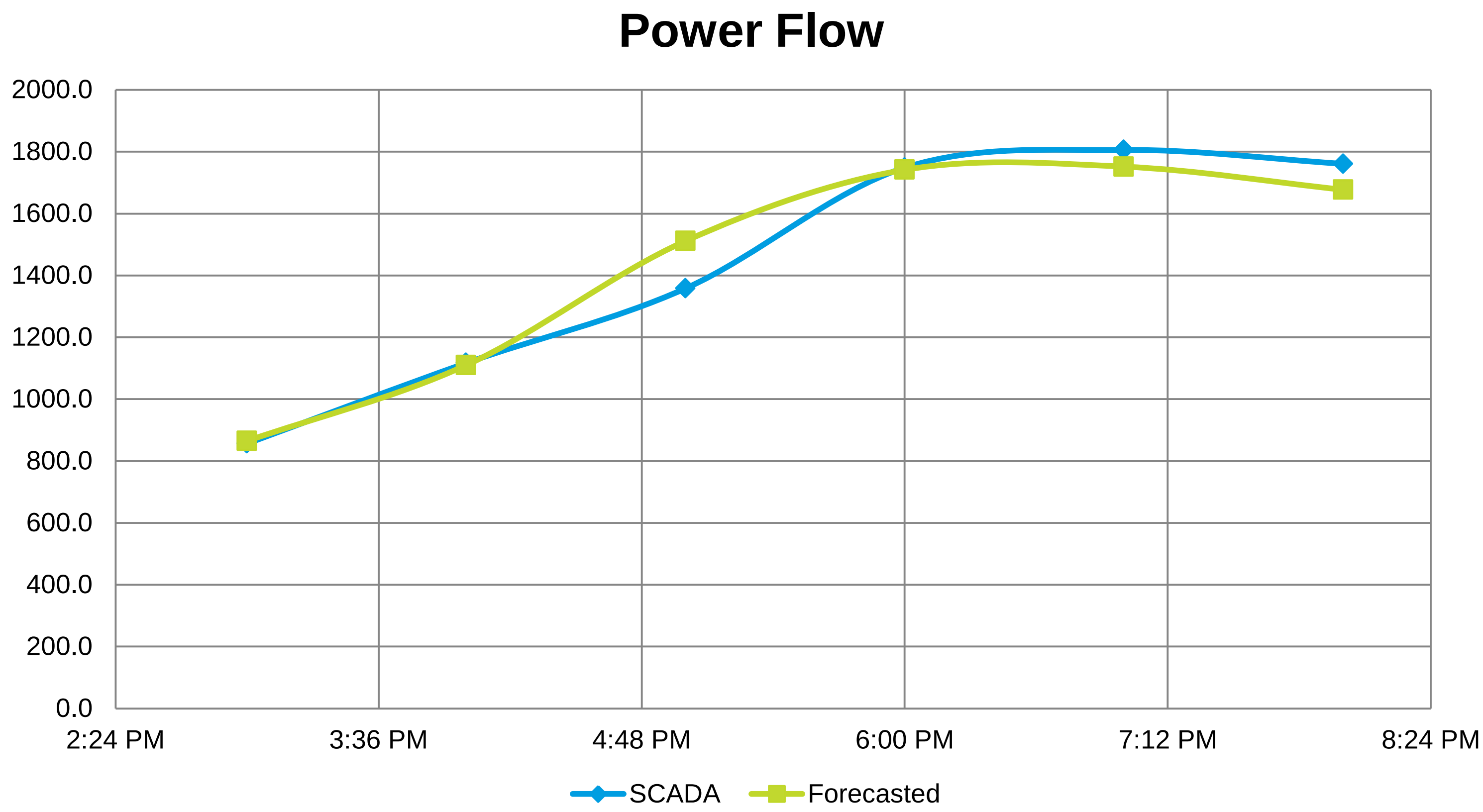


FSMA Demonstration

- Study Feeder 11 - Industrial/Residential circuit with 1.9 MW of PV
- Input real time SCADA data and voltage readings to program (FSMA), implement forecasted values in the field
- Solar output forecast using Clean Power Research data
- Testing was done on relatively sunny days with moderate temperatures

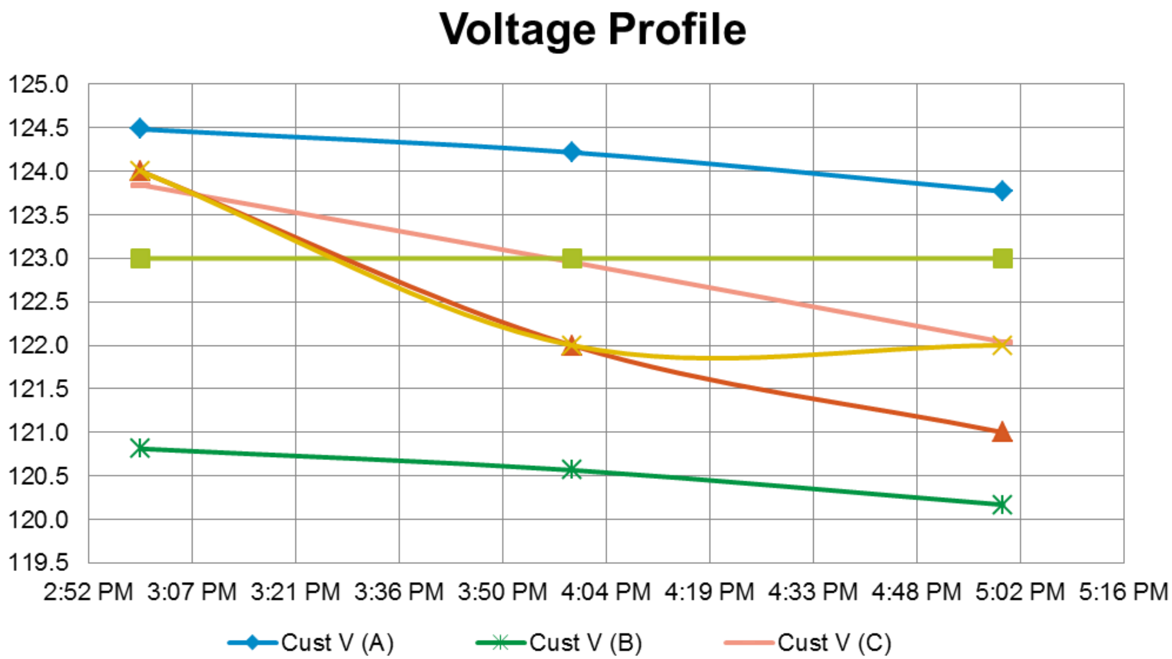


FSMA Demonstration Results



Variable	3:00 PM	4:00 PM	5:00 PM	6:00 PM	7:00 PM	8:00 PM
SCADA	856.5	1117.0	1358.1	1748.6	1805.8	1761.1
Forecasted	864.8	1110.1	1511.6	1741.7	1751.9	1677.3
Margin	0.97%	0.62%	11.30%	0.39%	2.99%	4.75%

FSMA Demonstration Results



Variable	3:00 PM	4:00 PM	5:00 PM
Cust V (A)	124.5	124.2	123.8
Cust V (B)	120.8	120.6	120.2
Cust V (C)	123.8	123.0	122.0
Cust V (A) Actual	123	123	123
Cust V (B) Actual	124	122	121
Cust V (C) Actual	124	122	122
Cust V (A) Margin	1.20%	0.99%	0.62%
Cust V (B) Margin	2.57%	1.18%	0.69%
Cust V (C) Margin	0.13%	0.78%	0.03%

Strict Penetration Limit Increase for Each Feeder

Strict Penetration Limit (Before and After)						
Feeder	Base Case			Max. Penetration w/ Upgrades		
	PV (%)	PV (MW)	Cost (k$)	PV(%)	PV(MW)	Cost(k$)
1	29.7	1.0	0.0	167.9	5.9	60.2
2	29.7	1.5	0.0	197.1	10.4	32.5
3	53.6	2.2	67.9	264.7	10.9	149.3
4	34.9	1.2	0.0	134.5	4.8	22.0
5	43.7	2.0	67.3	193.7	8.7	96.8
6	38.9	2.6	0.0	219.6	14.5	78.5
7	36.9	1.9	0.0	92.7	4.7	131.4
8	23.8	1.4	0.0	129.2	7.6	2.0
9	1.9	0.1	0.0	161.3	8.1	21.0
10	12.8	0.3	0.0	62.9	1.6	27.5
11	39.0	2.0	37.2	61.0	3.1	178.3
12	8.0	0.7	37.2	11.9	1.0	118.7
13	2.9	0.2	0.0	104.9	5.8	150.2
14	15.9	1.5	0.0	18.0	1.7	33.0
15	20.0	1.6	0.0	76.0	6.2	21.5
16	5.9	0.5	59.7	63.9	5.2	167.1
17	17.0	2.0	0.0	104.9	12.1	31.0
18	42.9	2.8	0.0	336.7	22.2	25.0
19	25.9	1.6	74.0	67.8	4.1	80.0
20	44.9	2.7	0.0	184.6	11.0	2.5
AVERAGE	**26.4**	**1.5**	**17.2**	**132.7**	**7.5**	**71.4**

← Minimum (feeder 14)

← Maximum (feeder 18)

Notes: The above does not include battery deployment

The above feeders represent different voltage levels.

Conclusions

- Every feeder is unique and can have a different hosting capacity
- There are a number of methods to leverage existing equipment to increase Hosting Capacity and provide Voltage Head Room
- Phase Balancing shows little direct impact, but it is important to keep the circuit balanced as PV penetration increases
- Dynamic Volt/VAR will take new controls, communications and central logic to run. Some utilities have already implemented Volt/VAR control, may need some new logic
- Smart Inverters have promise but modeling and operation at high penetration levels still poses some unknowns
- Even after dealing with Voltage issues, reverse power on V. Regs., on Power transformers, Distribution Automation Schemes, loading and protection issues will make analysis more complex
- For higher penetration levels on the distribution system, it will be important to keep an eye on the Transmission system