NATIONAL RENEWABLE ENERGY LABORATORY

Analysis of High-Penetration Levels of PV into the Distribution Grid in California:

NREL/SCE High-Penetration PV Grid Integration Project

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Final Project Webinar

December 17th, 2013

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL/SCE Hi-Pen PV Project Motivation

Project Background:

- A total of 500 MW of utility-scale PV will be installed by 2015 in SCE's service territory
- Most are large PV systems (1-5 MW)
- All are connected to the distribution system

Project Motivation:

- The large increase in PV deployment, mostly on the distribution system, is resulting in high-penetration scenarios on many circuits
- Distribution utilities have limited experience with high-penetration PV integration particularly in terms of methods to mitigate impact
- Accelerating and disseminating the experiences gained from high-penetration PV integration on the SCE system to the wider distribution engineering community accelerates the rate of PV interconnection in a safe, reliable and cost-effective manner

Project Objectives and Approach

Project Objectives:

- Model the impacts of high-penetration PV integration on real distribution circuits, validate PV impacts using field data and develop mitigation strategies to reduce PV related impact
- Improve PV impact modeling capabilities using experience/data gained within the project
- Demonstrate via field deployment the ability of PV inverters to implement advanced functionality to mitigate the impacts of high-penetration PV integration

Project Approach:

- Task 1 – Distribution system assessment
  - Select circuits to study/use for demonstration
- Task 2 – Modeling and Simulation
  - Develop validated models of study circuits, use validated models to develop mitigation strategies, and model PV impacts for many scenarios (assessment)
- Task 3 – Lab Testing
  - Test advanced PV inverter functionality prior to deployment, address PV impacts/concerns not covered by modeling
- Task 4 – Field Testing and Verification
  - Evaluate in the field PV inverters ability to mitigate PV impacts
  - Deploy data acquisition systems to collect data for validation and quantification of PV impact
- Task 5 – Results Dissemination
  - Annual project reports
- Task 6 – Project Management

Project Organization

SOUTHERN CALIFORNIA EDISON
An EDISON INTERNATIONAL® Company

- Utility partner and advisor
- Prime contractor

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

- Project task leader/PI
- Leads field demonstration, data acquisition, lab testing and results dissemination efforts
- Coordinates and contributes to other tasks

QUANTA TECHNOLOGY

- Distribution system assessment
- Interface with SCE for models and data
- Coordinates data acquisition installation
- Leads empirical modeling efforts

edd

- Leads distribution system modeling
- PV impact assessment
- Develop recommendations for PV impact mitigation methods
- Circuit validation

Other Collaborators

Satcon

CLEAN POWER® RESEARCH

SCE Solar Photovoltaic Program (SPVP) Overview

12/17/13

Sunil Shah

Southern California Edison

SPVP Original Vision

- To transform the PV market - 6/2009
- 250 MW Utility owned generation (UOG)
  - 1-2 MW on commercial warehouse rooftops
  - 50 MW / year with an average cost of $3.97/watt
- 250 MW PPAs IPP PV Solicitation
  - 50 MW / year for up to 5 years
  - Price capped at utility LOCE, 26c/kWH
- 10% of MW may be ground mounted

SPVP Changes

- First reduction in deployment to 125MW UOG/125 MW IPP
- Second reduction settled at 91 MW UOG
- 250 MW IPP would be created with less restrictions
  - Increase ground-mount allotment
- Primary driver being customer savings of $300M

SPVP Today

- 91 MW online UOG
- Across 22 rooftops and 1 ground-mount
  - NREL HPPV: Porterville & Fontana sites
- Program officially set to close YE 2013
- 10 MWdc Dexus site in Perris, CA – largest single rooftop in the US

SPVP 042 – Porterville

6.77 MWdc - 29,428

Trina Modules

33 acres

10 Satcon Inverters

SPVP 007 - PLD Redlands 3

3.20 MWdc - 10,840

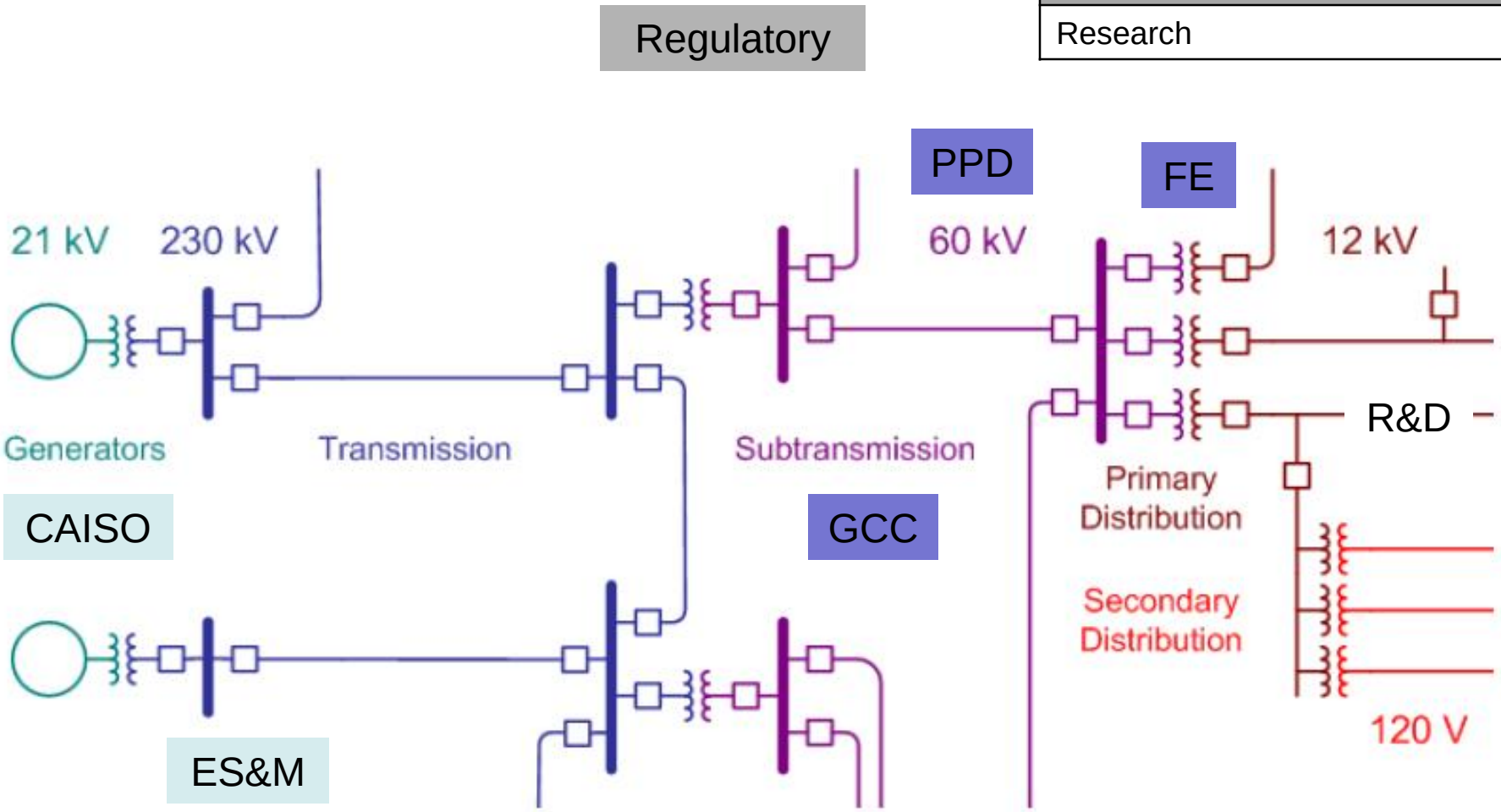
SunPower Modules

446,000 Square ft.

5 Satcon Inverters

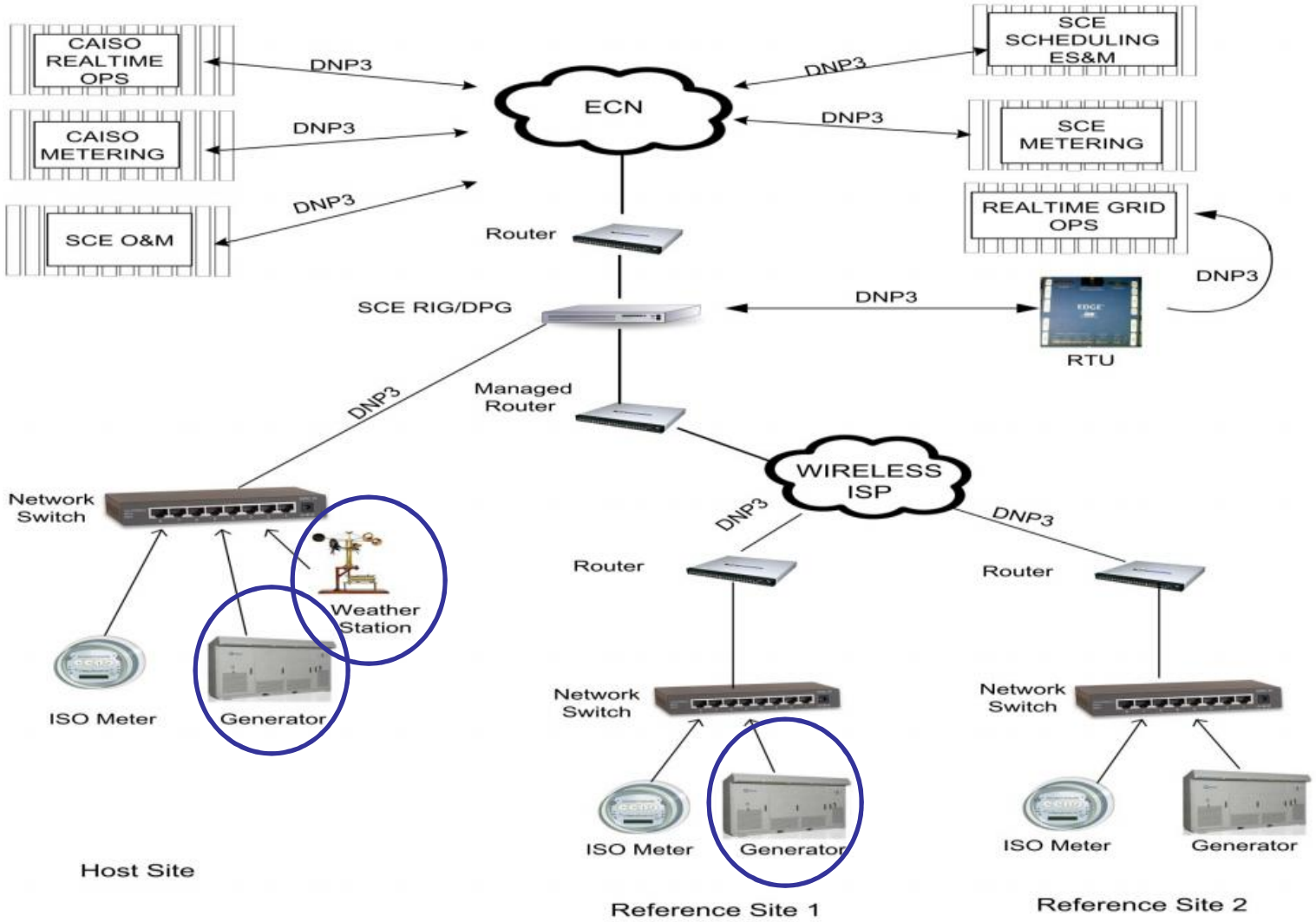
SPVP Data – NREL HPPV

Organizational Functions Key
Energy Markets
Real Time Ops/Planning
Regulatory
Research



Graphic Source: Von Meier, CIEE

SPVP Data Links



Distribution System PV Generation: Modeling and Analysis

Rich Seguin
Rich-Seguin@edd-us.com
December 17, 2013

Project Results

As part of the project we have investigated and documented the following:

- Hi Pen PV areas of concern
- A Study Criteria to measure the impact of Hi Pen PV
- A guide and analysis study procedure
- Conducted project Hi Pen PV impact studies for:
    - Fontana
        - Voltage Rise/Fall (Flicker)
        - Mitigation -95% Power Factor Setting
    - Porterville
        - Voltage Rise/Fall (Flicker)
        - Mitigation -95% Power Factor Setting
    - Palmdale
        - Voltage Rise/Fall (Flicker)
        - Mitigation -95% Power Factor Setting

Agenda

- Introduction
- Areas of Concerns
- Analysis Procedure
- Study Criteria
- Methods of Study
- Overview of Project Studies
    - Porterville
    - Palmdale
    - Fontana
- Summary

Introduction

Basic Questions

Will a new PV generator of a specified size and with a specified control create any problems?

What is the maximum PV generation that can be installed at a given location without creating problems?

What are the maximum “step changes” in generation that will occur, and at what frequency?

What mitigation strategies will allow larger levels of PV to be installed?

Areas of Concern - Impacts of PV

The impacts of the PV interconnection analyzed in terms of:

- Voltage regulation along the feeder
- High and Low voltage constraints
- Current capacity constraints
- Expected impacts due to fault current contributions from the interconnected PV
- Additional operation of voltage control circuit elements
- Other analysis discovered to be important to high penetration PV interconnection studies.

Analysis Procedure

PV Study Analysis Procedure

Base Case Model
- Build the Base Case
- Model the Active Device Controls
- Validate the Base Case

Time Series Input
- Obtain circuit measurement data
- Obtain PV measurement input

Validate the time series model
- Identify data anomalies
- Fix/exclude bad data points

PV Time Series Analysis
- Identify Critical Time Points **(Examine the entire year of time series measurement data**)
- Quantify parameters of interest for annual behavior and extent

PV Impact Analysis
- Run 24 hourly simulations over critical days identified by the time series analysis
- Quantify effects of PV, its sudden loss and its return
- Quantify Criteria Violations

PV Fault Analysis
- Fault analysis with and without PV

Summarize results and study criteria violations
- Develop Visualization Templates for review of results

Mitigation Strategies
- PV Side
- Utility Side

Base Case Model and Measurement Data

Multi-phase circuit model
- Active elements and control
- Existing generation and control
- Load distribution
- New generation and control

Measurement data (time synchronized)
- Start of circuit
- Load data
- Generation measurements

Sample Rates
- Hourly
- Minute/second (inside operating time of control devices)

Study Criteria

1. DOE/NREL Report 2003“Power System Aggregation Model and Field Configuration Equivalency Validation Testing”
2. Various Utility design/operations Input
3. Flicker Standards

Criteria	Possible Study Limit	Comments
Device Movement		
Cap Switching -	Change in number of operations with and without PV e.g. Cap Switching < 6 times per day	Depends on Type of Control, No of operations per day/year Note cap switching may actually be reduced
Voltage Regulators	Change in number of operations with and without PV	Depends on Bandwidth, No of operations per day/year
Substation LTC	Change in number of operations with and without PV	Depends on Bandwidth, No of operations per day/year
Voltage Impacts		
High Voltage – 126V	e.g. 126 V	Or Local Utility's Customer Maximum
Low voltage – 114V	e.g. 114 V	Or Local Utility's Customer Minumum
Flicker at Active Element	e.g. 0.5 V	Approx 25% of active element voltage bandwidth
Flicker at PCC/POI	e.g. 0.7 V	Threshold of visual perception
Overload	Normal Ratings	All devices Day-Day or Normal Ratings

Criteria	Possible Study Limit	Comments
Reverse flow		
Directional Relaying	Note Reverse Flow	If Directional relaying is used, any reverse current on any phase
Voltage Regulators	Minimum Regulator Flow with PV at Maximum to be no less than … % (e.g.20% of lowest flow without PV)	Uni-direction, Bi-directional Non Cogen
Substation Regulators	Same as Voltage Regulator above	Uni-direction, Bi-directional Non Cogen
Imbalance		
Flow	e.g. < 10 %	Reverse Flow and Synchronizing, Limits generation size/penetration
Voltage	e.g. < 3 %	Motor/generation heating, Synchronization, Limits generation size/penetration
Protection concerns		Generally not a concern if Isc PV < 0.1 Isc system
Reverse Flow (Only if there are directional relays)	Any reverse current flow on any phase	Directional Relays may trip. Consider reverse current with Power flow forward and Reactive Flow reversed.
Interrupting Ratings (1)	e.g. Isc < 8000 amps	Compare total fault current to interrupting ratings of fault interrupting devices e.g. fuses, reclosers, breakers.
In-Selectivity (3)	Review fuse curves	In-Selectivity due to increase fault current, loaded and unloaded
Fault Sensing (2)	Review fuse curves	In-Feed Case: Added generation may slow operation of upstream protective devices
Fuse Saving (9)	Review fuse curves	Fast clearing protective devices may not "save" fuse if new generation continues to provide fault current thru the fuse
TOV (Backfeeding fuse, recloser, or breaker)	Review Equipment BIL	If generation output is greater than the isolated load, opening upstream device may cause overvoltage. We will only report possible

Criteria	Possible Study Limit	Comments
Islanding		
Synchronsis and Induction	Load to generation must be > 3 to 1	Note that other generation sources may be present behind the same protective device e.g. biomass generation.
Inverter	UL 1741	Inverter Passes UL1741 Anti Islanding test. Note interaction between inverters may not be tested.
Efficiency/losses	e.g. Losses <3%	Line losses should be limited to a low % of the generation particularly for Express/dedicated PV Feeders
New PV	**Sudden loss and gain of PV**	
	100% of Nameplate	Screening Criteria - Voltage Flicker ok at 100% of Nameplate step change
	80% of Nameplate	Detailed Study - Voltage Flicker ok at 80% of Nameplate step change
Existing PV	Output Changes with new PV	Distance <2000ft
	Output Fixed at average output	Distance >2000ft

PV Assessment – Major Analysis Functions

Step Change – Analyzes variation in PV at Critical time points

Controller Movement – Estimates Control movements w/wo PV

Fault Analysis – Analyzes Protection System w/wo PV

Variability Analysis – Examines Step Change in PV generation

Mitigation – Analyzes Methods of Resolving Potential Study Criteria Violations (Repeat previous analysis with varying control solutions)

PV Assessment – Step Change

Step Change

- Detailed studies at extreme load and generation time points
- Analyze the loss and return of generation with and without regulation
- Can be used to analyze PV inverter power factor settings and control for mitigation

PV Assessment Methodology– Step Change

Study Model Power Flows

- Base condition
- Loss of generation without feeder controls operating
- Loss of generation with feeder controls operating
- Return of generation without feeder controls operating
- Return of generation with feeder controls operating.

The five power flows listed above are run for each critical time point selected for analysis, and there are five critical load/generation points, which are:

- Maximum load point
- Minimum load point
- PV Maximum Generation Point
- Maximum Ratio of PV Generation to Native Load
- Maximum Difference between PV Generation and Native Load

Note any time point may be analyzed

The methodology consists of monitoring the system's active devices and a series of power flows are run and all active device parameters reviewed against the study criteria.

PV Assessment – Step Change Impact Criteria

Table of DER Impact Criteria	
Initial Overvoltage	Initial Undervoltage
PV Step Down Overvoltage	PV Step Down Undervoltage
PV Step Up Overvoltage	PV Step Up Undervoltage
POI Initial Overvoltage	POI Initial Undervoltage
POI Step Down Overvoltage	POI Step Down Undervoltage
POI Step Up Overvoltage	POI Step Up Undervoltage
Step Down Voltage Change/Flicker	Step Up Voltage Change/Flicker
Step Down Controller Movement	Step Up Controller Movement
Step Down Voltage Change/Flicker	Step Up Voltage Change/Flicker
Step Down Controller Movement	Step Up Controller Movement
POI Voltage Change/Flicker (PV Step Down)	POI Voltage Change/Flicker (PV Step Up)
Reverse Flow	

PV Assessment Stepping Scenarios

Scenarios 1 – PV operating at full rated and 100% Loss and Return of generation at unity Inverter Power Factor.

Scenarios 2 – PV operating at full rated and the sudden loss of 80% of its generation and its return at unity Inverter Power Factor.

Possible Mitigation

Scenarios 3 – PV operating at full rated and 100% Loss and Return of generation at -0.90 Inverter Power Factor.

Scenarios 4 – PV operating at full rated and the sudden loss of 80% of its generation and its return at unity -0.90 Inverter Power Factor.

PV Assessment – Device Movement

Device Movement examines the number of operations a circuit active device would experience with and without PV

PV Assessment – Fault Analysis

Protection Review w/wo PV

- Percent increase in fault current at protective devices
- If sufficient faults current exist > 10% determine Impacts and effects on protective margins for:
  - Loadability
  - Selectivity
  - Sensitivity

PV Assessment – Mitigation Strategies

Generation side of PCC or POI

- Power factor control - fixed/scheduled
- Volt/Var control (active voltage control)
- Storage
- Others

Utility side of PCC

- Revise active device's control
- Equipment
  - Bidirectional or co-generation regulation
  - Reconductoring
  - Storage
- Others

PV Assessment – Overview of Projects

PV Assessment was made on the following High Pen ckts

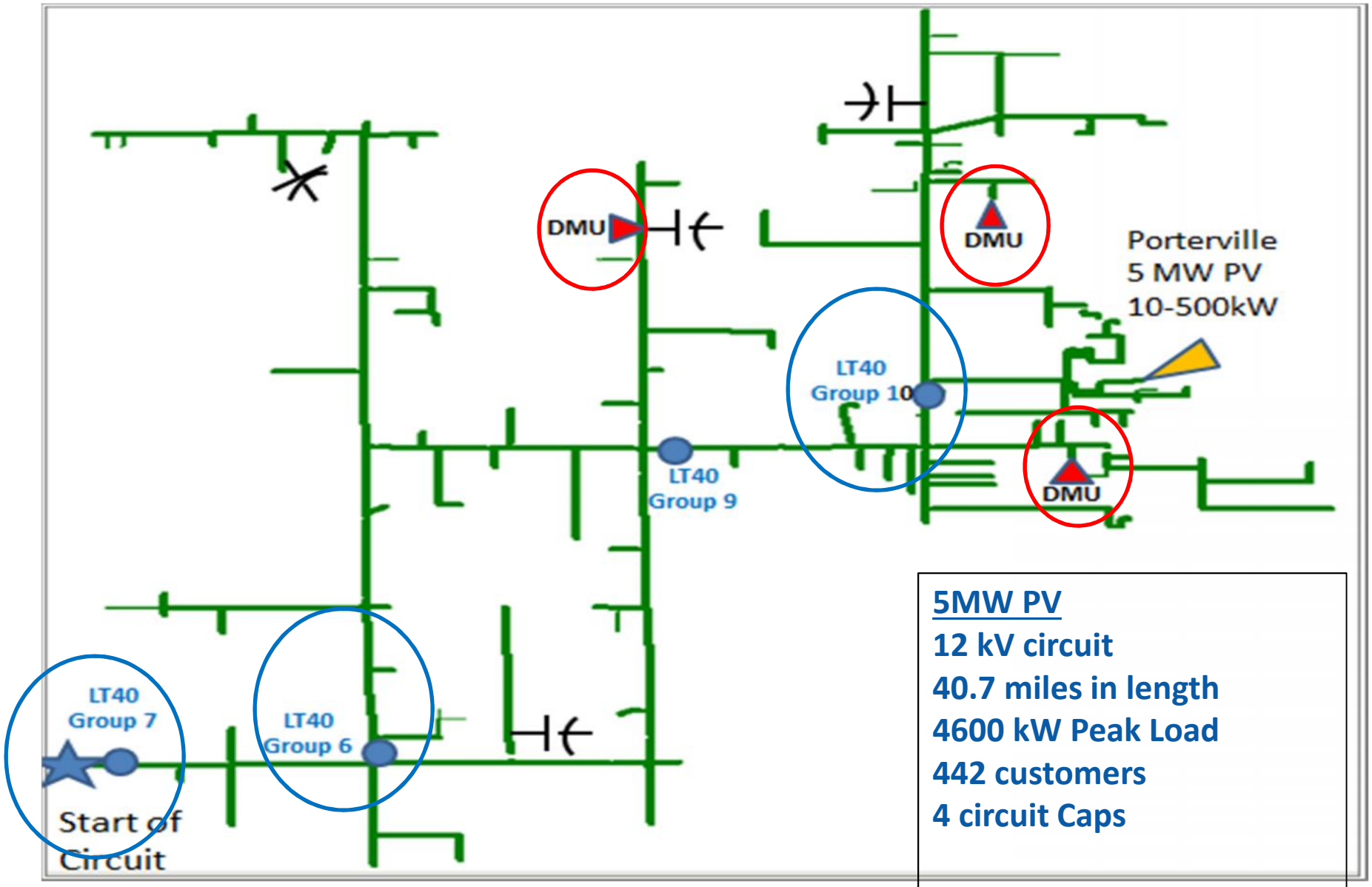
- Porterville – 10 @ 500kW = 5 MW
- Palmdale – 2 @ 1500kW = 3 MW
- Fontana – 1 @ 1500kW & 1 @ 3000kW = 4.5 MW

Porterville

issue

Voltage Rise/Fall with PV Variability

Porterville High Penetration Circuit



5MW PV
12 kV circuit
40.7 miles in length
4600 kW Peak Load
442 customers
4 circuit Caps

Porterville Circuit Capacitors

Structure	Device Number	Size (kVAR)	Control	Start Schedule	End Schedule	High voltage	Low Voltage
6046T	0013914	600	Time-Bias Voltage	7:04 AM	9:04 PM	126	121
894563E	0013089	600	Time-Bias Voltage	12:00 AM	12:00 AM	125	120
1351925E	0040409	600	Voltage	6:04 AM	10:04 PM	126	121
755658E	0013903	600	Time-Bias Voltage	9:04 AM	7:04 PM	126	121

Typical Cap Setting

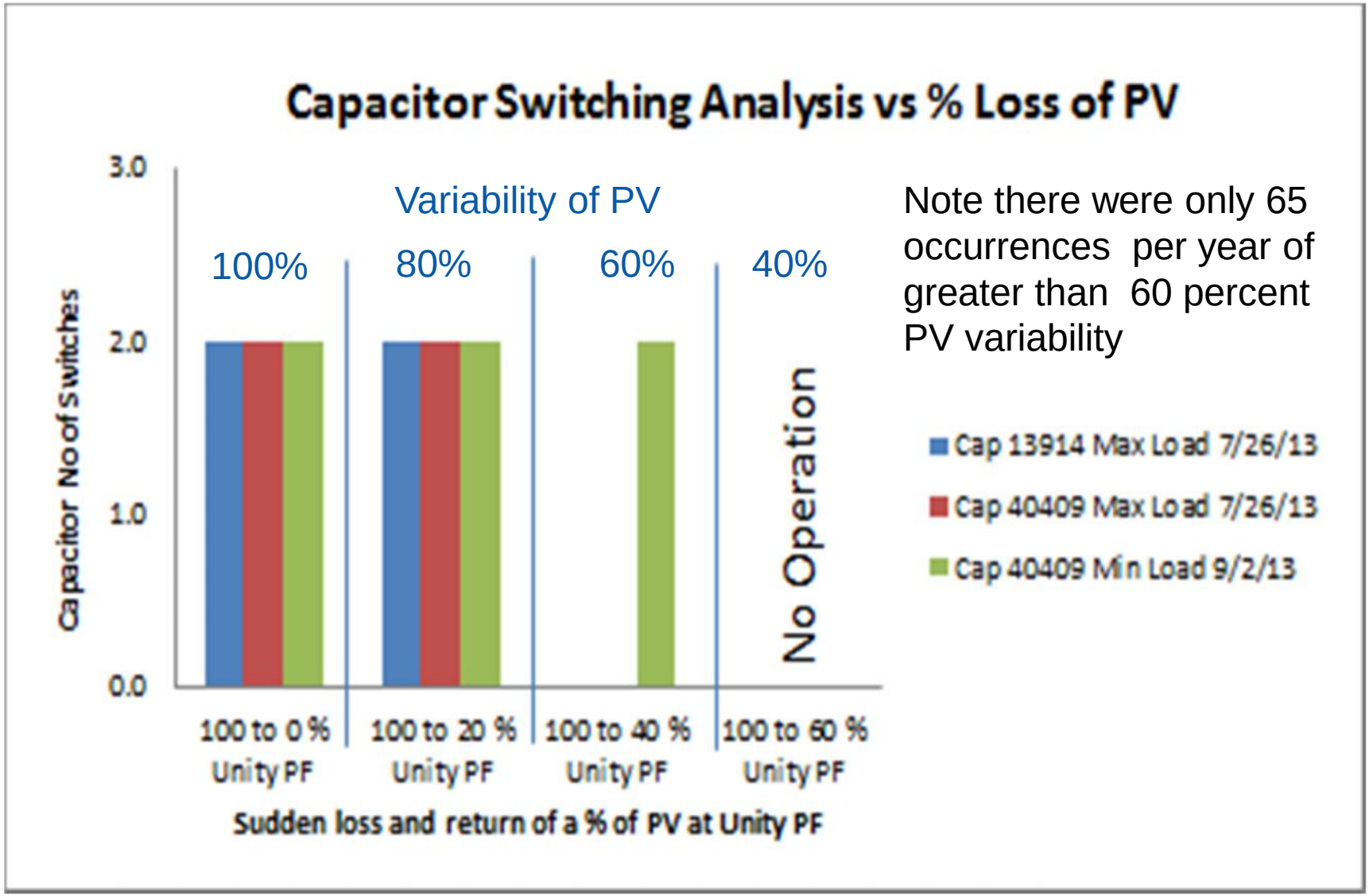
- high voltage over-ride 124V for 60 seconds
- low voltage over-ride 115V for 60 seconds
- high voltage during schedule: 126V
- low voltage during schedule: 122V
- high voltage during non-schedule: 122V
- low voltage during non-schedule: 118V
- high / low voltage threshold: 3 min
- maximum operations: 10
- emergency high voltage over-ride: 128V for 5 seconds

Capacitor Location	Flicker on 120V Base
600kVAr Cap 13089	1.7 Volts
600kVAr Cap 13903	0.7 Volts
600kVAr Cap 13914	1.3 Volts
600kVAr Cap 40409	2.8 Volts

PV Assessment – Step Change 100% Rise/Fall

Date & Time	Circuit	Component	Component Type	Criterion for Evaluation	Criteri	Calc Va		Pass/Fa
7/26/2013 12:00	Porterville	PV 5MW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.7	6.5	5.8	Fail
8/5/2013 14:00	Porterville	PV 5MW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.7	7.1	6.4	Fail
9/2/2013 11:00	Porterville	PV 5MW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.7	6.8	6.1	Fail
7/26/2013 12:00	Porterville	600kVAr Cap 13914	Switched Shunt Capacitor	Step Down Controller Movement	0	3.0	3.0	Fail
7/26/2013 12:00	Porterville	600kVAr Cap 40409	Switched Shunt Capacitor	Step Down Controller Movement	0	3.0	3.0	Fail
9/2/2013 11:00	Porterville	600kVAr Cap 40409	Switched Shunt Capacitor	Step Down Controller Movement	0	3.0	3.0	Fail
8/5/2013 14:00	Porterville	600kVAr Cap 40409	Switched Shunt Capacitor	Step Down Voltage Change/Flicker	0.5	6.2	5.7	Fail
8/5/2013 14:00	Porterville	600kVAr Cap 13903	Switched Shunt Capacitor	Step Down Voltage Change/Flicker	0.5	1.8	1.3	Fail
8/5/2013 14:00	Porterville	600kVAr Cap 13089	Switched Shunt Capacitor	Step Down Voltage Change/Flicker	0.5	1.3	0.8	Fail
9/2/2013 11:00	Porterville	600kVAr Cap 13914	Switched Shunt Capacitor	Step Down Voltage Change/Flicker	0.5	4.3	3.8	Fail
9/2/2013 11:00	Porterville	600kVAr Cap 40409	Switched Shunt Capacitor	Step Down Voltage Change/Flicker	0.5	5.8	5.3	Fail
9/2/2013 11:00	Porterville	600kVAr Cap 13903	Switched Shunt Capacitor	Step Down Voltage Change/Flicker	0.5	1.7	1.2	Fail
9/2/2013 11:00	Porterville	600kVAr Cap 13089	Switched Shunt Capacitor	Step Down Voltage Change/Flicker	0.5	1.2	0.7	Fail
7/26/2013 12:00	Porterville	600kVAr Cap 13914	Switched Shunt Capacitor	Step Up Controller Movement	0	3.0	3.0	Fail
7/26/2013 12:00	Porterville	600kVAr Cap 40409	Switched Shunt Capacitor	Step Up Controller Movement	0	3.0	3.0	Fail
9/2/2013 11:00	Porterville	600kVAr Cap 40409	Switched Shunt Capacitor	Step Up Controller Movement	0	3.0	3.0	Fail

Porterville Device Movement



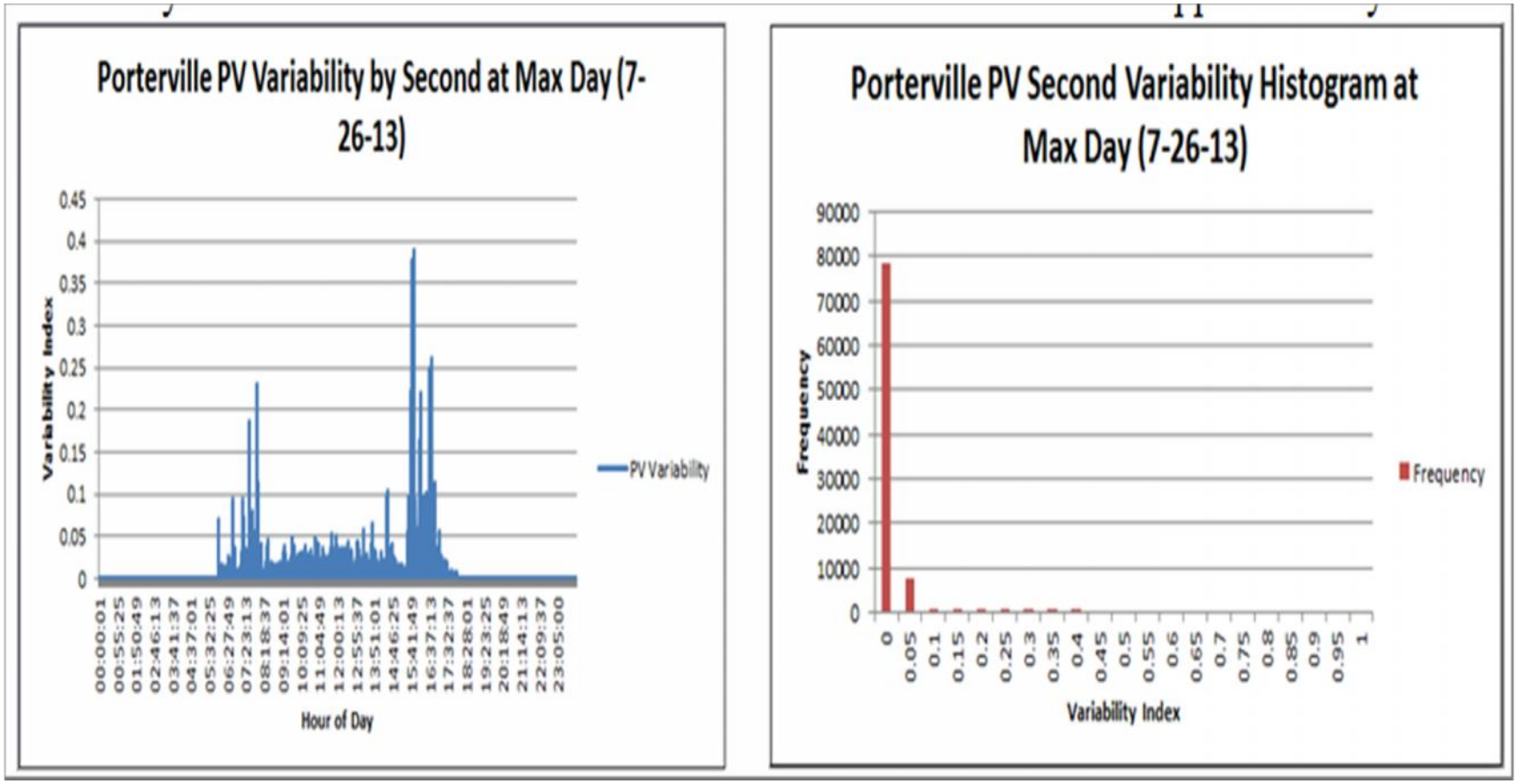
Note there were only 65 occurrences per year of greater than 60 percent PV variability

Porterville PV Variability 2011 CPR Data

	1 Minute Data (Instance)	1 Hour Data (Instance)
Total Instance	525600	8760
>90% variability	5	0
>80% variability	6	0
>70% variability	19	0
>60% variability	35 = 65	4
>50% variability	65	24
>40% variability	136	126
>30% variability	351	407
>20% variability	981	1546
>10% variability	3187	2854
>5% variability	7646	3597

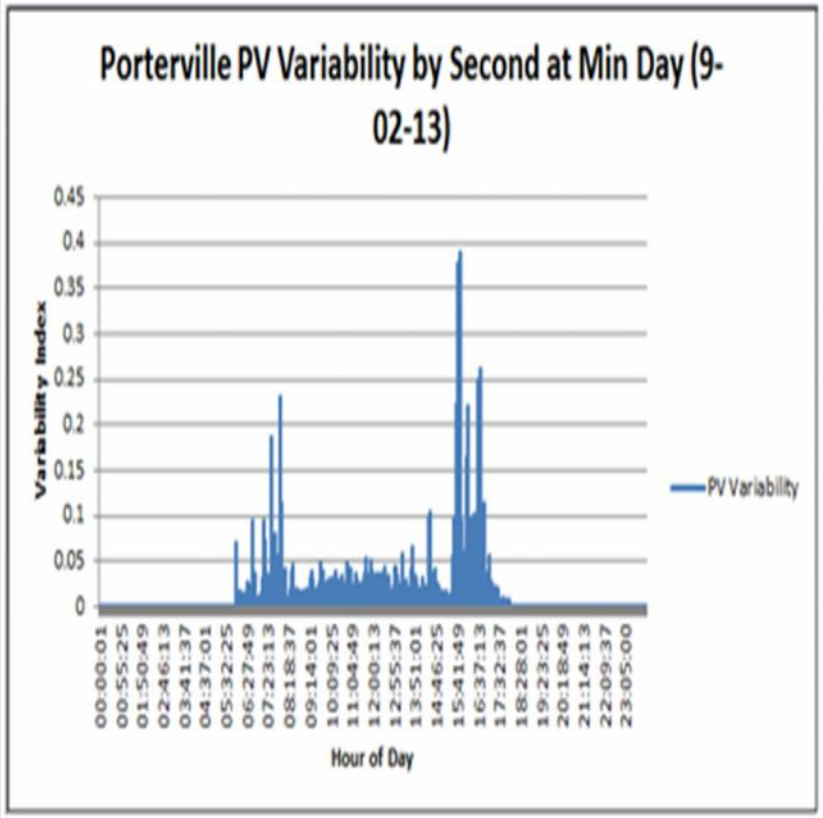
Variability of Porterville PV -1 sec Max Load Day

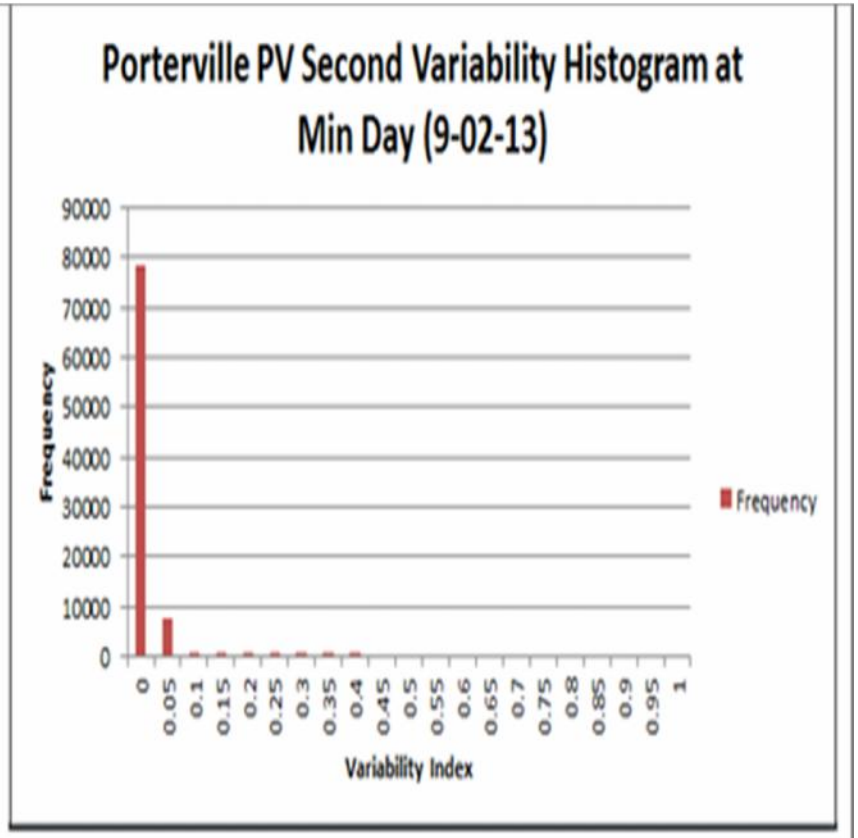
Max 1 Sec Variability is 40%



Variability of Porterville PV -1 sec Min Load Day

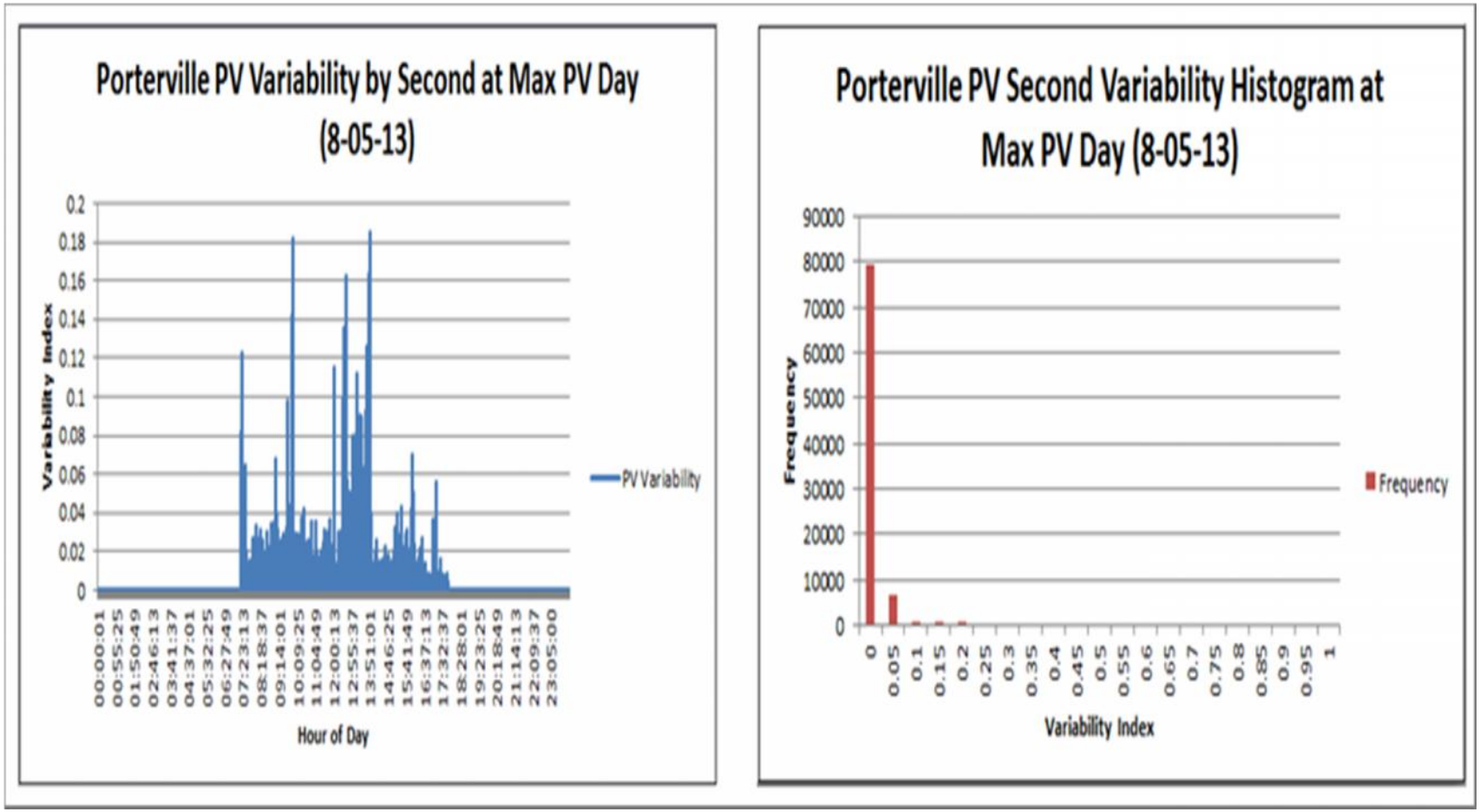
Max 1 Sec Variability - 40%





Variability of Porterville PV -1 sec Max PV Day

Max 1 Sec Variability - 18%



Max Variability did not exceed 40% and occurred less than 5% of the time

PV Assessment – Porterville Fault Analysis

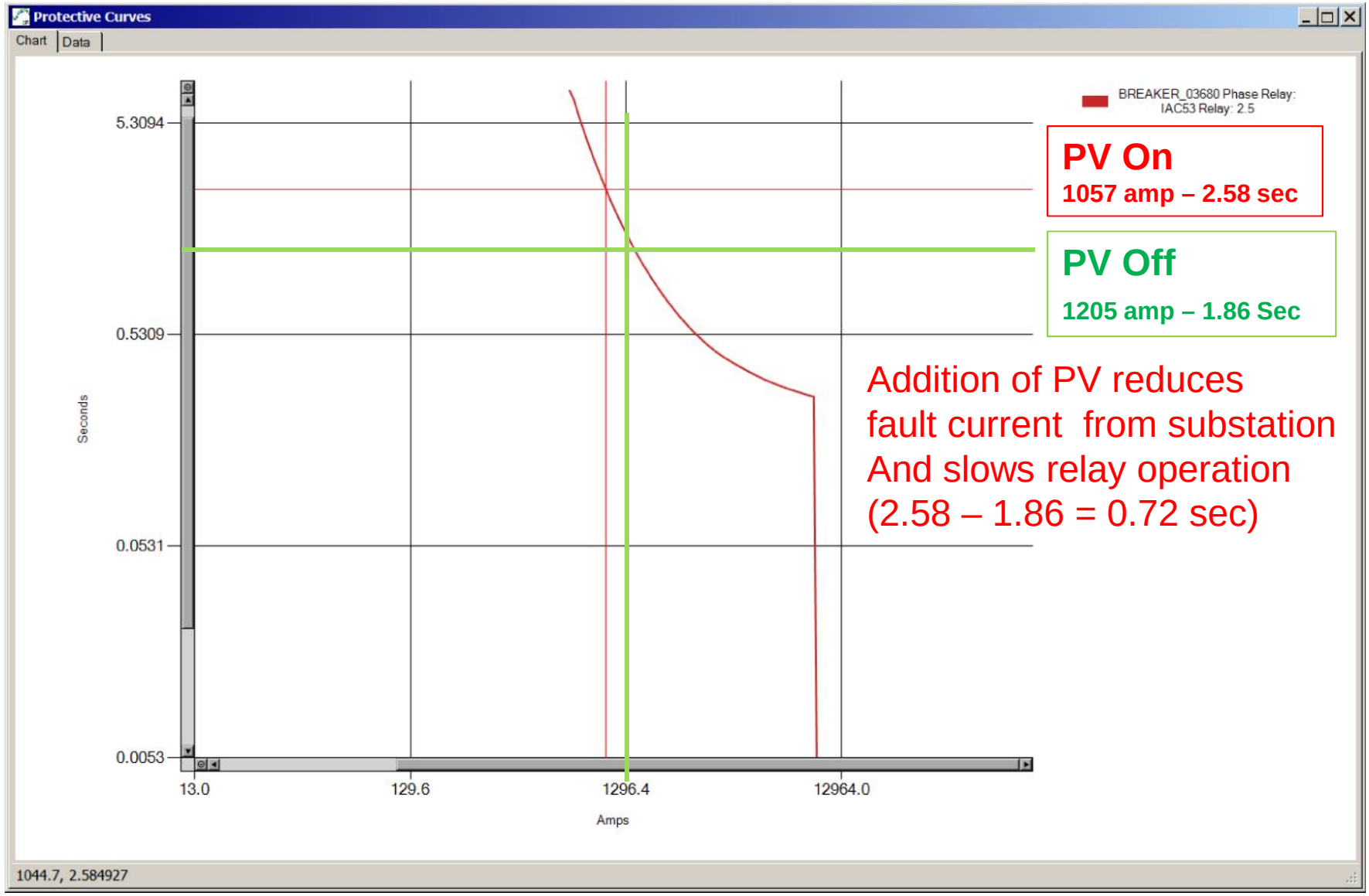
Protection Review w/wo PV

- Percent increase in fault current at protective devices

Circuit Location	System Fault Current at the POI Without PV	PV Fault Current 1.1 x Full load	Ratio
Porterville 5MW PV	1586 amps	266 amps	16.8%

- If sufficient faults current exist > 10%, determine Loadability, Selectivity, & Sensitivity impacts and effects on protective margins

Porterville In-Feed Effect - Desensitizing Relay



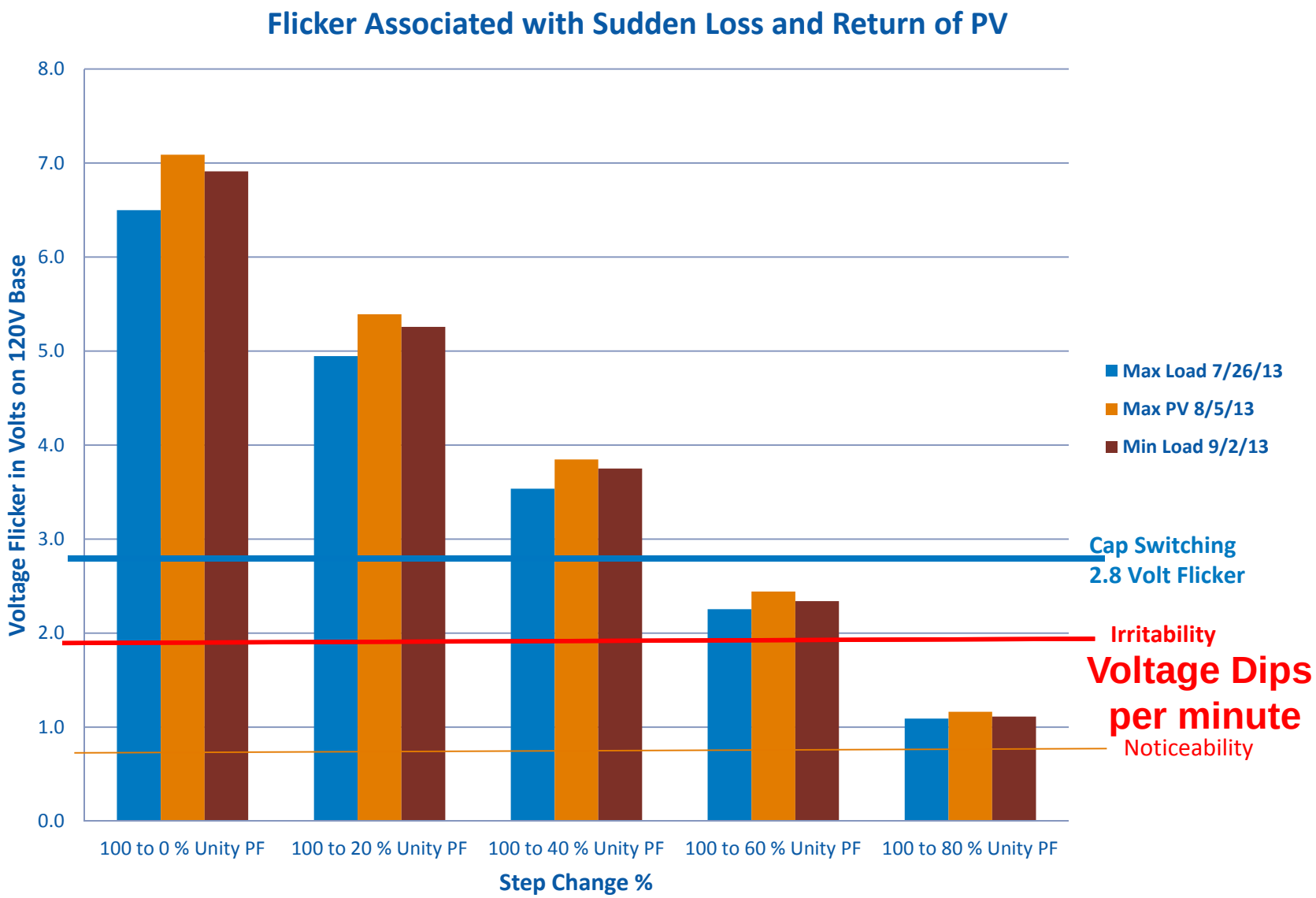
PV On
1057 amp – 2.58 sec

PV Off
1205 amp – 1.86 Sec

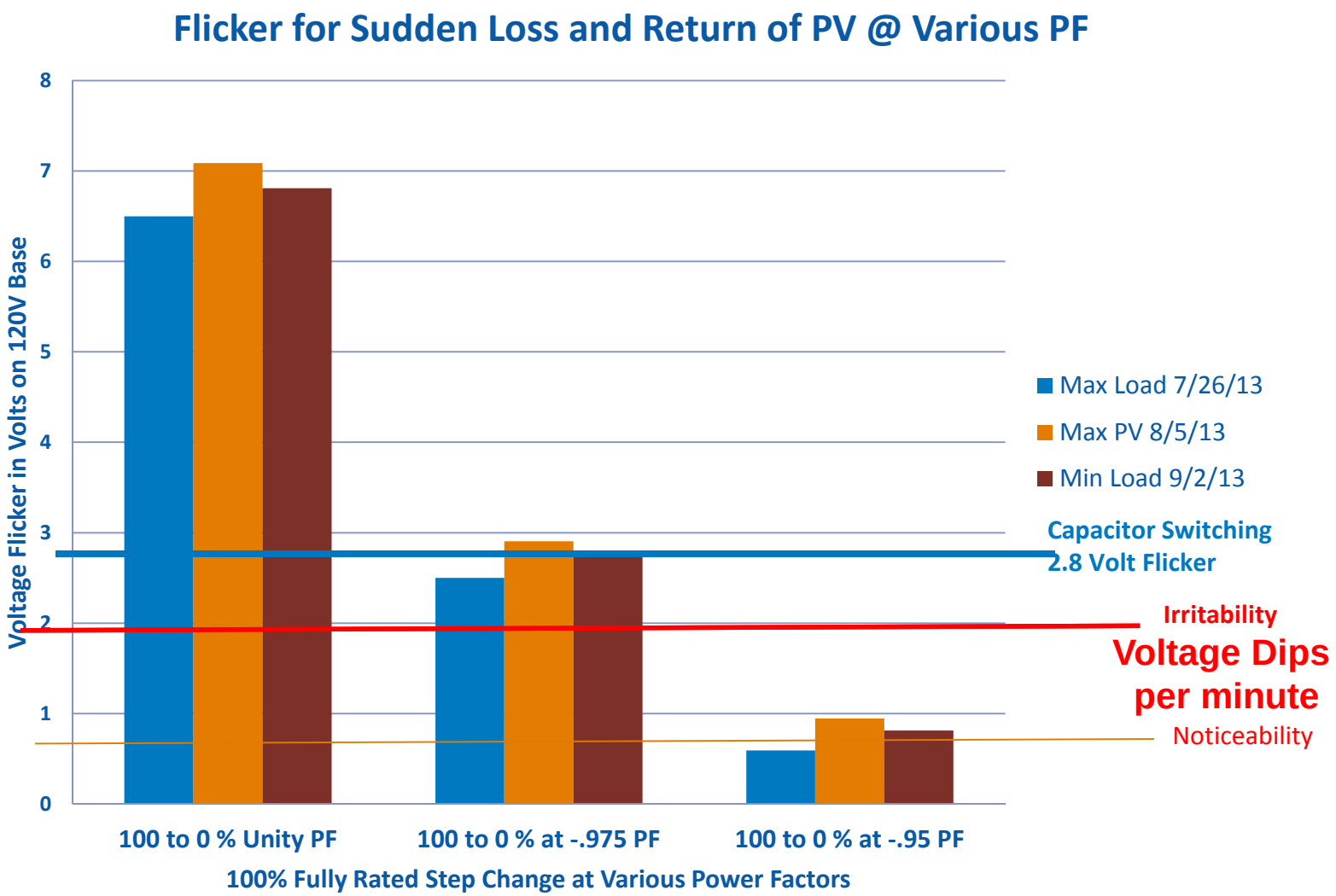
Addition of PV reduces fault current from substation And slows relay operation (2.58 – 1.86 = 0.72 sec)

No Protection Problem - Above is the worst example of the PV impact on protection

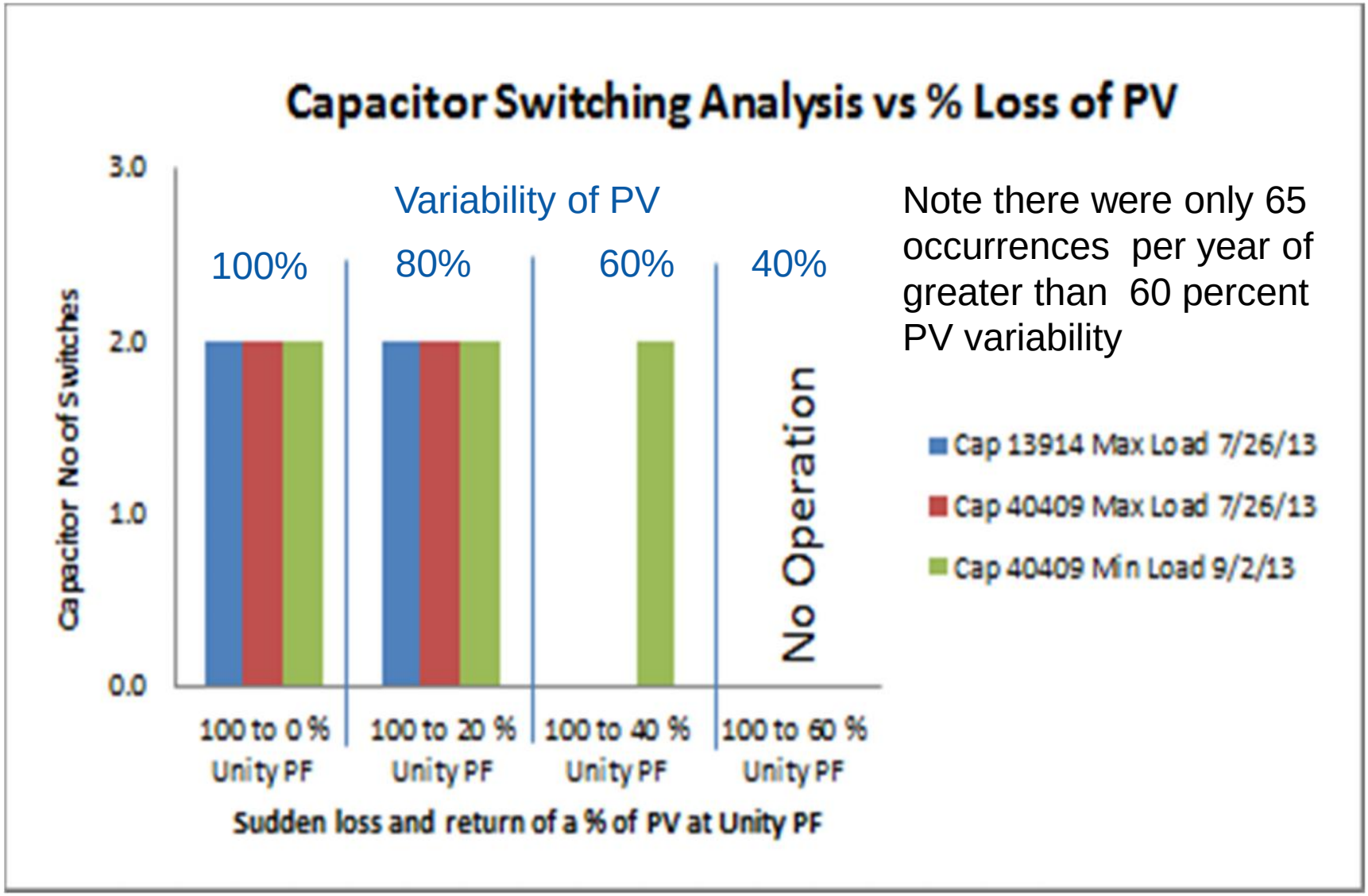
Mitigation using Variability and Power Factor



Mitigation using Variability and Power Factor

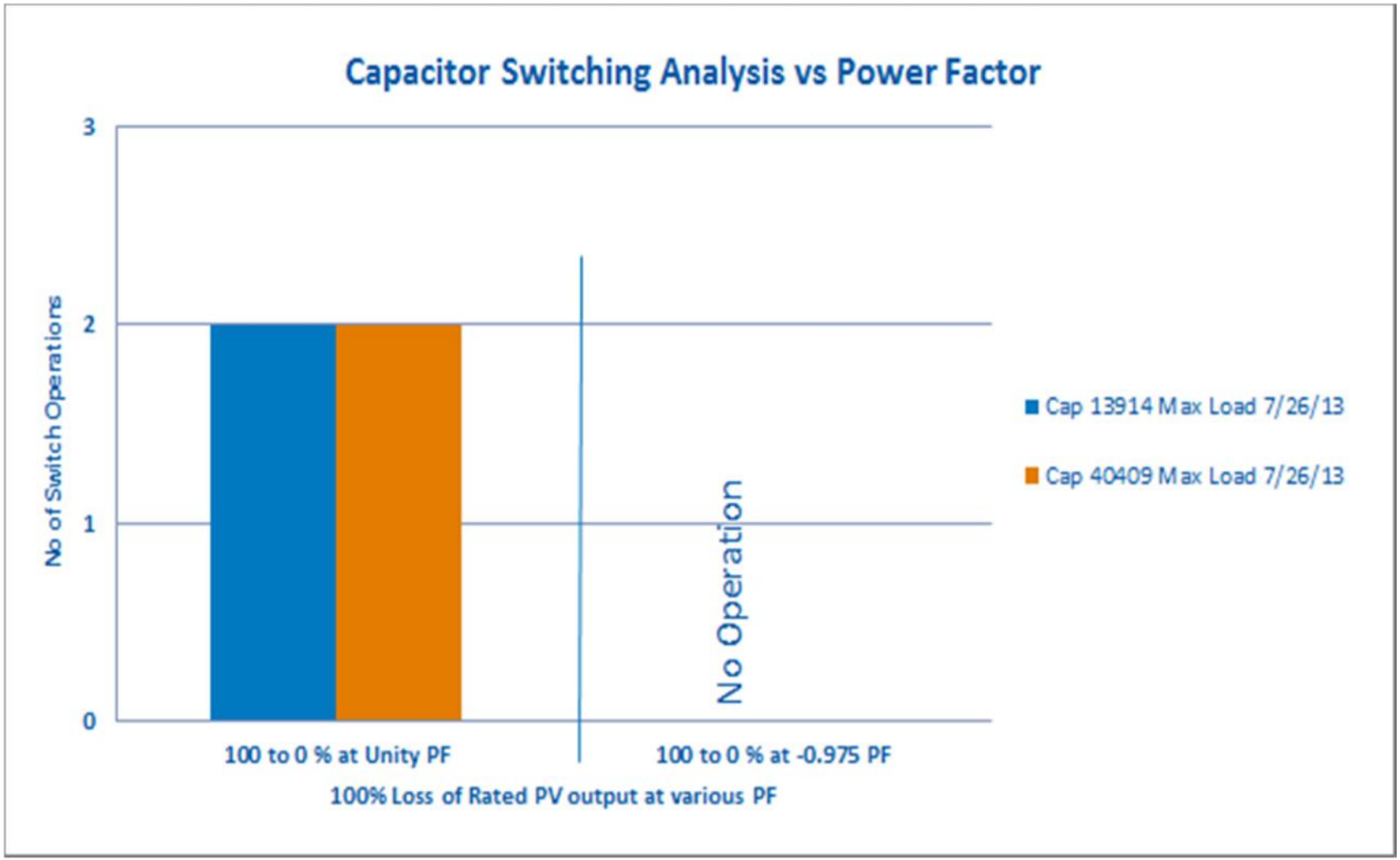


Mitigation using Variability and Power Factor



Note there were only 65 occurrences per year of greater than 60 percent PV variability

Mitigation using Variability and Power Factor



Summary of PV Analysis for Porterville

Mitigation

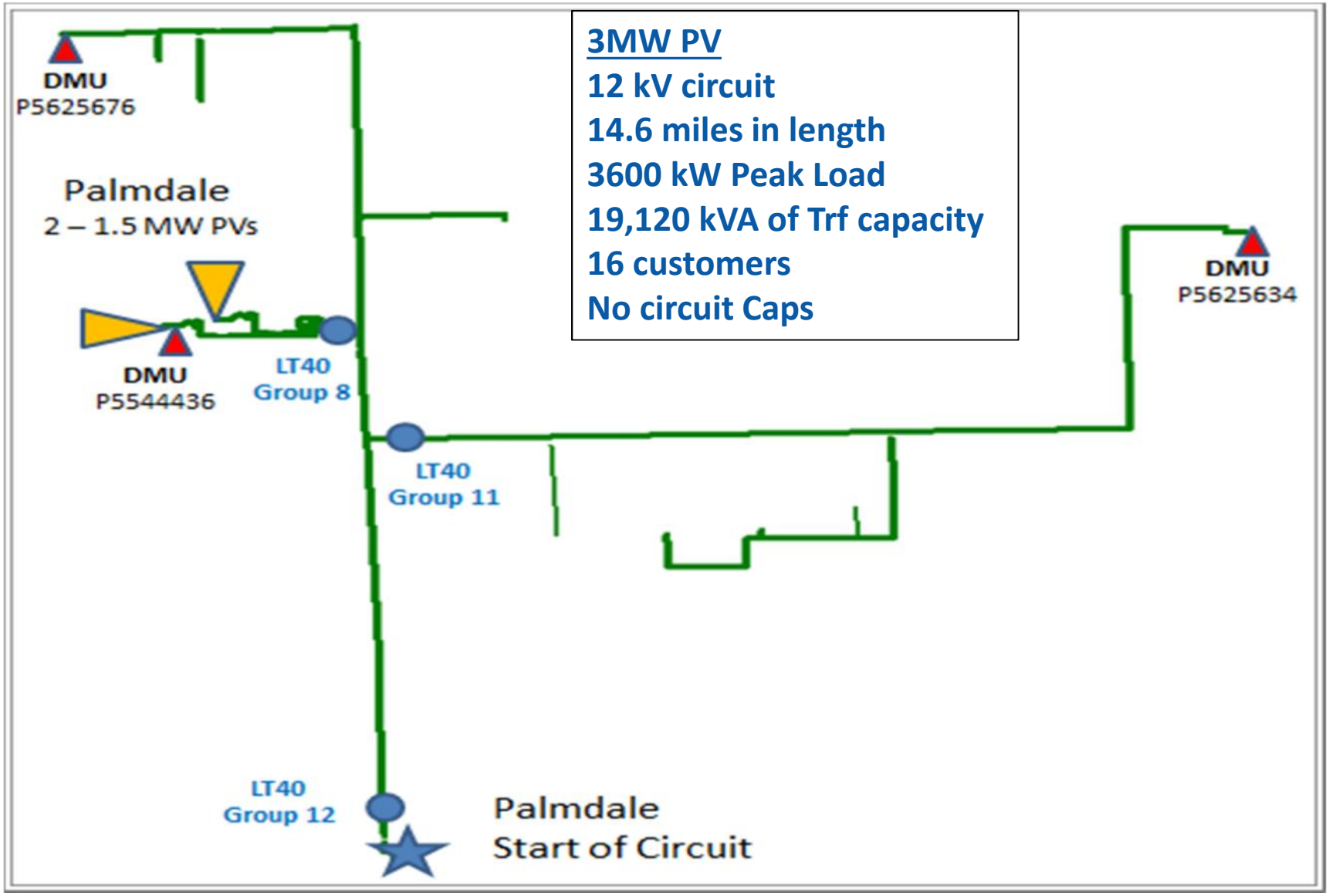
- Set fixed power factor setting of -95 Absorbing will resolve study criteria violations

Palmdale

issue

Voltage Rise/Fall with PV Variability

Palmdale High Penetration Circuit



3MW PV
12 kV circuit
14.6 miles in length
3600 kW Peak Load
19,120 kVA of Trf capacity
16 customers
No circuit Caps

PV Assessment – Palmdale Step Change

Violations for Scenario 100% - 0% @ 1.00pf (% of Rated KW)

Analysis Time Filter:
- 6/23/2013 2:00:00 PM (16 passed; 6 failed)
- 7/5/2013 12:00:00 PM (16 passed; 6 failed)
- 8/23/2013 12:00:00 PM (16 passed; 6 failed)

Feeder Filter:
- Palmdale

Component Type Filter:
- Voltage Regulator
- Inverter Type DR
- Breaker

Violation Type Filter:
- Initial Overvoltage
- Initial Undervoltage
- PV Step Down Overvoltage

Failures Only

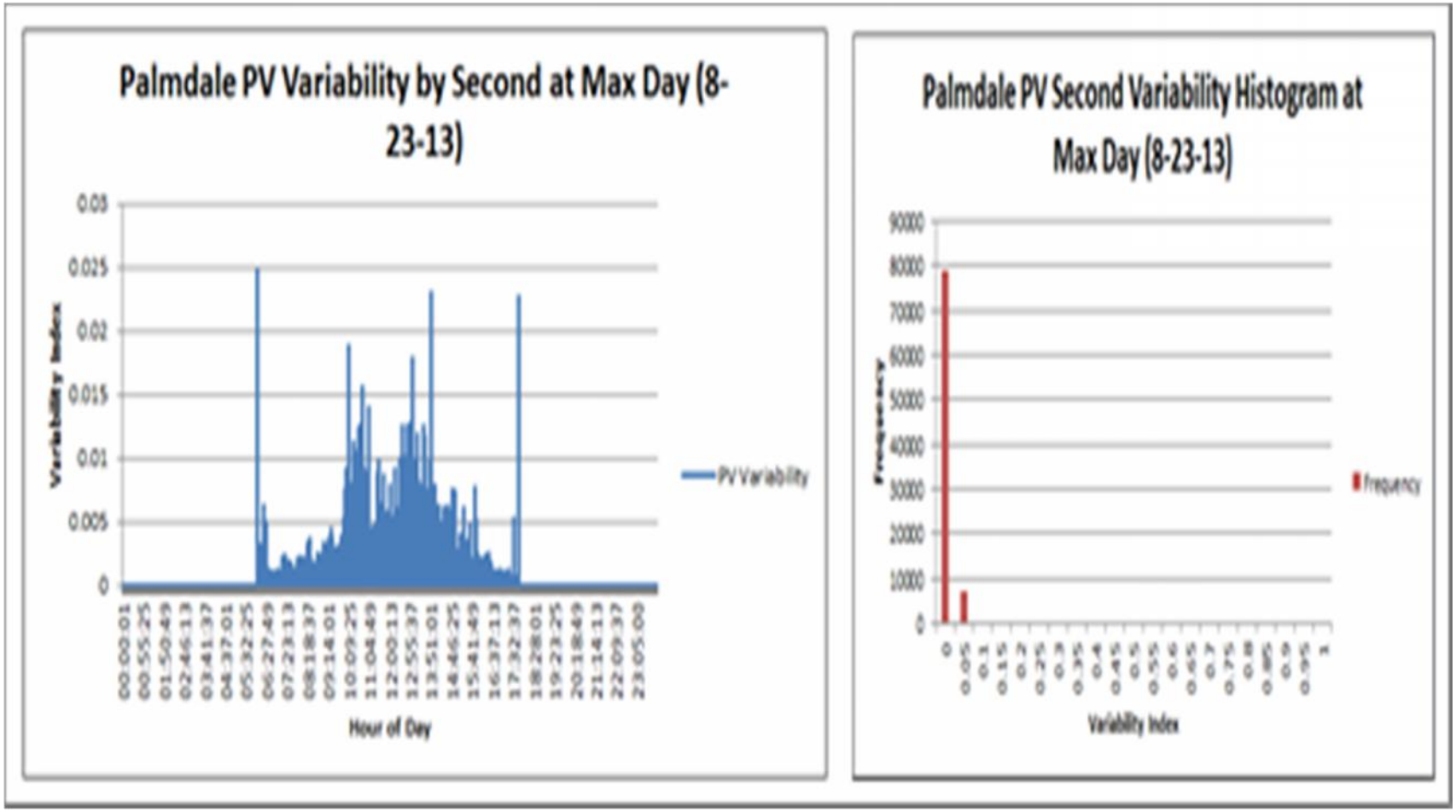
Analysis Time	Feeder	Cmp Name	Component Type	Violation Type	Criterion	Calc	Difference	% Vol	Pass/Fail
6/23/2013 2:00 PM	Palmdale	PV 1500kW 1	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	3.82	3.12	445.7	Fail
6/23/2013 2:00 PM	Palmdale	PV 1500kW 1	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	3.82	3.12	445.7	Fail
6/23/2013 2:00 PM	Palmdale	PV 1500kW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	4.02	3.32	474.2	Fail
6/23/2013 2:00 PM	Palmdale	PV 1500kW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	4.02	3.32	474.2	Fail
6/23/2013 2:00 PM	Palmdale	BREAKER_17850	Breaker	Reverse Flow	0.00	-504.09	504.09	100.0	Fail
6/23/2013 2:00 PM	Palmdale	PV 1500kW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	4.02	3.32	474.2	Fail
6/23/2013 2:00 PM	Palmdale	BREAKER_17850	Breaker	Reverse Flow	0.00	-504.09	504.09	100.0	Fail
7/5/2013 12:00 PM	Palmdale	PV 1500kW 1	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	3.82	3.12	445.6	Fail
7/5/2013 12:00 PM	Palmdale	PV 1500kW 1	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	3.82	3.12	445.6	Fail
7/5/2013 12:00 PM	Palmdale	PV 1500kW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	4.02	3.32	474.1	Fail
7/5/2013 12:00 PM	Palmdale	PV 1500kW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	4.02	3.32	474.1	Fail
7/5/2013 12:00 PM	Palmdale	BREAKER_17850	Breaker	Reverse Flow	0.00	-523.13	523.13	100.0	Fail
8/23/2013 12:0...	Palmdale	PV 1500kW 1	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	3.80	3.10	443.5	Fail
8/23/2013 12:0...	Palmdale	PV 1500kW 1	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	3.80	3.10	443.5	Fail
8/23/2013 12:0...	Palmdale	PV 1500kW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	4.00	3.30	471.8	Fail
8/23/2013 12:0...	Palmdale	PV 1500kW	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	4.00	3.30	471.8	Fail
8/23/2013 12:0...	Palmdale	BREAKER_17850	Breaker	Reverse Flow	0.00	-572.99	572.99	100.0	Fail

PV Assessment – Device Movement

There are no capacitors on the Palmdale Ckt

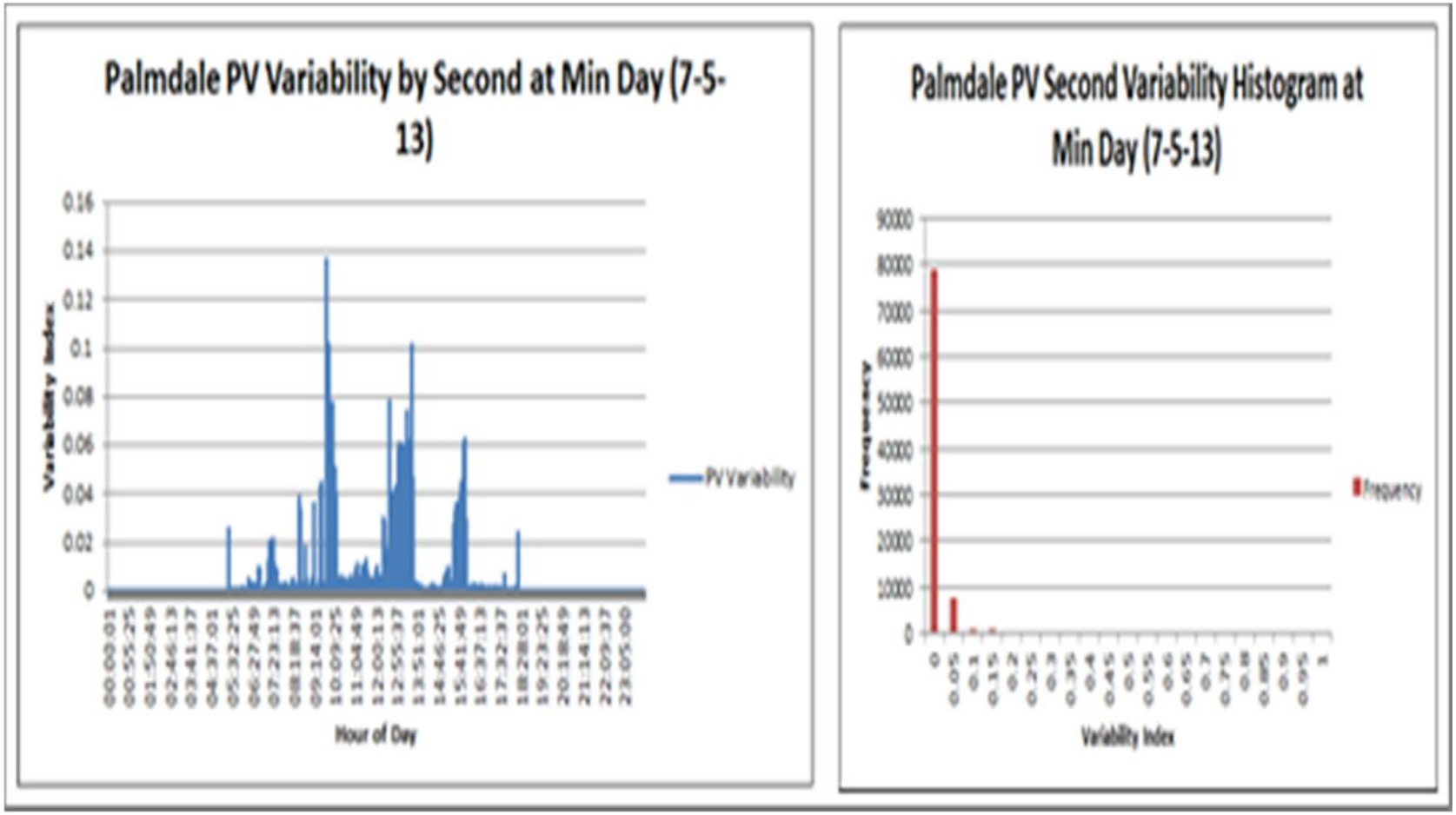
Variability of Palmdale PV -1 sec Max Load Day

Max 1 Sec Variability is 2.5%



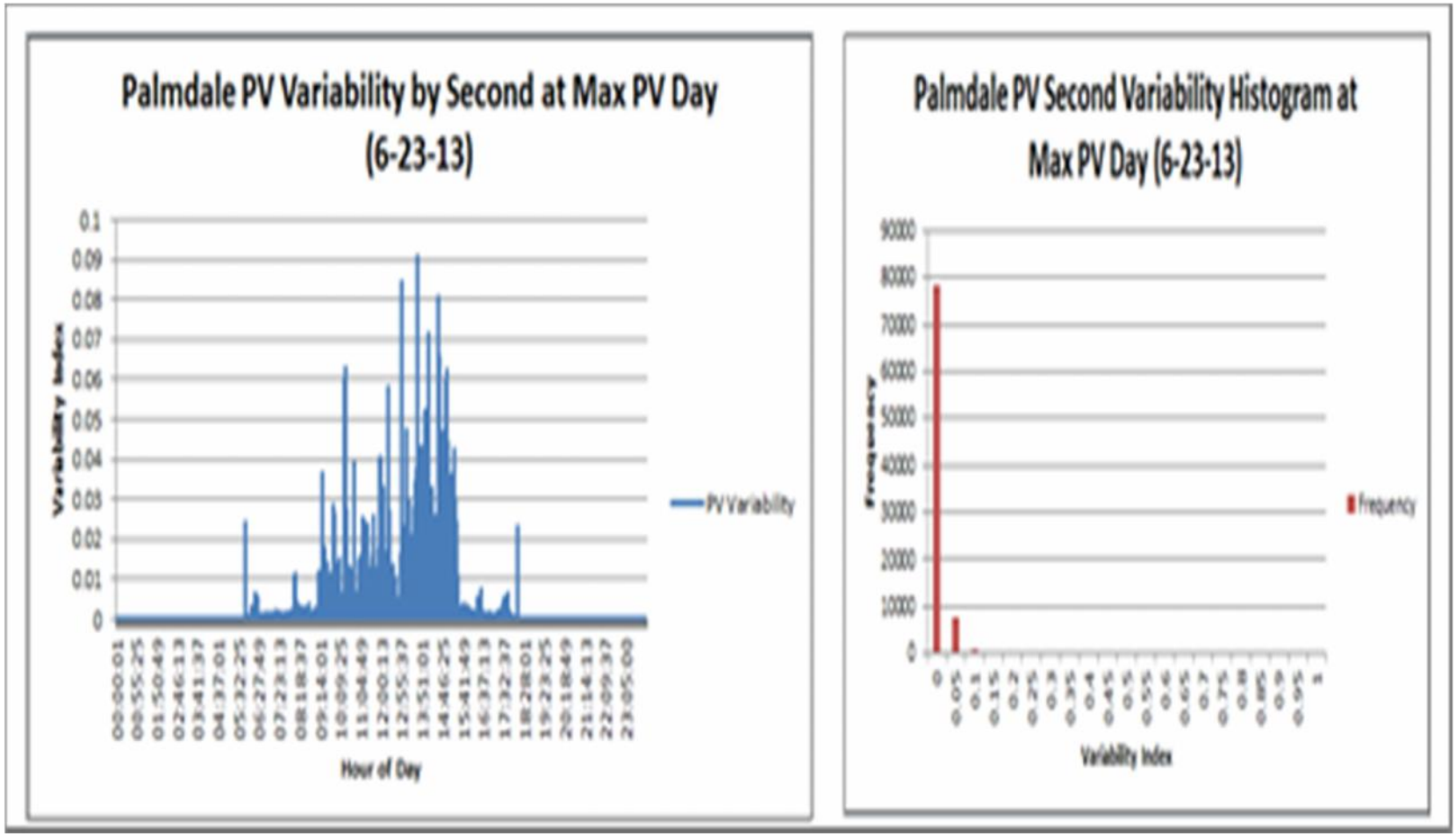
Variability of Palmdale PV -1 sec Min Load Day

Max 1 Sec Variability is 14%



Variability of Palmdale PV -1 sec Max PV Day

Max 1 Sec Variability is 9%



Max Variability did not exceed 14% and occurred less than 5% of the time

PV Assessment – Palmdale Fault Analysis

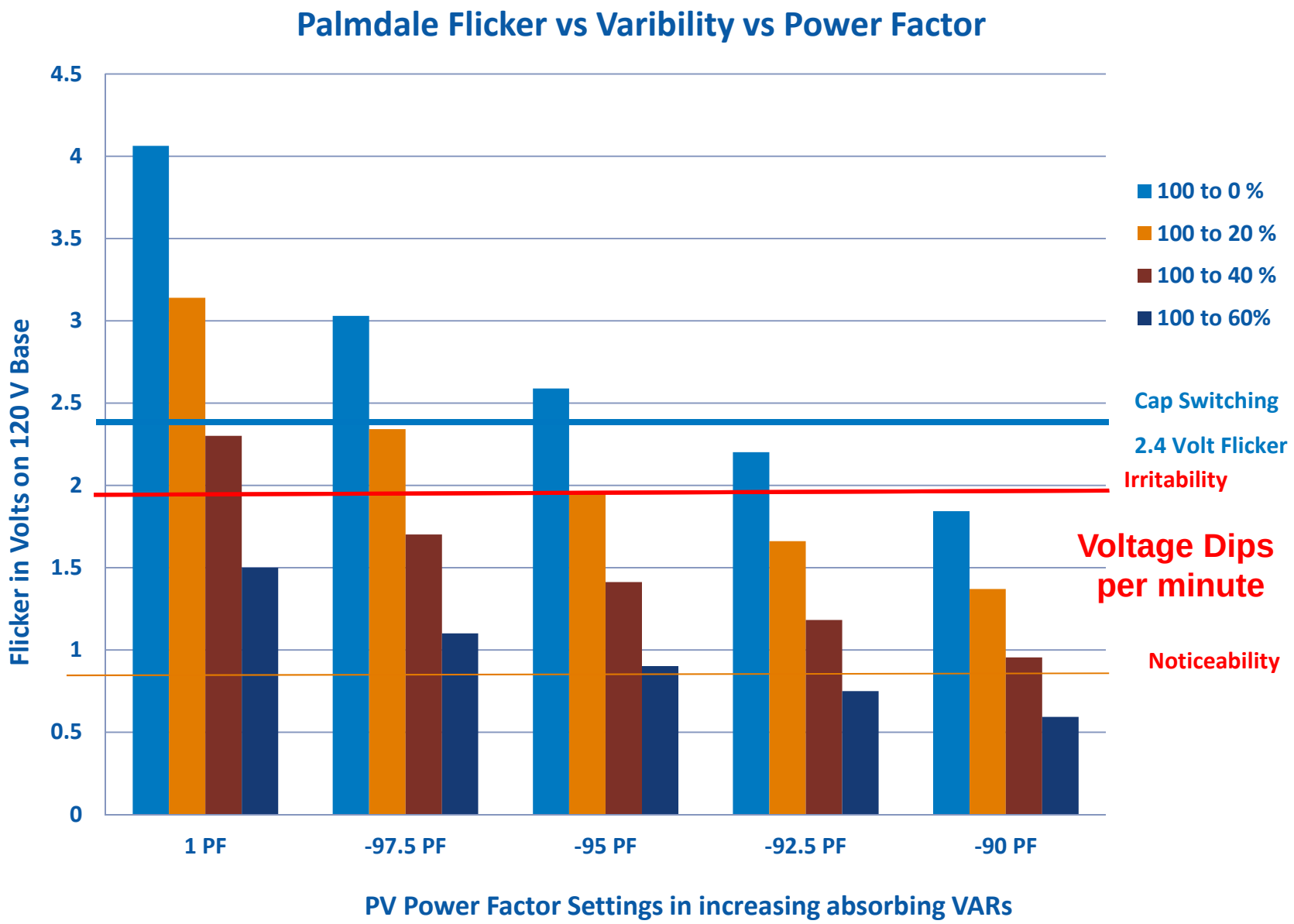
Protection Review w/wo PV

- Percent increase in fault current at protective devices

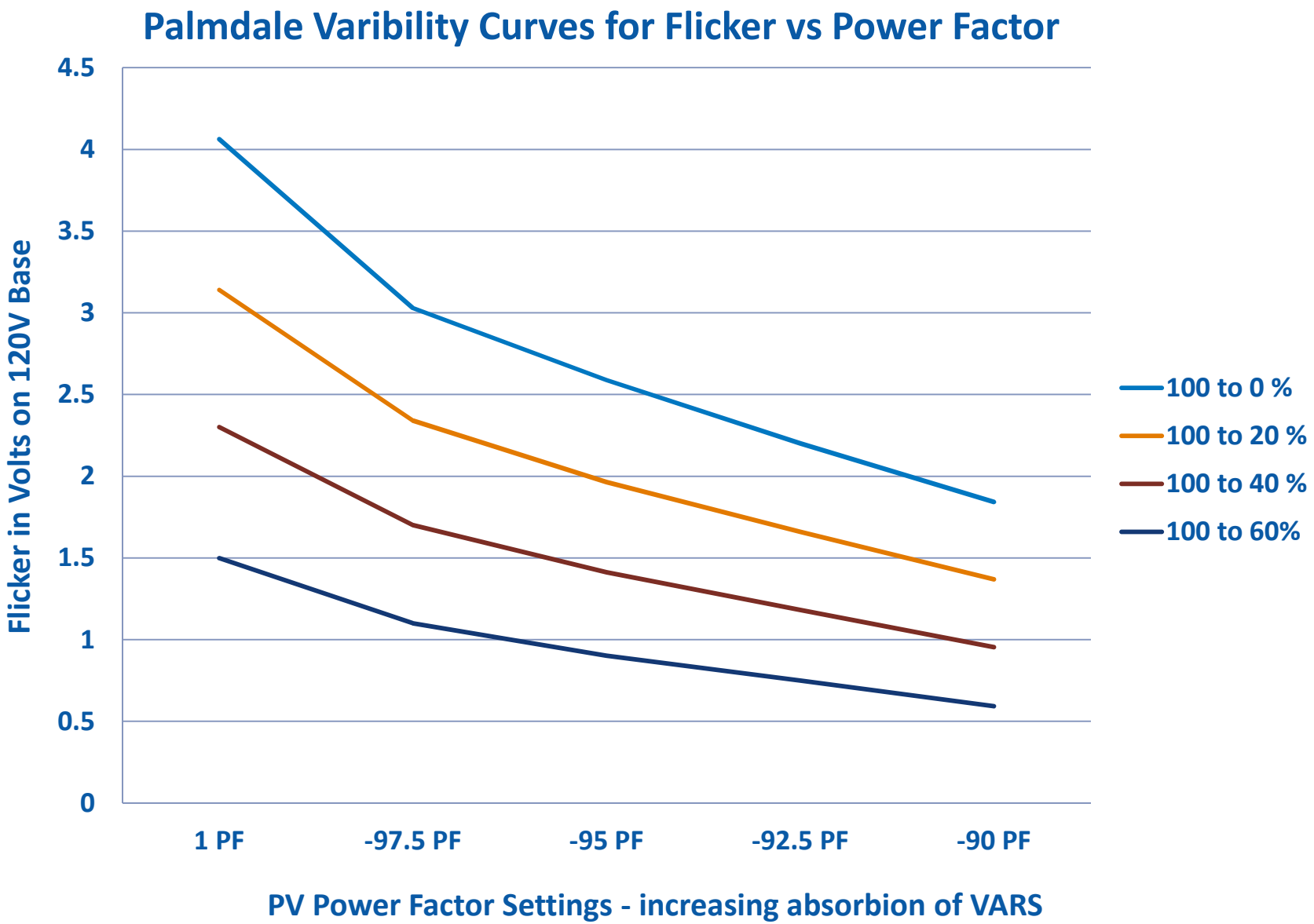
Circuit Location	System Fault Current at the POI Without PV	PV Fault Current 1.1 x Full load	Ratio
Palmdale East 1.5 MW PV	2280 amps	80 amps	4.5%
Palmdale West 1.5 MW PV	2176 amps	80 amps	4.7%

- If sufficient faults current exist > 10%, determine Loadability, Selectivity, & Sensitivity Impacts and effects on protective margins

Mitigation using Variability and Power Factor



Mitigation using Variability and Power Factor



Summary of PV Analysis for Palmdale

Mitigation

- Set fixed power factor setting of -95% Absorbing will resolve study criteria violations

No Mitigation

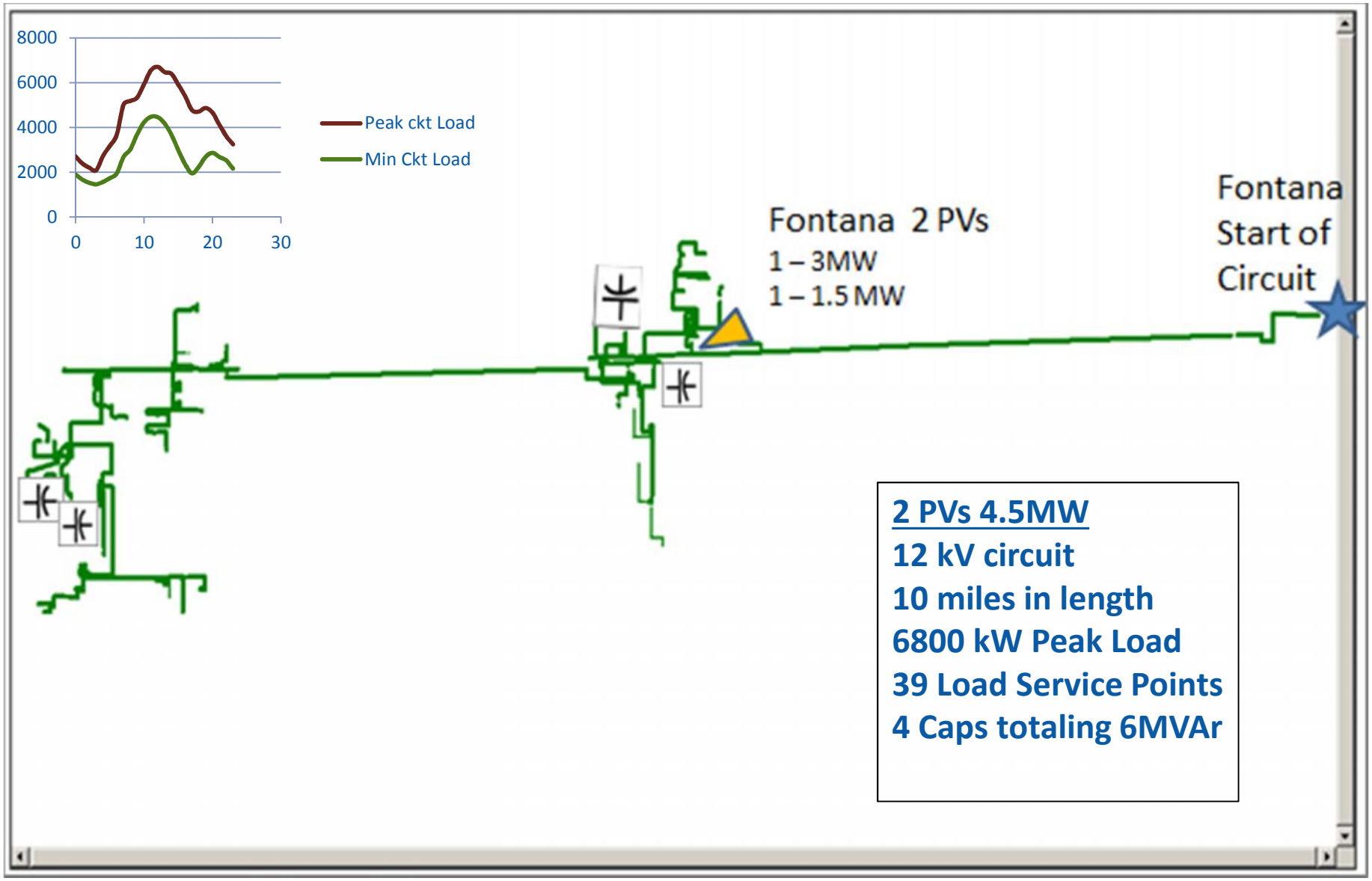
- If PV variability will be 80% or less
- If PV variability will be 60% or less and if circuit voltage variations caused by PV variability are allowed to have similar voltage variations to that of capacitor switching

Fontana

issue

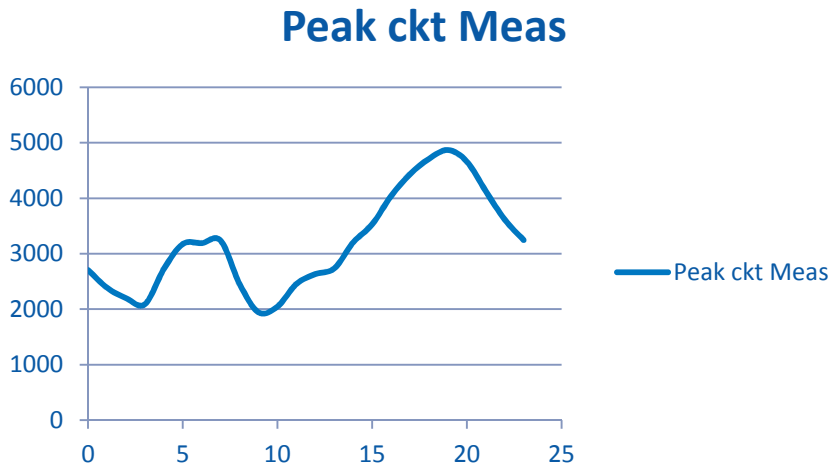
Voltage Rise/Fall with PV Variability

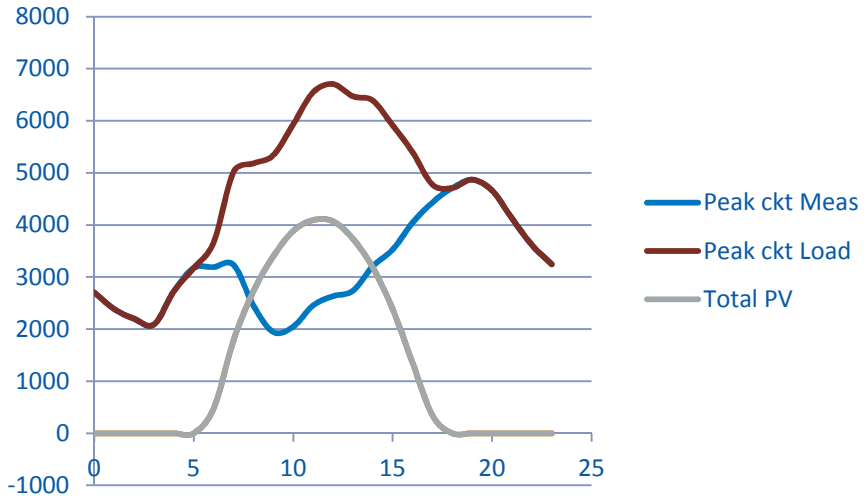
Fontana Circuit Model

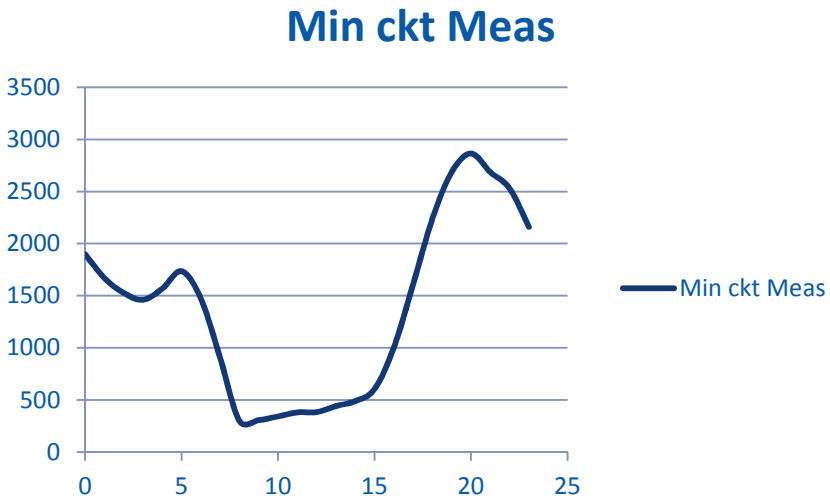


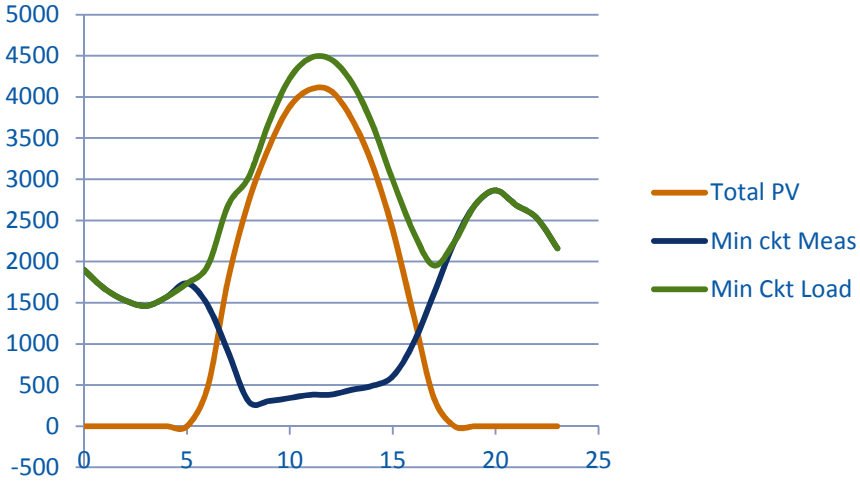
2 PVs 4.5MW
12 kV circuit
10 miles in length
6800 kW Peak Load
39 Load Service Points
4 Caps totaling 6MVAr

Fontana Circuit Model – Load Analysis









Fontana Step Change

Violations for Scenario 100% - 25% @ 1.00pf (% of Rated KW)

Analysis Time Filter:
- [x] 6/26/2011 11:00:00 AM (28 passed; 23 failed)
- [x] 9/7/2011 12:00:00 PM (39 passed; 12 failed)
- [x] 11/24/2011 7:00:00 AM (30 passed; 21 failed)

Feeder Filter:
- [x] Calabash Circuit

Component Type Filter:
- [ ] Switched Shunt Capacitor
- [x] Inverter Type DR
- [x] Breaker

Violation Type Filter:
- [x] Initial Overvoltage
- [x] Initial Undervoltage
- [x] PV Step Down Overvoltage
- [x] PV Step Down Undervoltage
- [x] PV Step Up Overvoltage
- [x] PV Step Up Undervoltage
- [x] POI Initial Overvoltage
- [x] POI Step Down Overvoltage
- [x] POI Step Up Overvoltage
- [x] Step Down Voltage Change/Flicker

[x] Failures Only

Analysis Time	Feeder	Cmp Name	Component Type	Violation Type	Criterion	Calc Value	Difference	% Viol	Pass/Fail
6/26/2011 11:00 AM	Calabash Circuit	PV 1.5MW/12kV	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	2.19	1.49	213.4	Fail
6/26/2011 11:00 AM	Calabash Circuit	PV 1.5MW/12kV	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	2.19	1.49	213.4	Fail
9/7/2011 12:00 PM	Calabash Circuit	PV 1.5MW/12kV	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	2.25	1.55	221.3	Fail
9/7/2011 12:00 PM	Calabash Circuit	PV 1.5MW/12kV	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	2.25	1.55	221.3	Fail
11/24/2011 7:00 AM	Calabash Circuit	PV 1.5MW/12kV	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	1.99	1.29	184.1	Fail
11/24/2011 7:00 AM	Calabash Circuit	PV 1.5MW/12kV	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	1.99	1.29	184.1	Fail
6/26/2011 11:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Initial Overvoltage	126.00	127.22	1.22	1.0	Fail
6/26/2011 11:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Step Up Overvoltage	126.00	127.22	1.22	1.0	Fail
6/26/2011 11:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	1.92	1.22	173.8	Fail
6/26/2011 11:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	1.92	1.22	173.8	Fail
9/7/2011 12:00 PM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	1.96	1.26	180.7	Fail
9/7/2011 12:00 PM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	1.96	1.26	180.7	Fail
11/24/2011 7:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Initial Overvoltage	126.00	126.52	0.52	0.4	Fail
11/24/2011 7:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Step Up Overvoltage	126.00	126.52	0.52	0.4	Fail
11/24/2011 7:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Voltage Change/Flicker (PV Step Down)	0.70	1.73	1.03	147.0	Fail
11/24/2011 7:00 AM	Calabash Circuit	PV 3MW/480v	Inverter Type DR	POI Voltage Change/Flicker (PV Step Up)	0.70	1.73	1.03	147.0	Fail

Fontana Device Movement

	No PV					With PV			
	Cap 1	Cap 2	Cap 3	Total		Cap 1	Cap 2	Cap 3	Total
Total Movement	668	17	335	1020		668	4	8	680
Jan	Not analyzed----------								
Feb	56	3	14	73		56		2	58
Mar	62	6	24	92		62			62
Apr	60	4	43	107		60			60
May	62		50	112		62		2	64
Jun	60		41	101		60			60
Jul	62	2	40	104		62	2	2	66
Aug	62	2	32	96		62	2	2	66
Sep	60		40	100		60			60
Oct	62		27	89		62			62
Nov	60		19	79		60			60
Dec	62		5	67		62			62
Total switches (1 on and 1 off represents a count of 2)									

Fontana PV Variability

Fontana PV Output - Minute over Minute Variation		
Change in Output	Loss of output (instances)	Gain in output (instances)
> 1/3 of Rated Output	51	75
> 1/2 of Rated Output	17	15
>3/4 of Rated Output	0	0

PV Assessment – Fontana Fault Analysis

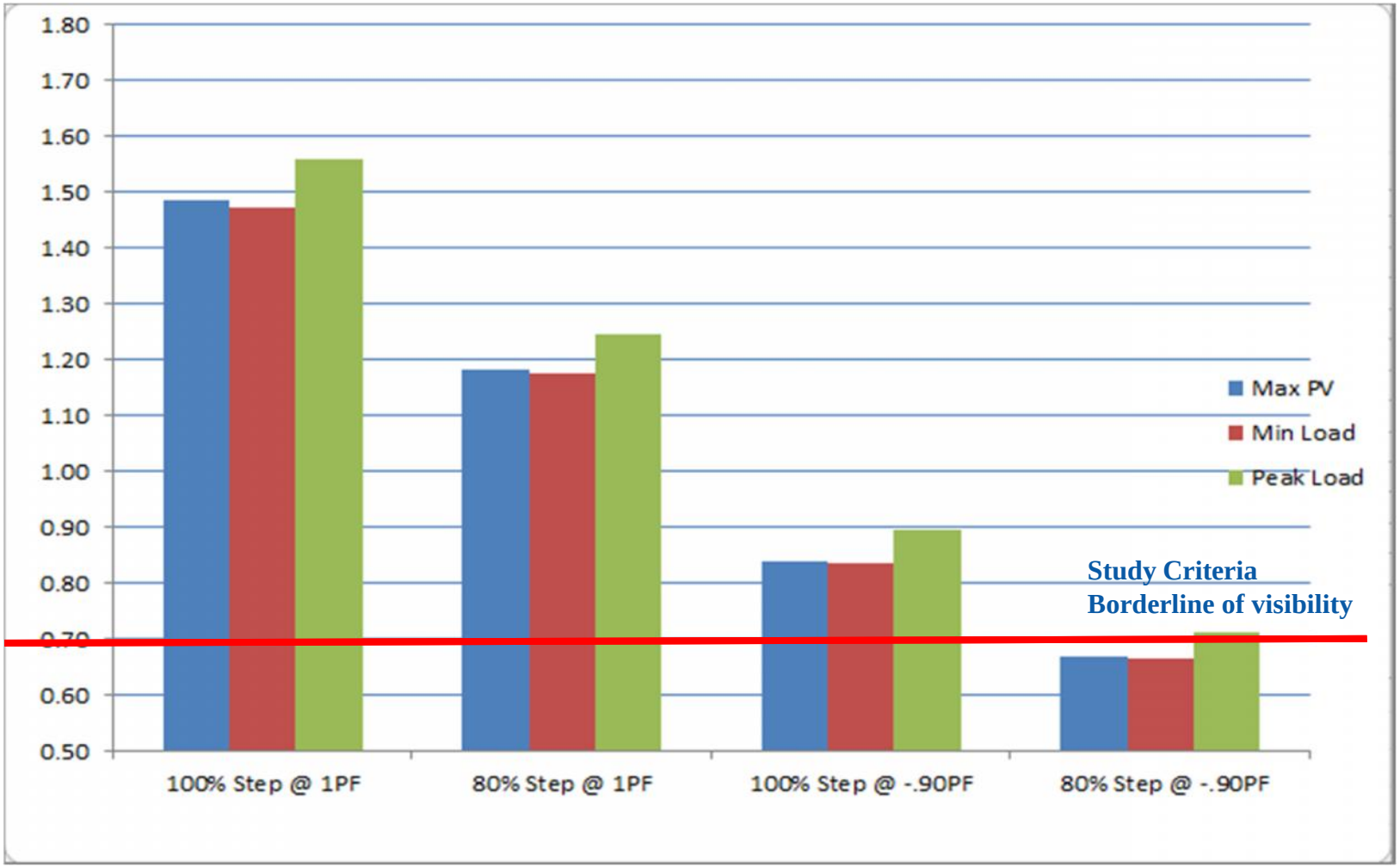
Protection Review w/wo PV

- Percent increase in fault current at protective devices

Fontana Circuit Location	System Fault Current at the POI Without PV	PV Fault Current 1.1 x Full load	Ratio
3MW PV	2250 amps	160 amps	7%
1.5MW PV	2000 amps	80 amps	4%

- If sufficient faults current exist > 10% determine Loadability, Selectivity, & Sensitivity Impacts and effects on protective margins

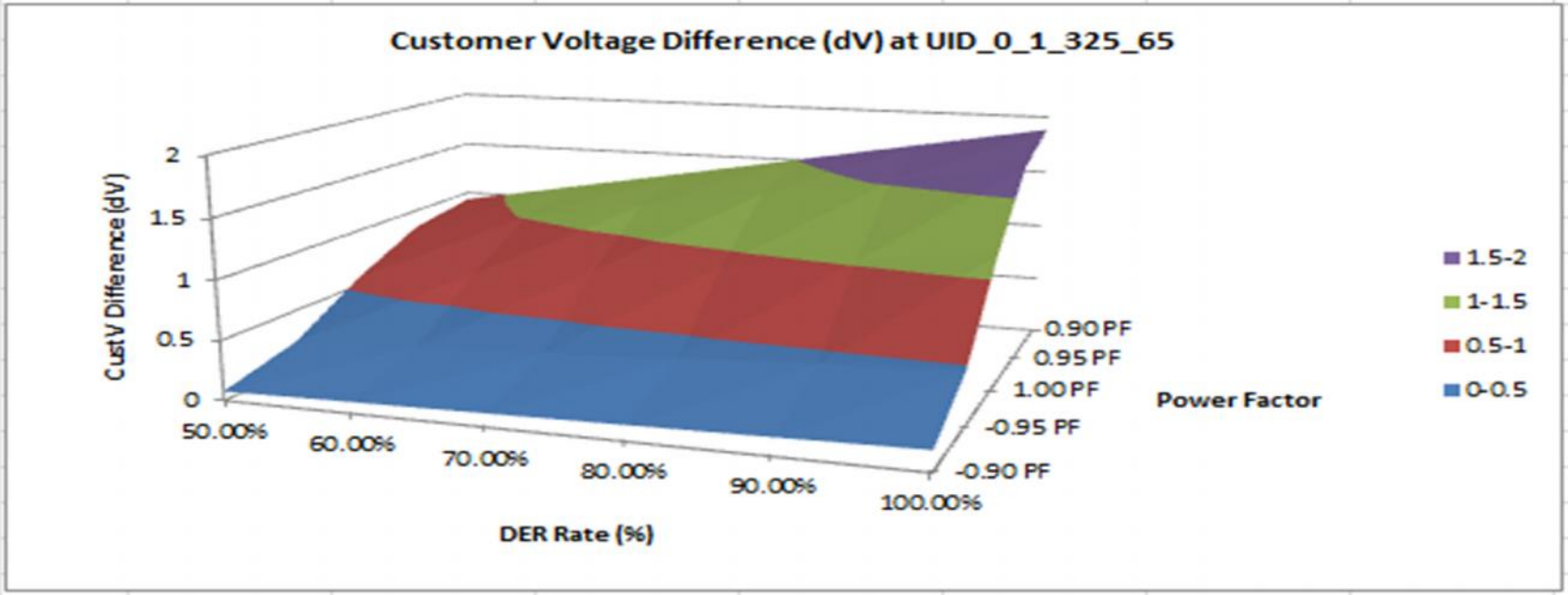
Mitigation using Variability and Power Factor



Mitigation using Variability and Power Factor

- Customer Voltage Variation at PV 2MW/480v (UID: UID_0_1_325_65, Type: PV)

		Power Factor				
		-0.90 PF	-0.95 PF	1.00 PF	0.95 PF	0.90 PF
DER (%)	50.00%	0.0795	0.2302	0.5732	0.8434	0.9337
	60.00%	0.0963	0.2777	0.6883	1.0142	1.1232
	70.00%	0.1137	0.3258	0.8041	1.1857	1.3135
	80.00%	0.1315	0.3743	0.9205	1.358	1.5046
	90.00%	0.1499	0.4234	1.0374	1.531	1.6965
	100.00%	0.1712	0.4755	1.155	1.7023	1.8867



Mitigation Summary for Fontana

3 MW PV 1 100% Loss and Return of PV Output									
		09/07/11		11/24/11			06/26/11		
		Max (Peak) Load Day			Min (Low) Load Day			Max PV Day	
Analysis Time Points	PF = 1	PF = - .95 Absorbing	Table No	PF = 1	PF = - .95 Absorbing	Table No	PF = 1	PF = - .95 Absorbing	Table No
Max Load Time		0	1-1	1	0	1-2	1	0	1-3
Min Load Time	0	0	NA	0	0	NA	0	0	NA
Max PV Time	1	0	1-4	1	0	1-5	1	0	1-6
Max Difference (Native Load - PV) Time	1	0	1-7	1	0	1-8	1	0	1-9
0 - Means no criteria violations									
1 - Means criteria violation (Voltage Rise over 0.7 Volts on 120v base)									

Mitigation Summary for Fontana

		Power Factor				
		-0.90 PF	-0.95 PF	1.00 PF	0.95 PF	0.90 PF
Final DER Loss	50%	-0.18	0.05	0.59	1.06	1.23
	60%	-0.22	0.07	0.72	1.28	1.48
	70%	-0.25	0.08	0.84	1.50	1.73
	80%	-0.28	0.10	0.96	1.72	1.99
	90%	-0.31	0.12	1.09	1.94	2.24
	100%	-0.33	0.14	1.22	2.16	2.50

Voltage Change on a 120Volt Base @ the POI

Summary of PV Analysis for Fontana

Mitigation

- Set fixed power factor setting of -95% Absorbing will resolve study criteria violations

No Mitigation

- If PV variability will be 60% or less
- If circuit voltage variations caused by PV variability are allowed to have similar voltage variations to that of capacitor switching

Summary

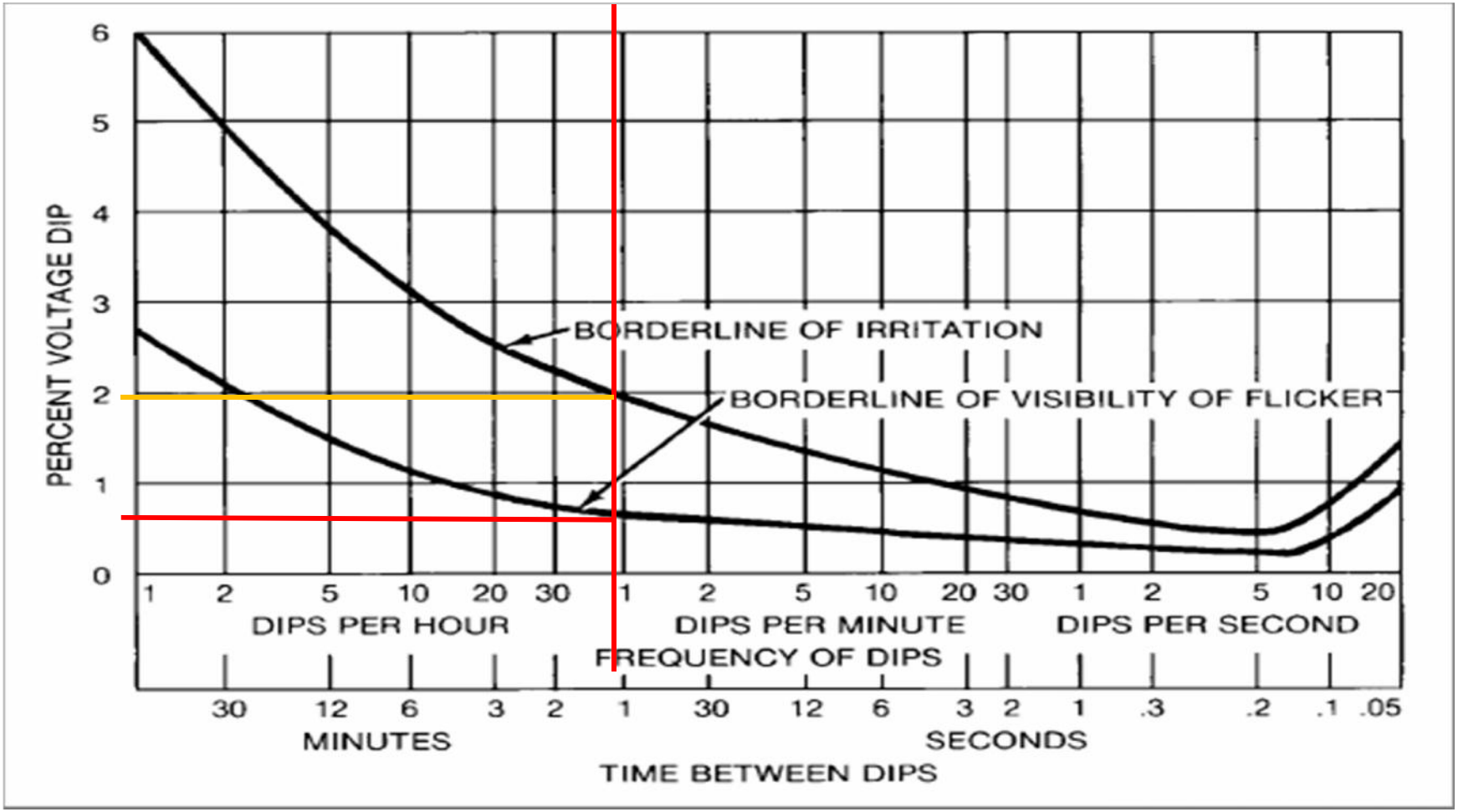
As part of this Hi Pen Project

- We have developed methodology for performing Hi Pen PV studies
- We have proposed a study criteria for evaluating impact of PV which is a function of existing utility design standards
- Developed various visualization tools for measuring the extent and frequency of potential problems as well as comparing mitigation measures.

EDD PV Assessment

Questions

Voltage Rise/Fall (Flicker)



Quasi-Static Time-Series and Transient Simulation Analysis Techniques for High PV Penetration

Farid Katiraei, Quanta Technology

Objectives

Time series or Quasi static (QS) time series analysis are part of high penetration PV impact studies for evaluation of:

- Impact of solar (generation) intermittency on voltage and power quality
- Impact of load & generation variations on operation of feeder control devices (voltage regulators, caps and LTC)

QS tools are new:

- How accurate and comparable is the results?
- What time step should be used (1 sec, 10 sec, 20 sec, etc.)?
- What it takes to make them a Utility – Grade study tool for day to day use
- What new models or library enhancement are needed?
- Develop benchmarks to evaluate controls for PV and analyze possible interaction among multiple PV plants

Methodology for Evaluating Tools

Using PSCAD/EMTDC as the reference for comparison

- The feeder under study is modeled in both PSCAD and OpenDSS
  - Control elements, variable generation and loads are implemented
  - 15 minute profiles are used for PV generators and variable loads
  - Apply PV systems with intermittent profile (15 min)
  - Incorporate variable loads with different profiles both for real and reactive power

Simulations are conducted in PSCAD (fix steps) and different time steps in OpenDSS

- The selected time steps are 5, 10, 15, 30, 40 and 50 seconds

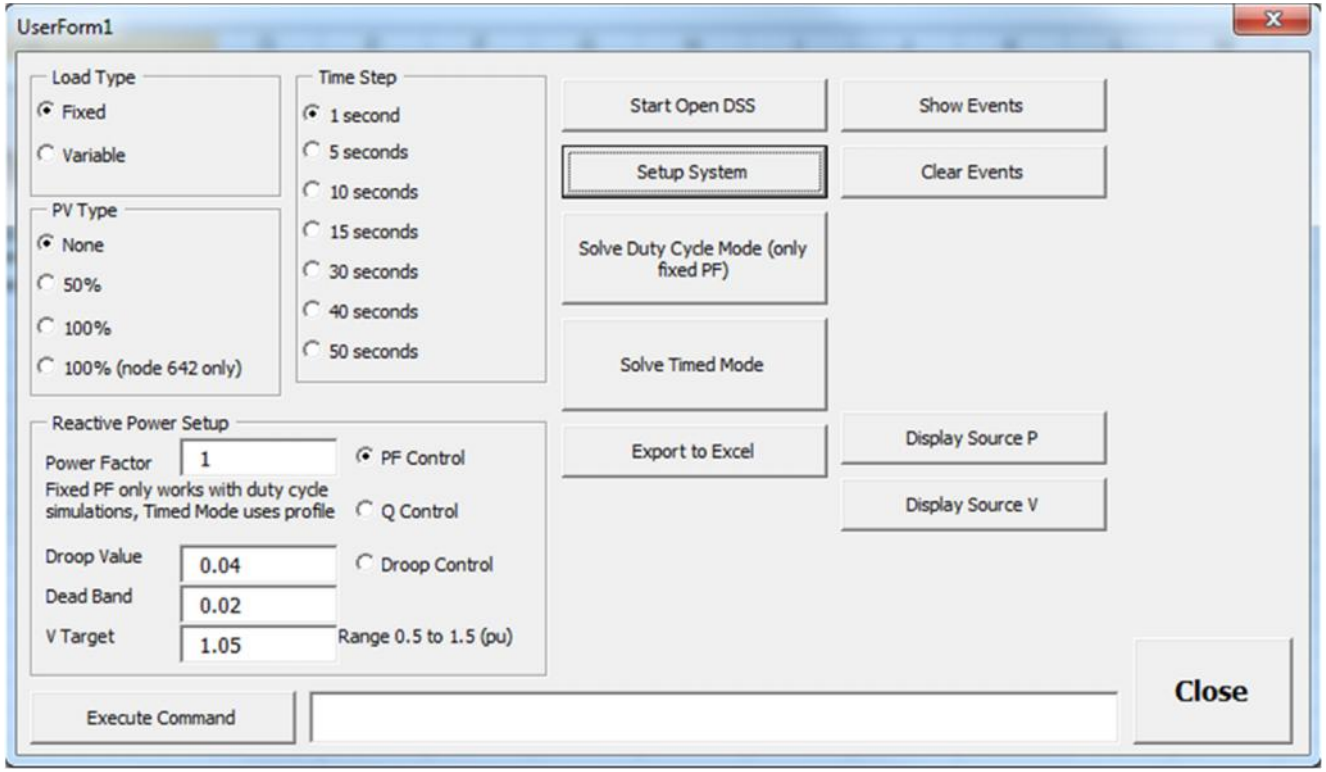
Comparison between the OpenDSS at different time steps and PSCAD results are made using:

- Voltage profile across the feeder
- Minimum and maximum tap settings,
- Number of changes for the different control elements

Enhancing PV Inverter Models

Implementing Voltage and Reactive Power control scheme for PV Inverter models:

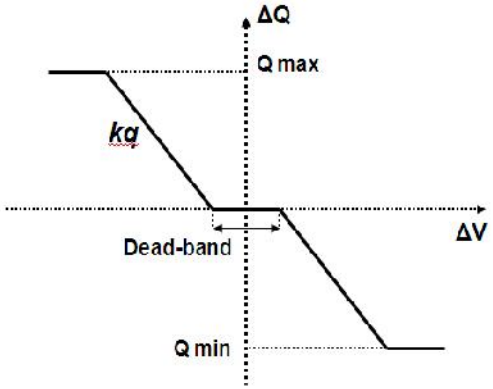
- Reactive power compensation - Variable Q control (with limits)
- Power Factor scheduling or Variable pf control (with limits)
- V-Q droop control

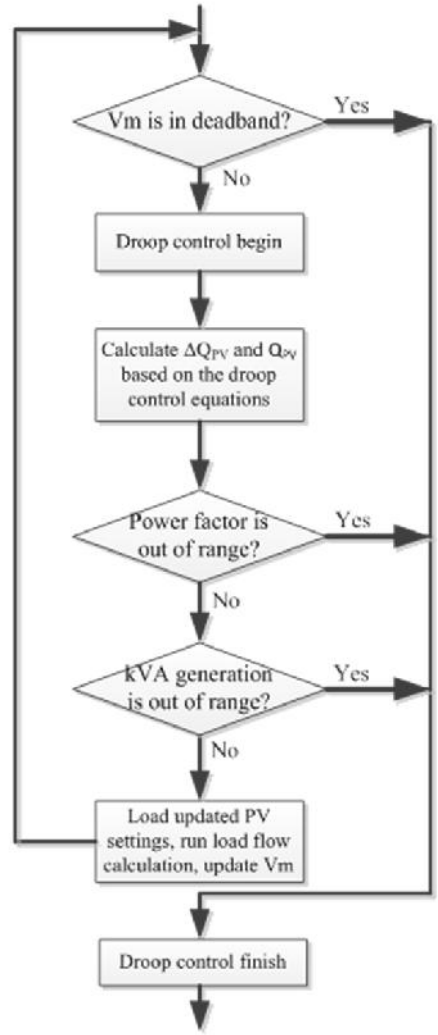


V(Q) Droop Control Scheme

PV inverter can dynamically adjust the voltage at a monitored location by following a V-Q droop control algorithm

- Droop control is a new and the most promising scheme
- Reactive power exchange with the system is determined based on severity of voltage change
- Avoiding excessive Q and/or possible low-freq. interactions





Benchmark for Study - IEEE 8500 Node

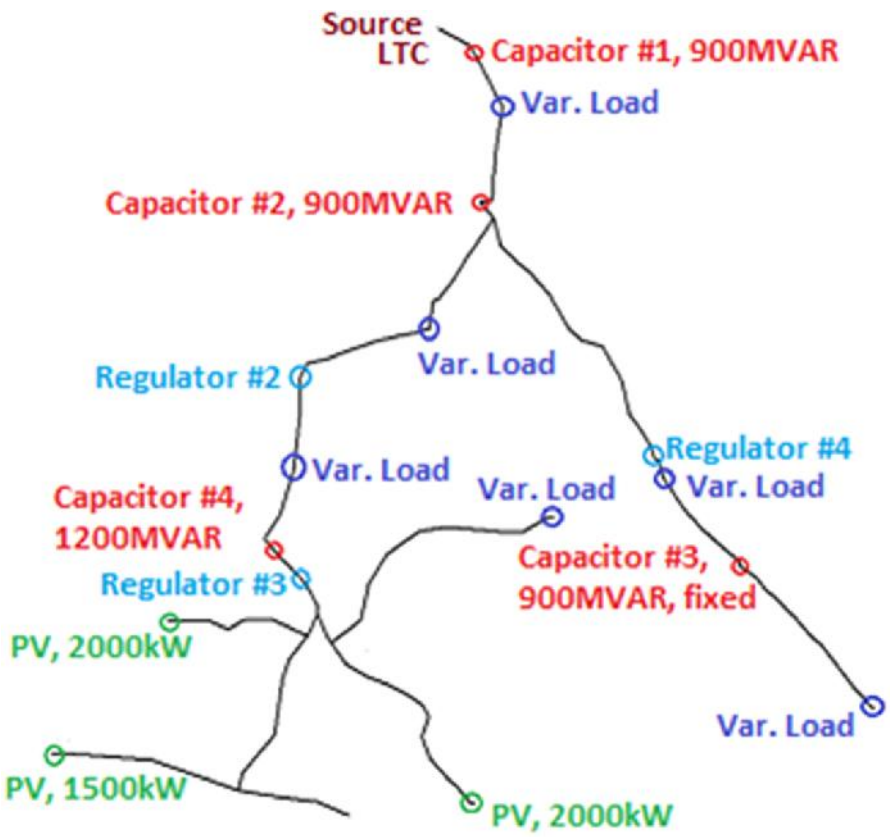
Reduced version of the IEEE 8500 node test feeder

- reduced to ***139*** nodes, representing the primary backbone feeder and associated branches
- LTC, 3 Voltage Regulators, and 4 Capacitors

Introduced 3 large PV plants

- Sized to cause reverse power flow through VR3 at 100% generation

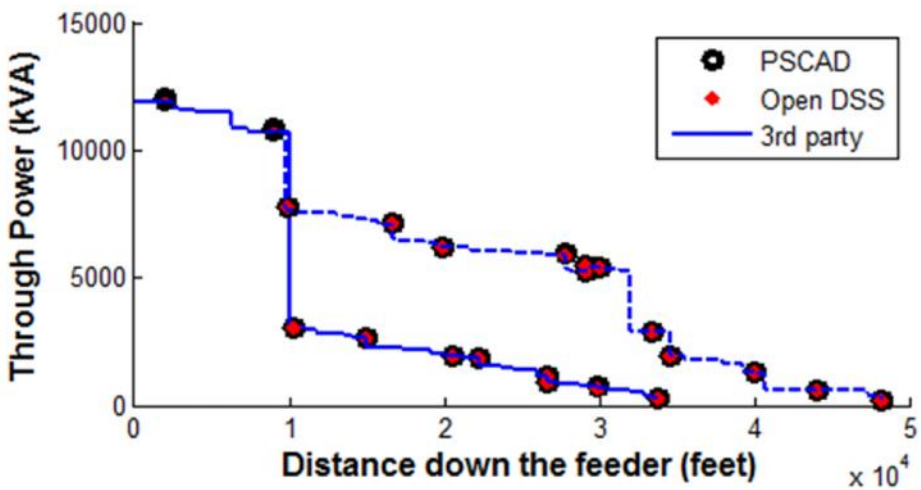
Five variable loads



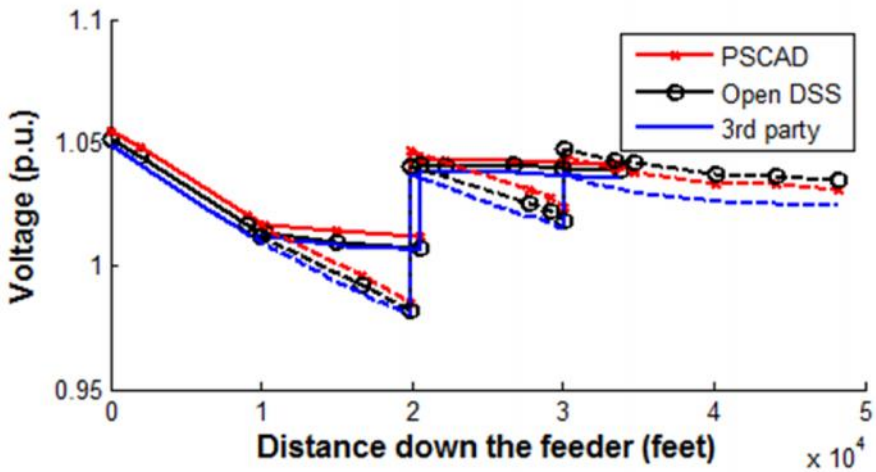
Model Verifications

Comparing power flow, voltage profiles and fault levels from OpenDSS with the results of other software tools:

- PSCAD/EMTDC
- Third Party commercial tool (utility grade)



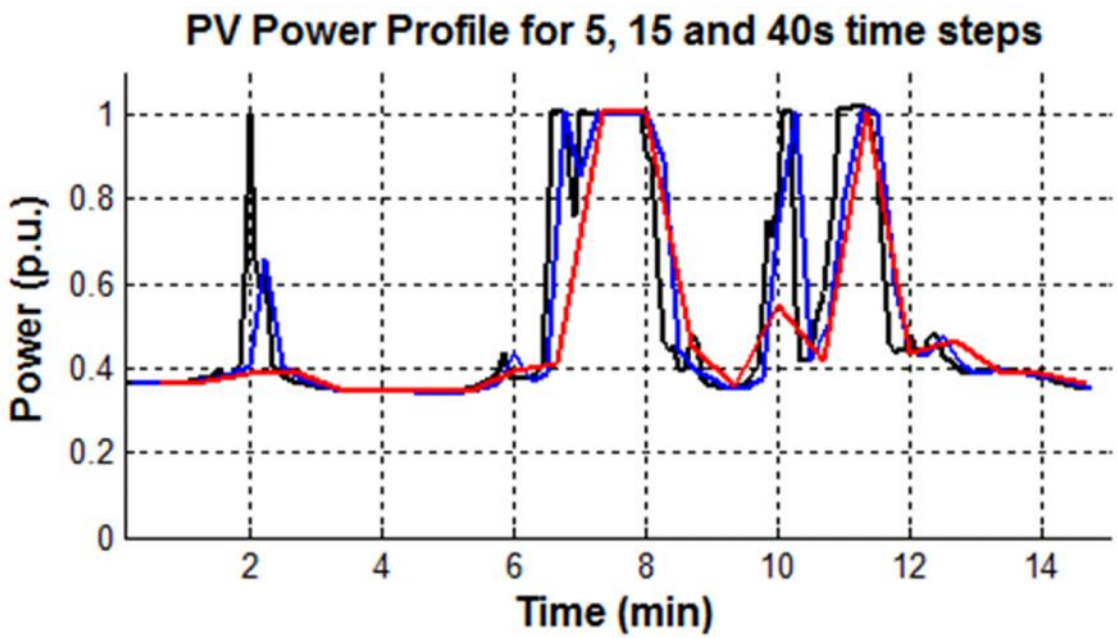
Power Flow Profile



Voltage Profile

Results and Findings - Profiles

Effect of time step on PV output power profile:



- 5 sec. interval provides good comparison between PSCAD and OpenDSS
- Above 30 seconds, the step size is too large to allow for timely operation of the control devices
- As the time step becomes larger, some fast changes will be eliminated because of sampling rate

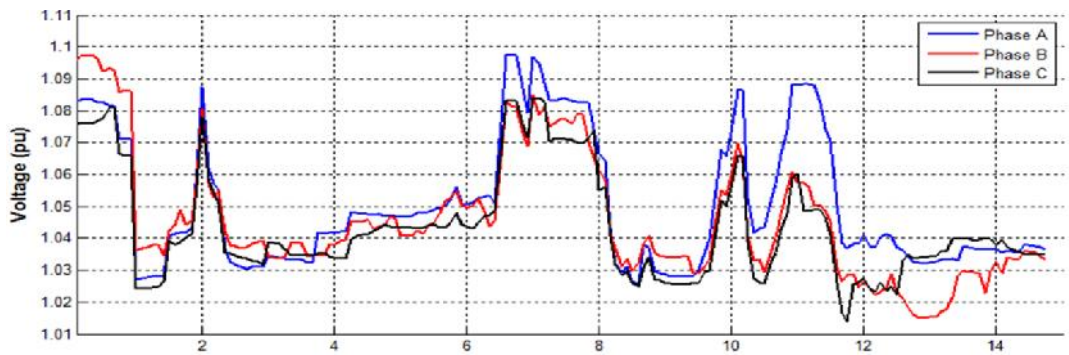
Results and Findings – Device Operation

Noticeable differences in # of operation and time of operation:

- In OpenDSS, both capacitors operate early, but in PSCAD, Cap #4 does not operate until much later.
- In PSCAD, the first capacitor operates and brings the voltage at Cap #4 below the maximum and prevents switching, which is delayed until the second generation peak.
- The time step in OpenDSS do not allow for this precision.

Need to assign/improve priority list

			PSCAD	OpenDSS					
				5s	10s	15s	30s	40s	50s
Load tap changer		Max	6	7	7	6	6	6	6
		Min	5	5	5	5	5	5	5
		# of changes	1	2	2	1	1	1	2
Reg. #3	A	Max	8	7	7	6	6	7	6
		Min	3	4	3	4	4	5	3
		# of changes	14	12	10	8	7	4	11
	B	Max	5	4	4	5	4	4	5
		Min	-1	-1	0	0	1	1	1
		# of changes	15	9	10	11	6	4	10
	C	Max	3	2	2	2	2	2	2
		Min	-2	-1	0	-1	-1	0	-1
		# of changes	14	11	7	7	7	3	9
Cap. #1		Opening time (s)	60.7	75	80	80	80	120	150
Cap. #4		Opening time (s)	487	75	80	80	80	120	150



Multiple Inverter Control Studies

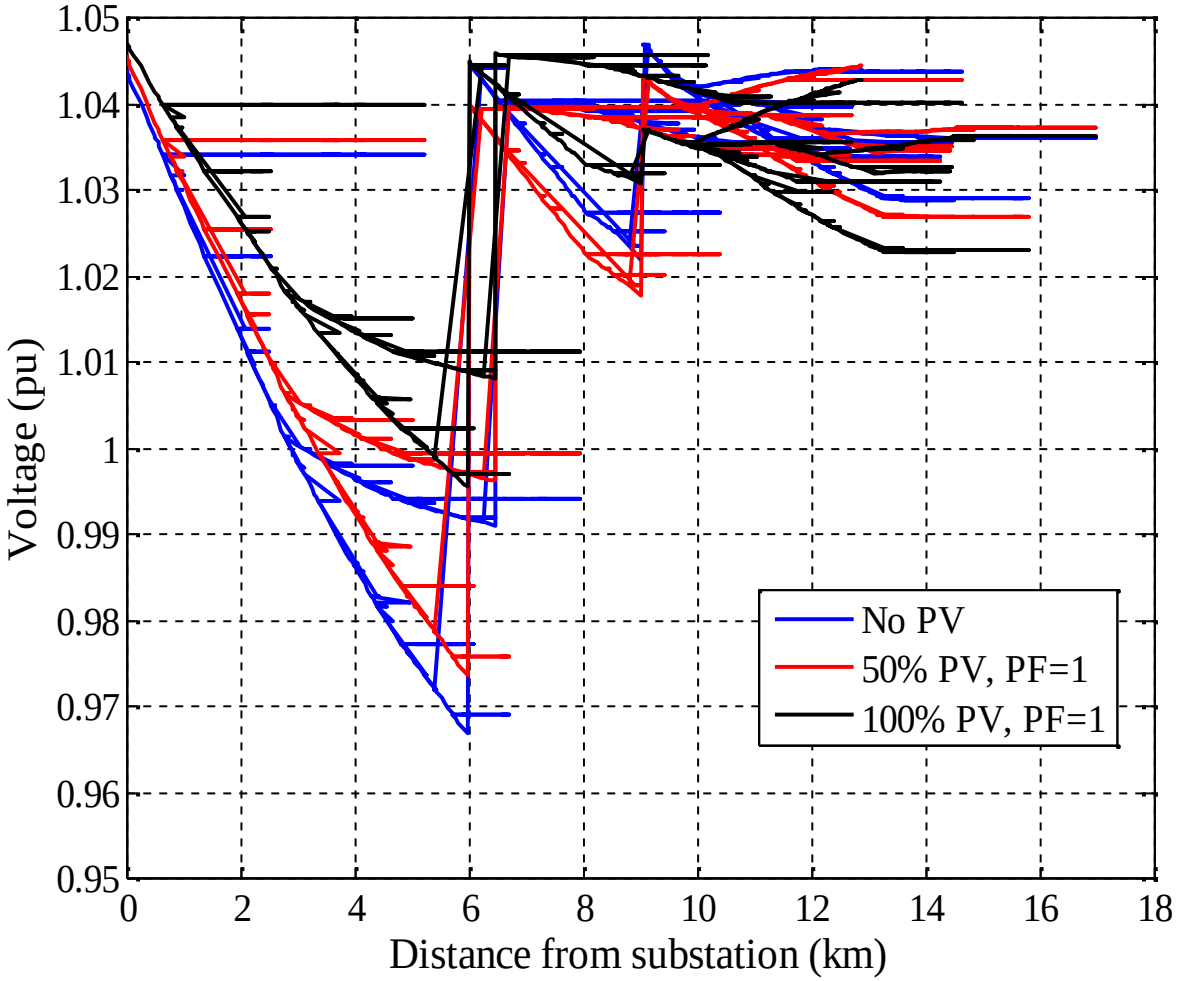
Find and compare applicable solutions for any of the following cases:

- 1 PV system (one of the 2MW unit): A PV control solution or no solution
- 2 PV systems (2 MW units): two different controls or same control, but different settings applied
- 3 PV systems: different controls or different settings.

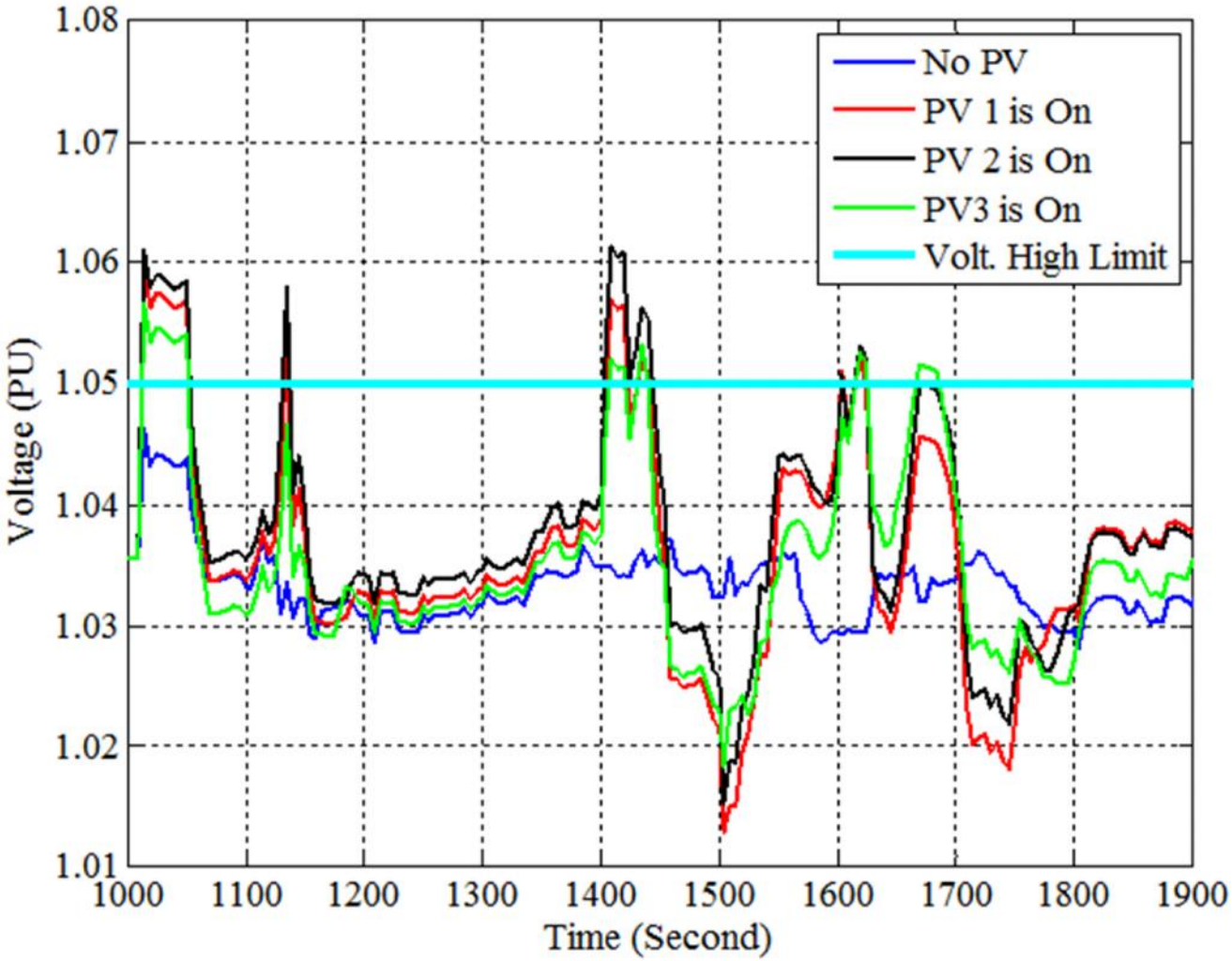
Determine if the mitigation solution would vary by the combination of the PV systems in service, as well as what type of control provides the most promising solution.

PV Impact on Feeder Voltage Profile

One of the 2 MW PV plants
Phase B voltage, distance from substation

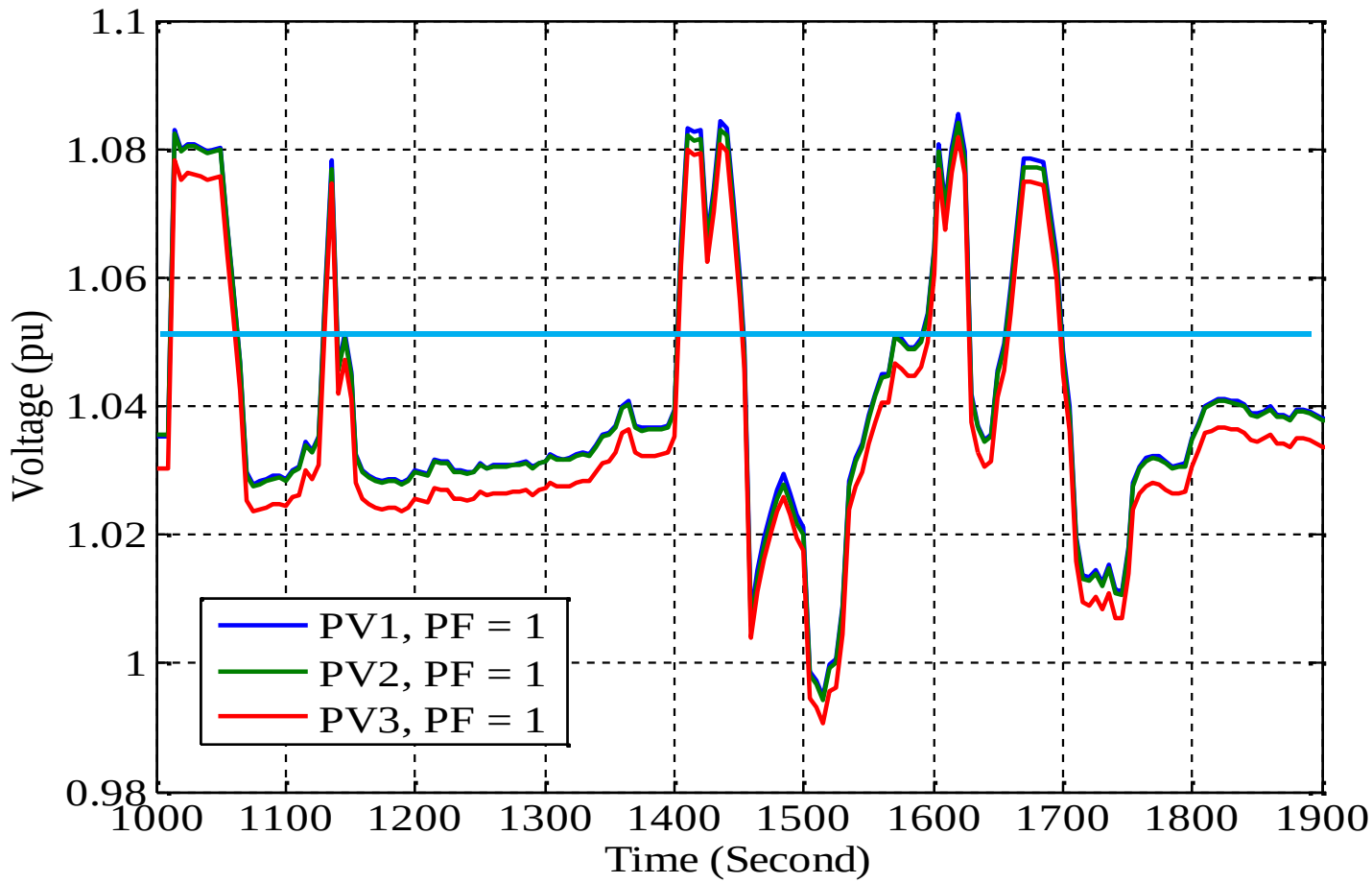


Voltage with Individual PV Systems

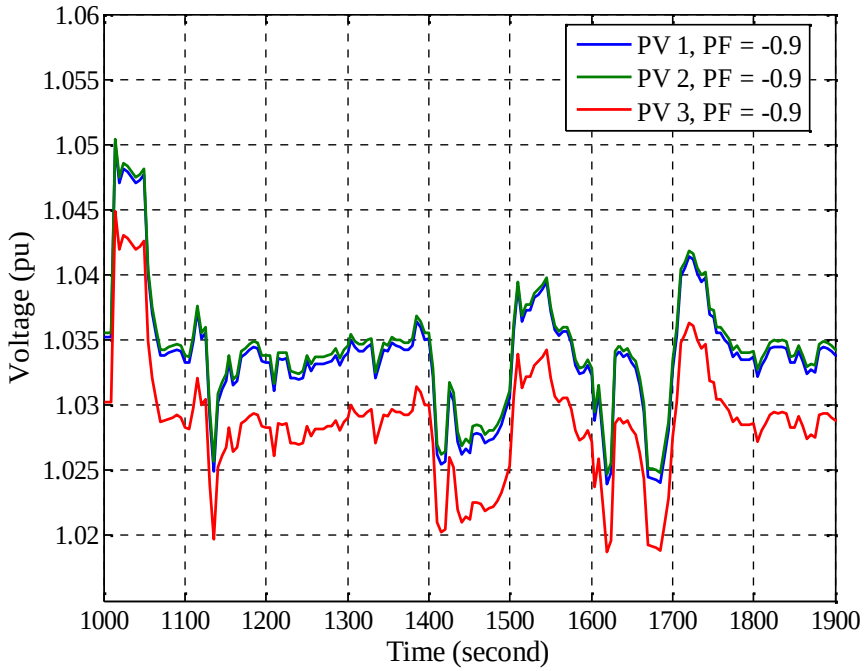


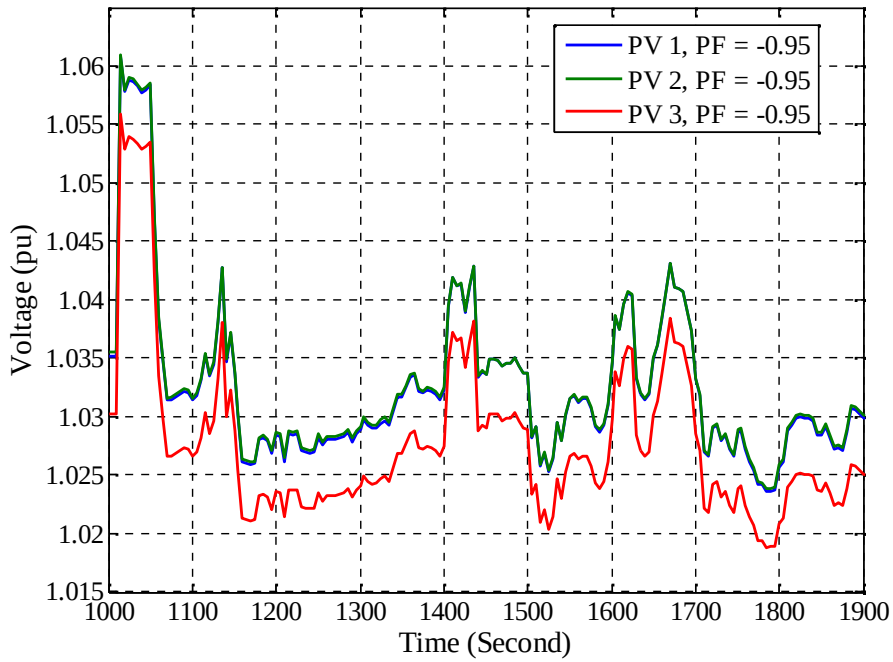
Variable PV & Variable Load

All PV Plants in service:



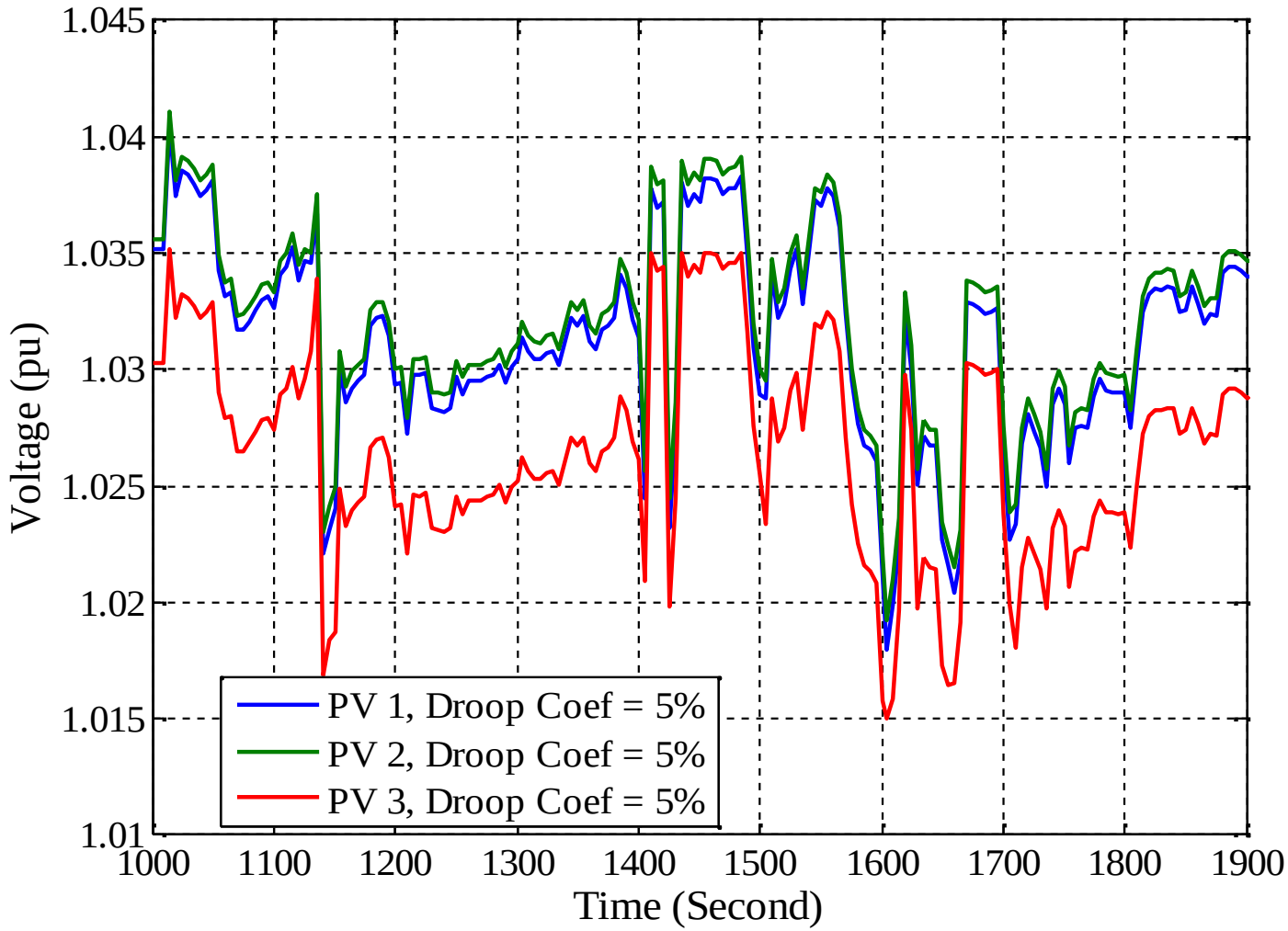
Mitigation - PF control





Comparing PF = -0.9 and -0.95

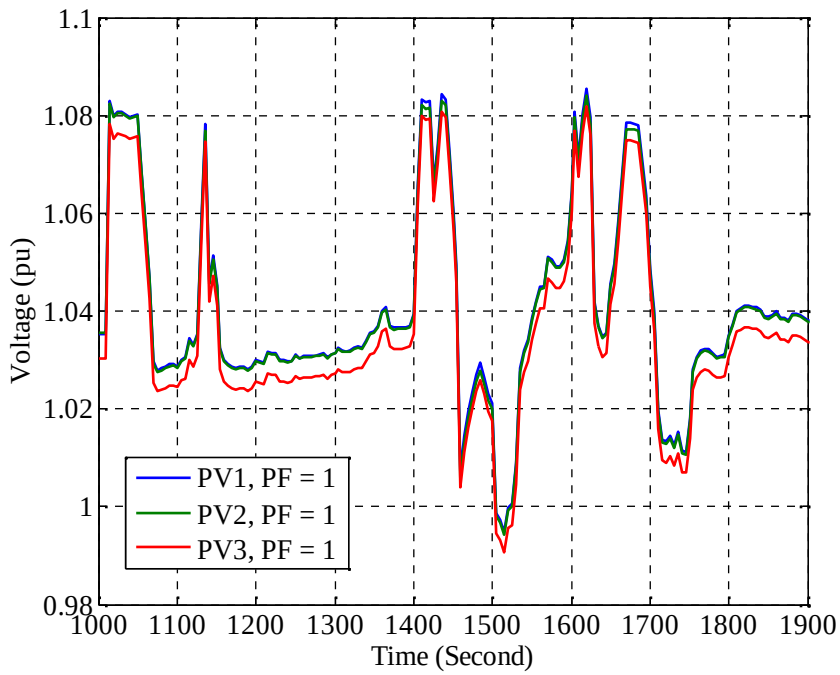
Mitigation - Droop Control

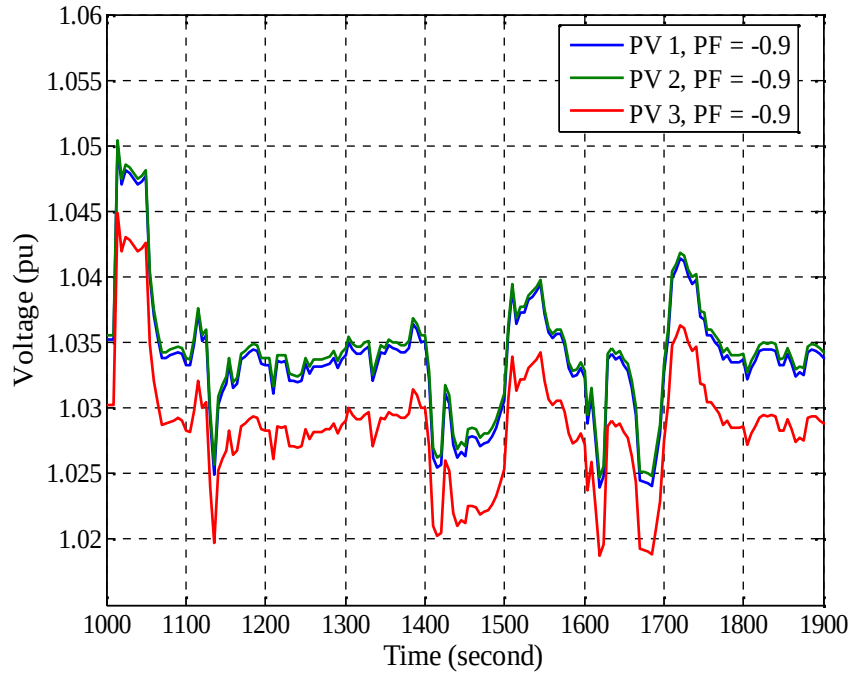


Simulations (case 1)

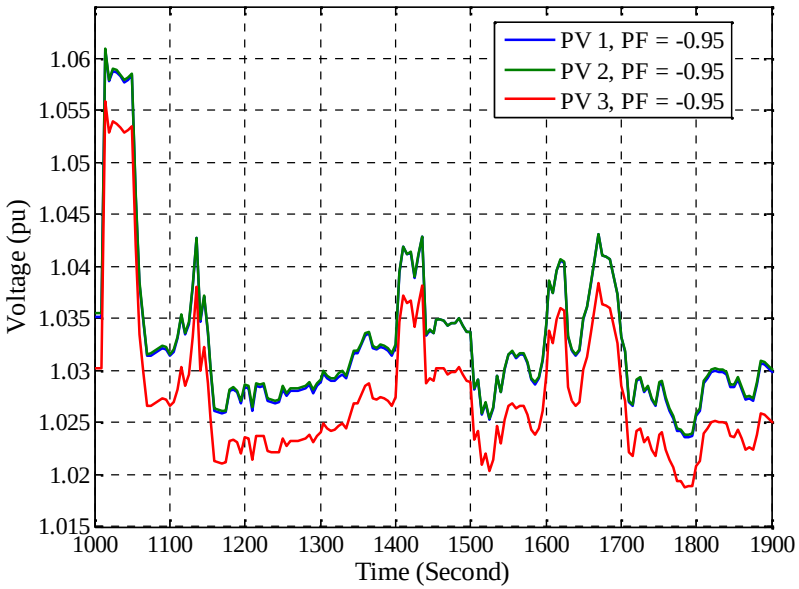
Variable PV profile and variable loads

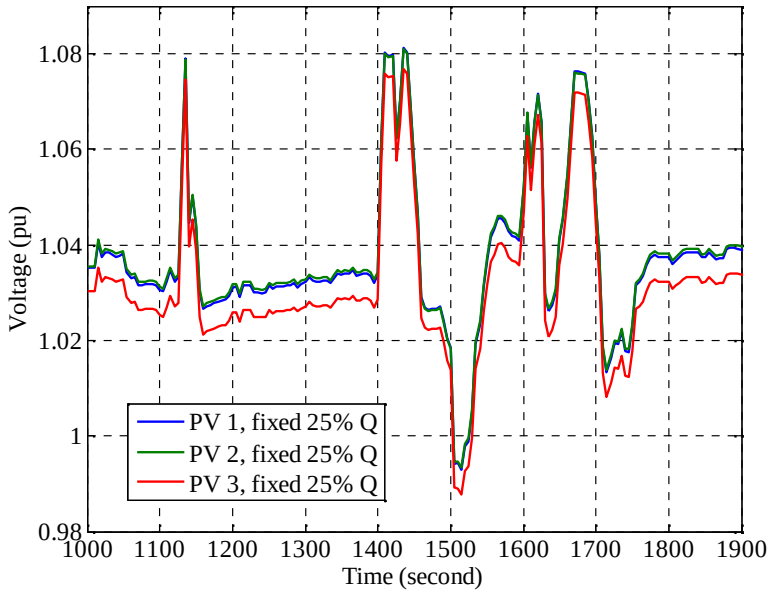
- PV with unity power factor
- PV with power factor 0.95 inductive or 0.9 inductive (anyone that is sufficient for 50% PV)
- PV with fixed reactive power absorption of 25% rated kVA power
- PV with droop control of 5% (reference voltage 1.025 pu, dead band 0.02 pu)

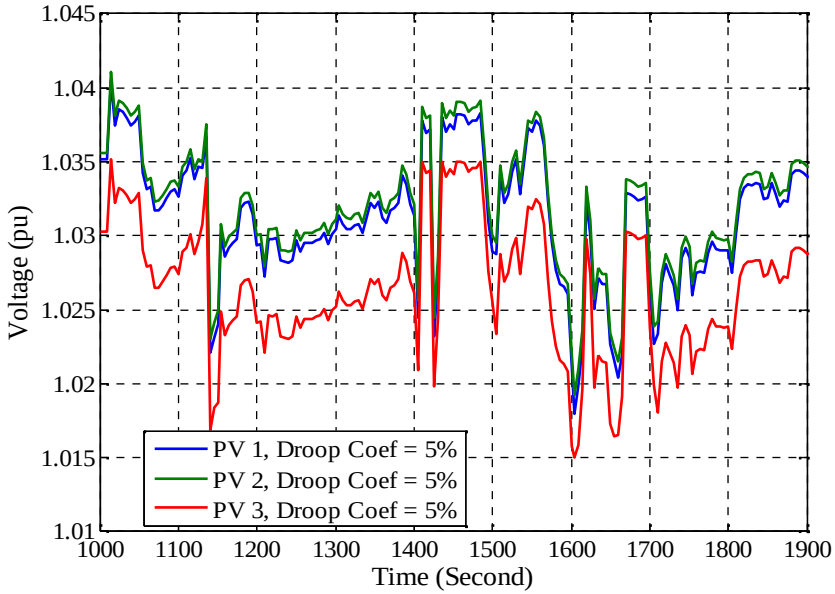




Simulations (case 1)



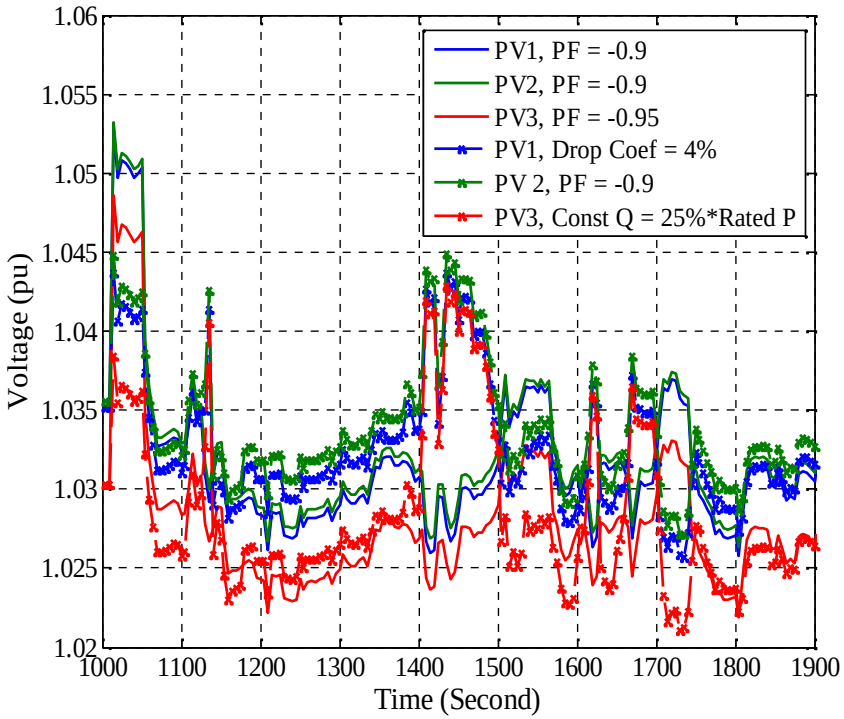


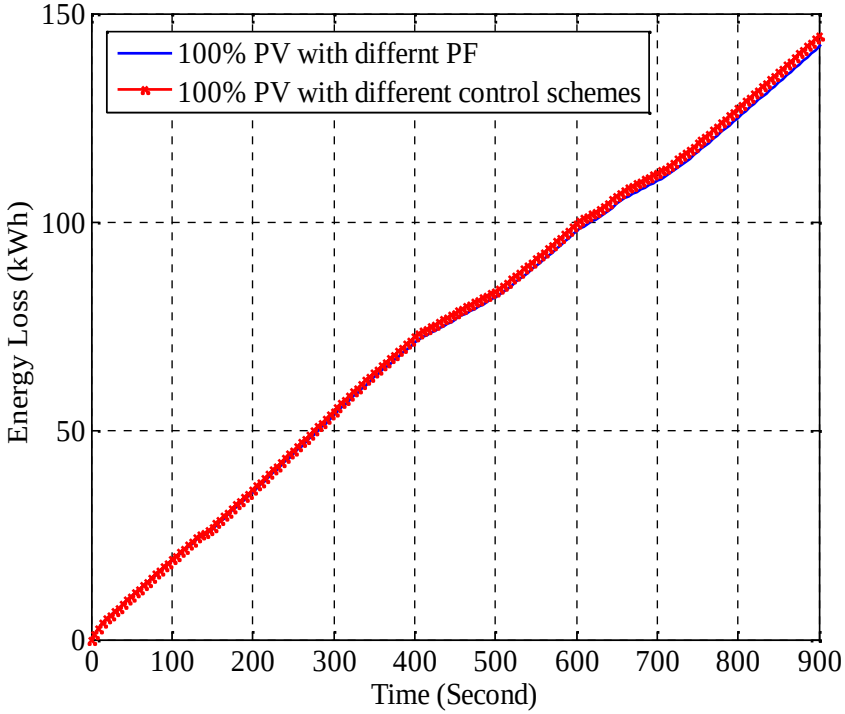


Simulations (case 2)

Investigate effects of utilizing different control schemes and/or different parameters for controls.

- PV units work in different control strategies
- PV1 works at 4% droop control mode (reference voltage =1.025 pu, deadband = 0.02 pu), PV2 works at 0.9 PF (absorbing Q) and PV3 works at fixed absorbing 25% rated 1.5 MW P or low limit power factor 0.85 (absorbing Q). Comparison case is PV units with different power factor.

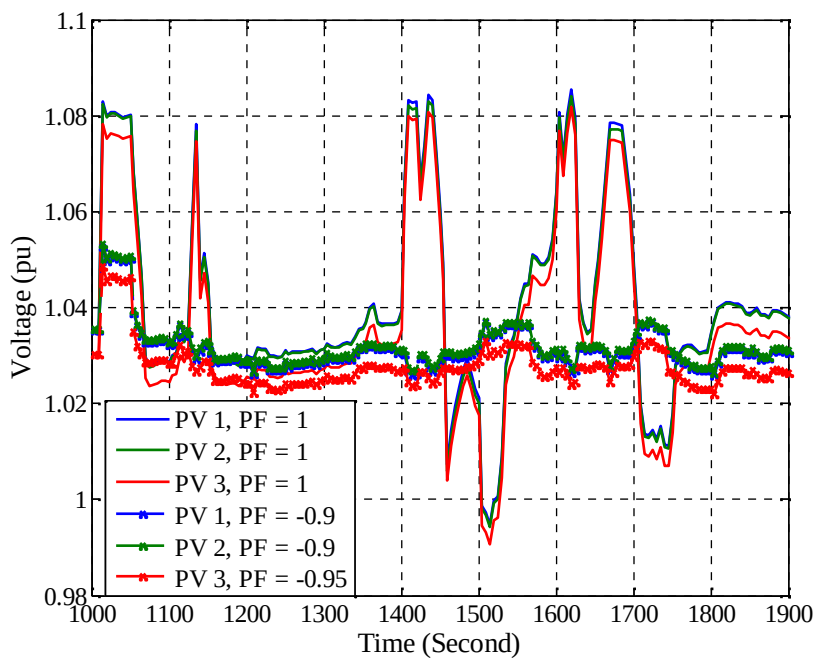


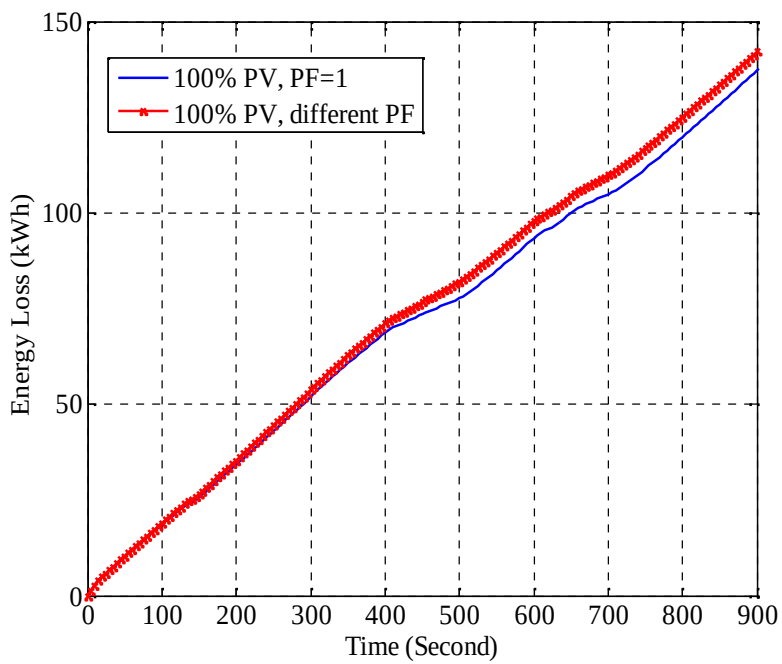


Simulations (case 2)

Investigate effects of utilizing different control schemes and/or different parameters for controls.

- PV Units with different power factors
- Simulation: Use variable load and variable solar radiation profile in this simulation. Set PV1 (2MW) power factor = -0.9, PV2 (2MW) power factor -0.9 and PV3 (1.5 MW) power factor=-0.95





Summary & Conclusions

Using time series analysis requires:

- Knowledge of proper selecting of time step (be aware!)
- Developing additional models
- Verifying the tools
- Automating the studies and model setup

- Mitigation solutions:
  - Verifying various control options for each PV system
  - Combination of different schemes for individual PVs (interactions)
  - Legacy Devices with fix setpoint control vs. new devices with dynamic controls

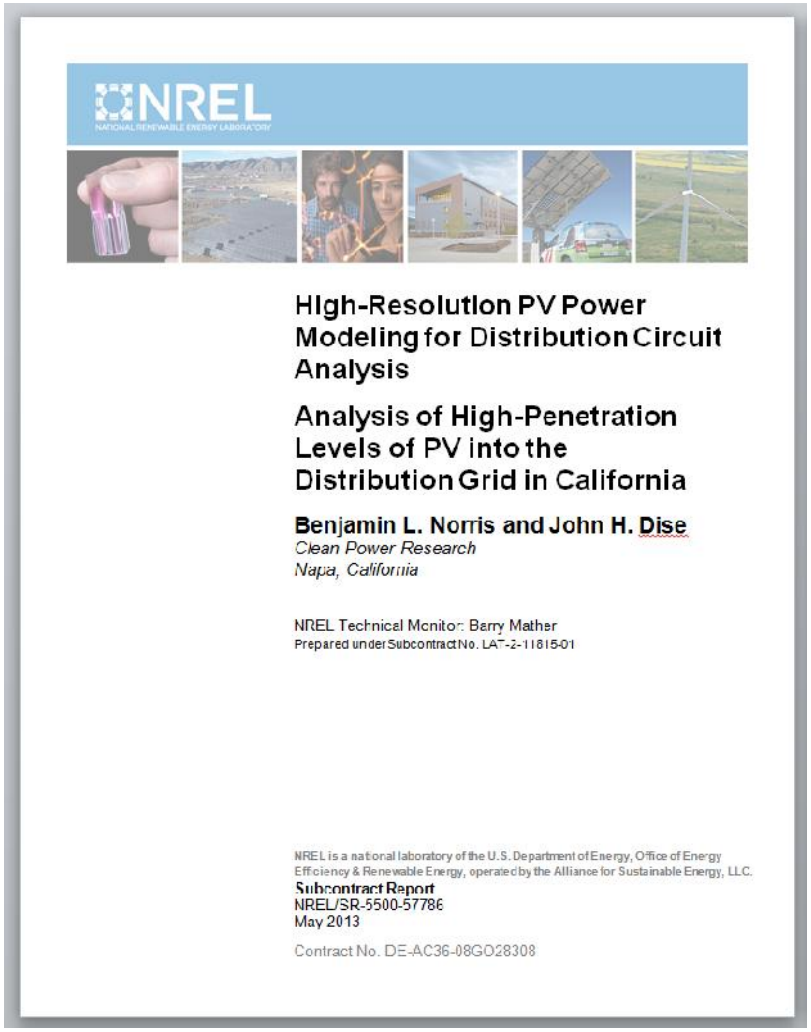
CPR: High-Res PV Resource Modeling

Motivation:

- Modern interconnection studies require increasingly complex and high-resolution data sets
- Methods to evaluate PV impacts are needed determine appropriate mitigation techniques

Findings:

- Publication describes a method using cloud-motion vectoring to create high temporal resolution PV resource data, appropriate for distribution system level PV impact studies, from 15-min or 30-min remote sensing data



NREL

NATIONAL RENEWABLE ENERGY LABORATORY

High-Resolution PV Power Modeling for Distribution Circuit Analysis

Analysis of High-Penetration Levels of PV into the Distribution Grid in California

Benjamin L. Norris and John H. Dise
Clean Power Research
Napa, California

NREL Technical Monitor: Barry Mather
Prepared under Subcontract No. LAT-2-11815-01

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Subcontract Report
NREL/SR-5500-57786
May 2013

Contract No. DE-AC36-08GO28308

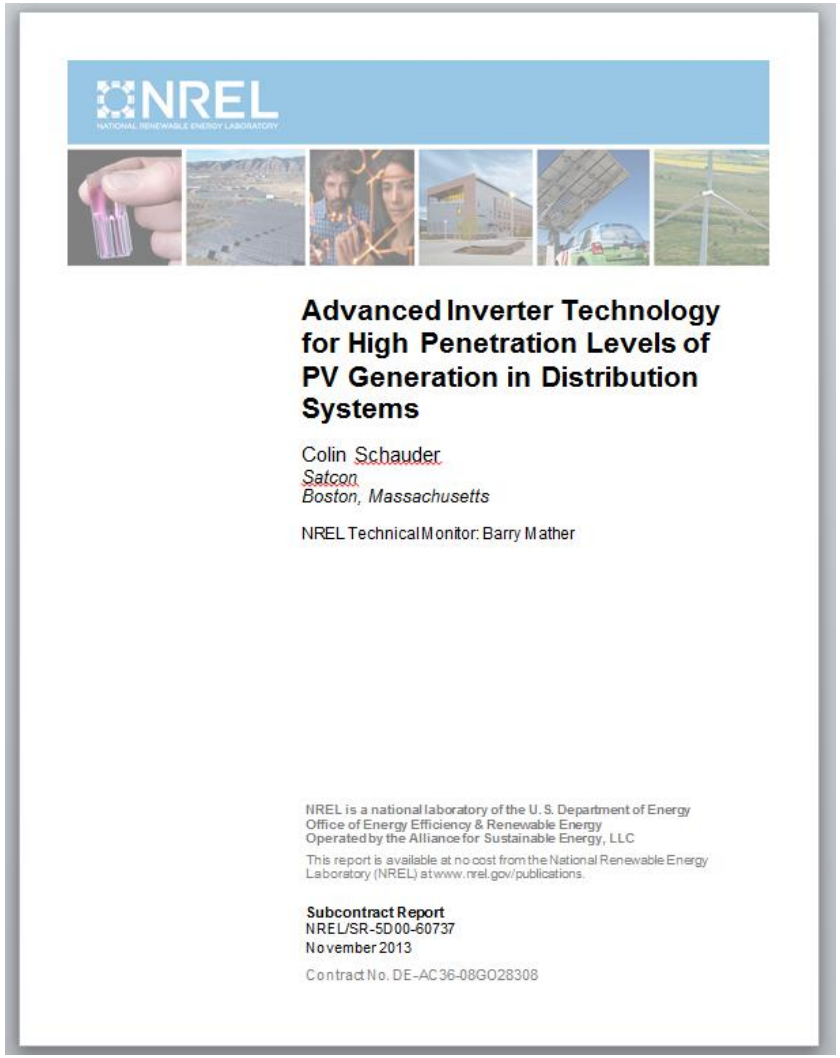
Satcon: Adv. PV Inverter Specifications

Motivation:

- Defines what capabilities exist within the primary PV system grid interface, the inverter, to potentially mitigate various impacts of high penetration PV such as:
  - Impact of solar (generation) intermittency on voltage and power quality
  - Impact of load & generation variations on operation of feeder control devices (voltage regulators, caps and LTC)
  - Specified PV inverter fault characteristics

Findings:

- Through the development of advanced PV inverter control the follow capabilities can be implemented with little additional equipment cost:
  - Reactive power control
  - Real power control
  - Steady-state voltage control
  - Fast automatic voltage control (flicker reduction)



NREL

Advanced Inverter Technology for High Penetration Levels of PV Generation in Distribution Systems

Colin Schauder
Satcon
Boston, Massachusetts

NREL Technical Monitor: Barry Mather

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Subcontract Report
NREL/SR-5D00-60737
November 2013

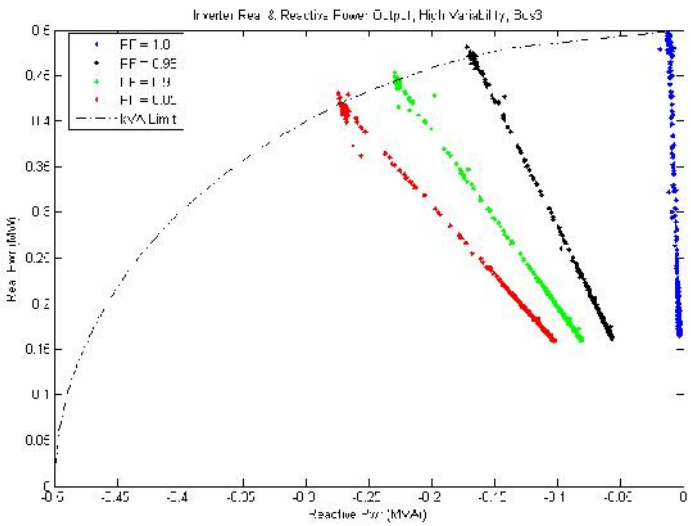
Contract No. DE-AC36-08GO28308

PHIL Testing of a Adv. PV Inverter

Motivation:

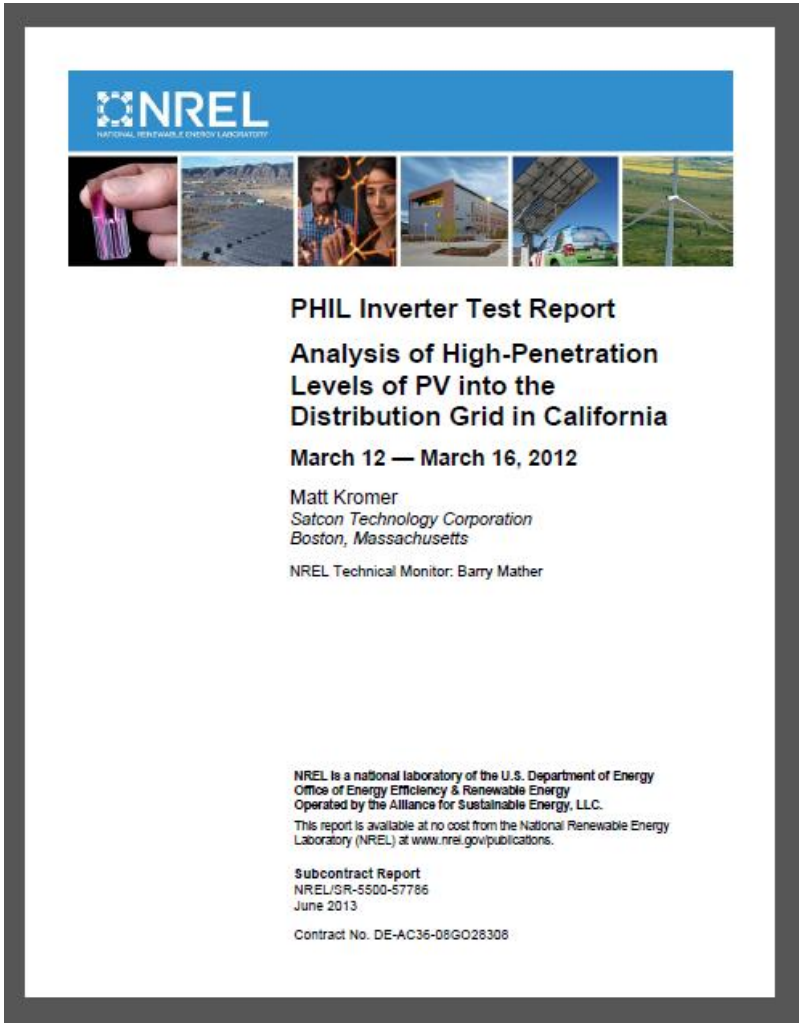
- Evaluate the ability/performance of a PV inverter to implement advanced PV mitigation functions: non-unity PF operation and constant kVAr set point operation
- Quantify the ability of such functions to mitigate PV impacts

Satcon: Adv. PV Inverter Lab Testing Report



Findings:

- Advanced PV inverter functions performed well except for PV inverter real power "fold back" under constant kVAr set point control (this was latter remedied by a slight modification in control tuning parameters)
- Power Hardware-in-Loop (PHIL) was demonstrated at the 500 kW level and the mitigation of PV impacts using the selected advanced functionality was verified



NREL

PHIL Inverter Test Report

Analysis of High-Penetration Levels of PV into the Distribution Grid in California

March 12 — March 16, 2012

Matt Kromer
Satcon Technology Corporation
Boston, Massachusetts

NREL Technical Monitor: Barry Mather

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Subcontract Report
NREL/SR-5500-57786
June 2013

Contract No. DE-AC36-08GO28308

Also see: J. Langston, K. Schoder, M. Steurer, O. Faruque, J. Hauer, R. Bravo, B. Mather, F. Katiraei, "Power hardware-in-the-loop testing of a 500kW photovoltaic array inverter," Proc. IEEE Indust. Electron. Conf., Montreal, Canada, Oct. 25-28, 2012, pp. 4797-4802.

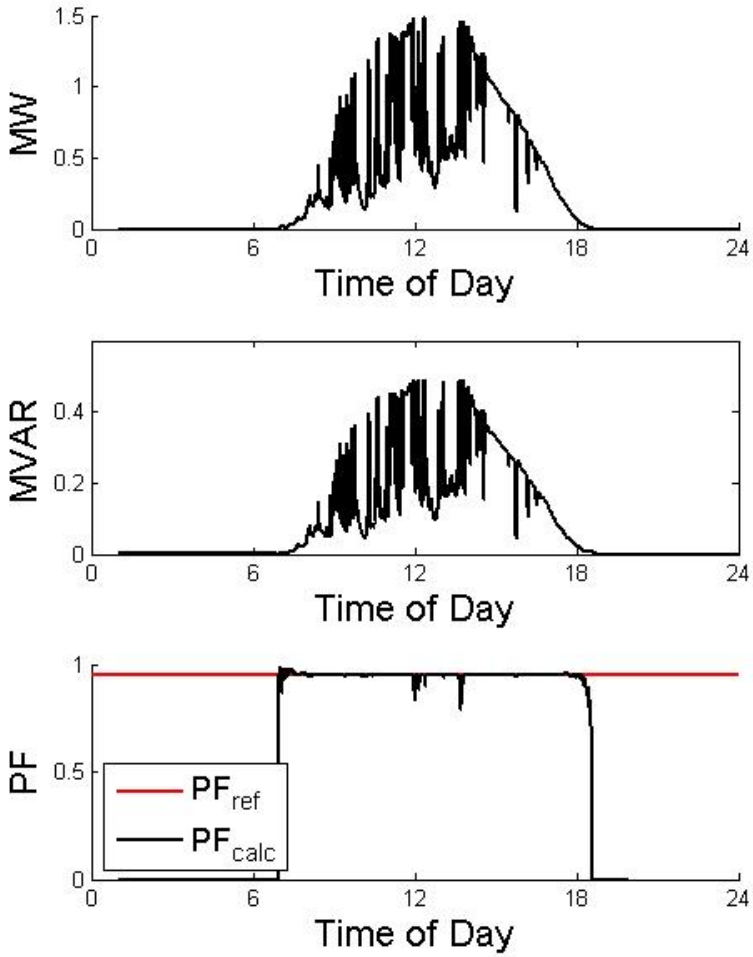
Field Deployment/Testing – Adv. Inverter

Motivation:

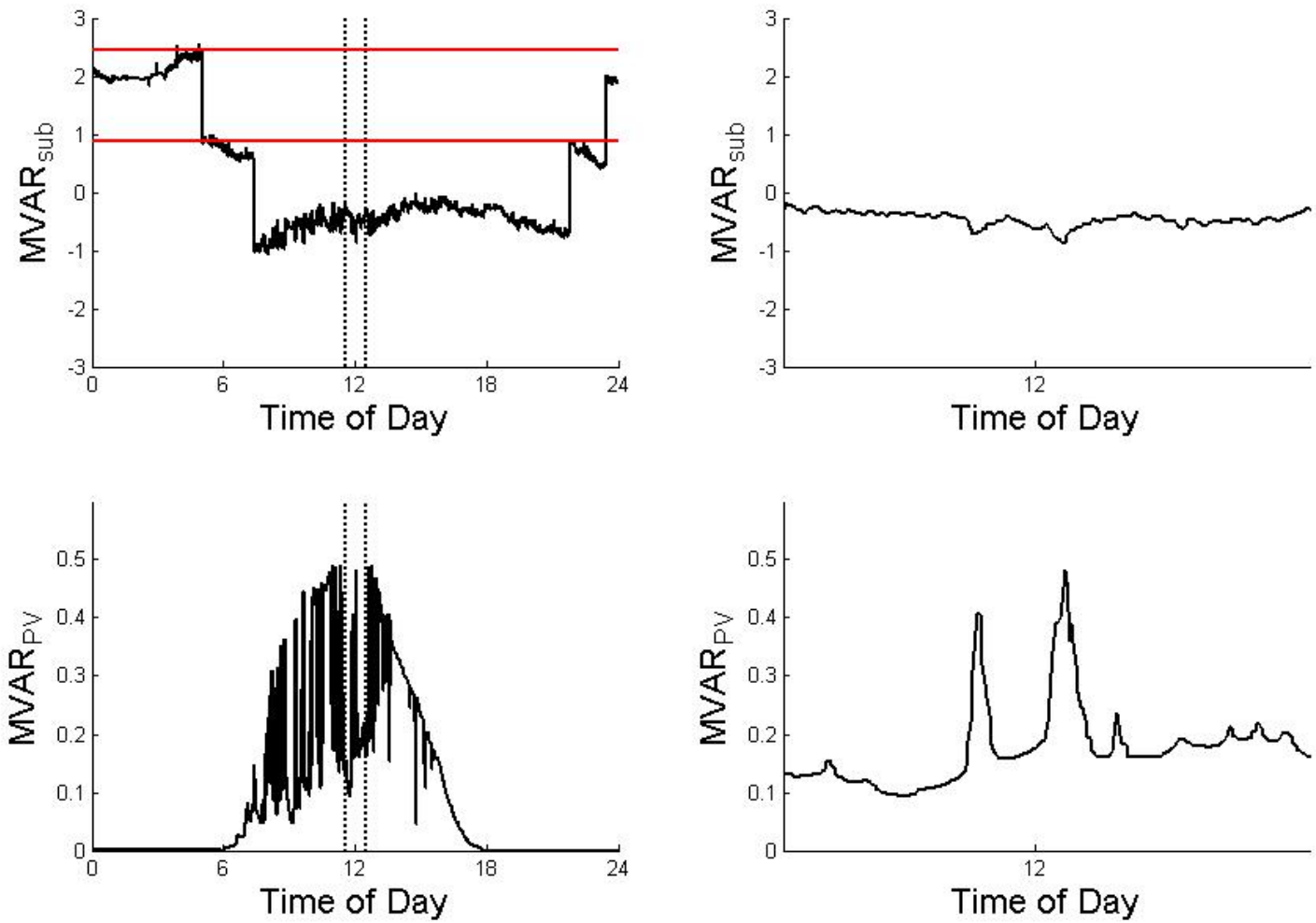
- Test the implementation and performance of operation of advanced PV inverter functions on a real distribution circuit (fielded system)

Field Test Specifics:

- Four 500 kW inverters on the Fontana Study Circuit were configured to operate at 0.95 PF inductive
- Circuit modeling was completed to show that the amount of VArs supplied from the sub-transmission system would be limited to be less than the circuit VAr loading without and capacitors operating on the circuit
- Field test ran over a 2 week period under relatively heavy circuit loading and high PV system power production

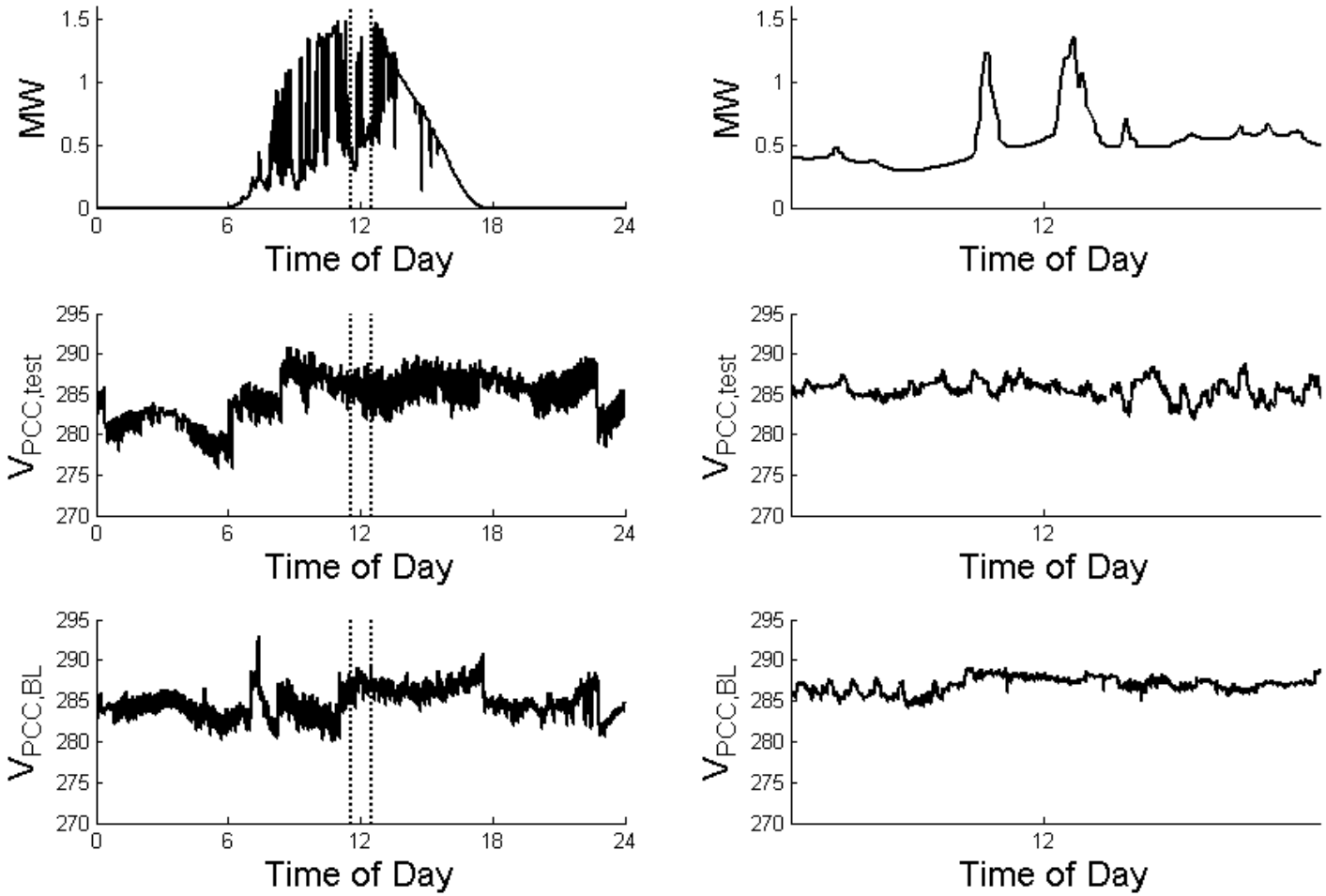


Field Deployment/Testing – Adv. Inverter



Findings: PV inverter tracked the PF set point very well but the set point was actually set to be capacitive. This underscores the unfamiliarity of the use of inductive VArs by utility personnel and the need to emphasize that the requested set points are probably counter-intuitive to those implementing them.

Field Deployment/Testing – PV Mitigation



Thur. Sept. 26th, 2013
Variable,
PF = 0.95

Tue. Sept. 24th, 2013
Clear,
PF = 1.0

Findings: The variability of substation voltage and adjacent loading swamps the voltage changes expected at the PV system point of common-coupling. Capacitor operation on the circuit is impacted by the off-unity PF operation (in this case it reduces cap switching due to capacitive PF set point)

Project co-funded by:

Itron CSI RD&D Program Manager

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Thank you for your attention

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