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EVALUATION OF HIGH PEN PV IN DISTRIBUTION CIRCUITS

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Feb 13-14, San Diego, CA

Project Goals

- Develop modeling tools to simulate distribution circuits
- Collaborate with Pacific Gas & Electric to acquire, analyze, and evaluate circuit performance data from circuits with high-pen PV
- Systematically utilize the modeling tools in combination with the field data to
  - Quantify PV integration limitations
  - Develop and evaluate progressively smarter systems for handling high-pen PV

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Tasks & Key Deliverables

Task 1: Project management

Task 2: Model development and evaluation

- **Model scenarios and comparisons to grid monitored data**

Task 3: Quantify PV integration limits

- **Determine limits for PV penetration within existing circuit architectures and with existing technology**

Task 4: Advanced inverter control

- **Assess the risks and benefits of advanced inverter control**

Task 5: Integrated distribution grid control

- **Progressively introduce and assess smart integrated distribution technologies/ controls to determine impacts on PV penetration**

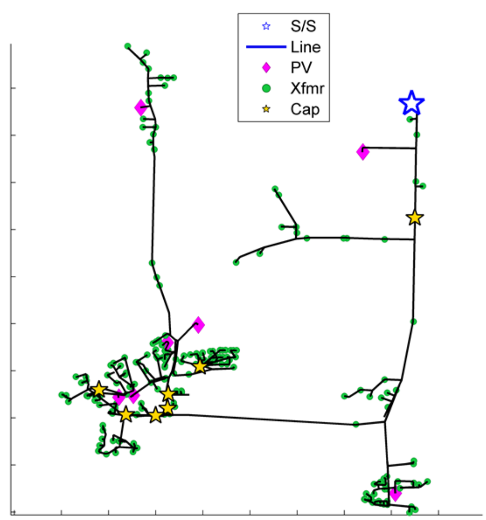
Task 6: Practical feasibility and outreach

- **Determine market potential of technology and encourage adoption**

Model Development and Evaluation

Commercial Circuit (Cayetano)

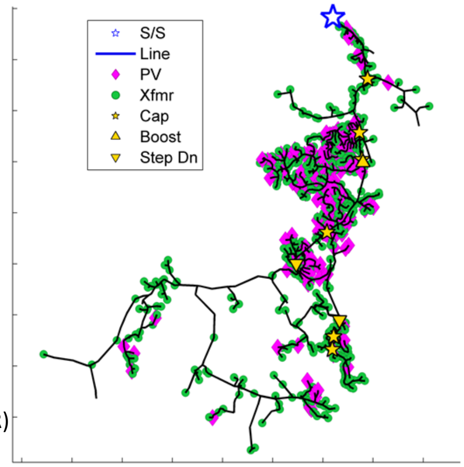
- 21 kV Wye
- Demand
  - > 12 MW max
  - > 1202 customers (237 Xfmrs)
  - > 91.2% energy for Commercial & Industrial customers
- PV Generation
  - > 1.873 MW (15.6% penetration)
  - > 7 installations (2 > 500kW)
- Equipment
  - > LTC (45 MVA, 10% regulation)
  - > 7 switched capacitors (9.6 MVAR)



Model Development and Evaluation

Residential Circuit (Menlo)

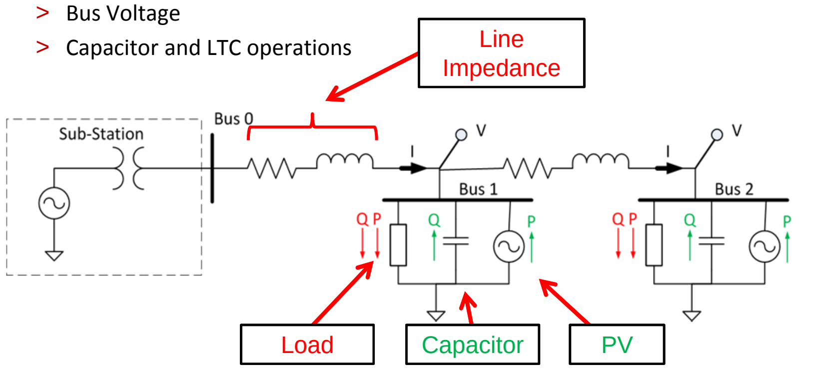
- 12 kV Delta
  - > Two 4.16kV Wye sections
- Demand
  - > 9.1 MW max
  - > 2681 customers (827 Xfmrs)
  - > 73.7% Domestic customers
- PV Generation
  - > 1.105 MW (12.1% pen)
  - > 165 installations (163 < 50kW)
- Equipment
  - > LTC (16MVA, 10% regulation)
  - > 4 sw'd, 2 fx'd Capacitors (3.6 MVAR)
  - > Booster (5.16 MVA, +3%)
  - > 2 Step-Downs (1 and 0.75 MVA)



Model Development and Evaluation

Balanced 3-Phase Feeder Model

- Steady-State voltage behavior on the primary feeder
  - > Bus Voltage
  - > Capacitor and LTC operations



- Does NOT provide information about Power Quality and Protective Devices

Quantify PV integration limits

- Determine limits for PV penetration within existing circuit architectures and with existing technology
- Scenarios
  > **Penetration**: 0 – 100% Nameplate Penetration
  > **Spatial Distributions**: Radial (new PV placed on existing buses with PV), Beginning, Middle, End
  > **Characteristic Demand Day**: Seasonal High and Low

Combustion Fuel Cells Distributed Power

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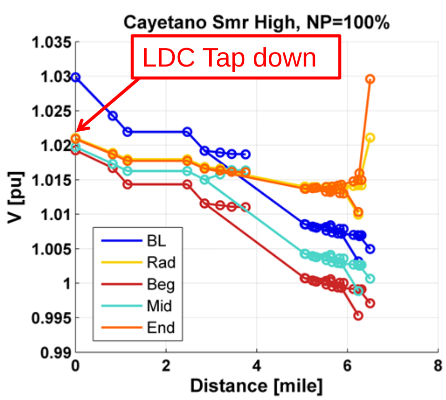
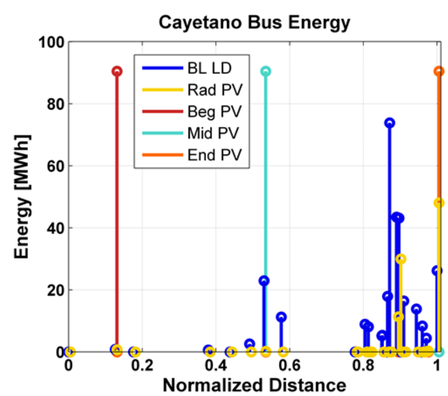
Quantify PV integration limits: LDC





- PV Generation support decreases net demand observed at Sub-Station
  > LDC taps down
- Spatial distribution affects LDC operation. In some instances, voltages outside of standards may occur if no mitigating actions are taken.
- LDC regulation reduced the number of capacitor switching operations that would otherwise be expected in the PV region.

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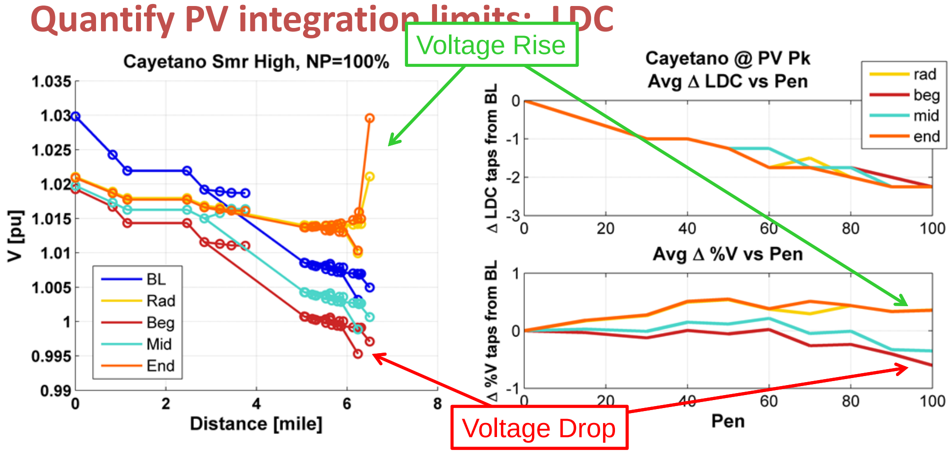
Quantify PV integration limits: LDC



- As PV Penetration increases
  - Ending PV Distributions trend to voltage rise → in these cases LDC decreases voltage rise
  - Beginning PV Distributions trend to voltage drop → in these cases LDC increases voltage drop

NOTE: Cayetano Summer High day did not have out of standard voltages, but demonstrates the trends caused by the interaction of the LDC and High Pen PV.

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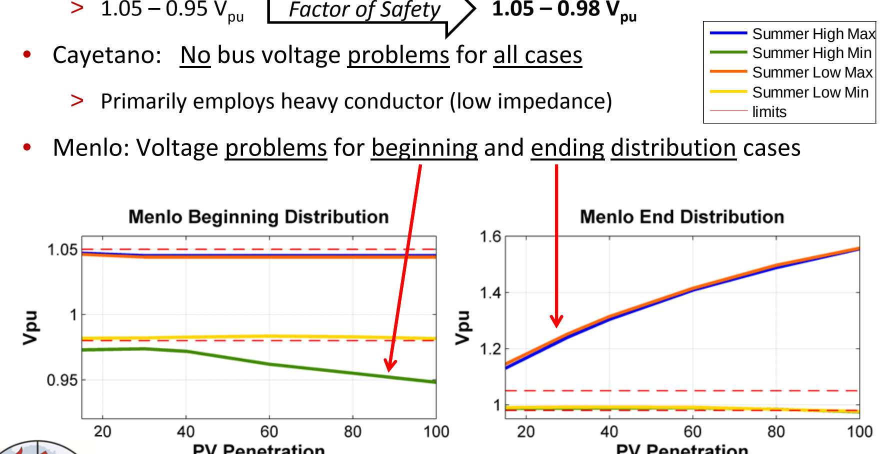
Quantify PV integration limits: Voltage

- Bus Voltage evaluated to ANSI C84.1 (Range A)
  - 1.05 – 0.95 V_{pu} *Factor of Safety* **1.05 – 0.98 V_{pu}**
- Cayetano: No bus voltage problems for all cases
  - Primarily employs heavy conductor (low impedance)
- Menlo: Voltage problems for beginning and ending distribution cases



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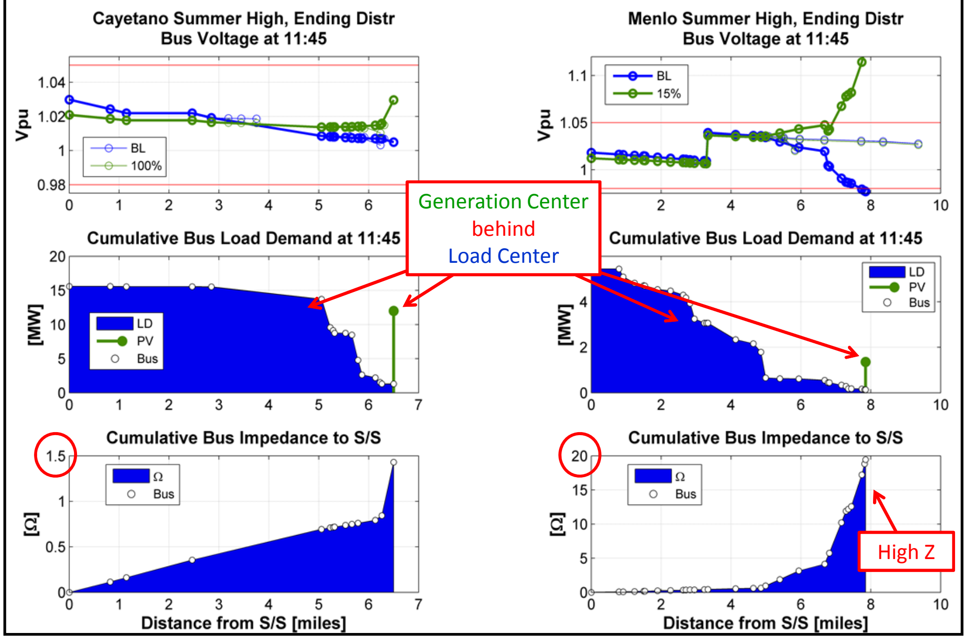
Quantify PV integration limits: High Voltage



Quantify PV integration limits: High Voltage

- Likelihood of exceeding voltage standard increases when:
  - Excess generation at lower penetrations
  - High impedance between GC and LC
  - Aggravated by high line impedance to the adjacent upstream bus.

- Siting PV to avoid exceeding voltage standard is important (see siting criteria below).

Circuit	Distribution	LC/GC	Ω to LC	Excess Generation [MW] at 100%	Initial Ω Upstream	Vmax [pu]
Menlo	End (Site 1)	0.51	19	8.9	4.46	1.5
	Mid	0.95	0.1	6.7	0.153	1.04
Cayetano	End	0.85	0.7	10.7	0.587	1.03

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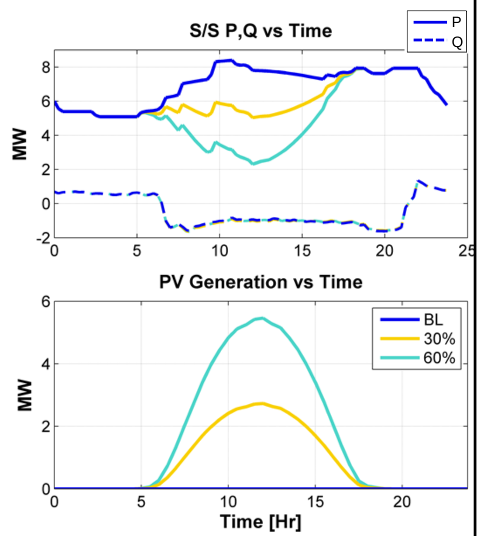
Quantify PV integration limits: Power Factor

- PV Generation provides real power support
- As PV Penetration increases, the power factor at Sub-Station will decrease
- Impact
  - High demand → marginal
  - Low demand → sensitive



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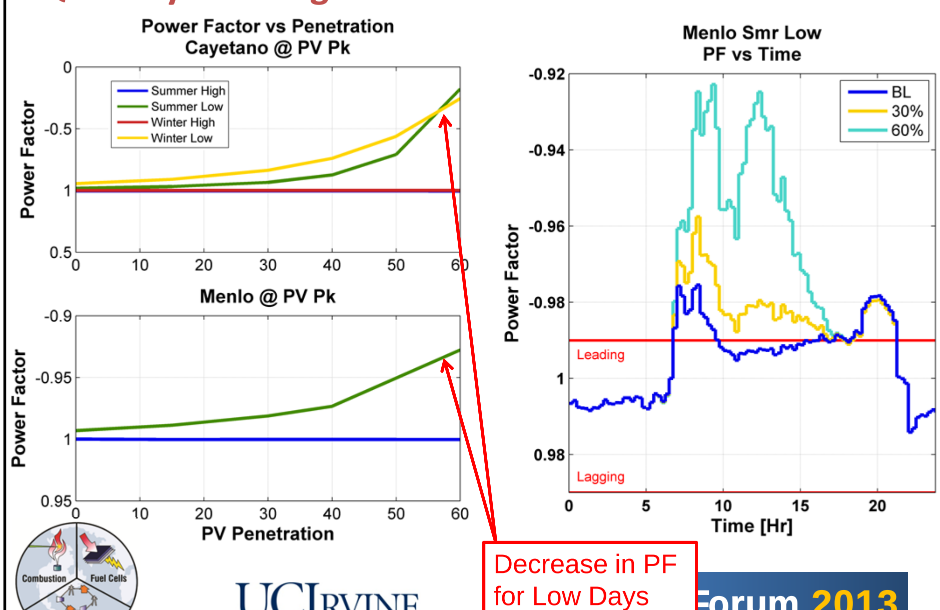
Quantify PV integration limits: Power Factor



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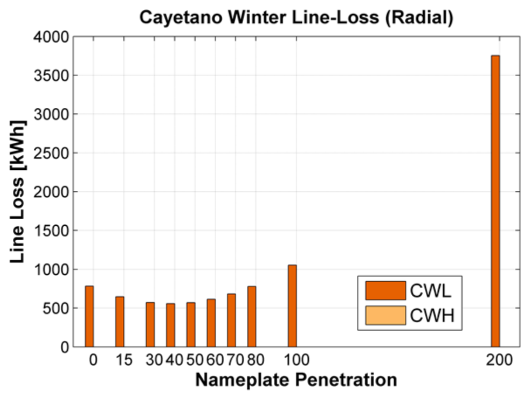
Quantify PV integration limits: Line Loss

- PV Generation is providing local demand support
  - As Penetrations increase, S/S current draw decreases
- I^2R Line loss has quadratic dependence on penetration



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Quantify PV integration limits: Line Loss

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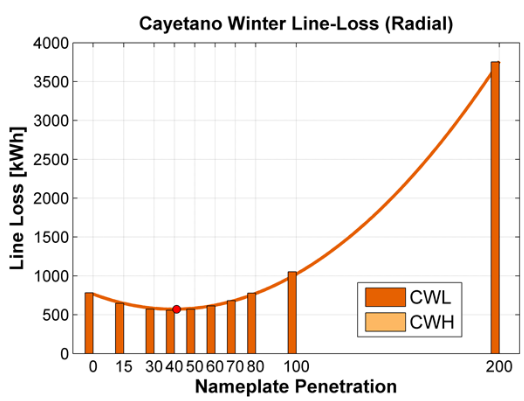

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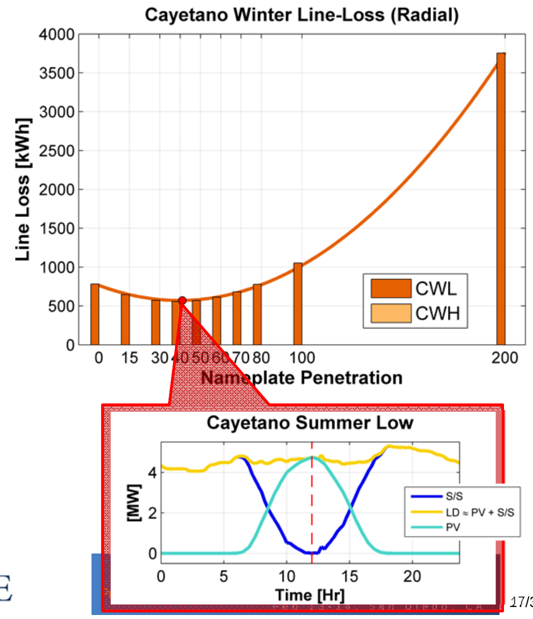
Quantify PV integration limits: Line Loss

- PV Generation is providing local demand support
  - > As Penetrations increase, S/S current draw decreases
- I^2R Line loss has quadratic dependence on penetration
- Minimum at “Break Even Point”
  - > Depends upon daily demand



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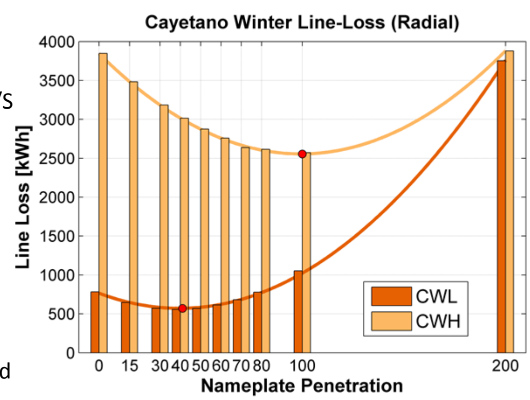
Quantify PV integration limits: Line Loss

- PV Generation is providing local demand support
  - > As Penetrations increase, S/S current draw decreases
- I^2R Line loss has quadratic dependence on penetration
- Minimum at “Break Even Point”
  - > Depends upon daily demand
- Interpolate to estimate optimum penetration (in terms of line loss)



Cayetano → 61% PV Penetration

Menlo → 56% PV Penetration

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Quantify PV integration limits: Summary

- Load Drop Compensation (at Sub-Station)
  - Total LTC operations increase with increasing penetration
  - LDC can mitigate high voltage conditions for end generation distributions
  - Increasing DG penetration does not affect capacitor switching in the circuits analyzed
  - LDC can exacerbate low voltage conditions for beginning generation distributions
- Buses with high system impedance and high PV penetration that produces reverse power flow are more likely to produce high voltage conditions
  - The proposed siting criteria can be used to mitigate high voltage conditions
- Decrease in Power Factor on Low Demand days during PV generation as PV penetration increase.
- Increased Levels of PV penetration will decrease line loss until Break Even Point penetration

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Advanced Inverter Control

- Evaluate advanced PV inverter controls
  - Volt – VAR Control (VVC)
  - Active Power Filter (APF)
- Identify potential benefits / risks
  - To the customer
  - To the utility

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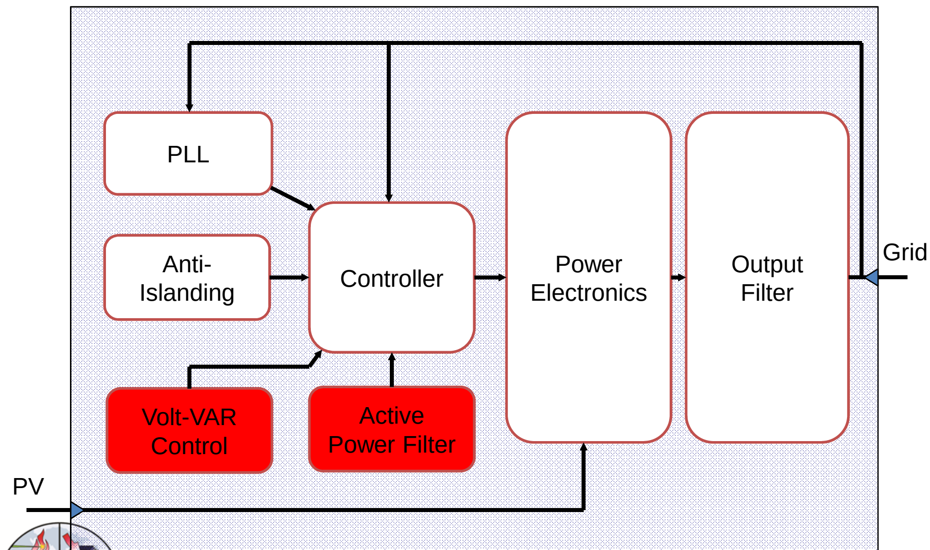
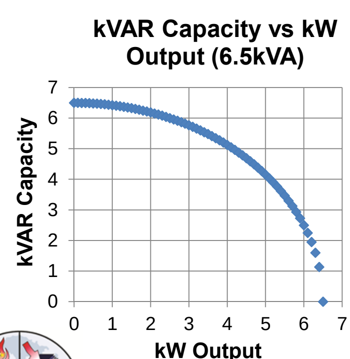
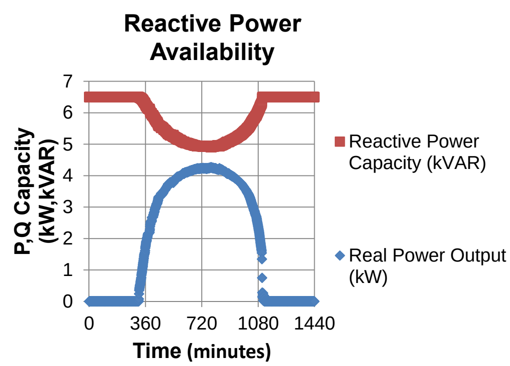
Advanced Inverter Control



Advanced Inverter Control

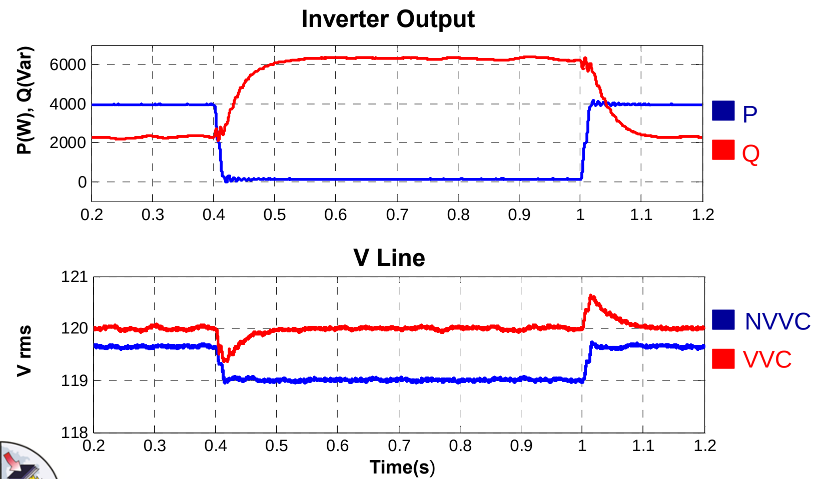
- Volt – VAR control
  - Standards don't currently allow volt-VAR control (IEEE 1547.8 investigating)
  - This study investigates challenges and opportunities of allowing inverters to provide **secondary service voltage regulation** via reactive power support





Advanced Inverter Control

- Response to abrupt shading



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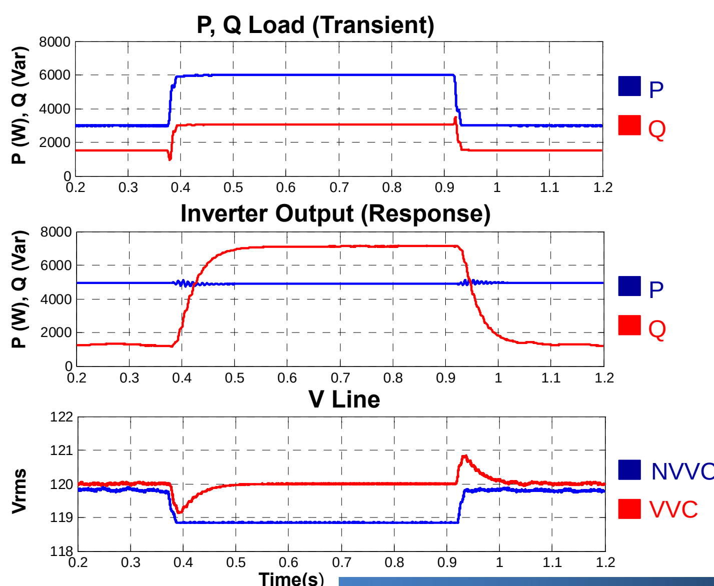

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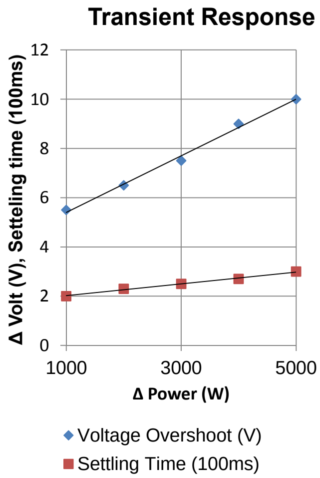
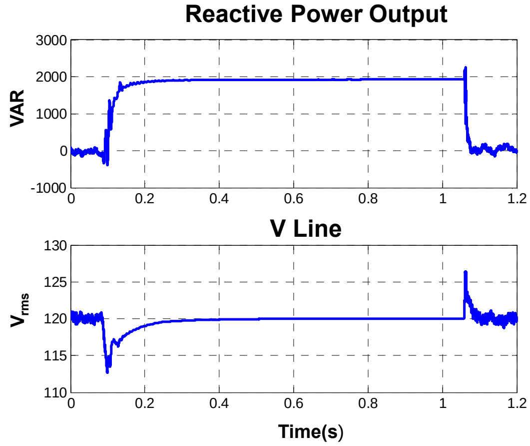
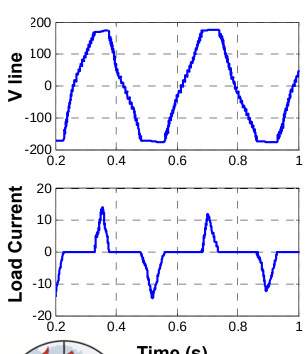
Advanced Inverter Control

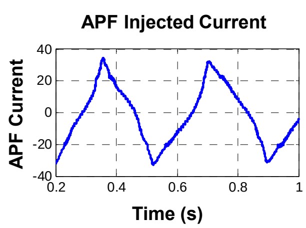


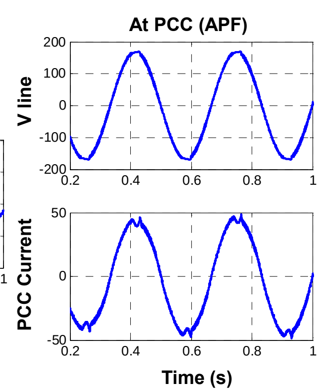


Advanced Inverter Control

- Active Power Filter
  - Compensates nonlinear loads
  - Improves power quality at customer premises







Progressively Smarter System: Advanced Steps

- Volt – VAR Control
  - > Potential Benefits
    - Secondary side line voltage regulation at customer premises
    - Reduced line voltage impact due to shading
  - > Potential Risks
    - Detrimental interactions amongst inverters
    - Possible injection of voltage flicker
- Active Power Filter
  - > Potential Benefits
    - Customer harmonic distortion reduction
  - > Potential Risks
    - Increased cost to customer

Progressively Smarter System: Traditional Steps

- Load Drop Compensation Low Voltage* condition:
  - > Identification: ❶Elevated PV penetrations, ❷Beginning generation distributions, ❸Middle and End Load Demand distribution
  - > Mitigation: ① LDC PV Current Compensation generation. ② Line Regulator
- High Voltage* condition:
  - > Identification: ❶ High system impedance at bus, ❷ excess generation, ❸Ending generation distribution, ❹Beginning and Middle Load Demand distribution
  - > Mitigation: ① Re-conductor, ② Site Selection
- Low Power Factor condition:
  - > Identification: ❶ Elevated PV Penetrations, ❷ Low Load Demand
  - > Mitigation: ① VAR Controlled Switching Capacitors

** High Voltage and Low Voltage refer to out of standard voltage limits as defined in ANSI C84.1 Range A*

Summary (Part 1)

- Increased penetration of PV will interact with voltage control equipment.
- Buses with high system impedance and high DG penetration that produces reverse power flow are more likely to produce high voltage conditions
- An optimal PV penetration to minimize line loss exists. Line loss increase from optimum for penetrations past this point.

Summary (Part 2)

- Advanced inverter controls can improve secondary service voltage regulation and power quality without hardware redesign.
- Voltage conditions out of standards produced by high penetration of PV can be mitigated using existing technology.
  - Advanced Inverter Controls, control setting changes on LDC, additional stages of voltage regulation, re-conductoring, etc.
  - Mitigation strategies dependent significantly upon circuit characteristics, equipment, controls, etc.
  - Mitigation strategies required for High Pen PV may require utility expenditures.

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THANK YOU

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Q &A AND DISCUSSION

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