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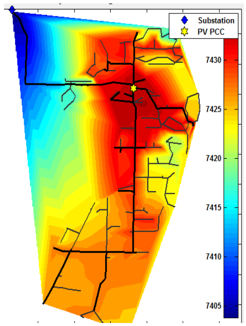

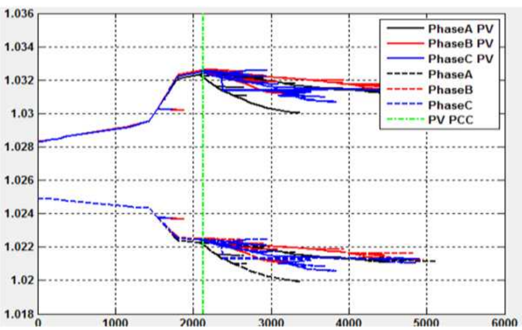

Impact of PV Variability and Ramping Events on Distribution Voltage Regulation Equipment

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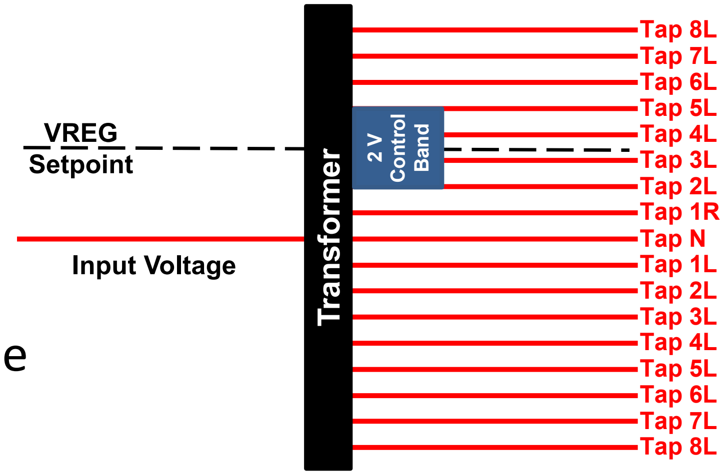
Introduction

- As the penetration of PV increases on the distribution system, there is rising concern about the interaction between PV variability and the system voltage regulation equipment.
- Before interconnecting PV, these grid impacts should be investigated in detail, and an efficient method of interconnection screening is needed.
- The impact of PV variability on voltage regulation equipment is separated into two categories:
  - The **short-term variability** can occur faster than the voltage regulation equipment, such as on-load tap changer (OLTC), can react, which causes extreme transient voltages during the PV ramp.
  - The **long-term variability** with frequent fluctuations in PV output can increase the number of total tap changes, leading to quicker degradation of equipment.

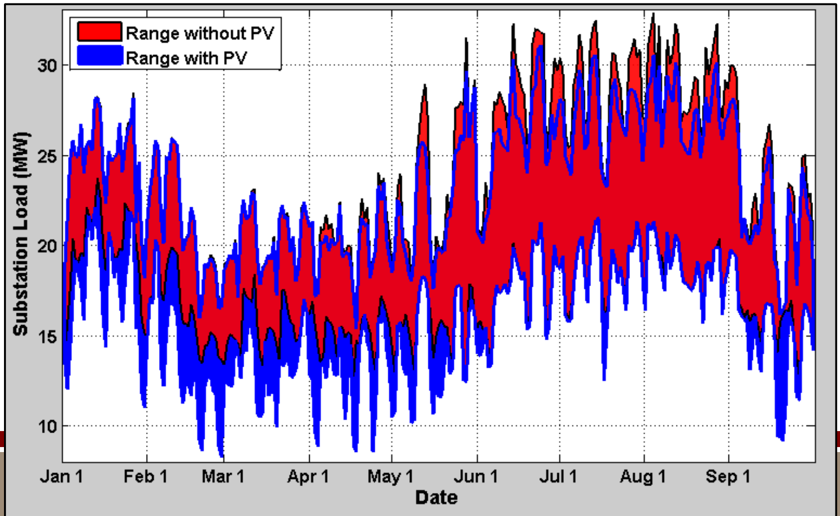
Background on Voltage Regulators

- Load Tap Changers (LTCs) and Voltage Regulators (VREGS)
  - Mechanical device for modifying the voltage by changing the tap of a transformer while maintaining current flow
  - Generally capable of changing voltage up to ±10% through incremental tap positions.
- Control
  - Changes taps to keep the output voltage at the VREG **setpoint** within a certain **bandwidth**
  - **Time delay** (generally 30 to 60 seconds) from the voltage going out of band until the control action
- Tap changes create wear and tear on the device



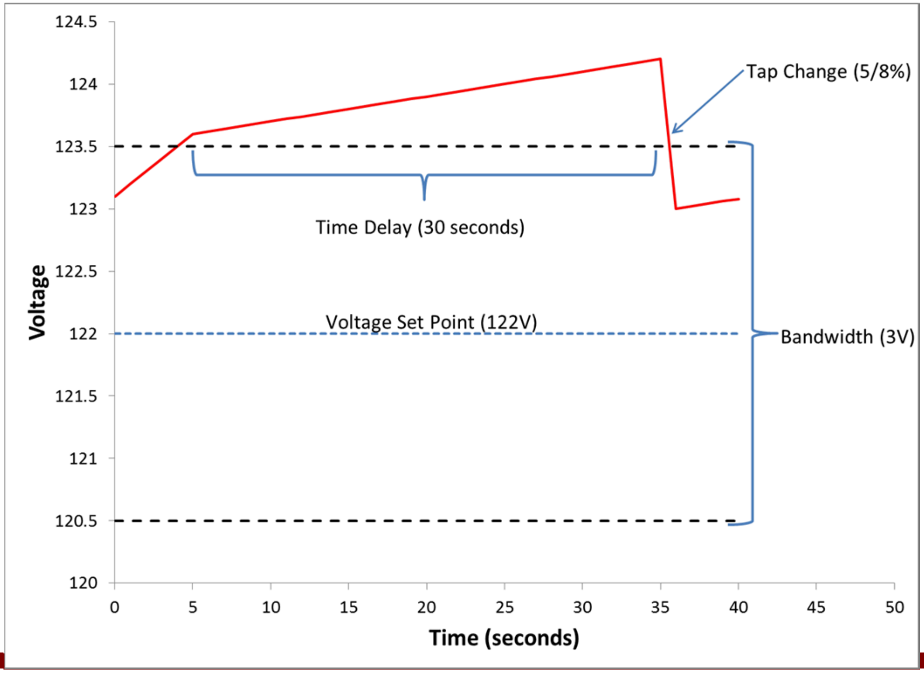
Background on QSTS

- PV output is highly variable and the potential interaction with control systems may not be adequately analyzed with traditional snapshot tools and methods
- Quasi-static time series (QSTS) power flow analysis
  - Captures time-dependent aspects of power flow, including the interaction between the daily changes in load and PV output
  - Simulation performed in OpenDSS
- Modelling voltage regulation equipment in QSTS



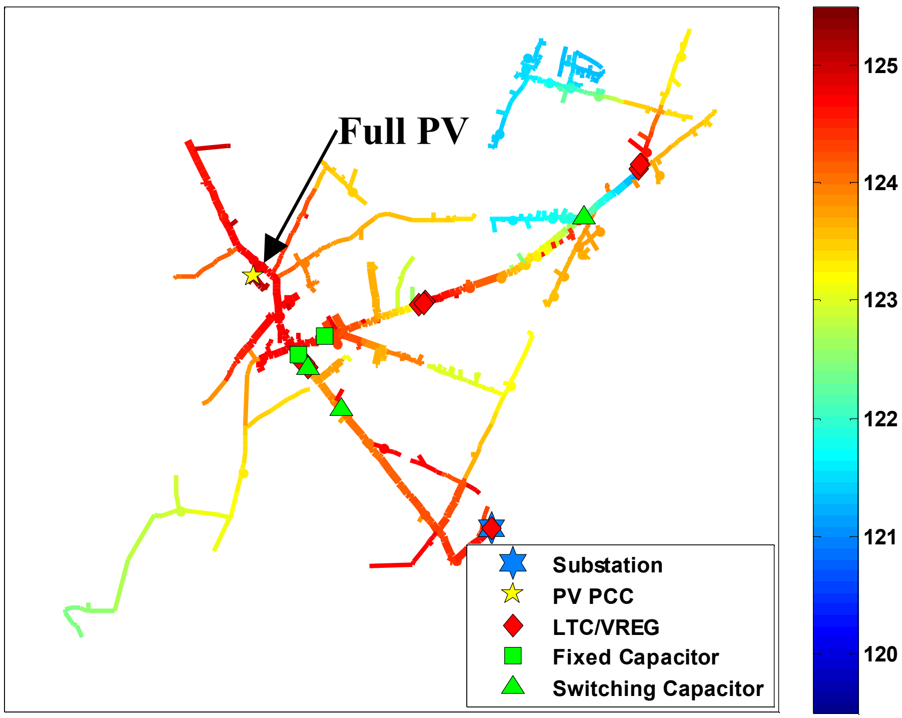
Short-Term PV Variability
Extreme Ramp Analysis

- Extreme ramps in PV output can cause the voltage to go out of band before the end of the delay time when the tap change returns the voltage to normal range
- Delay is part of distribution system design to reduce the number of unnecessary tap changes

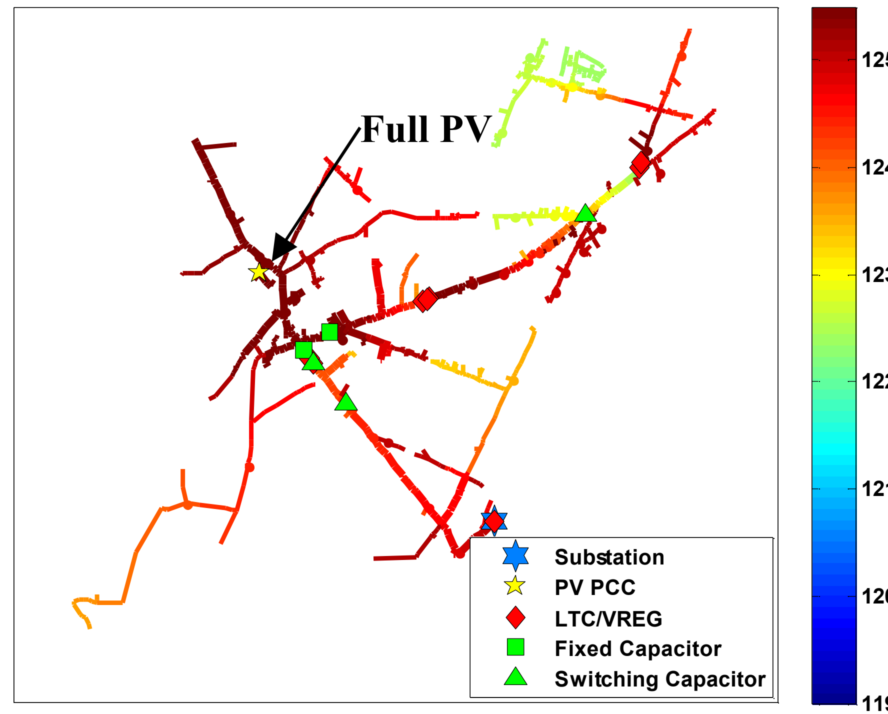


Extreme Voltages During Ramp

Steady-State



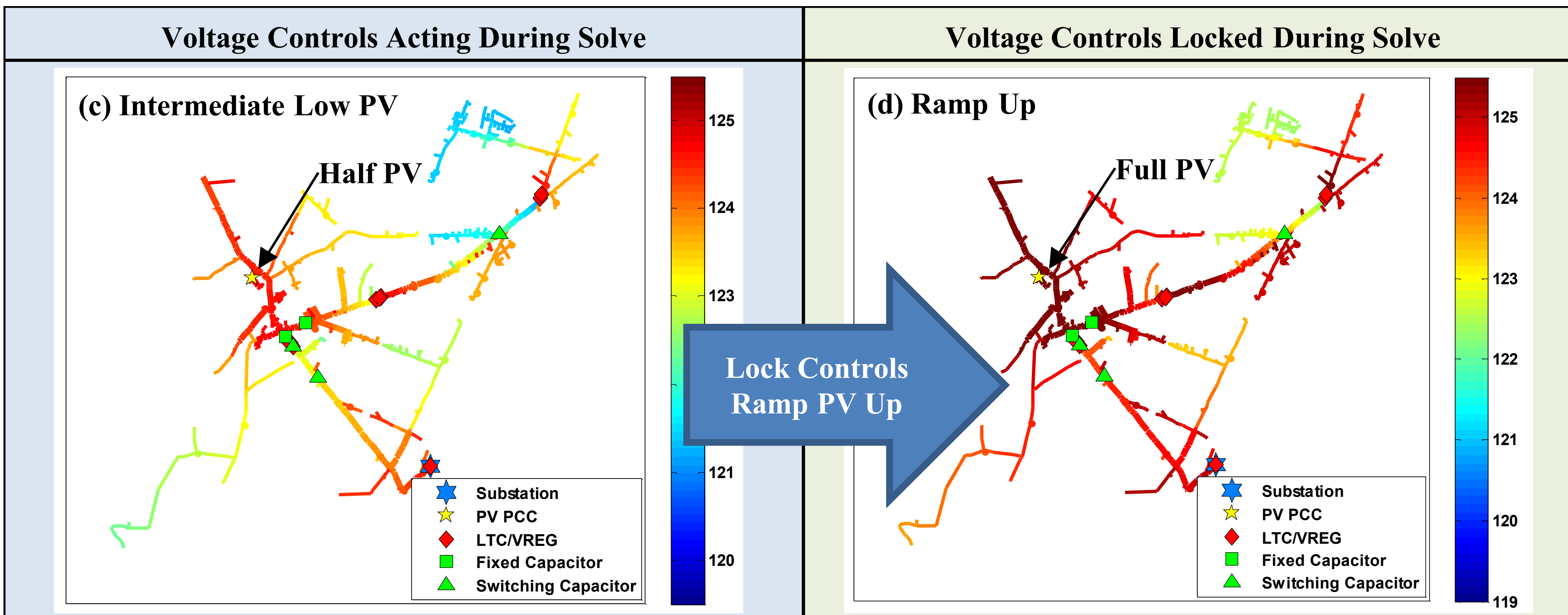
PV Ramp Up
During Delay Before Control Action



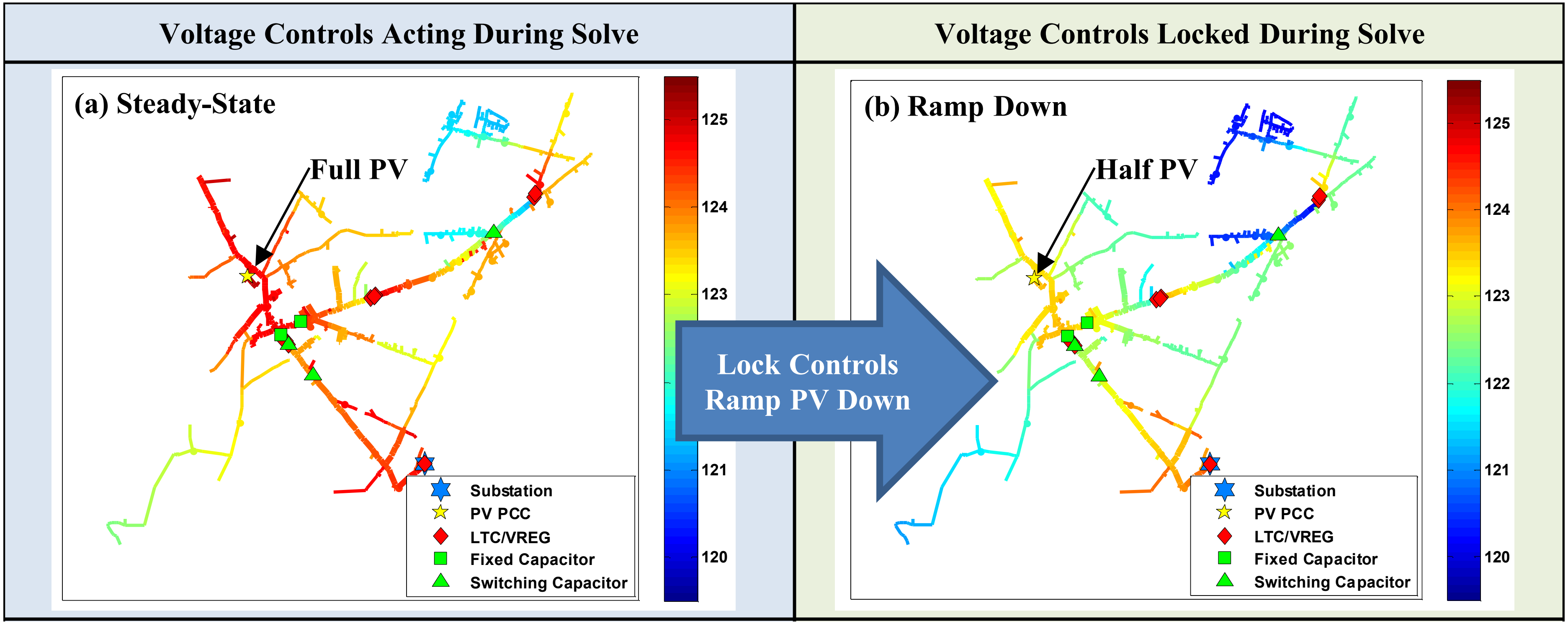
- Detect any issues from PV ramps with QSTS simulation of the PV output profile for the year for all PV ramps

PV Ramp Up Analysis

- New method for simulating issues from extreme PV ramps
  - Only simulate the worst case ramp, top 0.1% of 1-minute ramps
  - Do not need to even simulate the whole ramp, just the top and bottom

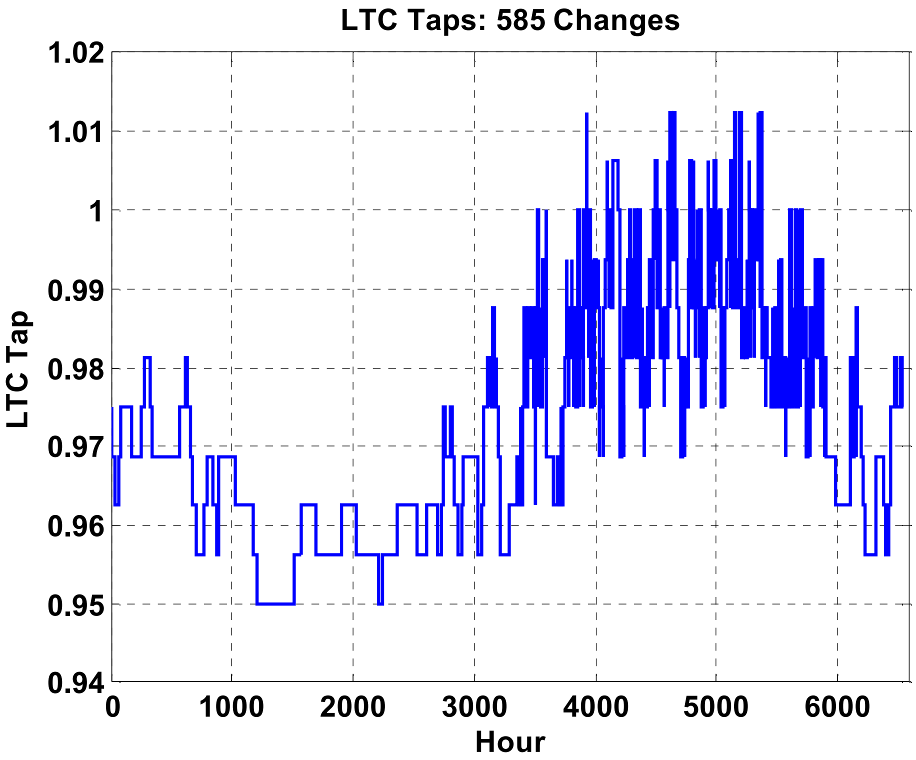


PV Ramp Down Analysis



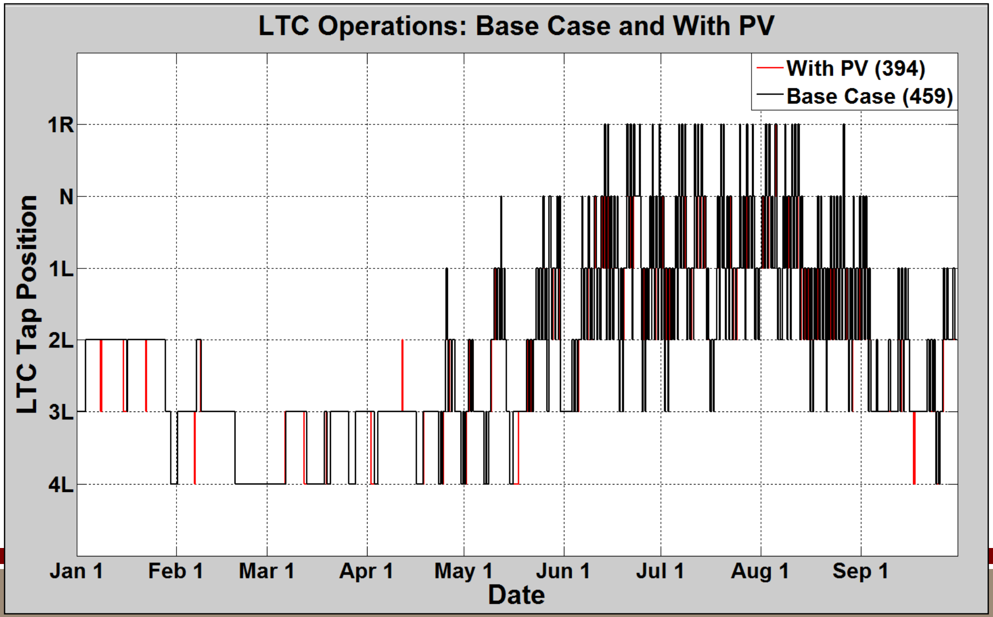
Long-Term PV Variability Tap Change Analysis

- Voltage regulators were designed for slow daily variability in load, not the high variability from PV
- High penetrations of PV on the feeder can increase the number of tap changes, and degradation of the equipment



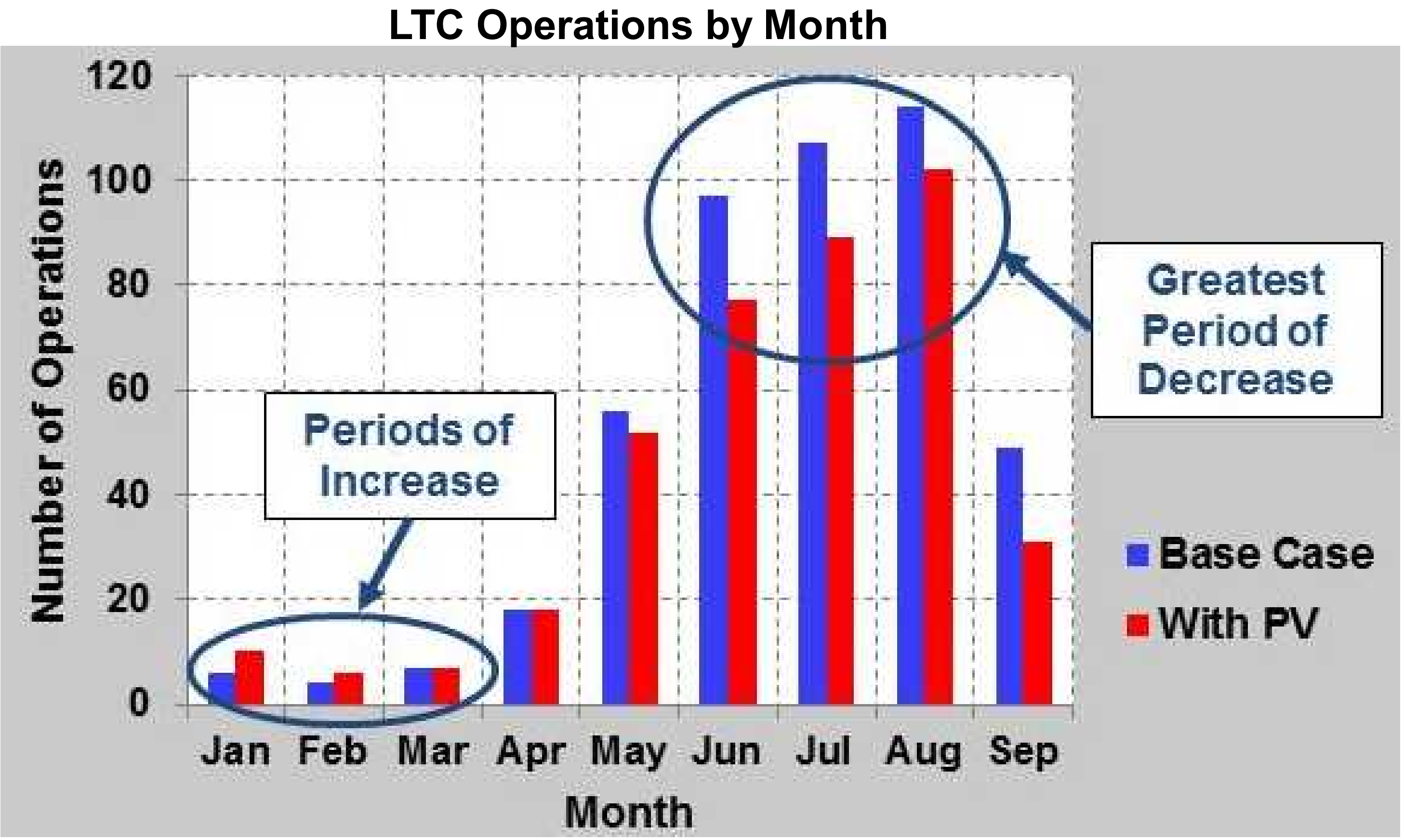
Complexity of Modeling Tap Changes

- High resolution data with appropriate local load and solar variability
- Modelling regulator controls
- Location of PV on the feeder
- Interaction between smart inverters and regulator load drop compensator control

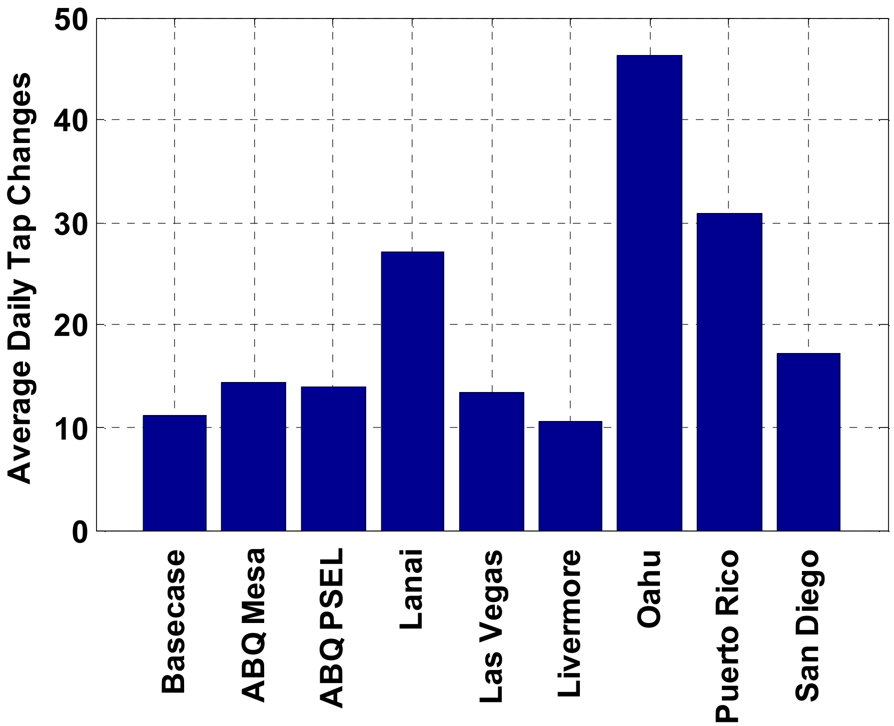


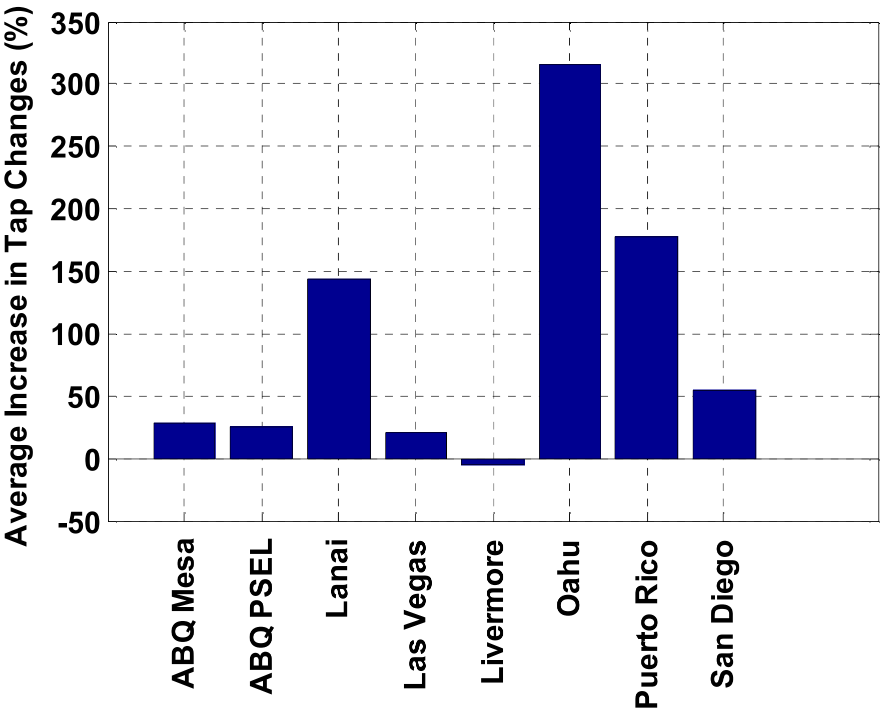
	Base Case	With PV	Percent Change
LTC Tap Changes	459	394	-14%

PV Impact to Tap Changes Variation by Time of Year



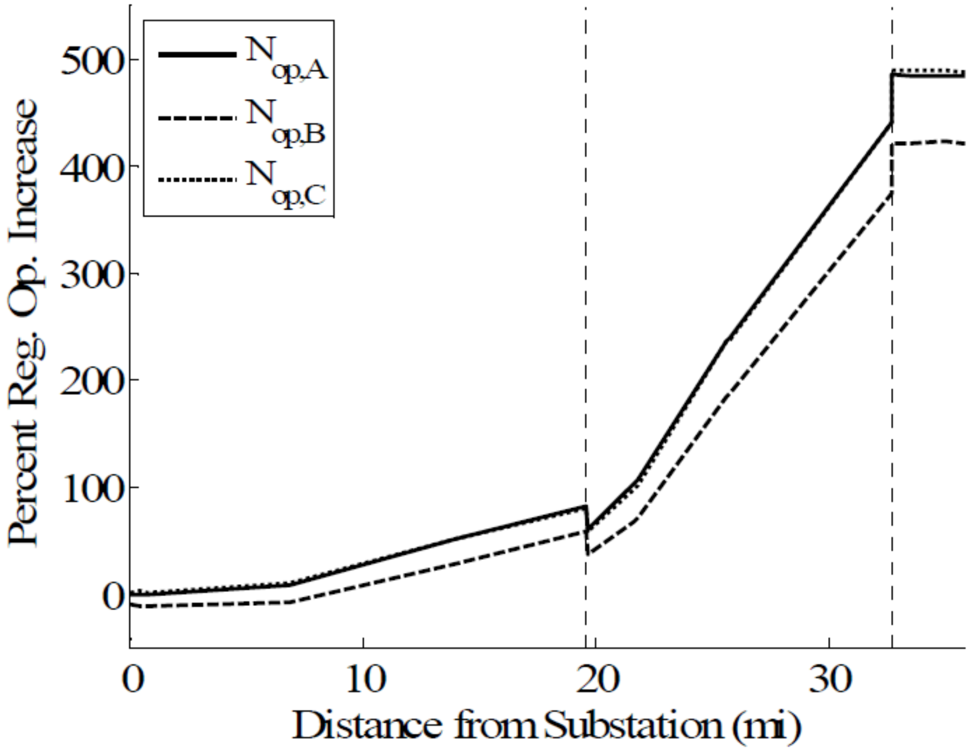
PV Impact to Tap Changes Variation with Irradiance Data





PV Impact to Tap Changes Variation by Location

- Percent increase in tap operations depending on the interconnection location along the length of the main 3-phase trunk



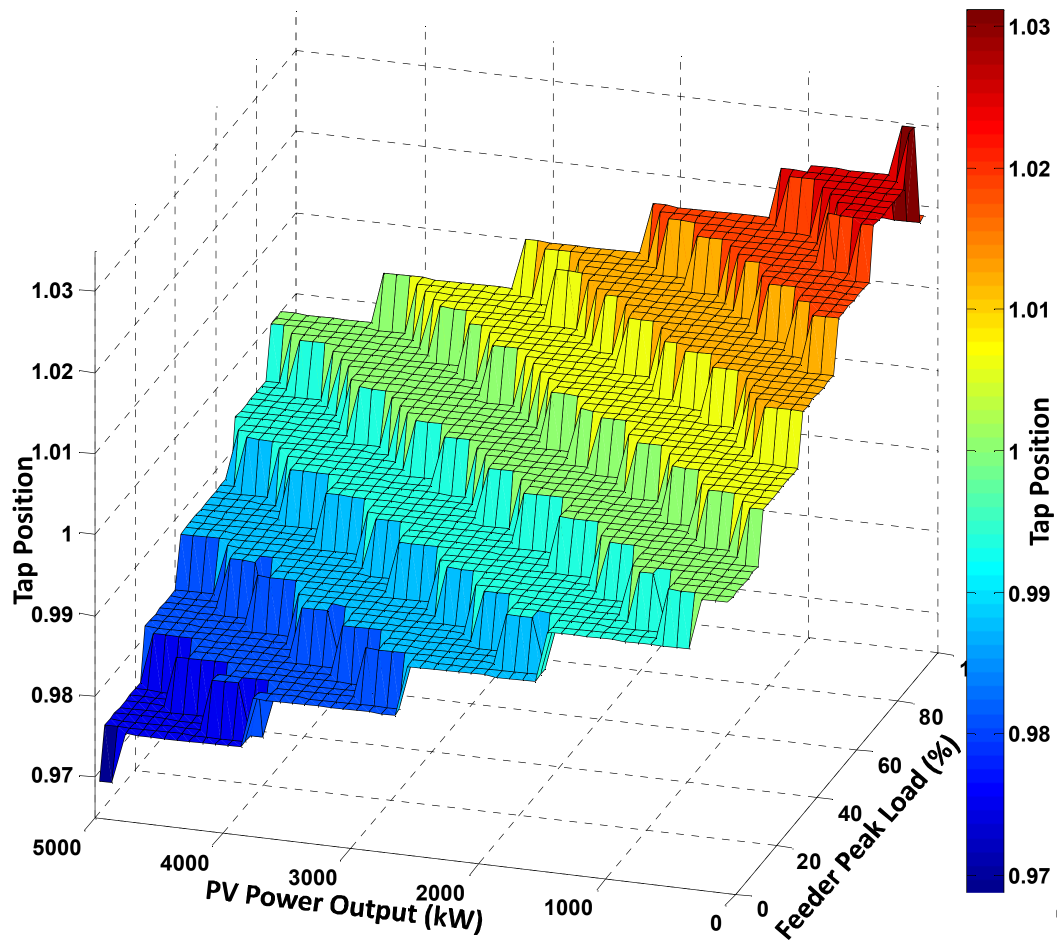
B. A. Mather, "Quasi-static time-series test feeder for PV integration analysis on distribution systems," in IEEE Power and Energy Society General Meeting, 2012.

Conventional Simulation Method

- The number of tap changes is simulated using QSTS
- Must have accurate high resolution data, and simulate long time periods to account for seasonal changes
- A 1-second resolution QSTS simulation for a 1 year period takes about 24 hours of computation
- To improve the interconnection process, a faster method is required
- Simple criteria like the ability of PV to force a tap change does not capture the full picture

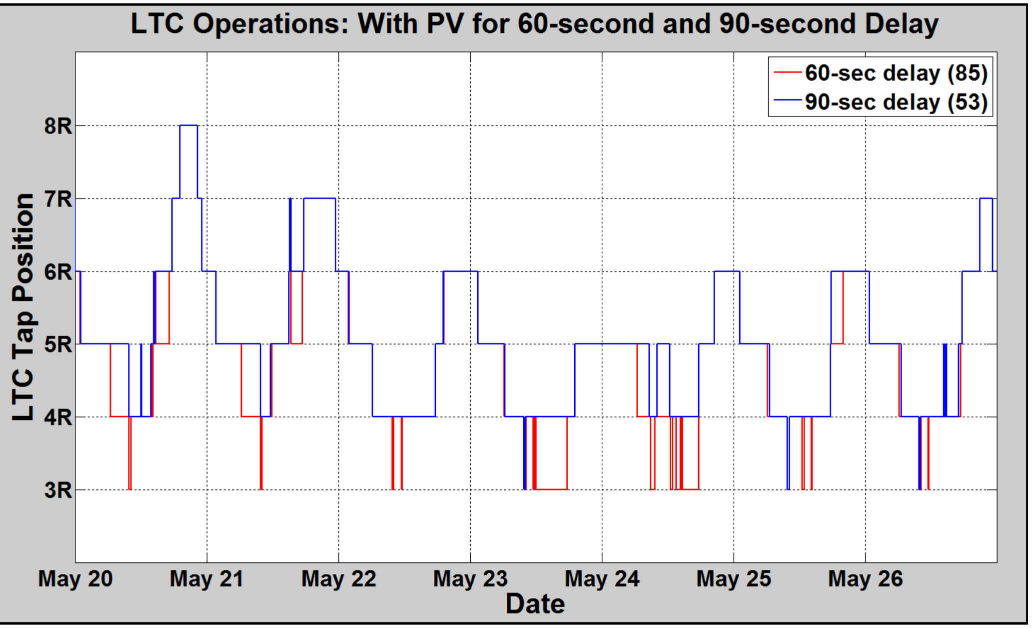
New way to Simulate Tap Position

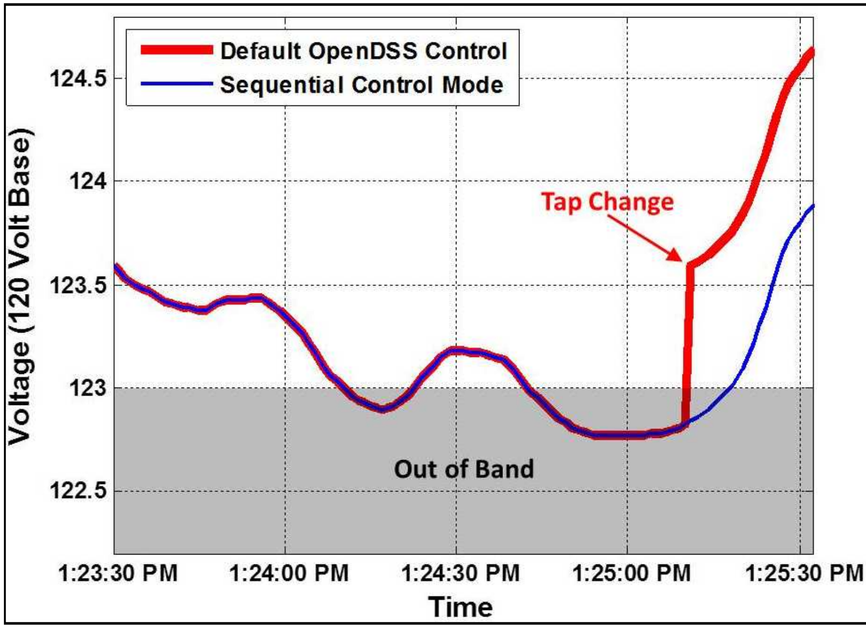
- Regulator tap position can be determined as a function of PV output and feeder load
- Using this function and the annual load and PV profiles, the tap can be determined for every time point in the year along with the total number of tap changes



Regulator Previous State

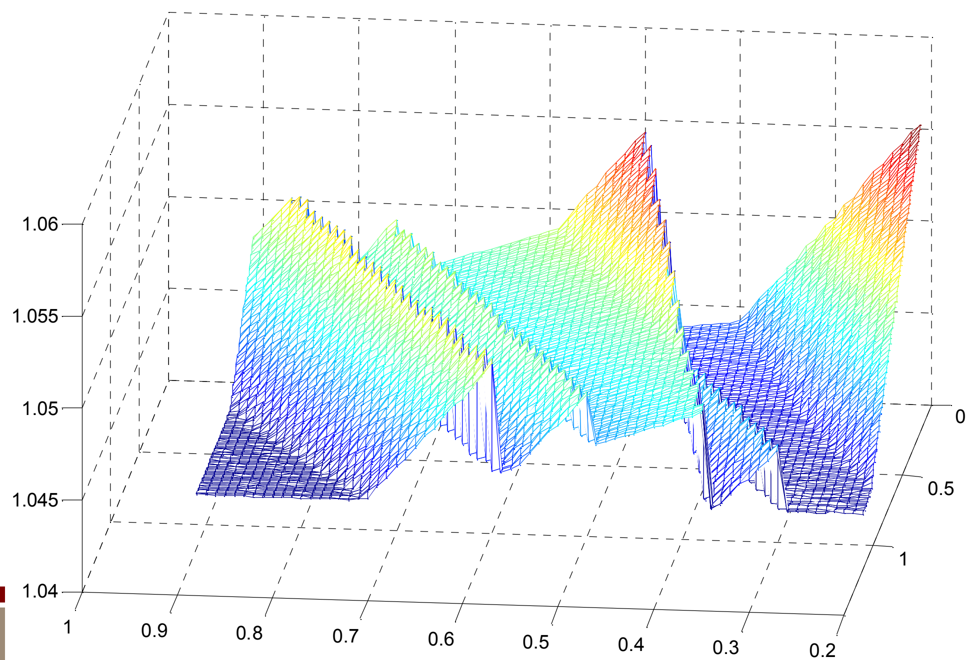
- Cannot just use the tap position function because regulator controls are also dependent on their previous state
- Whether a tap change actually occurs is due to the delay time and the control logic





Simulate Tap Position Using Voltage

- Model the high-side voltage of the regulator as a function of load and PV output
  - Determine heuristically testing combinations of load and PV values
  - Calculate using power transfer distribution factors (PTDF's)
- Analyze the tap position through time, modeling all delays and keeping downstream voltage within band



$$PTDF_{km,\mathbf{T}} = \underbrace{\begin{bmatrix} \frac{\partial P_{km}}{\partial \theta_k} & \frac{\partial P_{km}}{\partial \theta_m} & \frac{\partial P_{km}}{\partial V_k} & \frac{\partial P_{km}}{\partial V_m} \end{bmatrix}}_{\text{Line Derivatives}} \begin{bmatrix} \frac{\partial \theta_k}{\partial \mathbf{P}} \\ \frac{\partial \theta_m}{\partial \mathbf{P}} \\ \frac{\partial V_k}{\partial \mathbf{P}} \\ \frac{\partial V_m}{\partial \mathbf{P}} \end{bmatrix} \mathbf{T}$$

Rows of the Jacobian Inverse Matrix

Conclusions

- Two methods are proposed for screening potential PV systems for adverse impacts of PV variability on the distribution system without using time-series simulations.
- First, a technique to accurately characterize extreme feeder voltages due to high PV ramp rates is demonstrated using voltage regulation equipment locking and expected extreme PV ramping scenarios.
- Second, a method is described to determine the potential impact of a PV system on regulator tap changes using a voltage function to model the tap position throughout an entire year.
- Each of these methods aids in decreasing the complexity and length of time involved in screening potential PV interconnections.

Questions?