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Analysis of Conservation Voltage Reduction under Inverter-Based VAR-Support

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***Abstract*—Conservation voltage reduction (CVR) is a common technique used by utilities to strategically reduce demand during peak periods. As penetration levels of distributed generation (DG) continue to rise and advanced inverter capabilities become more common, it is unclear how the effectiveness of CVR will be impacted and how CVR interacts with advanced inverter functions. In this work, we investigated the mutual impacts of CVR and DG from photovoltaic (PV) systems (with and without autonomous Volt-VAR enabled). The analysis was conducted on an actual utility dataset, including a feeder model, measurement data from smart meters and intelligent reclosers, and metadata for more than 30 CVR events triggered by the utility over the year. The installed capacity of the modeled PV systems represented 66% of peak load, but reached instantaneous penetrations reached up to 2.5x the load consumption over the year. While the objectives of CVR and autonomous Volt-VAR are opposed to one another, this study found that their interactions were mostly inconsequential since the CVR events occurred when total PV output was low.**

***Keywords*—advanced inverter, advanced metering infrastructure (AMI), autonomous Volt-VAR, conservation voltage reduction (CVR), distributed generation (DG), high penetration photovoltaics (PV)**

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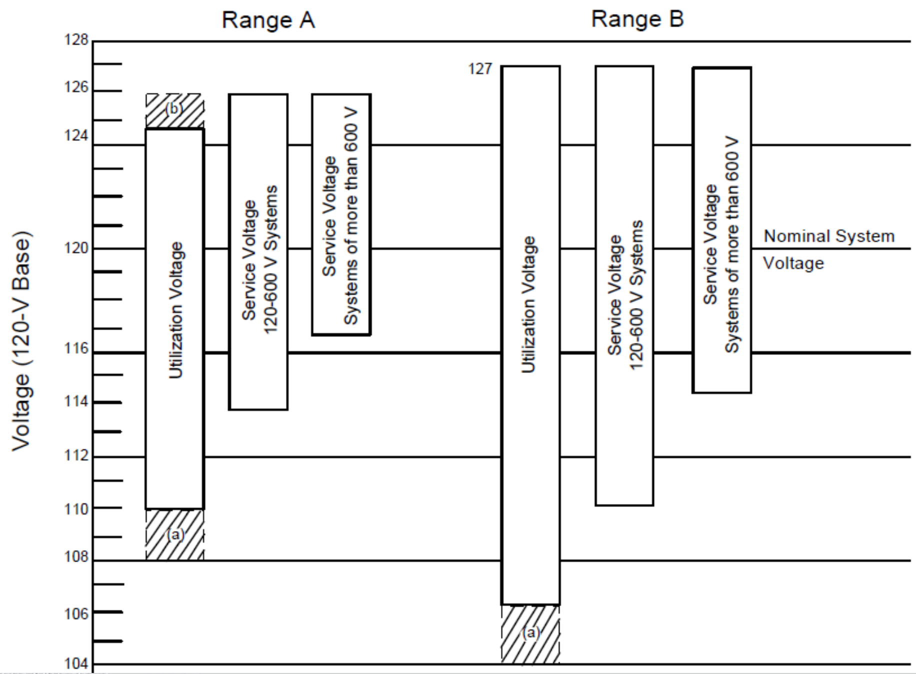
Contents

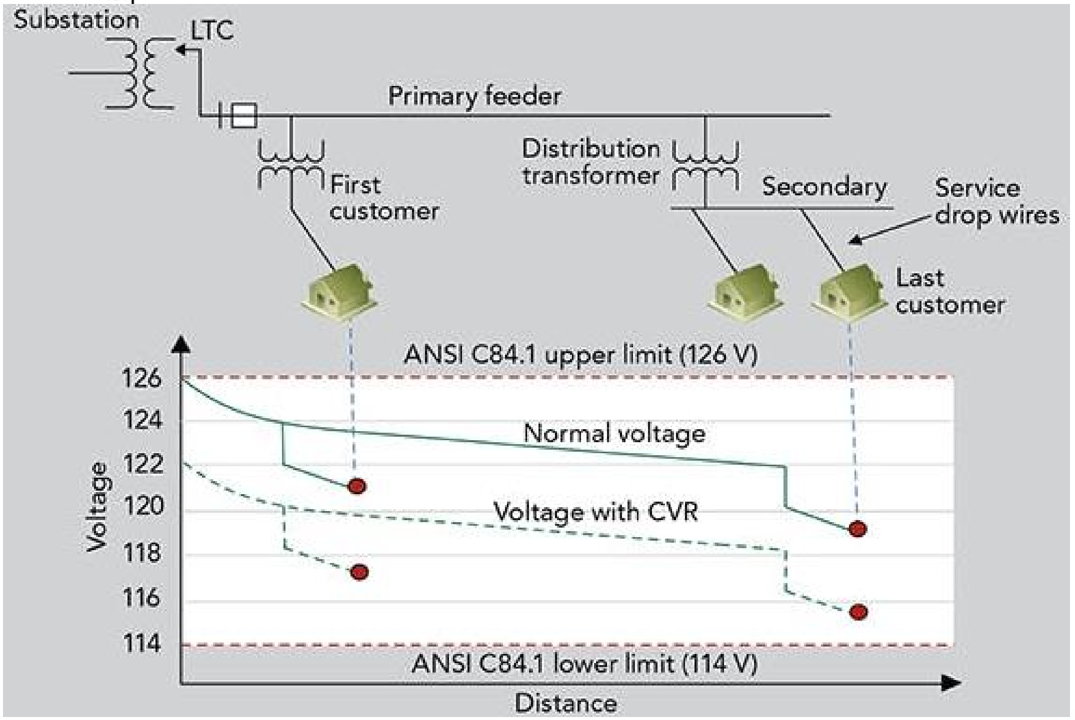
Introduction

- Conservation Voltage Reduction, or CVR, is a strategy used by distribution system operators in which the voltage is intentionally lowered to reduce energy demands
  - Voltage is often reduced by a few percent to operate closer to the lower limits of the ANSI utilization voltage range
- CVR events are often used as a way to reduce demand charges, i.e., fees that are charged based on peak demand over a given time frame
- The effectiveness of a CVR event can vary from feeder to feeder based on many factors, like network topology, conductor parameters, and load compositions
- However, as more distributed energy resources (DERs) are interconnected with the grid, CVR events may become less effective and/or predictable
  - This is particularly true for variable generators like distributed solar photovoltaic (PV) systems
  - PV inverters must now be capable of operating in a variety of grid-support modes [1], further complicating their impacts on CVR events

Background

- According to ANSI C84.1 [2], the utilization voltage must be maintained within between 114-126 V
- Under peak load conditions, a utility may initiate a CVR event for energy saving purposes or to avoid demand charges
- In practice, CVR events are carried out by sending SCADA commands to regulating equipment like step-voltage regulators (SVRs), load-tap changers (LTCs), and switchable capacitor banks
    - The commands would include new settings to regulate the voltage to a lower level

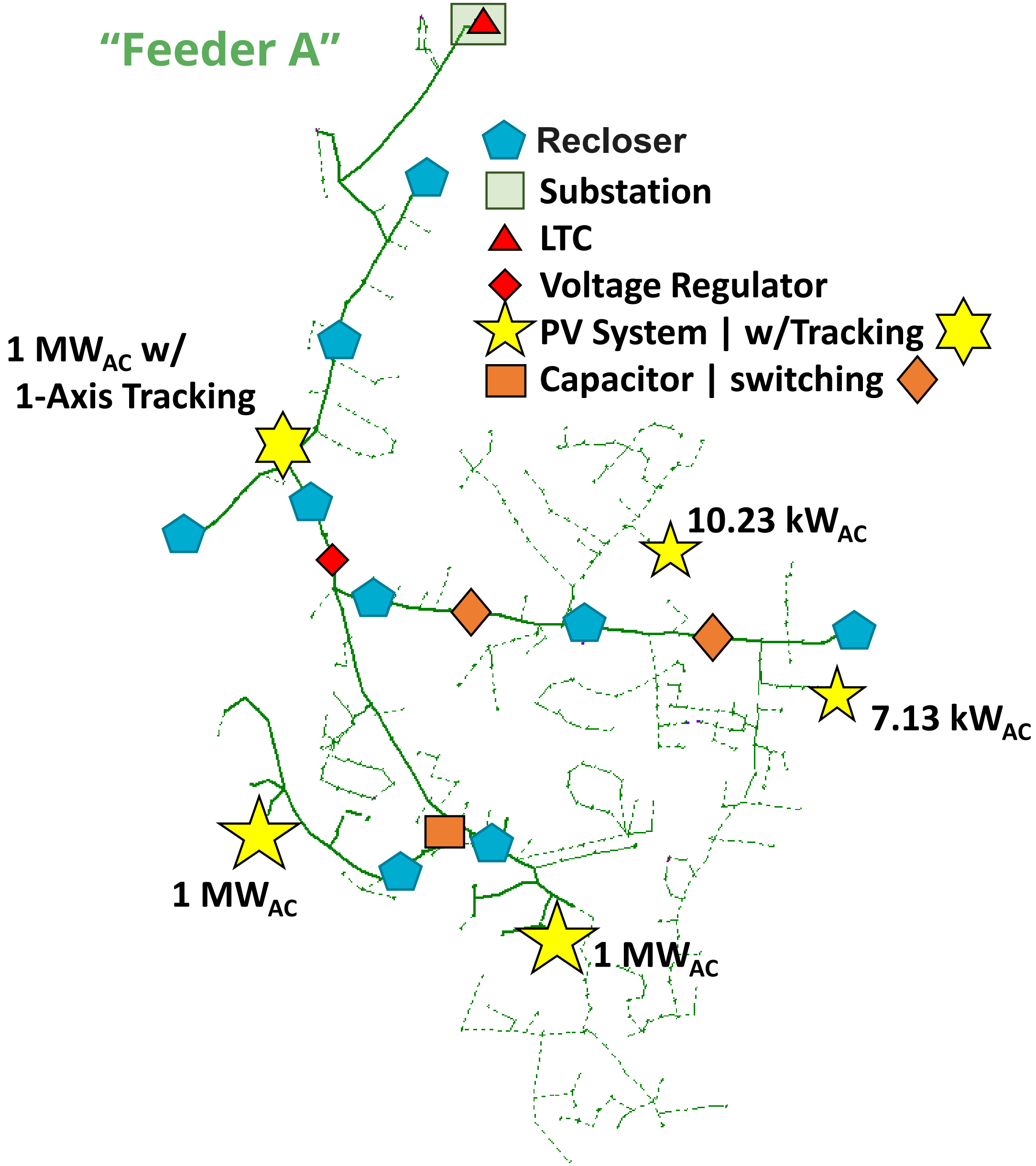




[3]

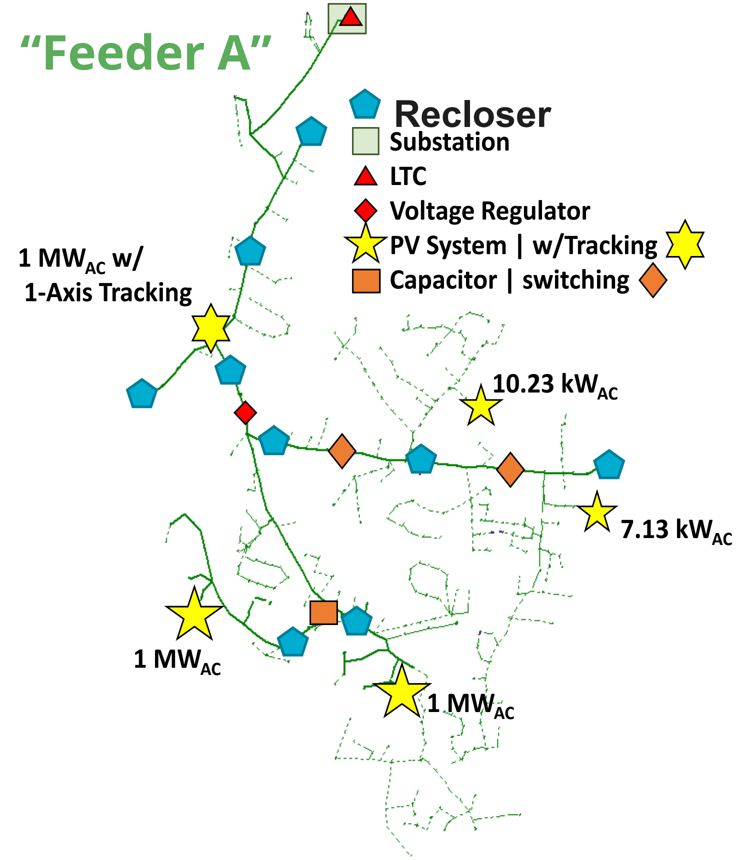
Test Circuit and Input Data

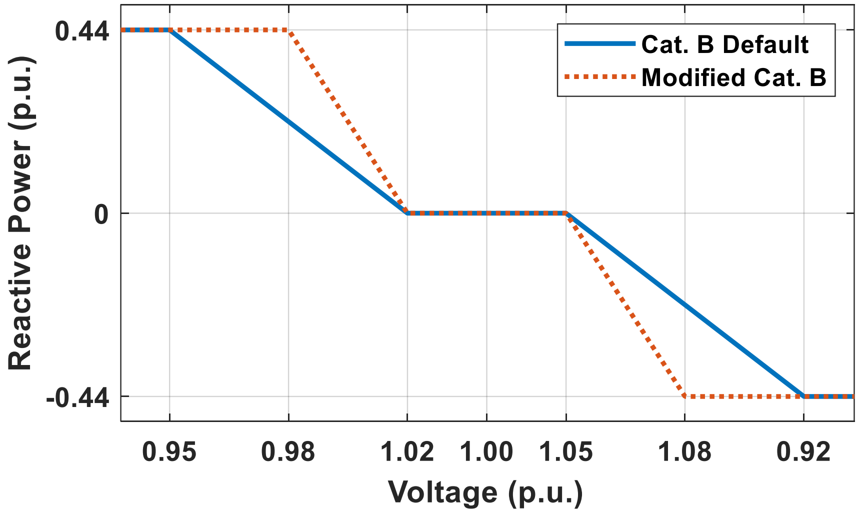
- Test circuit represents an actual utility distribution feeder that we will call "Feeder A"
- P, Q, V @ 15-min resolution from intelligent reclosers throughout the feeder
- Advanced Metering Infrastructure (AMI) real power data @ 15-min resolution for all customers
  - Per-phase reactive power allocation performed for each time point to generate Q profiles for each load
- Timing and duration of all CVR events for a full year was provided by the utility



Test Circuit and Input Data

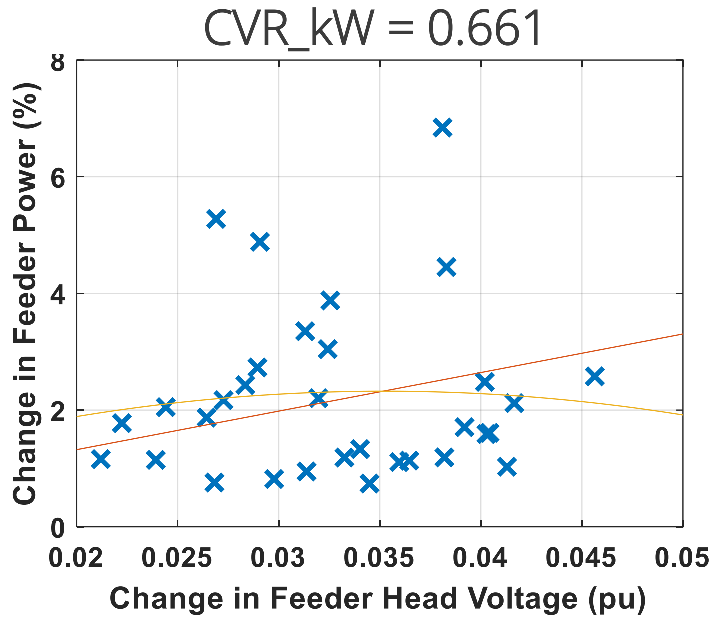
- The 3 large PV systems were added to the feeder to determine how the CVR events would be impacted under a high PV penetration scenario (66% of peak load, max. instantaneous penetration = 2.5x load consumption)
  - All PV systems had a DC/AC ratio of 1.4
  - PV generation profiles were derived using open-sourced irradiance and temperature data
- The CVR impact analysis was conducted for:
  - 1) All PV set to Unity Power Factor (PF)
  - 2) All PV set to operate in Volt-VAR mode with modified IEEE 1547 Cat. B default settings [1]:

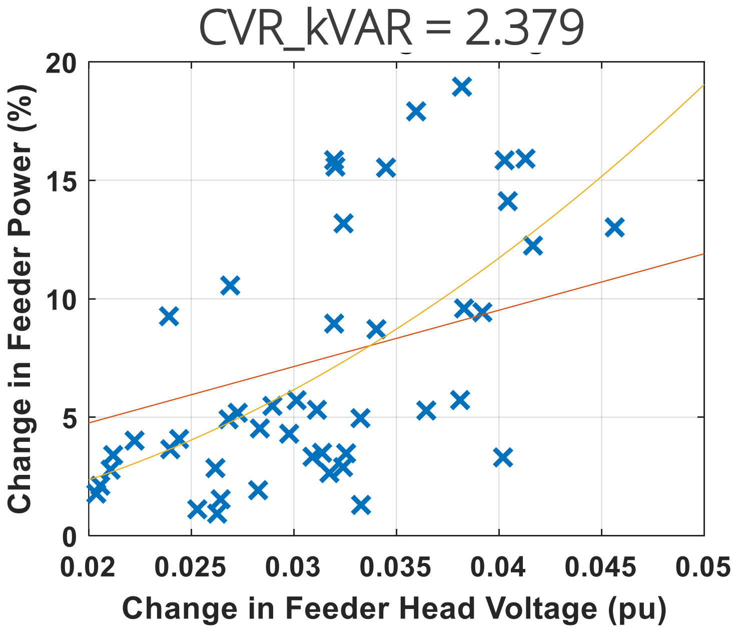




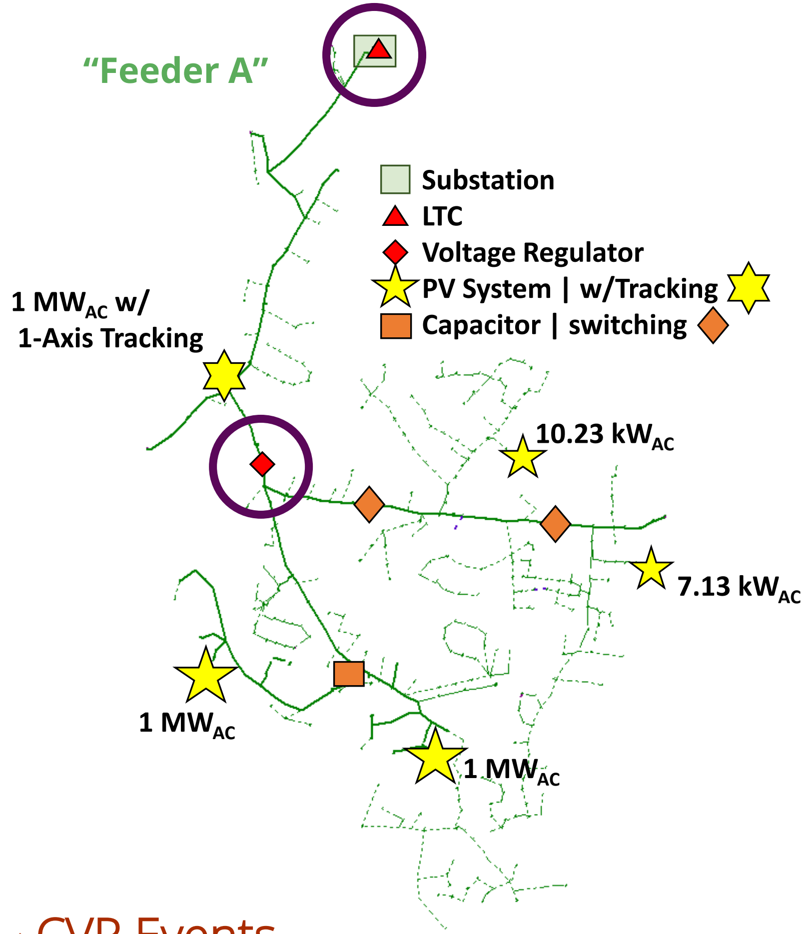
CVR Modeling – Load Response

- In order to analyze CVR events in simulation, the loads on the feeder have to be modeled with voltage-sensitivity
- In this work, the voltage-sensitivity is implemented using "CVR Factors"
  - Describes the % reduction in P (or Q) for a 1% reduction in voltage, appears as the linear fit in the figures on the right
- CVR Factors were derived from actual utility measurements from before and after each CVR event was triggered
  - First, we calculated the $\frac{\Delta P}{\Delta V}$ (top) and $\frac{\Delta Q}{\Delta V}$ (bottom) from the measurements at the feeder head and applied a linear regression
  - CVR Factors of 0.661* and 2.379* were calculated for real and reactive power, respectively
  - *calculated factors correspond to this specific test case, but do fall within the typical range (from OpenDSS: CVRwatts of 0.4-0.8 for real power, CVRvars of 2-3 for reactive)





CVR Modeling – Circuit Implementation



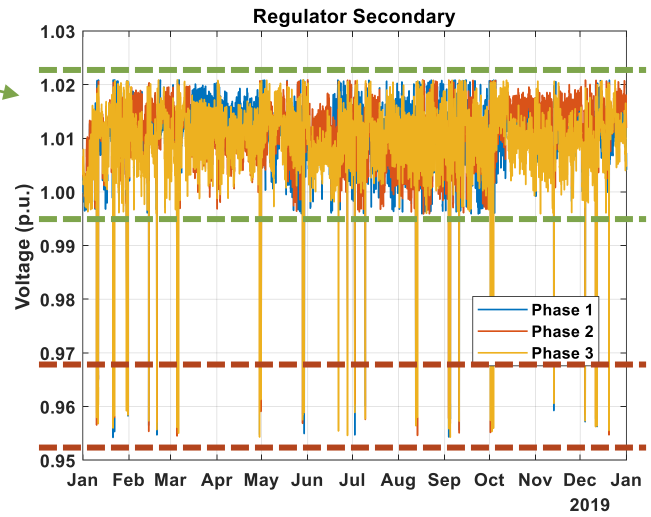
- All CVR events were carried out by *only* the substation transformer LTC and the voltage regulator
  - The capacitor banks were not part of the CVR scheme
  - 32 total CVR events, typically lasting around 2-3 hours (timing and duration provided by the utility)
  - During CVR, voltage set point drops from 121V to 116V (~4%)

Normal Operations

Tap Settings

Status		Tap	FORWARD Voltage (V)	Bandwidth (V)	Rset (V)	Xset (V)
A	☑	-1	121.0	3.0	3.0	3.0
B	☑	-1	121.0	3.0	3.0	3.0
C	☑	-1	121.0	3.0	3.0	3.0

☐ Same phase settings



CVR Events

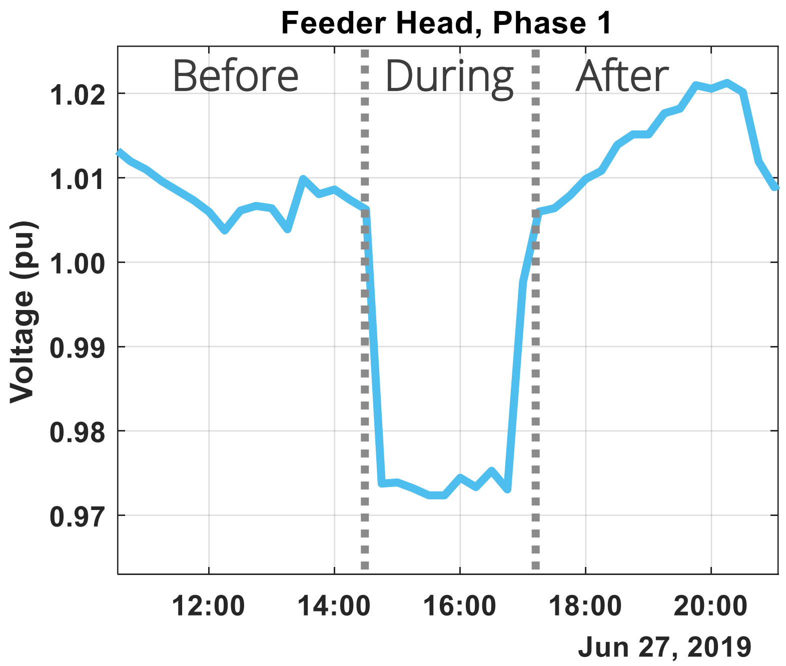
Tap Settings

Status		Tap	FORWARD Voltage (V)	Bandwidth (V)	Rset (V)	Xset (V)
A	☑	-1	116.0	3.0	3.0	3.0
B	☑	-1	116.0	3.0	3.0	3.0
C	☑	-1	116.0	3.0	3.0	3.0

☐ Same phase settings

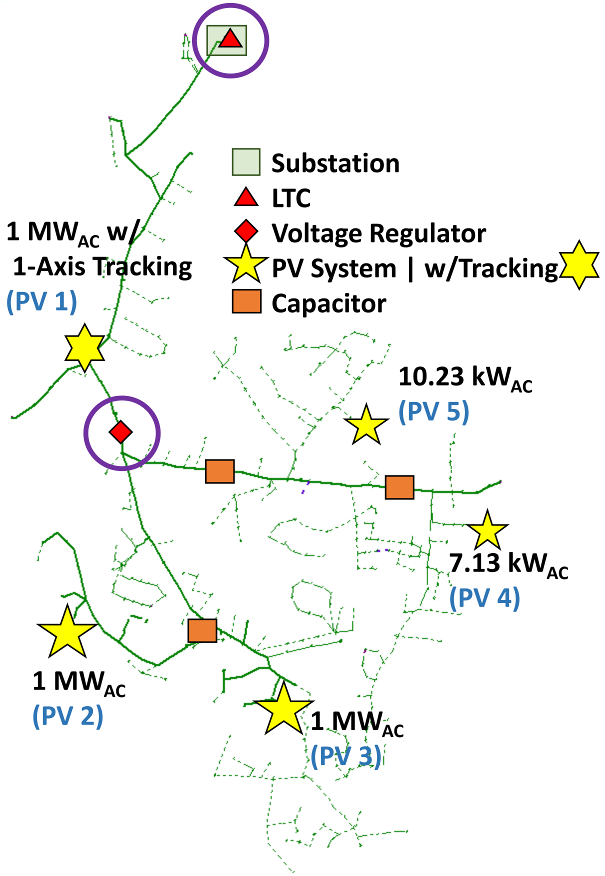
Overview of Analysis Procedure

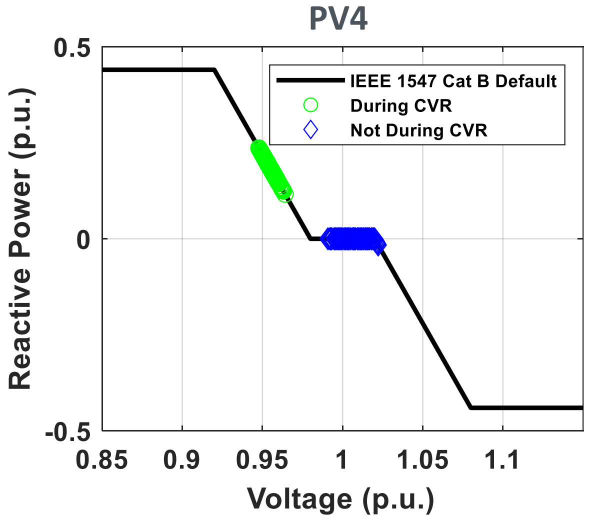
1. Compile the “Feeder A” Test Circuit in OpenDSS
2. Load in time points for CVR events
3. Apply CVR factors to all loads
4. Set all PV systems to operate with PF=1
5. Run QSTS simulation, modifying LTC and Voltage Regulator controls during CVR events
6. Enable autonomous Volt-VAR on all PVs
7. Re-run QSTS simulation
8. Calculate PV curtailment (Total PF=1 output – Total Volt-VAR output)
9. Analyze impacts of CVR on curtailment and impacts of Volt-VAR on CVR

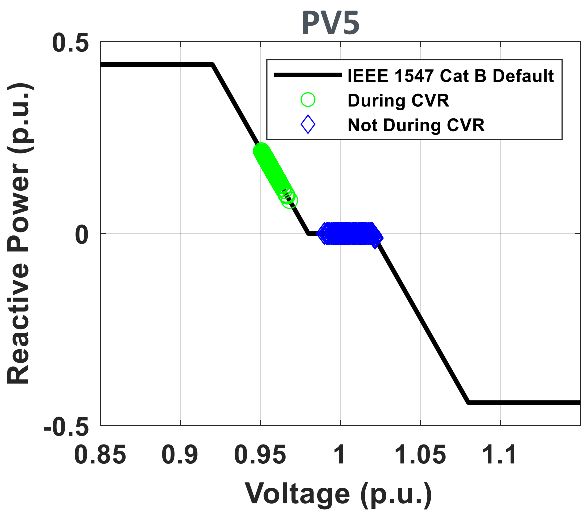


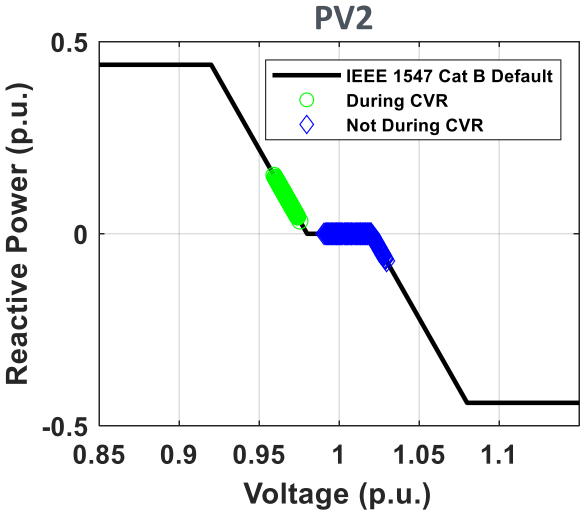
$$Curtailment_{kWh} = kWh_{PF=1} - kWh_{Volt-VAR}$$

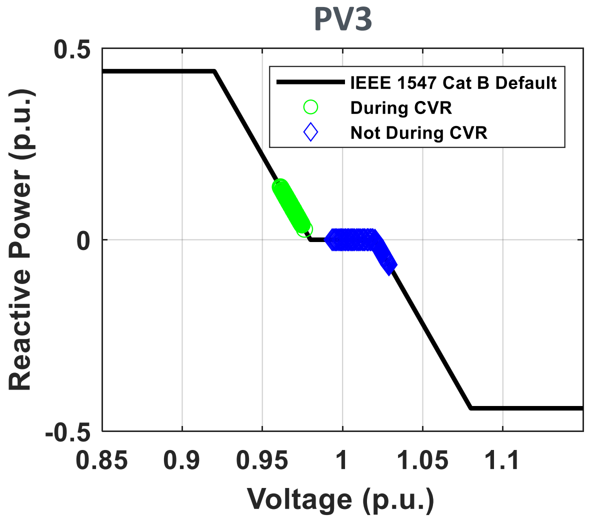
Results – CVR Impact on PV Output

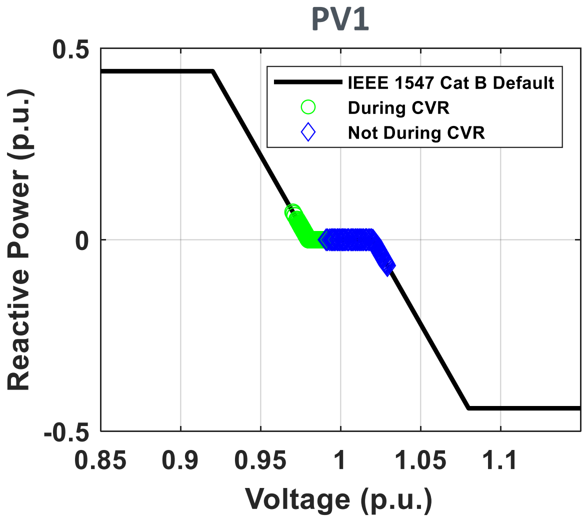






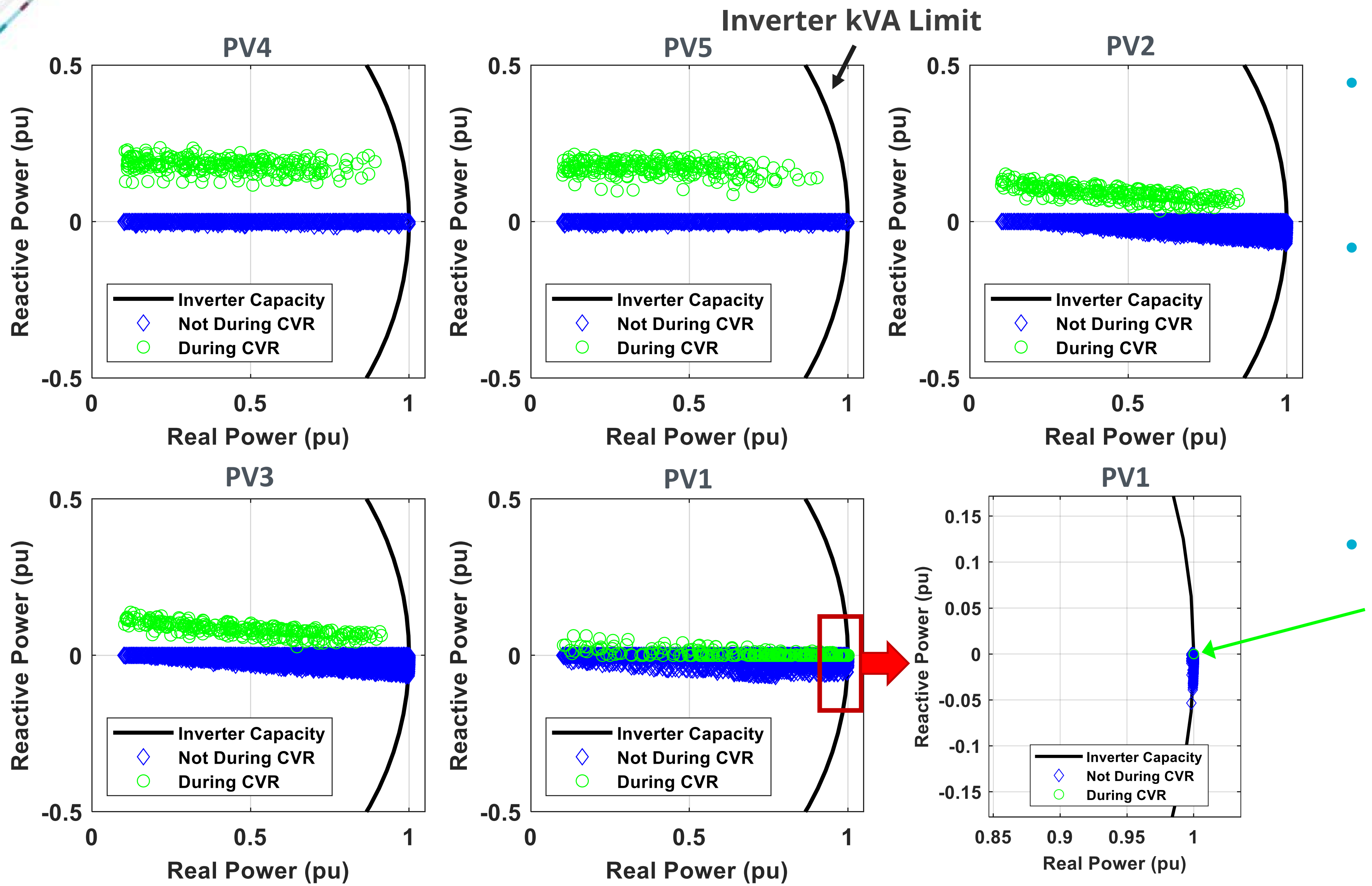






- During the CVR events, the voltages at the PV systems dropped low enough for the Volt-VAR controllers to start producing VARs

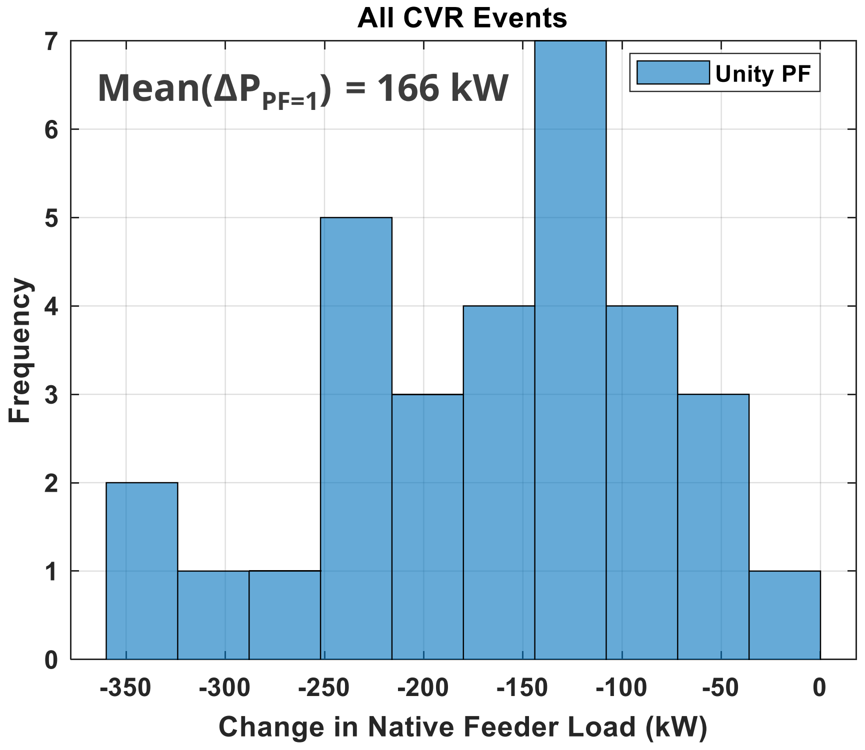
Results – CVR Impact on PV Output

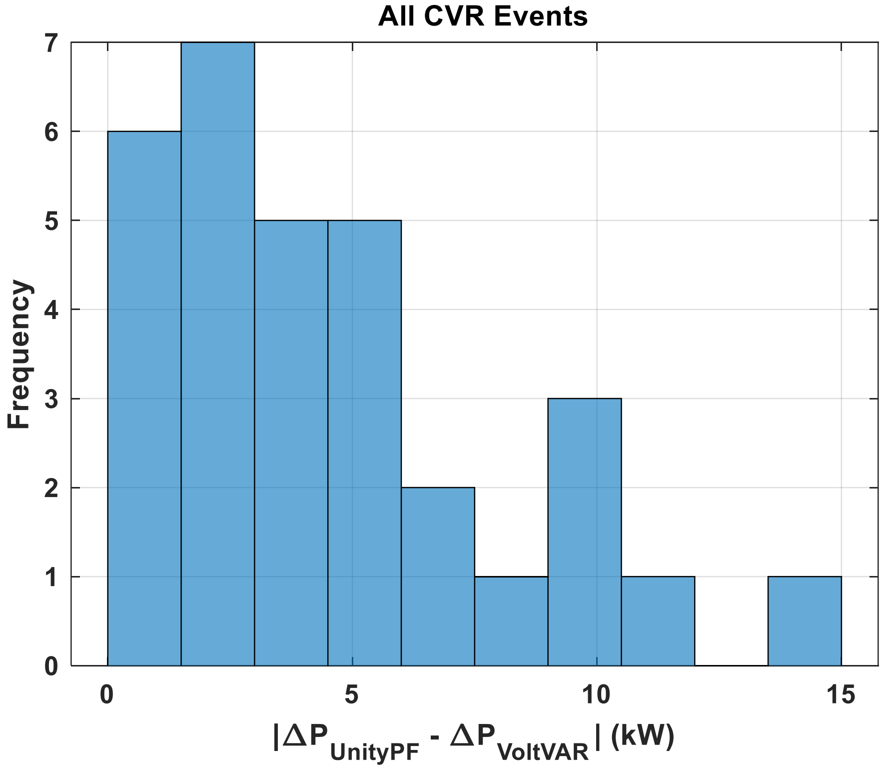


- No curtailment occurred for any PV system during any CVR event
- Real power is only curtailed to provide additional reactive power support when the inverter is already operating at its kVA limit
- PV1 (1-axis tracking) was the only one to have operated at its kVA limit during a CVR event, but no reactive power was required at that time

Results – Impact of Volt-VAR on CVR

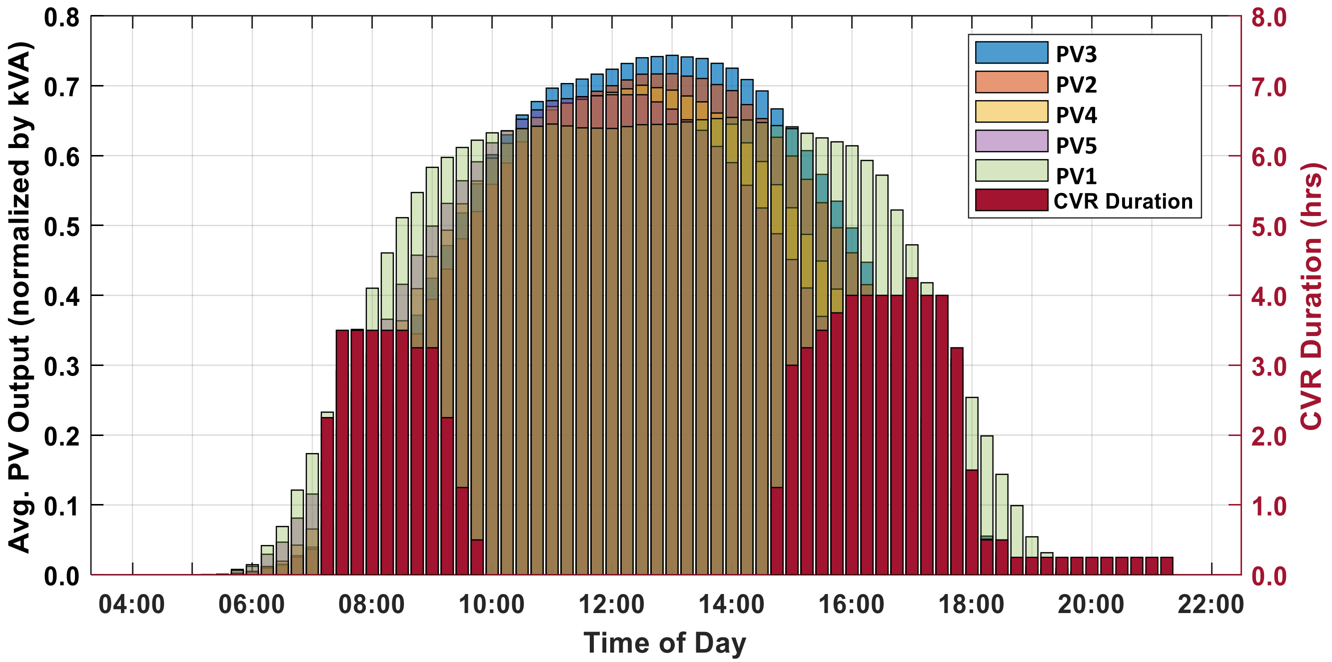
- For the unity PF case (PF=1), CVR resulted in an average reduction in power of **166 kW**
- To determine the impact of Volt-VAR on CVR, we compared difference between the change in native load during CVR for the PF=1 case ($\Delta P_{PF=1}$) and the Volt-VAR case ($\Delta P_{Volt\text{-}VAR}$)
  - Average value of $|\Delta P_{PF=1} - \Delta P_{Volt\text{-}VAR}|$ = **4.5 kW,** or in other words (4.5 kW / 166 kW) = **2.7%** difference on average





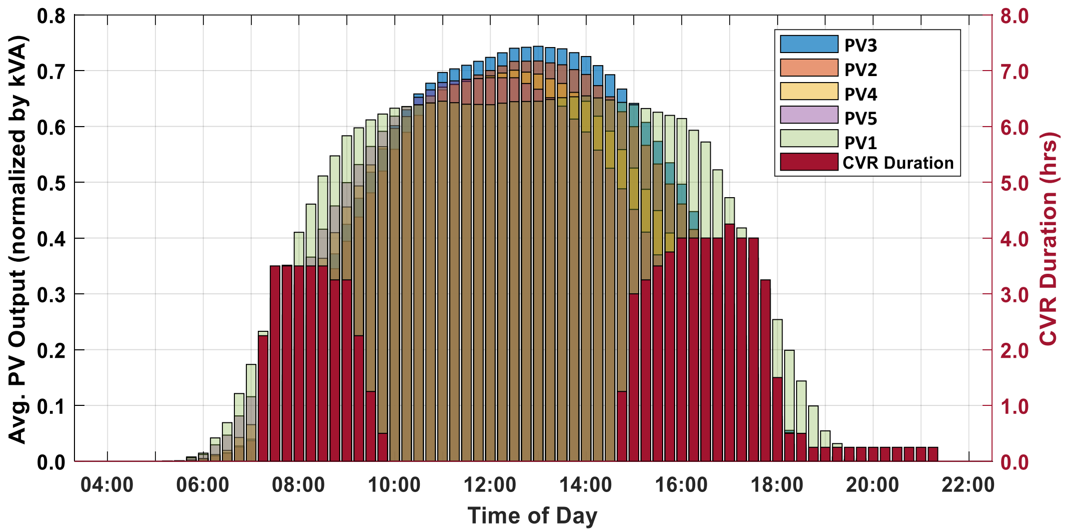
Discussion

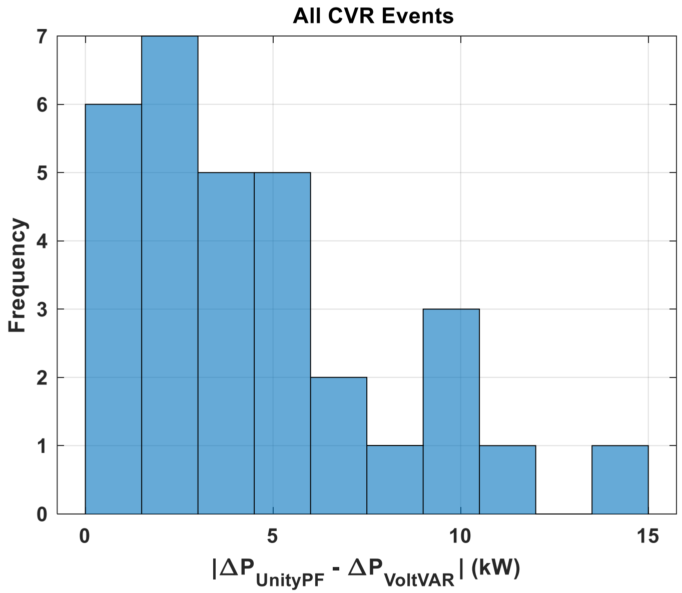
- Utilities typically implement CVR to reduce loading during times of high demand (e.g., morning and afternoon peaks), as was the case in this dataset (shown below in red)
- PV curtailment is most likely to occur during peak production hours (around midday as shown below) when the inverters are operating near full capacity and/or when loading conditions are low
- Given these characteristics, it follows that interactions between CVR on PV output would be expected to be marginal, if any



Conclusion

- PV inverters with Volt-VAR typically absorb VARs to compensate for voltage rise associated with real power injections
  - During CVR, PV inverters inject VARs to boost voltage
- CVR events did not overlap with peak PV production hours and did not cause any real power curtailment when Volt-VAR was enabled
- Implementing Volt-VAR did not have a significant impact on CVR, even with a high PV penetration (~66% of peak load)
  - On average, CVR reduced the feeder power by **166 kW**
  - On average, volt-VAR changed that value by **4.5 kW (2.7%)**





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