Integration of PEV and PV Sources into the Electric Distribution System

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Agenda

- **Overview**
- **Introduction to PEV impact studies**
  - Methodology and case studies
  - Mitigations and potential benefits
- **Introduction to PV-DG impact studies**
  - Steady-state and dynamic simulations
  - Mitigations and potential benefits
- **Conclusions**

Introduction to PEV impact studies

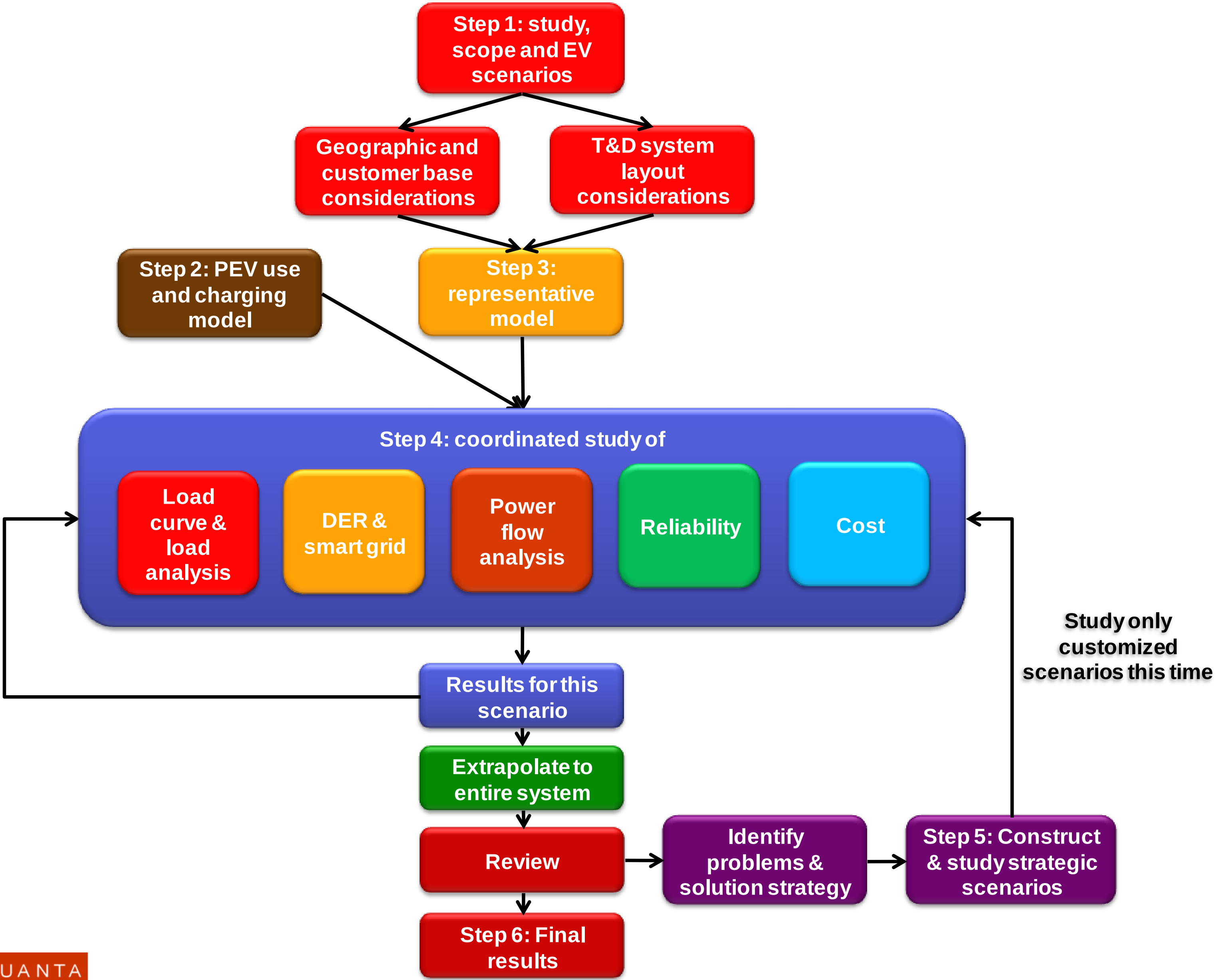
Overview - PEV

- **Plug-in Electric Vehicles (PEV) are coming**
  - National security in a traditional sense (energy policy)
  - National security in a broader sense (climate change)
- **PEV penetration projection varies significantly, however, the impact to power systems may arise in an early stage due to vehicle clustering effect**
- **Utilities have concerns over the increasing PEV popularity impacting their systems**

Methodology

- **A framework for long term PEV impact study on distribution systems**
  - Feeder characteristics can significantly differ
  - PEV impact is non-linear function of penetration rate
- **Key components:**
  - Representative feeder approach (statistical cluster analysis)
  - Sweep analysis (a wide range of penetration rates)
  - Monte Carlo simulation

Methodology (cont.)



Step 1: study, scope and EV scenarios

Geographic and customer base considerations

T&D system layout considerations

Step 2: PEV use and charging model

Step 3: representative model

Step 4: coordinated study of

- Load curve & load analysis
- DER & smart grid
- Power flow analysis
- Reliability
- Cost

Results for this scenario

Extrapolate to entire system

Review

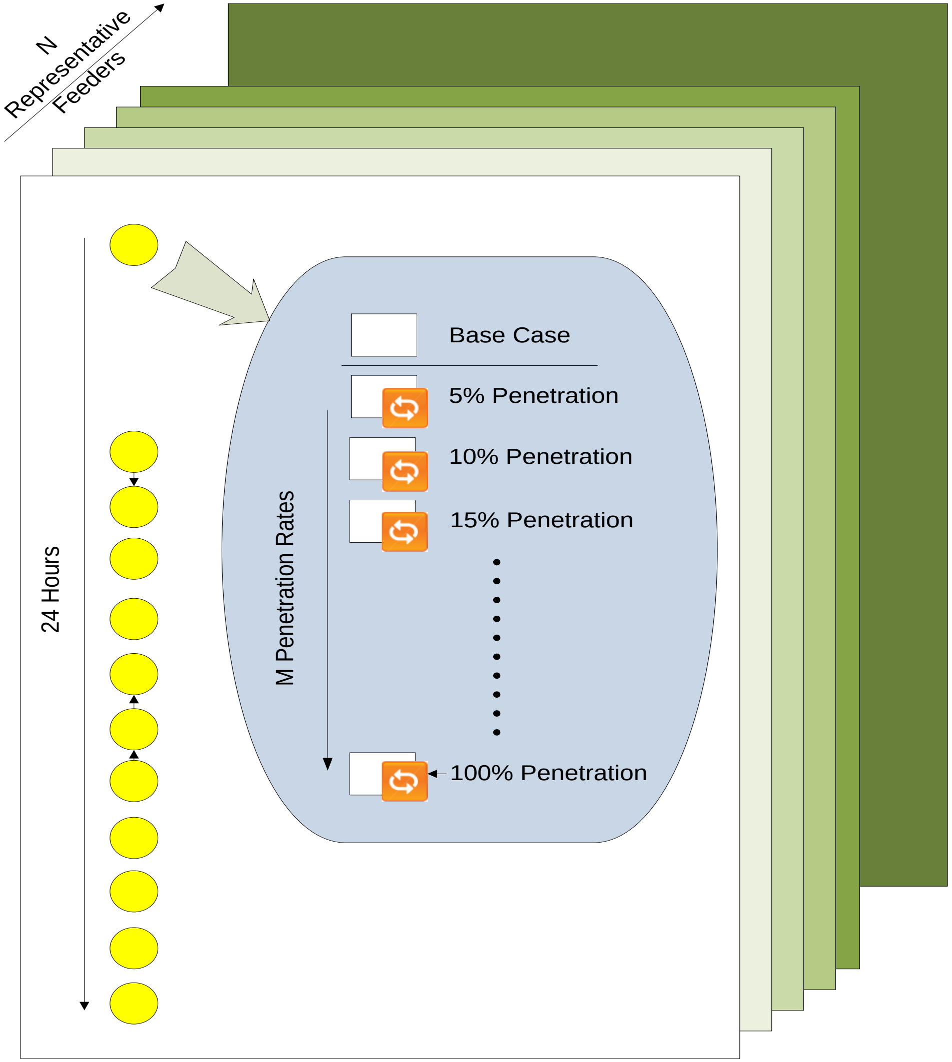
Identify problems & solution strategy

Step 5: Construct & study strategic scenarios

Study only customized scenarios this time

Step 6: Final results

Methodology (cont.)



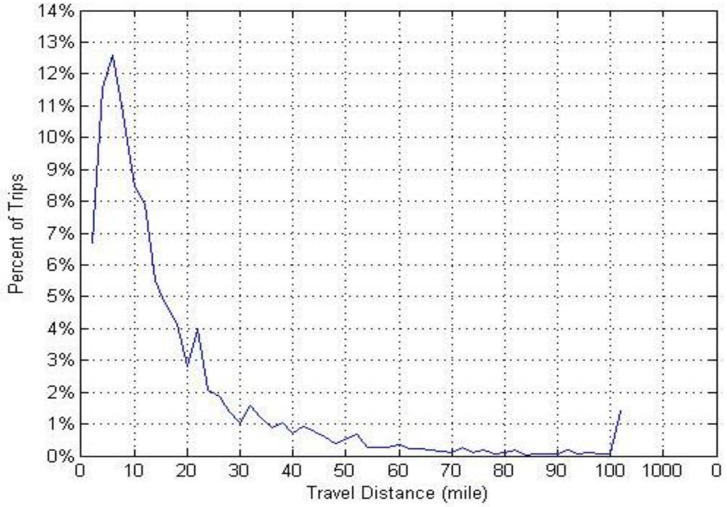
Data collection

- **PEV penetration rate**
- **PEV battery charging profile**
- **PEV charging scenario**
  - Driving Pattern Based:
    - Charging duration calculation needed
  - Time Stamp Based:
    - No charging duration information needed
    - Instead: hourly PEV charging distribution and co-incidence factors

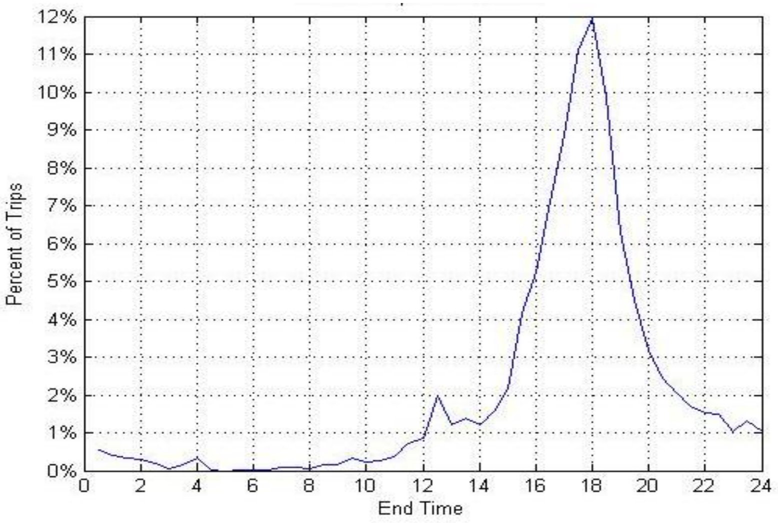
Driving pattern based PEV charging scenarios

- **PEV charging scenarios are developed based on vehicle usage patterns**
  - National Household Travel Survey 2009 by U.S. Department of Transportation
  - Trip end time determines charge start time
  - Trip duration determines charging duration (charge end time)
- **Solid data support, if travel data available**

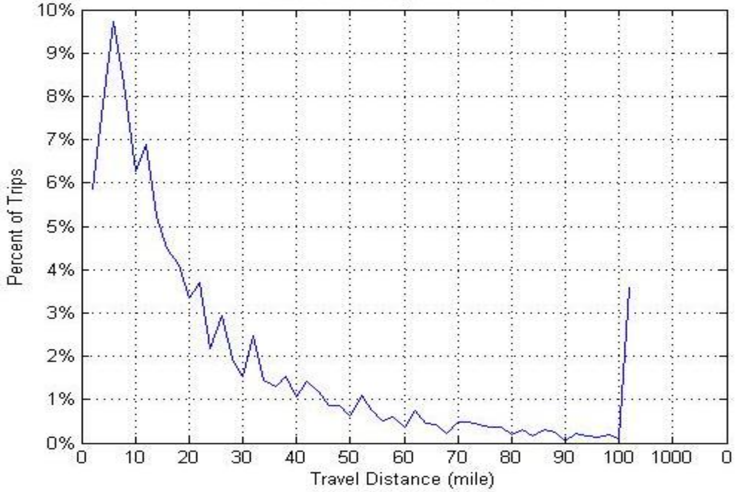
Driving pattern examples



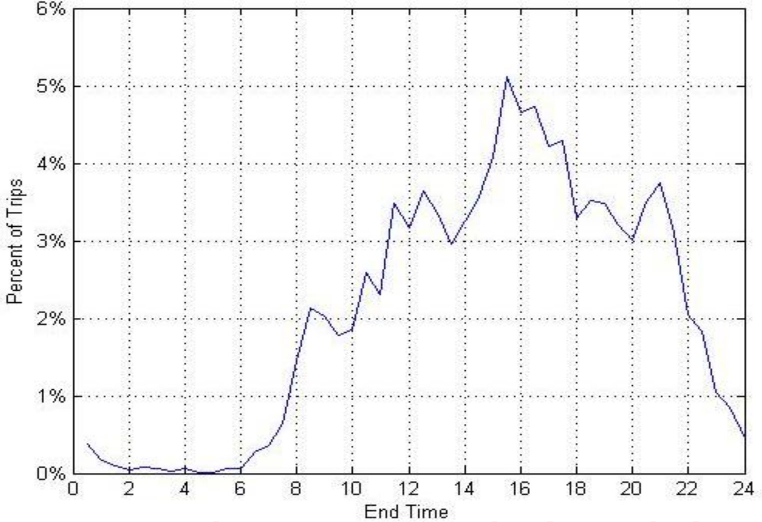
Urban Area Home to Office Commute Trip Distance Distribution



Urban Area Office to Home Commute Trip End Time Distribution



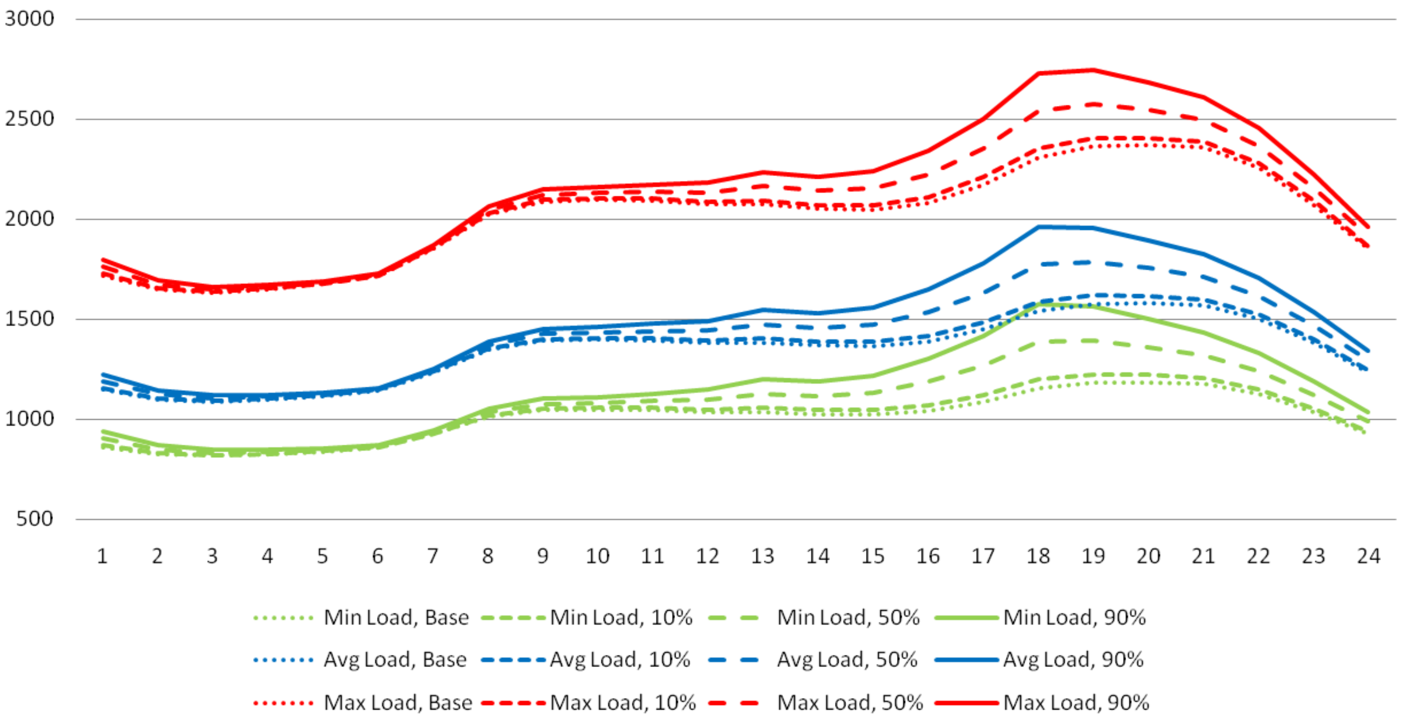
Non-Urban Area Errand Trip Distance Distribution



Non-Urban Area Errand Trip End Time Distribution

Sample results: feeder loading

- **Driving pattern based charging scenario; typical circuit design, national average travel pattern**

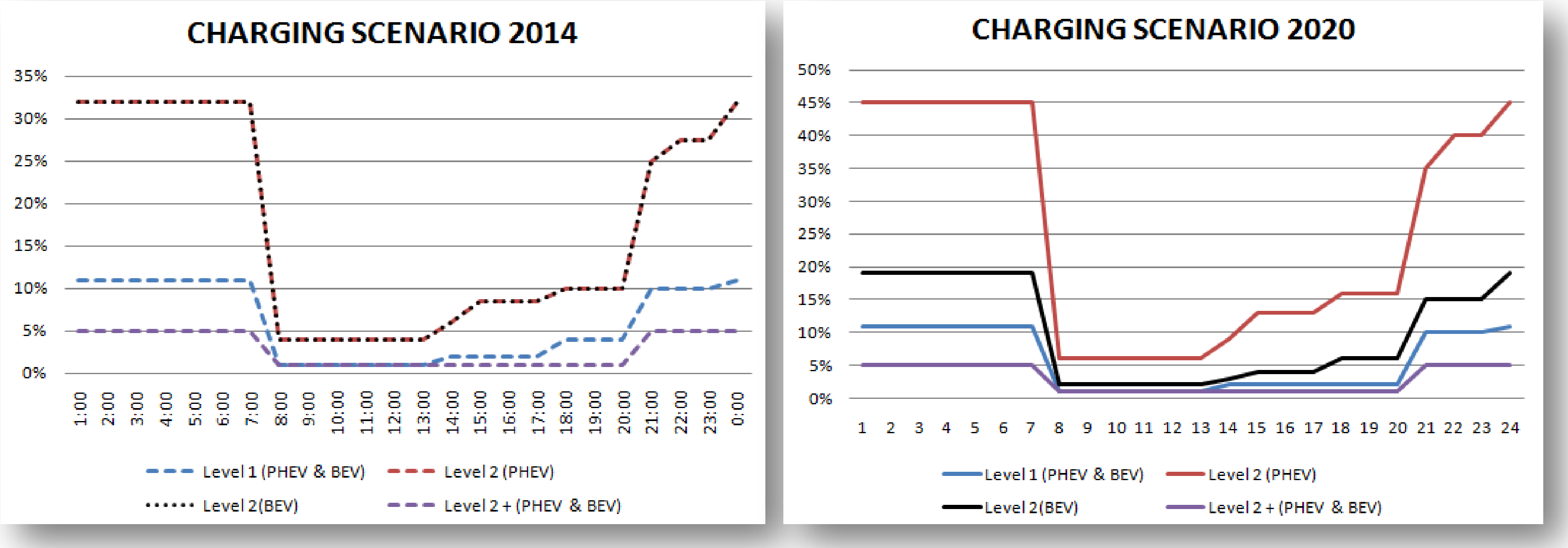


Time stamp based PEV charging scenarios

- **PEV charging scenarios are developed based on charging distribution projection**
  - Applied when no statistically representative travel data is available
  - Typically utility envisioned PEV charging patterns
  - Focus on instantaneous charging patterns, no charging duration considered
  - Additional information may be needed, such as co-incidence factors

Charging scenario examples

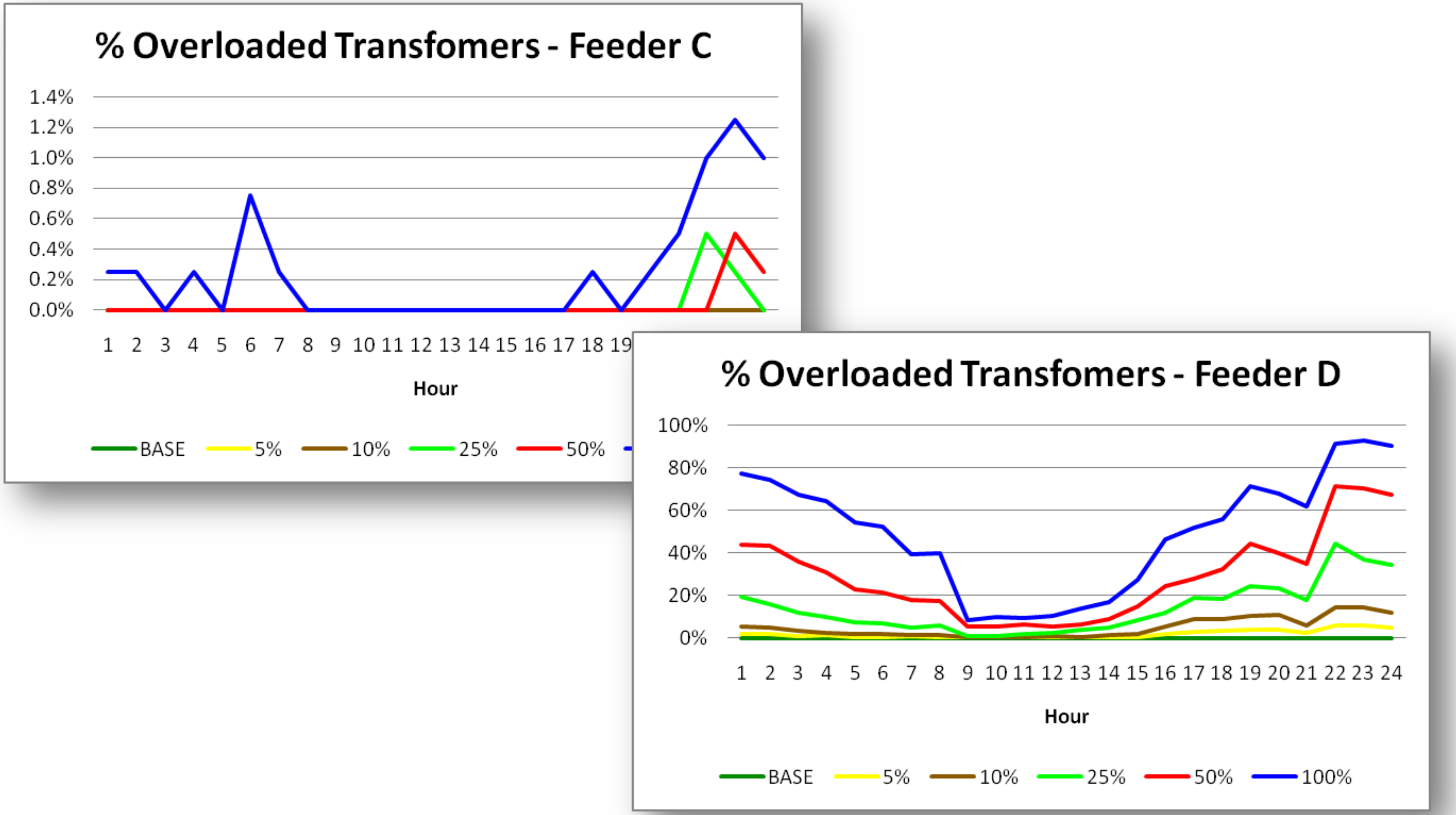
- **Utility envisioned charging scenarios:**



Residential Charging as an Example

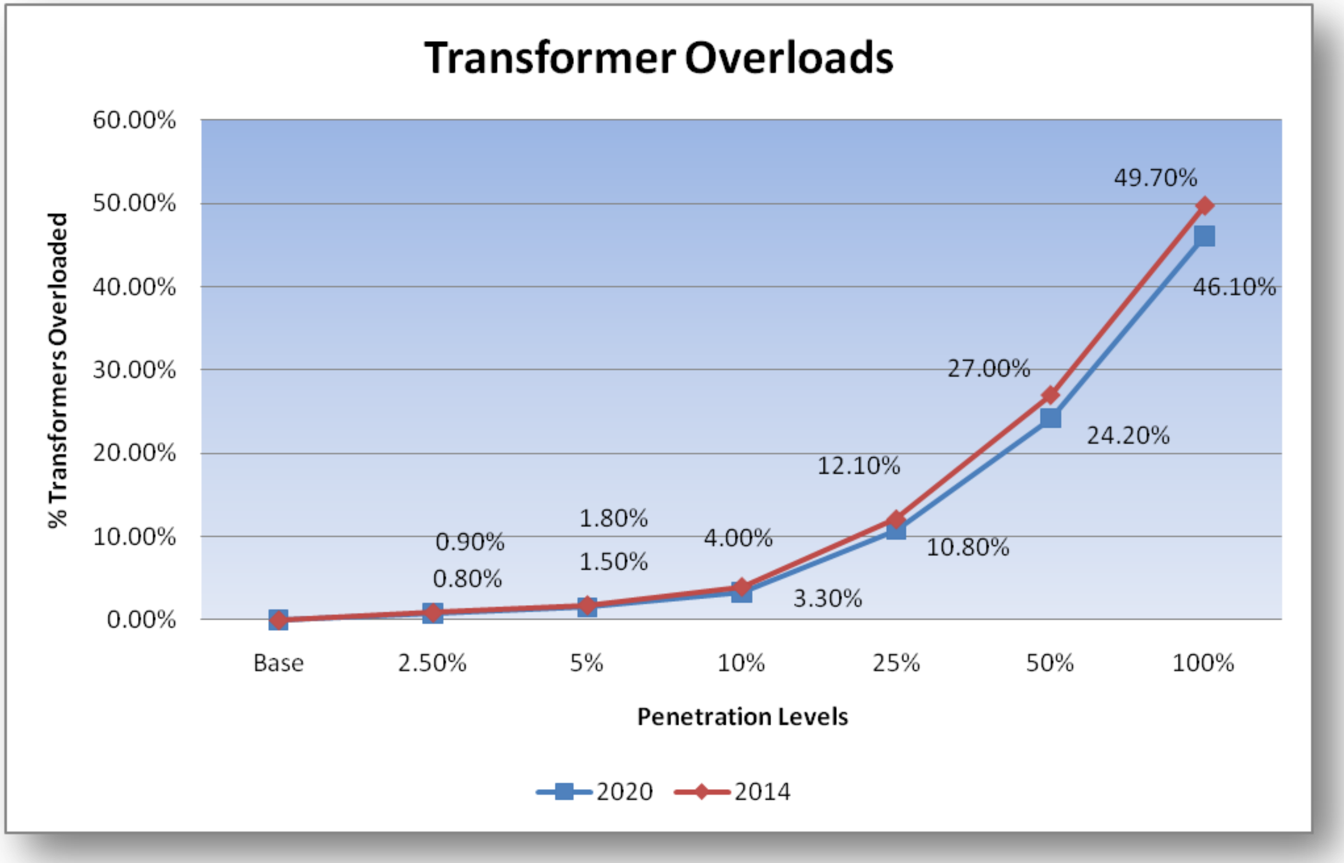
Sample results: transformer overload

- **Time stamp based charging scenario:**



System-wide results

- **Extrapolated from individual feeder studies:**



Mitigation measures

- **Mitigation options include capacity increasing approaches and charging management (smart grid technologies)**
- **Traditional T&D solutions**
  - Replace overloaded transformers
  - Reconductor overloaded line sections
  - Under voltage often eliminated by reconductoring. If not, install capacitors or voltage regulators
  - Feeders exceeding planning limits can be unloaded by building new feeders or transferring loads to neighbor feeders
  - Etc.

Charging management

- **Many of the impacts can be resolved by controlling the time and duration of PEV charging**

Opportunity	Near Term	Long Term
Tariff/TOU Rates	Tiered TOU Rates	Real Time Pricing (RTP) Critical Peak Pricing (CPP)
Smart Charging	User/Vehicle Controlled Charging	Utility Controlled Charging

- **Additional infrastructure, metering, monitoring and control equipment such as automated (smart) metering system will be required for two way communication**

Impact of controlled charging

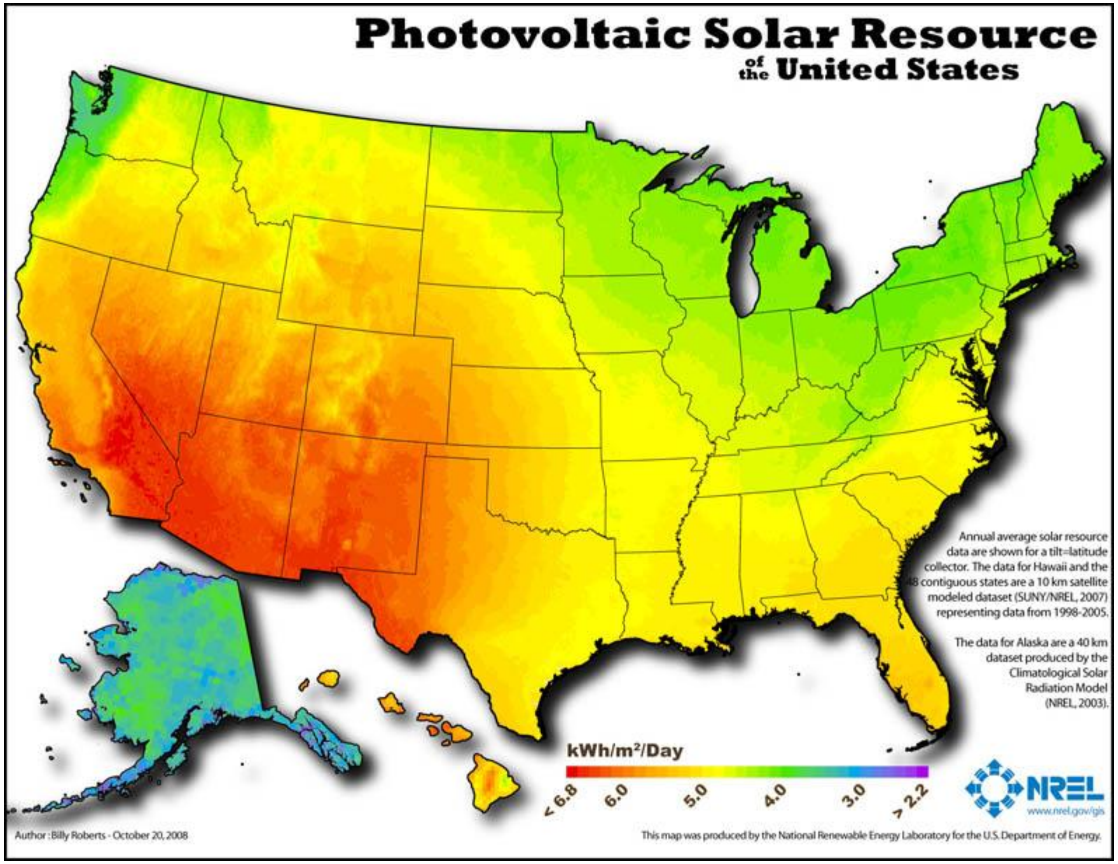
- **An example from a utility specific study:**
  - For penetration levels below 20%, overloaded conductor and customers experiencing under voltage were eliminated
  - For penetration levels between 25 and 60%, the amount of overloaded conductor and customers experiencing under voltage were reduced by half when compared with the uncontrolled scenario
  - At high penetration levels, the impact on overloaded conductor and customers with under voltage was the same for both scenarios

Potential benefits

- A new, and attractive, revenue source for utilities
- Improve load factor and asset utilization
- Potential for integration with smart grid initiatives, Distributed Energy Resources (DER) like Photovoltaic Distributed Generation (PV-DG), and Distributed Energy Storage (DES)
- Potential for advanced applications such as Vehicle to Grid (V2G)
- Utilities are starting to explore concepts such as integration of PEVs, PV-DG, and Community Energy Storage (CES) via low voltage (DC) secondary buses

Introduction to PV impact studies

Introduction to PV-DG integration studies



Annual average solar resource data are shown for a tilt=latitude collector. The data for Hawaii and the 48 contiguous states are a 10 km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.

The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

Author : Billy Roberts - October 20, 2008

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

Background

- PV-DG is rapidly growing, **not only in the southwest!**
- Utilities along North America must comply with Renewable Portfolio Standards (RPS) requirements (e.g., the goal for the state of California is 33% by 2020)
  - There are incentives in place
- PV-DG has diverse **impacts** on distribution system planning and operation (e.g., solar **intermittency** due to cloud cover can have a significant impact on voltage variations)
  - Impacts are not localized and grow as proliferation increases
  - Impacts are not only of steady state but also of **dynamic/transient** nature (e.g., Transient Overvoltage TOV)
- This may represent a challenge for distribution planners, who are used to deal with steady state studies but not be familiar with **dynamic modeling and analysis**

Impact studies

- **Typical Scope Of Work**
  - Identify the local and/or system-wide impacts of PV-DG on the power distribution grid
  - Provide utility customers with guidelines regarding the expected impacts as a function of the penetration degree of PV-DG
  - Determine potential mitigation measures for any problems discovered in the study
- **Additional Tasks**
  - Inverter testing in a laboratory setting
  - Development of interconnection standards (PV-DG readiness studies)

Objectives

- Understand steady-state impacts
- Understand dynamic impacts
- Identify adverse impacts
- Determine remedial measures and economic impacts

PV-DG types

- **Utility scale PV-DG**: large commercial PV-DG plants with capacities larger than 1 MW (three-phase generation)

- **Medium scale PV-DG**: small commercial PV-DG with capacities between 10 kW and 1 MW (it can be three-phase or single-phase)

- **Small scale PV-DG**: small residential PV-DG under NEM agreements. Capacities less than 10 kW (single-phase generation)

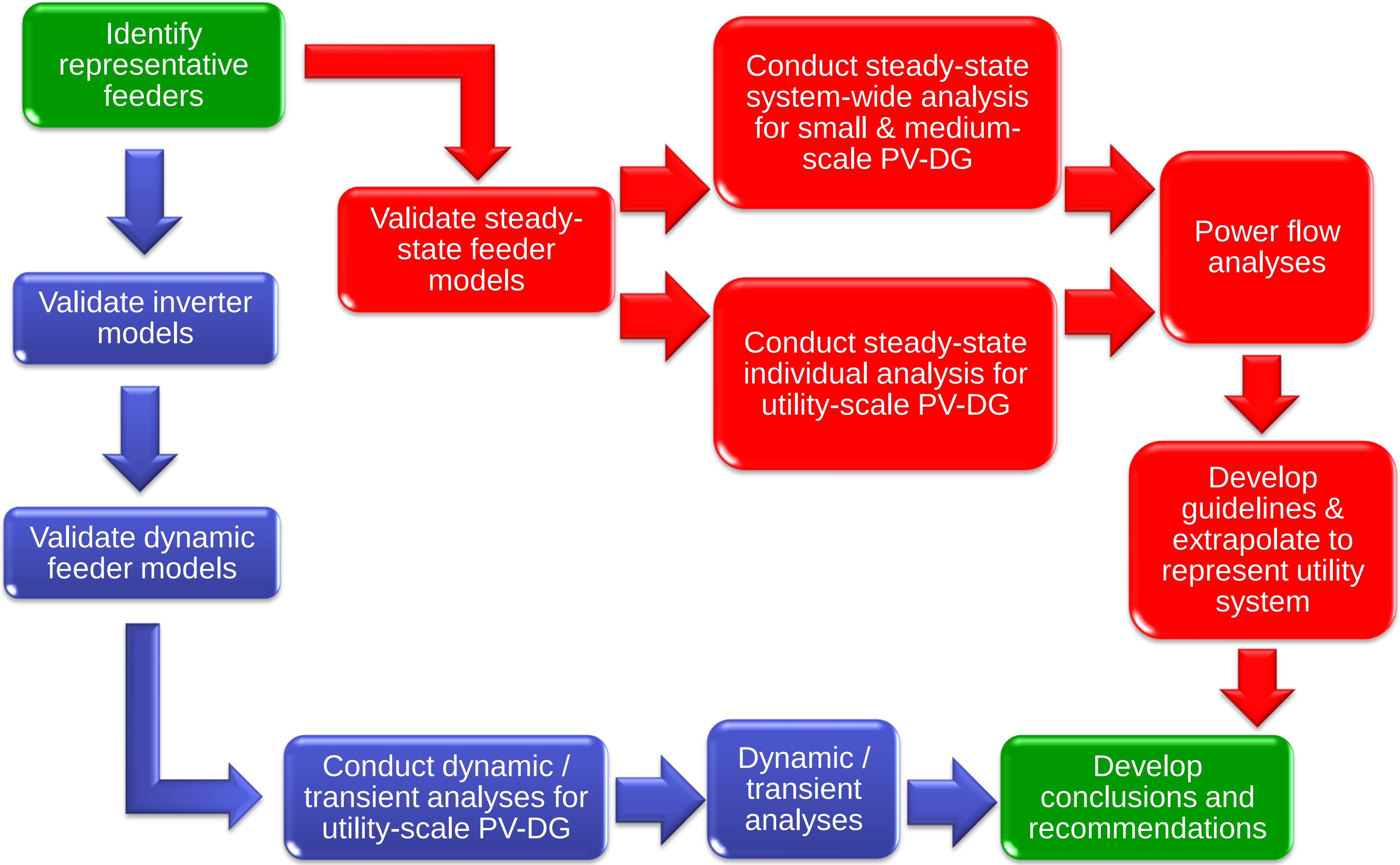
Uncertainties

- **Utility scale PV-DG:** utilities know where they will be installed, e.g., on industrial feeders, on rooftops of large warehouses, studies are more **deterministic** in nature and impacts are localized
- **Small and medium scale PV-DG:** they are being installed on residential and commercial feeders, studies are **non-deterministic** in nature (we have to deal with **uncertainties and different penetration scenarios**) and impacts are spread along the system
- Proliferation of PV-DG also implies propagation of power electronic devices in the utility system (**inverters**). This means that we have to pay more attention to harmonics and their interaction with system components such as capacitors, and have to perform **power quality** studies to evaluate potential impacts.

Need for steady state and dynamic simulations

- These impacts can only be studied through simulations, we have to use both steady state software and “dynamic” simulation software
- In order to model and handle uncertainties we may need to perform thousands of simulations (statistical scenario modeling)
- Potential impacts are:
  - Reverse power flow
  - Interaction with LTC, capacitor banks and voltage regulators
  - Voltage variations
  - Reactive power fluctuations
  - Losses increase and power factor modification
  - Potential impacts on overcurrent and overvoltage protection systems
  - Voltage unbalance (single-phase PV-DG)
  - THD increase

Methodology



Identify representative feeders

Validate inverter models

Validate dynamic feeder models

Validate steady-state feeder models

Conduct steady-state system-wide analysis for small & medium-scale PV-DG

Conduct steady-state individual analysis for utility-scale PV-DG

Power flow analyses

Develop guidelines & extrapolate to represent utility system

Conduct dynamic / transient analyses for utility-scale PV-DG

Dynamic / transient analyses

Develop conclusions and recommendations

Representative feeders

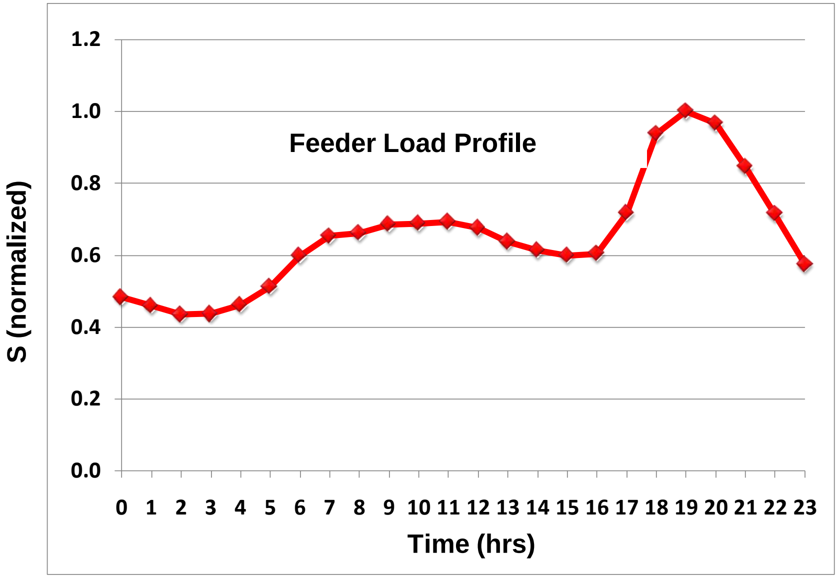
- **<u>Large PV-DG:</u>** utilities are interested in impacts on a set of individual feeders, representative feeders are identified from interconnection request database
    - Simulations are conducted for each feeder for a set of predefined scenarios
- **<u>Medium and small scale PV-DG:</u>** utilities are interested in overall system impact, representative feeders are identified using a **clustering algorithm** (it is labor, time and cost prohibitive to study all system feeders)
    - Thousands of simulations are performed to model uncertainty for different scenarios. Simulations are conducted using a statistical approach but only for the representative feeders. Results are extrapolated to the system

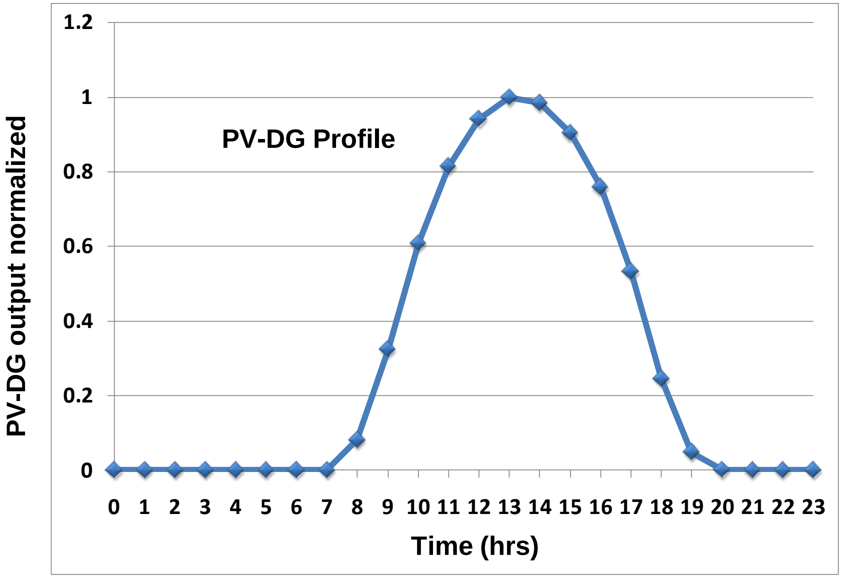
Steady state simulation overview

- **Analysis of different PV-DG penetration scenarios**
- **Inputs**
  - Typical PV-DG injection profile
  - PV-DG capacity (kW)
  - Feeder models (distribution analysis software)
  - 24 hour feeder load curves and status of voltage control equipment (voltage regulators and capacitor banks)

Approach for utility scale PV-DG

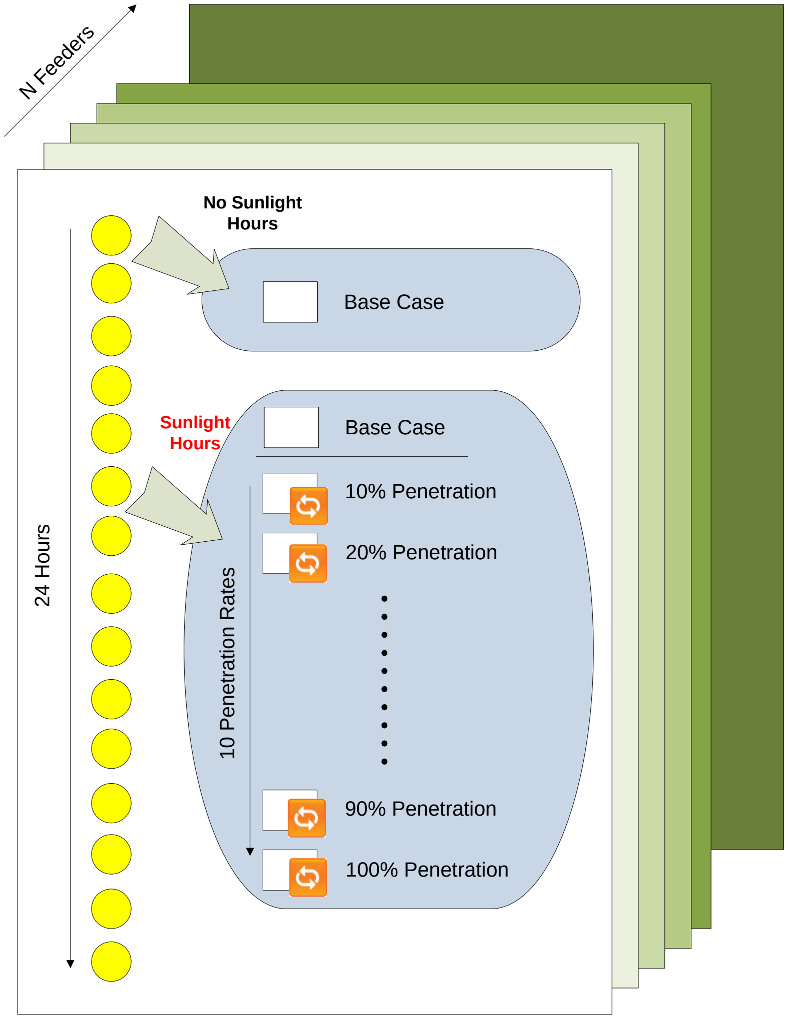
- Analysis for utility scale PV-DG consists on the modeling and simulation of **a combination of several feeder loadings and PV-DG injection conditions**
- The worst impacts are expected if a combination of low feeder loading conditions (daylight) and high injection of PV generation occurs. This may cause reverse power flows and overvoltages



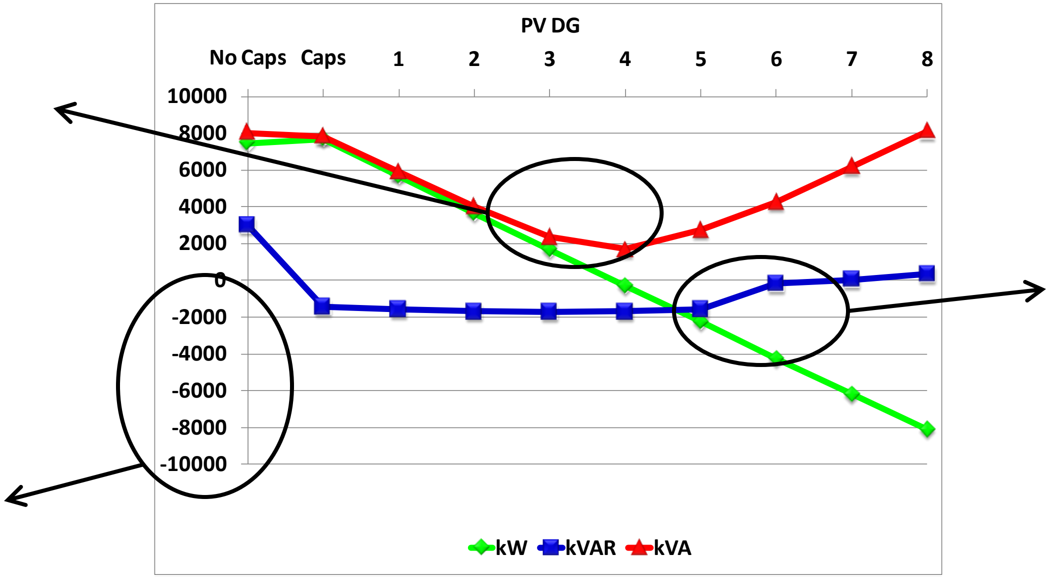


Approach for small / medium scale PV-DG

- Random assignment of PV-DG location and simulation of several penetration scenarios for representative feeders

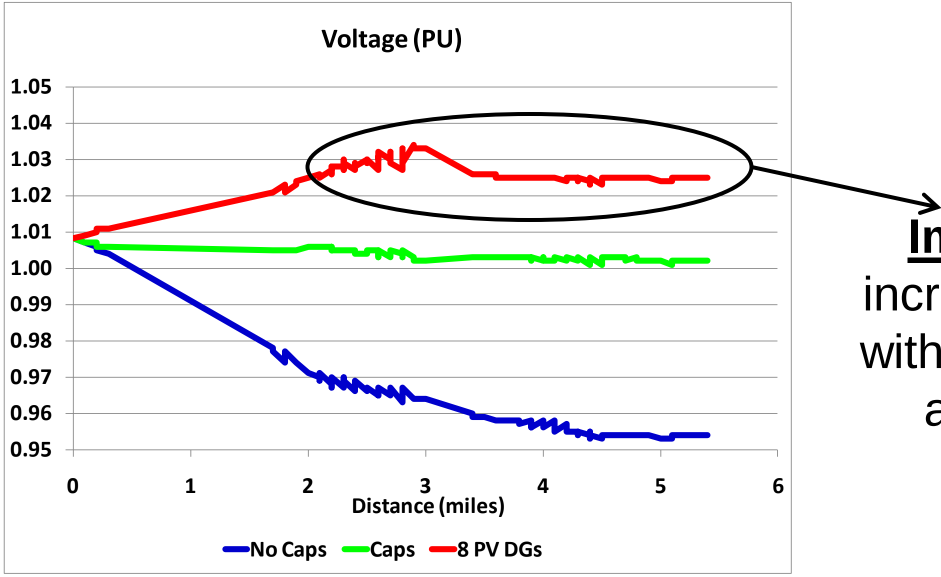


Results (utility scale PV-DG)



Impact: reactive power fluctuation due to capacitor switching

Impact: reverse power flow



Impact: voltage increase, interaction with capacitor banks and regulators

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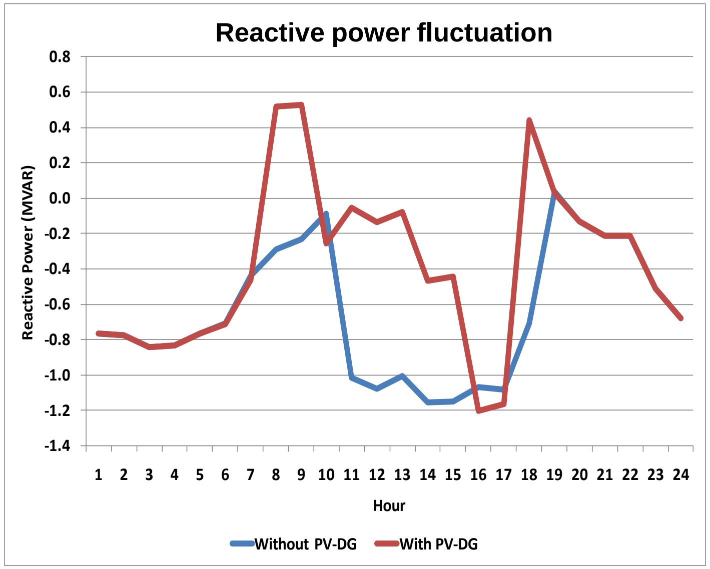
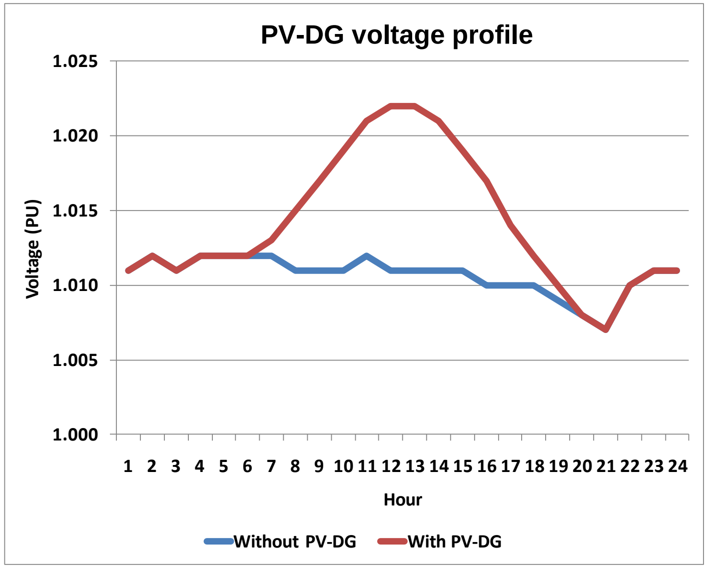
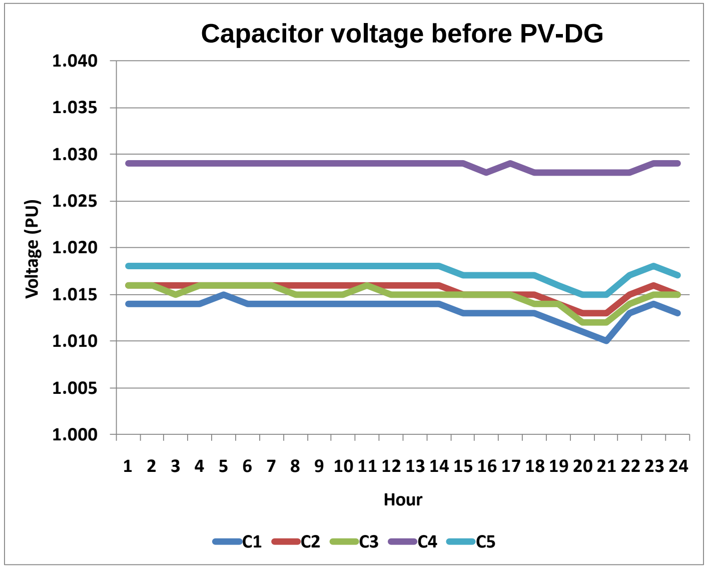
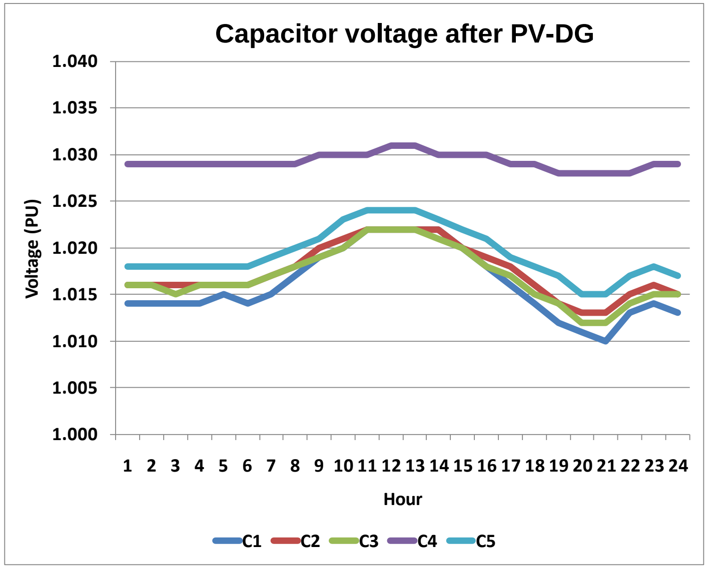
Results (utility scale PV-DG)

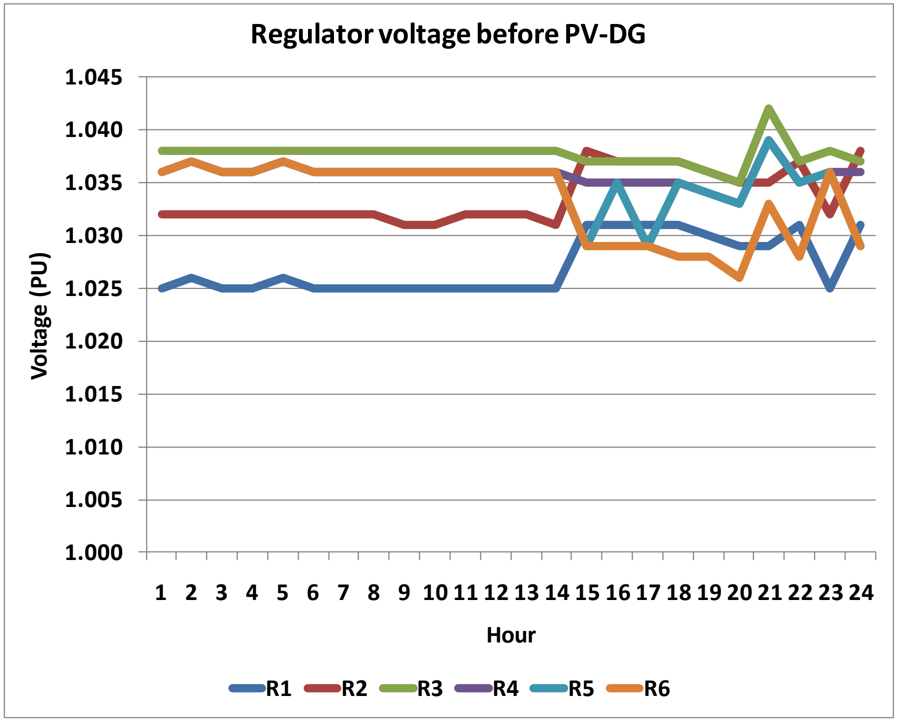


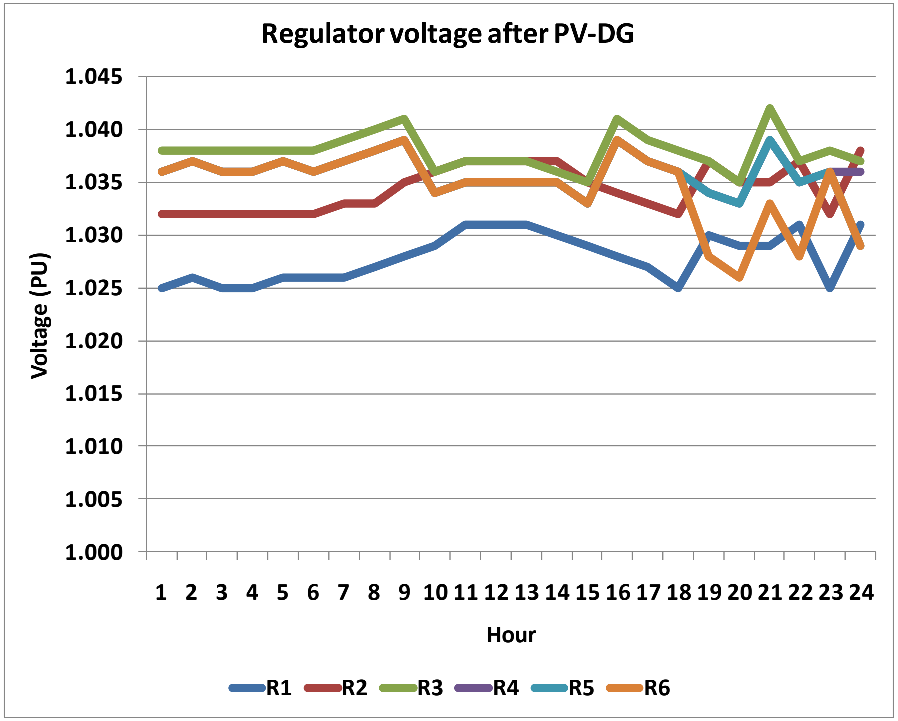






Results (utility scale PV-DG)





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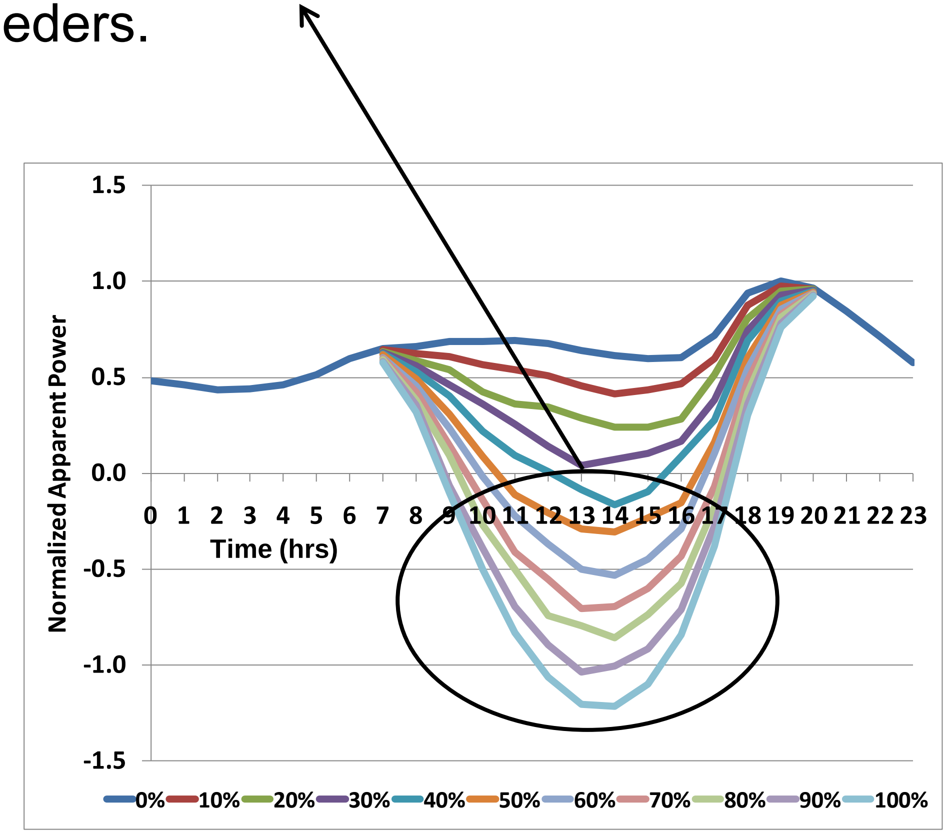
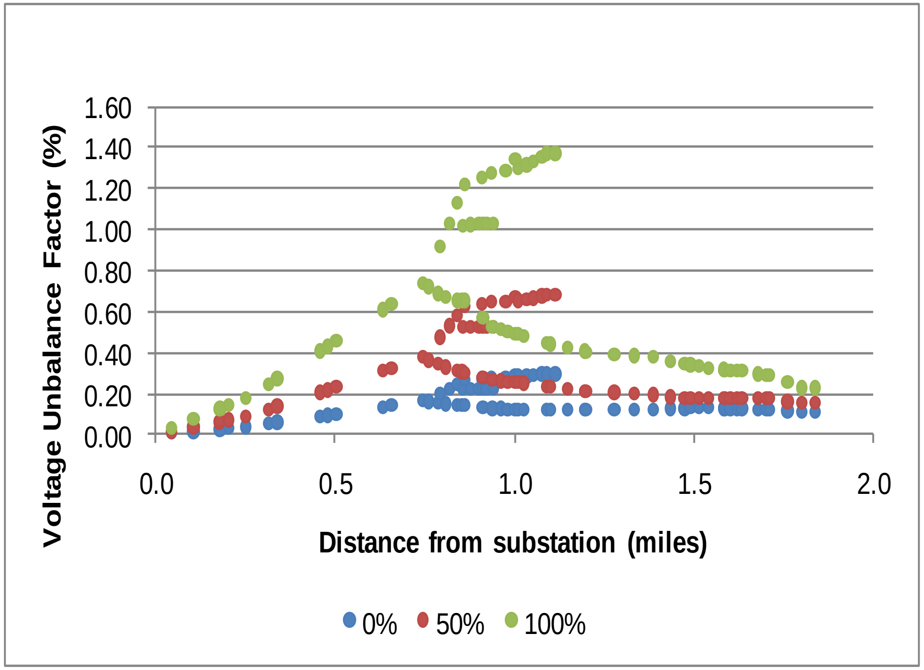
Results (small and medium scale PV-DG)

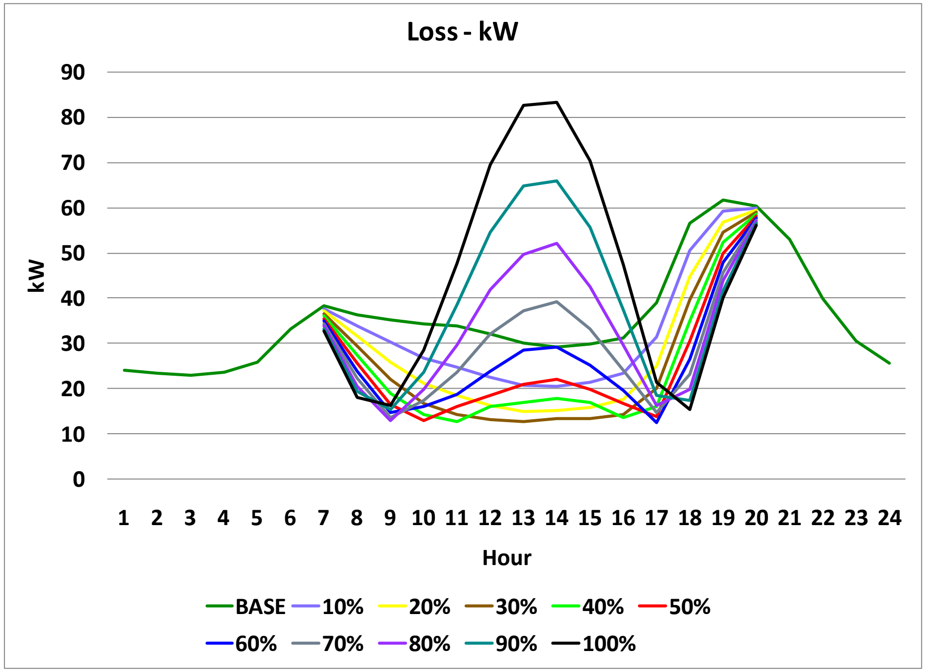
- Significant impacts may occur for high penetration levels. This will likely cause **<u>reverse power flows</u> and <u>overvoltages</u>**, particularly on “weak” feeders.



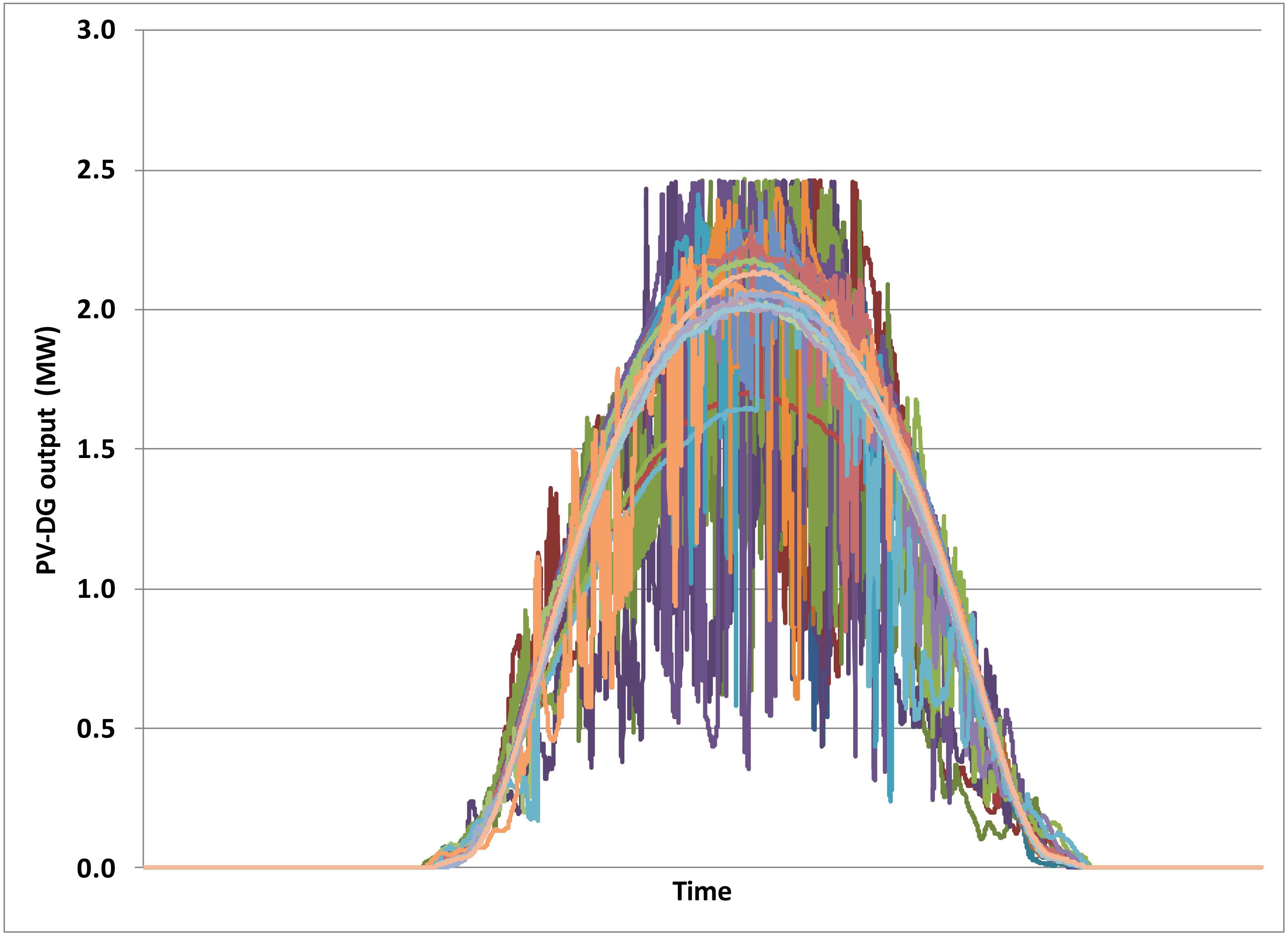
Results (small and medium scale PV-DG)

- Feeder **unbalance** (single-phase PV-DG) and **losses** are also affected as a function of the penetration level





Why dynamic analyses are necessary?



Dynamic simulation overview

- **Study focus**
  - Large-scale integration of solar PV generation
    - Utility scale PV-DG (three-phase)
    - Residential PV-DG (single-phase)
  - Impact of PV-DG intermittency, islanding and feeder transient and switching phenomena

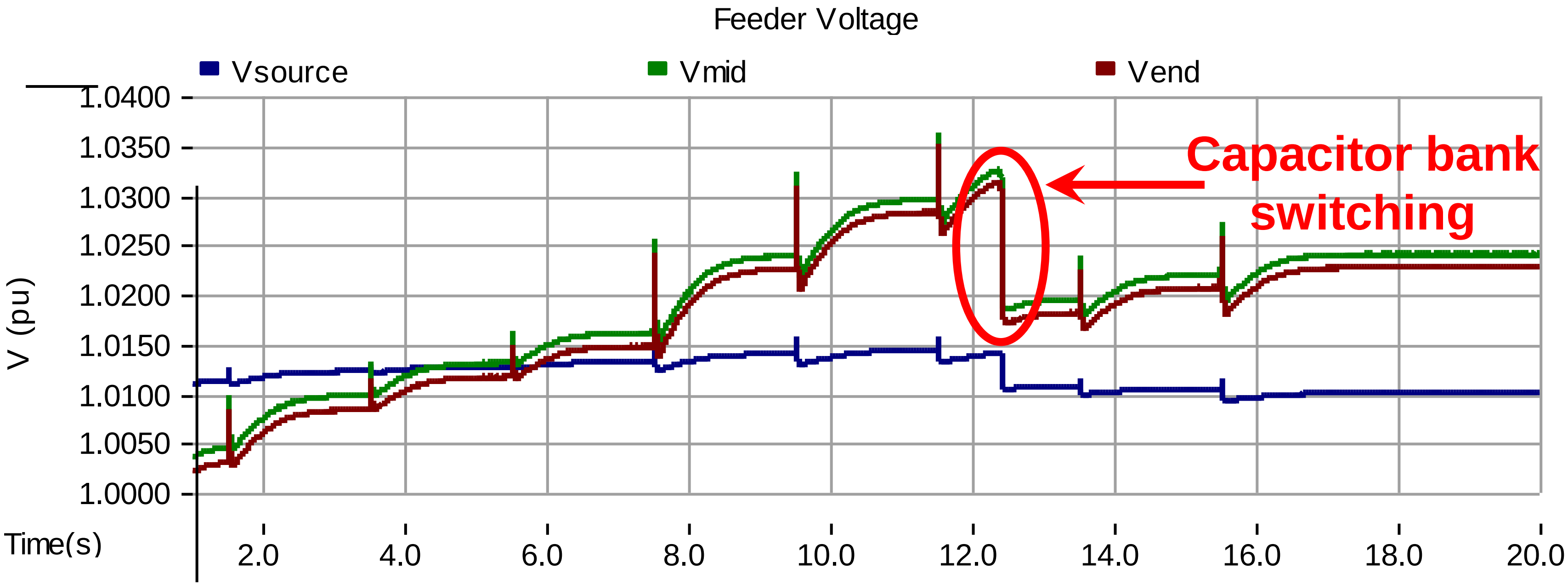
- **Typical study scenarios**
  - Sudden change in solar radiations (intermittency)
  - Islanding cases, e.g., opening of feeder circuit breaker
  - Feeder voltage variations (e.g., load connection/disconnection)

Dynamic analysis

- Potential issues such are temporary overvoltages can occur during islanding conditions (main breaker operation)
- **Results from dynamic simulations are of critical importance for ensuring the reliable operation of feeders with utility scale PV-DG**
- Dynamic/transient impacts of PV-DG cannot be identified using conventional distribution analysis software, more detailed modeling and simulations are necessary
- Dynamic and steady state studies are complementary. Dynamic analyses help define criteria and standard for integration and operation of PV-DG on power distribution systems

Results (utility scale PV-DG)

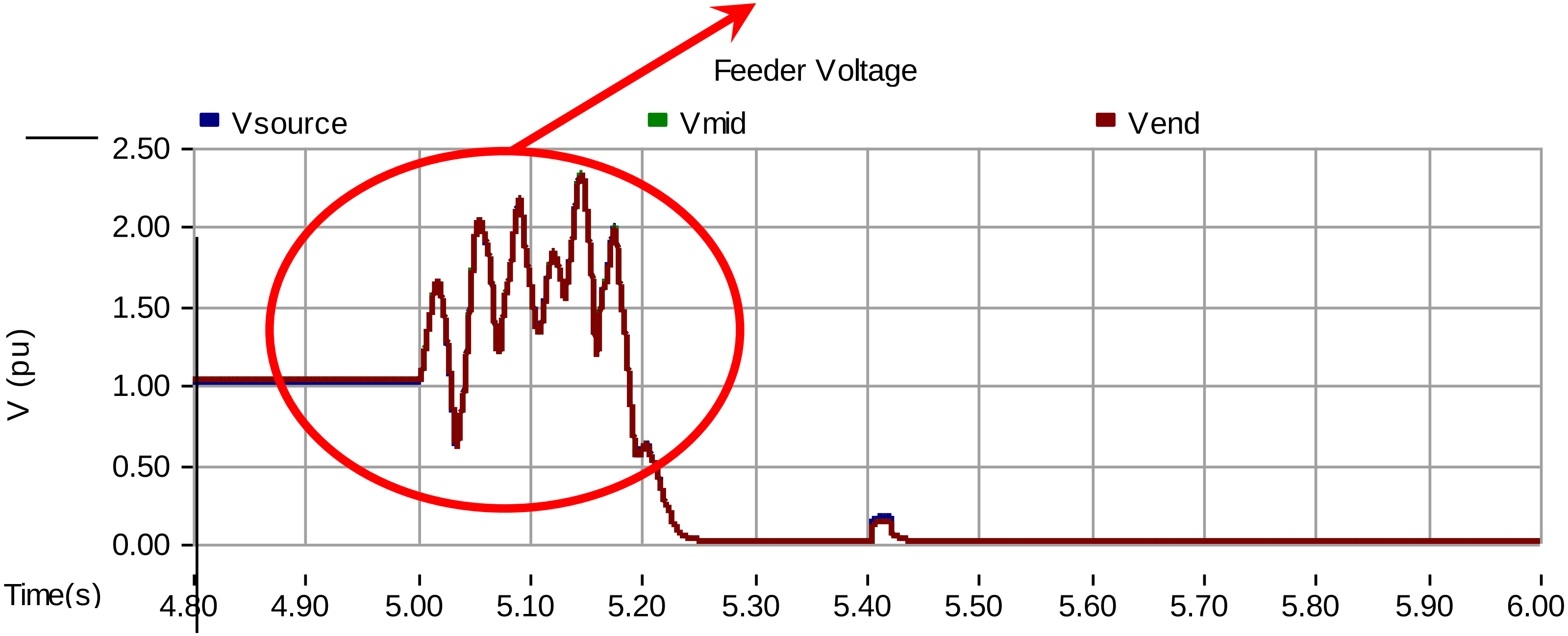
- Capacitor bank switching



Results (utility scale PV-DG)

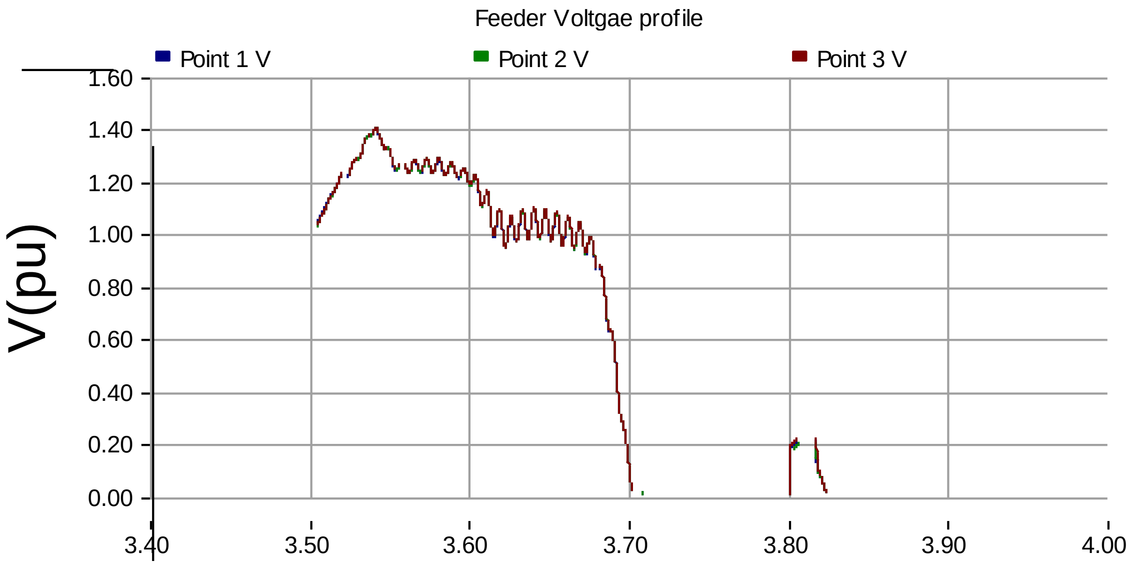
- Potential impacts due to TOV during islanding conditions

TOV for about 0.2 sec due to opening of feeder breaker at t = 5 sec and 100% PV-DG

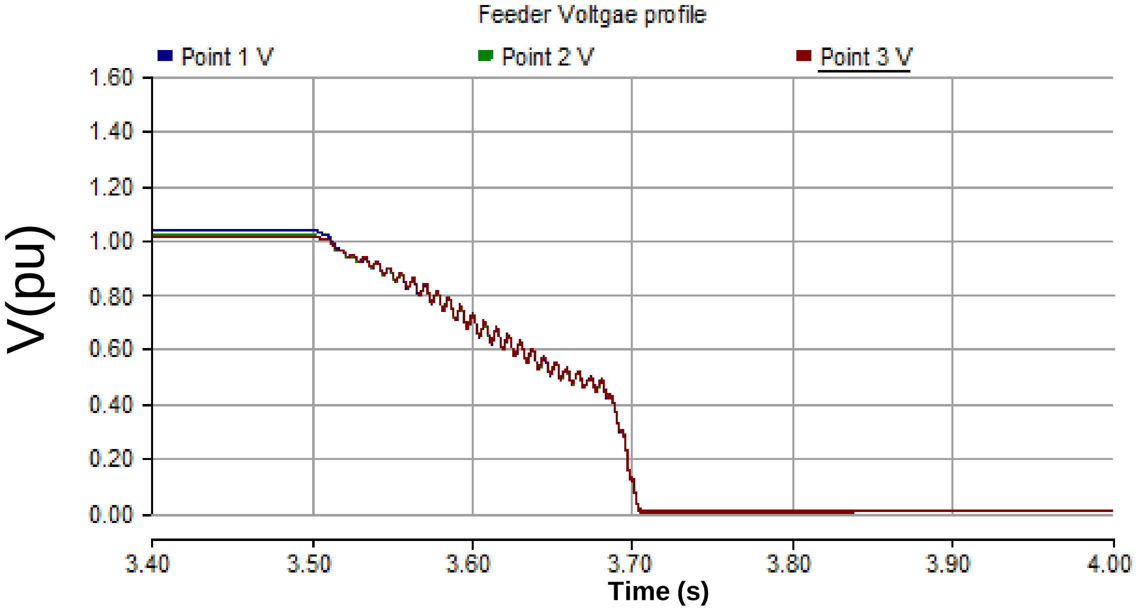


Results (small scale PV-DG)

P(PV-DG) > Load



P(PV-DG) = Load



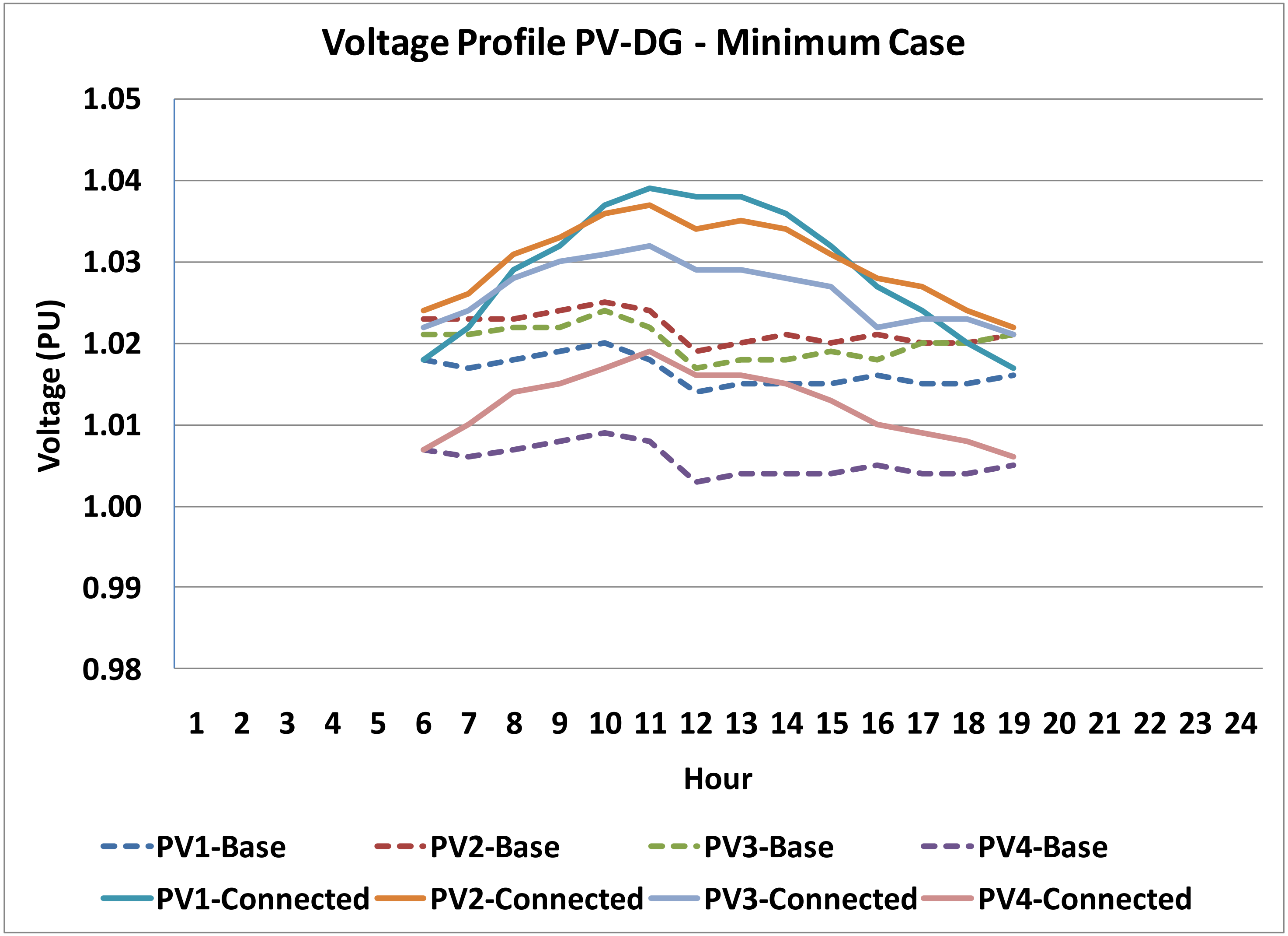
Mitigation measures

- The objective of the mitigation measures is to reduce or minimize impacts caused by the interconnection of PV-DG to distribution systems
- Common mitigation measures include:
    - Operating PV-DG at leading power factor (absorbing VArs)
    - Modifying operation mode of line voltage regulators (e.g., to cogeneration or bidirectional modes)
    - Relocating capacitor banks and modifying settings of capacitor banks (e.g., switching off fixed capacitor banks and modifying switch off and switch on settings of voltage-controlled banks)
    - Modifying reference voltage of Load Tap Changers (LTCs) and compensating current offset on Line Drop Compensation (LDC) applications
    - Using express feeders for interconnection of large utility-scale PV-DG facilities

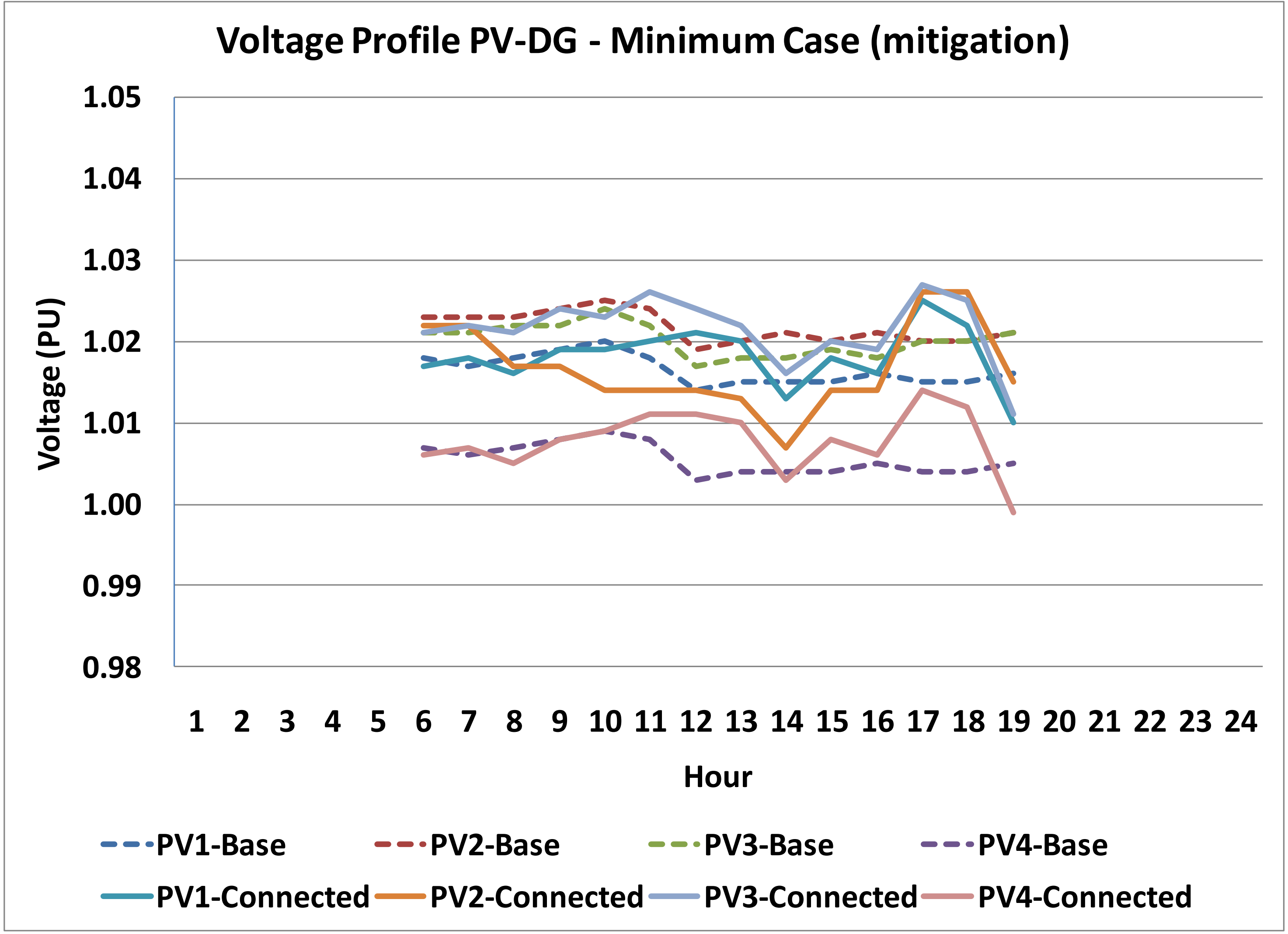
Mitigation measures

- More advanced mitigation measures may include:
  - Using Distributed Energy Storage (DES)
  - Using Static Synchronous Compensator (D-STATCOM)
  - Implementing a dynamic VAr compensation scheme via PV-DG inverters
  - Increasing express feeder design voltage (e.g., using 25 kV instead of 13.2 kV)

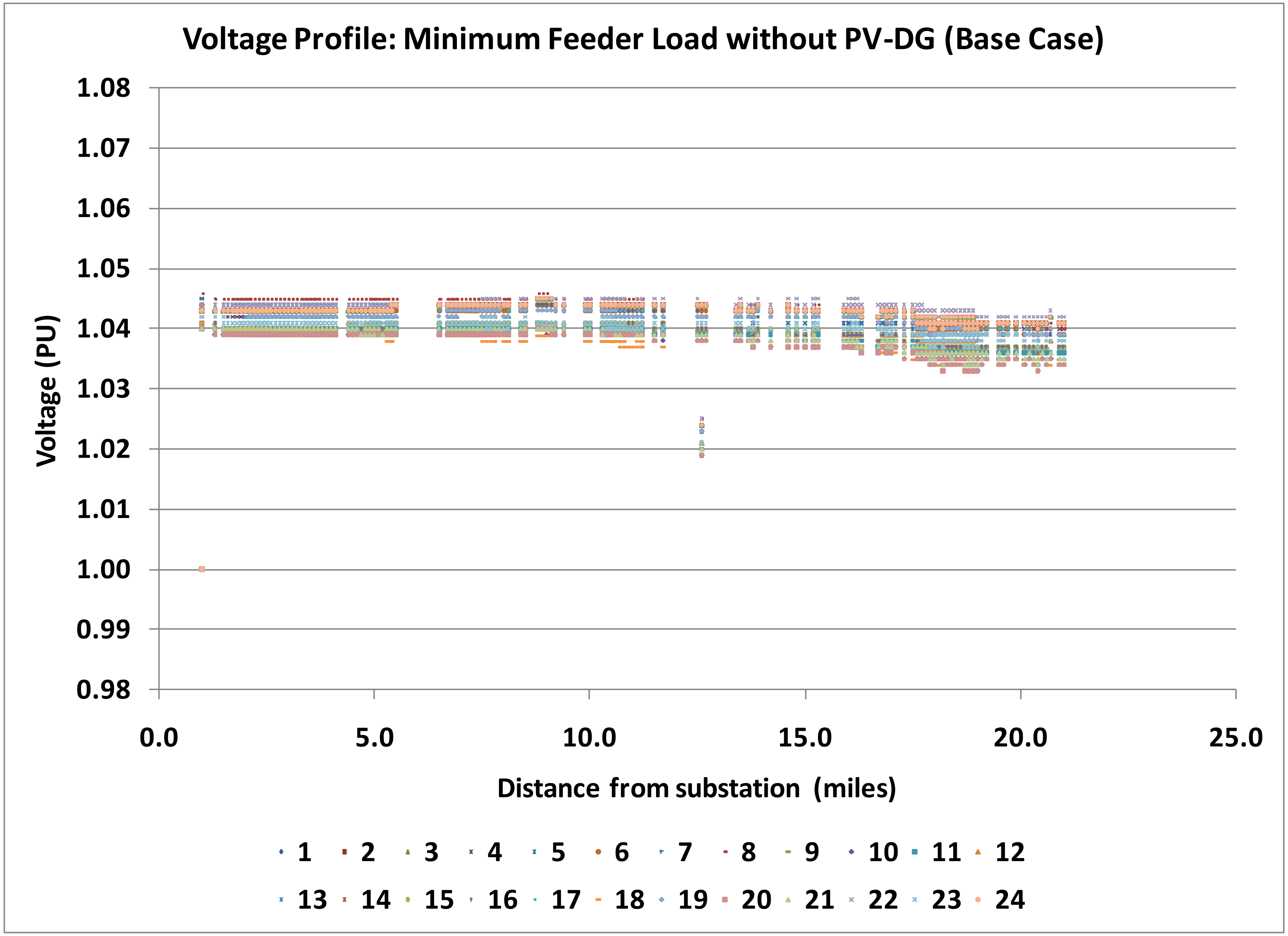
Mitigation measures – example (PV)



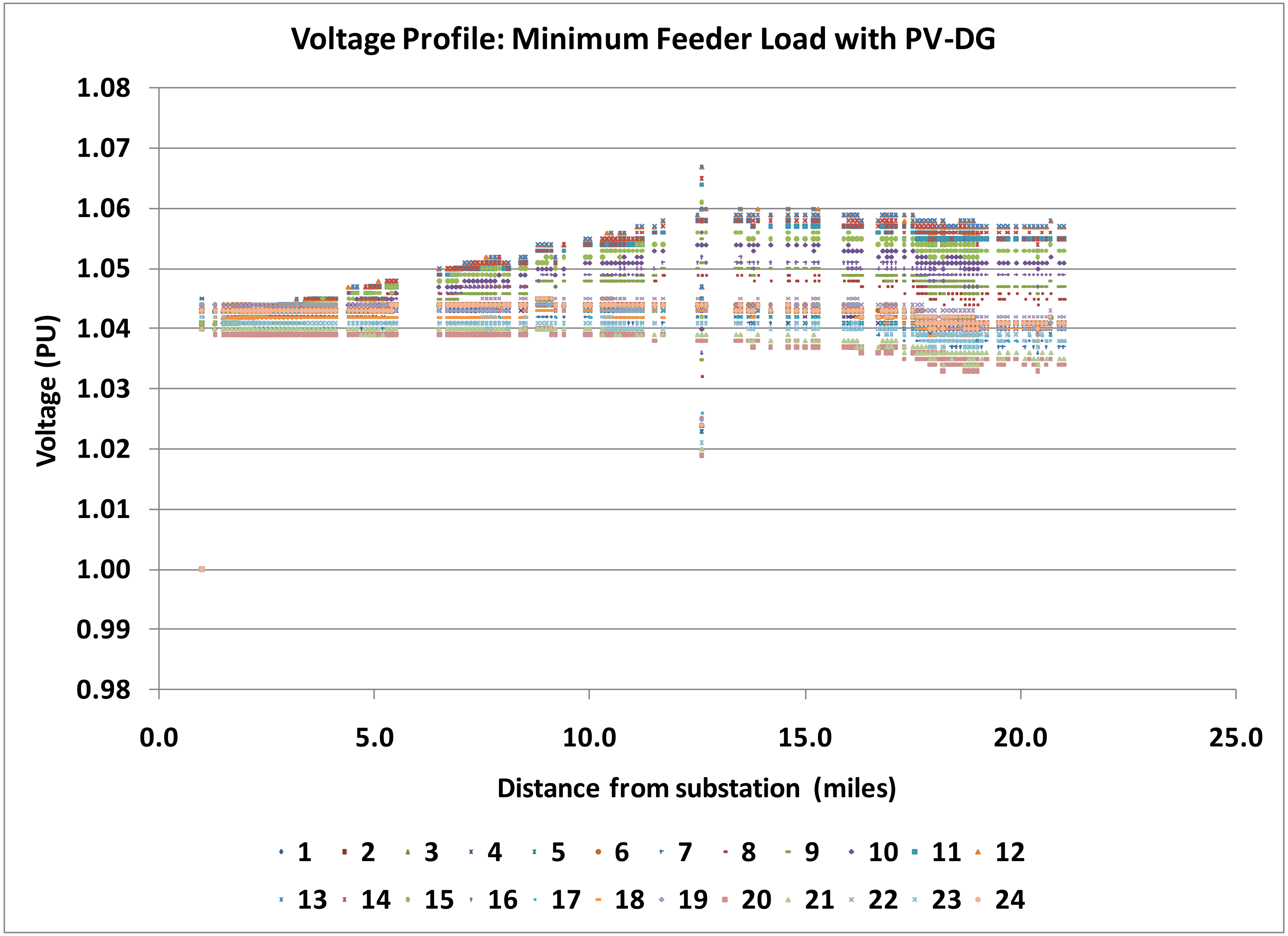
Mitigation measures – example (PV + mitigation)



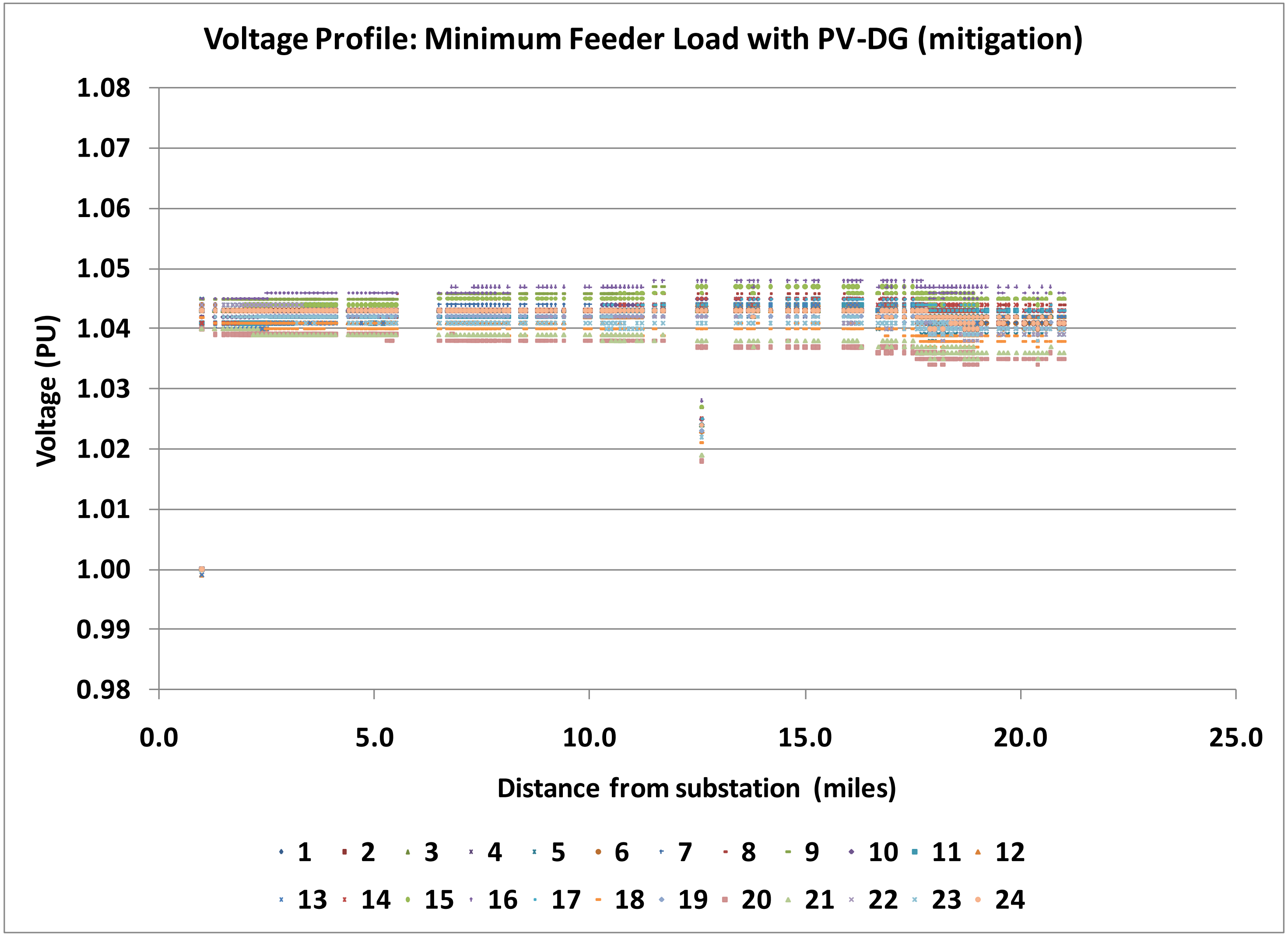
Mitigation measures – example (no PV)



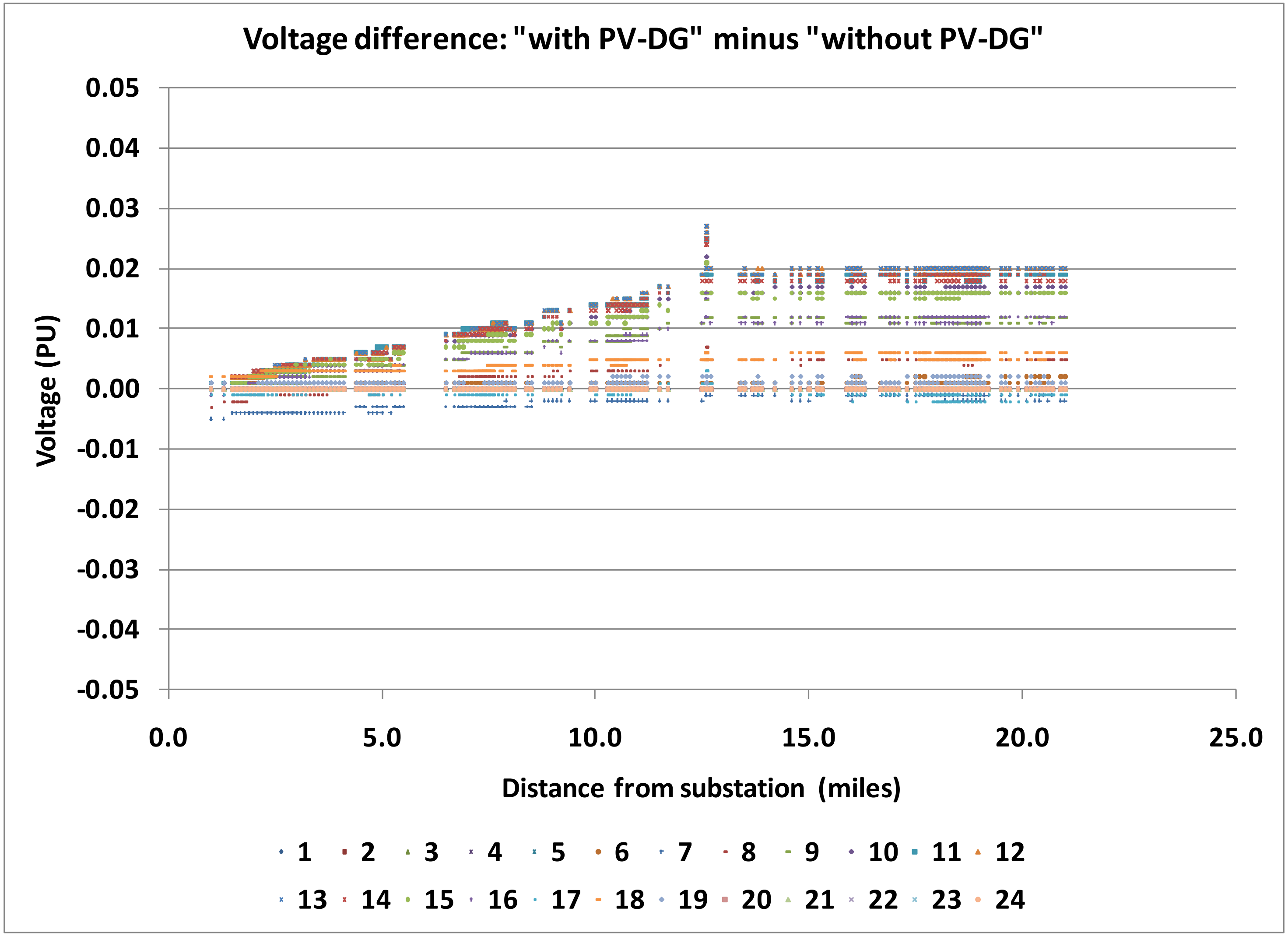
Mitigation measures – example (PV)



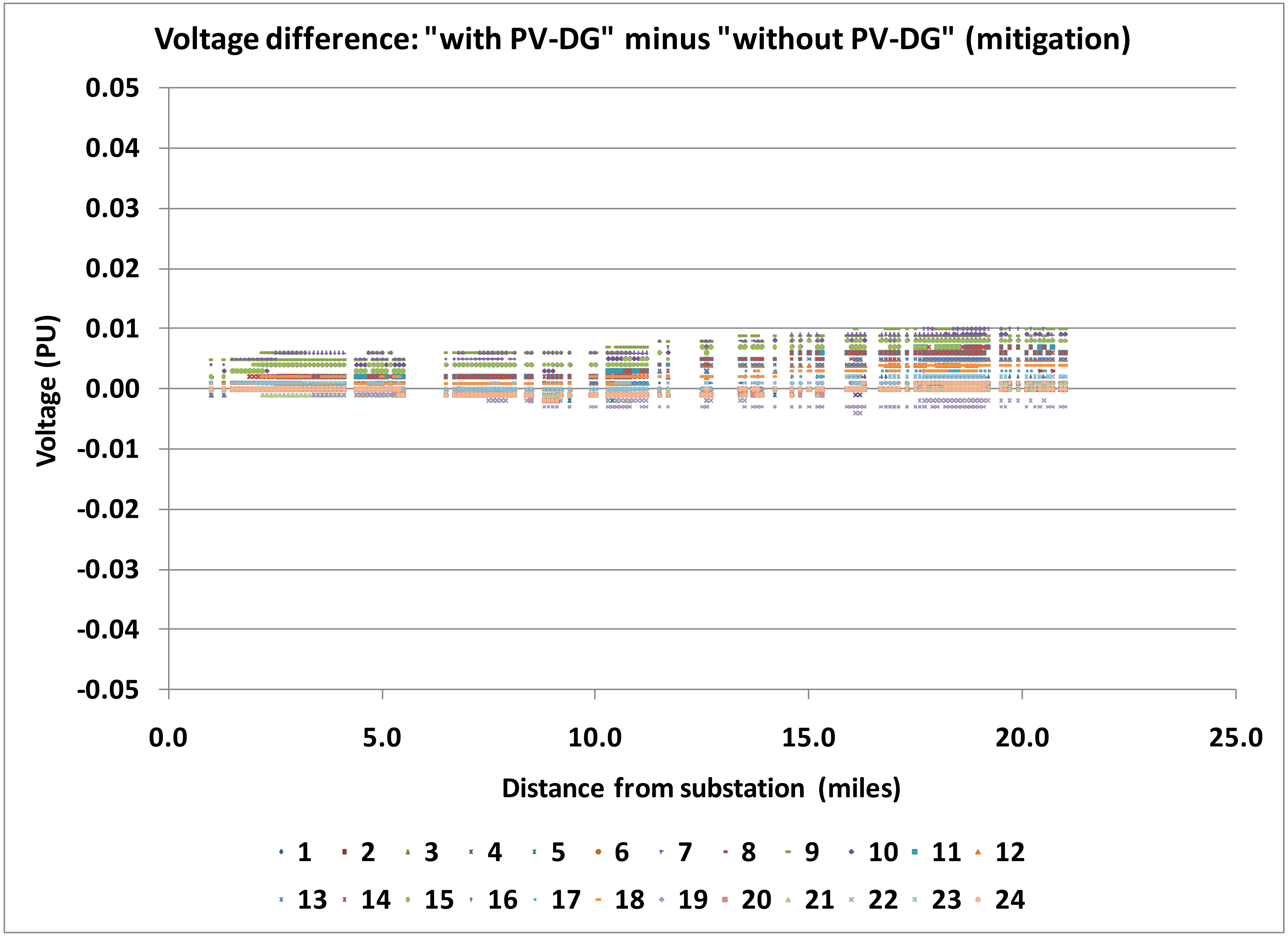
Mitigation measures – example (PV + mitigation)



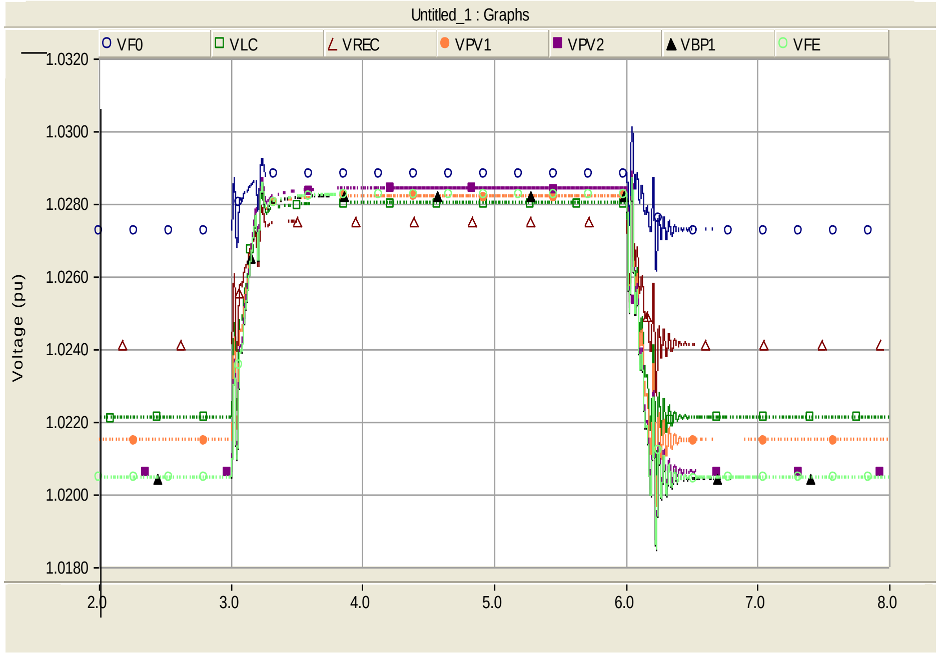
Voltage difference (no mitigation)

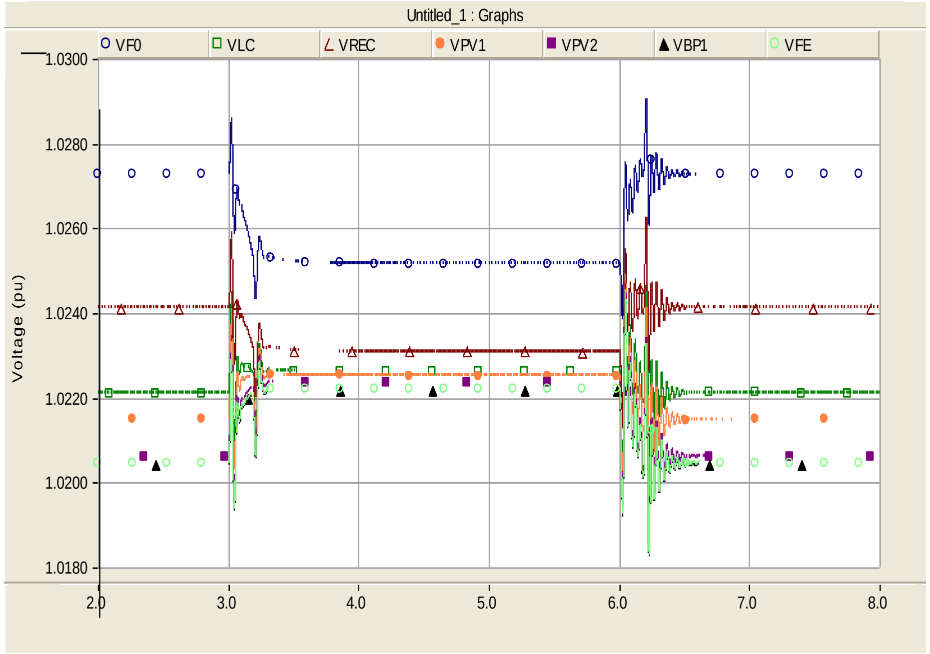


Voltage difference (mitigation)



Comparison (no mitigation vs. mitigation)

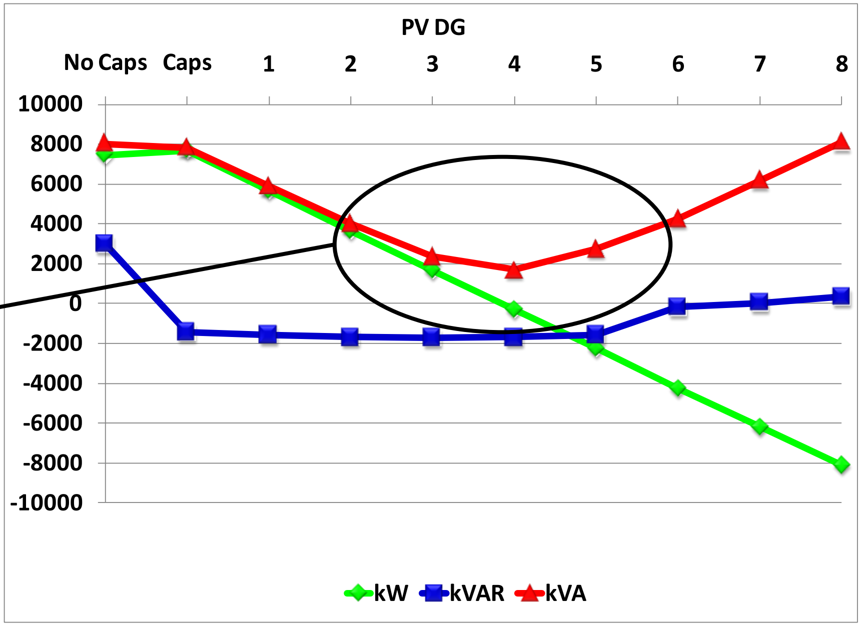




Potential benefits

- If **intermittency** and **firmness** issues are addressed e.g., by using Distributed Energy Storage (DES), potential benefits of PV-DG are:
- **Capacity release:** for moderate penetration levels (enough for offsetting the feeder load) PV-DG help unloading feeder sections, moderately reducing feeder losses, and releasing feeder and substation capacity. This applies only to "daylight peaking" feeders

Potential benefit:
capacity relief. However, PV-DG is not firm, **Distributed Energy Storage** is required



Potential benefits

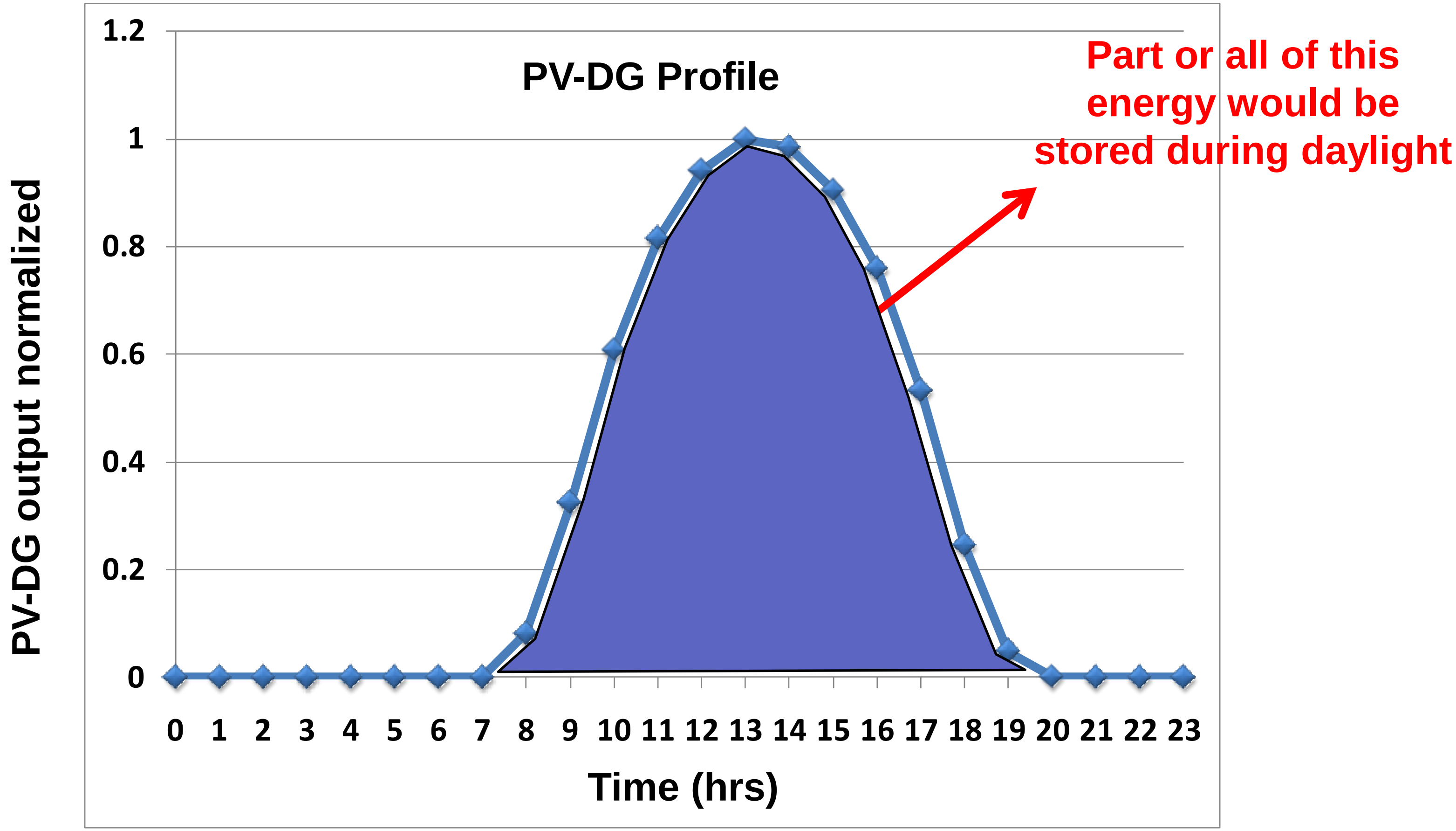
- **Local voltage support:** if located on areas where this is required and if interaction with capacitor banks and intermittency are properly managed
- **Increased operational flexibility:** PV-DG may be used to facilitate feeder restoration, e.g., if used as part of a microgrid, it may help improve system reliability. There are practical applications in place that demonstrate this concept, e.g., AEP’s Balls Gap substation

PEV, PV-DG and DES synergies

- If the energy generated by PV-DG plants could be stored and released when PEVs are being charged then it could provide the following benefits:
  - Mitigate the impacts caused by PV-DG, e.g., overvoltages
  - Mitigate the impacts caused by PHEVs, e.g., overloads
- Therefore, the utilization of DES would allow utilities **"killing two birds with one stone"**
- Moreover, this solution would increase the operational flexibility of the distribution system

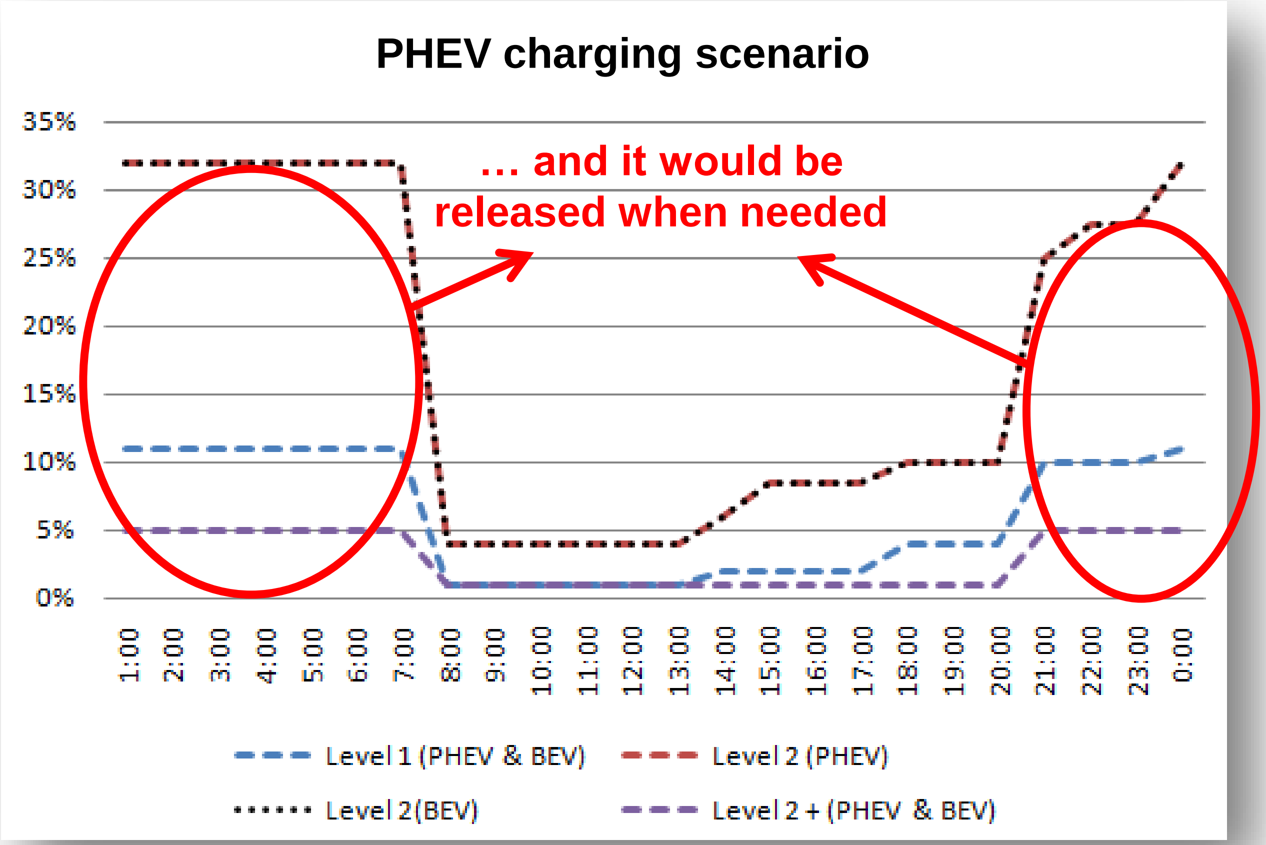
PEV, PV-DG and DES synergies

- This idea is illustrated in the following figures



PEV, PV-DG and DES synergies

- This idea is illustrated in the following figures



… and it would be released when needed

Conclusions

Conclusions

- PEV impacts in some feeders may be of significance even at low penetration levels if charging is uncontrolled, this depends on specific feeder features such as voltage levels and load profiles and customer behavior (driving and charging patterns). Some of the potential impacts are:
  - Overloaded distribution transformers
  - Overloaded conductors and cable
  - Low voltage to customers
  - Violations of planning limits
- Most of these impacts can be resolved by directly or indirectly (customer incentives) controlling the time and duration of PEV charging

Conclusions

- Based on these results the following measures can be recommended:
    - Utilities should understand the potential impact of PEVs on their respective service territories.
    - Set up a system to identify new PEVs when they come onto the system. A key to managing costs and keeping impacts to a minimum through pro-active actions is to know where the PEVs are before problems become serious.
    - Study how PEV adoption rates, particularly on a local-area basis, can be predicted or trended, in order to support planning of required additions

Conclusions

- Studies for large scale PV-DG usually require analyzing specific plant locations and penetration scenarios. Studies for residential and commercial scale PV-DG require statistical analyses for handling uncertainty about location and occurrence. Moreover, they require analyzing a set of representative feeders and extrapolating results to overall system. These studies analyze both steady state and dynamic conditions
- Dynamic/transient impacts of PV-DG cannot be identified using conventional distribution analysis software, more detailed modeling and simulations and specialized software are necessary
- Typical impacts are reverse power flow, reactive power fluctuations, interaction with capacitor banks and voltage regulators, voltage variations, reactive power fluctuations, localized overloads (distribution transformers and lines), etc.

Thank You!