Modeling, Analysis and Deployment of High PV Penetration in a Distribution System

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ARIZONA STATE UNIVERSITY

PSERC

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Project partners

- Sponsor: Department of Energy
- Arizona Public Service Company - Lead
- Arizona State University
- GE Global Research and GE Energy
- National Renewable Energy Laboratory
- ViaSol Energy Solutions

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Distribution System Analysis Tools for Studying High Penetration of PV with Grid Support Features

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The methods, results and conclusions shown are preliminary and based on an ongoing project, and are subject to change as more data become available.

Outline

- Description of the high PV penetration deployment
- Development of feeder model using GIS and PV/AMI data
- Power flow analysis and preliminary results
- Protection coordination analysis
- Anti-islanding study methods

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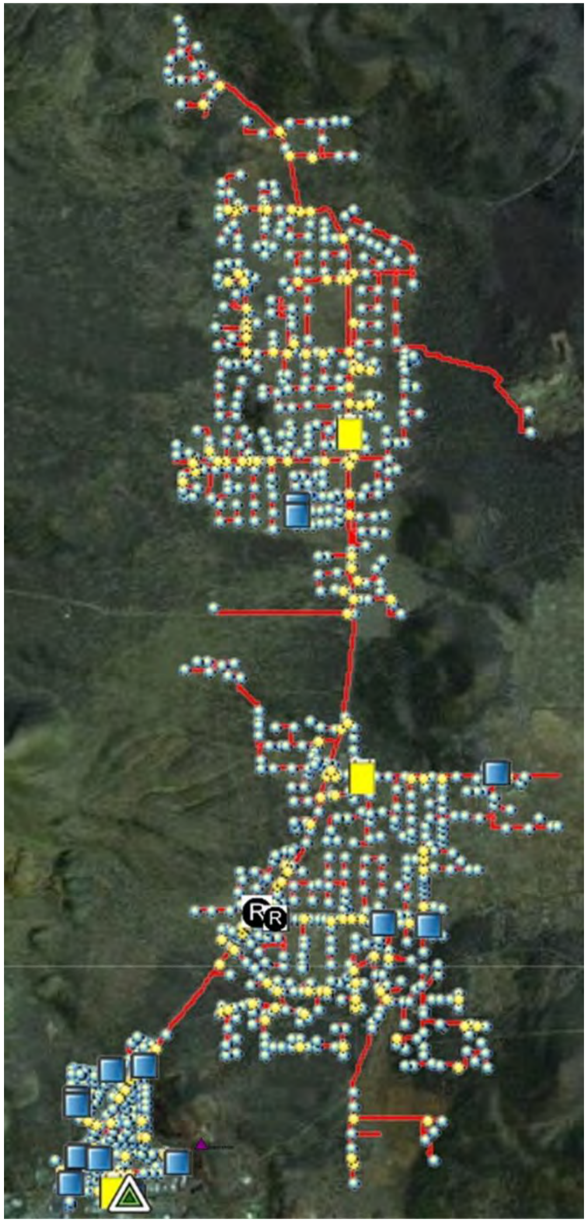
Feeder Information

- Located in Flagstaff, AZ
- Radial feeder 9 miles long
- Peak load: ~ 7 MW (winter peaking)
- Max. capacity: ~ 13 MW
- Customers: ~ 3000 residential, ~ 300 commercial/industrial



Feeder Details

Equipment Name	Total Number	Legend
Primary feeder segment	1809	Red line
Transformer	921	Blue dot
Fuse	186	Orange dot
Capacitor bank	3	Blue pushpin
Switch	18	Green pushpin
OCR (recloser)	2	Black circles
Voltage regulator	0	N/A

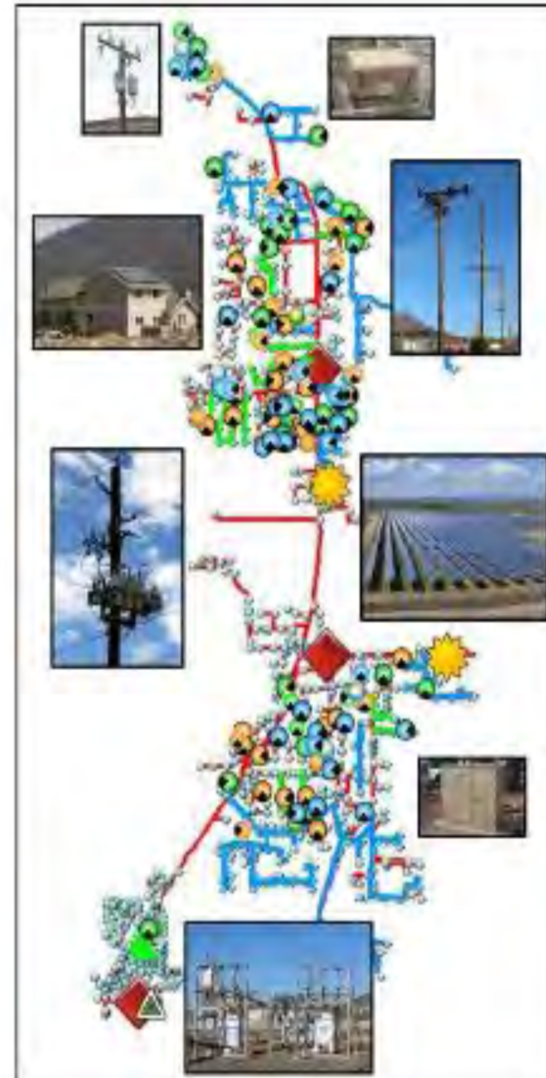
PV Systems Deployed: Residential

- Residential - 470 kW
  - 125 systems deployed, owned and operated by APS (additionally a few customer owned)
  - 2 kW, 3 kW and 4 kW types
  - Inverters from 3 different inverter manufacturers
  - PV panels from 6 different manufacturers
  - PV panel ratings from 185 W to 235 W with series connected strings ranging from 7 to 13 panels, and 1 to 2 strings in parallel
  - Combination of various orientations (South, East facing etc.) and various tilt angles

PV Systems Deployed: Larger Systems

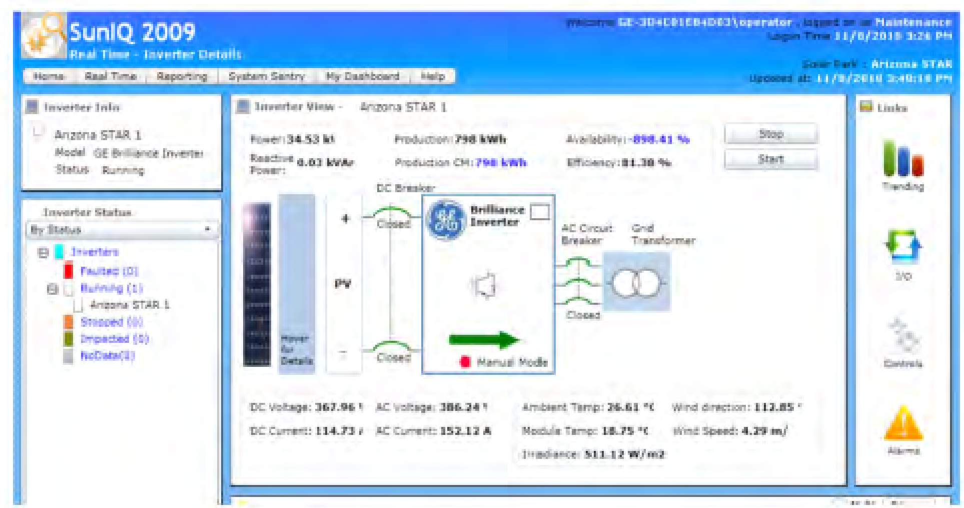
- 600 kW PV system with a 700 kVA GE smart inverter (project partner) at Doney Park renewable energy site

- A 333 kW (ground-mounted) and a 75 kW (roof-top) commercial PV system



GE Smart Inverter

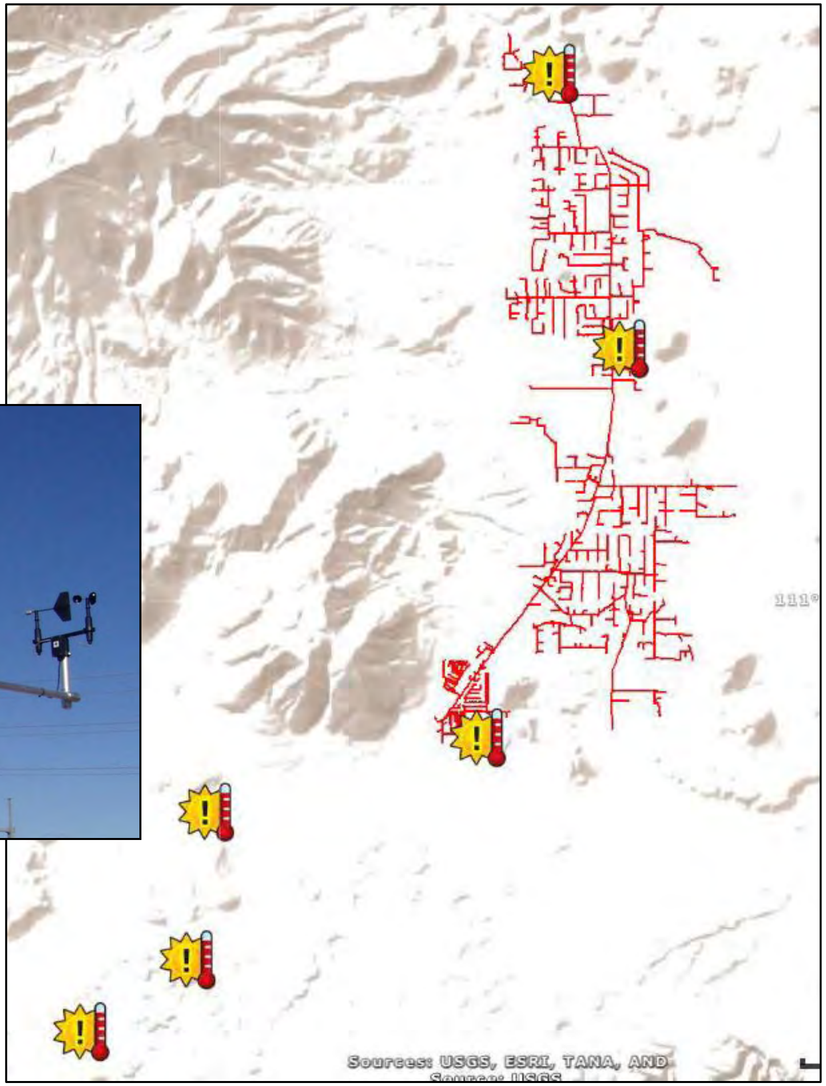
- 3-phase, 480V, 700kVA Inverter
- Grid support features
  - Voltage regulation
  - Reactive power / power factor support
  - High/low/zero voltage ride-through
- Can help mitigate intermittency effects
- Extensive communication and monitoring features
- Integrates into utility operations and SCADA functions



Data Acquisition - Weather Stations

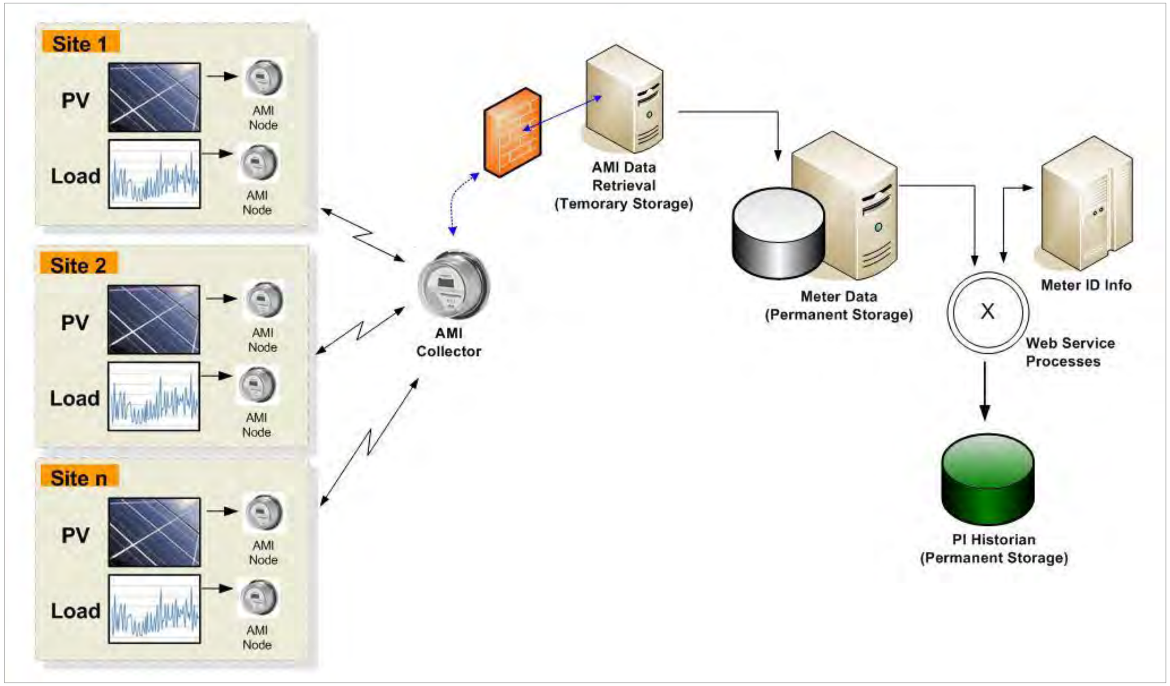
Weather Stations
- 7 locations - 4 along feeder, 3 in near by substations
- 1-second data capture
- Campbell Scientific CR1000-based
- GPS time synchronized
- Data transfer using DNP3 over TCP/IP

Environmental Parameters
- solar irradiance
- wind speed/direction
- site temperature
- relative humidity
- atmospheric pressure



Data Acquisition – AMI

- Elster REX 2 AMI meters on all customer loads (~ 3000)
- Record customer demand (hourly intervals)
- Record PV generation (15 min intervals)
- Retrieve data nightly (day-behind)
- Used in load modeling

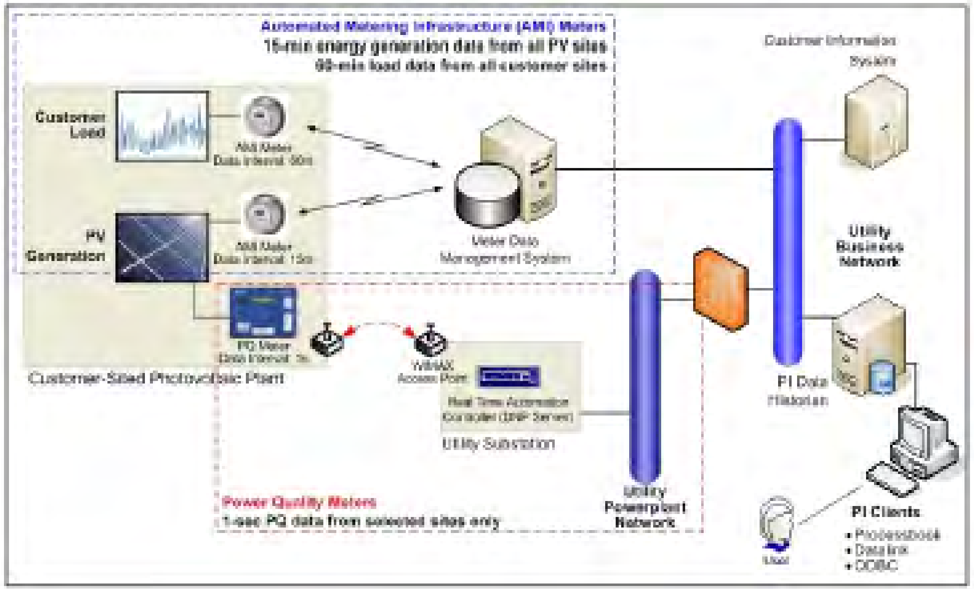


Data Acquisition – PV systems

- All the 125 residential PV units have dedicated AMI meters for 15-min PV generation data
- Used in steady-state power flow analysis

- In addition, 17 residential PV systems have more elaborate DAS with
  - SEL 734P PQ meters
  - 1- sec data
  - Retrieve data using APS SCADA (semi real-time)
  - Parameters monitored
    - V, I, kW, kWh, kVAr
    - harmonics, PQ as needed

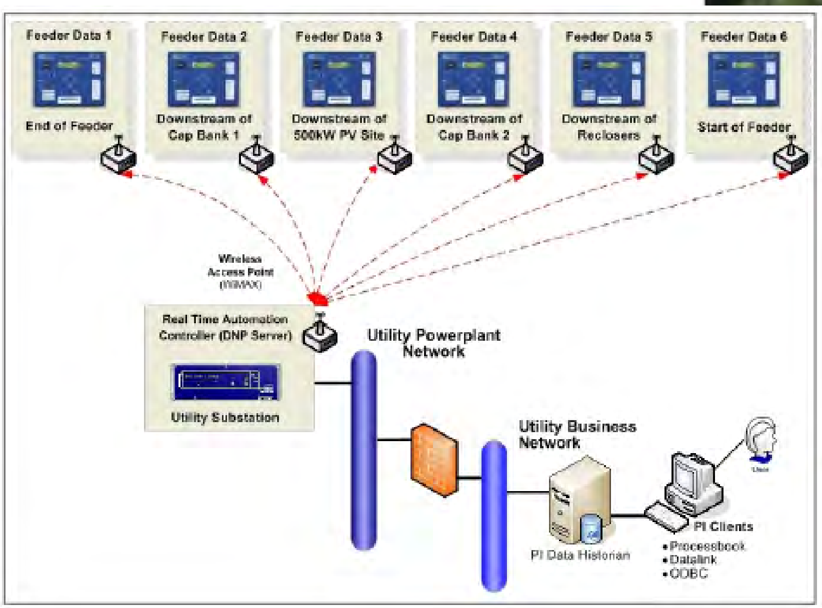
- The utility-scale inverters monitor > 100 internal/external parameters



High Bandwidth Feeder Data Acquisition

- 6 high bandwidth DAS along the feeder
- SEL 735 PQ meters
- High event sample rate
- GPS synchronized
- Event based data capture – e.g., change in solar irradiance, faults, low voltage
- Wireless cross-device triggering of all DAS based on events or at set time
- Data availability – real time
- Parameters monitored (> 70)
  – V, I, kW, kWh, kVAr, harmonics and other PQ
- Used in steady-state and dynamic model validation and grid operations

Feeder DAS locations



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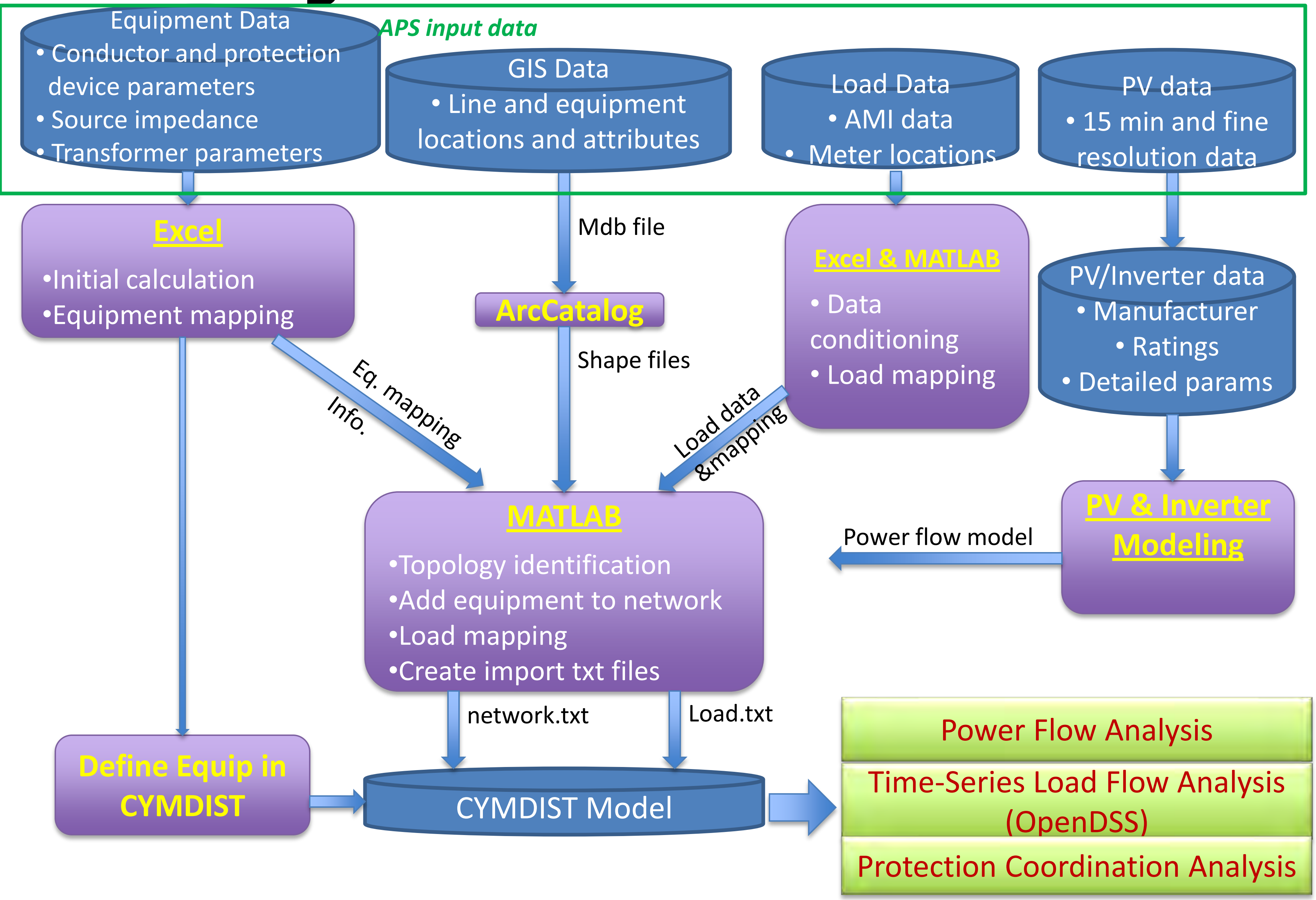
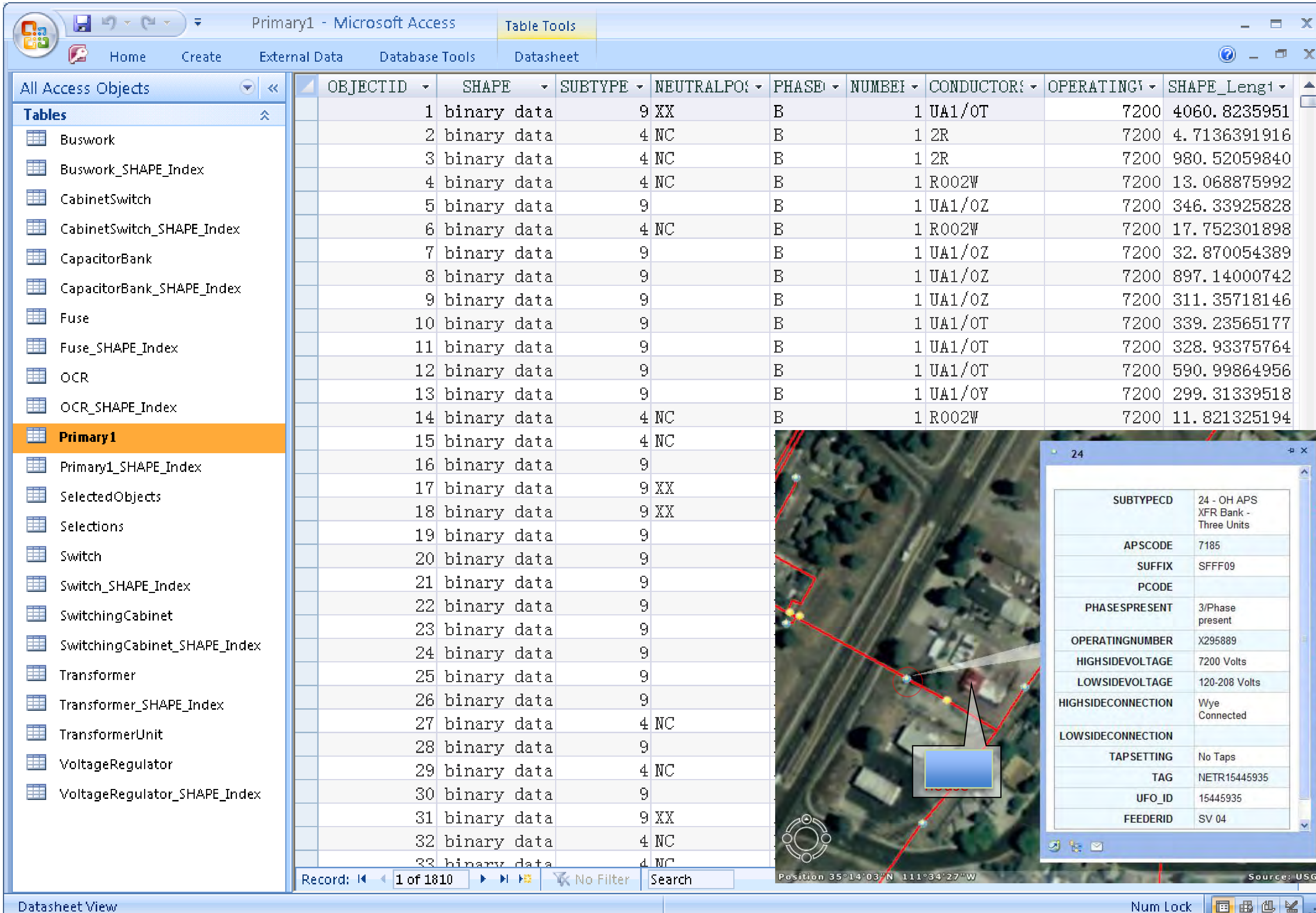
Modeling Process

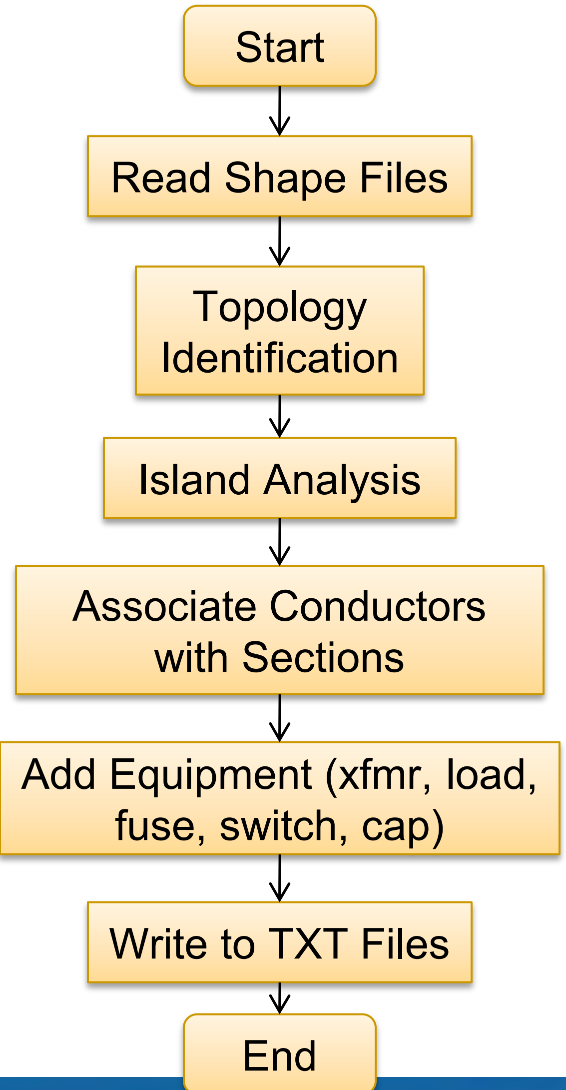


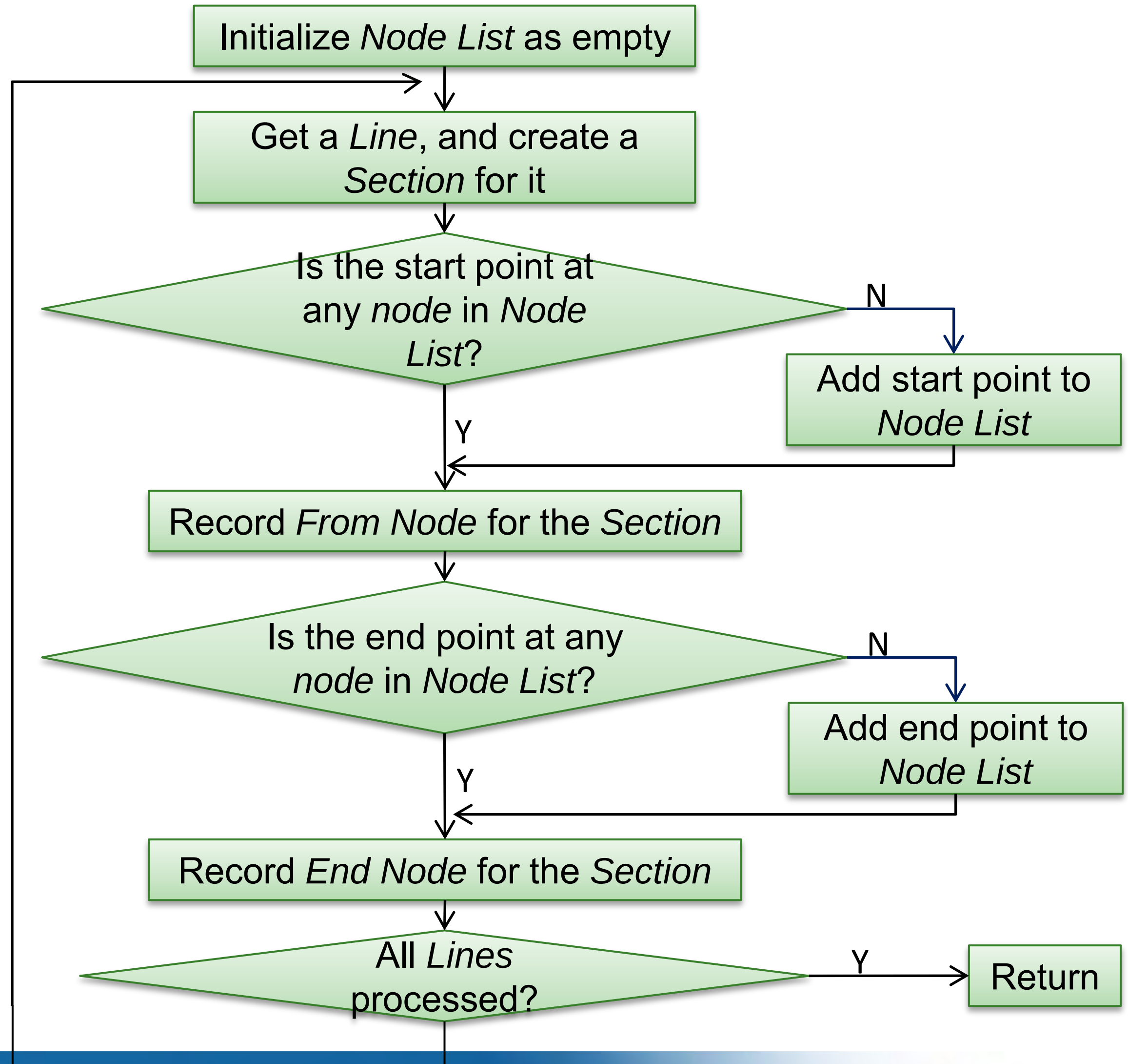
GIS Data—MDB File



Feeder Network Model Development

(Auto conversion of GIS data to CYMDIST model using MATLAB)





Conductor Modeling

- Primary: 39 line types – 25 overhead,14 underground
- Secondary: 28 line types – all underground cables

Conductor types per GIS

UG or OH	Primary				Neutral		
	No. of conductors per GIS	Line type per GIS	APS conductor code	Relevant Standard	APS conductor code	Relevant Standard	Comment
UG	1	1/0A	Unknown	6215	Concentric		Primary could be any of the varieties of UA 1/0
UG	2	1/0A	Unknown	6215	Concentric		Primary could be any of the varieties of UA 1/0
UG	3	1/0A	Unknown	6215	Concentric		Primary could be any of the varieties of UA 1/0
OH	1	2R	Unknown	6251	Same as primary		Primary could be R002V or R002W
…	…	…	…	…	…	…	…

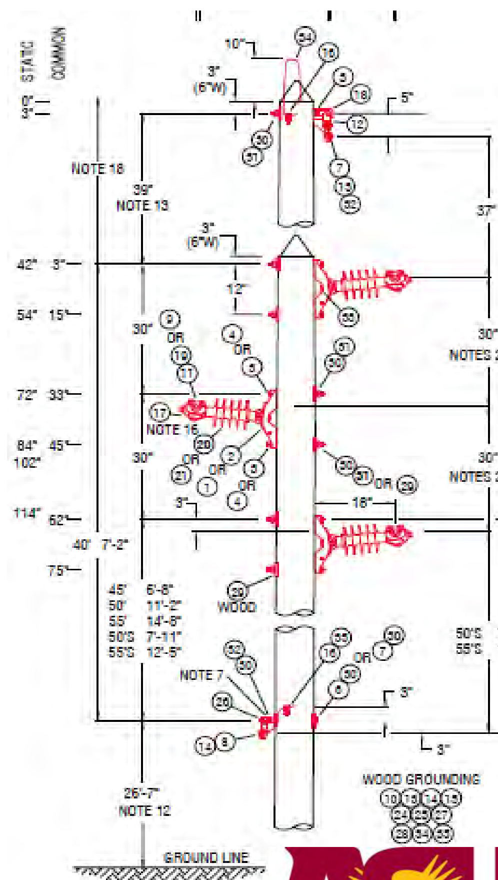
- Diameter, stranding, resistances, GMR values from APS standards, various handbooks and other standards

Conductor data

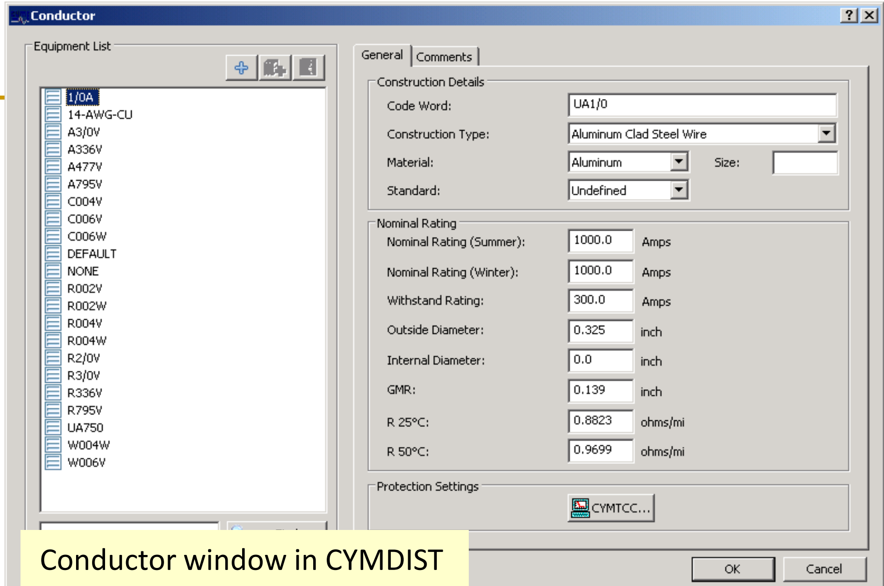
UG/ OH	Line type per GIS	APS conductor code	Relevant Standard	Material	Size	Stranding	Dia (In.)	GMR (In.)	AC Res @25C Ohm/mile	AC Res @50C Ohm/mile
UG	1/0A	Unknown	6215	Al		SOLID HD	0.325	0.139	0.8823	0.9699
OH	2R	R002V	6251	ACSR	2	6\1	0.316	0.05016	1.41	1.69
OH	2R	R002W	6251	ACSR	2	7\1	0.325	0.06048	1.41	1.65
OH	4R	R004V	6251	ACSR	4	6\1	0.25	0.05244	2.24	2.57
…	…	…	…	…	…	…	…	…	…	…

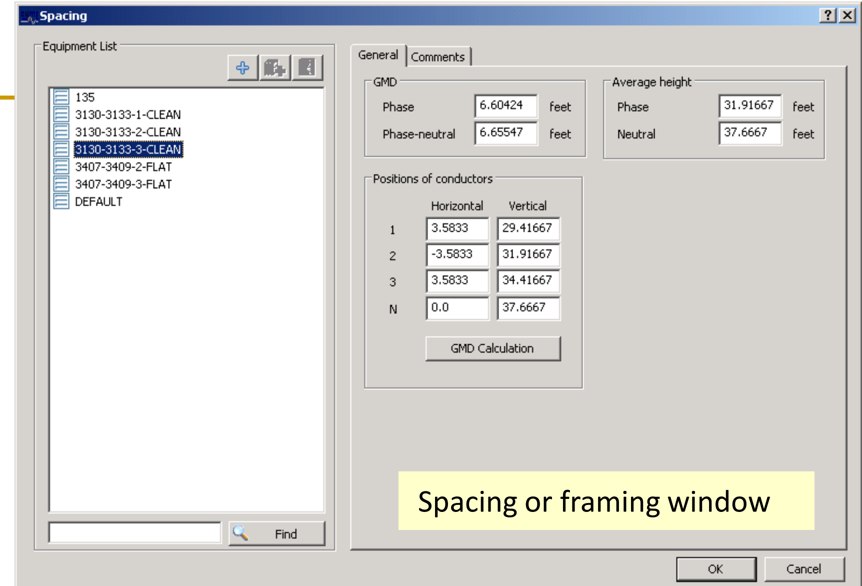
- Positive and zero sequence impedances for all line types and susceptance for cables obtained directly in CYMDIST

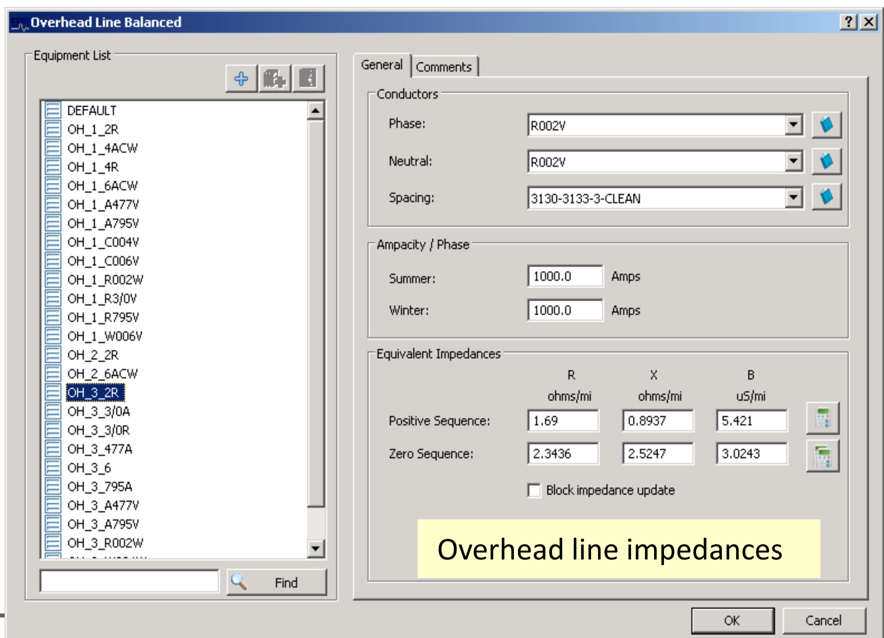
Typical framing methods used in Flagstaff modeled
- ‘Clean’ construction
- Cross arm construction

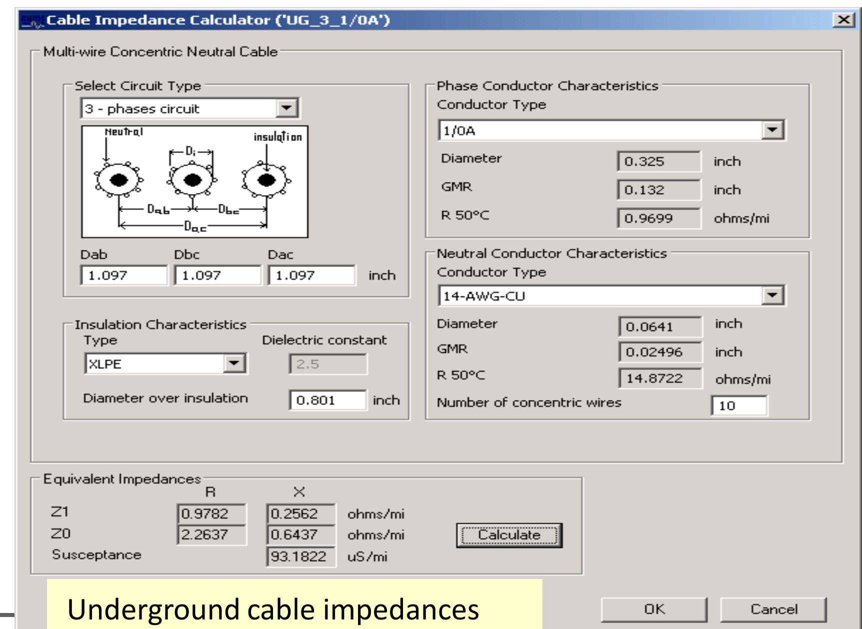


Equipment Modeling in CYMDIST: Conductors



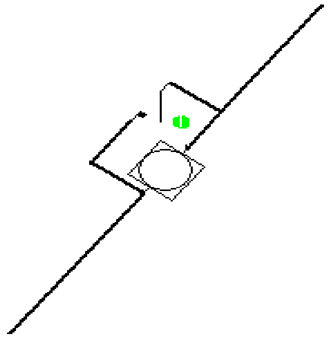




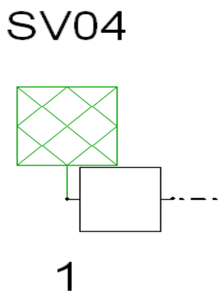


Protective Devices Modeling

- Fuses
  - Fuses for protecting primary sides
    - *Types, ratings provided in GIS data*
  - Transformer fuses
    - *Types and ratings based on transformer rating and APS standard*
  - Street light fuses
    - *Ratings from APS standards*
- Reclosers (One in main line and one in branch)
  - *Parameters are given by APS standard*
- Substation Relay
  - *Parameters are given by APS standard*
- Protective device library is constructed in CYMDIST and CYMTCC

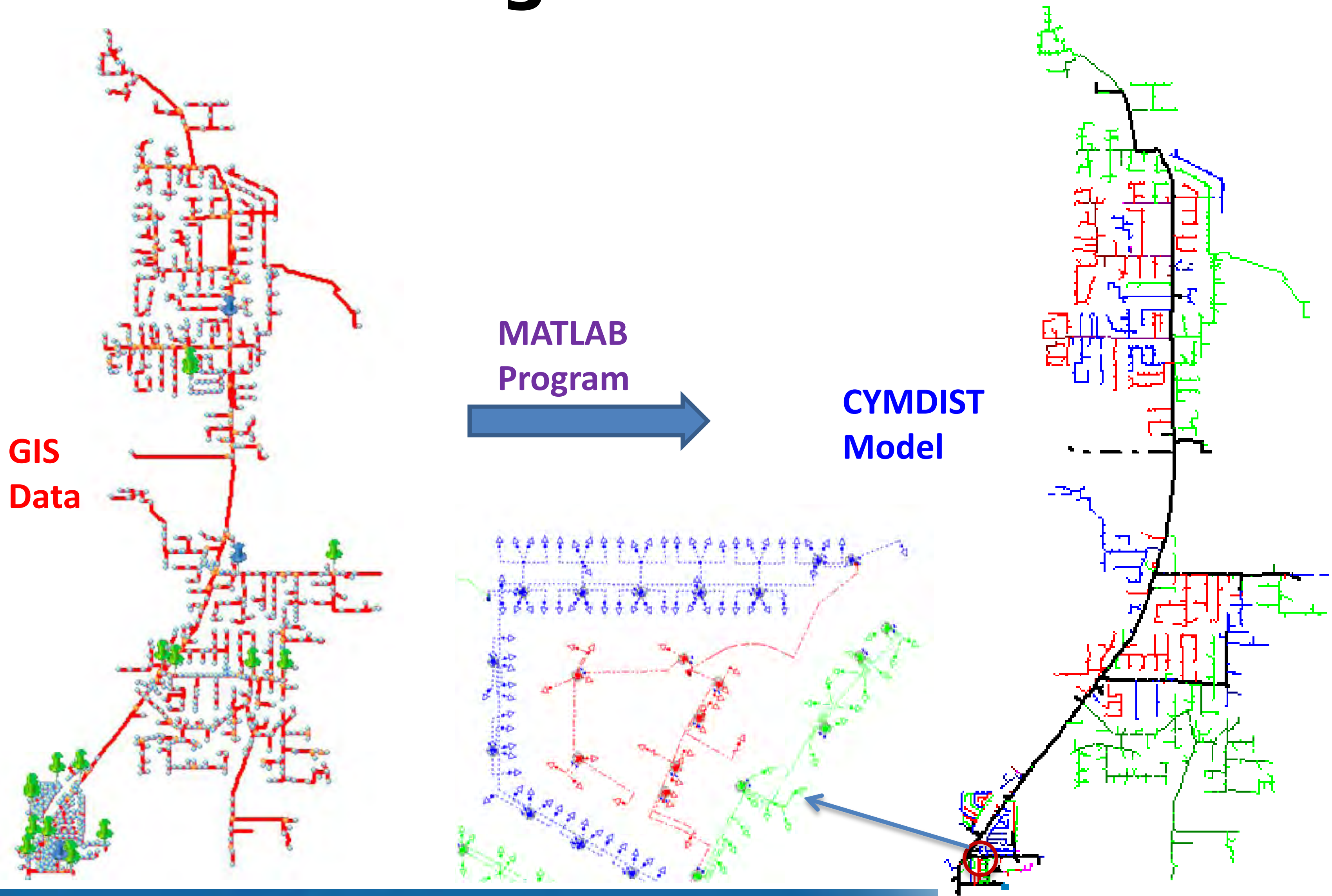


Screen shots of recloser modeling in CYMDIST



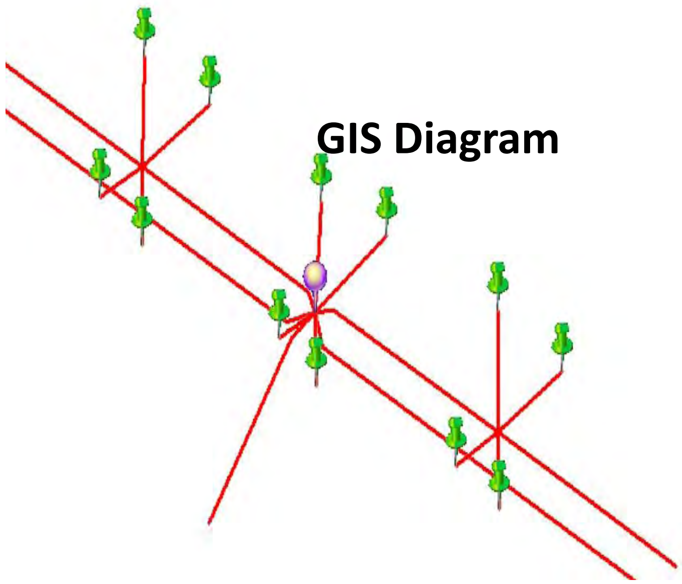
Screen shots of substation relay modeling in CYMDIST

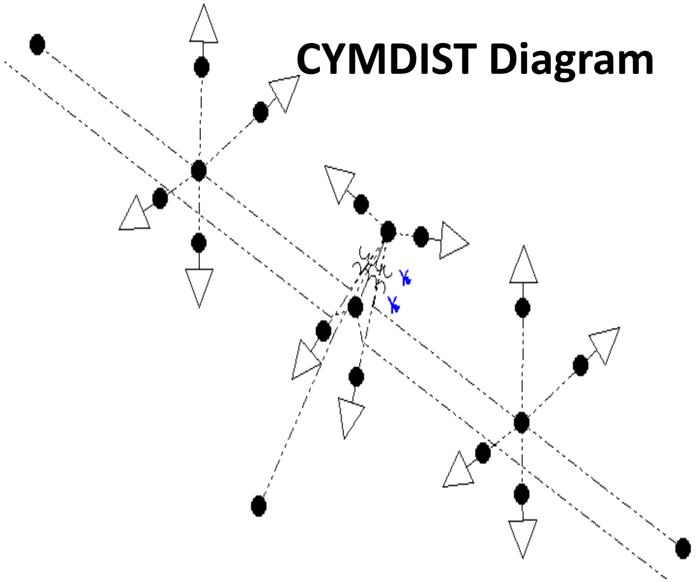
Feeder Modeling Outcome



Modeling of Meter Loads

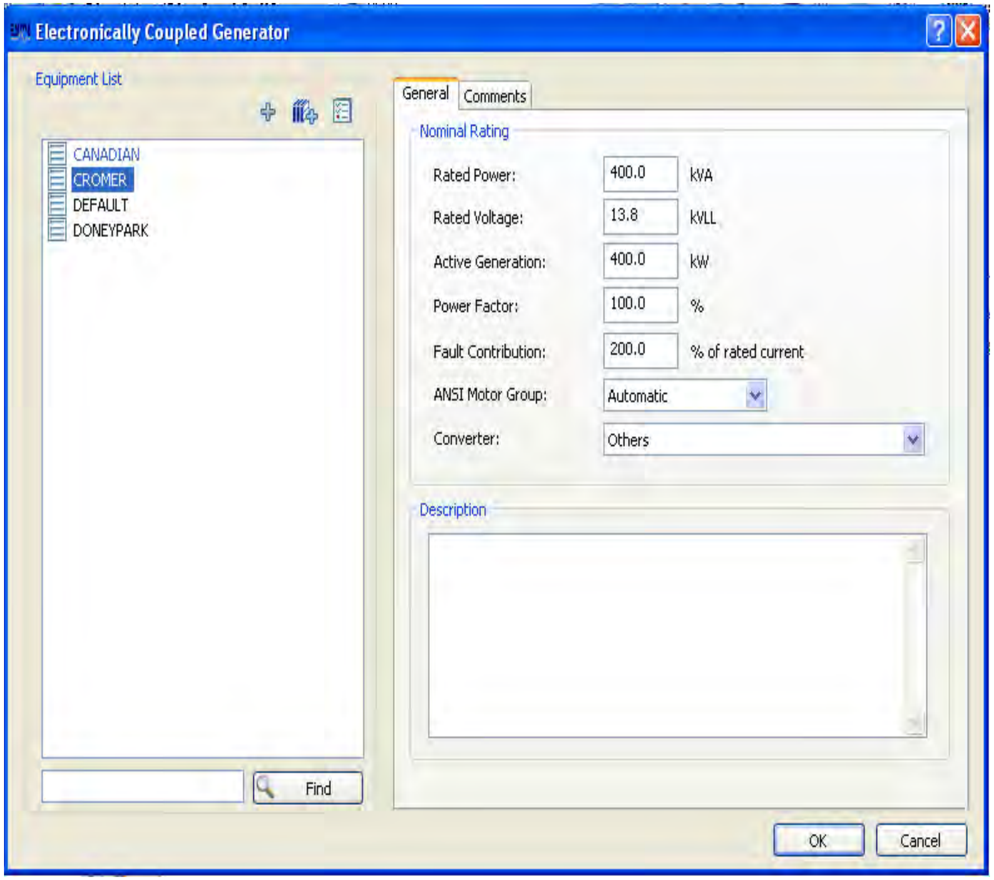
- AMI meter data with corresponding transformer ID and coordinates used
- MATLAB code to match meters to the nearest load points and summing up meter data when multiple meters correspond to same load points
- kW data for almost all the loads available in 60 min or 15 min intervals, and are directly input to CYMDIST
- Power factor for all loads is presently assumed as 0.9; to be refined as DAS measurements become available in Phase 3 of the project





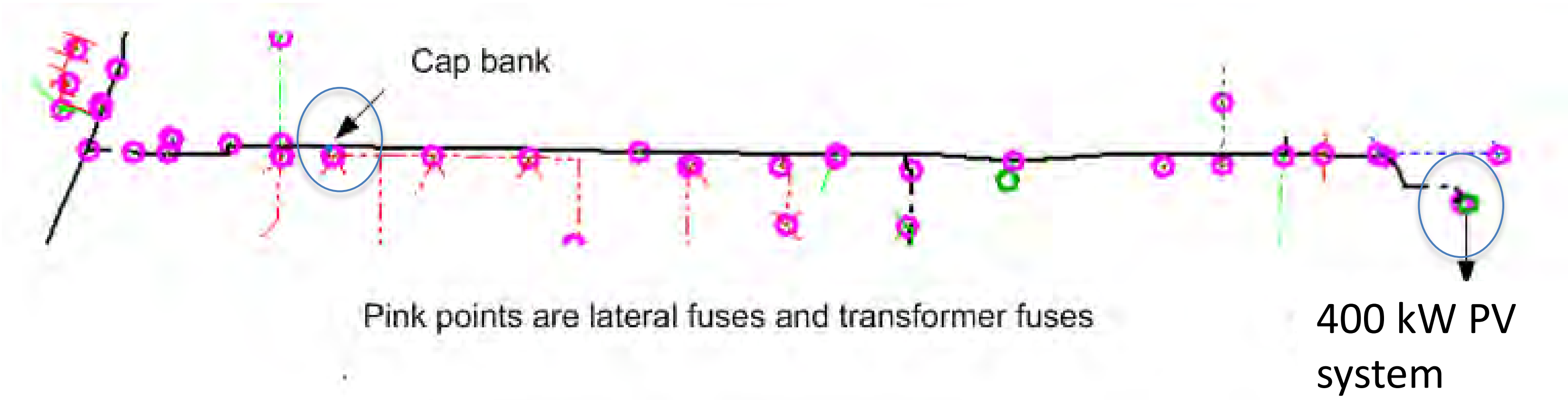
Photovoltaic Generator Modeling

- 125 small residential PV systems (totaling 470 kW) and the 2 large PV systems (408 kW and 600 kW) are modeled as electronically coupled generators in CYMDIST
- Automated process to associate PV with correct end points and create a PV section in CYMDIST
- Active power set equal to the measured data for each of the 127 PV systems in each time interval
- Fault current contribution presently set at 200% of the rated current – to be modified as we get data from manufacturers

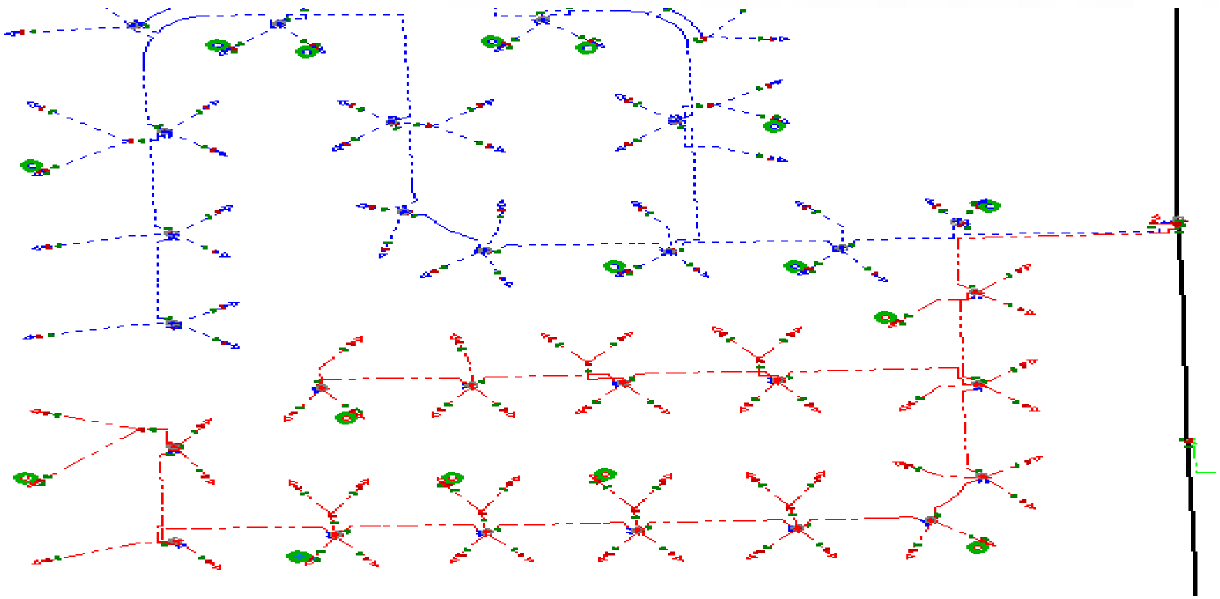


Generator window in CYMDIST

Screenshot of PVs in CYMDIST Model



400 kW PV system



Part of CYMDIST model – Green circles are PVs

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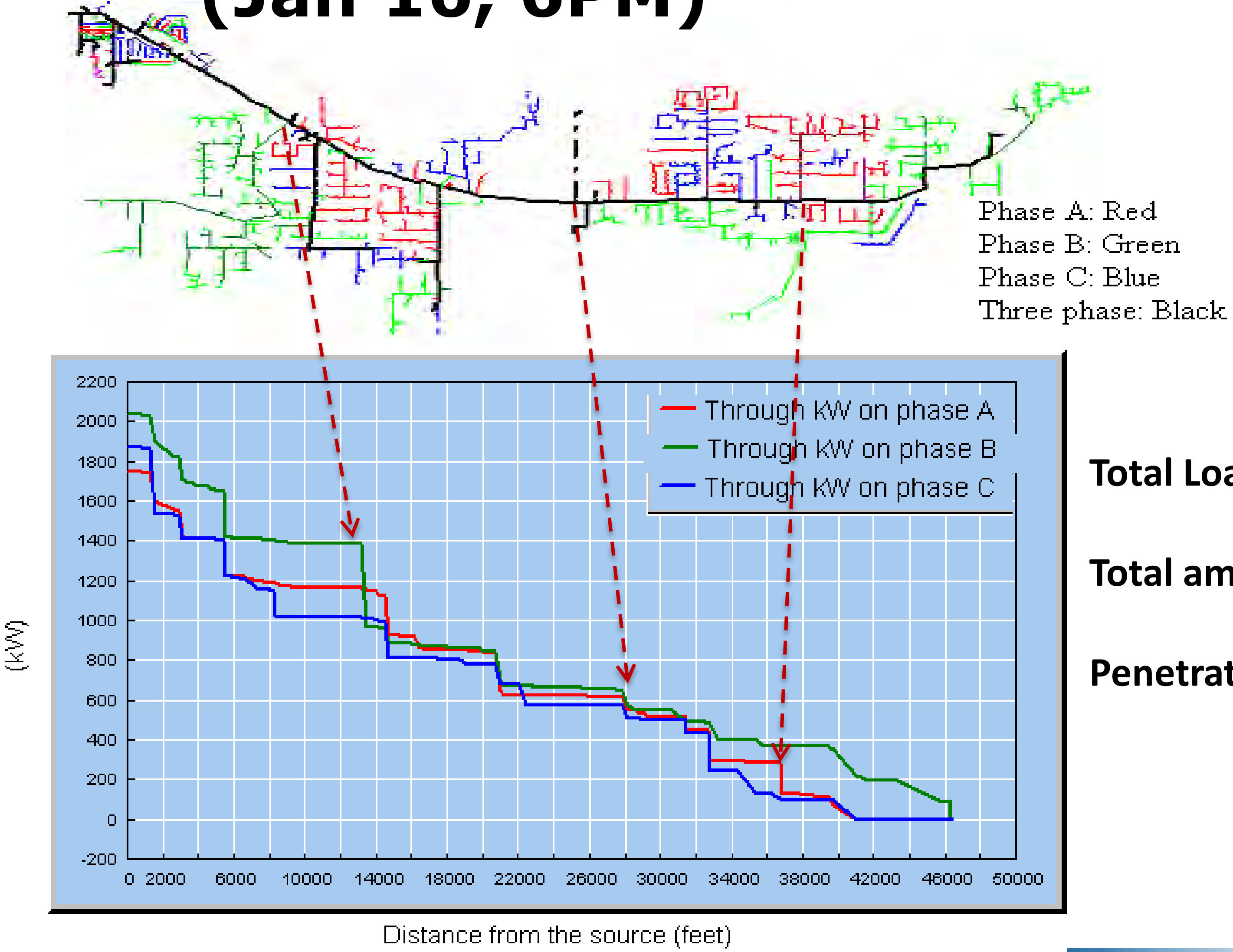
Power Flow Analysis with CYMDIST Model

- AMI data from Jan 2012 to May 2012 and corresponding measured PV data are considered
- Power flow results for the following two conditions with and without PV are shown
  - Highest load case – Jan 16, 6 PM
  - Highest PV penetration case - May 4, 1PM
- Penetration at the substation corresponding to this feeder at a given time is defined as

$$\text{Penetration} = \frac{\text{Total measured PVoutput}}{\text{Measured feeder head load} + \text{Total measured PV output}}$$

- Penetration levels at other locations within the feeder can be significantly higher – e.g., downstream of the main recloser, or near the two large PV systems, and at some transformers with multiple PVs the penetration can be higher than 100%
- Voltage profile, kW and kVAR profile and loss estimate (no-load loss not considered)

kW Profile at Highest Load (Jan 16, 6PM)

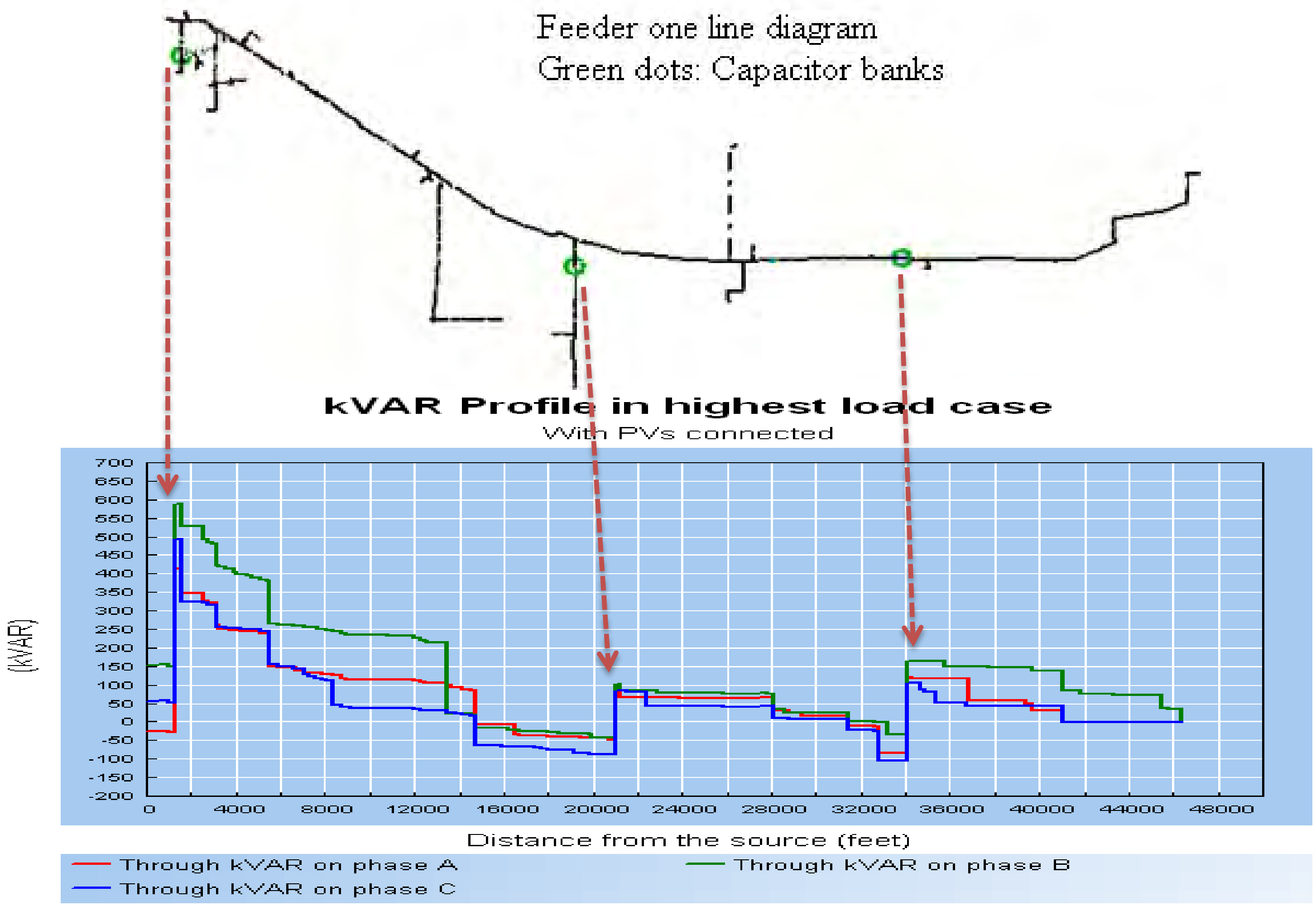


Total Load: 5484 kW

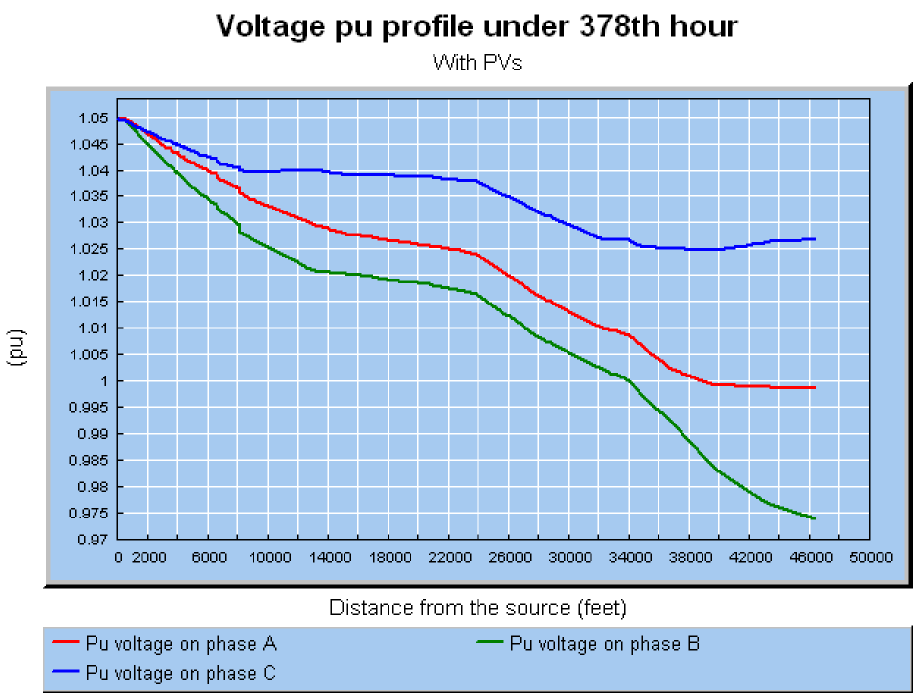
Total amount of PV: 3.3 kW

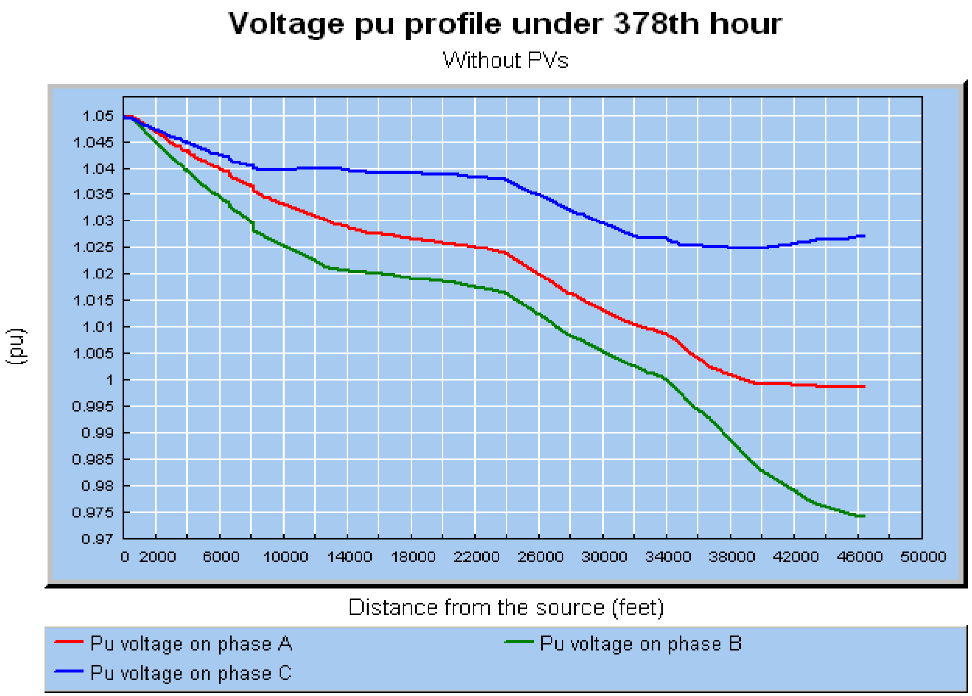
Penetration: 0.06%

kVAR Profile at Highest Load (Jan 16, 6PM)



Voltage Profile at Highest Load Condition (Jan 16, 6 PM)





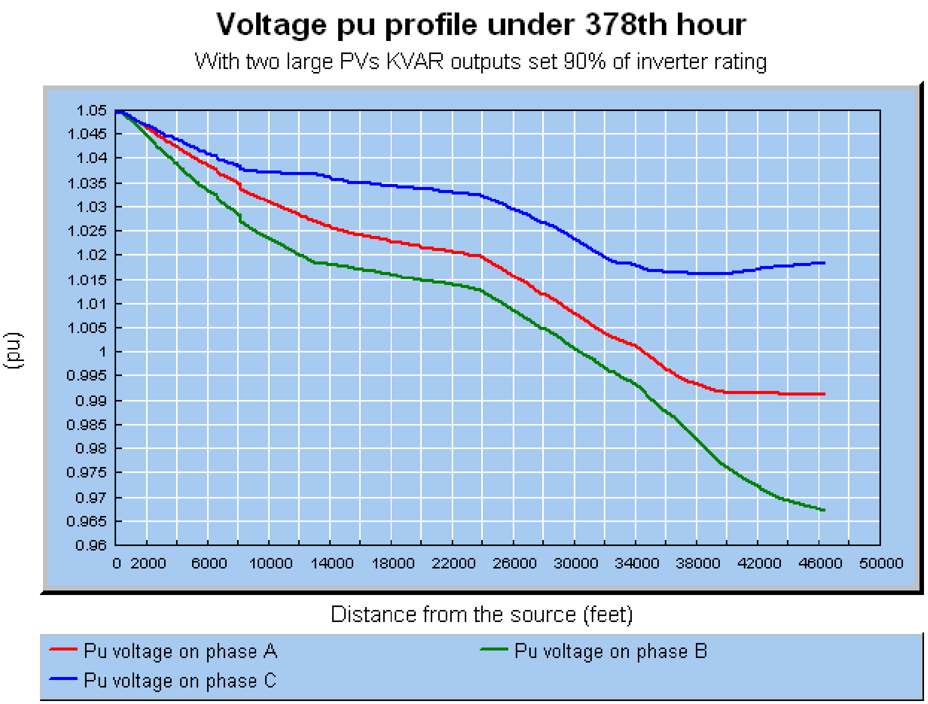
Total Loads: 5484 kW

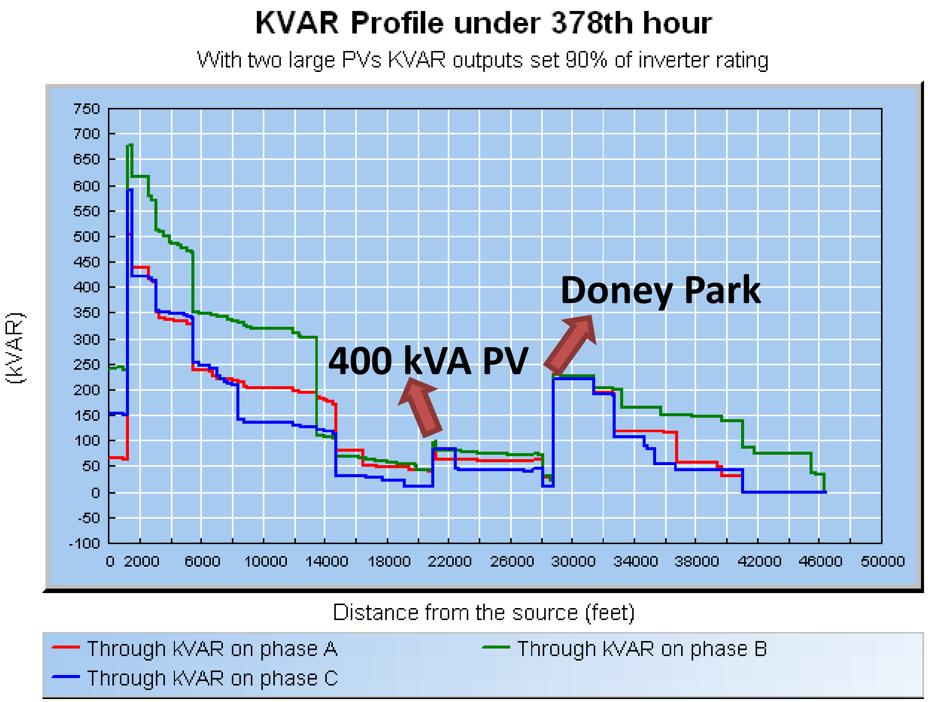
Total amount of PV: 3.336 kW

Penetration: 0.06%

If morning peak load along with significant PV generation is considered the impact on voltage profile is significant

Voltage profile at highest load with reactive power support from two large PVs (90% of inverter rating) (Jan 16, 6 PM)

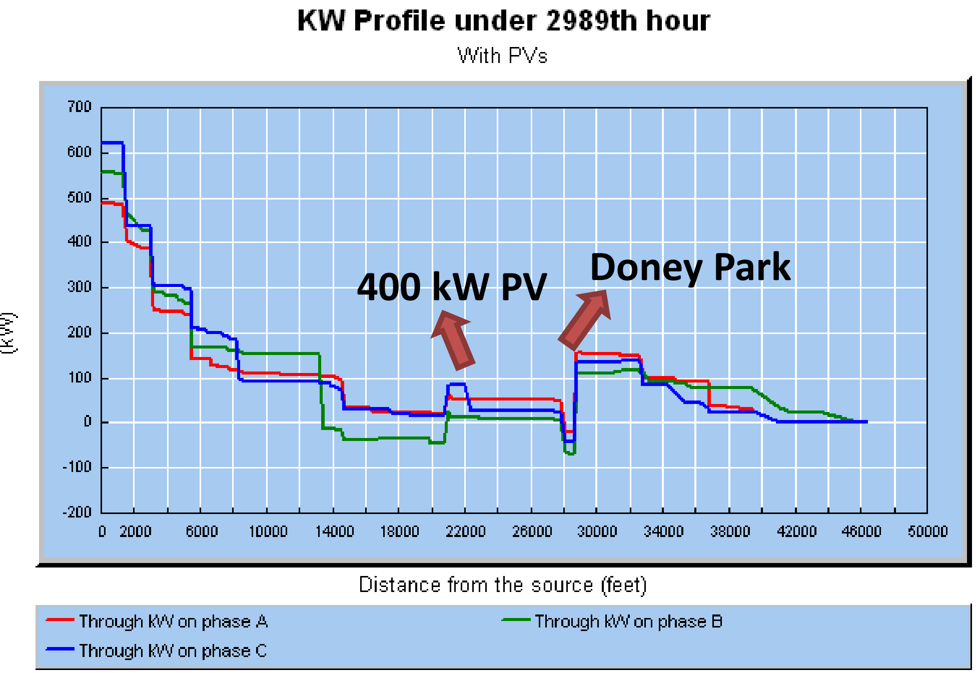


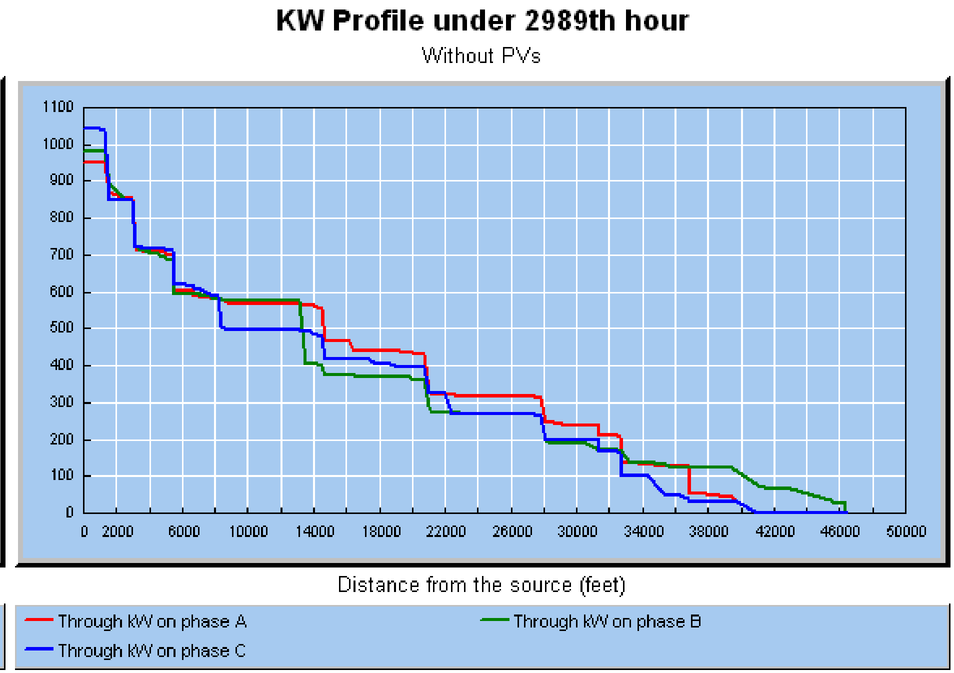


Two capacitor banks turned off automatically

- Reactive power from the two large inverters sufficient to maintain voltage without the two downstream capacitors

kW Profile at Highest Penetration (30.66%) (May 4, 1 PM)



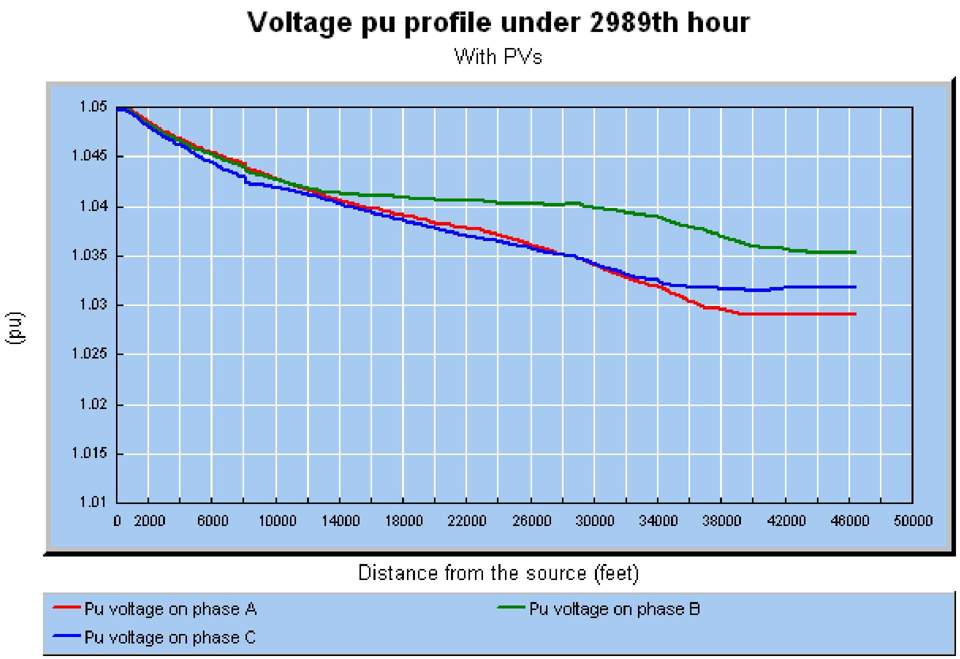


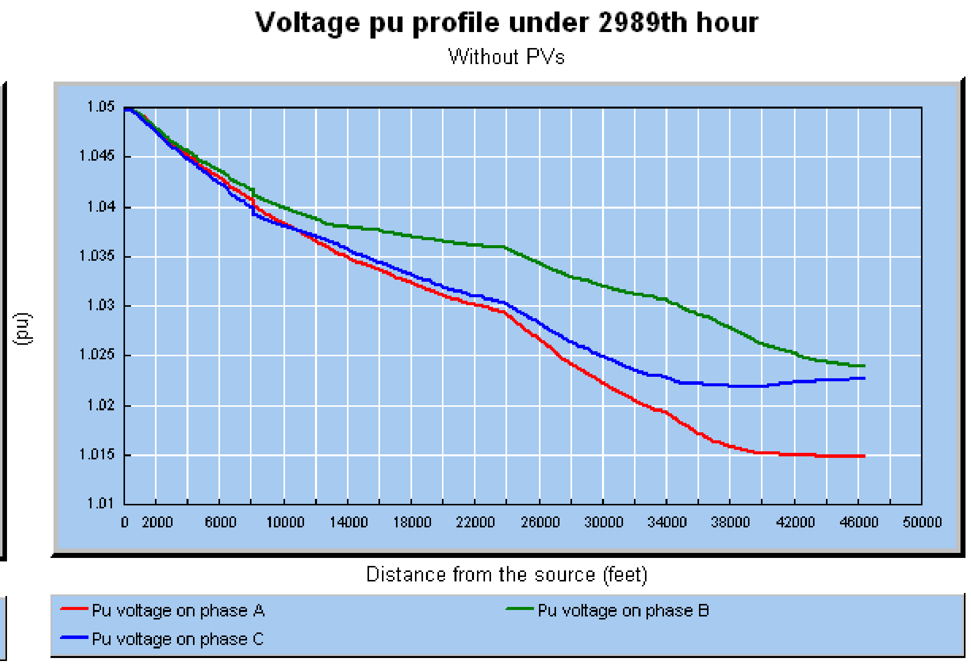
Total Loads: 2937 kW
Total amount of PV: 1299 kW
Penetration: **30.66 %**

	Without PV	**With PV**
kW Losses	41.28	27.38

No-load losses not included

Voltage Profile at Highest Penetration (May 4, 1 PM)



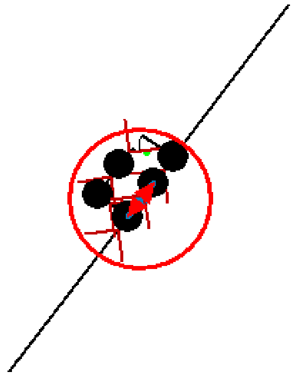


- Significant improvements in both voltage magnitude and in phase unbalance

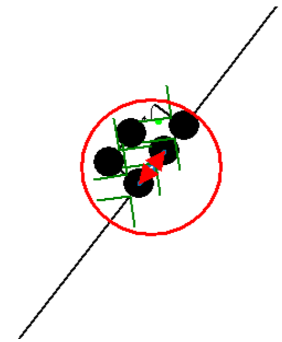
Total Loads: 2937 kW
Total amount of PV: 1299 kW
Penetration: 30.66 %

Reverse Power Flow in Recloser

Under high load /low PV condition

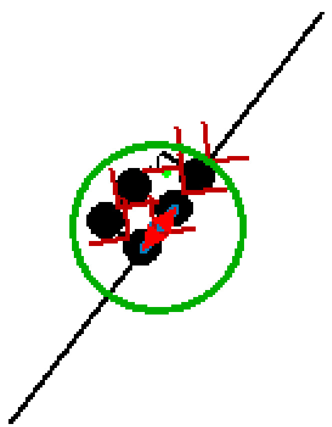


Real power through recloser

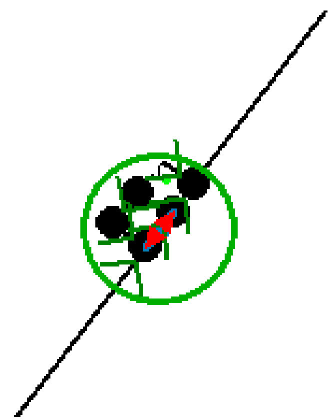


Reactive power through recloser

Under high PV penetration

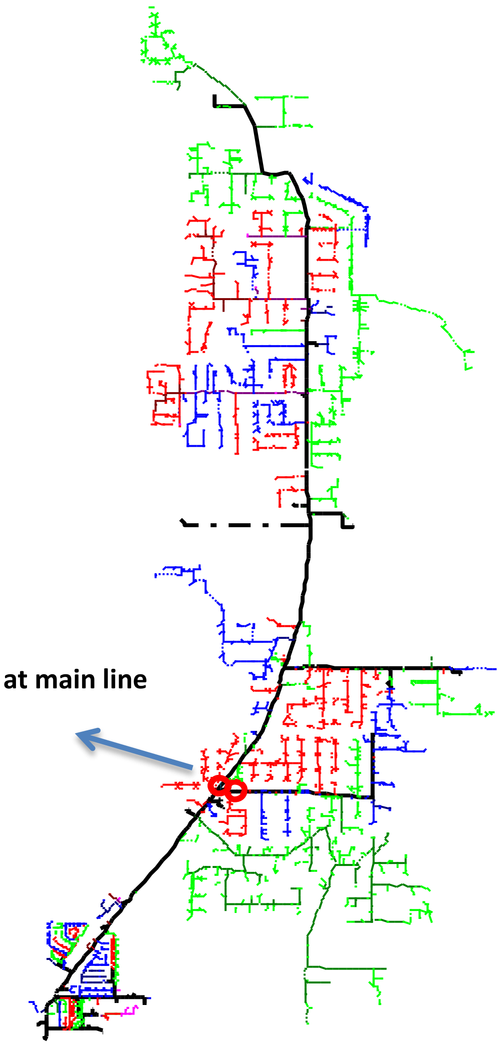


Real power through recloser



Reactive power through recloser

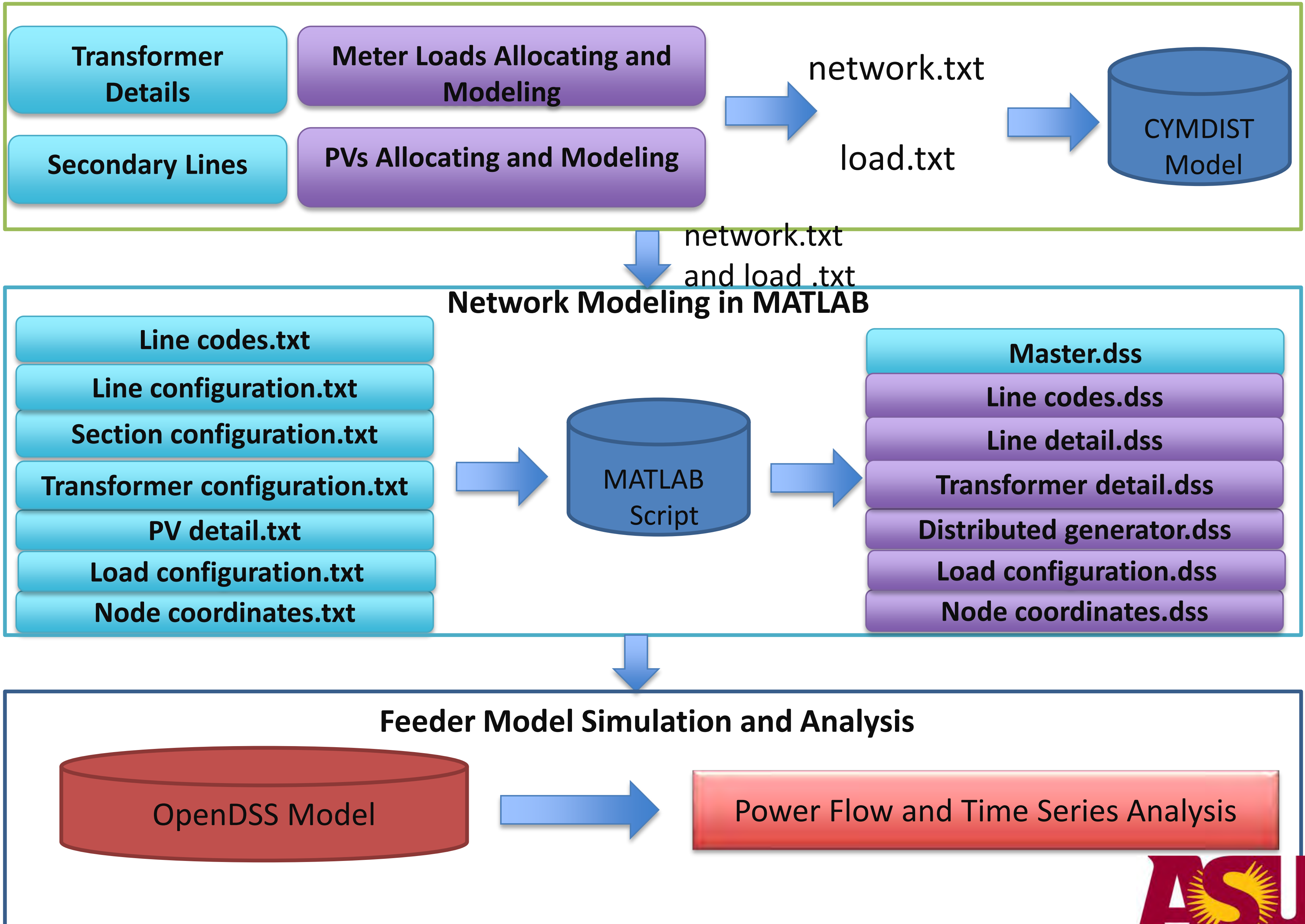
Recloser at main line



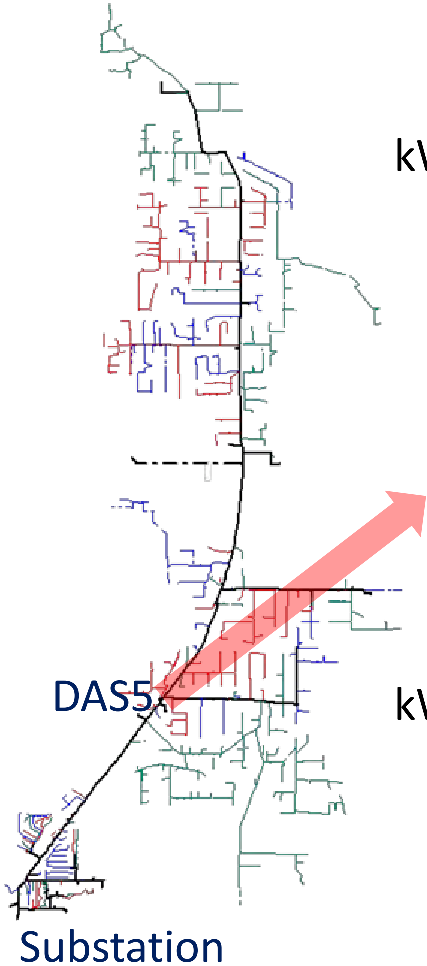
Time-Series Analysis using OpenDSS

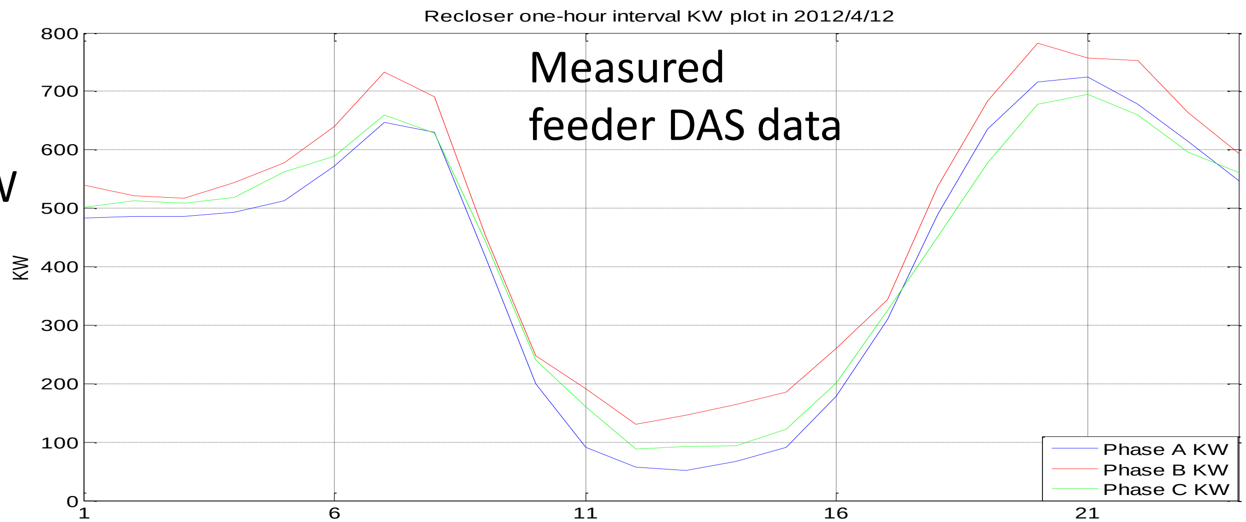
- High PV penetration feeder model also developed in OpenDSS
- OpenDSS is an open source distribution system analysis tool with several advanced features - especially time-series analysis
- Time series analysis helps to analyze the distribution system over a defined interval – a week, day or minutes for different study objectives such as impact of clouds, impact of PV on capacitor bank operation and impact on other control devices
- Time series analysis will also be used to validate the feeder model by comparison with feeder and residential DAS over long time intervals

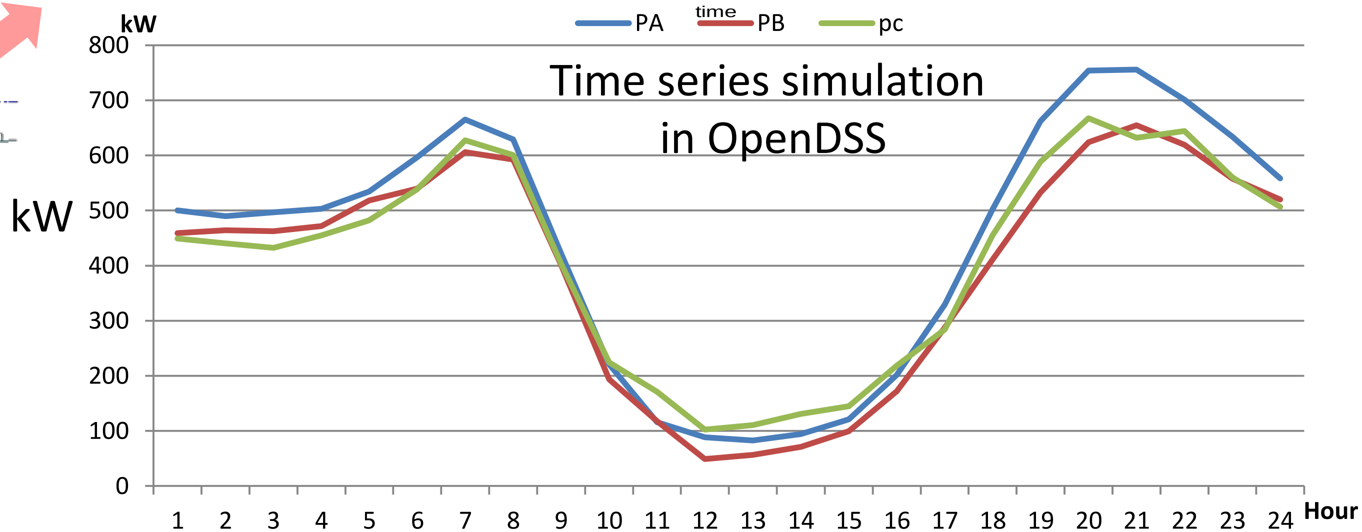
Modeling Procedure for OpenDSS



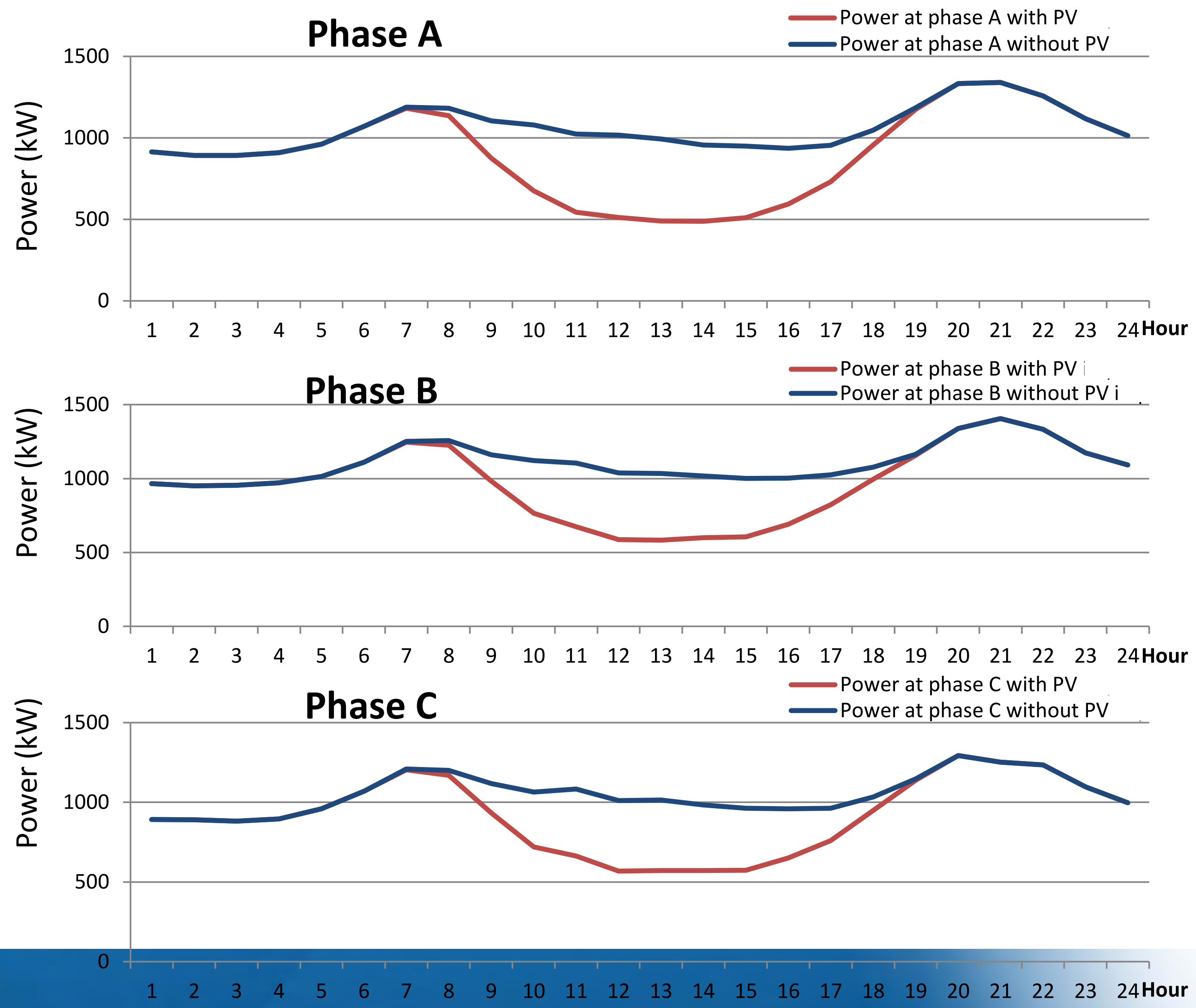
Preliminary Comparison of Model and Measured Results at Feeder DAS 05 for April 12, 2012 - kW







Time Series Analysis (OpenDSS) of Power Flow at Substation with and without PV (April 12)



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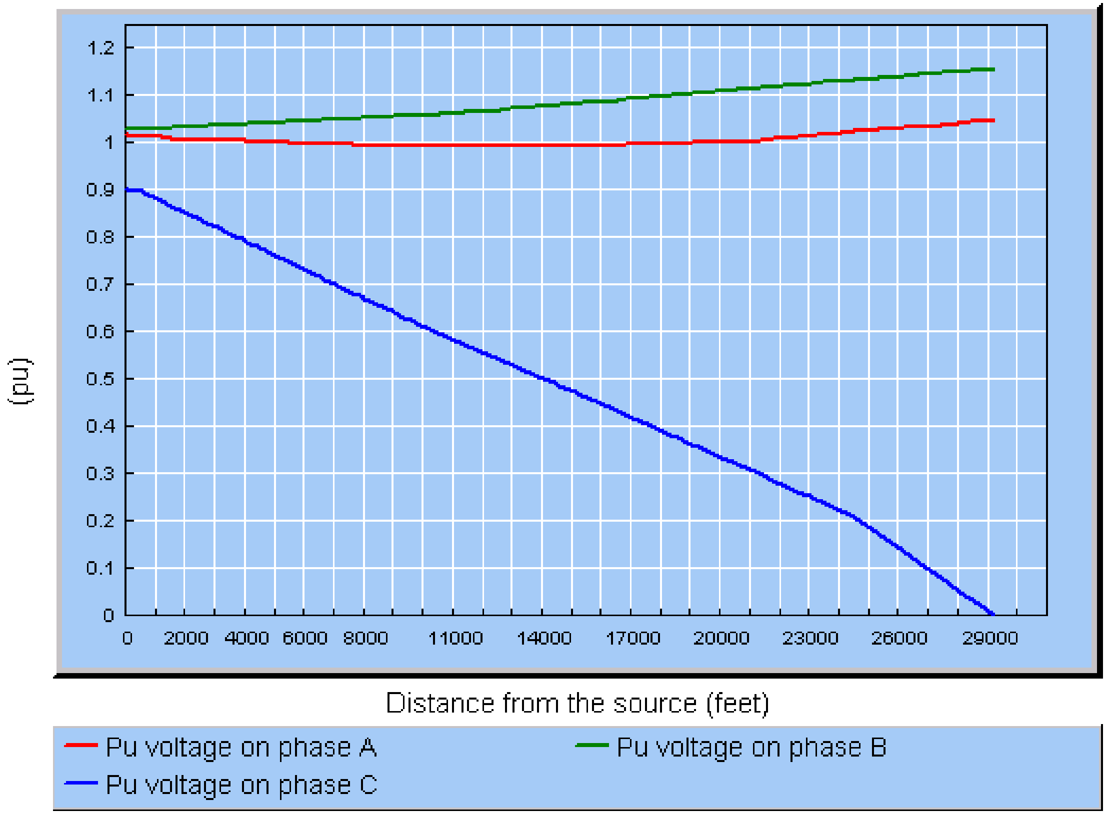
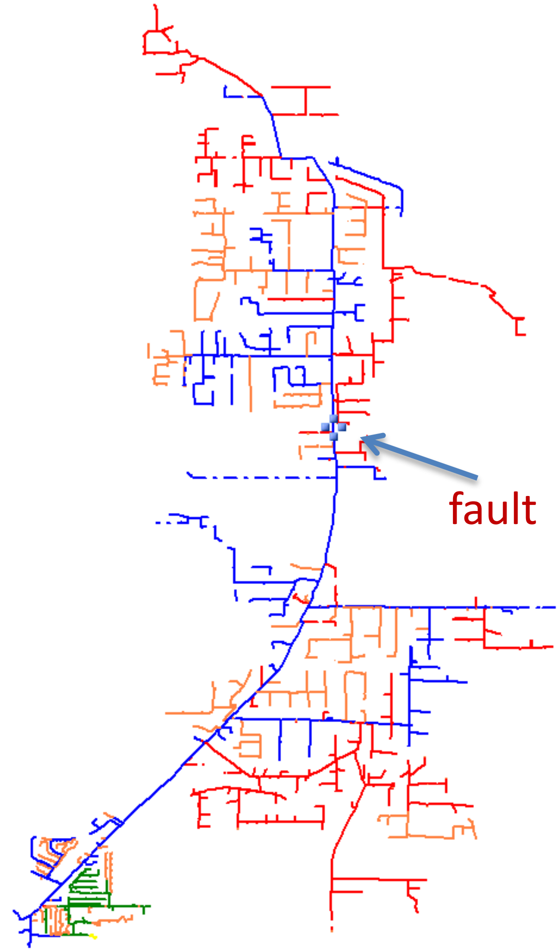
Fault Analysis with CYMTCC

- Protection impact study includes
  - Fuse-fuse coordination for various scenarios
  - Fuse-recloser coordination and nuisance blowing of fuses
  - Relay sensitivity for remote faults
- CYMTCC (an optional module in CYMDIST) has two protection related analysis
  - Minimum fault analysis and fault flow analysis
- **Minimum fault analysis** to verify if the protective devices can adequately detect and clear the minimum faults in their respective protection zones
  - Ensured that all primary nodes are protected without PV
  - Automatically disconnects DG under fault, hence, can not be directly used to study impact due to fault currents from PV if remains connected
- **Fault flow analysis** applies a given type of fault at a given location and gives the fault current and voltage profile at any point on the feeder; used here to study impact of PV for various fault conditions

Fault Flow Analysis

- Voltage profile with a line to ground fault on phase C in the middle of the feeder



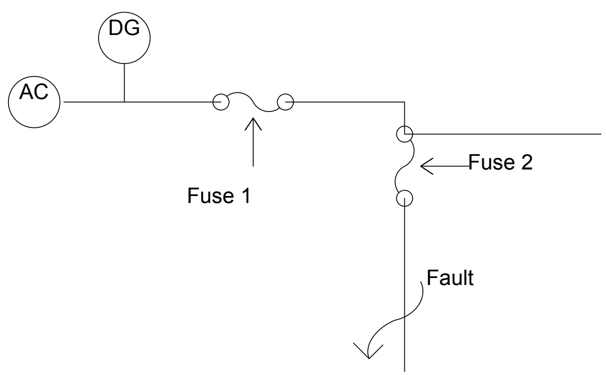


Greater than (%)	Lower than or equal to (%)	Line width	Color
0	85	2	
85	90	2	
90	95	2	
95	105	2	
105	999999	2	

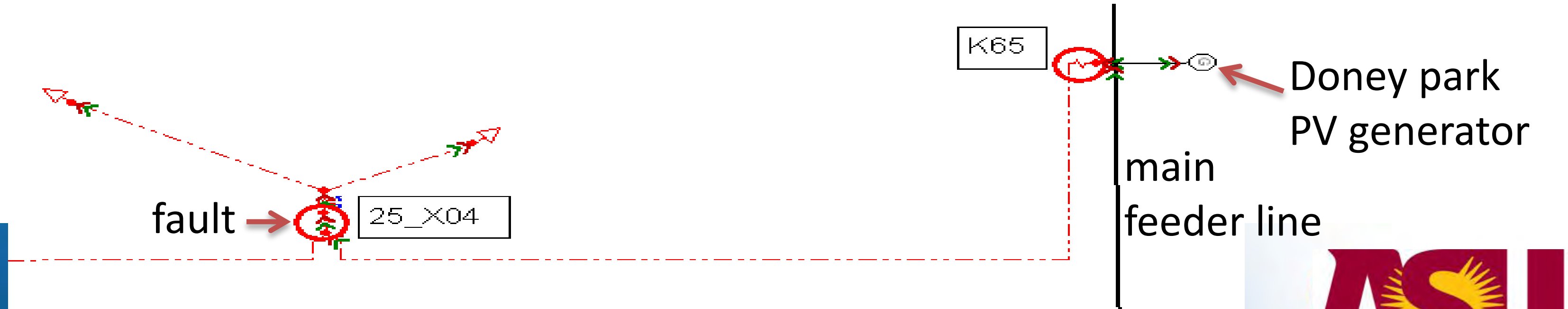
Fuse Coordination Study

Situation 1: DG located upstream of fault

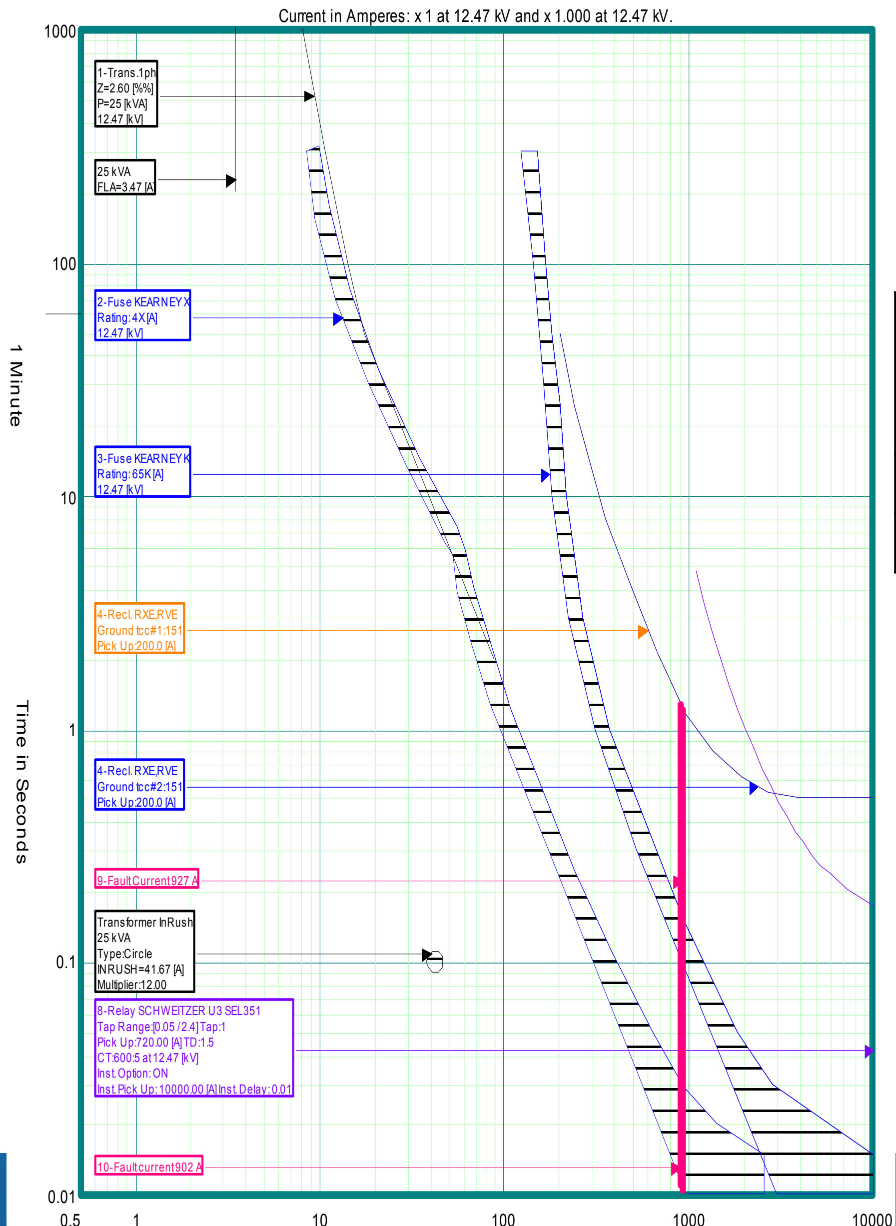
- When DG is upstream of two originally coordinated fuses as shown, fault currents flowing through fuses 1 and 2 increase due to DG contribution
- With increased currents in **both** fuses, fuse-fuse coordination is maintained; need to ensure the increased fault current does not exceed the ratings of the fuses



- For the 600 kW Doney Park PV, Situation 1 is studied considering the two nearest coordinated fuses - upstream transformer fuse X04 and upstream fuse K65



Impact of PV Penetration on Fuse Coordination



- L-G fault applied at the transformer primary, and fault currents at Fuse X04 and Fuse K65 with and without PV studied

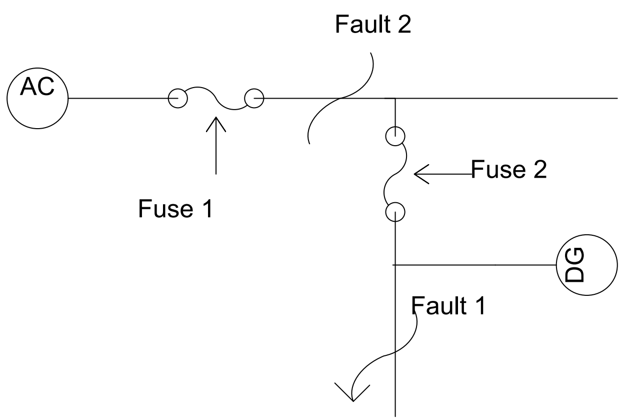
	Without PV		With PV	
	Fault current	Operating time	Fault current	Operating time
Fuse X04	902.09 A	0.0302 s	927.51 A	0.0291 s
Fuse K65	902.08 A	0.1596 s	927.51 A	0.1509 s

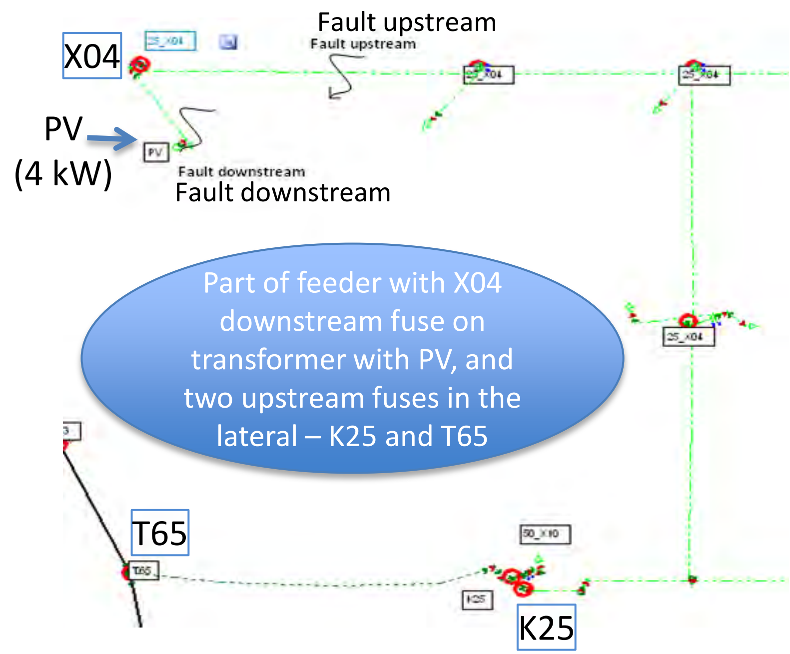
- Fuse coordination is maintained and fault currents do not exceed the ratings of either fuse

Impact of PV Penetration on Fuse Coordination

Situation 2: DG located downstream of fault

- For Fault 1, Fuse 2 is expected to operate faster than Fuse 1
- For Fault 2, Fuse 2 should not operate and Fuse 1 is expected to isolate the fault
- Whether or not Fuse 2 opens for Fault 2 depends on DG fault current contribution





	Downstream fault		Upstream fault	
	Fault current	**Operating time**	**Fault current**	**Operating time**
Fuse X04	55.45 A	6.99 s	1.11 A	No operation
Fuse K25	55.09 A	No operation	478.67 A	0.098 s

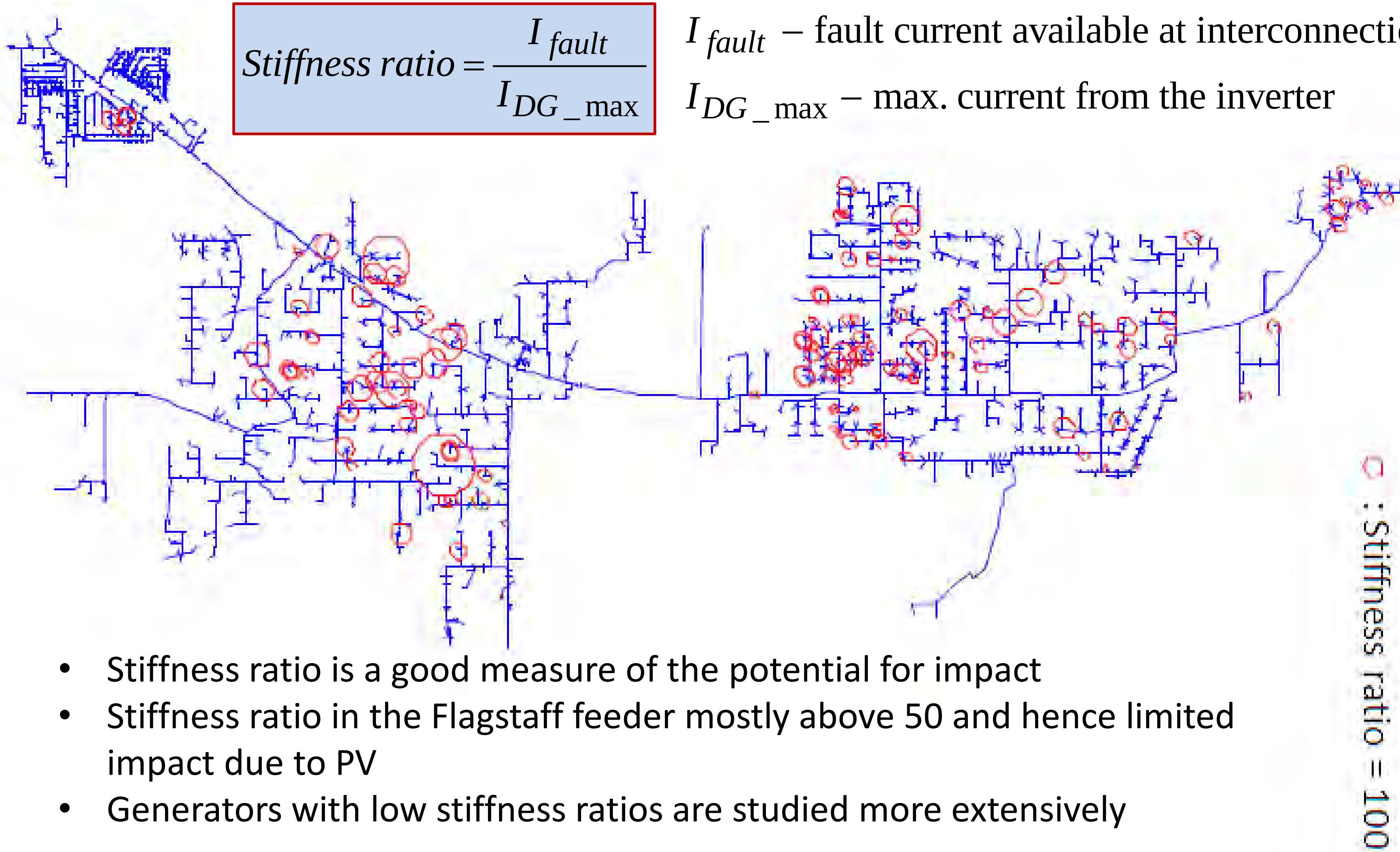
Since, fault current magnitude of roof top PV inverters is limited (~2 X rated current), downstream fuses do not clear for upstream faults

Stiffness Ratio

$$Stiffness\ ratio = \frac{I_{fault}}{I_{DG\_max}}$$

I_{fault} – fault current available at interconnection

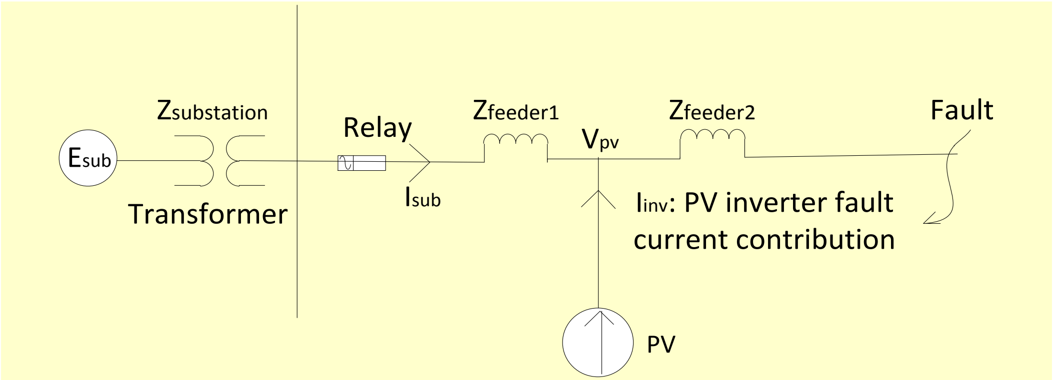
I_{DG_max} – max. current from the inverter



- Stiffness ratio is a good measure of the potential for impact
- Stiffness ratio in the Flagstaff feeder mostly above 50 and hence limited impact due to PV
- Generators with low stiffness ratios are studied more extensively

Impact on Relay Sensitivity

- With large DG penetration, the fault current seen at substation relay may be reduced, which impacts its sensitivity to detect remote faults



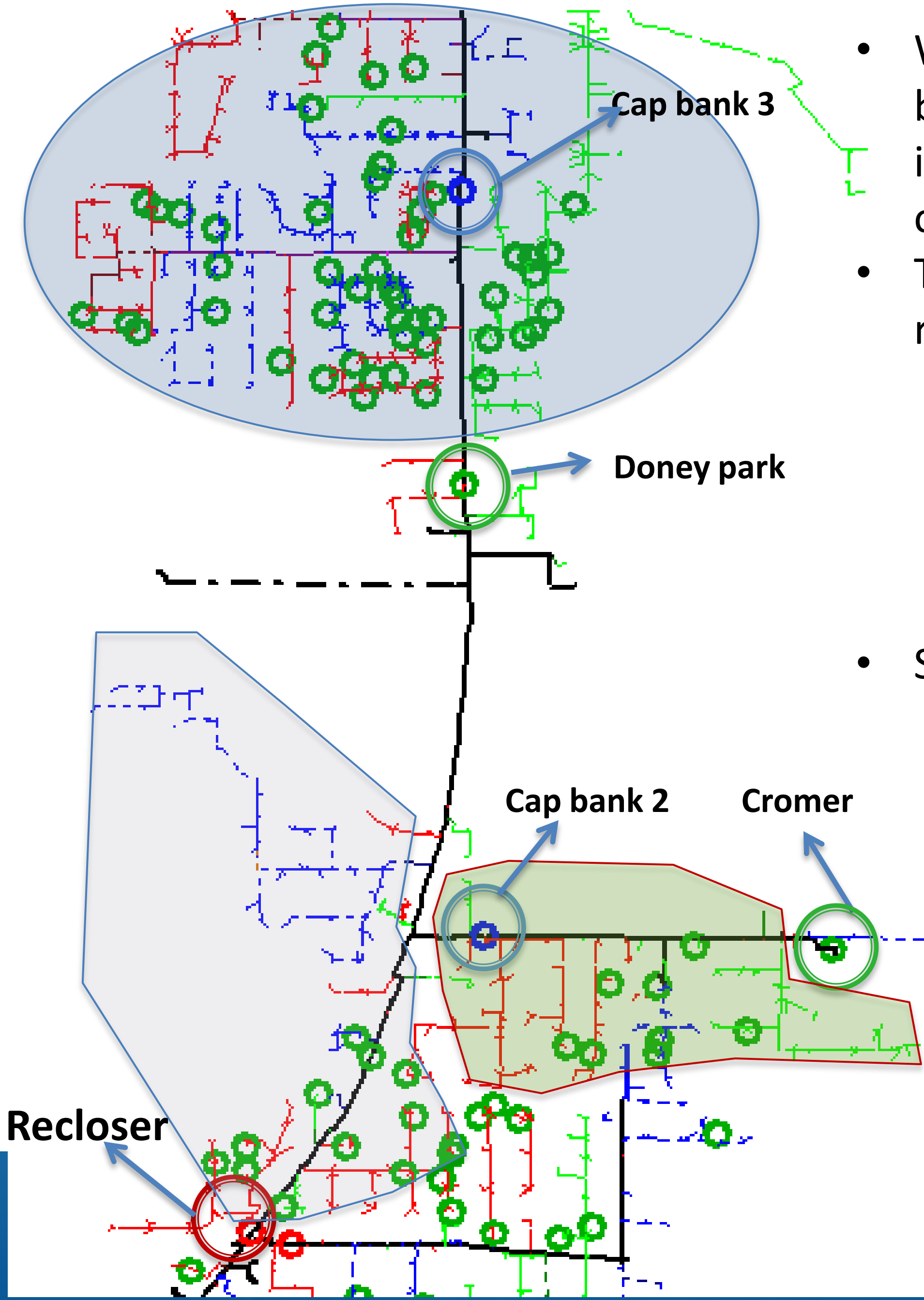
$$I_{reduction} = \frac{I_{inv} \cdot Z_{feeder2}}{Z_{substation} + Z_{feeder1} + Z_{feeder2}}$$

		Fault Phase	Current seen by relay without PV (A)			Current seen by relay with PV (A)		
			Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Phase faults	Three-phase	ABC	849.88	857.44	868.06	789.58	804.78	811.98
	Line-to-line	AB	775.46	708.38	182.21	686.23	**691.28**	98.29
		BC	162.46	786.34	715.11	73.53	**707.14**	696.55
		CA	703.43	174.35	794.60	681.59	88.34	**712.11**

Outline

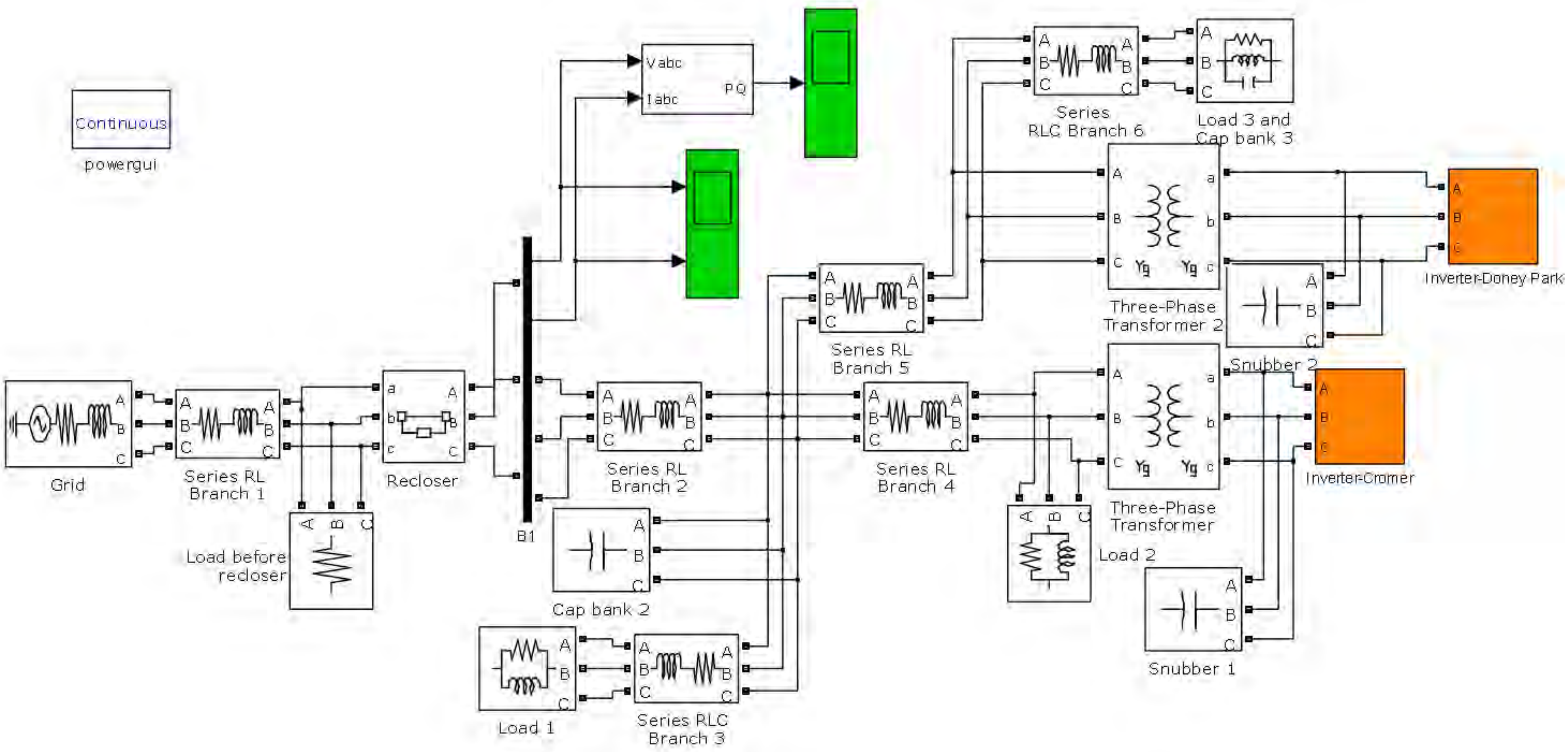
- Description of the high PV penetration deployment
- Development of feeder model using GIS and PV/AMI data
- Power flow analysis and preliminary results
- Protection coordination analysis
- Anti-islanding study methods

Islanding Protection Study

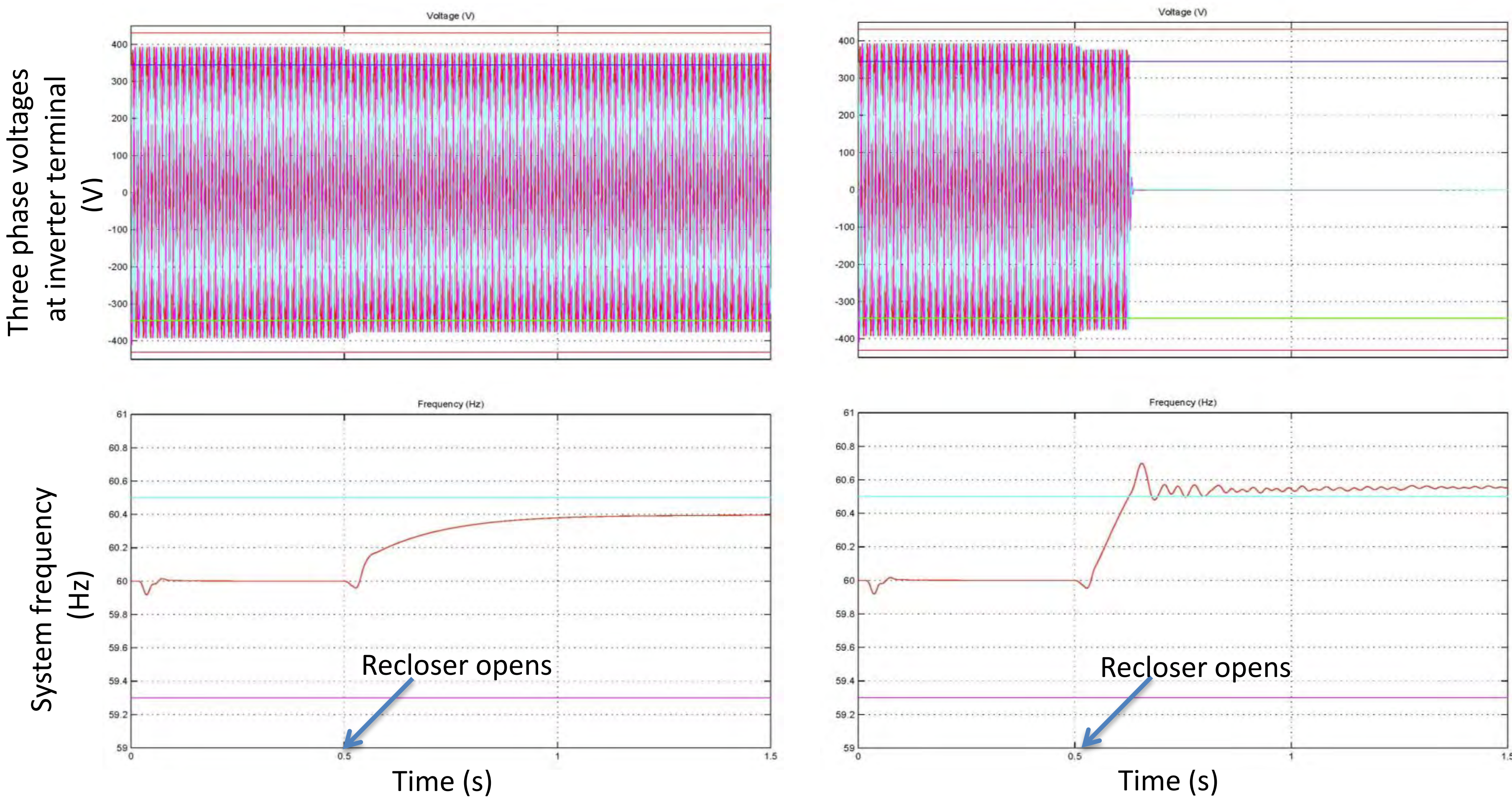


- When Recloser 1 opens possibility of both the larger PV systems forming an island and energizing the section downstream of the recloser *under perfect load-DG match*
- The two inverters are modeled in detail with relevant control loops and *assumed parameters*
  - *dq* reference-frame-based control with active anti-islanding scheme employed
  - positive feedback on frequency/voltage
  - Tested individually with worst case, matching RLC load
- Simplified model of feeder for islanding study
  - Group loads downstream of recloser into three zones as shown
  - Each combined load can be modeled as a combination of constant P-Q, constant impedance loads, or detailed model
  - Obtain series line impedance from power flow, matching the resistive and reactive losses individually

SimPowerSystems Model of Simplified Feeder with Large PV Inverters



Preliminary Results from Islanding Study



With active island detection disabled, inverters remain on with slightly lower voltage; small changes in load can lead to island detection

With active island detection enabled both inverters detect island and turn off in 0.2 s

- Actual AI methods and control parameters for inverters in field needed
- Single phase inverter models with anti-islanding also developed

Future Work

- Phase 3:
  - Extensive validation with field DAS
  - Quasi-steady-state and dynamic models
  - Grid support features of utility-scale inverters
- Phase 4:
  - Energy storage study and demonstration
  - Study on microgrids and other advanced features
- Phase 5:
  - Extension to larger distribution systems
  - Recommendations for high penetration design

Summary

- Large scale PV implemented in a feeder leading to higher than 30% peak penetration at feeder head, and higher levels at some other locations
- Extensive data acquisition systems
- Extensive modeling and impact analysis using GIS, AMI and installed feeder/residential DAS
- Modeling process established and software tools developed that can be adapted for evolving needs
- Preliminary modeling results show improved voltage profile along feeder, and low impact on protection coordination at present levels of penetration