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

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PSERC Webinar

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Acknowledgements

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

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High Penetration of Photovoltaic Generation Study – Flagstaff Community Power

DOE Grant #: DE-EE0004679

Partners: APS (Lead), GE, NREL and ViaSol

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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

- Issues to be studied for high PV penetration
- Test feeder details
- Feeder model development and automation
- Steady-state analysis and results
- Modeling in quasi-static analysis tools and model validation
- Modeling in transient analysis tools
  - Network reduction
  - Dynamic phasor approach
  - Automated model development in MATLAB/Simulink
  - Dynamic analysis examples

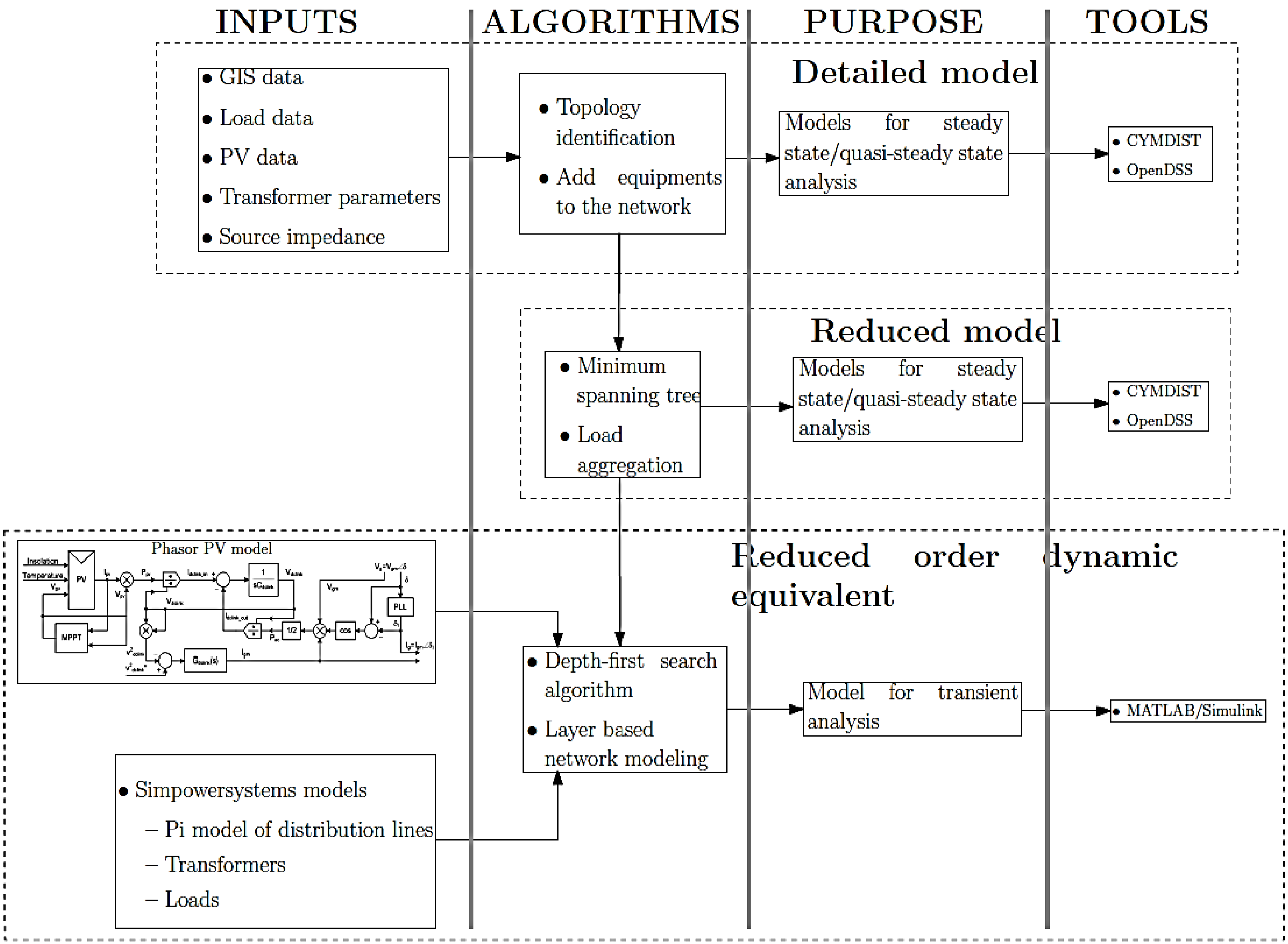
High PV penetration impact

- Impact analysis
  - Voltage profile
    - Interaction with conventional voltage regulating devices
  - Protection coordination
    - Under reverse power flow
  - Power quality
    - harmonics, voltage flicker, phase unbalance
  - Islanding detection
  - Control with grid interactive inverters
  - Storage, microgrid in supporting high penetration

Data for study and operation

- GIS (geographic information system)
- AMI (advanced metering infrastructure)
- Solar data
- Distribution DAS (data acquisition system)
- Design details of inverters ?
- Future: real-time inverter/system information (plug & play smart inverters)

Tools for static, time-series and dynamic/transient analysis



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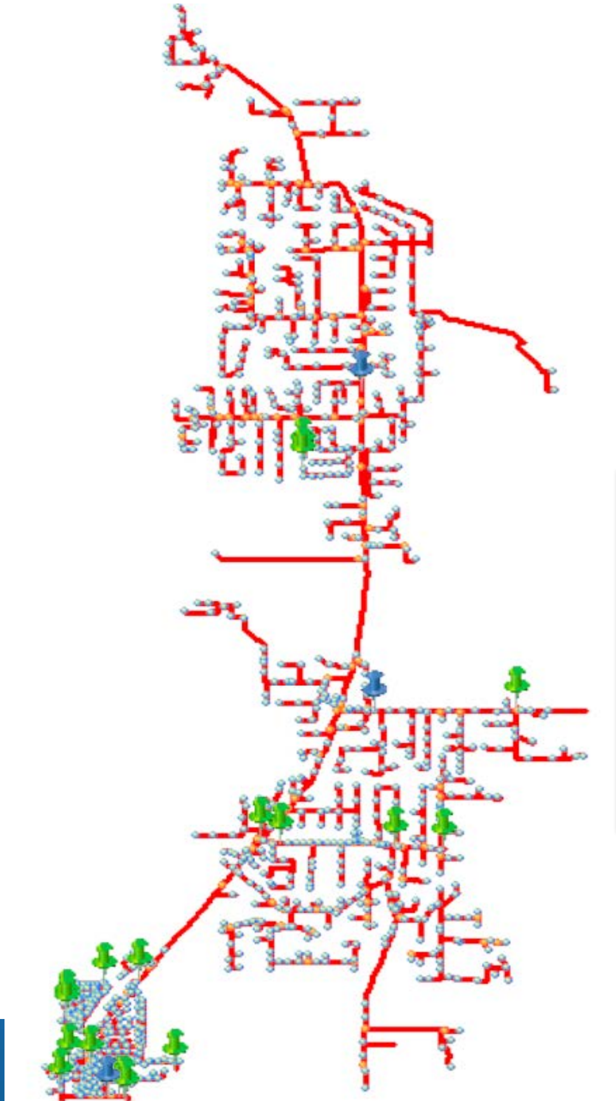
High PV penetration feeder in Flagstaff, AZ



Feeder length	9 miles
Peak load	~ 7 MW
Capacity	~ 13 MW
Customers	
Residential	~ 3000
Commercial	~ 300

Primary segments	1809
Transformers	921
Fuses	186
Capacitor banks	3
OCR (recloser)	2

# residential PV	> 125
Residential PV (kW)	467 kW
Cromer	471 kW
Doney park	604 kW
Total	1.55 MW

High Bandwidth Feeder and PV Data Acquisition

6 High bandwidth feeder DAS

- SEL 735 PQ meters, 1-s data
- GPS synchronized and event based data capture
- Parameters monitored (> 70)
  - V, I, kW, kWh, kVAR, harmonics

17 Residential PV DAS

- SEL 734P PQ meters, 1s and 1 min data

6 Weather stations

- 1 s data, GPS synchronized
- Irradiance, temperature, rain, relative humidity …

AMI

- AMI meters on all customer loads (~ 3300)
- 15 min and hourly data for modeling

Feeder DAS locations

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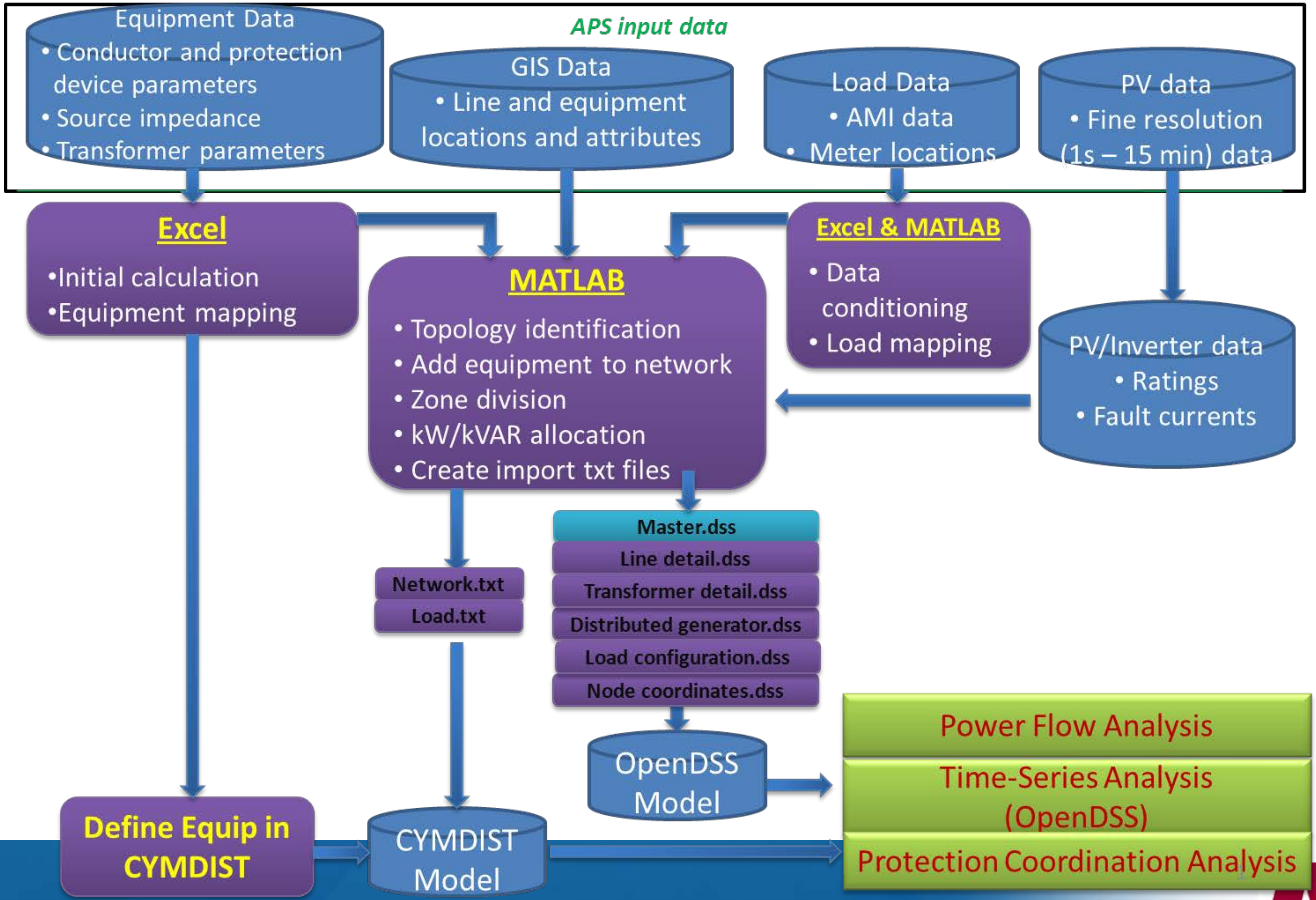
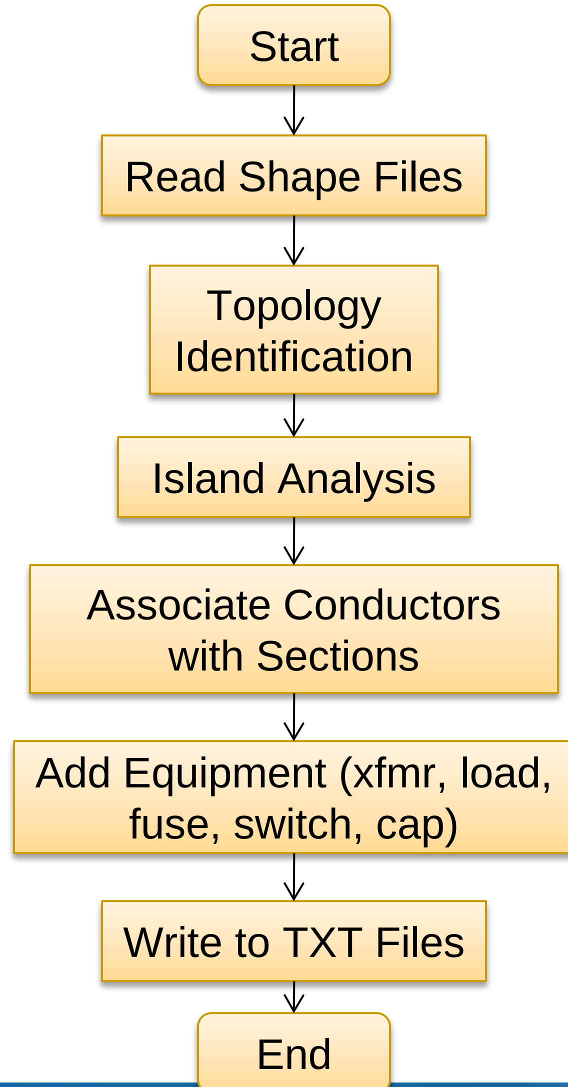
Static and quasi-static modeling

- Automation of modeling process is the main focus

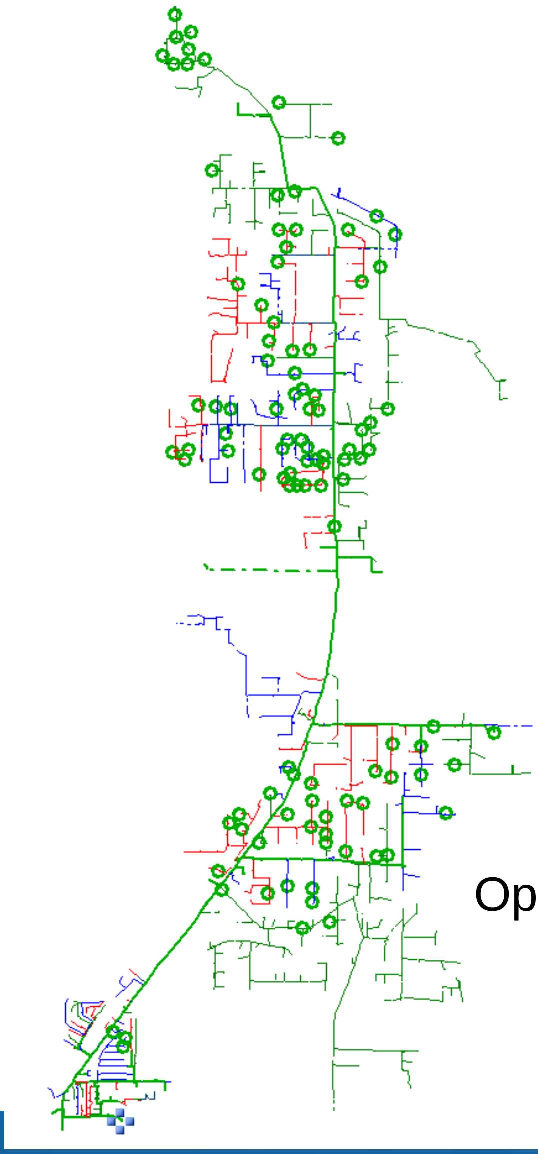


Feeder Network Model Development

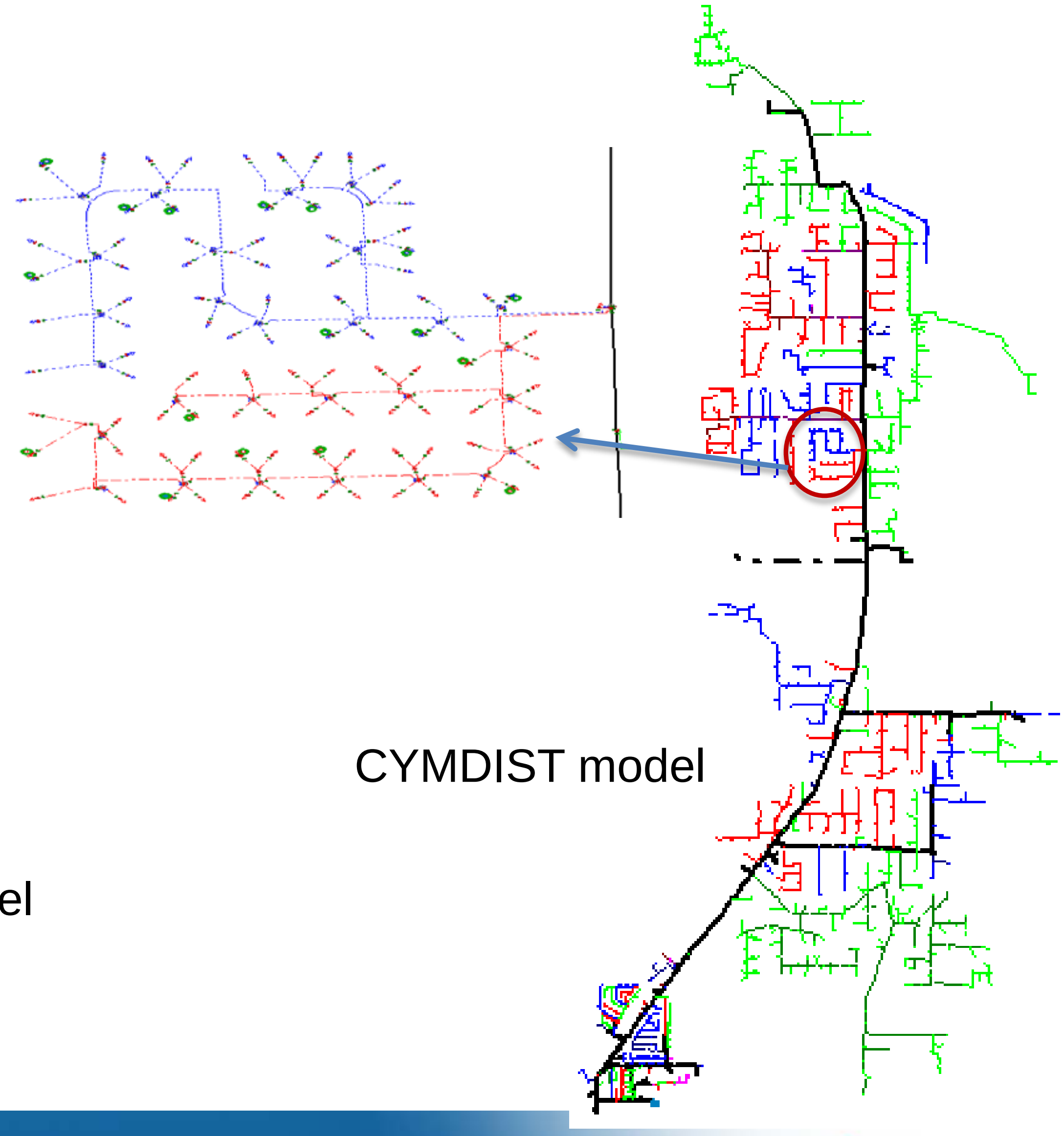
(Auto conversion of GIS data to CYMDIST model using MATLAB)



Feeder Model



OpenDSS model



CYMDIST model

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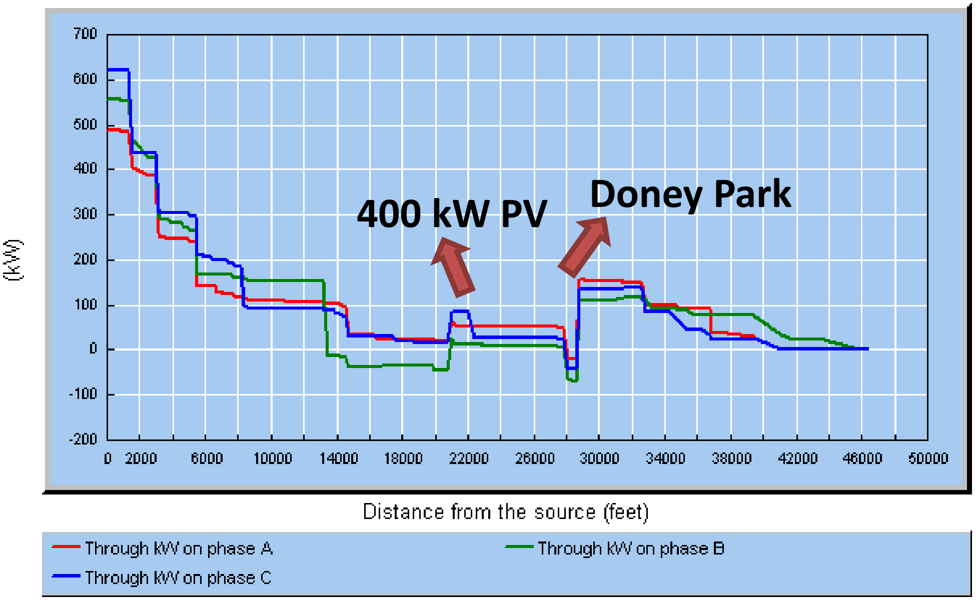
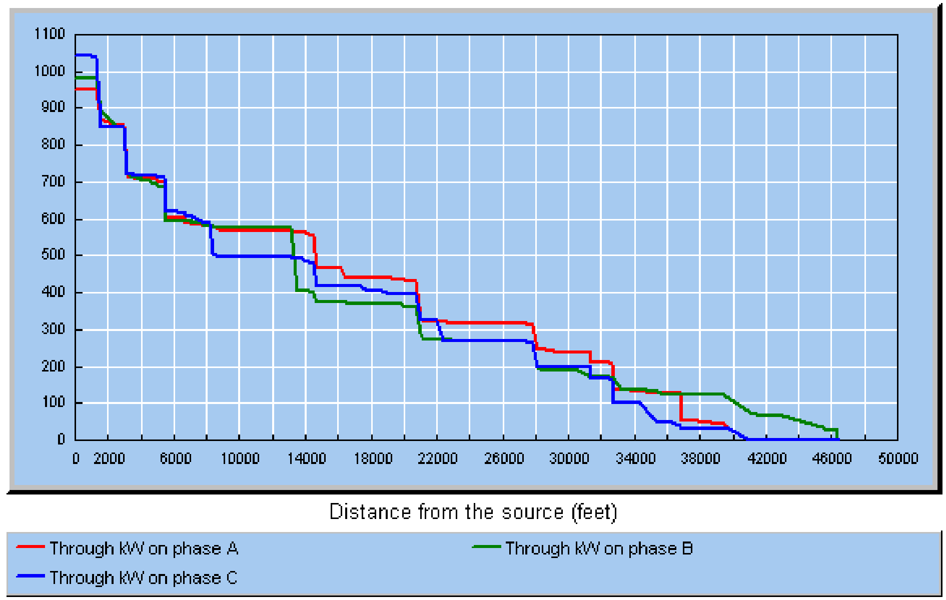
kW profile at high penetration

kW profile along feeder with PVs



kW profile along feeder without PVs



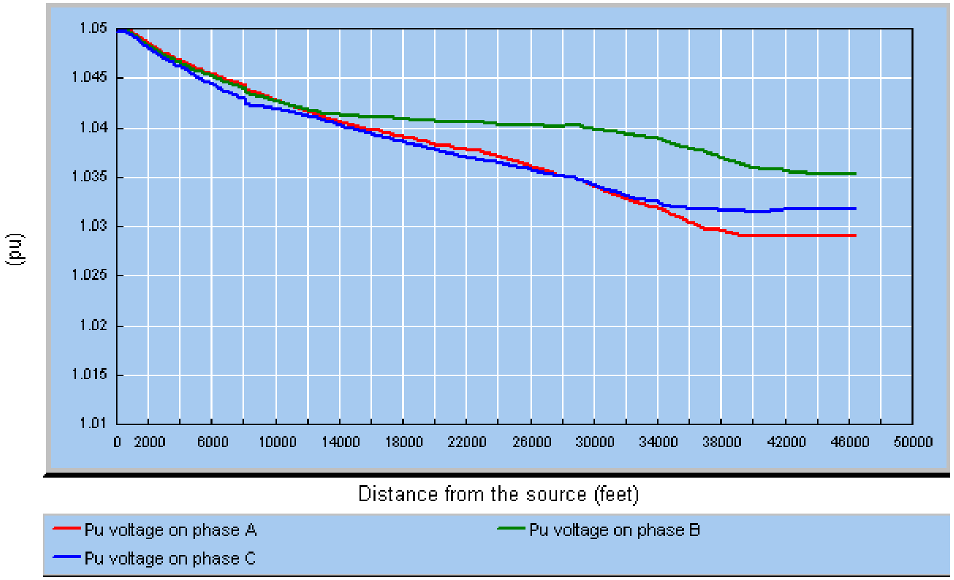
Total Loads: 2937 kW
Total amount of PV: 1299 kW
Penetration: 30.66 %
(May 2012 results)

	Without PV	With PV
kW Losses	41.28 kW	27.38 kW

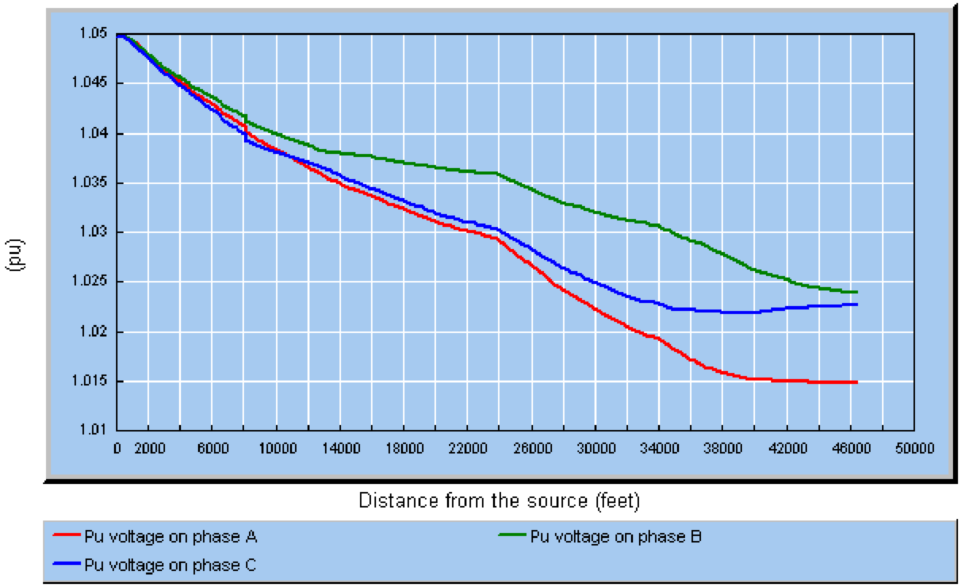
No-load losses not included

Voltage profile at high penetration

Voltage profile along feeder with PVs

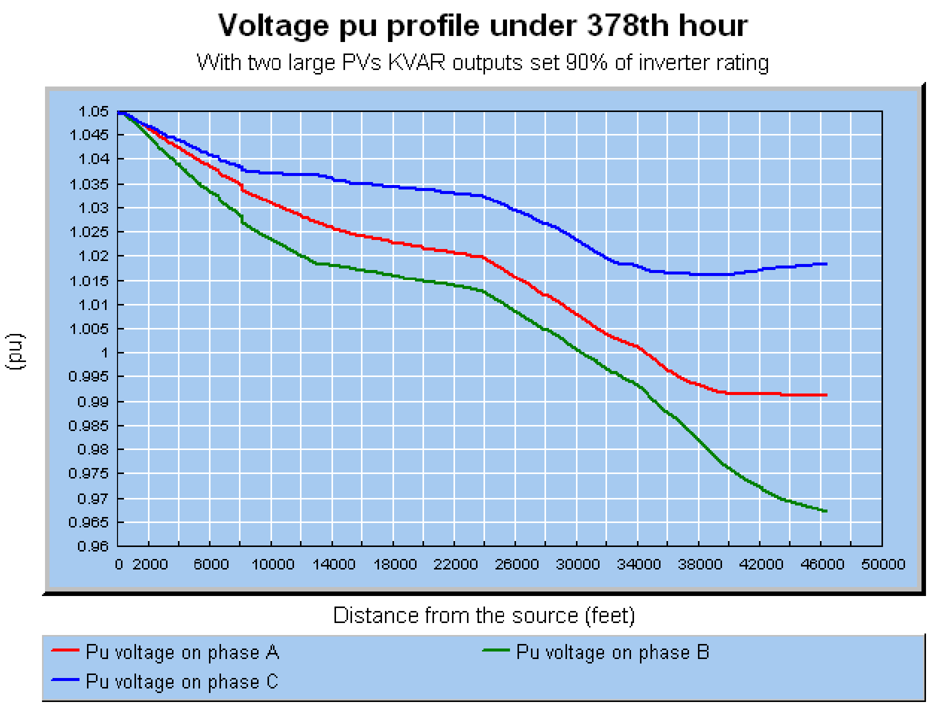


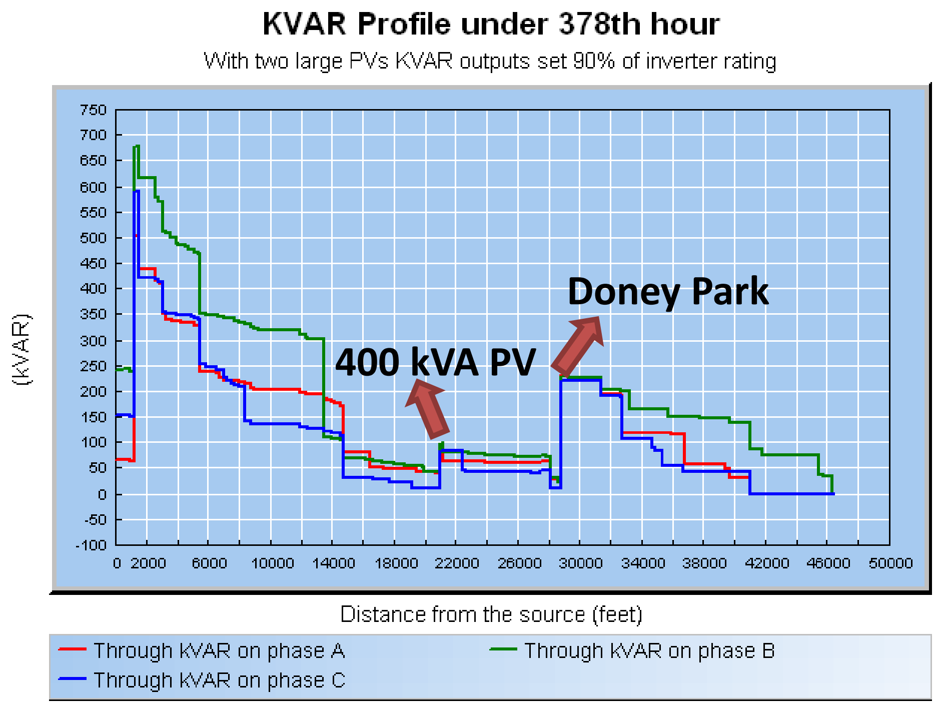
Voltage profile along feeder without PVs



- Improvements in both voltage magnitude and phase unbalance with high penetration of PV

Reactive power support from two large PVs (at highest load)





Two capacitor banks turned off automatically

- Reactive power from the two large inverters (at 90% of the total kVA rating) sufficient to maintain voltage without the two capacitor banks

Fault Analysis with CYMTCC

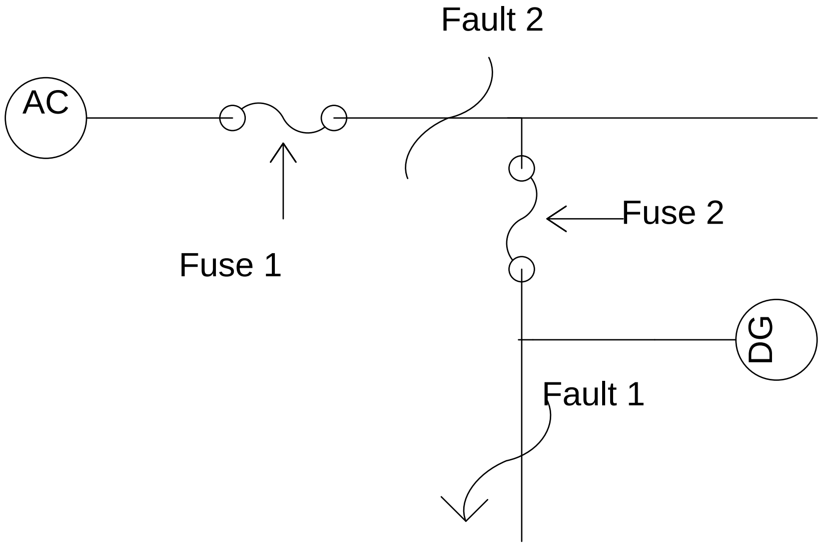
- Protection impact study includes
  - Fuse-fuse coordination for various scenarios
  - Fuse-recloser coordination and nuisance blowing of fuses
  - Relay sensitivity for remote faults
- CYMTCC (module in CYMDIST) has two protection related analysis
  - **Minimum fault analysis** to verify if the protection devices can adequately detect and clear the minimum faults in their respective protection zones
  - **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

Impact of PV Penetration on Fuse Coordination[20]

Situation 1: DG located upstream of fault

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 (Fuse 2)	55.45 A	6.99 s	1.11 A	No operation
Fuse K25 (Fuse 1)	55.09 A	No operation	478.67 A	0.098 s

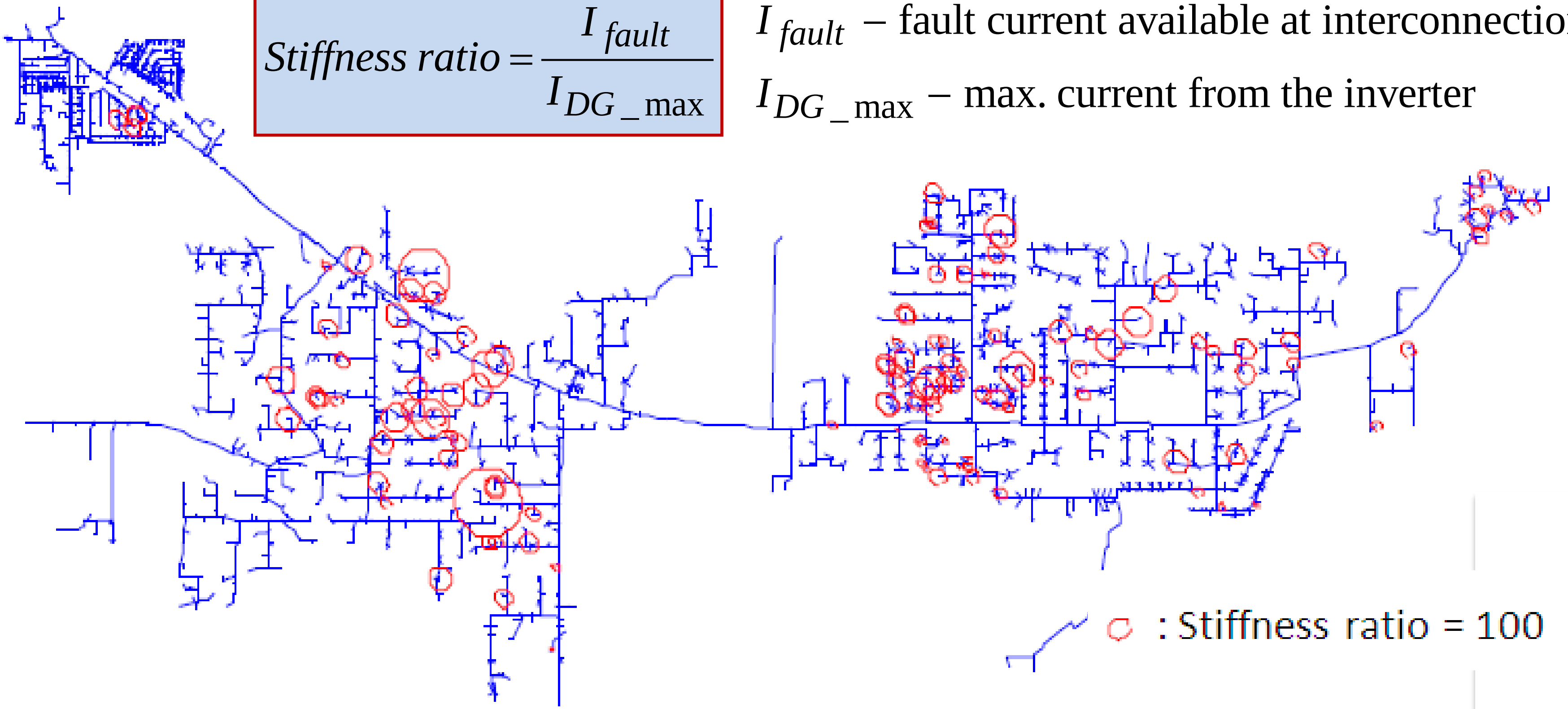
- No violations observed in the studied cases for Situation 1 or 2

Stiffness Ratio

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

I_{fault} – fault current available at interconnection

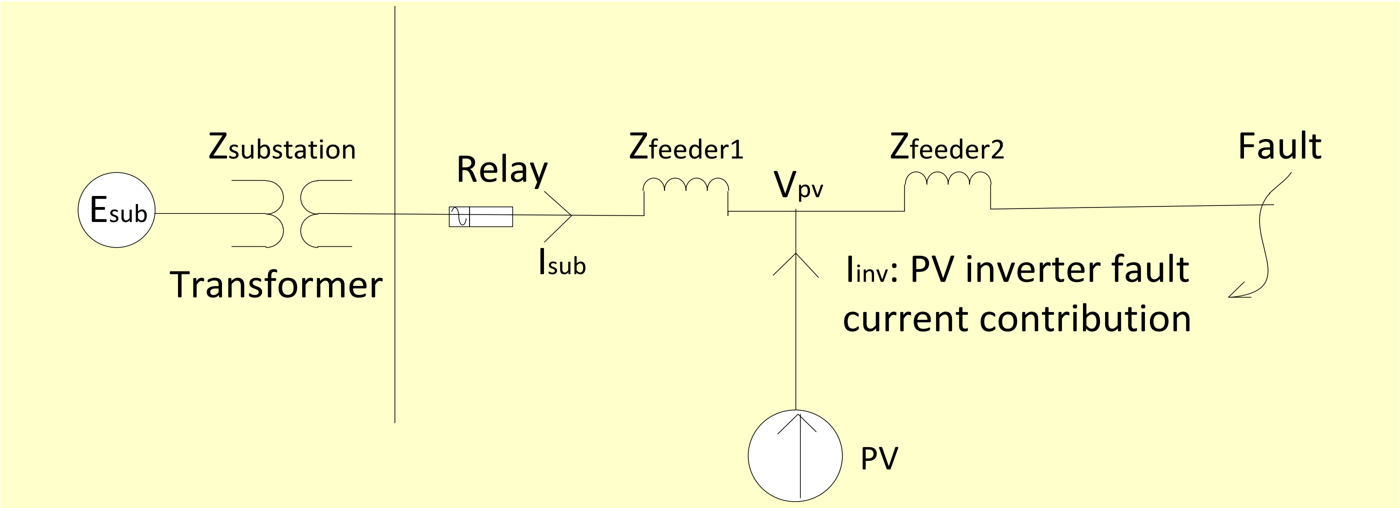
I_{DG_max} – max. current from the inverter



- Stiffness ratio is a good measure of the potential for impact
- Stiffness ratio in the Flagstaff feeder mostly above 50, and hence limited adverse 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



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

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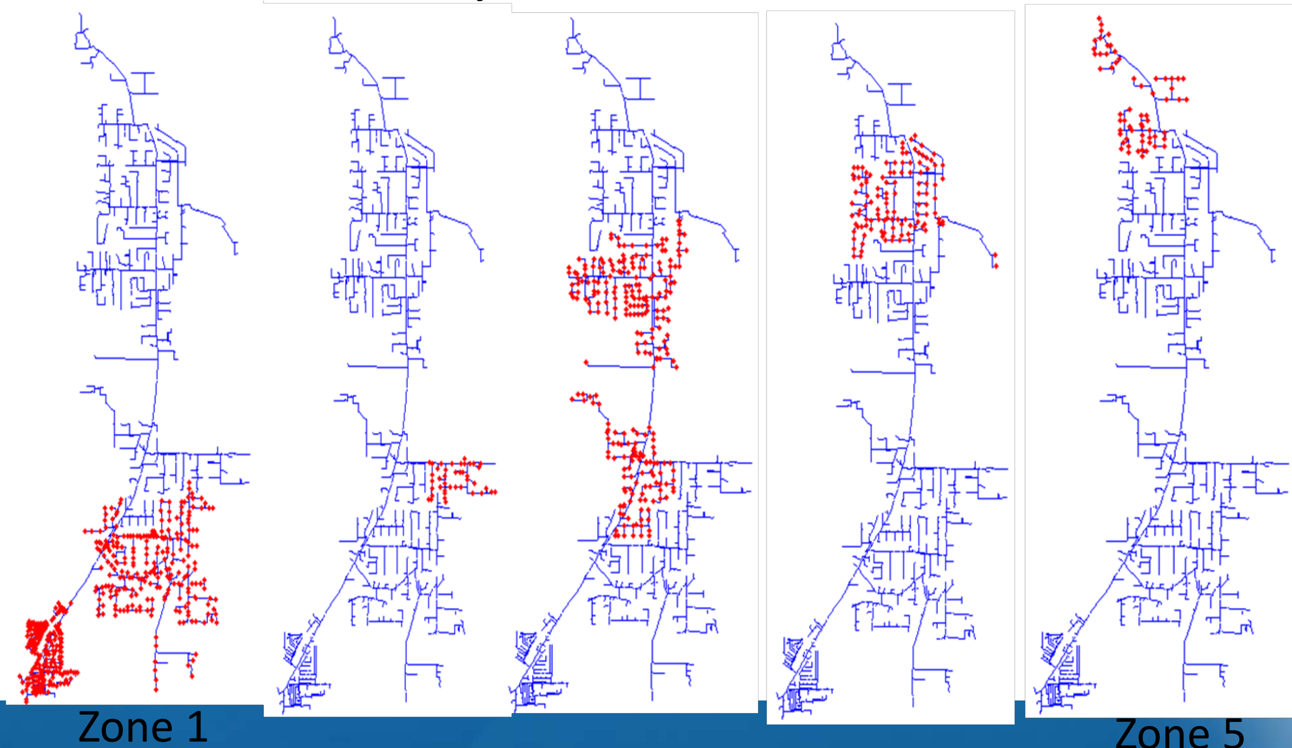
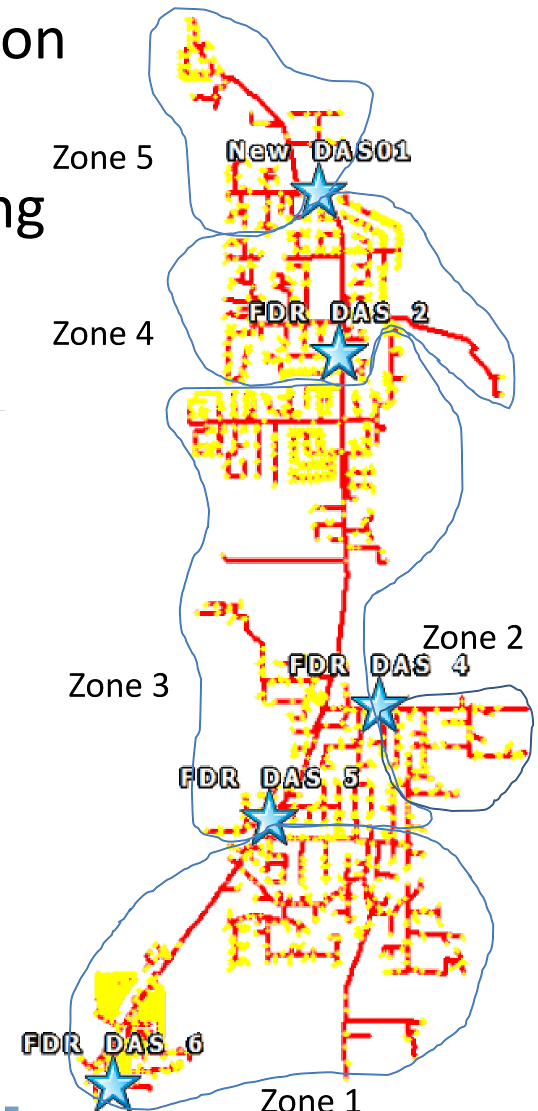
Time-Series Analysis using OpenDSS

- Snap shot power flow for a few select cases alone are not enough to understand the time varying effects of PV
- Time series analysis helps to analyze the distribution system over a defined, longer interval – a season, week, or day at fine time resolutions
- Time series analysis performs a sequence of power flow simulations using time-series load and PV data, with the converged state of one run providing the initial state for the next
- Operation of components with low-frequency dynamics such as switched capacitors can be studied
- OpenDSS with a COM interface is an effective tool for time-series analysis

Zone division for load (kW, kVAR) data

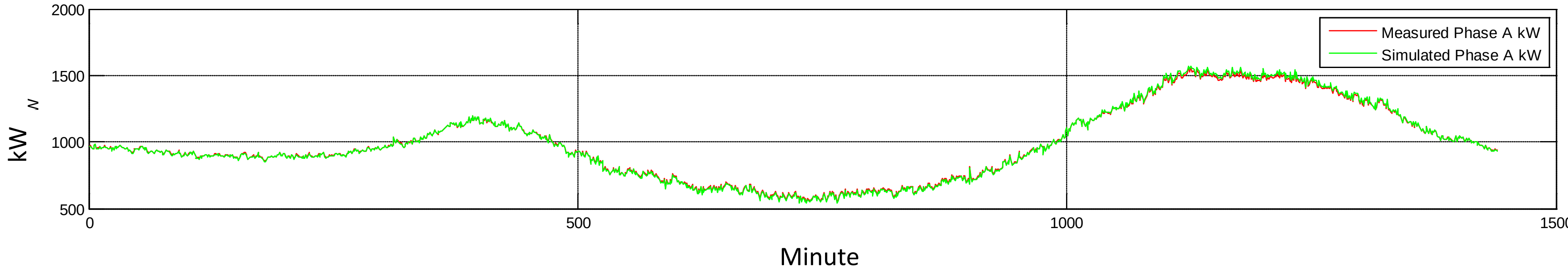
- Feeder divided into 5 zones based on DAS location
- DAS measurements in each zone used for load kW and kVAR allocation with AMI used for scaling
- Allows use of 1 s data from feeder DAS for time-series analysis

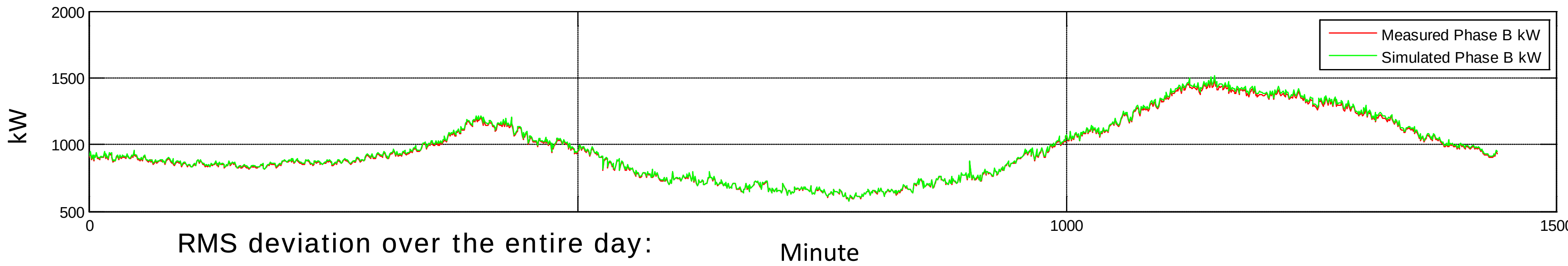




Time-series analysis and validation (kW)

Measured and simulated 1-min interval kW plot of each phase at the substation on 9/25/2012



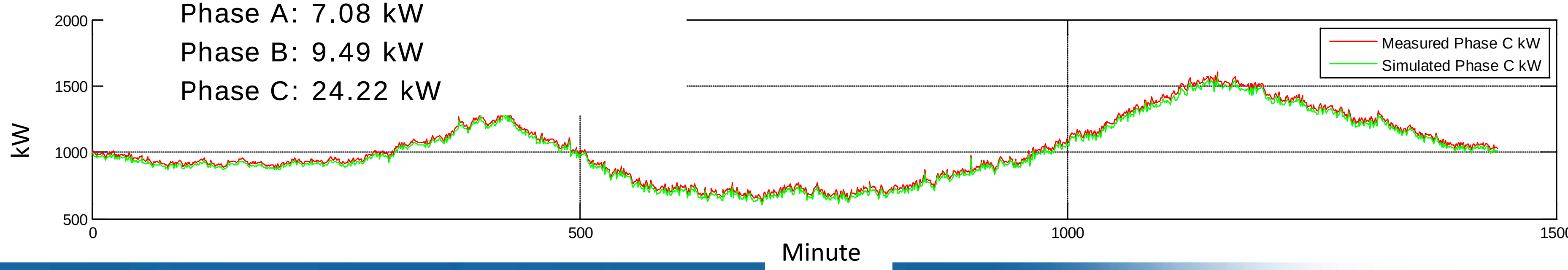


RMS deviation over the entire day:

Phase A: 7.08 kW

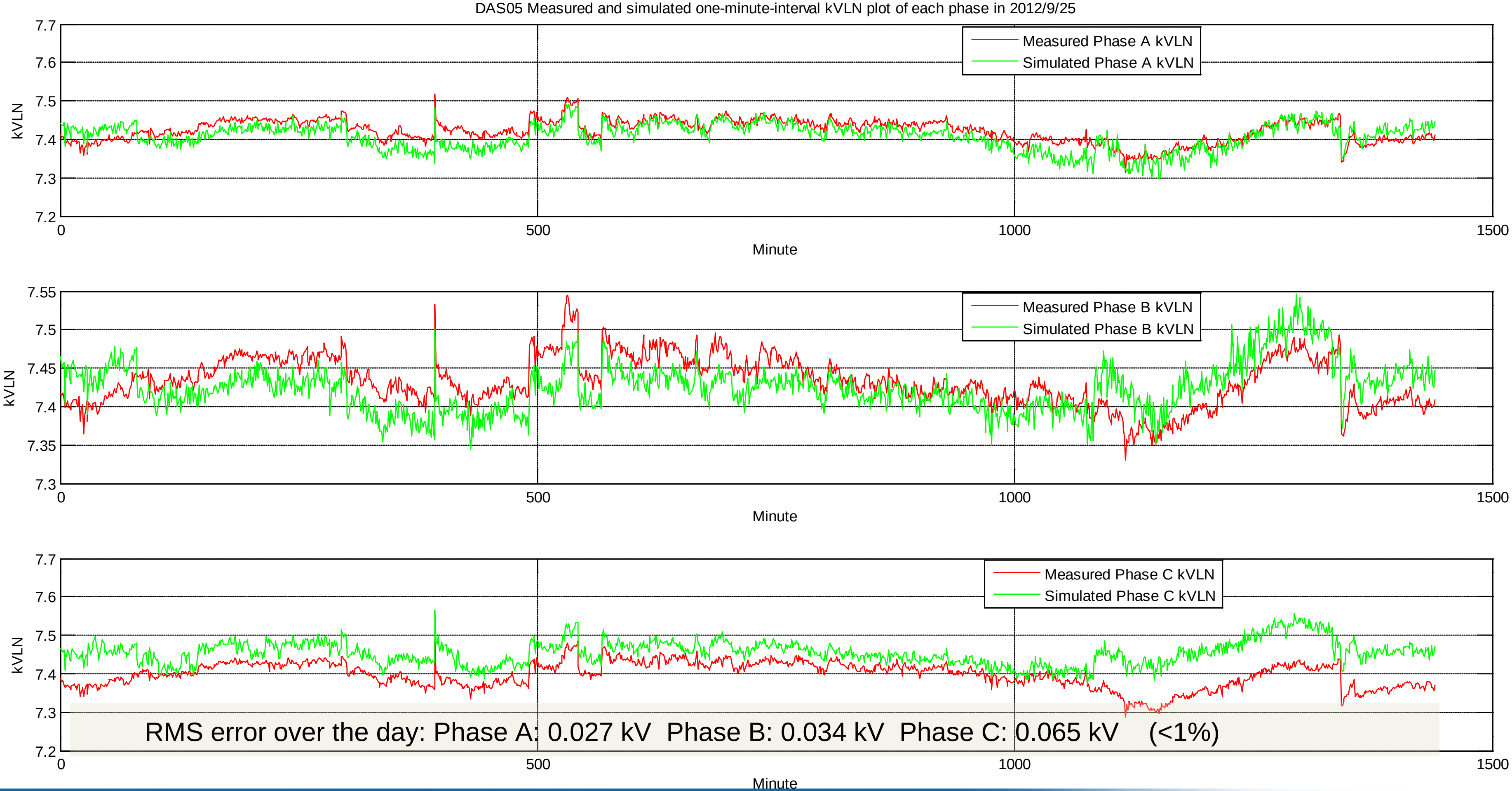
Phase B: 9.49 kW

Phase C: 24.22 kW



Time-series analysis and validation (kW)

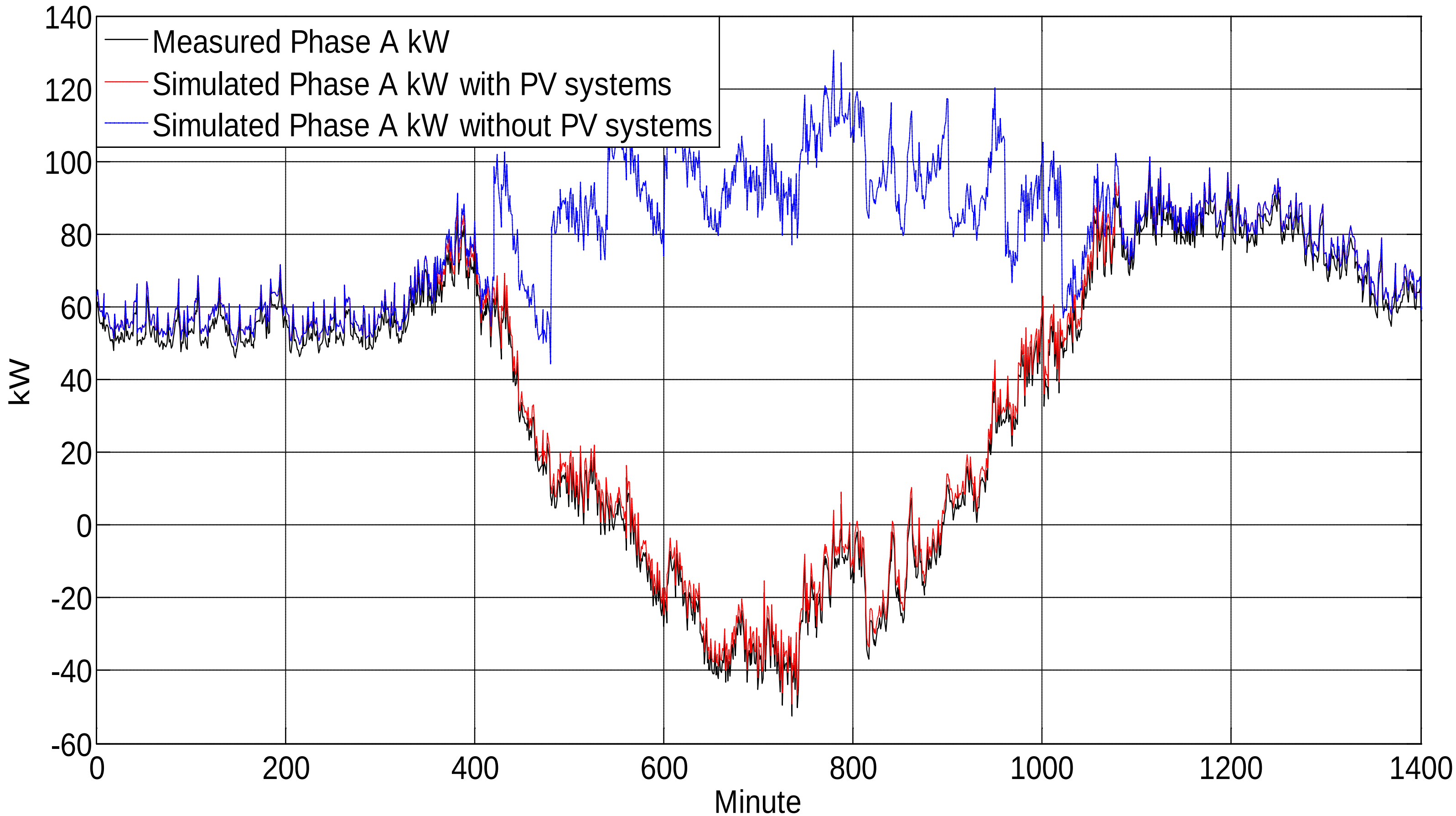
- Measured and simulated 1-min interval voltage at DAS 05 (middle of the feeder) on 9/25/2012



RMS error over the day: Phase A: 0.027 kV Phase B: 0.034 kV Phase C: 0.065 kV (<1%)

Time series analysis with and without PV

Measured and simulated 1-min interval kW plot of phase A at DAS04 over a day compared with simulated results of no PV scenario



Outline

- Test feeder details
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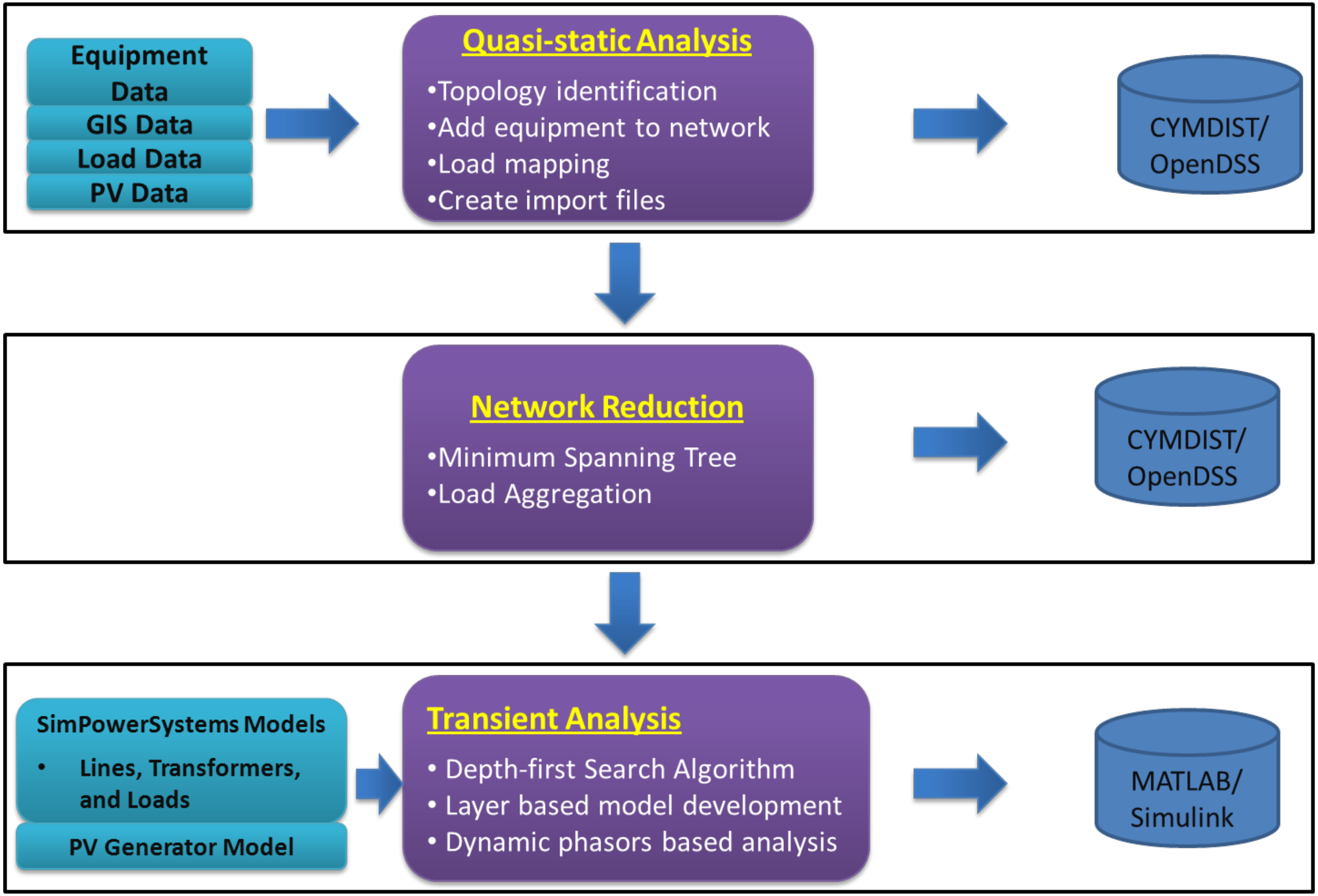
- Modeling in transient analysis tools
  - Network reduction
  - Validation of dynamic phasor solvers in MATLAB/Simulink
  - Automated model development in MATLAB/Simulink

Approach for dynamic modeling

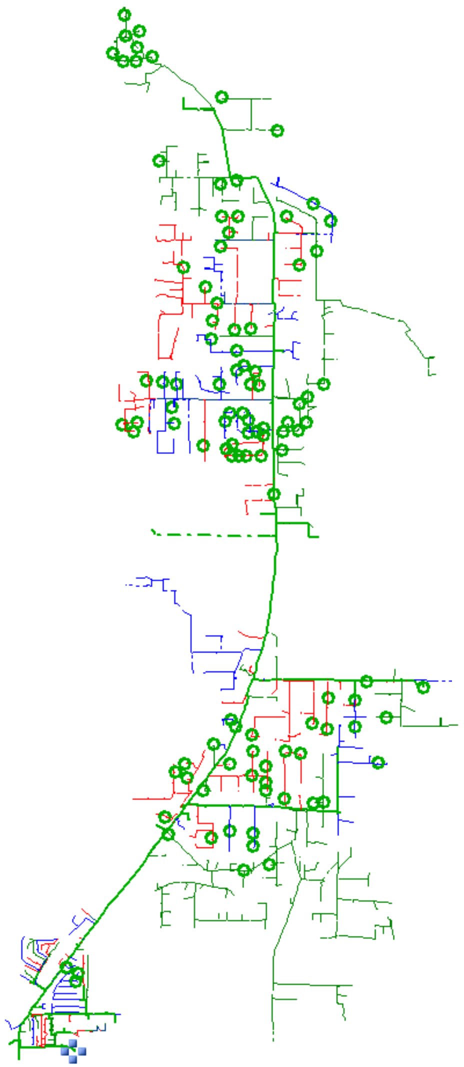


Network reduction approach

- Minimum Spanning Tree algorithm to reduce the feeder model
  - The algorithm identifies the nearest three-phase section for each load and PV generator.
  - Aggregates all the loads, without PV generators, for each phase and links it to the nearest three-phase section
  - Retains all the loads which have PV generators associated, since the final goal is to study the dynamic impact of PV inverters on the distribution system

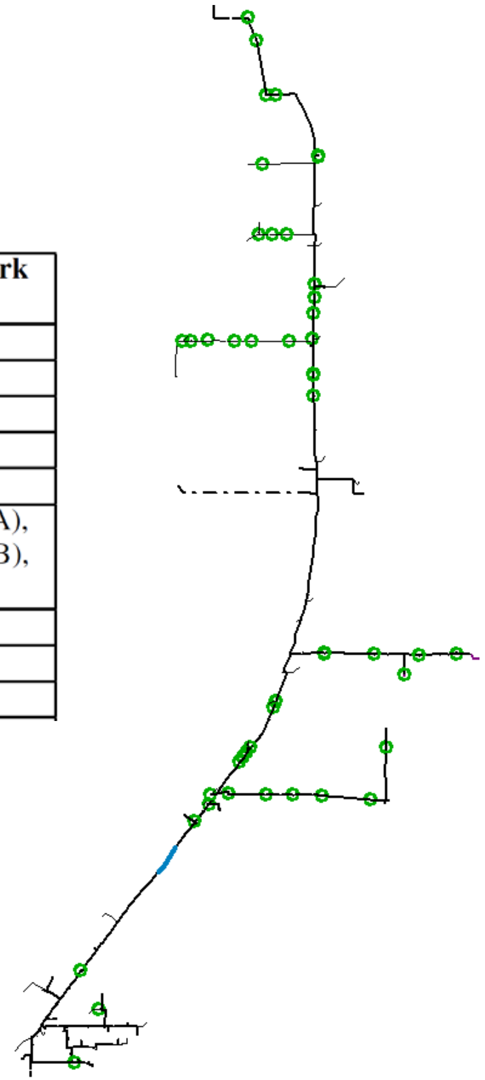
Result of network reduction

Full model

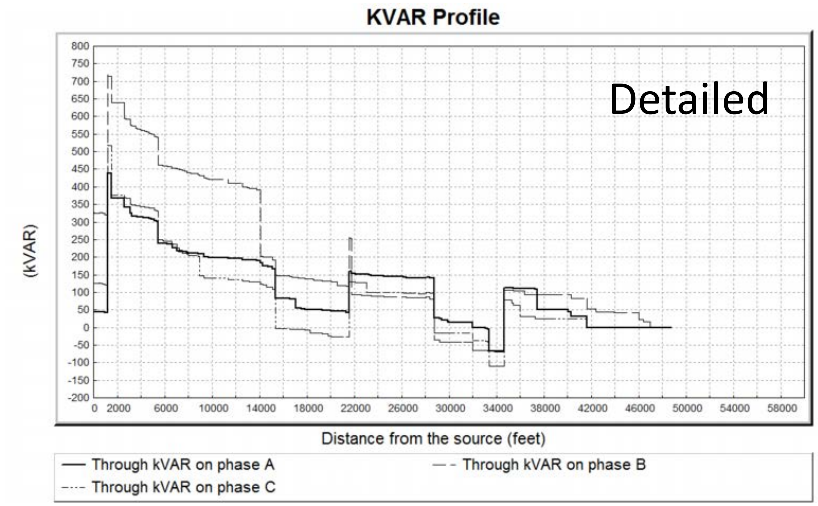


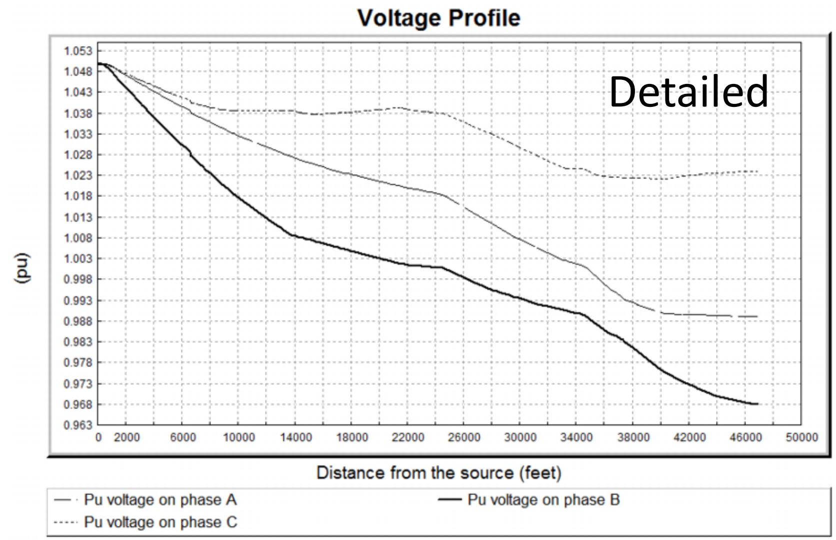
Device	Original network	After network reduction
Number of nodes	3032	738
Number of sections	4094	1142
Number of Transformers	929	174
Number of PV generators	107	107
Number of Loads	921	287
Current drawn from the sub-station (Amps)	226.9(Phase A), 284.9(Phase B), 246.1(Phase C)	231.7(Phase A), 281.8(Phase B), 251(Phase B)
Line losses (kW)	119.97	118.07
Cable losses (kW)	4.74	3.27
Transformer losses (kW)	57.29	15.55

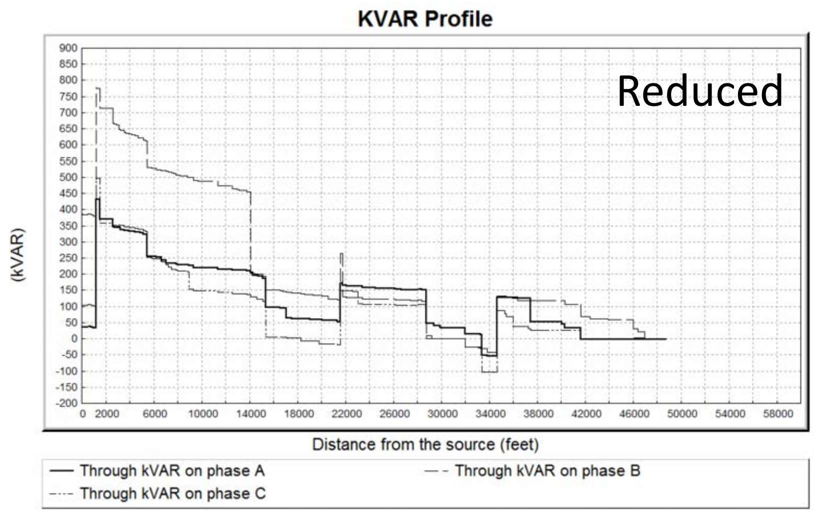
Reduced model

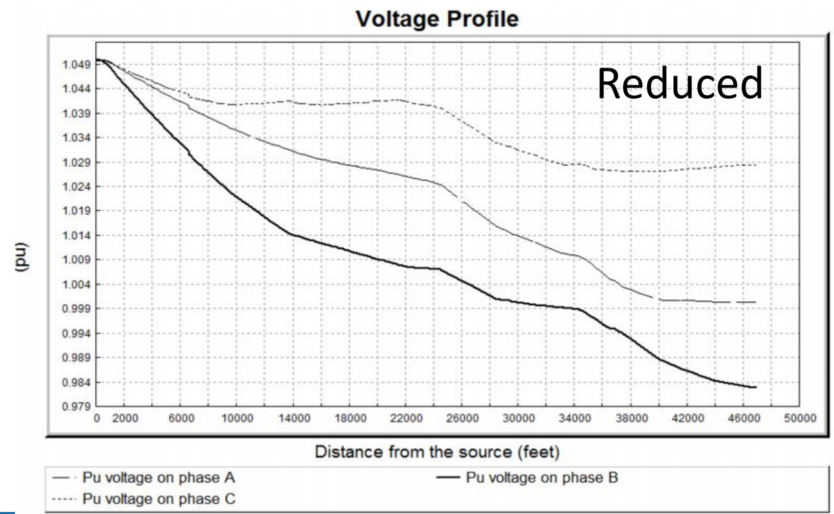


Comparison of the detailed and reduced feeder models



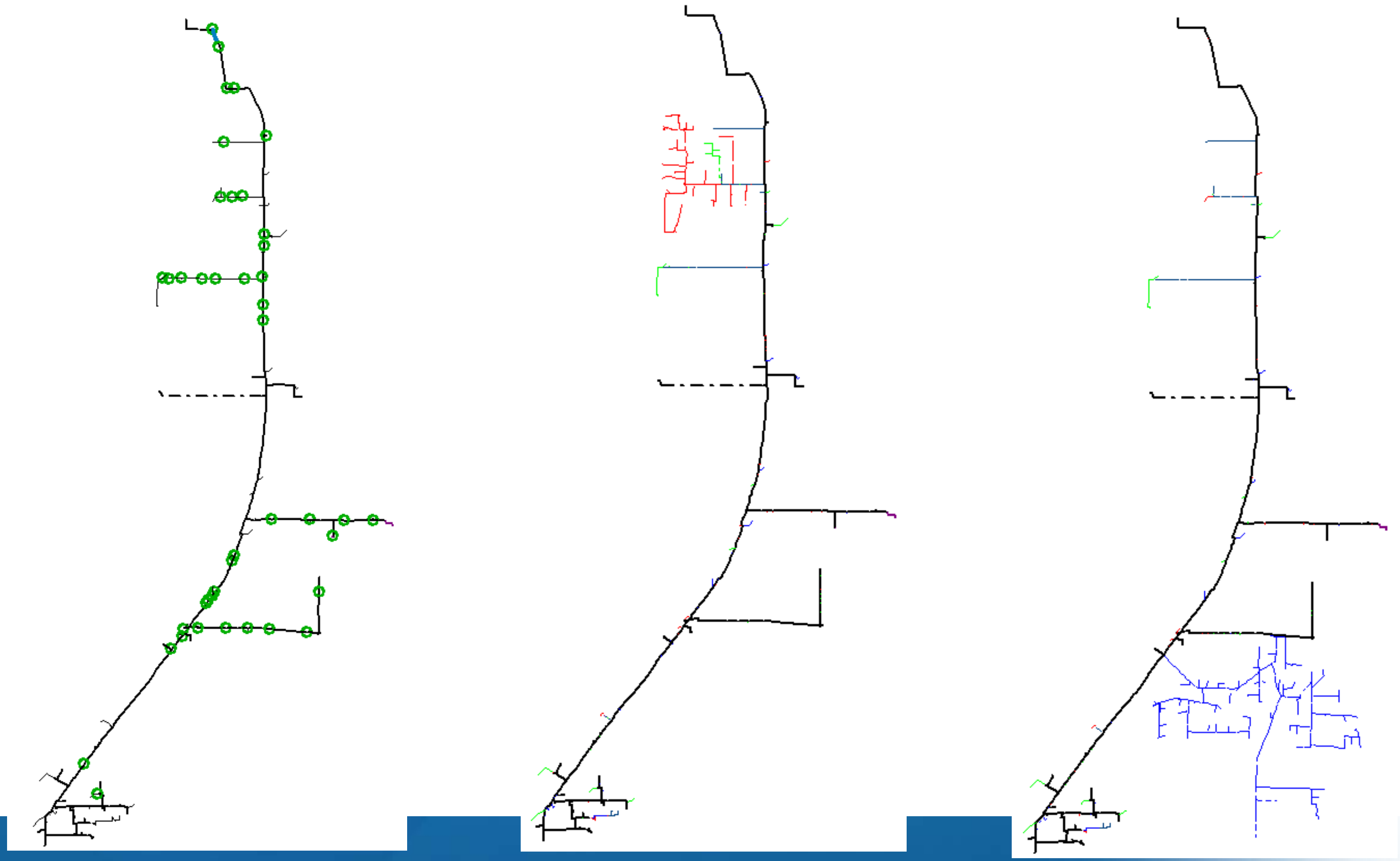






Network reduction

- Tool also allows to selectively retain a section of the feeder in full detail depending on a given study objective (Ex: lateral microgrid)



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Dynamic phasor method

- Dynamic phasor is a general averaging procedure applicable to a broad class of circuits and systems
- The dynamic phasor method is based on the fact that the waveform $x(\cdot)$ can be approximated on the time interval $[t-T, t]$ to arbitrary accuracy with a Fourier series representation of the form

$$x(t-T+\tau) = \sum_k \langle x \rangle_k(t) e^{jk\omega_s(t-T+\tau)}$$

- where the sum is over all integers k (but typically a very small subset), $\omega_s = \frac{2\pi}{T}, \tau \in [0, T]$, and $\langle x \rangle_k(t)$ are the complex Fourier coefficients.

$$\langle x \rangle_k(t) = \frac{1}{T} \int_{t-T}^{t} x(t-T+\tau) e^{-jk\omega_s(t-T+\tau)} d\tau$$

- The analysis computes the time-evolution of the Fourier series coefficients as the window of length T slides over the actual waveform; transients can be interpreted in terms of envelop variation

Reference: S. R. Sanders, J. M. Noworolski, X. Z. Liu, and G. C. Verghese, "Generalized averaging method for power conversion circuits," *Power Electronics, IEEE Transactions on*, vol. 6, pp. 251-259, 1991.

Dynamic phasor method

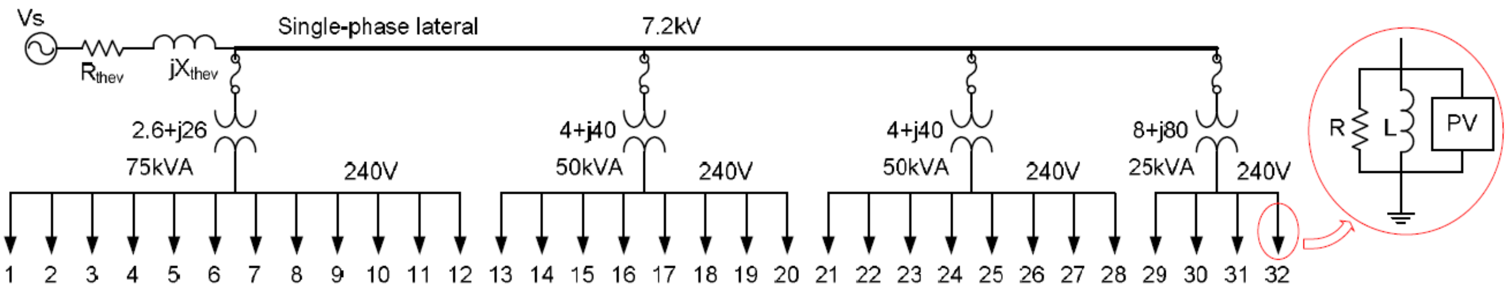
- Derivative of the k^{th} dynamic phasor coefficient

$$\frac{d\langle x_k \rangle}{dt} = \left\langle \frac{dx}{dt} \right\rangle_k - jk\omega_s \langle x_k \rangle$$

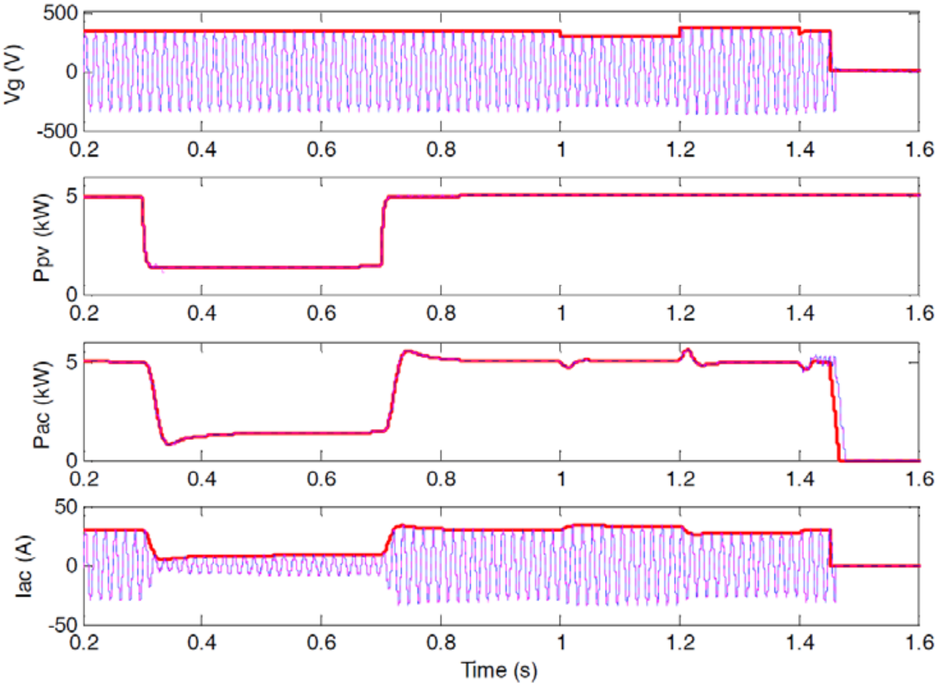
- Multiplication in time-domain involves convolution in phasor domain

$$\langle xy \rangle_k = \sum_l \langle x \rangle_{k-l} \langle y \rangle_l$$

An example dynamic phasor analysis

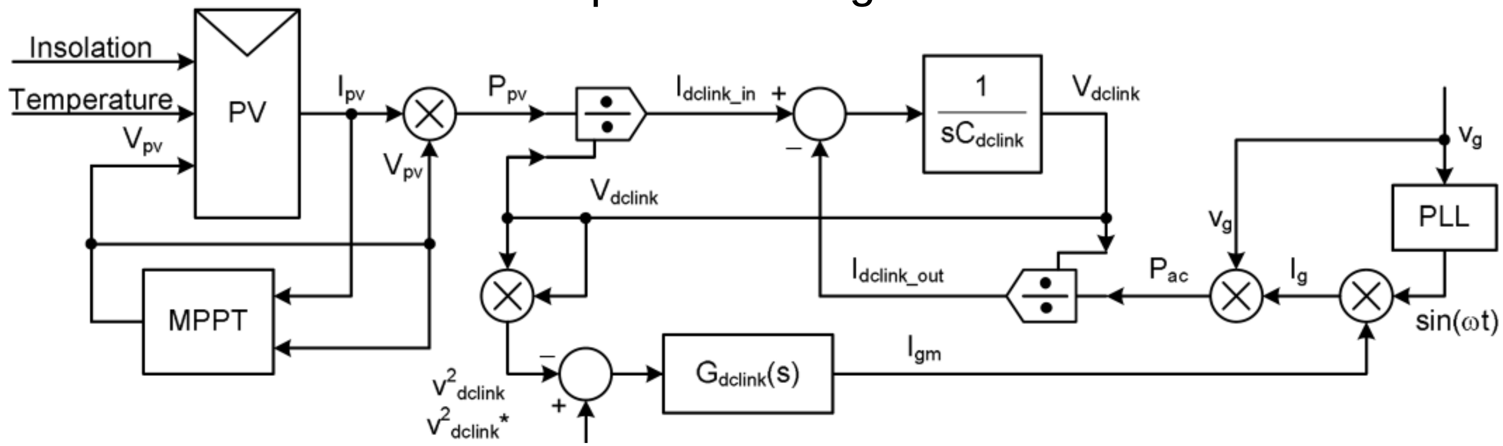


- sudden change in insolation from 100% to 40% at t=0.3s.
- sudden change in insolation from 40% back to 100% at t=0.7s
- step change in *Vs* from 1 p.u. to 0.9 p.u. at t=1s
- step change in *Vs* from 0.9 p.u. to 1.1 p.u. at t=1.2s

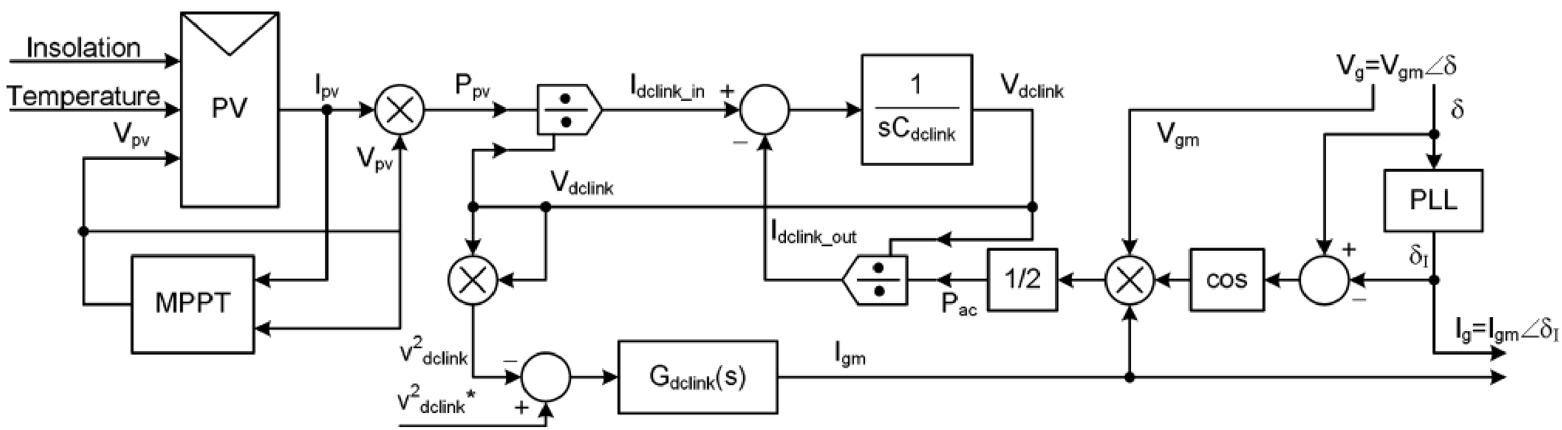


Models of PV generators

Simplified average model



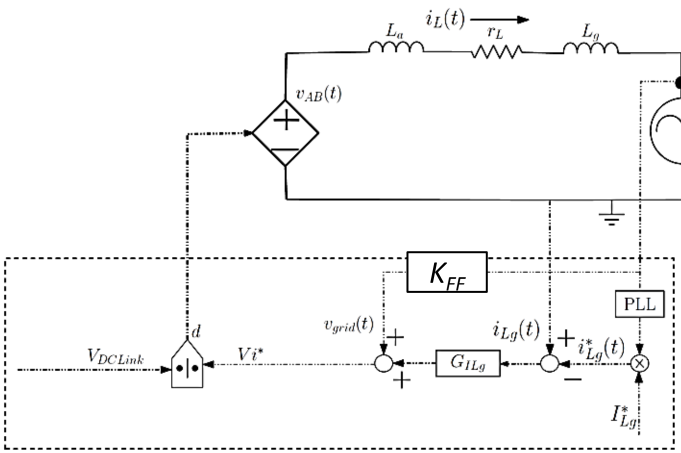
Model for phasor analysis



Dynamic phasor example

Time domain model

$$L\,\frac{di_L}{dt} + r_L\, i_L(t) + v_{grid}(t) = v_{AB}(t) \;\Longrightarrow$$



$$G_{iLg}(s) = \frac{K(1+ {}^{s}/_{\omega_z})}{(1+ {}^{s}/_{\omega_p})}\,, \omega = 2\pi 60$$

$$v_{AB}(t) = m\sin(\omega t + \theta)\, V_{DCLink}$$

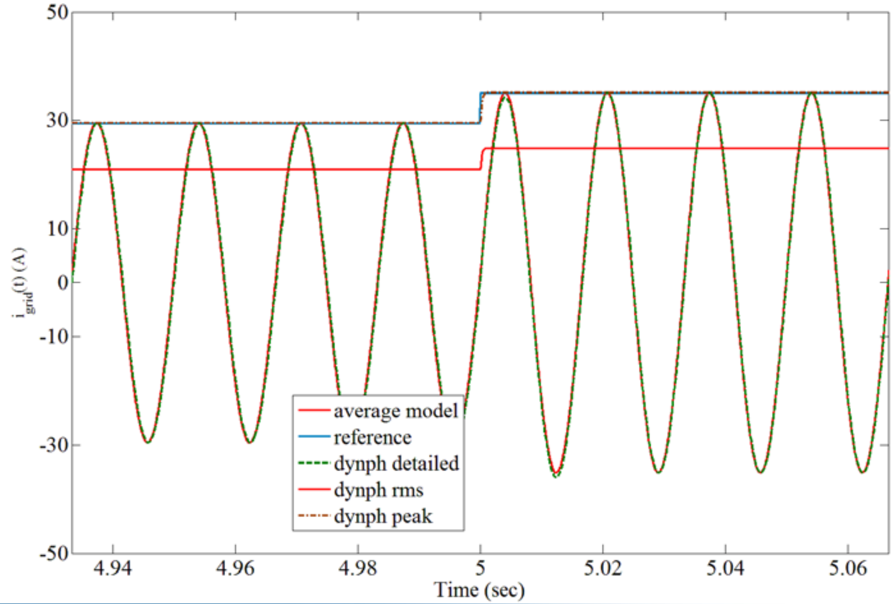
*Superscripts R and I in phasor model refer to real and imaginary components respectively

Dynamic phasor model*

$$\frac{d\langle i_L\rangle_1^R}{dt} = \omega\,\langle i_L\rangle_1^I + \frac{1}{L}\left(-r_L\,\langle i_L\rangle_1^R - \frac{m\sin(\theta)V_{dc}}{2}\right)$$

$$\frac{d\langle i_L\rangle_1^I}{dt} = -\,\omega\,\langle i_L\rangle_1^R + \frac{1}{L}\left(-r_L\,\langle i_L\rangle_1^I - \langle\frac{V_{grid}}{2}\rangle_1^I - \frac{m\,V_{DC}\,\cos(\theta)}{2}\right)$$

Response to change in grid current reference



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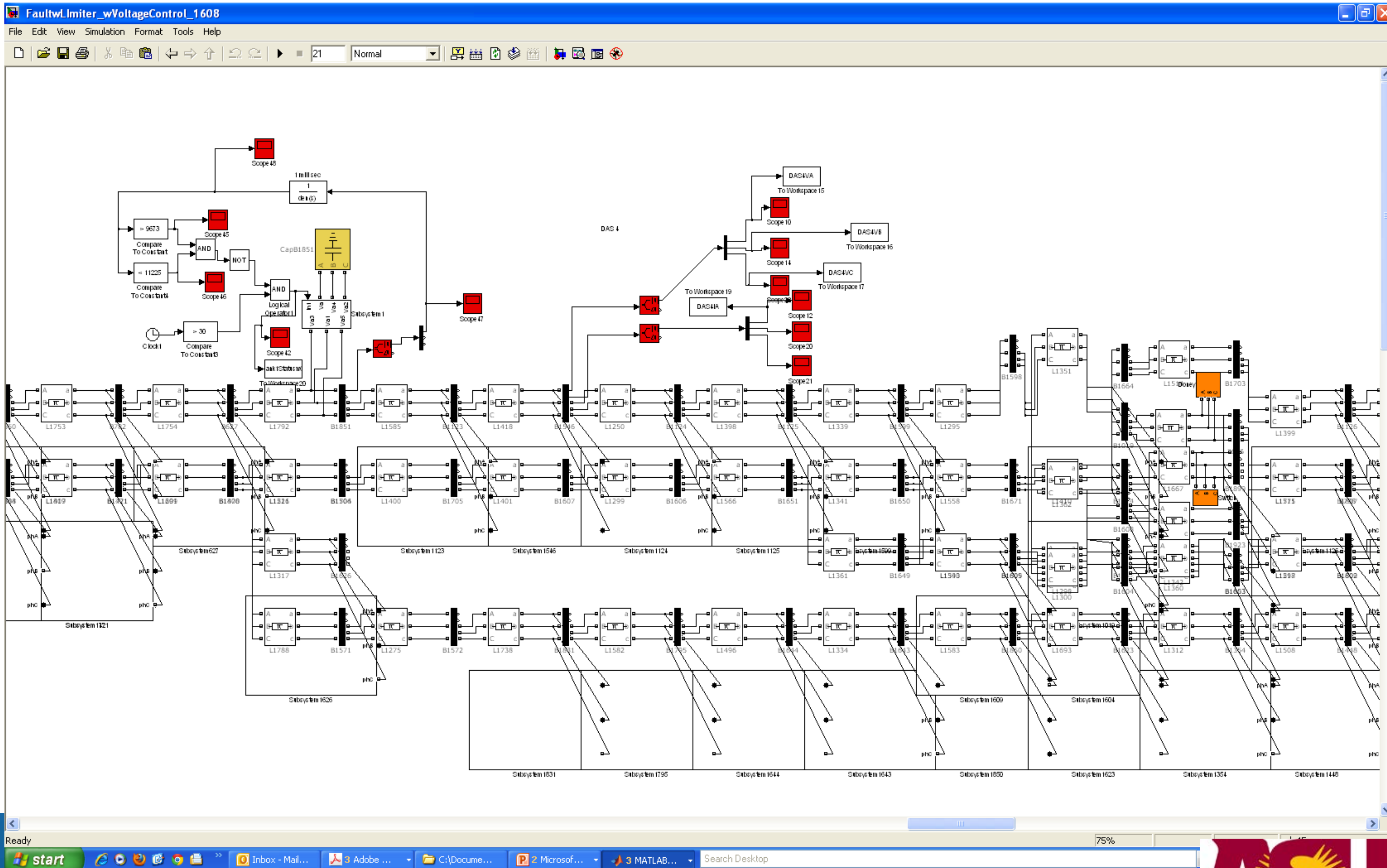
Modeling in SimPowerSystem

- Automation of schematic development from GIS for transient analysis tool using depth-first search algorithm
- SimPowerSystems has an in-built dynamic phasor solver (dynamic phasor models for other transient tools also developed)
- Possible transient studies: impact of cloud and high ramp rates, impact on cap banks, control interaction, islanding
- Example: transient simulation with many step changes in insolation and load over 70 s requires 15 min of CPU time

Automated model construction in Simulink from GIS

- Depth-first search algorithm has been used for exploring the feeder
- Layer based approach
  - Layer 1 contains all the three-phase distribution lines
  - Layer 2 contains the subsystems consisting of all the distribution transformers, loads, and single-phase PV generators
- All relevant control loops in inverter are modeled in detail
  - DC link voltage controller, PLL, island detection
  - Current loop considered ideal due to its high bandwidth

A small part of Simpowersystem model



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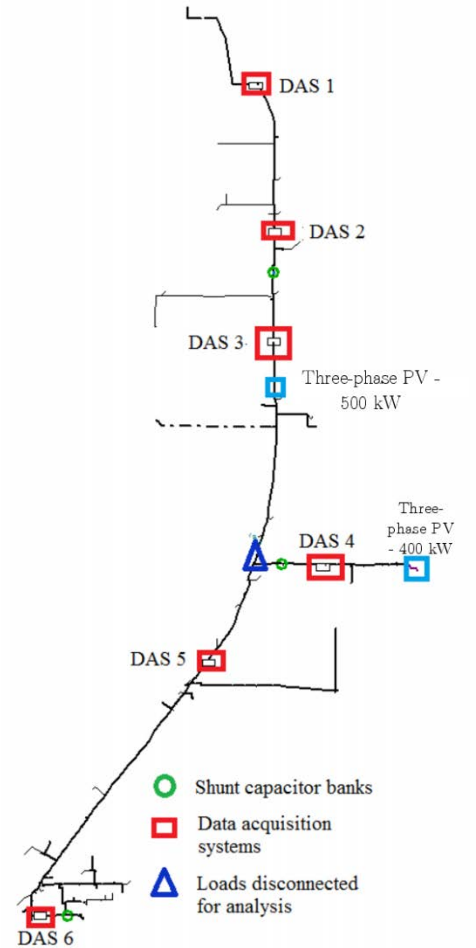
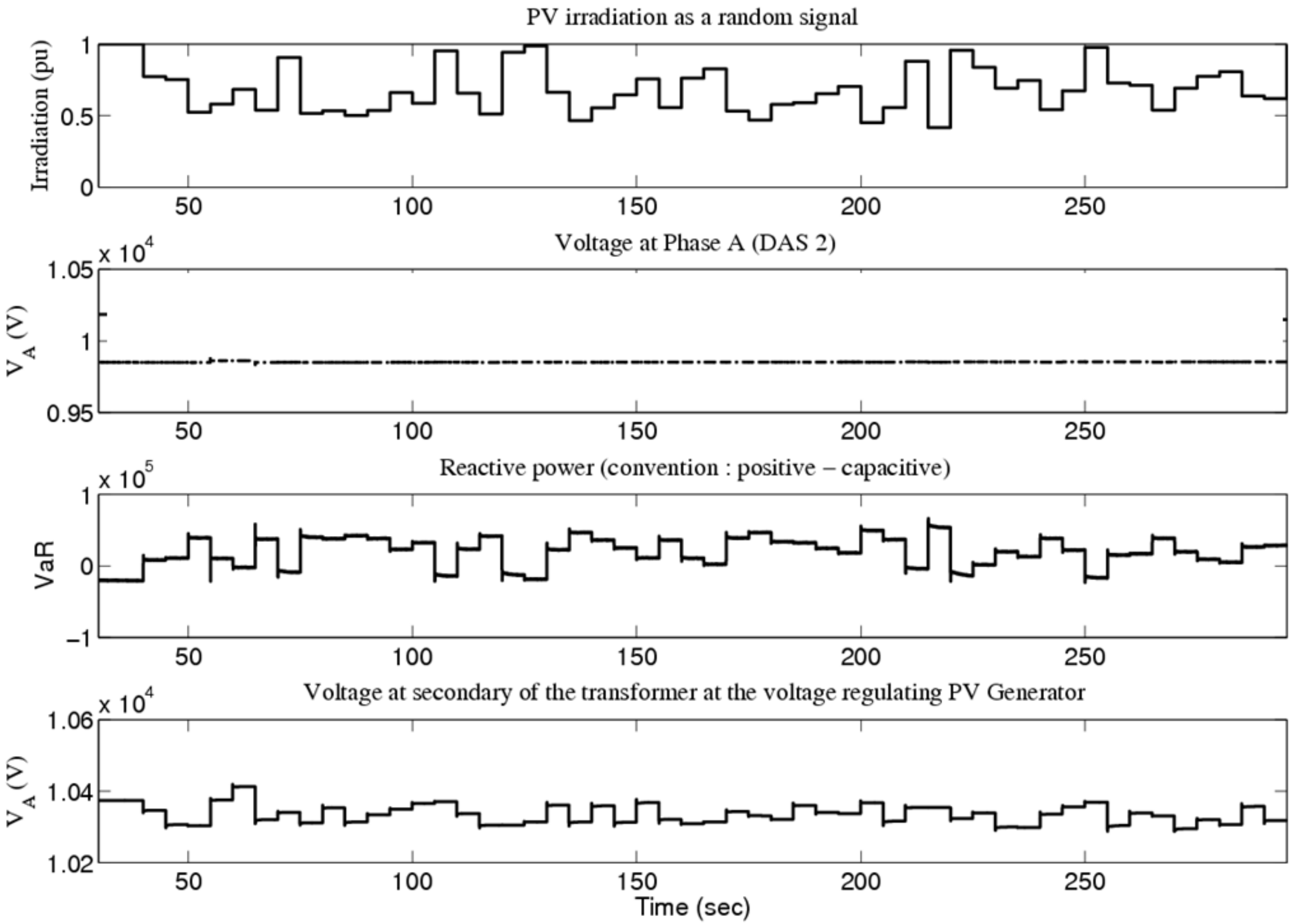
  – Dynamic analysis examples

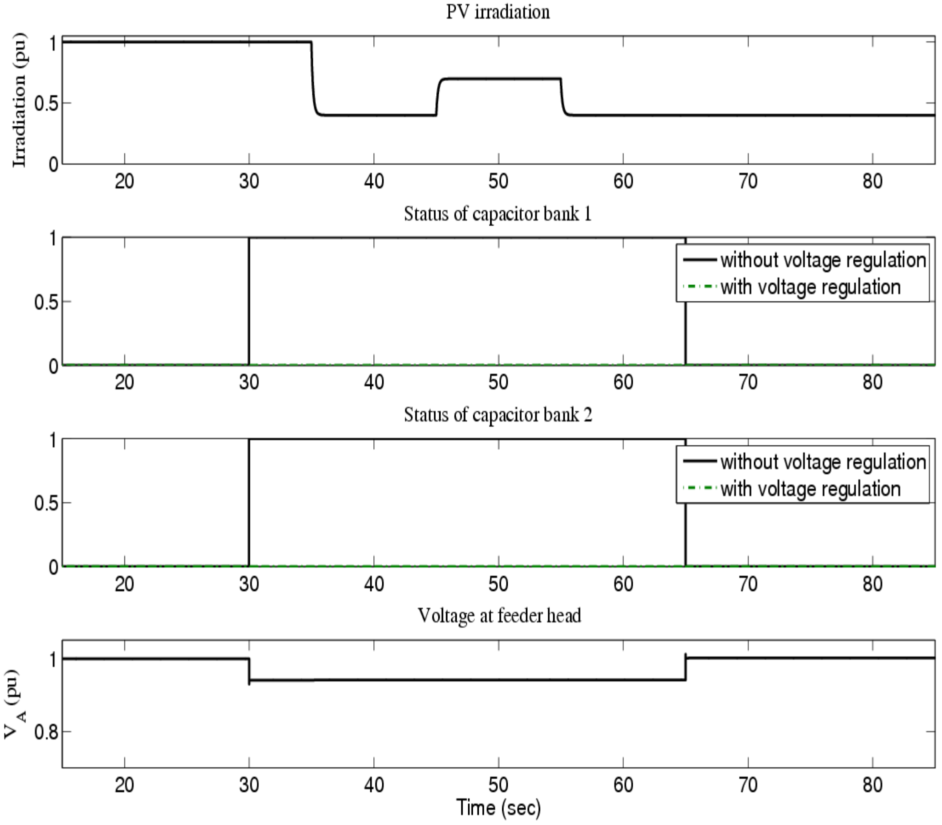
Example results: Random variation in PV and voltage regulation by DG

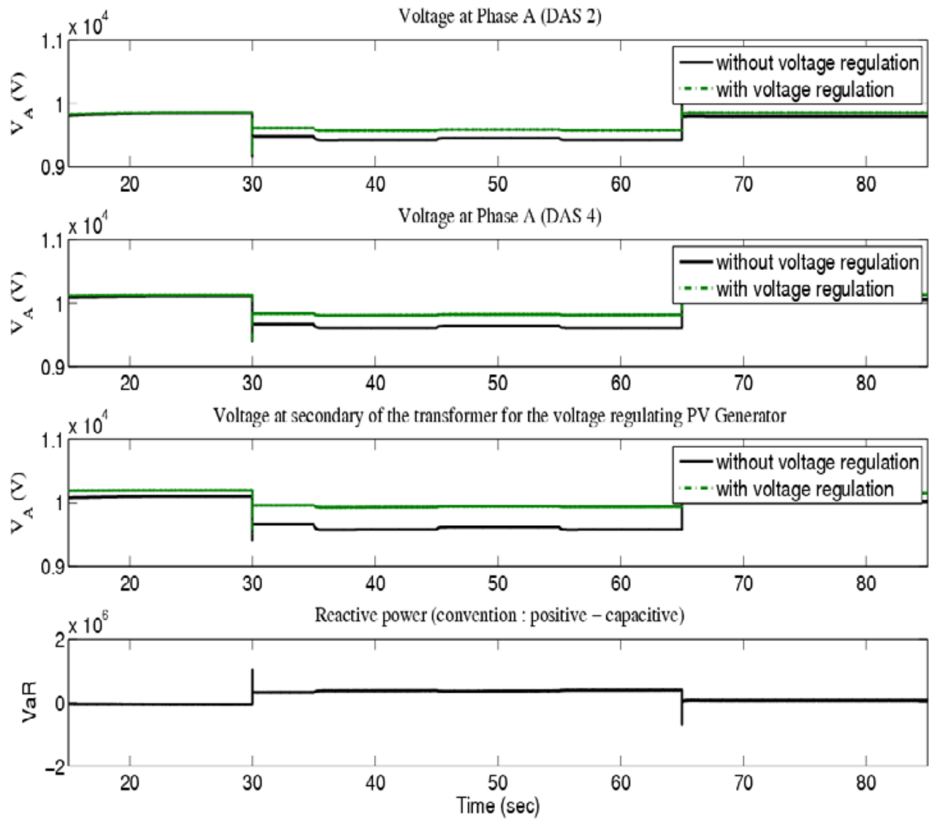




Example results – Cap bank operation

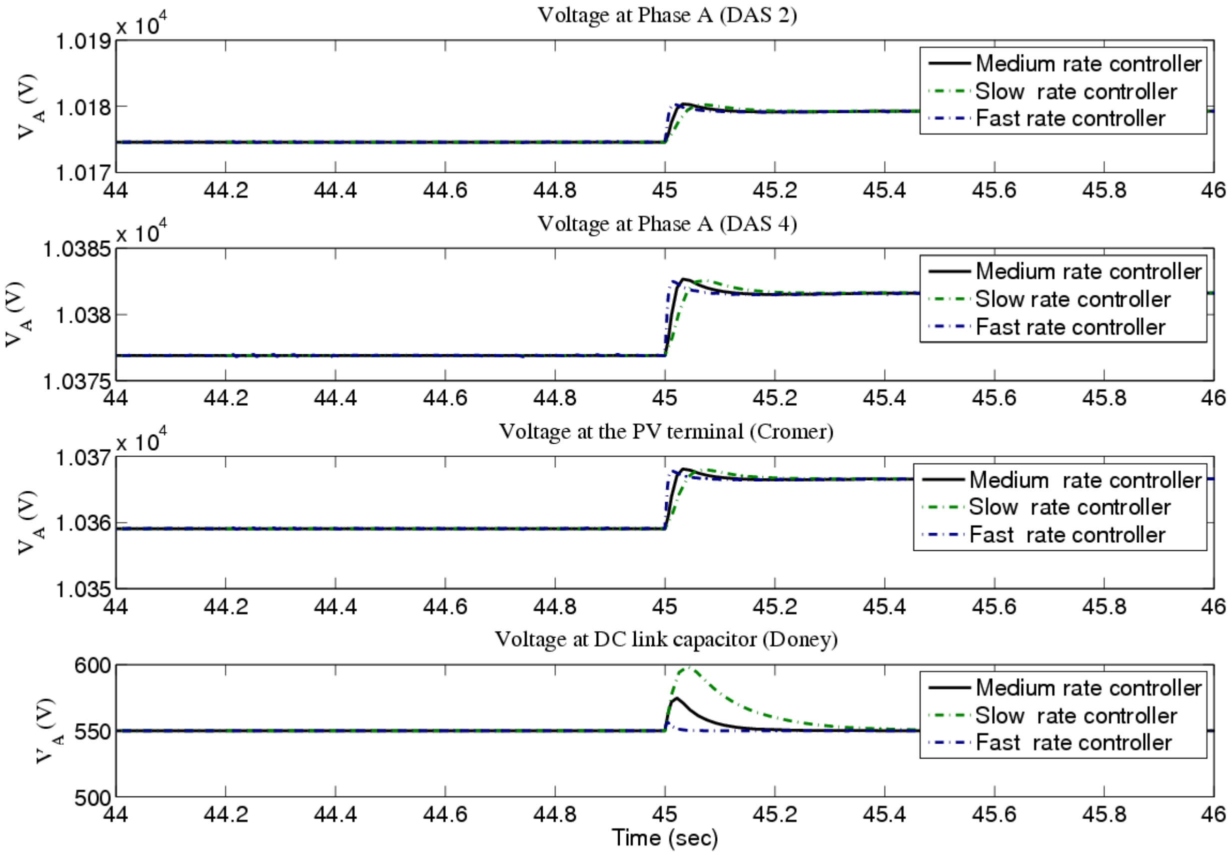
- Change in substation voltage (1 to 0.95 pu) at 30s and (0.95 to 1 pu) at 65s
- Change in solar insolation at 35s, 45s and 55s





Example results: Different controller bandwidths

- Change in solar insolation from 70% to 90% at 45 s
- Performance with different DC link voltage controller bandwidths (only maximum power tracking control)



Summary

- Steady-state (snap shot) voltage and fault analysis with PV using CYMDIST and OpenDSS
- Extensive time series analysis using OpenDSS over longer duration and field validation
- Dynamic phasor approach in Simulink for dynamic analysis including control functions of PV inverters in large distribution systems (typically with reduced network model)
- Software tools developed for automation that can be adapted for other feeders and other studies