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

Raja Ayyanar

School of Electrical, Computer and Energy Engineering Arizona State University

> PSERC Webinar October 2, 2012





Acknowledgements

High Penetration of Photovoltaic Generation Study – Flagstaff Community Power: DOE Grant #: DE-EE0002060

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

Some of the work related to OpenDSS and inverter modeling supported by the PSERC project:

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

Faculty Raja Ayyanar Gerald T Heydt Vijay Vittal

Post doc Xiaolin Mao

Graduate students

Yingying Tang Adarsh Nagarajan Ziwei Yu Parag Mitra



This material is based upon work supported by the Department of Energy under Award Number(s) DE-EE0002060.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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



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



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





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



Modeling Process



GIS Data—**MDB File**

💽 🖟 🔊 - 🔍 - 🔍 - Prima	ary1 - Microsoft Ac	cess	Table Tools						x
🐸 🕼 Home Create Exter	mal Data 👘 Databa	se Tools	Datasheet						» x
All Access Objects 💿 <	OBJECTID 🧃	SHAP	e 🔹 sub,	TYPE - NEUTRALPO: -	PHASE -	NUMBEL - CONDUCTOR: -	OPERATING - S	SHAPE_Leng1	- 🔺
Tables 🛛 🕆		1 binary	data	9 XX	В	1 UA1/OT	7200	4060.823595	1
💷 Buswork		2 binary	data 🛛	4 NC	В	1 2R	7200	4.713639191	6
Buswork SHAPE Index		3 binary	data	4 NC	В	1 2R	7200	980.5205984	.0
	· · · · · · · · · · · · · · · · · · ·	4 binary	data 🛛	4 NC	В	1 R002₩	7200	13.06887599	2
		5 binary	data 🛛	9	В	1 UA1/0Z	7200	346.3392582	8
CabinetSwitch_SHAPE_Index		6 binary	data 🛛	4 NC	В	1 R002₩	7200	17.75230189	8
CapacitorBank		7 binary	data	9	B	1 UA1/0Z	7200	32.87005438	9
CapacitorBank SHAPE Index		8 binary	'data	9	B	1 UA1/0Z	7200	897.1400074	2
		9 binary	data	9	В	1 UA1/0Z	7200	311.3571814	6
	1	0 binary	data Jata	9	В	1 UA1/0T	7200	339.2356517	<u>7</u>
E Fuse_SHAPE_Index	1	l binary	' data	9	В	1 UA1/UI	7200	328.9337576	4
🛄 OCR	1	2 binary 2 binary	data data	9	D	1 UA1/01	7200	090.9986490 000.91990E1	0
OCR_SHAPE_Index	1	s binary	data data	9 4 NC	P	1 UAI/UI 1 R002W	7200	299.3133901	0
Primary 1	1	f Dinary 5 binary	data	4 NC		1 K0024	1200	11. 82132319	4
Drimanul SHADE Index	1	6 hinary	data	9			24		+⇒ ×
	1	7 hinary	data	9 88	1 () () () () () () () () () (2010 101			-
SelectedObjects	1	8 hinary	data	9 XX			SUBTYPECD	24 - OH APS XFR Bank -	
Selections	1	9 binarv	data data	9	12	and the second		Three Units	4
🛄 Switch	2	0 binarv	data	9		a / 1/2 a	APSCODE	7185	-
Switch SHAPE Index	2	1 binary	data	9		- Martin Bar	PCODE	SFFF09	-
	2	2 binary	data	9	\checkmark		PHA SE SPRE SENT	3/Phase	-
	2	3 binary	data	9		III Starting	OPERATING	present	
SwitchingCabinet_SHAPE_Index	2	4 binary	data	9	7			7200 Volts	- 1
📰 Transformer	2	5 binary	data 🛛	9		11 A Bell	LOWSIDEVOLTAGE	120-208 Volts	
Transformer_SHAPE_Index	2	6 binary	[,] data	9	2111		HIGHSIDECONNECTION	Wye	
TransformerLinit	2	7 binary	data	4 NC				Connected	-
	2	8 binary	data 🛛	9	611.0		TAPSETTING	No Taps	-
VoltageRegulator	2	9 binary	data 🛛	4 NC			TAG	NETR15445935	
VoltageRegulator_SHAPE_Index	3	0 binary	data	9	100		UFO_ID	15445935	
	3	1 binary	data	9 XX	00	Martin Contractor	FEEDERID	SV 04	~
	3	2 binary	data	4 NC			3 🐮 🖂		
	Record: M 4 1 of	3 hinary 1810 🕨 🕨	· datal N 🙀 📉 No	Filter Search	Position 35	14'03 N 111'34'27'W	A PARTY	Sourc	e: USGS
Datasheet View			1				Num L	ock 🔲 🔀 🕮	٠

Feeder Network Model Development

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





Conductor Modeling

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

Conductor types per GIS

	Primary			Neutral			
UG or OH	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

	Line	APS							AC Res	AC Res
UG/	type per	conductor	Relevant				Dia	GMR	@25C	@50C
OH	GIS	code	Standard	Material	Size	Stranding	(In.)	(In.)	Ohm/mile	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

Conductor		<u>? ×</u>	5 ₽	acing		<u>? × </u>
■ Conductor General Equipment List General 14-AWG-CU A300 A336V A4 A336V A4 A336V M A795V CO C006V No C006V No C006V No R002V N R002W V R004W C R30V R36V R36V R R36V R W004W R W004W R	rai Comments onstruction Details Code Word: Construction Type: Material: Standard: Standard: Standard: Nominal Rating Nominal Rating (Winter): Withstand Rating: Outside Diameter: GMR: R 25°C: R 50°C: Otection Settings	2 × UA1/0 Aluminum Clad Steel Wire ▼ Aluminum ▼ Size: Undefined ▼ 1000.0 Amps 1000.0 Amps 0.325 inch 0.0 inch 0.325 inch 0.8823 ohms/mi 0.9699 ohms/mi		aupment List 135 3130-3133-1-CLEAN 3130-3133-2-CLEAN 5100-3133-3-CLEAN 3407-3409-2-FLAT 3407-3409-3-FLAT DEFAULT		General Comments GMD Phase 6.60424 feet Phase-neutral 6.65547 feet Positions of conductors Horizontal Vertical 1 3.5833 29.41667 2 3.5833 31.91667 3 3.5833 31.91667 M 0.0 37.6667 GMD Calculation
Conductor window in CYMI	DIST		ſ		Sec. Find	
		OK Cancel				OK Cancel

verhead Line Balanced			? ×
quipment List	General Comments		
+ 🚯 🖪	Candustan		. 1
	Conductors		
OH 1 2R	Phase:	R002V 💌 📢	
OH_1_4ACW			
OH_1_4R	Neutral:	R002V 🗾 📡	
OH_1_6ACW			
OH_1_A477V	Spacing:	3130-3133-3-CLEAN	
OH_1_A795V			
OH_1_C004V	Ampacity / Phase		1
OH_1_C006V	C. mana	1000.0 Amps	
	Summer:	Amps	
OH 1 P795V	Winter:	1000.0 Amps	
		· · · · · · · · · · · · · · · · · · ·	
OH 2 2R	Equivalent Impedances		
OH 2 6ACW		R X B	
OH_3_2R		ohms/mi ohms/mi uS/mi	
OH_3_3/0A	Pocitive Sequence:	1 69 0 8037 5 421	
OH_3_3/0R	Positive bequerice.	1.07 0.0937 0.421	
OH_3_477A	Zero Sequence:	2.3436 2.5247 3.0243 📻	
OH_3_6			
OH_3_795A		Block impedance update	
	0		
	Overl	nead line impedances	
G Find		·	
		OK Cancel	

Select Circuit Type 3 - phases circuit Image: Select Circuit Imad	0.325 inch 0.132 inch 0.9699 ohms/mi Characteristics Inch 0.0641 inch 0.02496 inch 14.8722 ohms/mi ic wires 10
Equivalent Impedances R X Z1 0.9782 0.2562 ohms/mi Z0 2.2637 0.6437 ohms/mi Susceptance 93.1822 uS/mi	
Underground cable impedances	OK Cancel

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 MATLAB Program **CYMDIST** Model GIS Data



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

Equipment List		Concept Le 20021			
	+ 🌇 🗄	Comments			
CANADIAN CROMER DEFAULT DONEYPARK		Rated Power: Rated Voltage: Active Generation: Power Factor: Fault Contribution: ANSI Motor Group: Converter:	400.0 13.8 400.0 100.0 200.0 Automatic Others	kvA kvLL kW % % of rated current	>
		Description			
	Find				2

Generator window in CYMDIST



Screenshot of PVs in CYMDIST Model





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



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

Total measured PVoutput

Penetration =

Measured feeder head load + 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)







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)



• 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







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)





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



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





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 Coordination⁴³



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

	With	out PV	With PV		
	Fault	Operating	Fault	Operating	
	current	time	current	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 Coordination⁴⁴

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



	Downstr	eam fault	Upstrea	am fault
	Fault	Fault Operating		Operating
	current	time	current	time
Fuse X04	55.45 A	6.99 s	1.11 A	No
				operation
Fuse K25	55.09 A	No	478.67 A	0.098 s
		operation		



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 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

45



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



	phase	ABC	849.88	857.44	868.06	789.58	804.78	811.98
Phase		AB	775.46	708.38	182.21	686.23	691.28	98.29
faults	s Line-to-	BC	162.46	786.34	715.11	73.53	707.14	696.55
	inic	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

