NREL NATIONAL RENEWABLE ENERGY LABORATORY

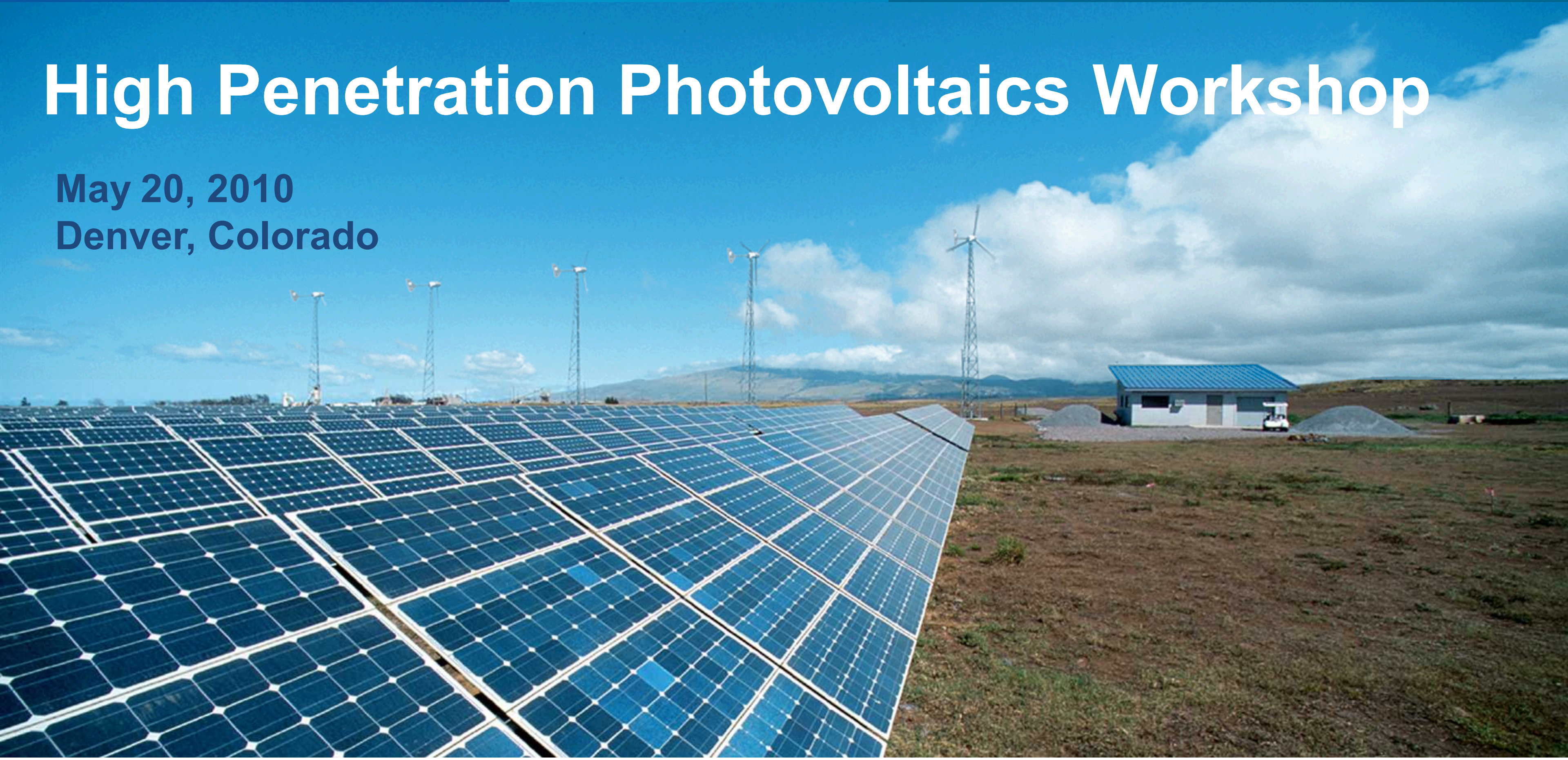
Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

SAND2010-8874P

High Penetration Photovoltaics Workshop

May 20, 2010
Denver, Colorado



Modeling PV Systems in Bulk System Studies

Abraham Ellis, Sandia National Laboratories

aellis@sandia.gov

PV Systems Characteristics

- Different than conventional generators
  - Collector system
  - Converter interface
  - Low short circuit current
  - Zero inertia
  - Non-dispatchable, variable
- Behavior "programmable"
  - Trip thresholds
  - Reactive power
  - Active power

Sandia National Laboratories

Why Are Models Needed?

- Generator Interconnection Studies
- Grid Planning/Expansion Studies
- Evaluation of Future Scenarios

- Key questions addressed by simulation
  - Does the system meet performance standards?
  - How does the addition new equipment affect grid reliability or stability?
  - What system upgrades are needed?

Sandia National Laboratories

Type of Grid Planning Models

- Power flow
  - Overloads, static voltage stability & control
- Dynamic
  - Rotor angle stability, voltage recovery
- Short circuit
  - Breaker duty, protection design/coordination
- Detailed, high-order
  - Plant design, control interaction, harmonics, etc.

Conventional models OK for conventional CSP, but not PV

Sandia National Laboratories

Desirable Characteristics of Models

- NERC Integration of Variable Generation Task Force (IVGTF) has identified the lack of industry-standard validated models as major barrier to renewable energy development

"Validated, generic, non-confidential, and standard power flow and stability (positive-sequence) models for variable generation technologies are needed. Such models should be readily and publicly available to power utilities and all other industry stakeholders. Model parameters should be provided by variable generation manufacturers and a common model validation standard across all technologies should be adopted. The NERC Planning Committee should undertake a review of the appropriate Modeling, Data and Analysis (MOD) Standards to ensure high levels of variable generation can be simulated."

Source: NERC Special Report, Accommodating High Levels of Variable Generation, http://www.nerc.com/files/IVGTF_Report_041609.pdf

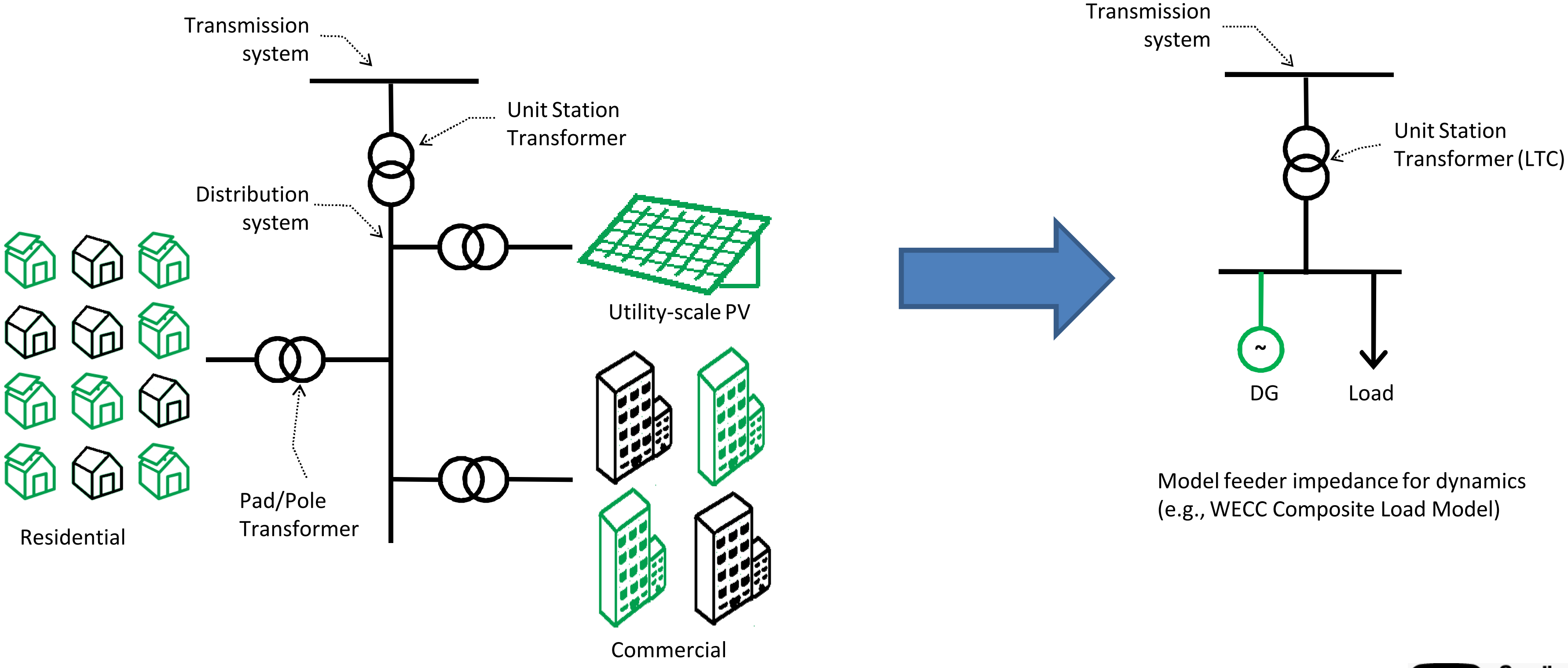
Sandia National Laboratories

WECC REMTF

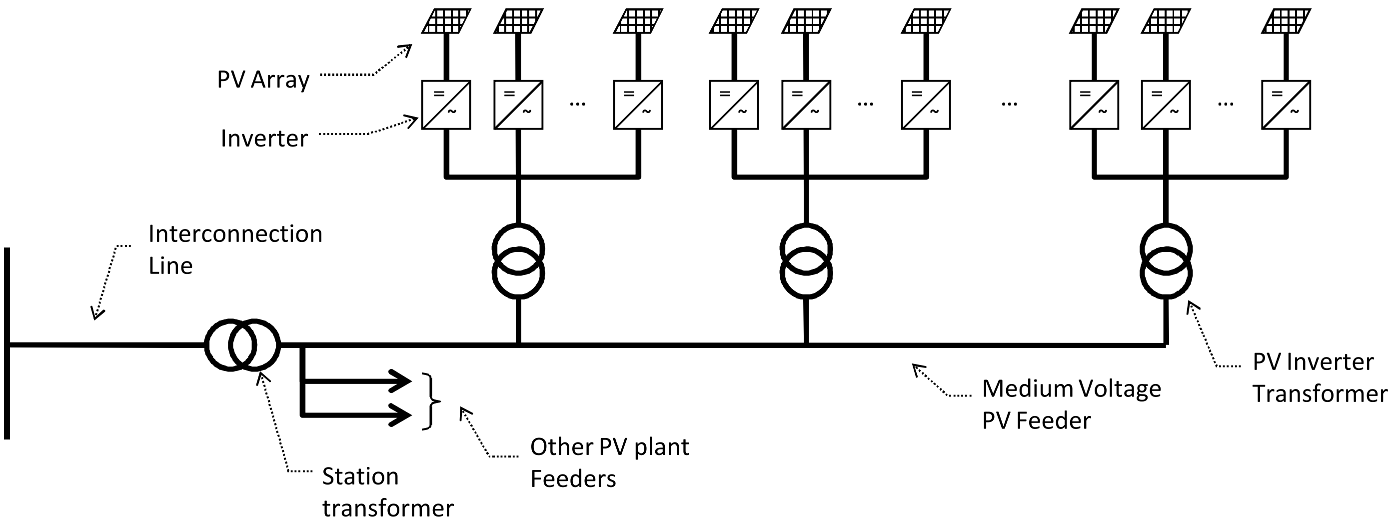
- REMTF Charter
  - Develop validated generic, non-proprietary, positive-sequence power flow and dynamic simulation models for distributed and central-station solar and wind generation for large-scale simulations
  - Issue guidelines, model documentation
  - Coordinate with stakeholders groups
- Current Participants
  - Sandia (lead), NREL, GE, Siemens (program developers), Satcon, SunPower, American Capital Energy, EPRI, NVEnergy, APS, SCE, PG&E, BEW, NPPT

Load Flow Model – Distributed PV

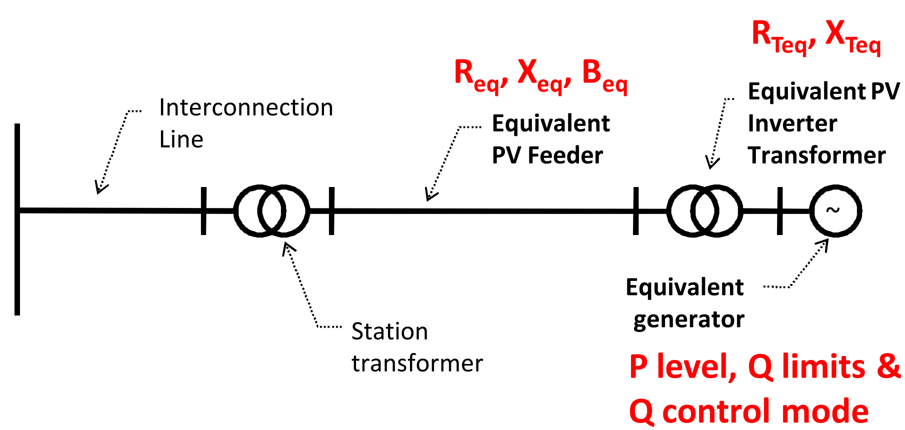
- Need to model effects of distributed PV on bulk grid
- Implement as addition to WECC composite load model



Load Flow Model – Utility-Scale PV Plants



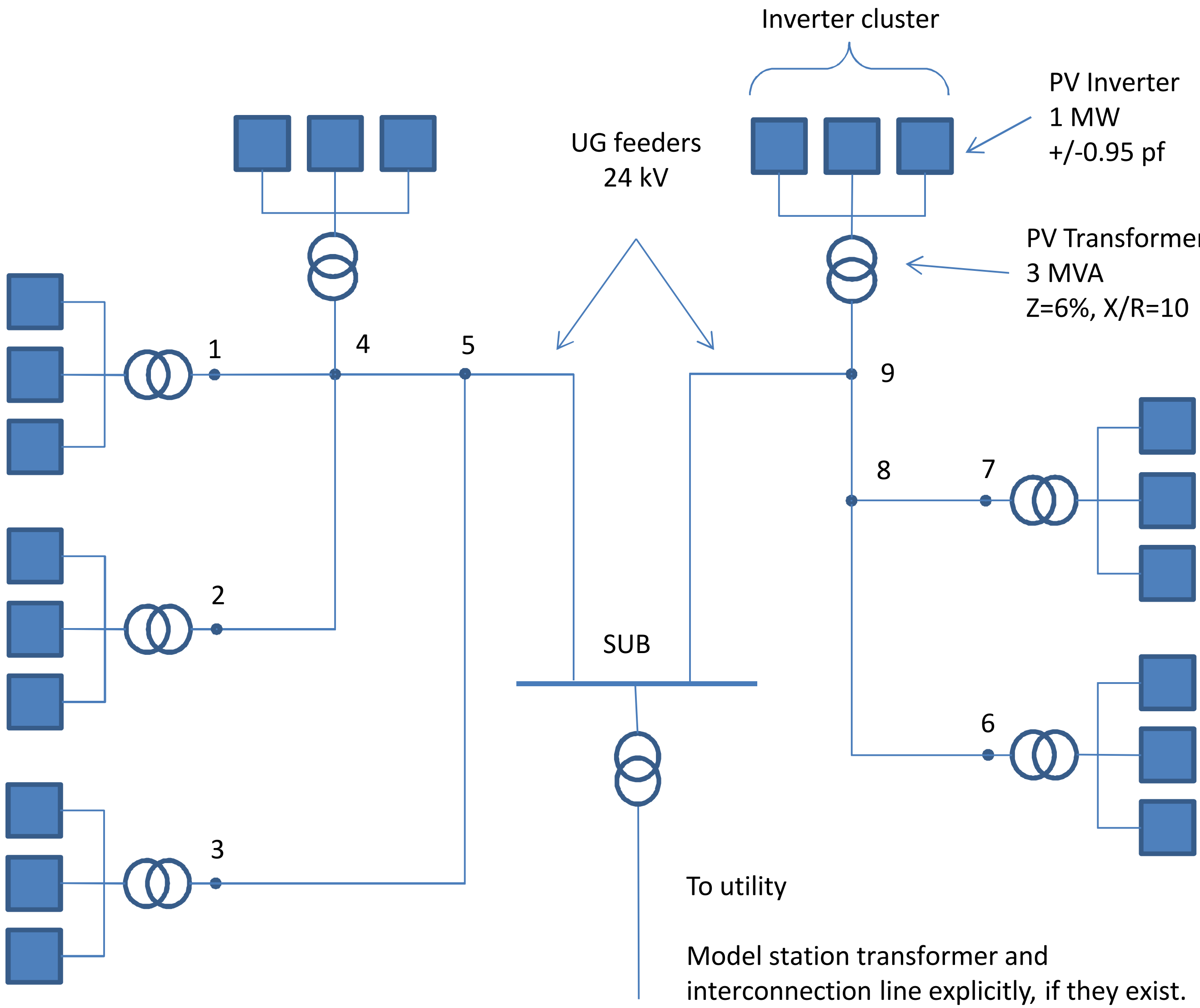
Equivalencing



Model interconnection line and station transformer explicitly, if they exist

Sandia National Laboratories

Example – 21 MW System



Example – 21 MW System

Collector System Equivalent on 100 MVA base, 24 kV

From	To	R	X	B	n	R n^2	X n^2
1	4	0.03682	0.00701	0.000000691	3	0.33136	0.06307
2	4	0.02455	0.00467	0.000001036	3	0.22091	0.04205
4	5	0.02455	0.00467	0.000001036	9	1.98816	0.37843
3	5	0.02557	0.02116	0.000000235	3	0.23016	0.19042
5	**SUB**	**0.02557**	**0.02116**	**0.000000235**	**12**	**3.68251**	**3.04673**
6	8	0.03747	0.00868	0.000000561	3	0.33726	0.07809
7	8	0.02455	0.00467	0.000001036	3	0.22091	0.04205
8	9	0.02109	0.02501	0.000000199	6	0.75925	0.90025
9	**SUB**	**0.02109**	**0.02501**	**0.000000199**	**9**	**1.70831**	**2.02555**

RESULTS

Partial R sum	9.4788
Partial X sum	6.7666
N	21

Collector System Equivalent
(Same units as R, X & B data)

Req	0.021494	pu
Xeq	0.015344	pu
Beq	0.000005	pu

PV Transformer Equivalent

$$Z_{Teq} = \frac{Z_T}{M} = \frac{0.00597 + j0.05970}{7} = 0.00085 + j0.00853$$ pu on 3 MVA base

$$= 0.02843 + j0.28430$$ pu on 100 MVA base

PV Generator Equivalent

$$Pgen = 1\ MW * 21 = 21\ MW$$

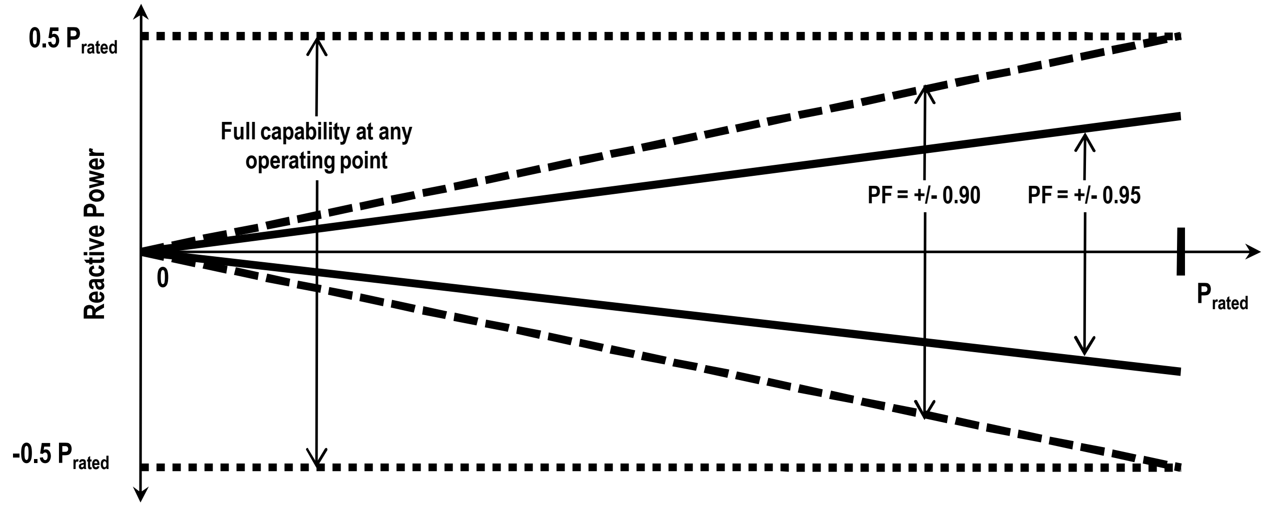
$$Q\min = -Q\max = Pgen \times \tan\left(\cos^{-1}(PF)\right) = 6.9\ MVAR$$

Reactive
control vari

Sandia National Laboratories

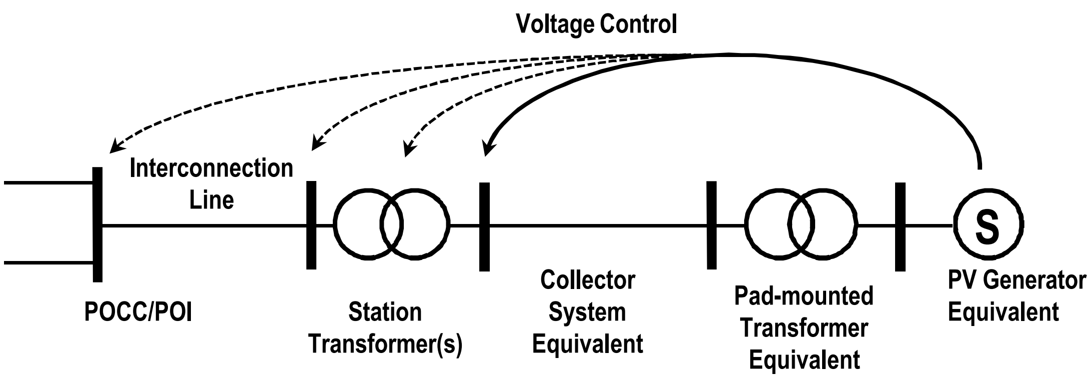
Reactive Power

Reactive Power Capability of Inverters: What is the reactive power capability? What about partial power? Check spec sheet!



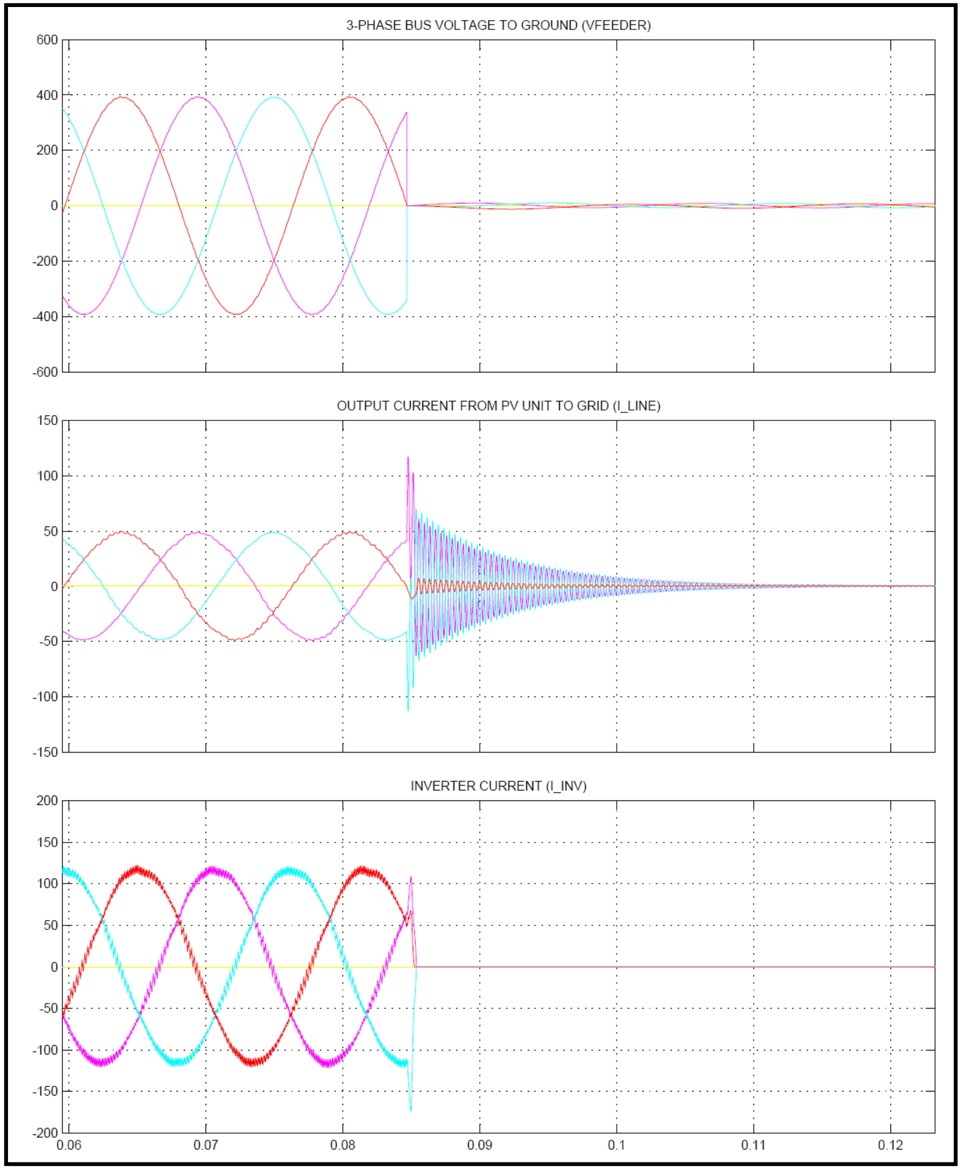
Reactive Control Options

- Fixed PF/Var setting
- Volt/Var droop
- Closed-lop Voltage Control



Sandia National Laboratories

Transient Behavior of PV Inverters



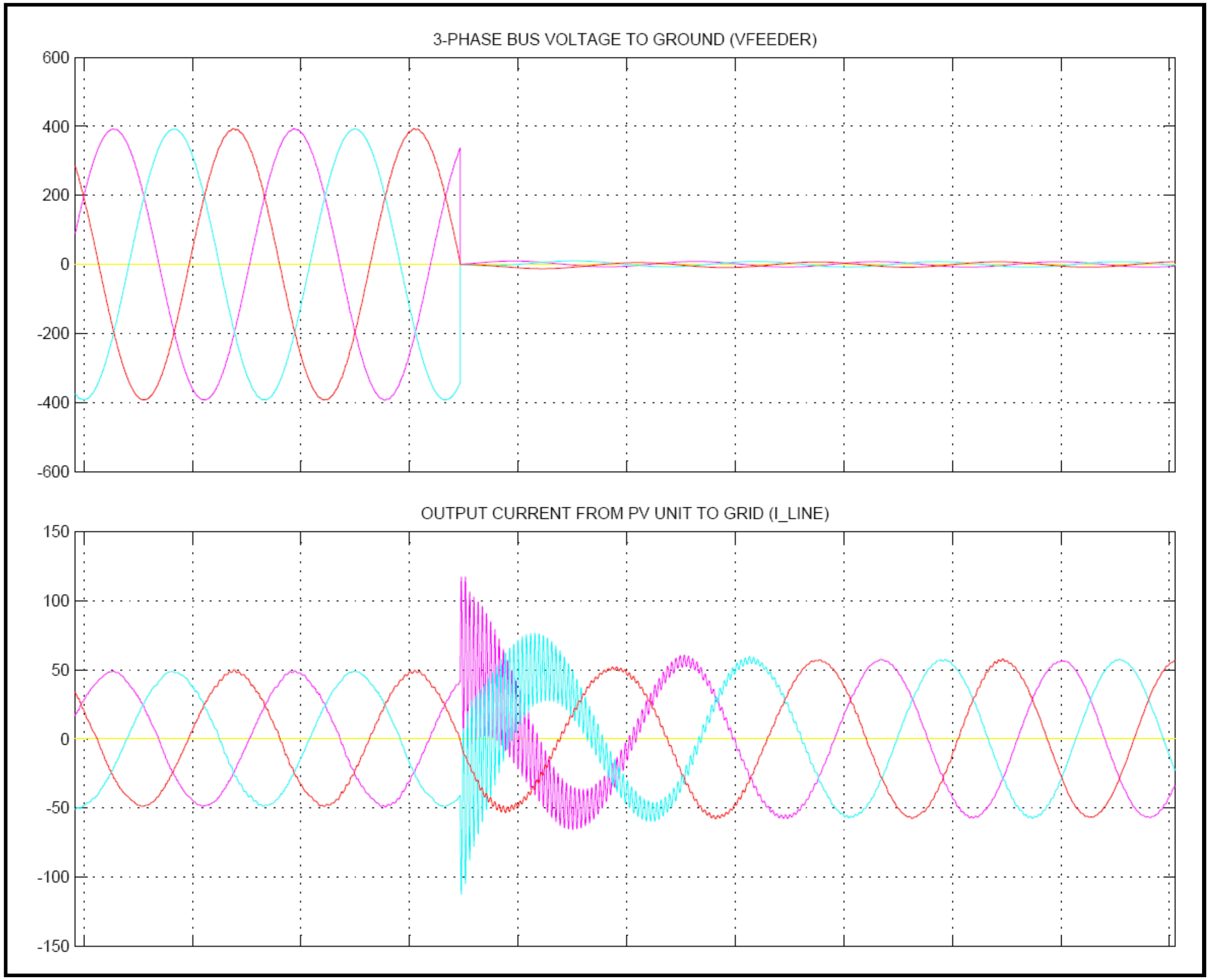
Grid Voltage Monitoring Enabled – Unit Trips During L-L-L-G Fault

In this case the AC voltage drops instantaneously and triggers an "instantaneous AC under-voltage" trip. Inverter gating stops immediately and the AC contactor releases after a few cycles. The filter capacitor rings with the grid inductance for a short time.

Source: Colin Schauder, Satcon Technology Corporation - Transient Modeling for Inverter-Based Distributed Generation, March 2, 2010

Sandia National Laboratories

Transient Behavior of PV Inverters



Grid Voltage Monitoring Disabled to Allow Ride-Through During L-L-L-G Fault

In this case the grid voltage monitoring has been disabled so the inverter keeps running (with limited 60 Hz current output).

Note the high frequency resonant discharge of the filter capacitor.

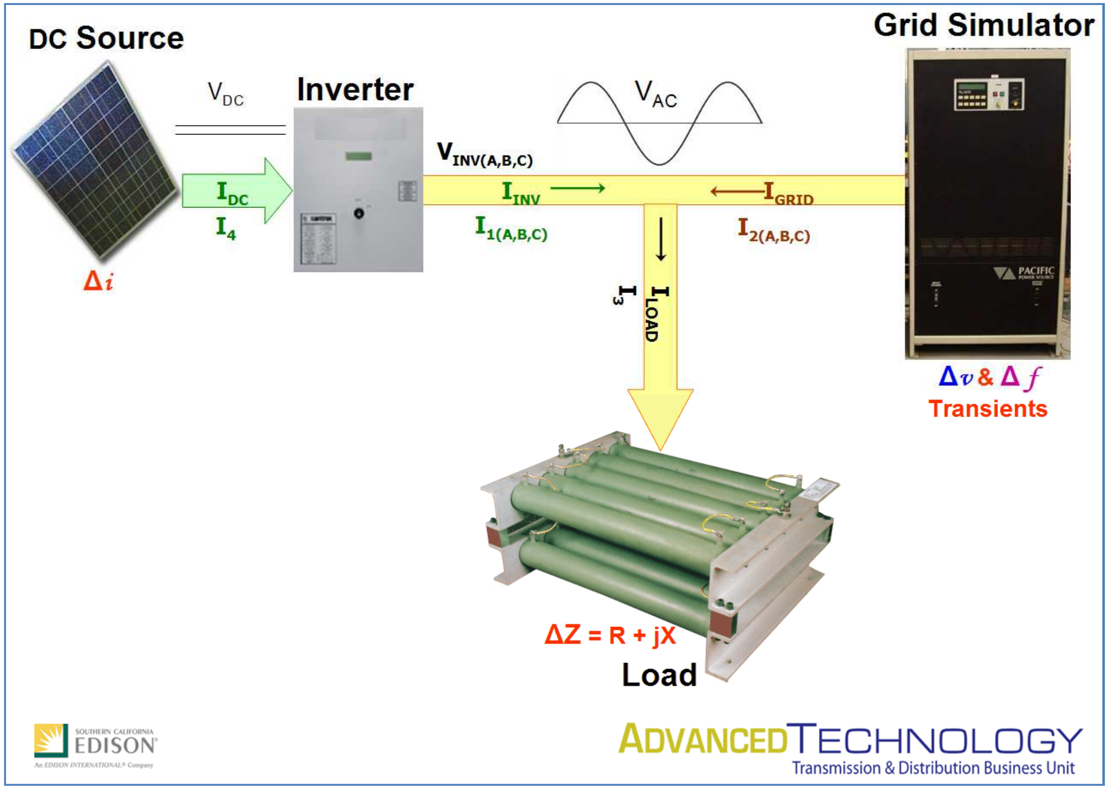
If the voltage drop is not so abrupt, then much less ringing occur.

Source: Colin Schauder, Satcon Technology Corporation - Transient Modeling for Inverter-Based Distributed Generation, March 2, 2010

Sandia National Laboratories

Model Validation/Verification

- Laboratory testing is first step
- Also need to validate against field data



Source: Richard Bravo, SCE, 3-phase solar inverter test procedures (Draft)

REMTF working with SCE/NREL inverter characterization project

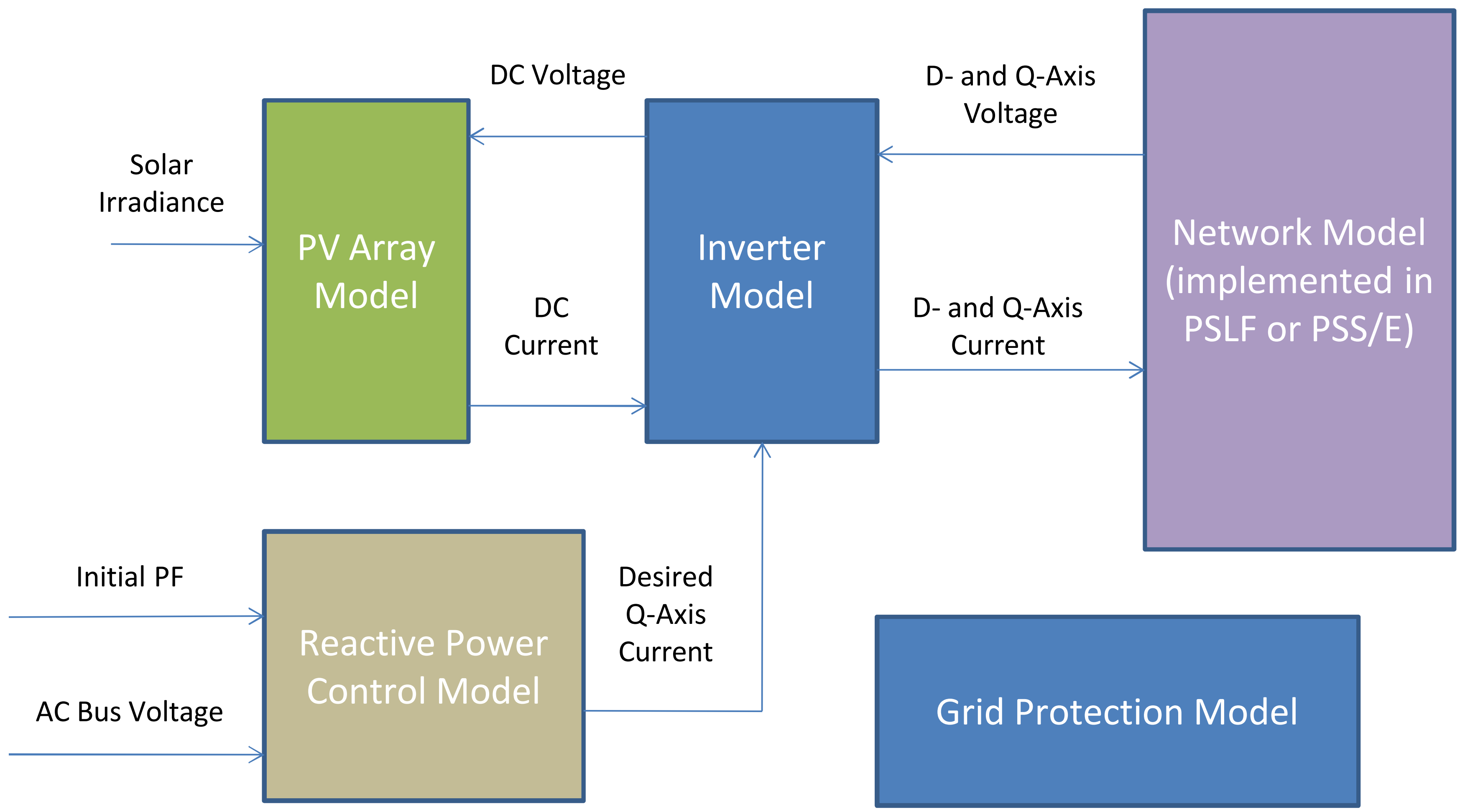
Sandia National Laboratories

Dynamic Models – Basic Specs

- Approximate aggregate dynamic response for entire PV plant
- Suitable for simulation of grid events
  - 3-ph (up to 9 cycles) & 1-ph faults (up to 30 cycles) faults, frequency events, oscillatory events (up to 10 Hz bandwidth)
  - Assume constant irradiance during electrical disturbance
    - Model extension should handle irradiance input (user beware!)
  - Protection module to mimic “LVRT” curve (piecewise linear)
- Numerically stable with time steps of ¼ to ½ cycle
  - Faster internal integration may be needed for some important controls
- Include existing and emerging control options & capabilities
  - LVRT, Volt/Var control options, power control (ramp rate), behavior during fault, frequency support??
- Initializes from power flow without special scripts

Sandia National Laboratories

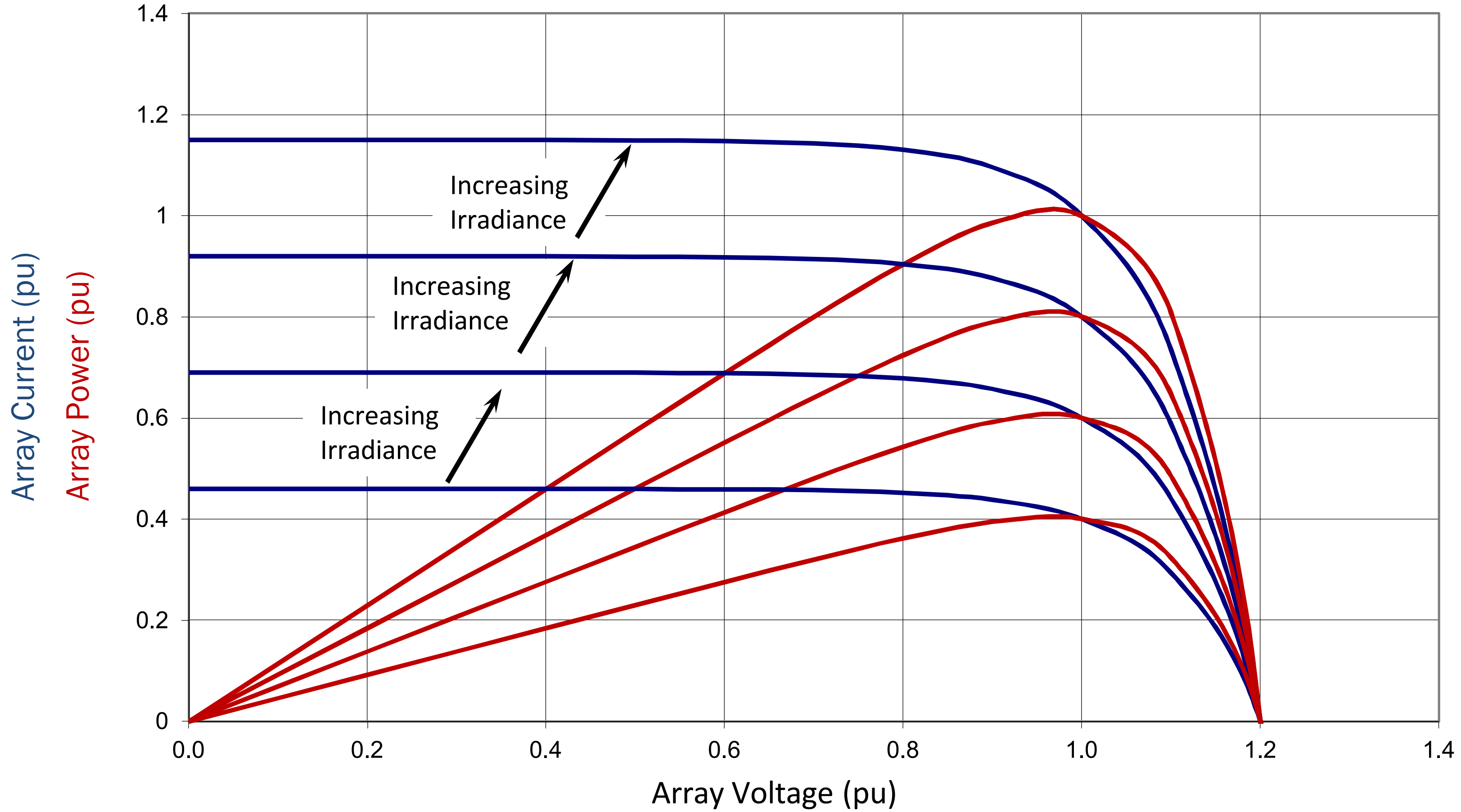
Model Connectivity



Source: Mike Behnke, BEW Engineering – Proposal for Generic PV System Model, March 2, 2010

Sandia National Laboratories

PV Array Model



Source: Mike Behnke, BEW Engineering – Proposal for Generic PV System Model, March 2, 2010

Sandia National Laboratories

Summary

- PV systems are different than conventional generation in key respects
  - Low short circuit current, no inertia, collector system
  - Inverter dynamic behavior can be "programmed"
- Need to make progress on PV system models to make solar "mainstream"
- WECC REMTF working on model development and guidelines
  - Goal is to meet NERC definition of adequate models
  - Wide industry participation

Sandia National Laboratories