NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Sandia National Laboratories

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

Utility/Lab Workshop on PV Technology and Systems

November 8-9, 2010
Tempe, Arizona

Distribution System Models
Power System Studies and Modeling PV Inverters

Ben Kroposki, PhD, PE
NREL

SEPA
solar electric power association

SRP
Delivering more than power.™

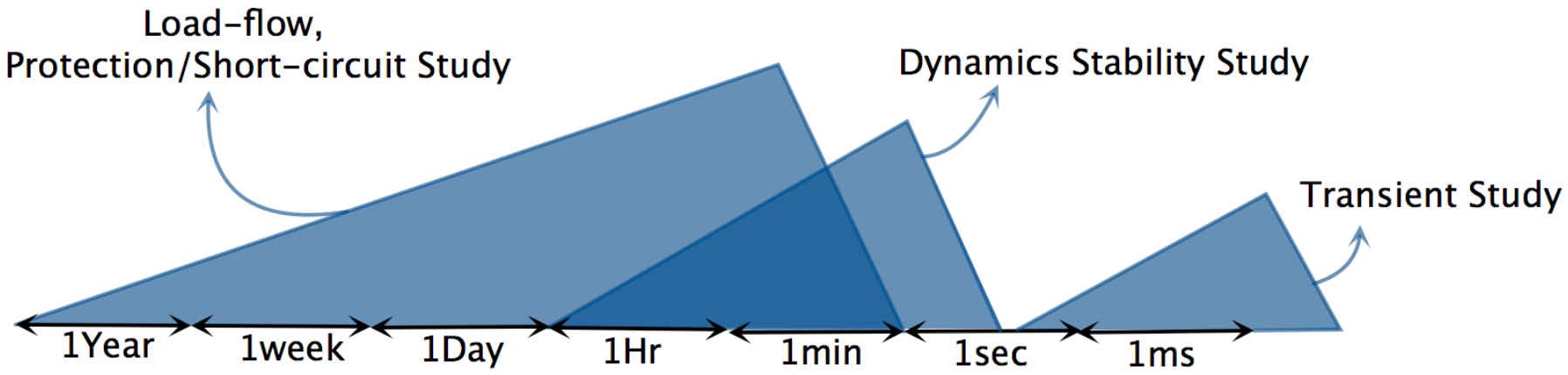
EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Power System Studies

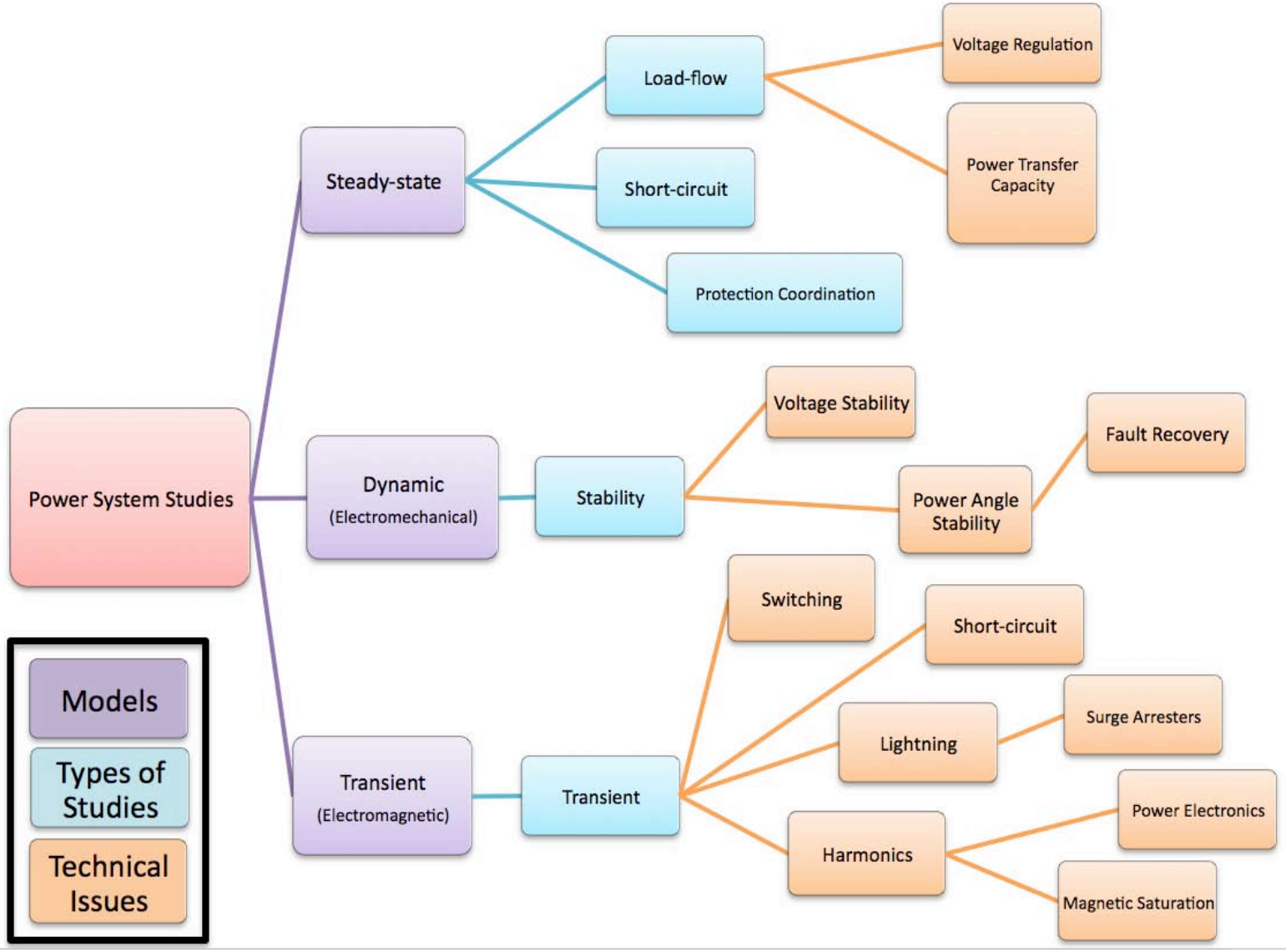
Steady-State
- Production Cost Models
- Load (Power) Flow
- Voltage Regulation
- Power Transfer
- Short-Circuit Study

Dynamic
- Voltage Stability
- Power angle Stability

Transient
- Transient Stability
- Harmonics



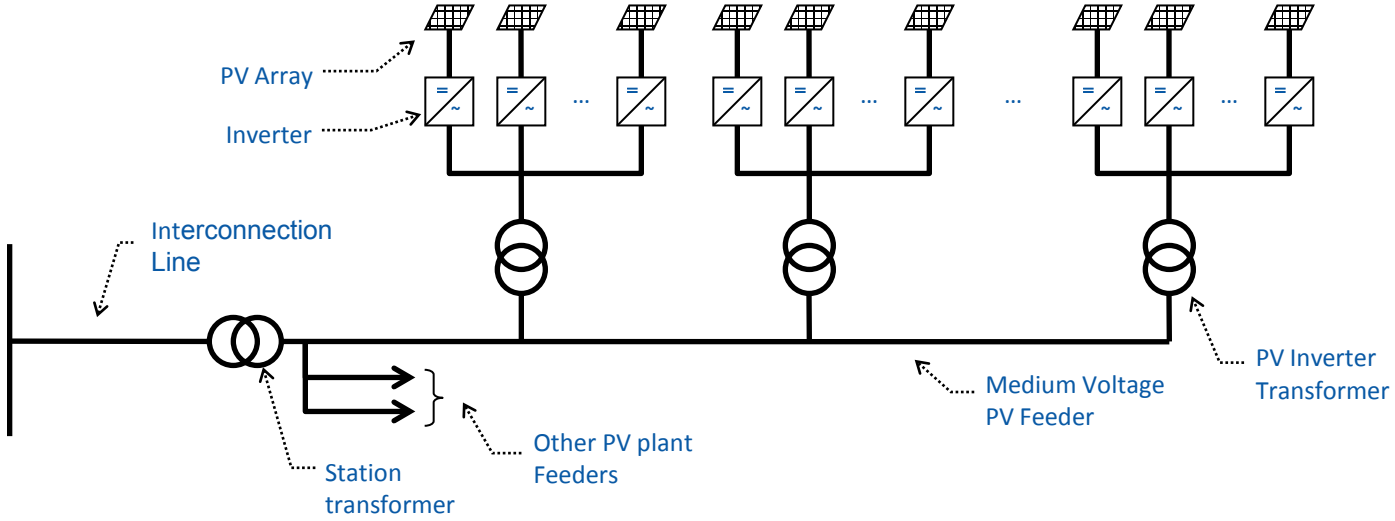
Power System Studies



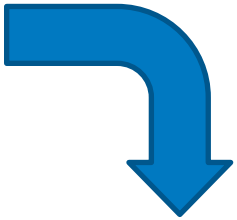
Load Flow (Power Flow) Studies

- Load flow or power flow studies are used to help determine the state of the power system.
- Load flow studies determine system voltages, currents, the active and reactive powers as well as the power factors.
- These parameters are used to determine system losses, conductor ampacity ratings, and voltage levels at particular (busses) connection points of the power system.
- Therefore, reliable power systems require utility engineers to study four basic steady-state operating conditions.
  - Generation supplies the load plus losses on the system.
  - Maintain bus voltage near nominal or rated value.
  - Generation operates within specified real and reactive power constraints.
  - Determine transmission and distribution lines are not overloaded
  - Solutions at a fixed frequency.

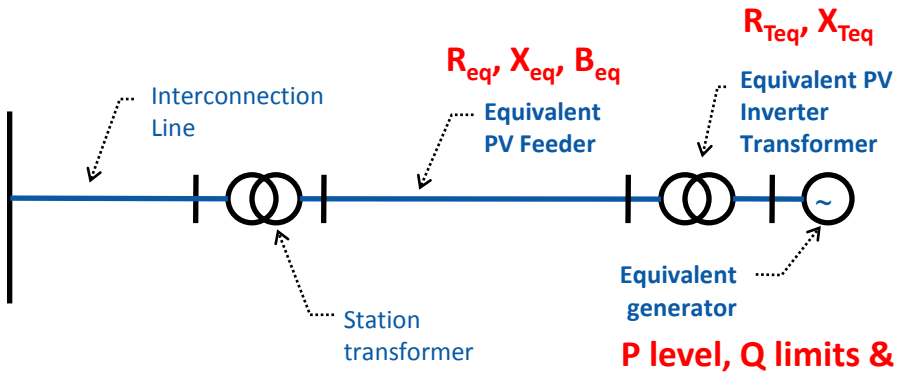
Load Flow Model – Utility Scale PV Plants



Equivalencing



Model interconnection line and station transformer explicitly, if they exist

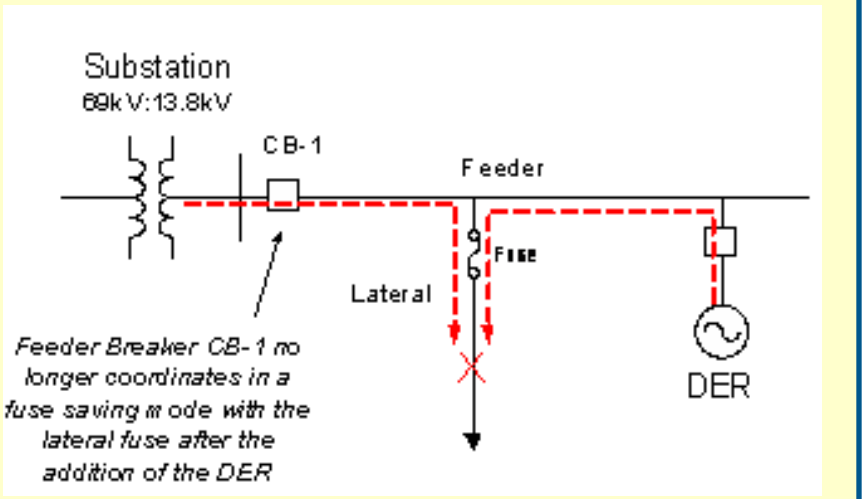


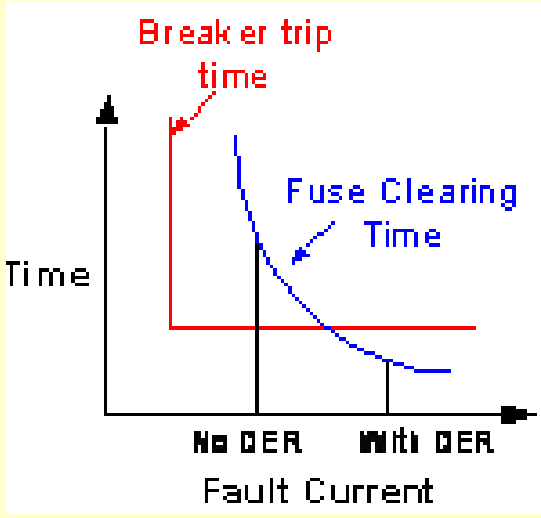
Source: Abe Ellis, Sandia

Short-Circuit Studies

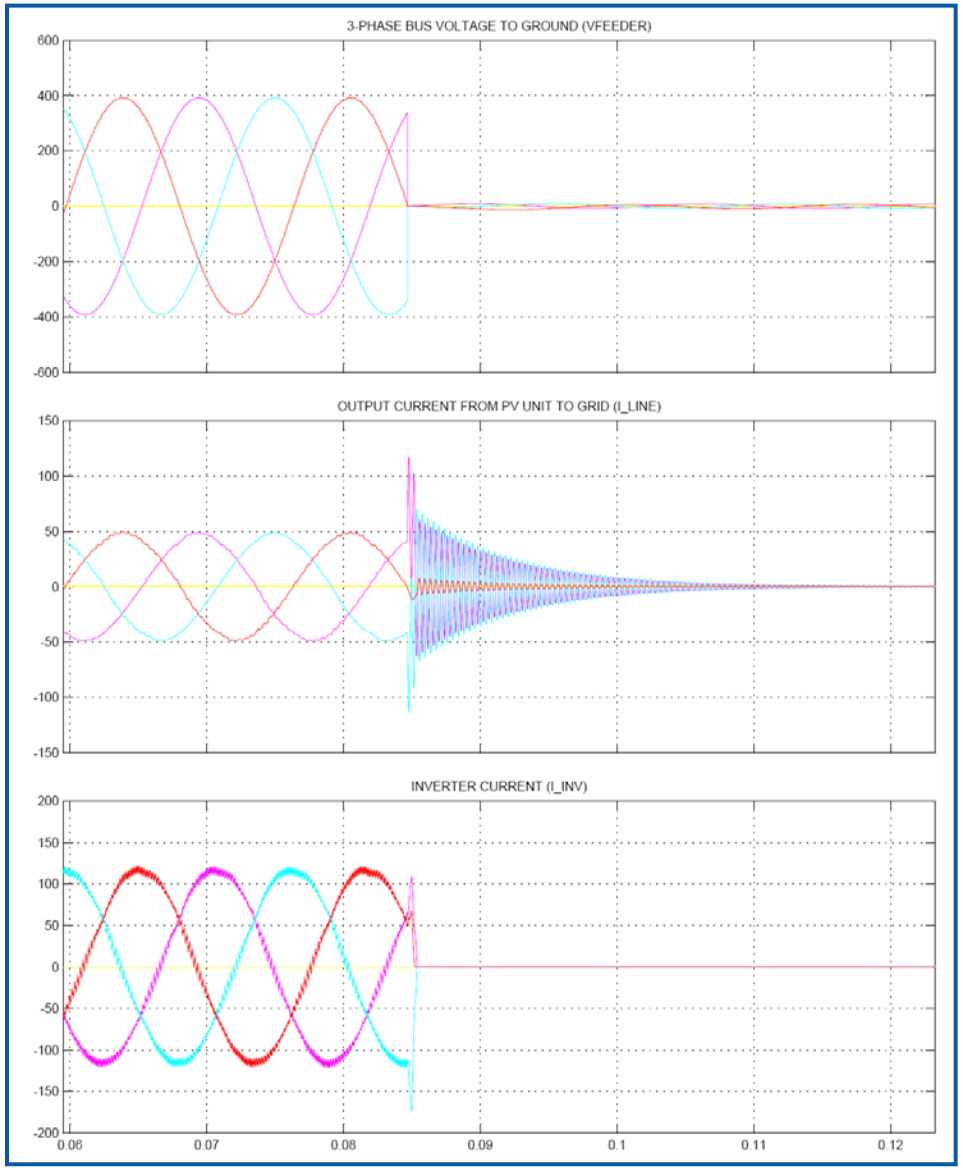
- Short circuit or fault studies are conducted to determine the magnitude of currents flowing through the electrical system during faults.
- Short-circuit studies ensure that the wide range of electrical equipment used to generate, transmit, and distribute electrical power is sufficiently sized to interrupt or withstand short-circuit current.
- A short circuit study is essential for determining parameters used in relay settings.

Short-Circuit Study





Short-Circuit Response of PV Inverter

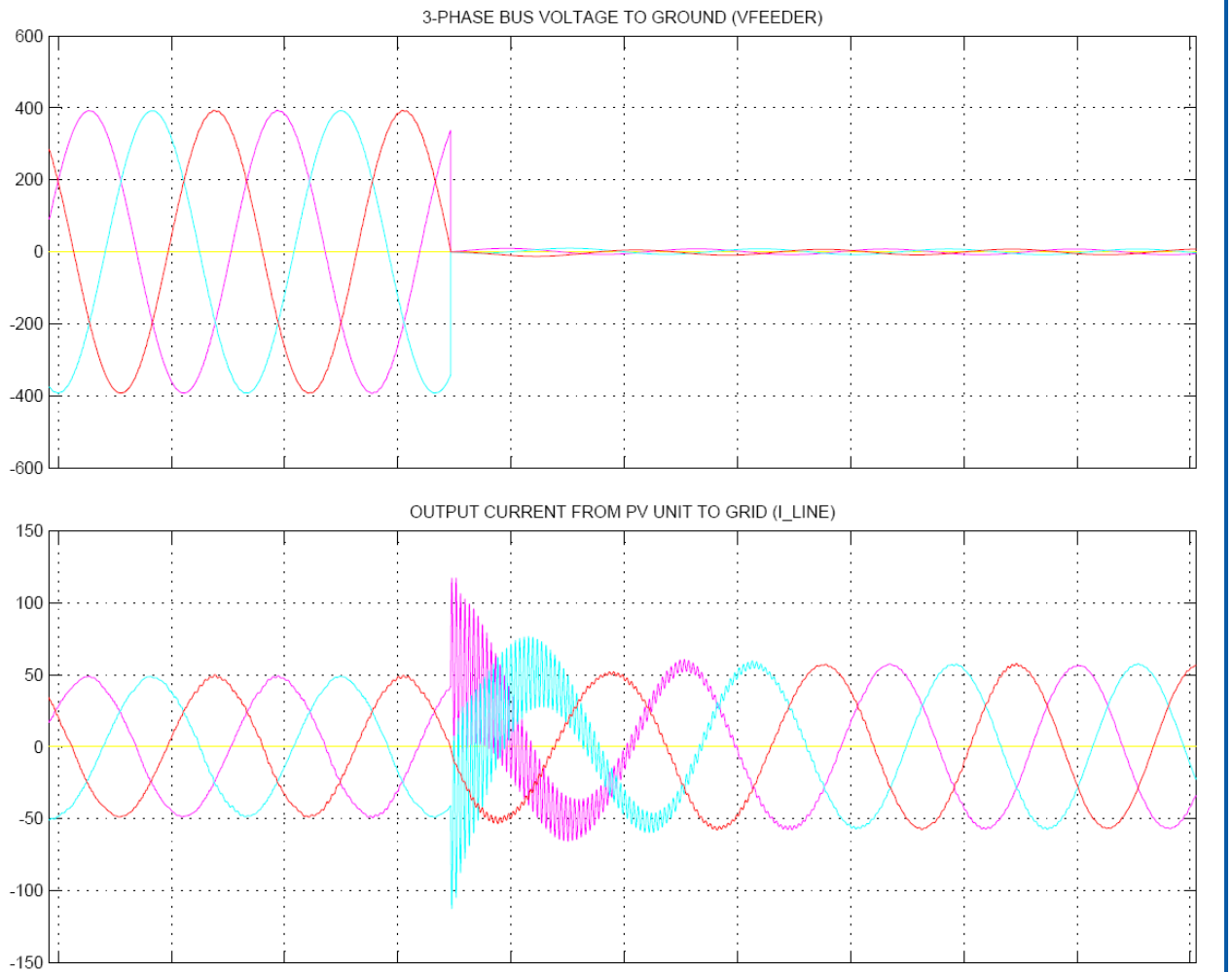


Grid Voltage Monitoring Enabled – Unit Trips During L-L-L-G Fault

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

Low-Voltage Ride Through (LVRT)



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

Stability Studies

- Stability focuses on one particular key electrical element, the magnitude and phase angle of the machine terminals voltage:
  - Rotor angle stability – The angle between the machine rotor and the stator is called the power angle (real power). Power increase as the power angle increases (up to a certain extent, 90 degree).
  - Voltage Stability – The magnitude of the machine terminal voltage (reactive power).
  - Dynamic modeling includes modeling the exciter system, turbine governor, and synchronous machine. Steady-state models use simple constant voltage source generator models. Both dynamic and steady-state studies methods use linear equations to determine the machine stability condition due to small changes about equilibrium.
  - Transient studies are performed to determine if the system will remain in synchronism following major disturbances such as faults, sudden loss or gain of load, loss of generation, or line switching. Transient stability studies generally focus on 1 to 10 second period after a disturbance.

Wind Turbine Models

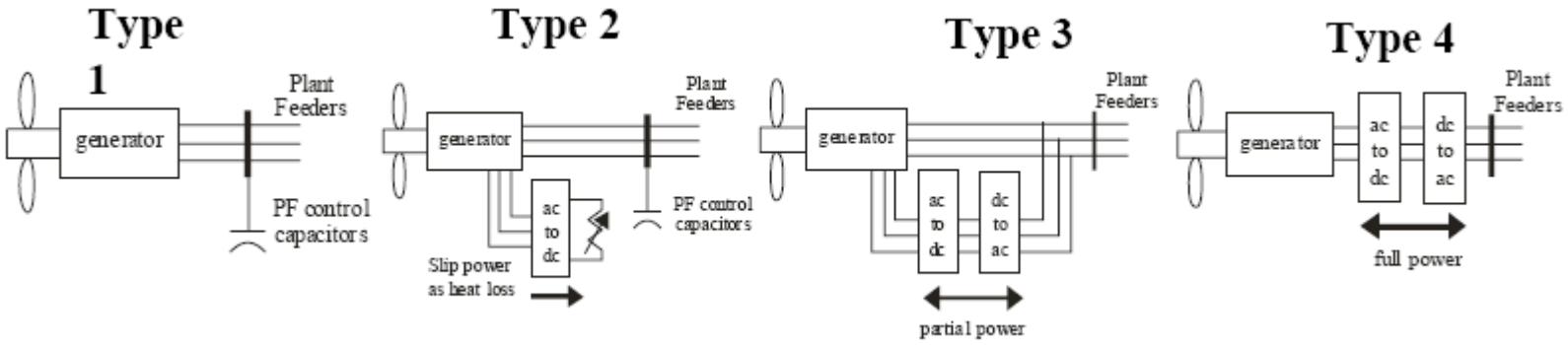
General Wind turbine Model Types

Type 1 – conventional induction generator

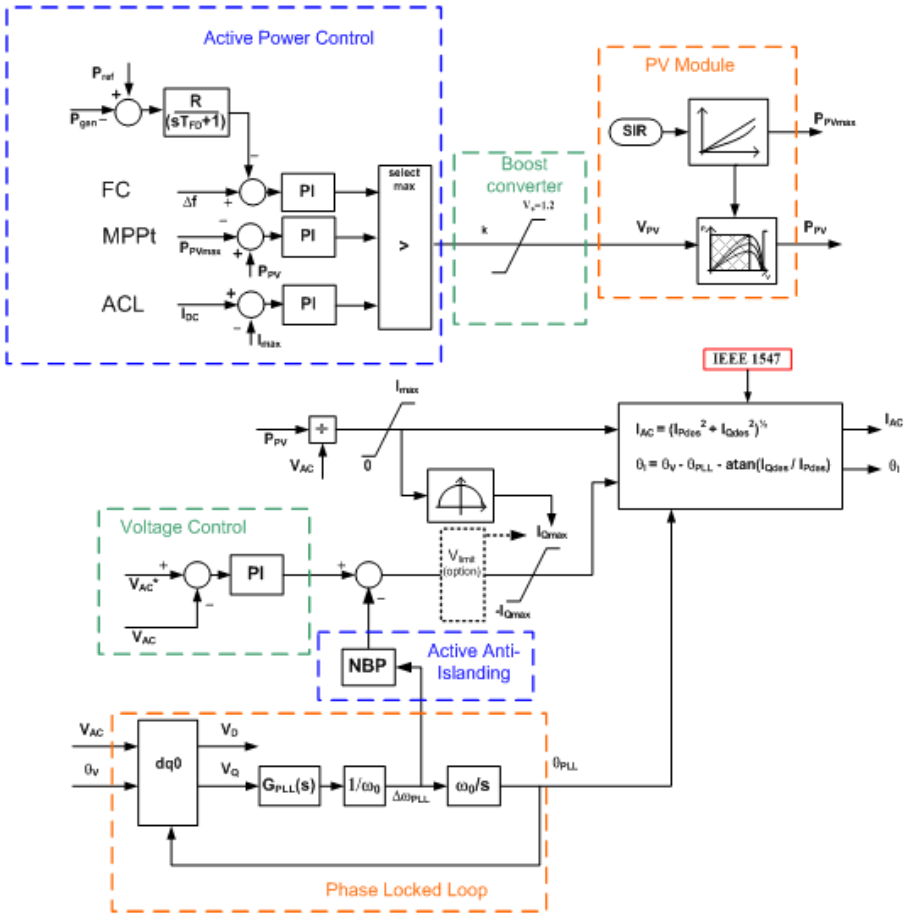
Type 2 – wound rotor induction generator, variable rotor resistance

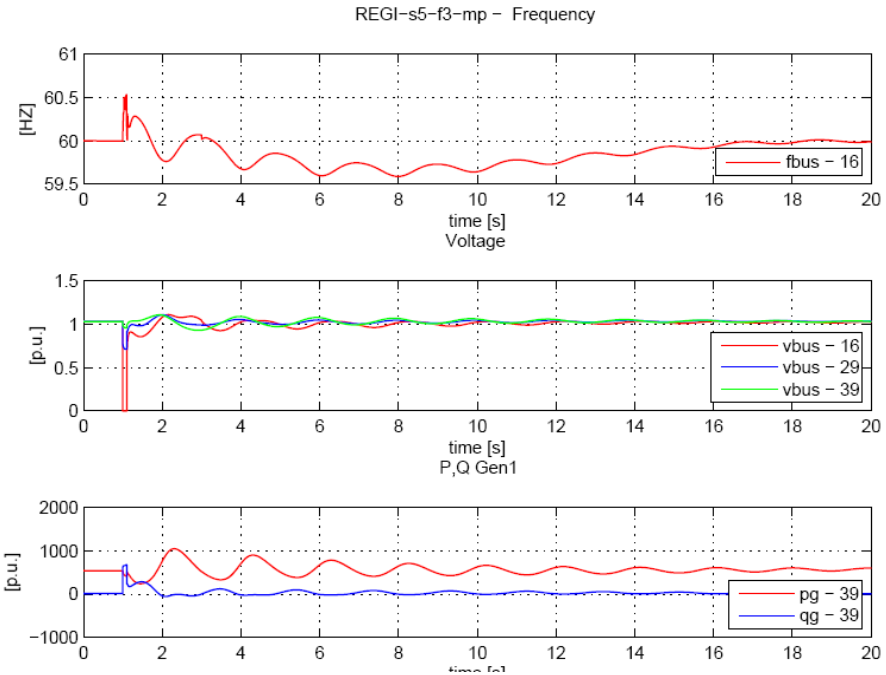
Type 3 – doubly-fed induction generator

Type 4 – full converter interface



PV Dynamic Modeling





Source: General Electric, *Transmission System Performance Analysis for High-Penetration Photovoltaics*
http://www1.eere.energy.gov/solar/pdfs/42300.pdf

Potential PV Model Types

Should we start to define standardized models?????

Type 1 – 1547 compliant PV inverter (no VR, no LVRT, quick trip points)

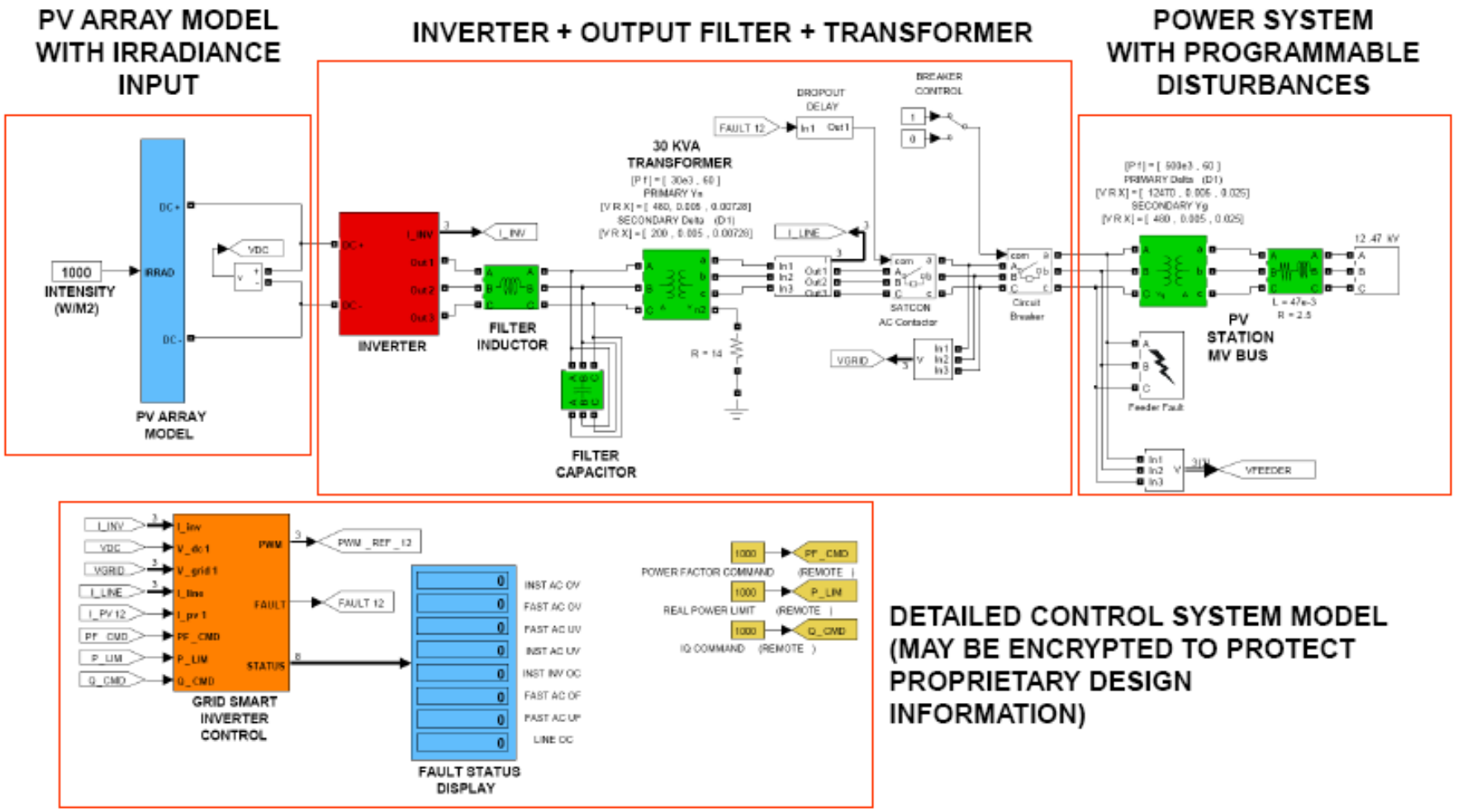
Type 2 – PV inverter with VR, LVRT

Type 3 – PV inverter with energy storage

Power Quality Studies

- Power quality consists of voltage, frequency, and current waveforms. The desirable voltage versus time waveform should be absent of harmonic distortion or ripples along the sinusoidal voltage waveform. This ripple or harmonics produced can have adverse effect such as:
  - Additional losses that results in overheating of various electric machines.
  - Interference with normal operation of communication circuits.
  - Harmonic resonance, which results in equipment failure in sensitive electronic equipment.
  - Performance modification of some interrupting devices and protective relays.

High detail inverter model with controls



DETAILED CONTROL SYSTEM MODEL (MAY BE ENCRYPTED TO PROTECT PROPRIETARY DESIGN INFORMATION)

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

Commercially Available Simulation Programs*

ASPEN: Advanced Systems for Power Engineering (ASPEN) used primarily to determine equipment ratings, fault current levels, and protection coordination on the transmission level network.

PowerWorld: PowerWorld is a visualization tool used to analyze the system performance under different power demand scenarios. Transmission planners, power marketers, and system operators typically use the software.

SKM-Dapper: DAPPER performs traditional short circuit analysis with an integrated set of modules. The module includes design and analysis including load flow and voltage drop calculations, motor starting, demand and design load analysis, feeder, raceway and transformer sizing.

CYMDIST: CYMDIST performs power systems analysis on balanced or unbalanced three-phase, two-phase and single-phase systems that are operated in radial, looped or meshed configurations. The module includes voltage drop and power flow analysis, fault calculations and, protective device coordination.

DEW: Distributed Engineering Workstation utilizes Intergraded System Models (ISM). The architecture and ISM provide the developer with a mechanism to directly use the results of existing (relay) analyses, model parameters, and external data to create custom calculations, analyses, and reports.

SynerGEE: SynerGEE performs power system analysis using detailed load modeling on radial, looped and mesh network systems comprised on multiple voltages.

PSLF: GE Positive Sequence Load Flow Software (PSLF) is a full-scale program designed to perform load flow, dynamic simulation, and short circuit analysis. Typically used by power system engineers for simulating the transfer of large blocks of power across a transmission grid.

PSS/E: The Power System Simulator for Engineering or PSS/E, essentially has the same system capability as PSLF a software program. Again, this package is typically used by electrical transmission planners performing load flow, dynamic simulation, and short circuit analysis for obtaining a reliable power system.

PowerFactory: PowerFactory offers a research version that allows the user to create custom models and control strategies as Matlab or programmed functions.

PSCAD: PSCad offers the ability to create custom components as well as custom control algorithms.

SimPowerSystems: Built on the Matlab-Simulink, SimPowerSystems offers the flexibility to create detailed system models, custom algorithms, interfaces, and components both for power systems and power electronics.

* List is not inclusive. Other programs exist, but have not yet been evaluated.

Commercially Available Simulation Programs*

Power System Study Type	ASPEN -OneLiner	PowerWorld	SKM-Dapper	CYMEDIST	DEW	SynerGEE	PSLF	PSS/E	PowerFactory	PSCAD	Matlab/SimPower
Steady-state Models											
Load-flow		x	x	x	x	x	x	x	x		
Short-circuit	x		x	x	x	x	x	x	x	x	x
Protection Coordination	x		x	x		x			x		
Voltage Regulation			x	x	x	x	x	x	x		
Power Transfer Capacity		x	x	x	x	x	x	x	x		

* List is not inclusive. Other programs exist, but have not yet been evaluated.

Commercially Available Simulation Programs*

Power System Study Type	ASPEN -OneLiner	PowerWorld	SKM-Dapper	CYMEDIST	DEW	SynerGEE	PSLF	PSS/E	PowerFactory	PSCAD	Matlab /SimPower
Dynamic (Electromechanical) Models											
Power Angle Stability							x	x	x		
Voltage Stability							x	x	x		

* List is not inclusive. Other programs exist, but have not yet been evaluated.

Commercially Available Simulation Programs*

Power System Study Type	ASPEN -OneLiner	PowerWorld	SKM-Dapper	CYMEDIST	DEW	SynerGEE	PSLF	PSS/E	PowerFactory	PSCAD	Matlab /SimPower
Transient (Electromagnetic) Models											
Harmonics									x	x	x
Switching									x	x	x
Lightning									x	x	x
Short-circuit									x	x	x

* List is not inclusive. Other programs exist, but have not yet been evaluated.

Summary

Steady-State

- Typically model PV as a constant power source (P) with no reactive power component (Q)
- As reactive power control is allowed, model could have Q set points

Short-circuit

- Short-circuit analysis usually assumed as 1.1 p.u. for 0.16 sec. recent testing has shown that it is usually a much shorter time period.
- As LVRT happens, fault time would increase.

Dynamic

- Typically model PV as a constant power source (P) with no reactive power component (Q) but include protective set points (v,f)

Transient

- Very dependent on control algorithms used in inverter

Aggregation

- Need to develop method to aggregate hundred to thousands of distributed sources

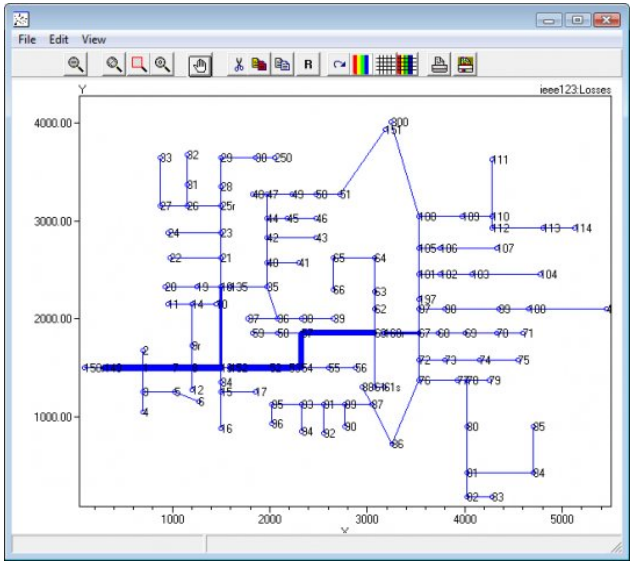
Summary

Commercial Software

- Commercially available software has started to implement standardized models for DR.
- Need to standardize PV models at various time-scales

Open Source Software

- **GridLAB-D** (http://www.gridlabd.org/)
- GridLAB-D is a flexible simulation environment that can be integrated with a variety of third-party data management and analysis tools. The core of GridLAB-D has an advanced algorithm that simultaneously coordinates the state of millions of independent devices, each of which is described by multiple differential equations.



- **Open-DSS**
- (http://sourceforge.net/projects/electricdss/)