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UVIG Short Course on the Integration and Interconnection of Variable Generation into Power Systems

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Session 4
PV Plant Design and Operations

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Topics

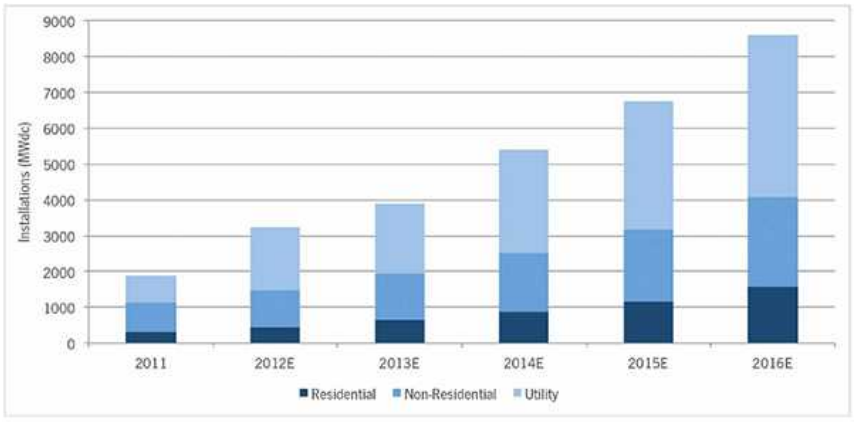
- Large-scale PV plants
  - Components and design considerations
- PV plant operations
  - Plant control capabilities
  - Output variability
- Q&A

Copper Mountain 48 MW_{ac} PV Plant

- This material applies specifically to…
  - Large-scale (50MW+), transmission-connected PV plants
  - Flat plate PV (excludes CPV and other solar technologies)
  - As always, there are exceptions

PV Plants Getting Larger and Larger

- Large, utility-scale PV plants represent an increasingly large portion of total PV installations
  - Large PV plants in the US as of 08/12
    - 4 plants >50MW_{ac}, several >50MW_{ac} under construction, a few >200MW_{ac}
    - Agua Caliente, AZ: 250MW_{ac} online, 290MW_{ac} when complete
  - Large PV plants elsewhere:
    - 24 plants >50MW_{ac}, many >50MW_{ac} under construction
  - http://www.pvresources.com/PVPowerPlants/Top50.aspx



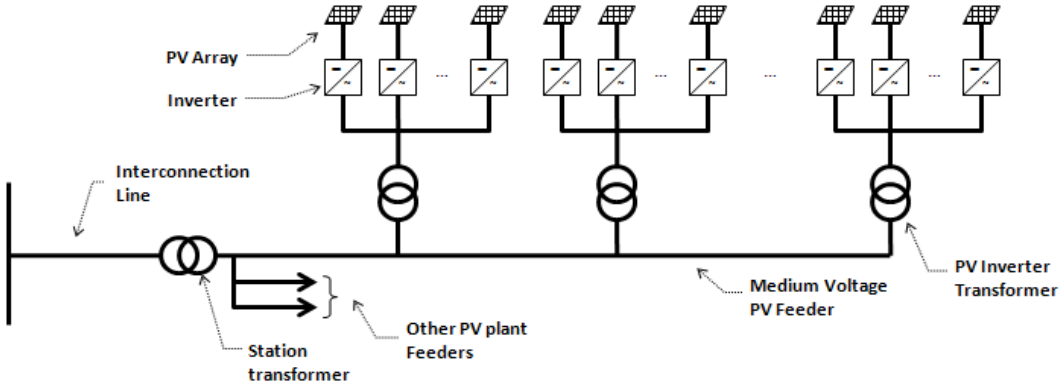
Note: Full report contains market forecast through 2016 by state and market segment.

SEIA, Solar Market Insight Report 2012 Q2

Agua Caliente Solar Project near Yuma, AZ. Photo Courtesy of FirstSolar.

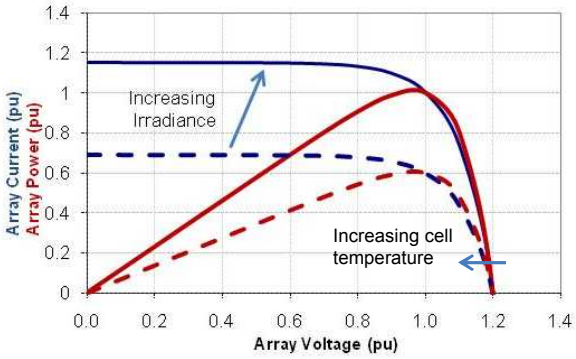
Large PV Plant Design

- PV array: modules & mounting (most visible), dc wiring and switchgear
- PV inverters
- AC collector system: transformers & MV UG/OH collectors
- Station equipment: transformer, reactive compensation (if needed), breakers, station service supply
- Monitoring, controls and protection



PV Modules

- Convert sunlight to electricity (dc)
  - Nonlinear I vs. V characteristic (IV Curve)
  - Current and power are roughly proportional to irradiance
  - Voltage and power are affected by temperature
  - Rated at Standard Test Conditions (STC) of 1kW/m^2 and 25°C cell temp.
    - Irradiance is ~1kW/m^2 on a clear day on a plane perpendicular to direct sunlight; can reach 1.3kW/m^2 (*cloud enhancement*)
    - Cell temp. 40-60°C at full sun, depending on ambient temp., wind speed/direction …
- Typical PV modules for large plants
  - 100W to 400W at STC, 20 to 70 V_{OC}



Nameplate Module Data at STC

I_{SC} – Short circuit current
V_{OC} – Open circuit voltage
V_{MP}, I_{MP} – Max power operating point
P_{MP} = Rated $V_{MP} \times I_{MP}$

PV Module Technologies

- Crystalline silicon (c-Si)
  - Polycrystalline, Monocrystalline
  - Commercially-available module efficiency: 15%-20%
- Thin Film
  - Cadmium Telluride (CdTe), Cadmium indium gallium selenide (CIGS), Amorphous silicon (a-Si)
  - Commercially available module efficiency: 7% to 12%

Figure 2-7: U.S. Module Production by Technology, 2011

Module Manufacturing by Tech.	Capacity						Production					
	Q1	Q2	Q3	Q4	2011 Annual (Year-end)	Y/Y	Q1	Q2	Q3	Q4	2011 Total	Y/Y
Crystalline Si	334	339	314	328	1,312	-11%	270	225	205	134	834	4%
CdTe	96	106	116	126	502	46%	76	75	78	55	284	12%
CIGS	65	72	78	68	270	13%	29	28	26	8	91	-2%
Amorphous Si	18	18	18	18	70	0%	3	2	2	2	10	-92%
Total	**512**	**534**	**525**	**539**	**2,154**	**2%**	**378**	**330**	**312**	**199**	**1,219**	**-4%**

Source: SEIA, US Solar Market Insight™ 2011 Year-in-Review

- Trends for all technologies: $/W↓; module efficiency↑

PV Module Technologies

- Examples of PV plants with crystalline and thin film (CdTe) modules

PV Plant Footprint

- Plants are not contiguous
  - Terrain features, land access (environmental considerations, leases, roads, …)
- Other factors
  - Module efficiency
  - Ground coverage ratio (GCR)
    - 35-40% for 1-axis tracking (no tilt)
    - ~50% for fixed, tilted rack
  - DC to AC ratio

DeSoto 25MW PV Plant (2009) near Fort Myers, FL. Courtesy of FPL

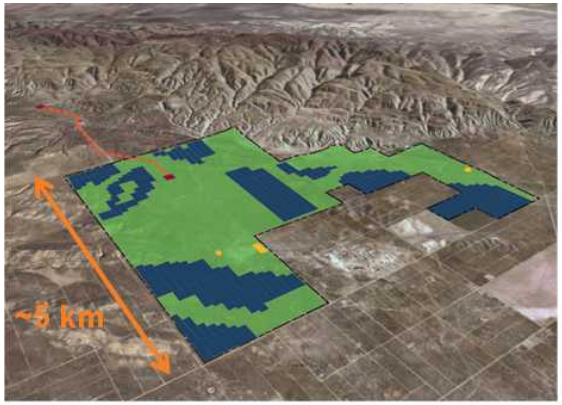
- Large-scale PV use 5 to 8 acres per MW_{dc} (STC) in contiguous square array

PV Plant Footprint

- Large PV plant footprint

Agua Caliente 290 MW_{ac} 410 MW_{dc}
Photo courtesy of FirstSolar

Charts courtesy of
SunPower Corporation



Solar Array Open Space

250 MW – CA Valley Solar Ranch

601 MW – Antelope Valley, CA
Overlaid on Washington, DC For Comparison

PV Array Support Structures

- Large PV systems are ground mounted
  - Steel and concrete supports
- Fixed tilt or tracking (1 axis)
  - Tracking is East-West
    - N-S tilt can be zero or nonzero
  - Tracking results in higher cost and lower GCR, but higher energy yield
  - Cost-effectiveness increases with high efficiency modules


DC disconnects are for array reconfiguration at Sandia and are not required in commercial installations


Lanai 1.5 MW PV System. Courtesy of SunPower


Nellis AFB 14 MV PV system (Wikipedia)

PV Array Electrical Connections

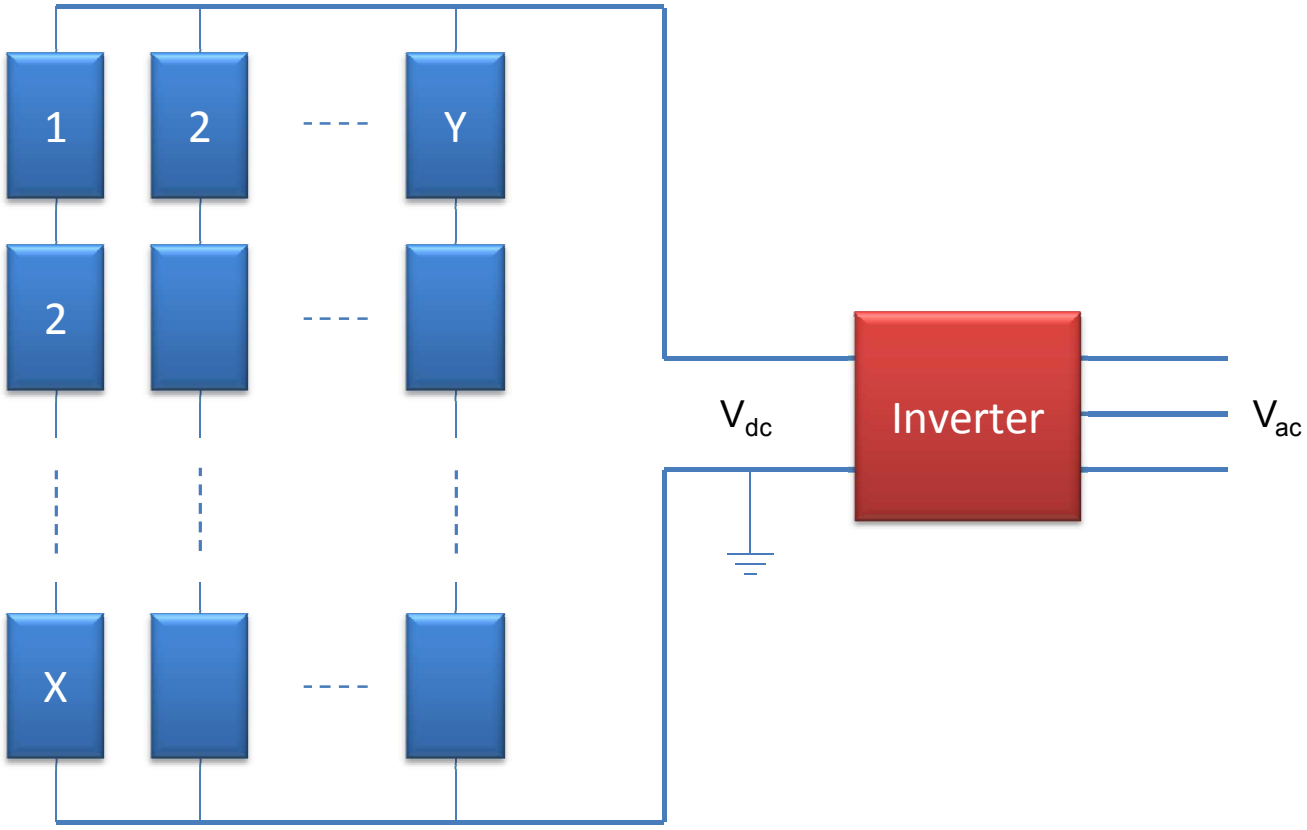
- DC connections
  - String: *X* PV modules in series to achieve a certain V_{OC}
    - $600V_{dc}$ or $1000V_{dc}$ (present)
    - $1500V_{dc}$ (future—lower losses, cost)
  - Array: *Y* strings are paralleled in a combiner box for connection to an inverter
    - 300-500kW inverters for $600V_{dc}$ systems
    - 750kW+ inverters for $1000V_{dc}$ systems
  - Ratio of PV to inverter power rating (DC/AC ratio)
    - Typically 1.1 to 1.2, but could be higher (consult with inverter manufacturer)
    - Able to push more PV energy to the grid (higher capacity factor)
    - Reserve capacity

PV Array Electrical Connections

- DC grounding
  - Ungrounded (neither current carrying conductor grounded)
    - Common in EU; allowed (possibly required) by evolving US codes
    - Improved safety for single fault ground fault
    - Easier to detect ground faults through isolation monitoring
  - Positive or negative grounded system
    - Required for PV systems on buildings
    - Allows arcing current to flow in order to detect (usually at inverter)
  - Bipolar system (not common for large-scale PV)
  - Grounding of metallic and module frames is required
- DC ground fault detection/interruption is a current issue under consideration

PV Array Electrical Connections

- DC connections

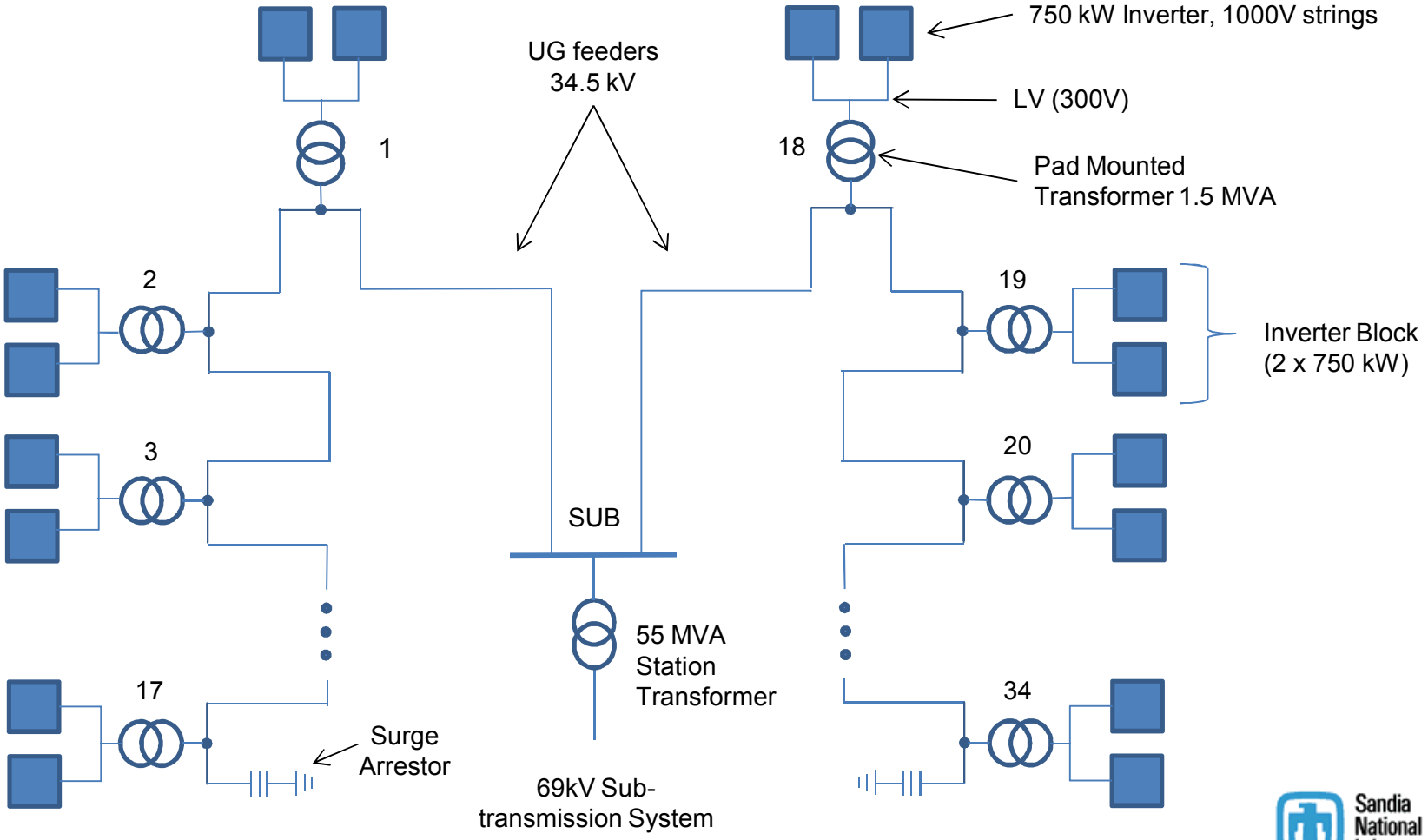


PV Array Electrical Connections

- AC Connections
  - Block: *Z* inverters connected to a transformer or transformer bank (inverters and transformer are typically co-located)
    - 1MW for 600V_{dc} system
    - 2MW to 2.5MW for 1000V_{dc} system
  - Blocks connect to station transformer(s) via MV collectors
    - Typically UG (OH may be used if shading, aesthetics are not an issue)
  - Choice of collector voltage class is a design consideration
    - Factors include power level, interconnection voltage, losses, voltage/reactive management, cost
    - 15kV class typical for small plants (up to 20MW)
    - 38kV class typical for large plants (20MW+)
      - Leverage 34.5 kV nominal wind collector equipment

PV Plant Topology

- Example for a 51MW, 1000V_{dc} PV plant



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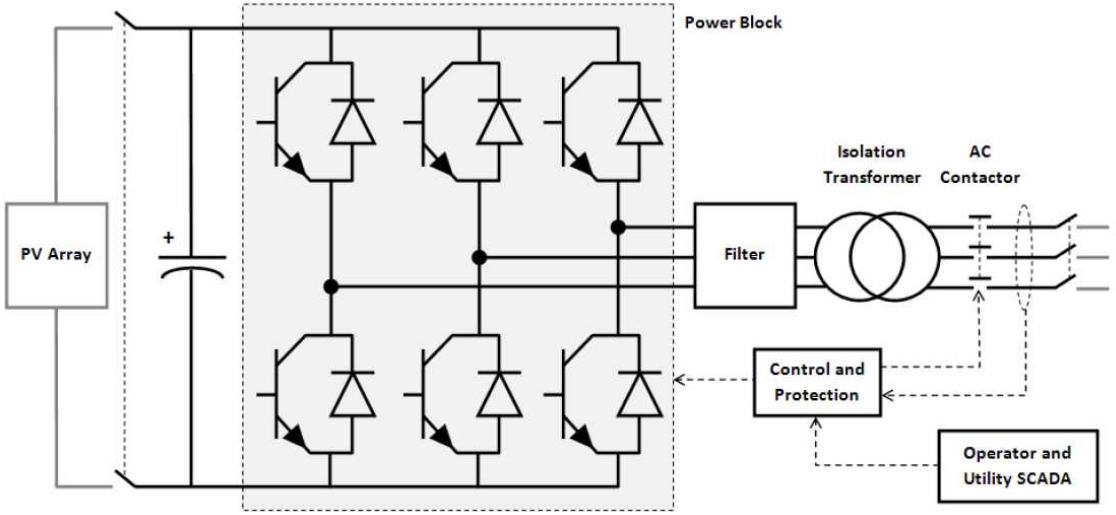
PV Plant Transformer Connections

- Substation transformer winding configuration and pad mounted transformer connections depend on utility and plant design requirements
  - Transmission protection coordination
  - Voltage control & protection inside the plant during faults
- Example for a 51MW plant, 1000V_{dc}, 34.5kV collector
  - 34.5kV grounded wye / 69kV delta substation transformer
    - Some utilities require grounded wye primary winding, added tertiary closed delta winding for zero sequence currents sourcing
  - Oil-filled 2- or 3-widing, MV / LV pad mounted transformer
    - LV inverter output is generally three wire, ungrounded

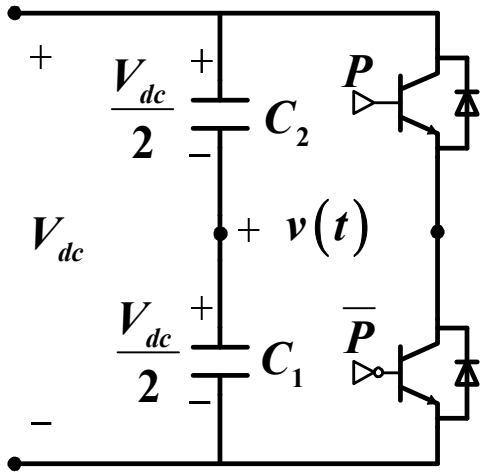
PV Inverters

- Typical inverters used in large PV plants
  - IGBTs with high frequency PWM driver
  - DC voltage source topology
  - AC current regulated
  - Single-stage design (no dc boost stage)
  - No dedicated isolation transformer (LV/MV transformer winding provides galvanic isolation)

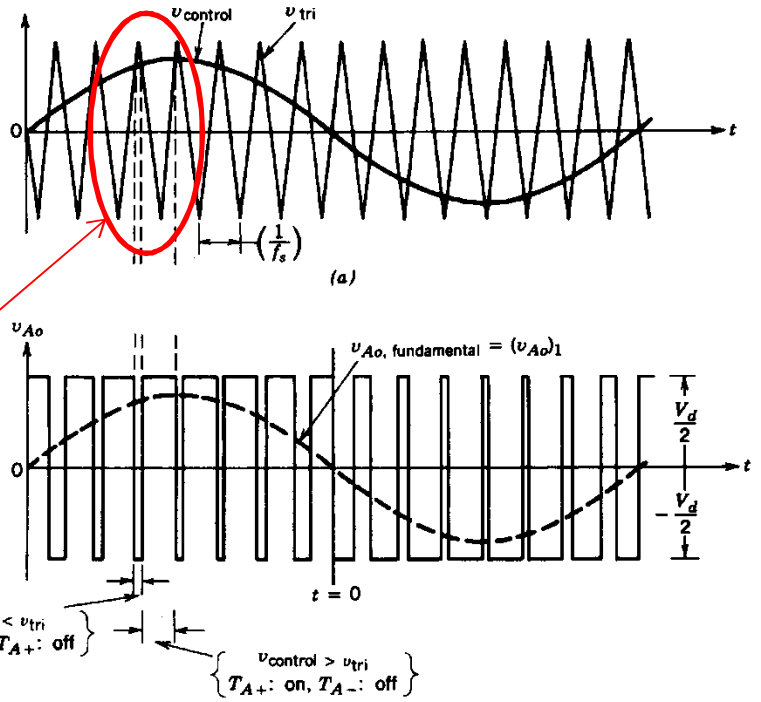


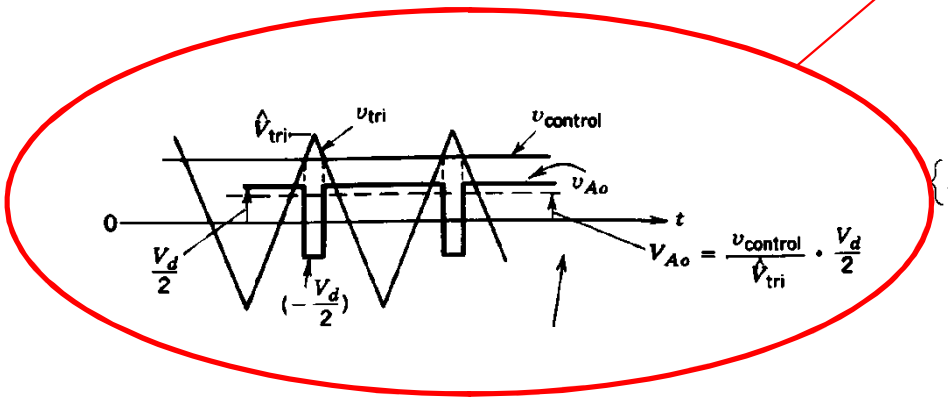
PV Inverters

- Sinusoidal Pulse Width Modulation



Carrier and Modulating Signals





PV Inverters

- AC terminal characteristics
  - ~200V_{ac} (600V_{dc} system) or ~350V_{ac} (1000V_{dc} system)
    - Depends on inverter design (filter design, etc.)
    - Stepped up to MV by dedicated or shared pad mounted transformer
    - A low voltage, dry type isolation transformer is integrated into inverters designed for commercial-scale applications (480V_{ac} output)
  - Low short-circuit current (~120% of nominal), no inertia
  - Grid support features (as required)
    - Voltage and frequency tolerance
    - Controlled current injection during fault
    - Reactive support capability
    - Active power control capability

PV Inverters

- Example of large PV inverter (Satcon Prism 1.5 MW)

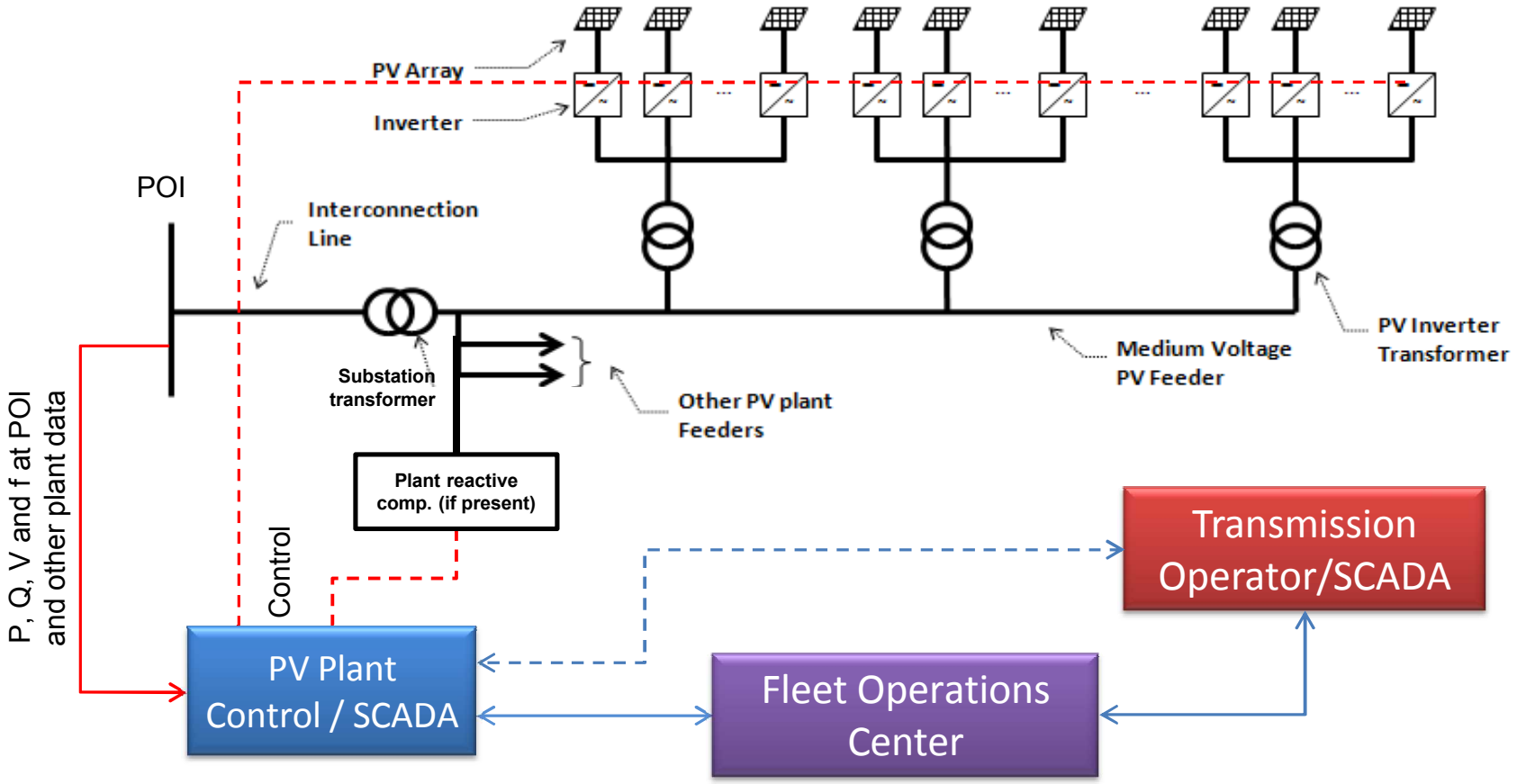
Photo courtesy of Satcon

PV Plant Operational Considerations

- PV Plant Control Capabilities
- PV Plant Output Variability

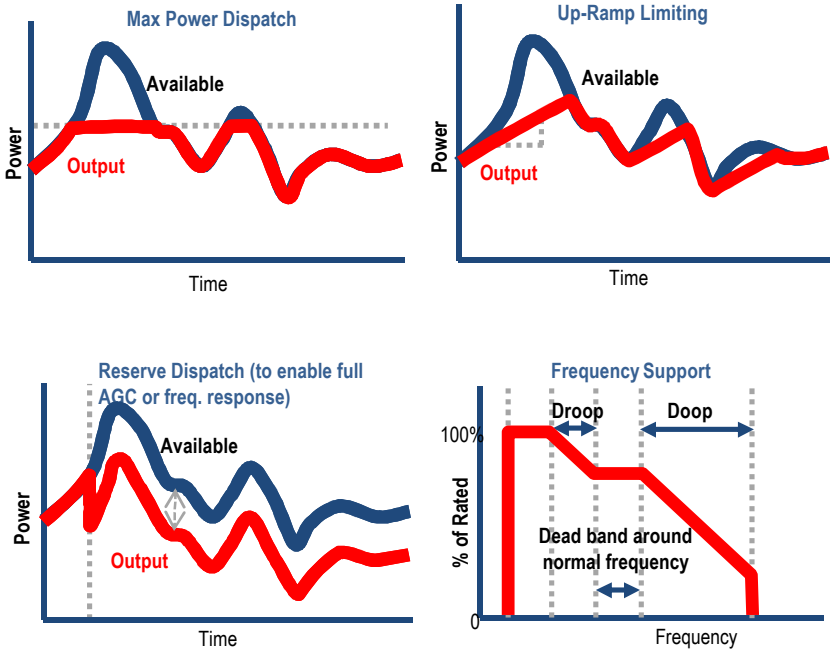
PV Plant Control / SCADA

- Coordinate operation of inverters and other controllable assets inside the plant (custom integration typically needed)



PV Plant Control Capability

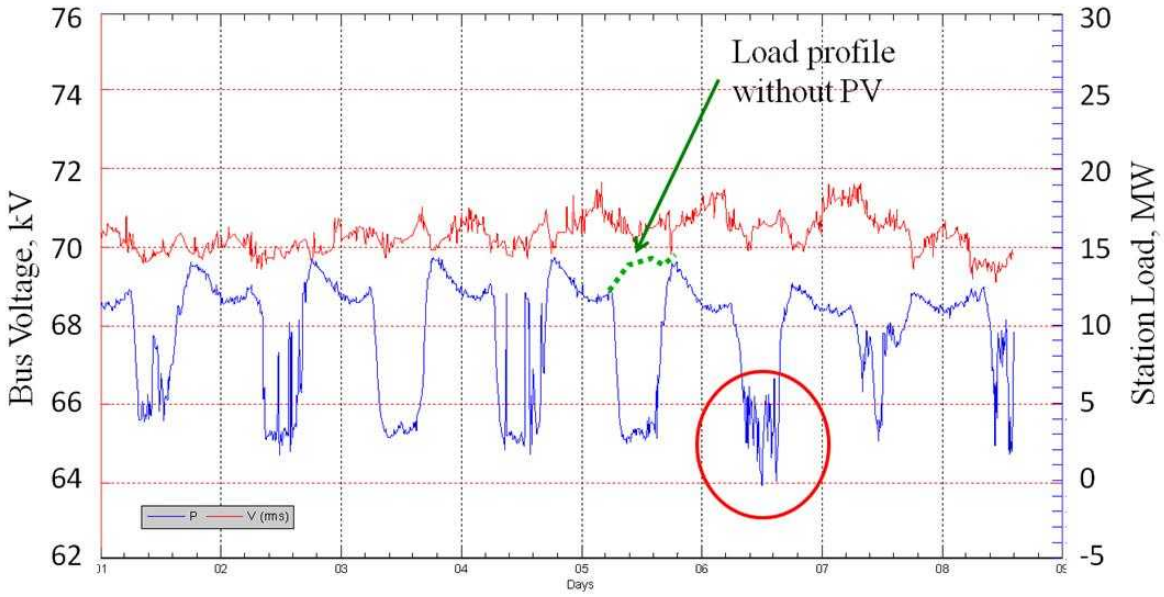
- Supervisory control functions
  - (Slow) closed loop voltage or reactive power control
  - (Slow) active power control
    - Power limiting (curtailment)
    - (Down) AGC response
- Inverter functions
  - Dynamic voltage support
  - (High) frequency response
  - (Up) ramp limiting
  - VRT/FRT



Note: Enabling some active power control functions could impact plant production!

PV Plant Output Variability

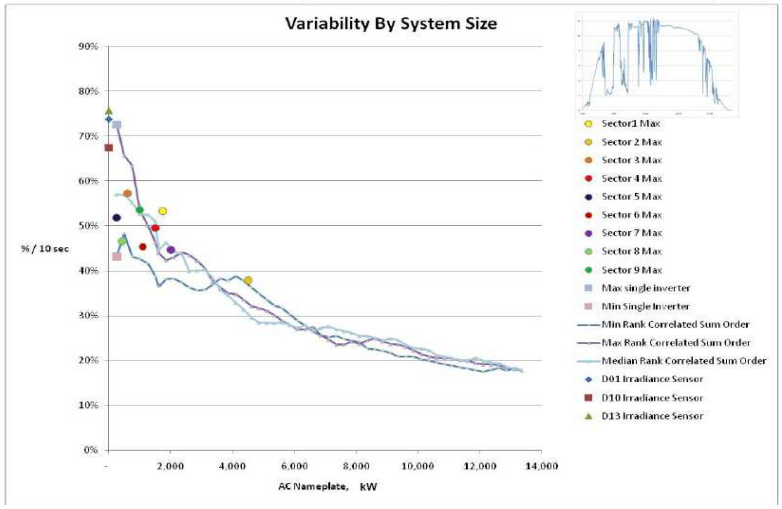
- Variability single large PV plant output rarely causes local system impacts that need mitigation
  - Exception would be weak grids or small (island) grids
  - Aggregated output variability of a fleet of plants

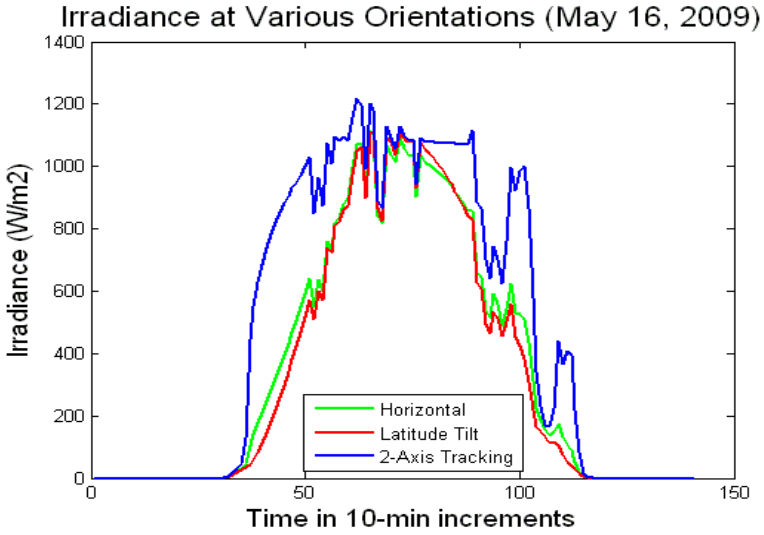


PV Plant Output Variability

- PV plant output variability depends on several factors
  - Local weather (irradiance variability)
  - Plant characteristics
    - Footprint and shape
    - Tracking system
    - DC/AC ratio …

Maximum 10 second change, on the highest 1-minute variability day





Questions?