American Superconductor®

PV Grid Integration with SolarTie™ Solution

Emerging Technologies Working Group (ETWG) Solar Workshop

Monday April 25, 2011

ERCOT

Powered by AMSC®

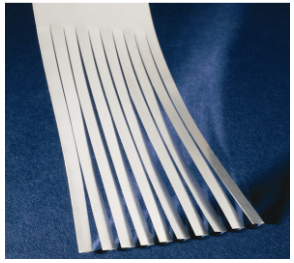
Today's Outline

- Introduction to AMSC
- PV Opportunity in Texas
- Utility Concerns
- PV System Integration
- AMSC D-VAR® System and SolarTie™ Grid Interconnection Solution

AMSC – Company Highlights

Market/Ticker:	NASDAQ/AMSC
Founded:	1987
Headquarters:	Devens, MA, USA
Other Manufacturing Locations	Middleton, WI and New Berlin, WI Klagenfurt, Austria Suzhou, China
Employees:	850+
Patents owned or licensed:	500+

AMSC's Position in the Power Infrastructure

	Generation	Delivery ("the Grid")	Use
	Network Solutions Team		
Power Systems 	✓ Wind turbine designs ✓ Wind turbine electrical systems ✓ Solar plant electrical systems	✓ Grid reliability solutions ✓ Grid capacity solutions ✓ Wind plant grid interconnection systems ✓ Solar plant grid interconnection systems	✓ Industrial power quality solutions ✓ Energy storage ✓ Electric vehicles ✓ Hybrid apps ▶ Motor controls ▶ Defense industry
Superconductors 	✓ SeaTitan™ wind generators ▶ Power plant generators ▶ Power plant transformers	✓ Superconductor cables ✓ Secure Super Grids™ (smart power cables) ✓ Superconductor Electricity Pipelines ✓ Fault current limiters ▶ Transformers	✓ Degaussing cables ✓ Ship propulsion motors ▶ Industrial motors ▶ Magnetic processing ▶ NMR spectroscopy ▶ MagLev trains

✓ **AMSC Focus Today** ▶ **AMSC Future Opportunity**

Nearly 10% of World's Wind-Generated Electricity "Powered by AMSC®"

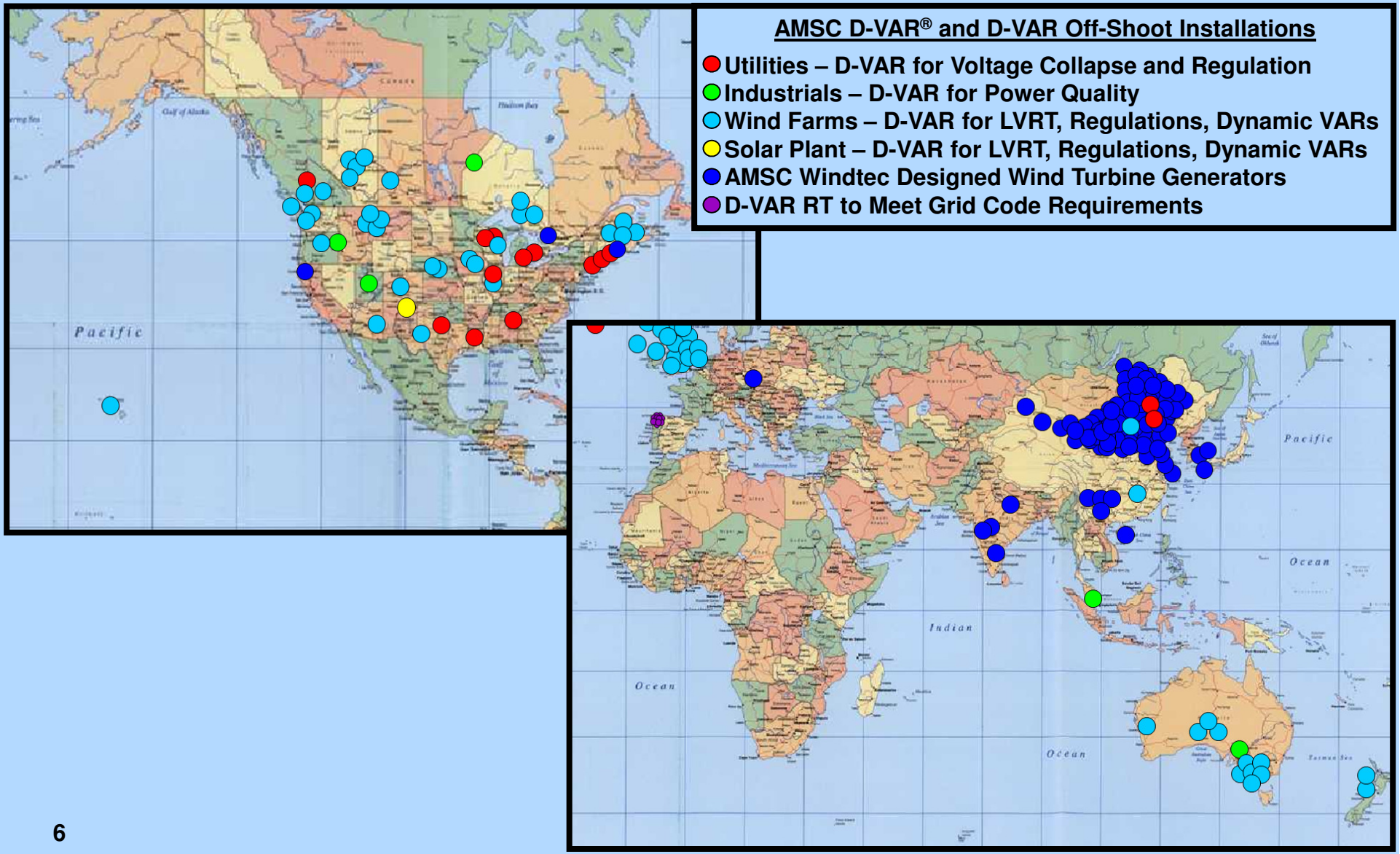
Wind Turbine Designs, Controls, & Converters

- Relied upon by more than a dozen wind turbine manufacturers worldwide, including two of the world's top 10 producers
- Utilized in thousands of wind turbines today
- Shipments to date sufficient to power 10 GW of wind power

Wind Plant Interconnection Solutions

- Worldwide leader in connecting renewable energy sources to the power grid
- D-VAR® and D-VAR RT technology utilized at more than 70 wind plants worldwide
- Shipments to date sufficient to allow interconnection of 5 GW of wind power

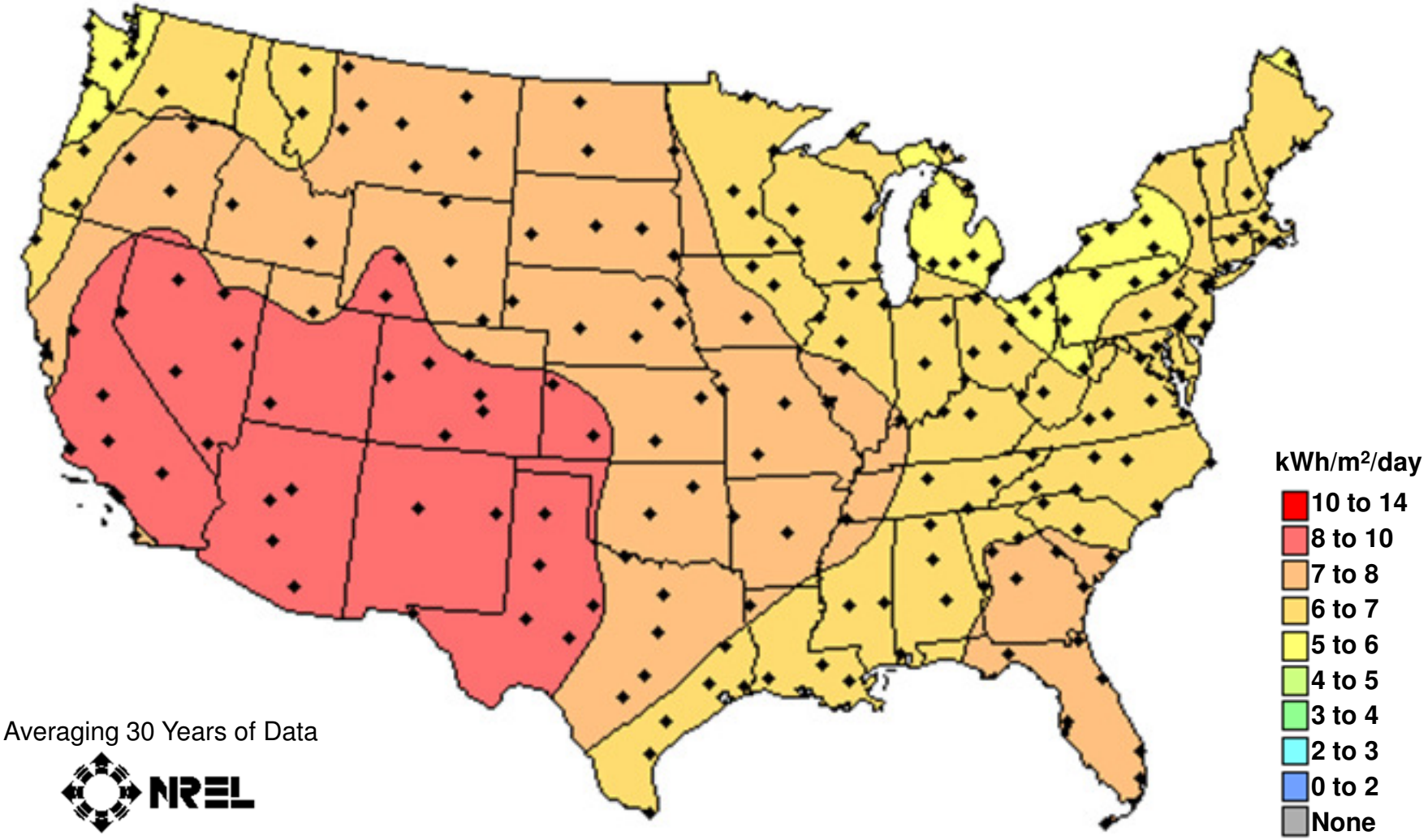
AMSC Power System Worldwide Installations



AMSC D-VAR® and D-VAR Off-Shoot Installations

- Utilities – D-VAR for Voltage Collapse and Regulation
- Industrials – D-VAR for Power Quality
- Wind Farms – D-VAR for LVRT, Regulations, Dynamic VARs
- Solar Plant – D-VAR for LVRT, Regulations, Dynamic VARs
- AMSC Windtec Designed Wind Turbine Generators
- D-VAR RT to Meet Grid Code Requirements

North American Solar Opportunity
Maximum Daily Solar Radiation - USA



Averaging 30 Years of Data

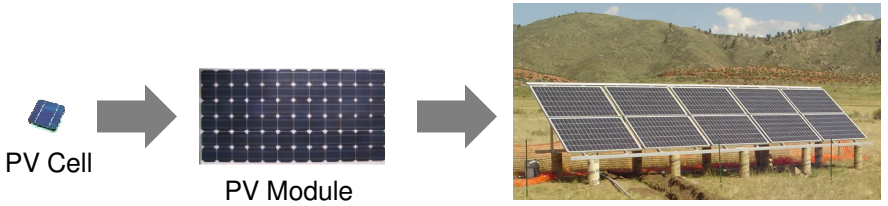
NREL

National Renewable Energy Laboratory
Resource Assessment Program

How a Photovoltaic System Works

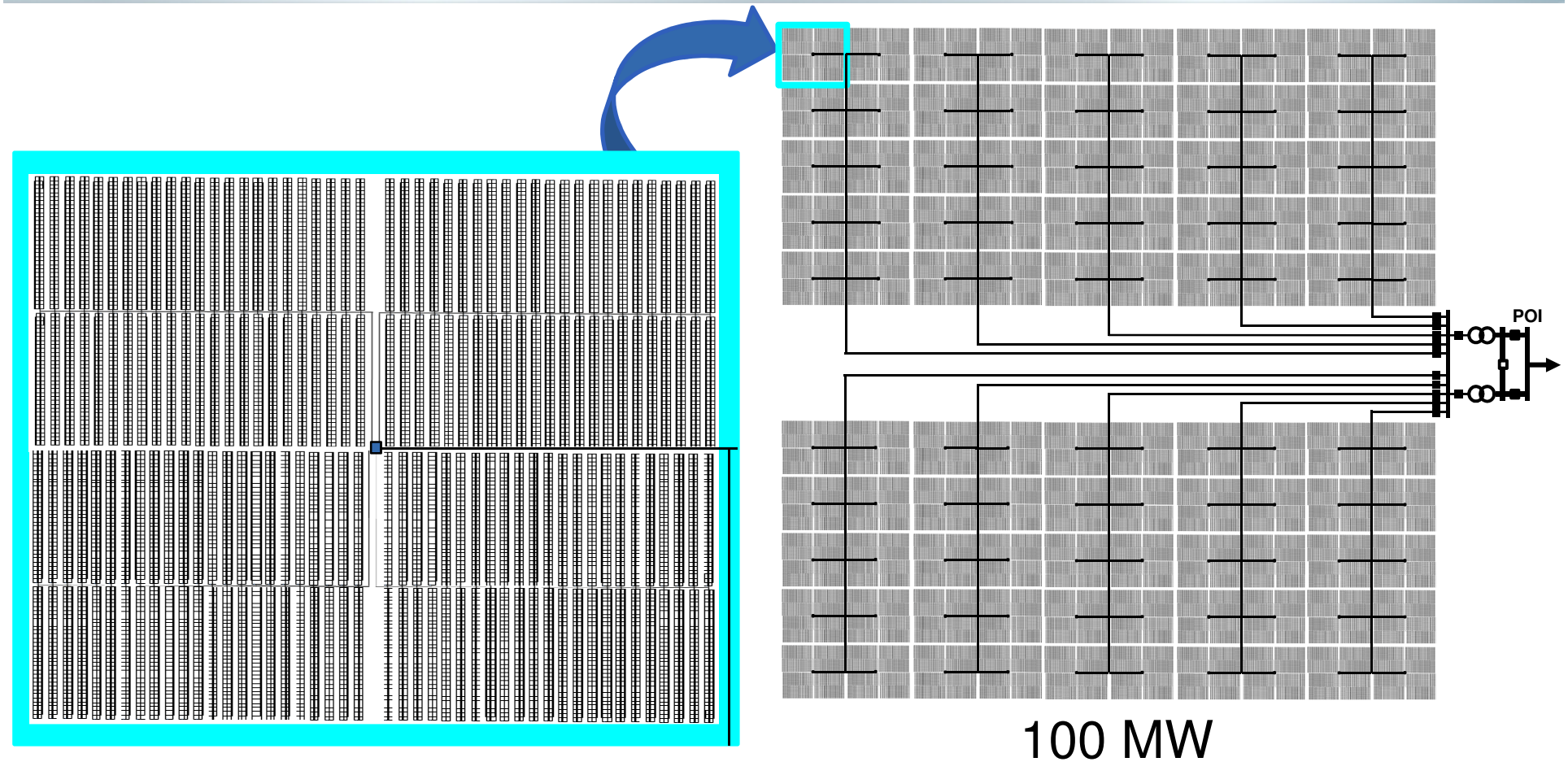
SOLTEN II (11 MW) – Granadilla Industrial Estate, Canary Islands

Photovoltaic Array (15 MW) – Nellis Air Force Base, Las Vegas, NV



- Solar PV cells > modules > arrays convert sunlight directly to direct current electricity
- Inverters convert DC current from the PV arrays to AC current
- Low voltage and medium voltage collector system
- Transformers used to tie the collector system into the transmission system

Example of 100 MW PV Collector Grid



1 MW Block

700ft by 500ft (214m by 153m)

100 MW

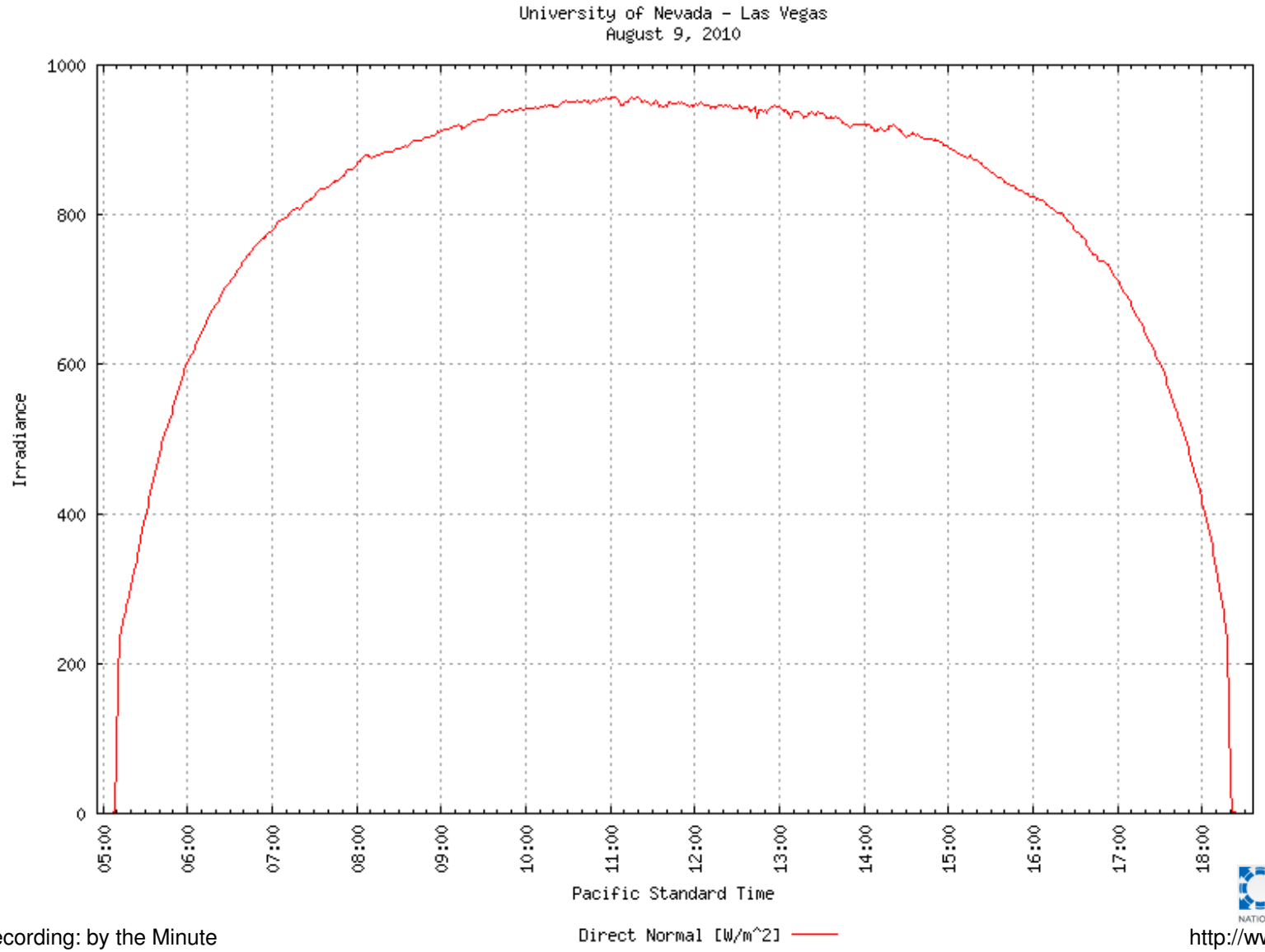
~1.25 Square Miles (3.3 km^2)

Utility Concerns with PV Plants

Utilities have many concerns about new generation on their transmission and distribution facilities. For PV plants, most of their concerns fall into the following categories:

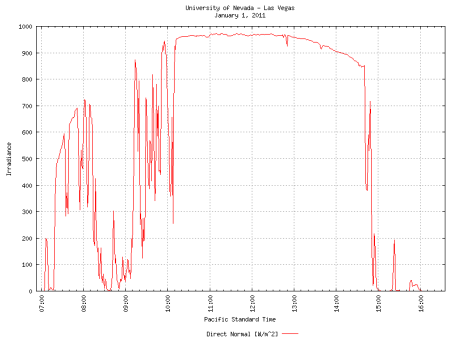
- **System ACE**
  - PV Plant's ramp rates in the morning and evening along with their response to clouds are major utility concerns as they impact system ACE and area voltages
- **System Normal and Contingency Operation (Slow Regulation)**
  - PV Plant's impact on system normal and contingency flows and voltage
- **Transient and Voltage Stability (Dynamic Events)**
  - The dynamic change in the PV plant's output along with other system events could cause unforeseen fast acting issues
- **Power Quality**
  - Electromagnetic transients, flicker, and harmonics impacts are all issues that PV Plants need to aware of and know that their plant is not causing system problems
- **HVRT, LVRT, and Islanding**
  - PV Plants along with all other generation must be able to handle correctly these newer issues that have come from the new interconnection grid codes
- **Fault Currents**
  - Additional PV Plant's impact on short circuit current ratings

Example of a Sunny Day in Las Vegas

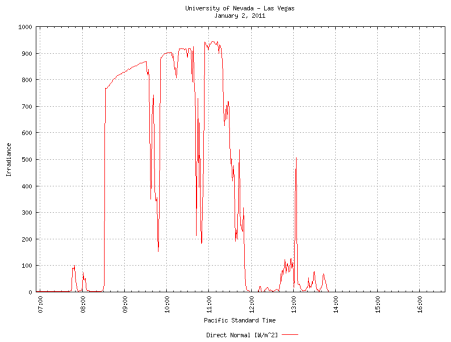


http://www.nrel.gov/midc/

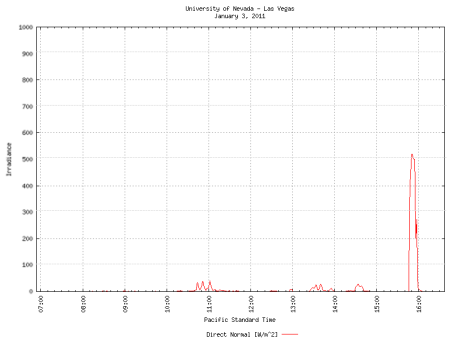
Example of the First Seven Days of January



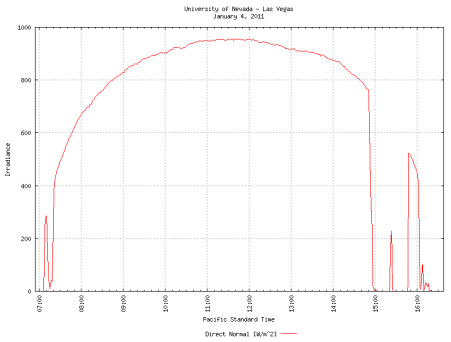
Saturday Jan 1st



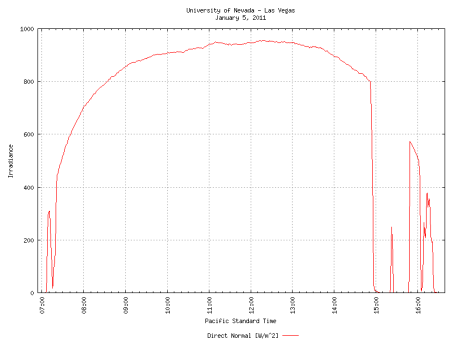
Sunday Jan 2nd



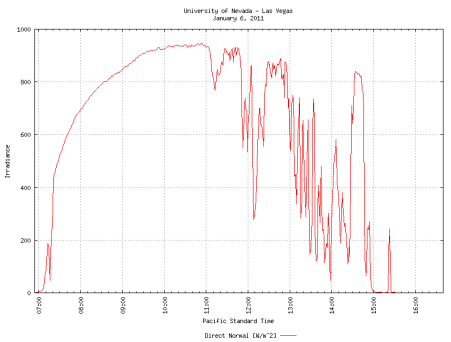
Monday Jan 3rd



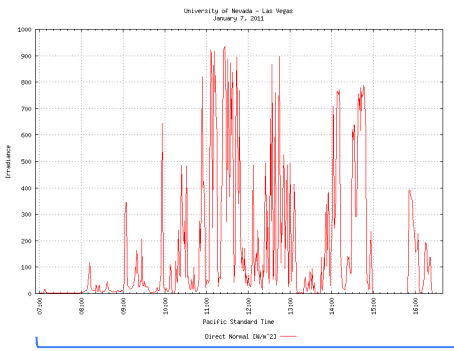
Tuesday Jan 4th

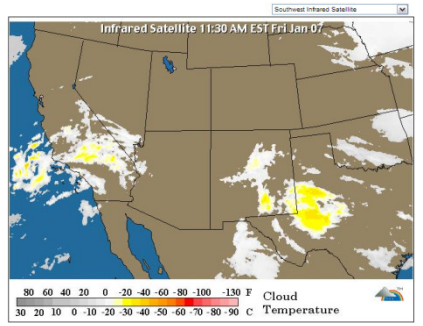


Wednesday Jan 5th



Thursday Jan 6th





Friday Jan 7th

http://www.nrel.gov/midc/

AMSC Grid Management Experience Connecting Renewables to the Grid

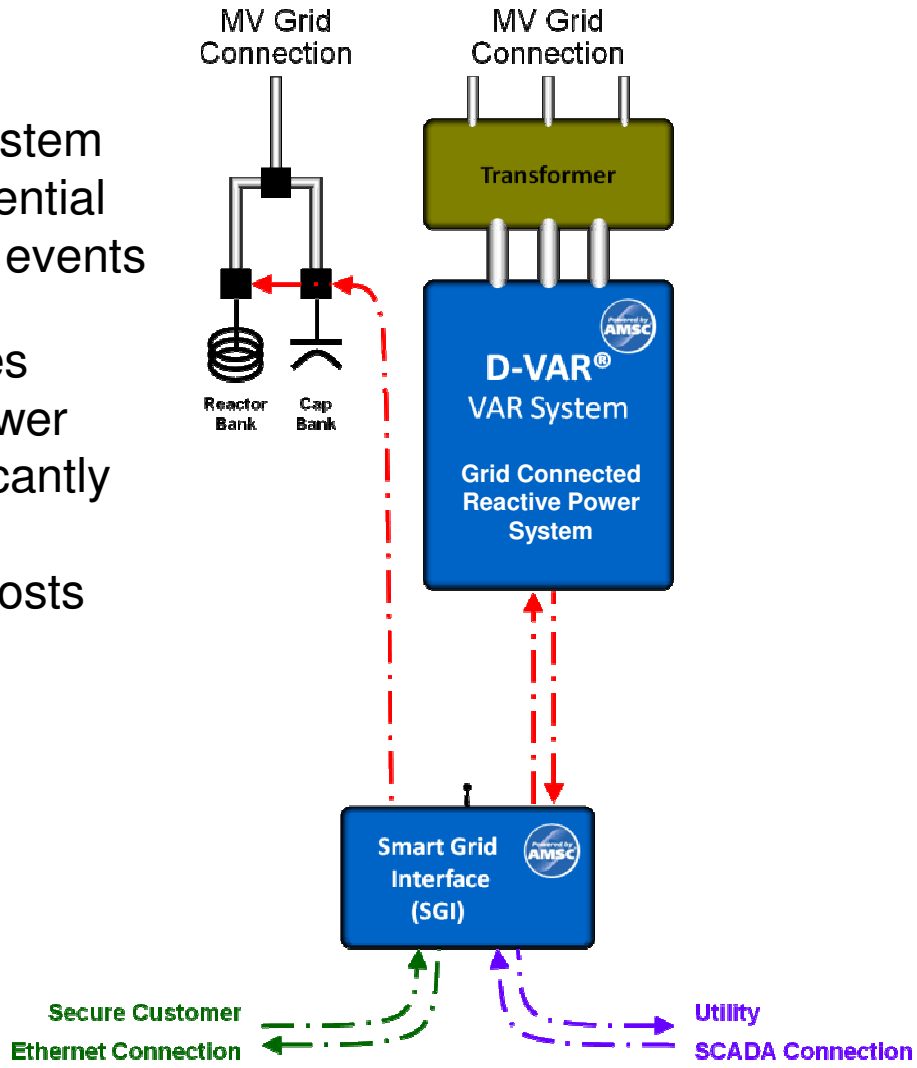
- Just as wind power plants are required to act more like conventional power plants, so too are Solar PV plants
- Existing renewable generation interconnection requirements and grid codes have to also be met by Solar PV plants
- Upfront planning for Solar PV plants is required to establish:
  - The least cost design considering initial system costs and collector system losses
  - The optimum design of the inverter system for real and reactive power control
  - The Solar PV plant's need for additional reactive capability to meet voltage regulation, power factor, and dynamic VAR response requirements

AMSC Grid Management Experience
Meeting Interconnection Requirements

- Developers need to coordinate with multiple vendors to meet interconnection requirements and grid codes
- Multiple parties are usually involved in planning and design of the PV systems, voltage/power factor control, SCADA . . .
- AMSC solutions reduce these additional challenges and risks

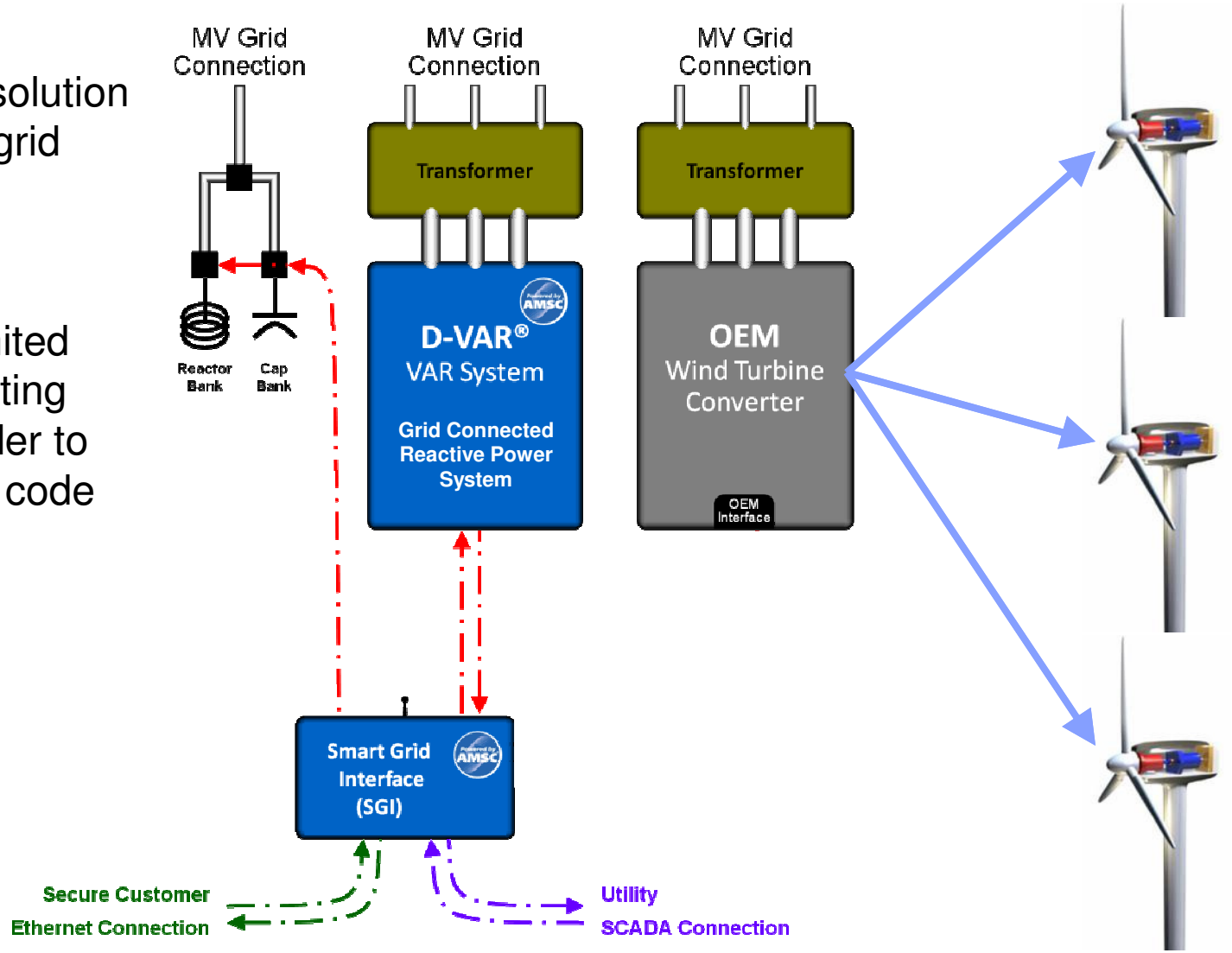
D-VAR® System – Utility/Industrial Support

- Helping utilities recovery their system voltage from potential voltage collapse events
- Helping industries improve their power quality by significantly reducing their electric outage costs



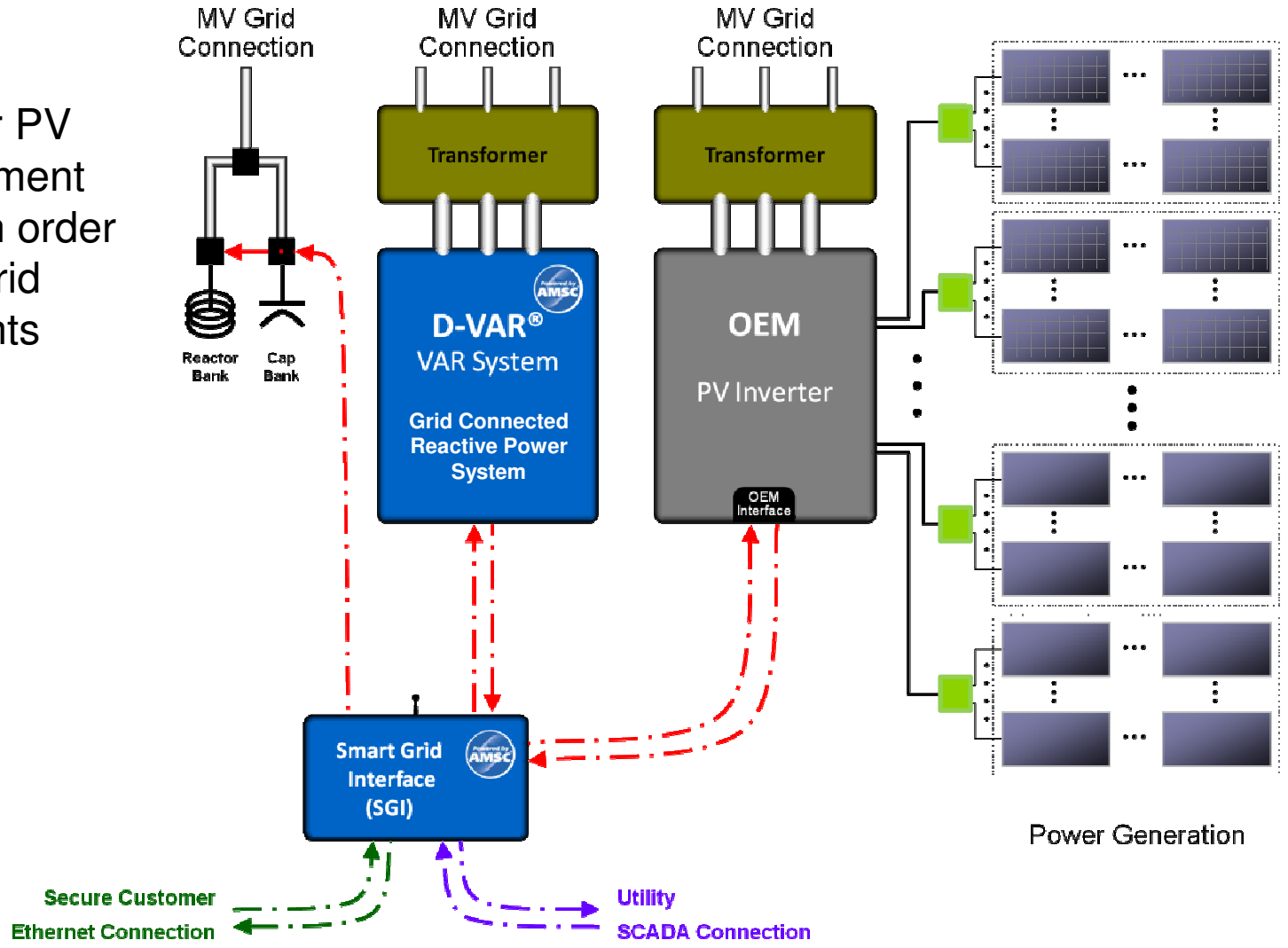
D-VAR® System – Grid Support for Wind Plants

- Utility/industrial solution applied to meet grid interconnection requirements
- Supplements limited capability of existing equipment in order to comply with grid code requirements

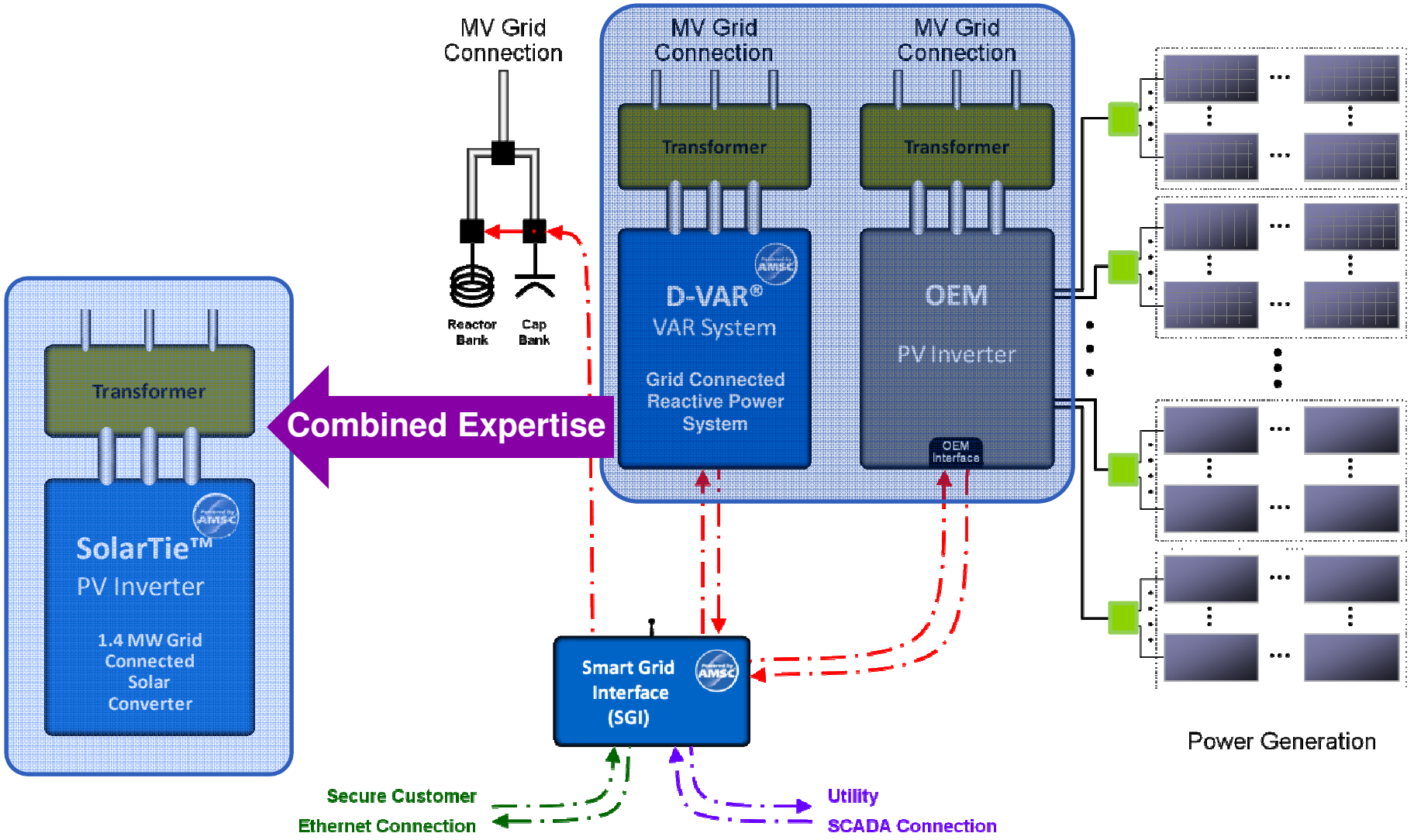


D-VAR® System – Grid Support for Solar Plants

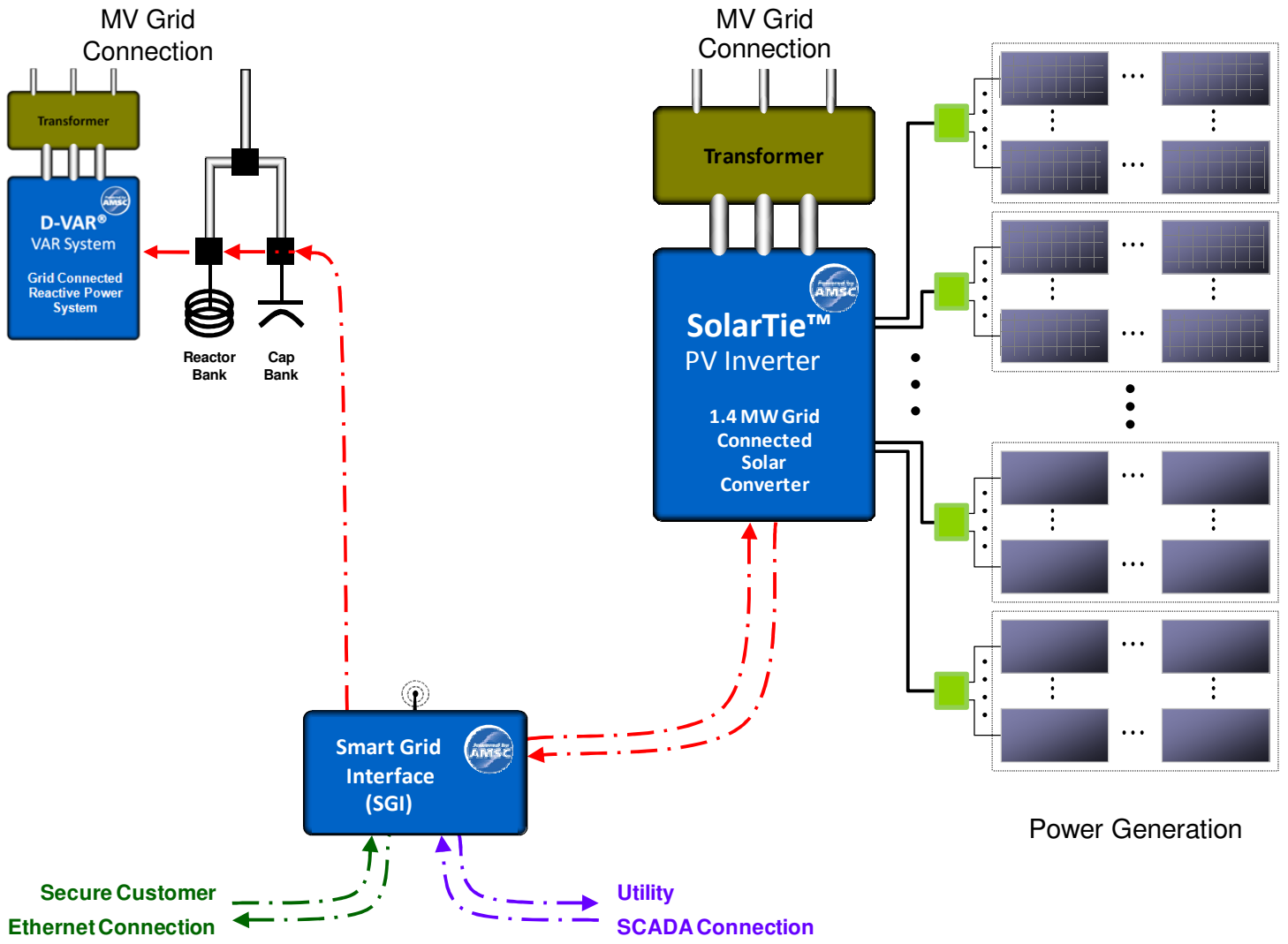
- Beginning to be installed at Solar PV Plants to supplement their capability in order to comply with grid code requirements



SolarTie™ Solution includes PowerModule™ & D-VAR® System Technologies

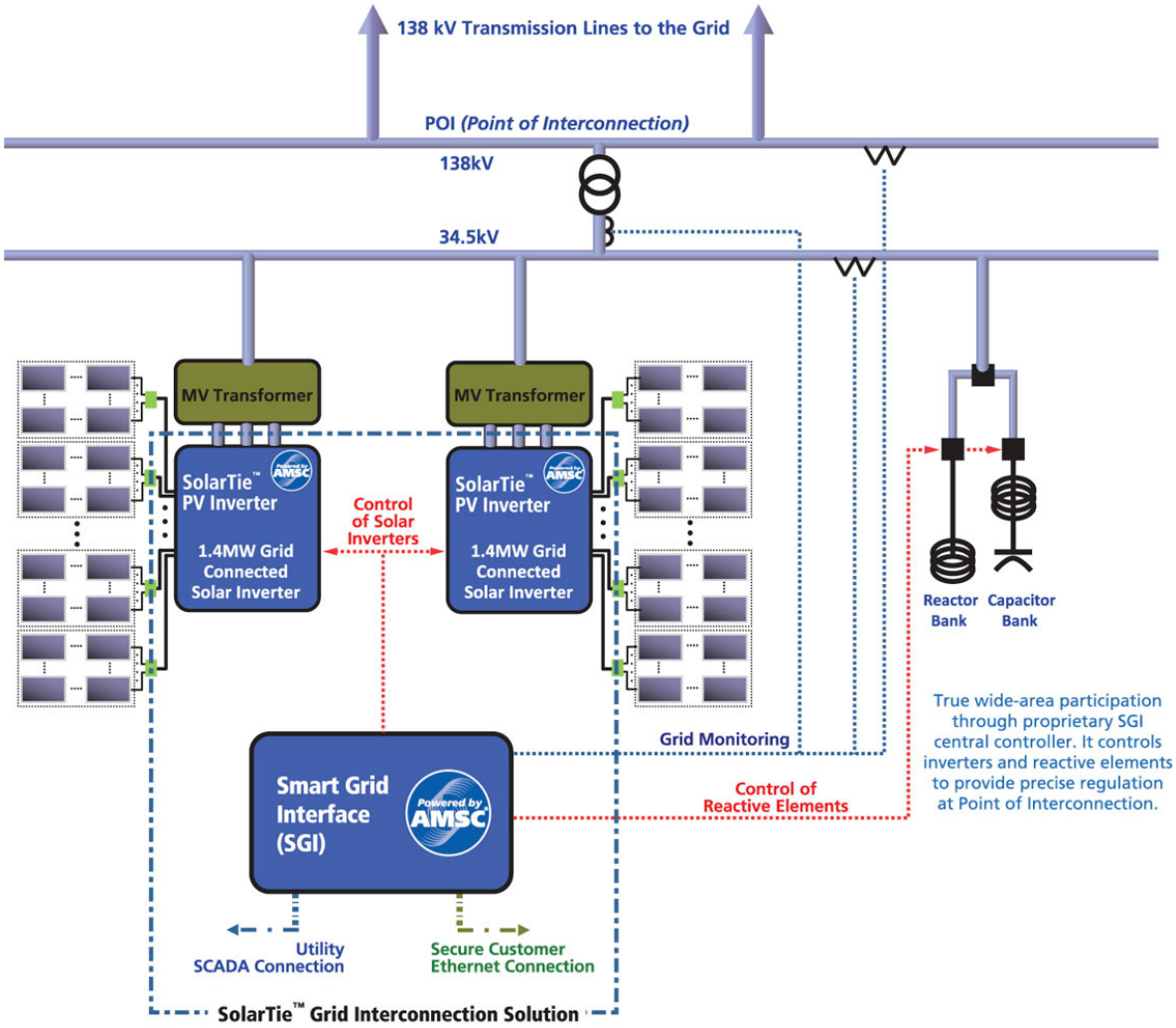


AMSC SolarTie™ Grid Interconnection Solution
Smart Grid Management Support

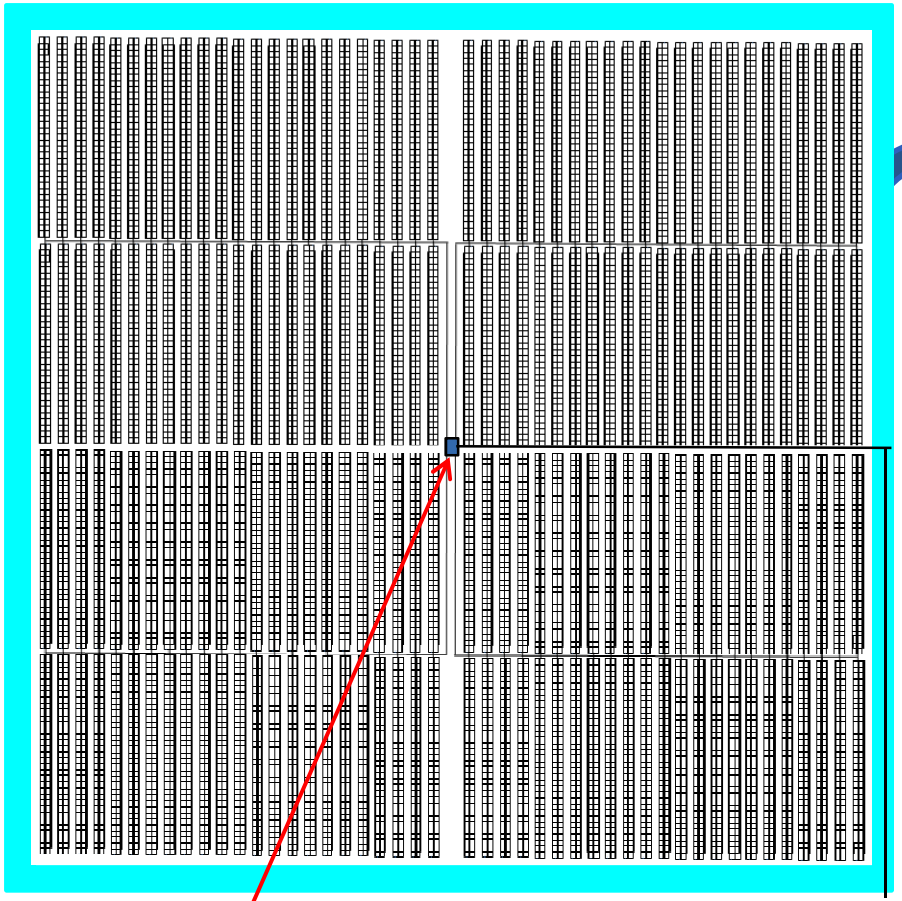


SolarTie™ Grid Interconnection Solution Will Use AMSC Grid Management Experience

- **SolarTie Inverters**
  - Utilizes D-VAR® technology
  - Uses same platform as in thousands of wind turbines worldwide
  - Maximizes MW output
- **Wide Area Participation**
  - Smart Grid Interface (SGI) controls the inverters and other devices to efficiently meet POI real and reactive power requirements
- **Secure Communication**
  - Provides safe gateway for plant to utility two-way communication



AMSC SolarTie™ Inverter and SGI on a Large PV Solar Plant

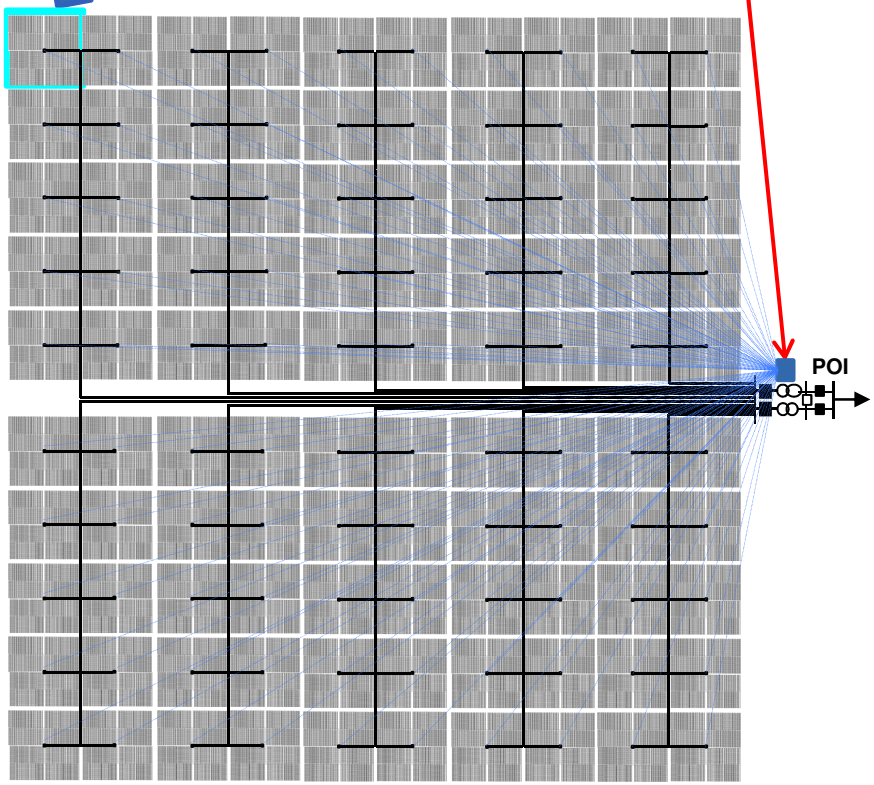


1 MW Block 700' by 700'
(214m by 214m)

SolarTie™ Inverter[1]

140 MW PV Power Plant

Smart Grid Interface (SGI)[1]

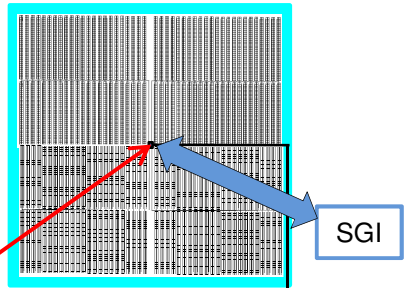


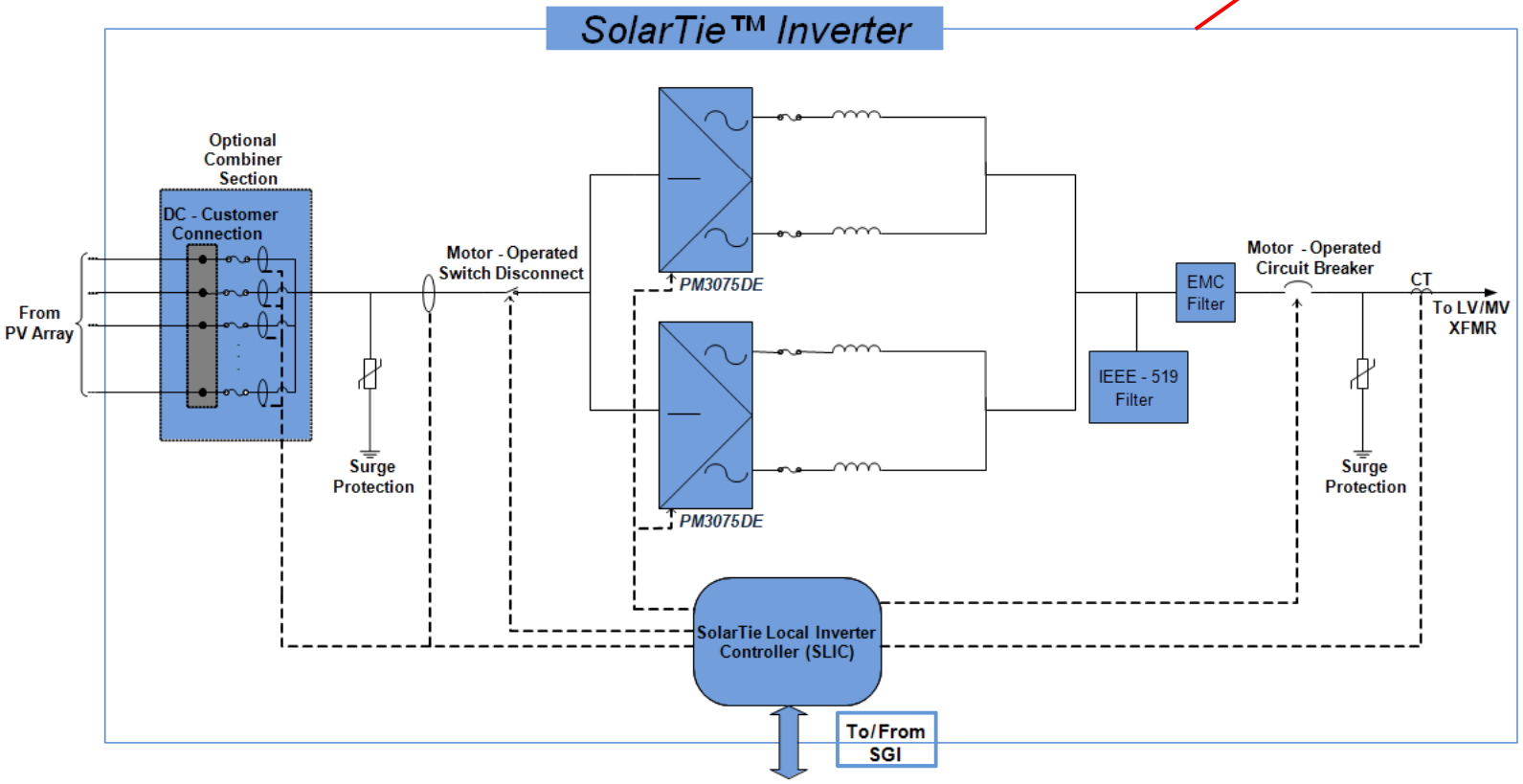
140 MW ~1.5 Square Miles (~4 km²)

1 *Final installation design may differ from configuration shown here*

SolarTie™ Inverter

- **Flexible Solar PV Inverter Block -** developed for utility-scale multi-MW installations
- **Utilizes PM3000 Series Inverters -** proven technology in wind applications worldwide

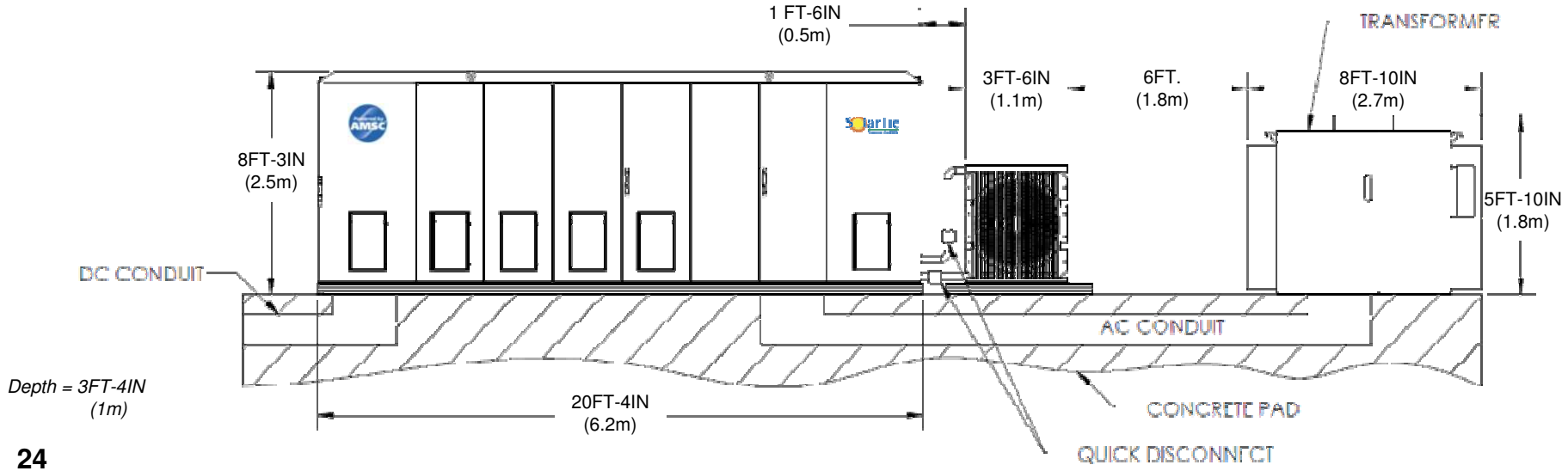




SolarTie™ Enclosure

SolarTie™ System

- **Easy Installation**
  - Simple pad-mount design – *inverter, heat exchanger, and transformer*
  - Outdoor rated enclosure – *extra/external shelter not needed*
  - Standard transformer – *no need for special and costly dual-winding transformer*
  - Liquid cooling system comes fully charged from factory
- **Environmental Robustness** – *cooling system using lessons learned from real and harsh utility-scale sites*



SolarTie™ Inverter - Key Characteristics

- **Voltage/Power Factor Control**
  - Settable power factor for steady-state voltage or power factor control
- **True Sub-Cycle Transient Response**
  - The SolarTie system provides sub-cycle detection and response to grid disturbances
- **Superior Environmental Ratings**
  - Outdoor design rated for -40℃ to 50℃ operating temperature (no additional enclosure required)
  - Maximizing power electronics and other sensitive component life-times with liquid-cooling and sealed designs
- **Inverter Start-Up up to 1000 VDC**
  - Inverter can start operation at 1000 VDC array voltage
- **Wide AC Output Voltage**
  - Settable 268 to 480 VAC output voltage minimizes BoS cost

SolarTie™ Grid Interconnection Solution Will Use AMSC Grid Management Experience

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- **Wide Area Participation**
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- **Secure Communication**
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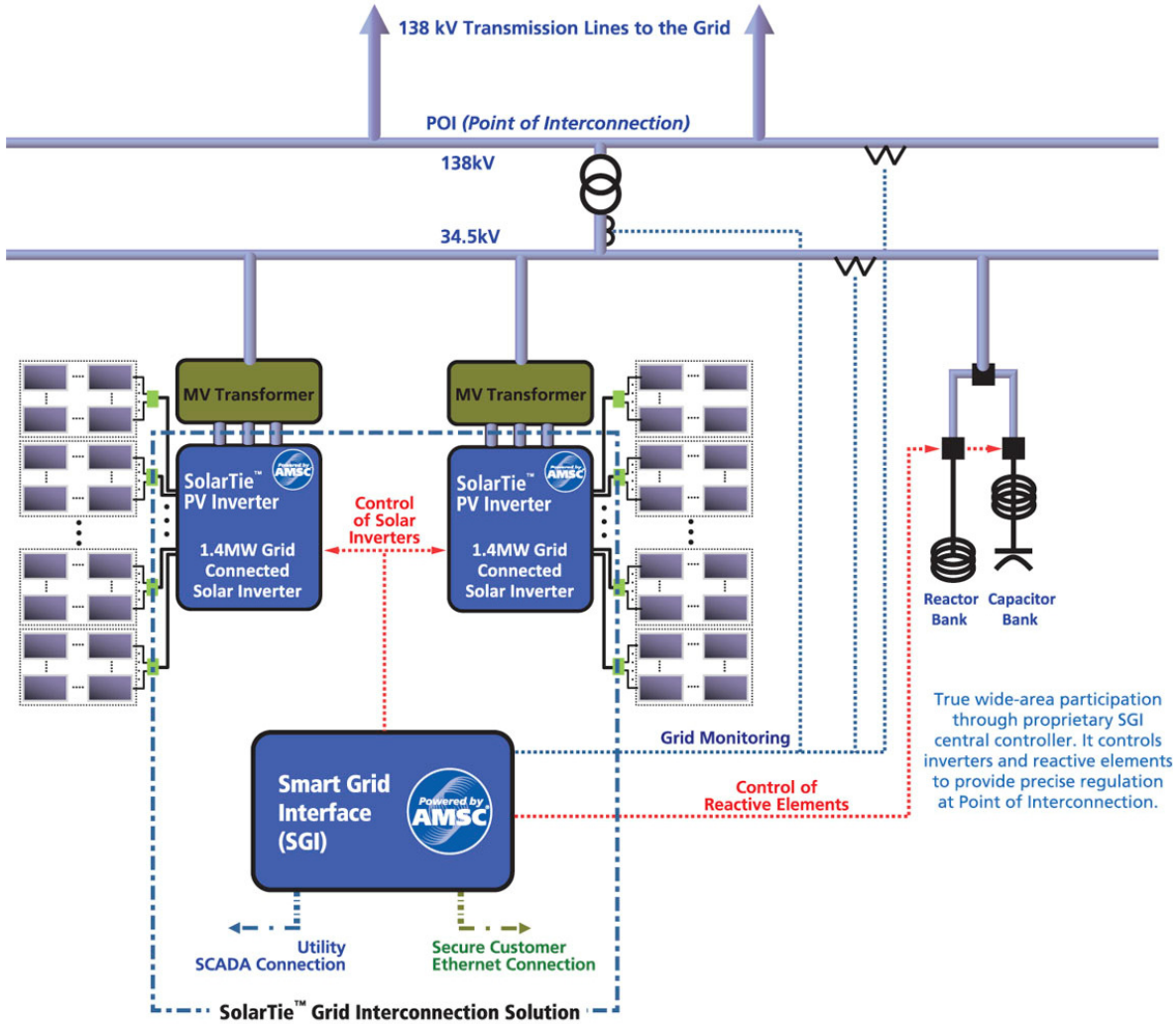
- **Interconnection Studies**
  - Network planning group with utility planning experience

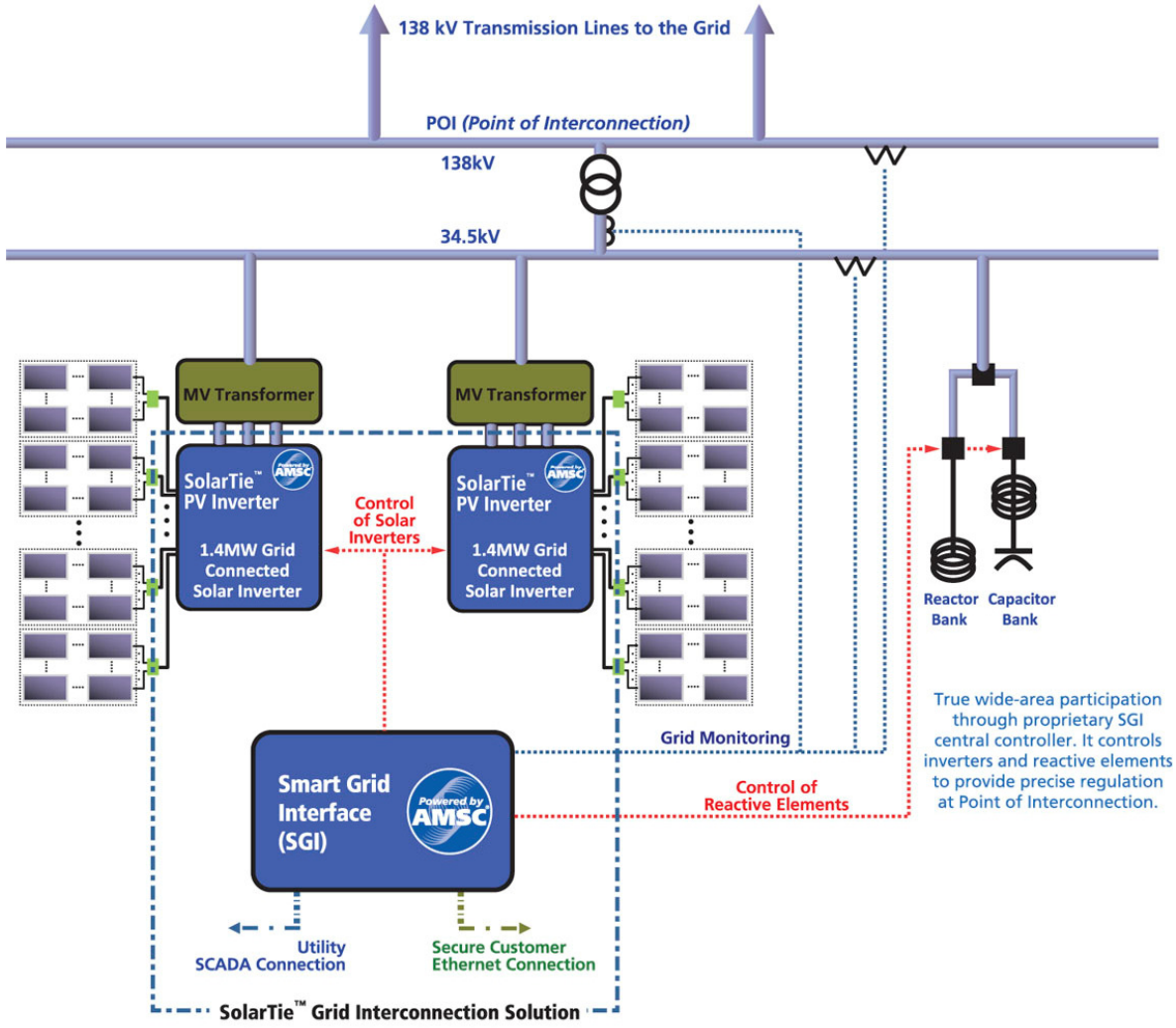


Wind Farm Generator Locations and Feeder Layout

- Goal - arranged WTGs to catch the prevailing winds
- Install anemometers
- Install WTGs along ridge lines or hilltops in clustered arrangements

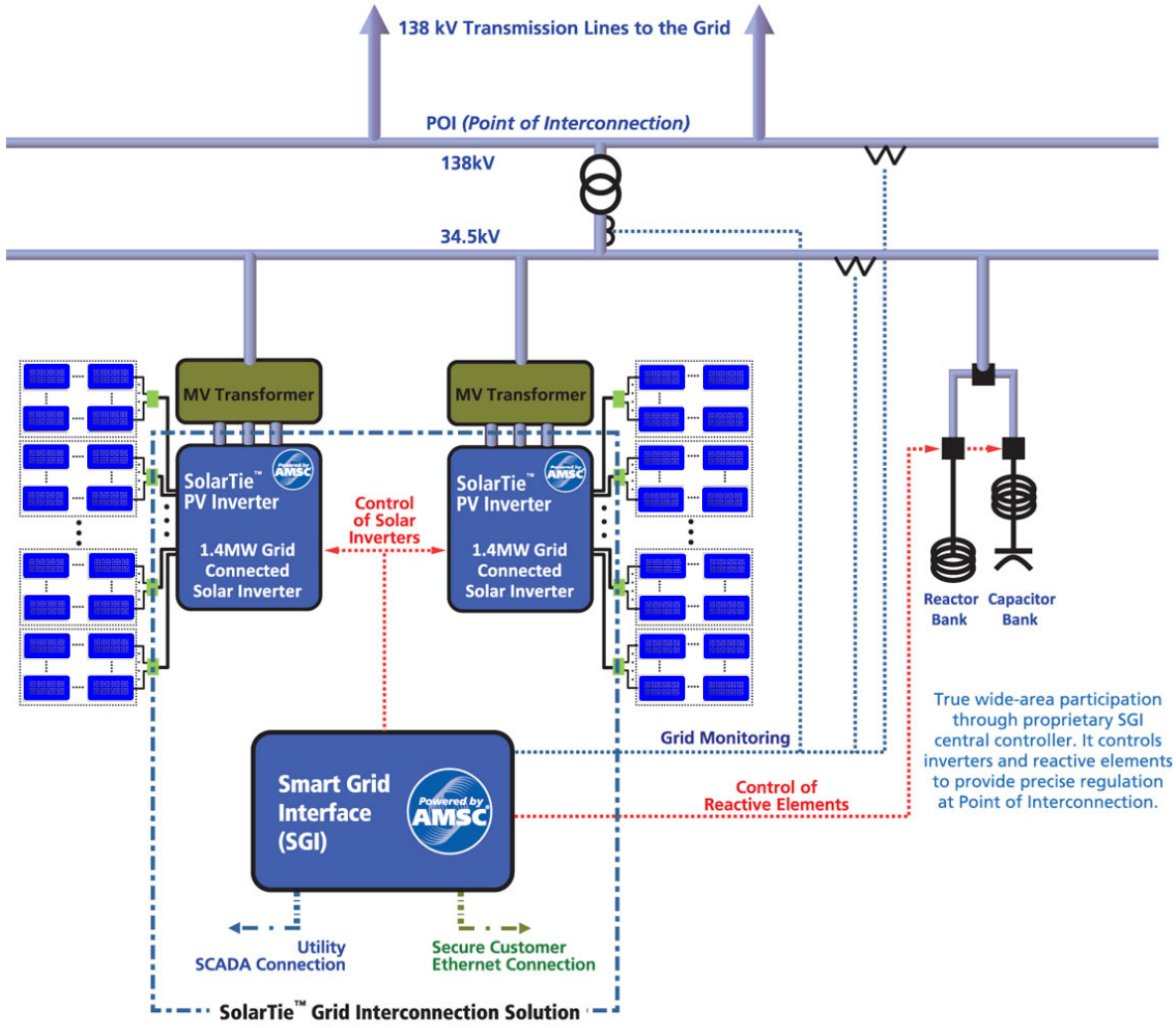
Solar Plant Interconnection Studies

- **Interconnection Studies**
  - Network planning group with utility planning experience



Solar Plant Interconnection Studies

- **Interconnection Studies**
  - Network planning group with utility planning experience
    - Decide on DC Voltage for PV Panels 600V/1000V



Solar Plant Interconnection Studies

- **Interconnection Studies**
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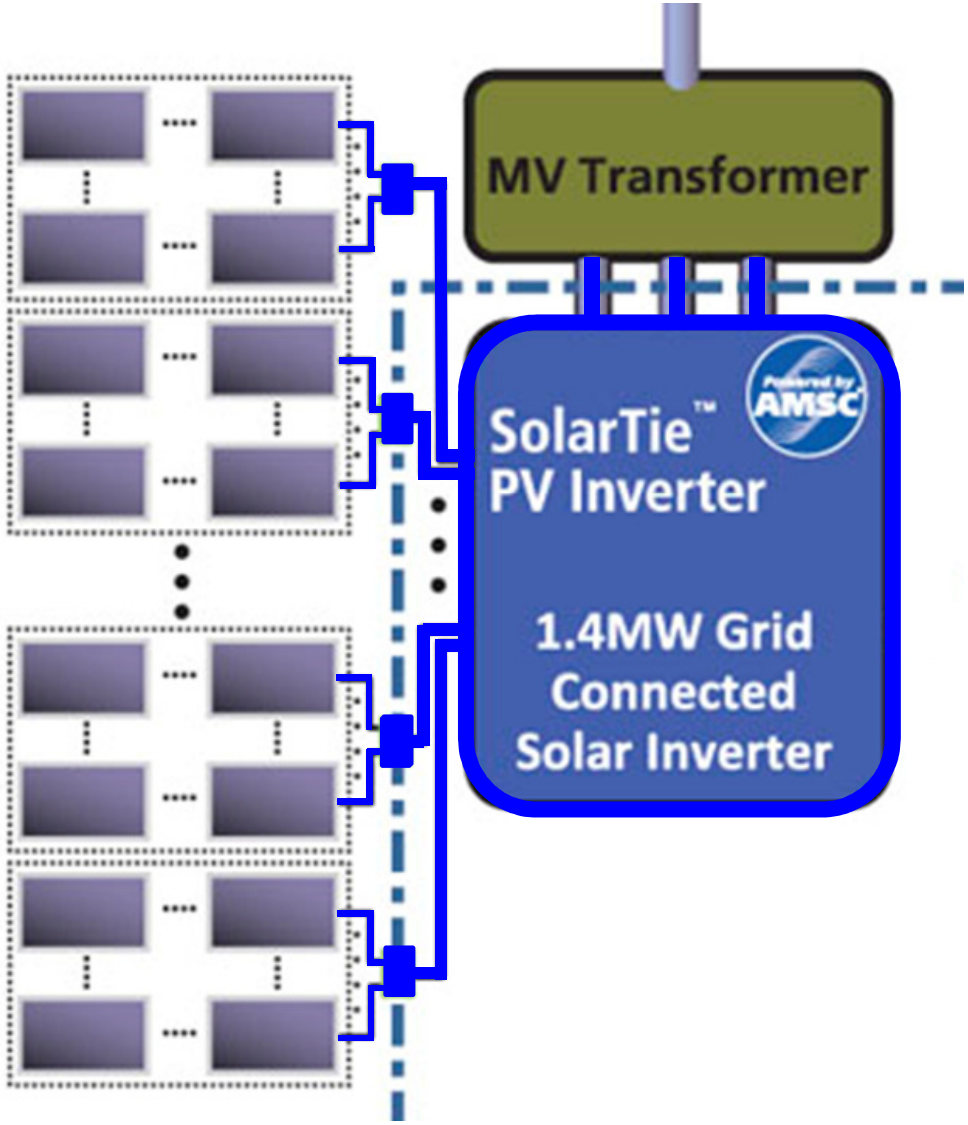
    - Decide on DC Voltage for PV Panels 600V/1000V
    - Determine Minimum DC Voltage
      - Helps increase efficiency at low sunlight
      - Helps Size the Inverters
      - Sets the Inverter's AC Voltage
      - Helps Determine the Number of Inverters



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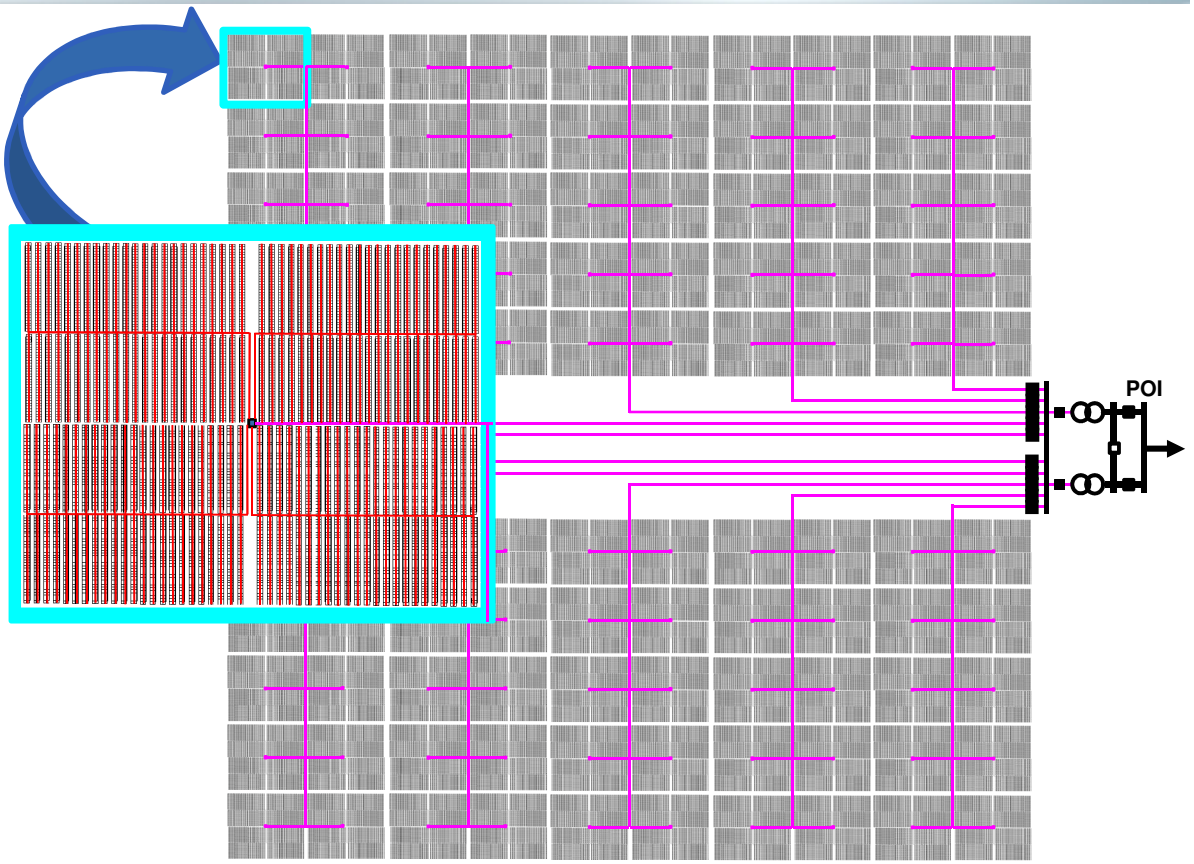
      - Set AC Voltage
      - Set Inverter Size and Number
    - Design the **DC** and **AC** Collector Systems
    - Determine System Losses



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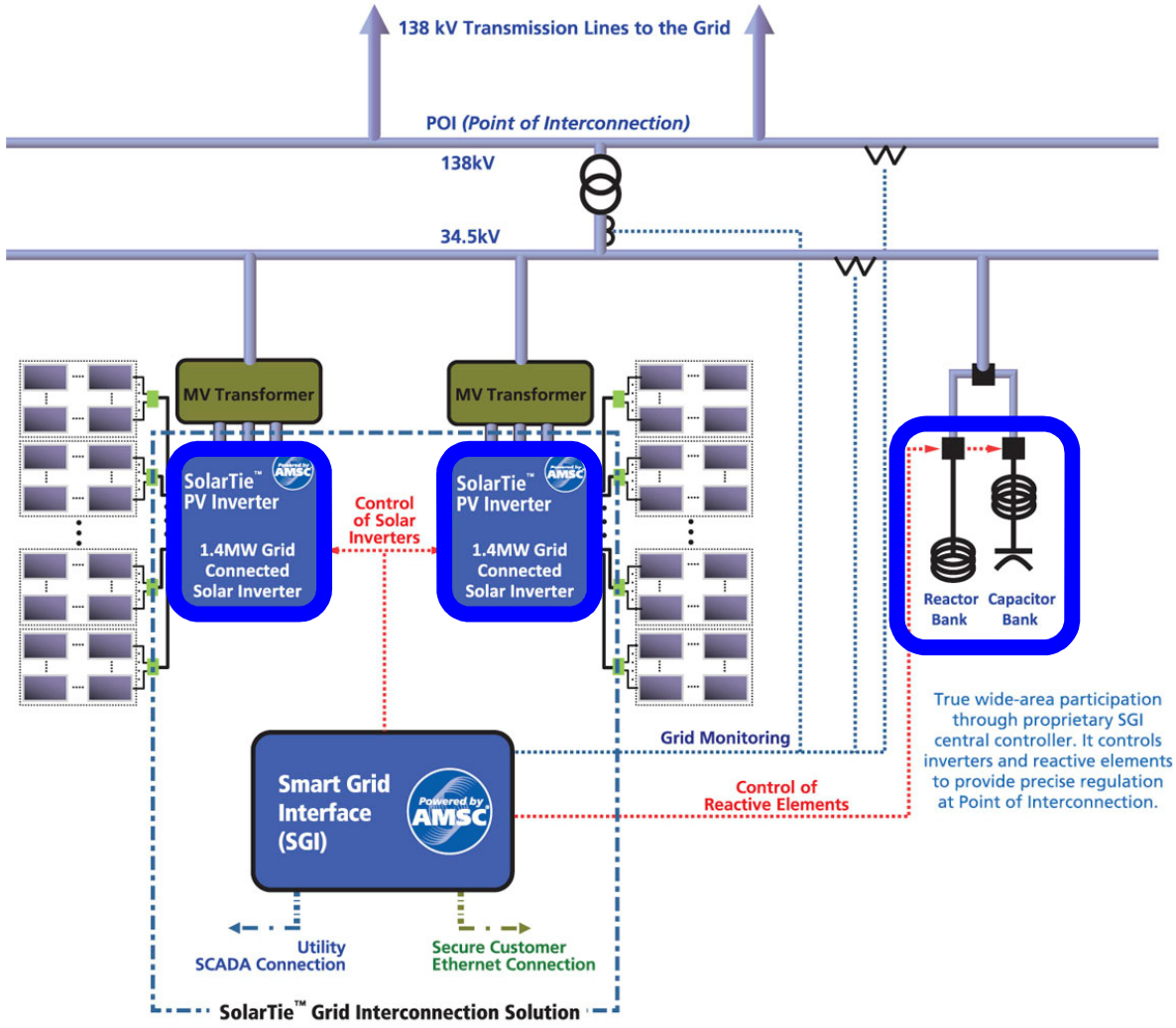
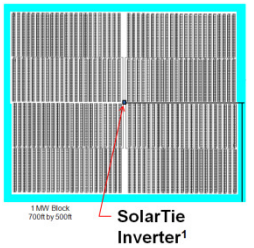
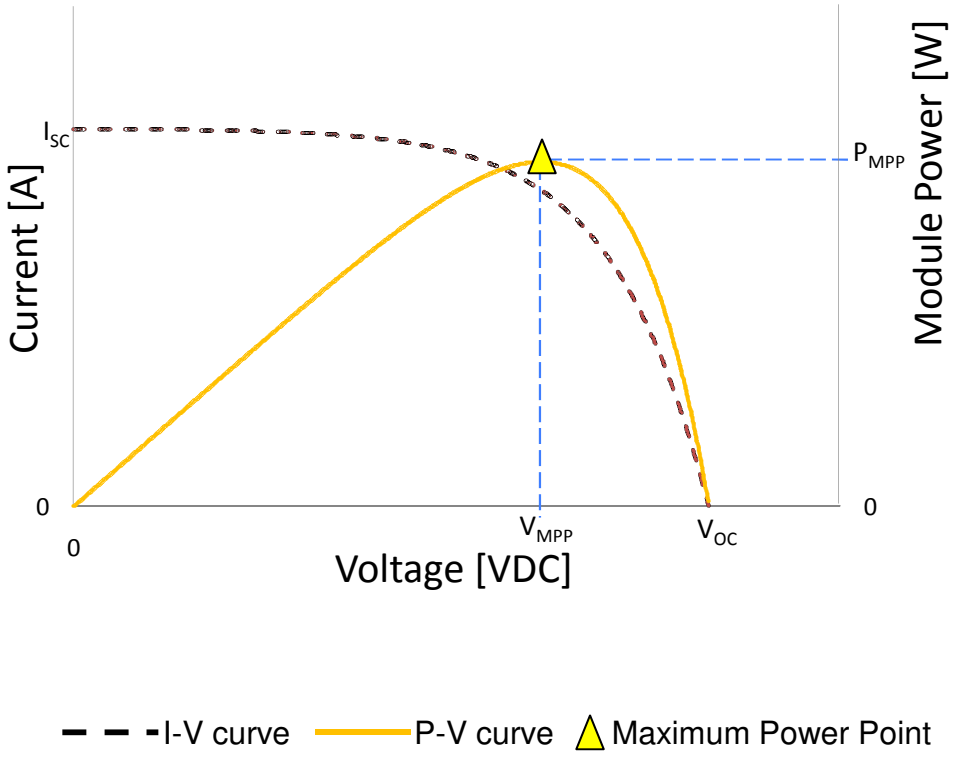
    - Design the DC and AC Collector Systems
    - Determine System Losses
    - Develop System to Meet Grid Code Voltage and/or PF Requirements



PhotoVoltaic (PV) Panels Introduction

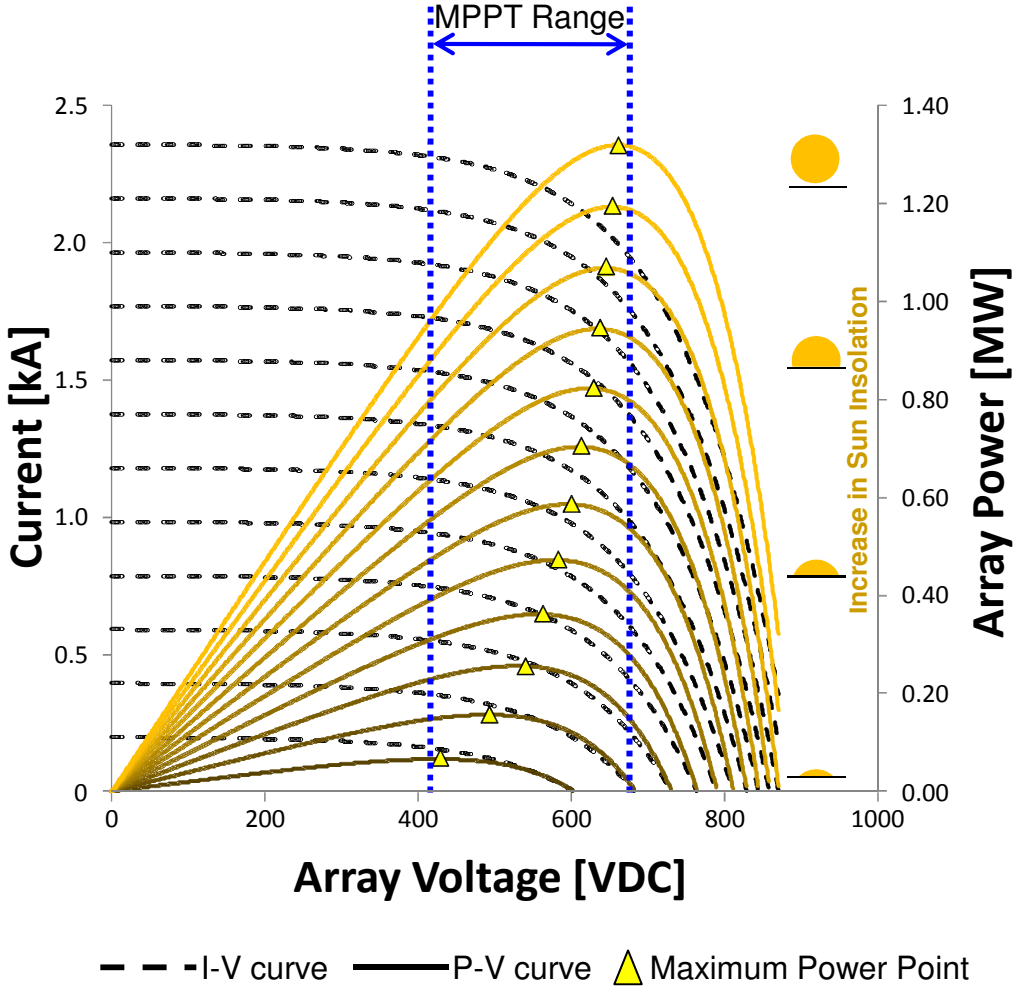
- Photovoltaic Modules are mainly characterized by its I-V curve
- I-V characteristics are of a non-linear type
- Short Circuit current (I_{SC}) is the current level at zero terminal volts
- Panel open circuit voltage (V_{OC}) is the voltage level at zero amps
- Power available at PV panel terminals is determined by P = I x V curve
- Its maximum point (on the vertical axis) is called MPP (Maximum Power Point)
- The panel terminal voltage leading to MPP is called V_{MPP} (Voltage level for MPP)





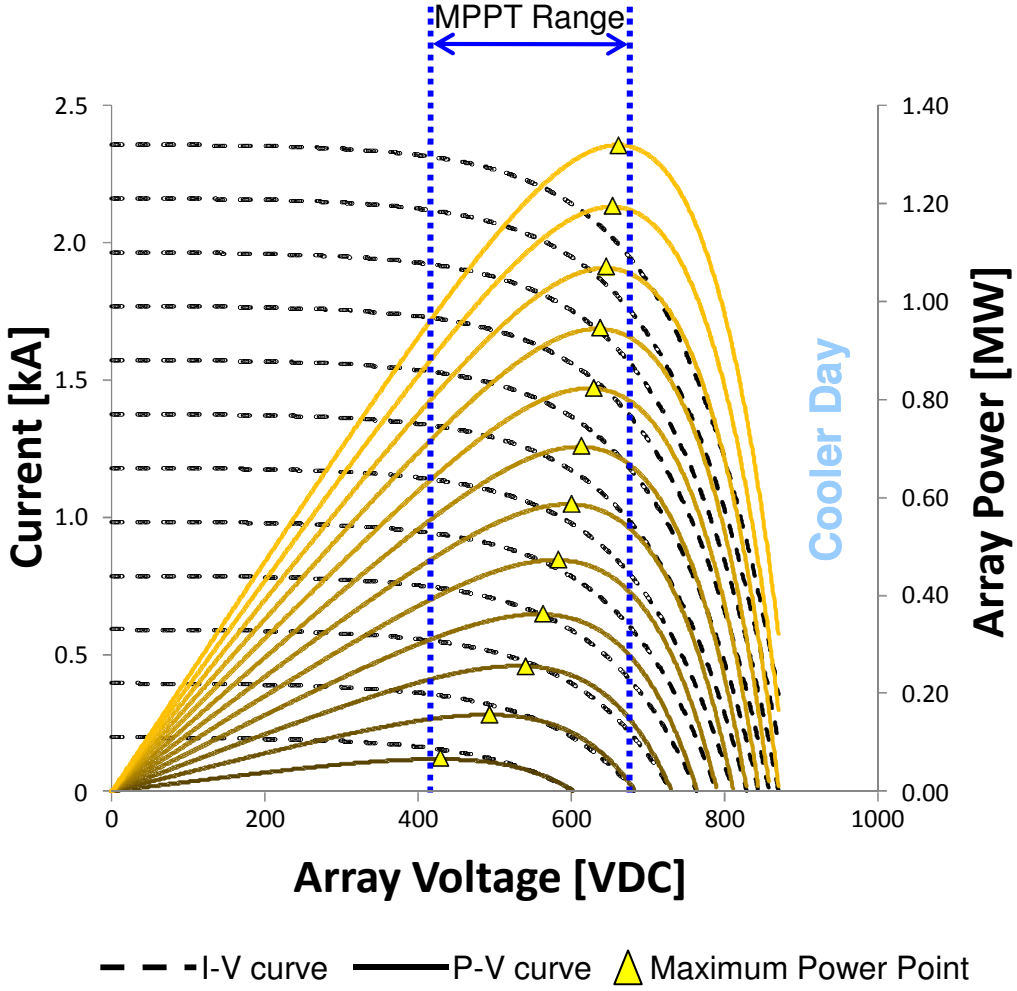
MPPT – Maximum Power Point Tracking Insolation Impact

- I-V curve changes due to sun insolation and so does the power characteristic
- As the module power curve changes, P_{MPP} and V_{MPP} change as well
- Thus, the correct voltage (V_{MPP}) has to be applied to PV panel to harvest the maximum power available, which changes constantly during the day
- Solar Inverters are equipped with MPPT algorithms that track array's Maximum Power Point during the day
- Tracking can be done by changing inverter DC voltage and measuring resultant power
- The MPPT range is the interval between minimum and maximum V_{MPP} during the day



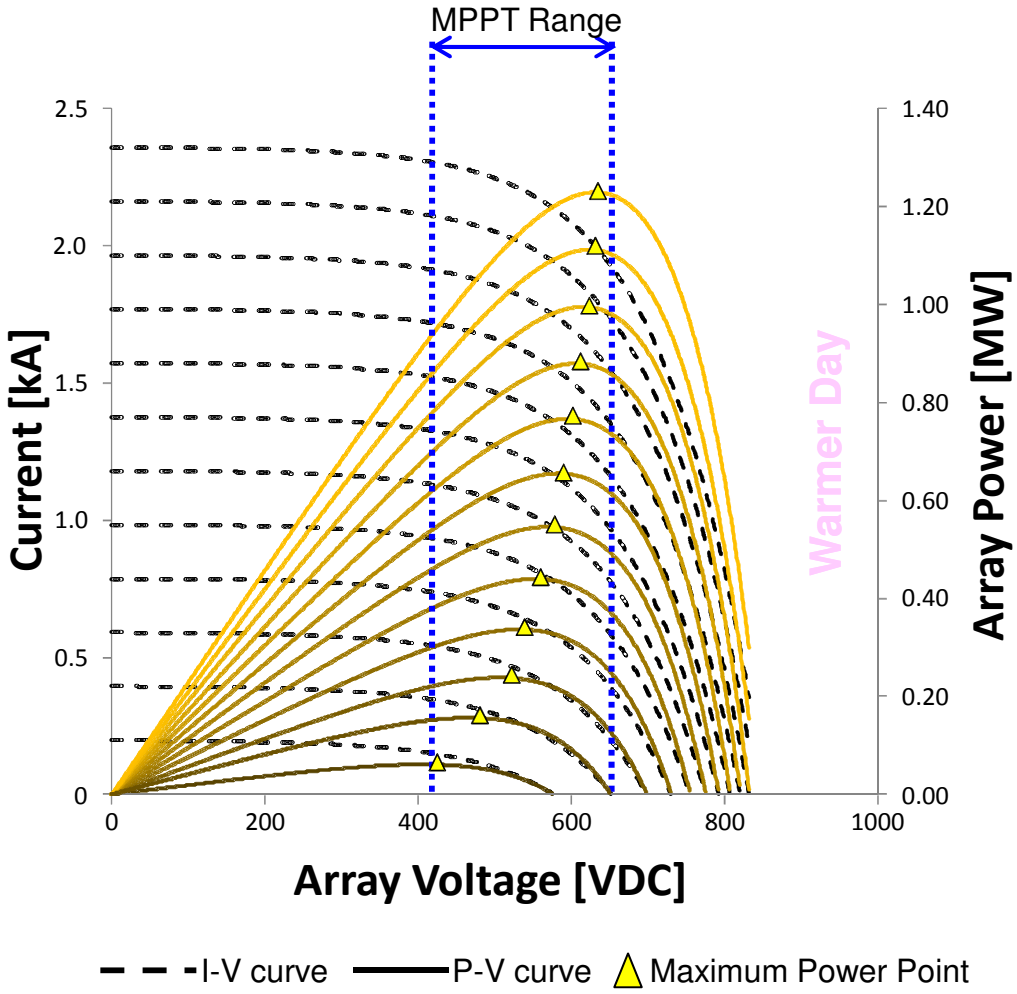
MPPT – Maximum Power Point Tracking Temperature Impact

- I-V curve also changes due to temperature change and so also does the power characteristic



MPPT – Maximum Power Point Tracking Temperature Impact

- I-V curve also changes due to temperature change and so also does the power characteristic
- The temperature changes could be due to the change of the temperature during a given day, but also includes seasonal changes in temperature
- Maximum power output will likely be on a full sunshine winter day
- Thus, the MPPT is always changing except at night of course
- Key to all of this is the minimum of the MPPT Range DC voltage.

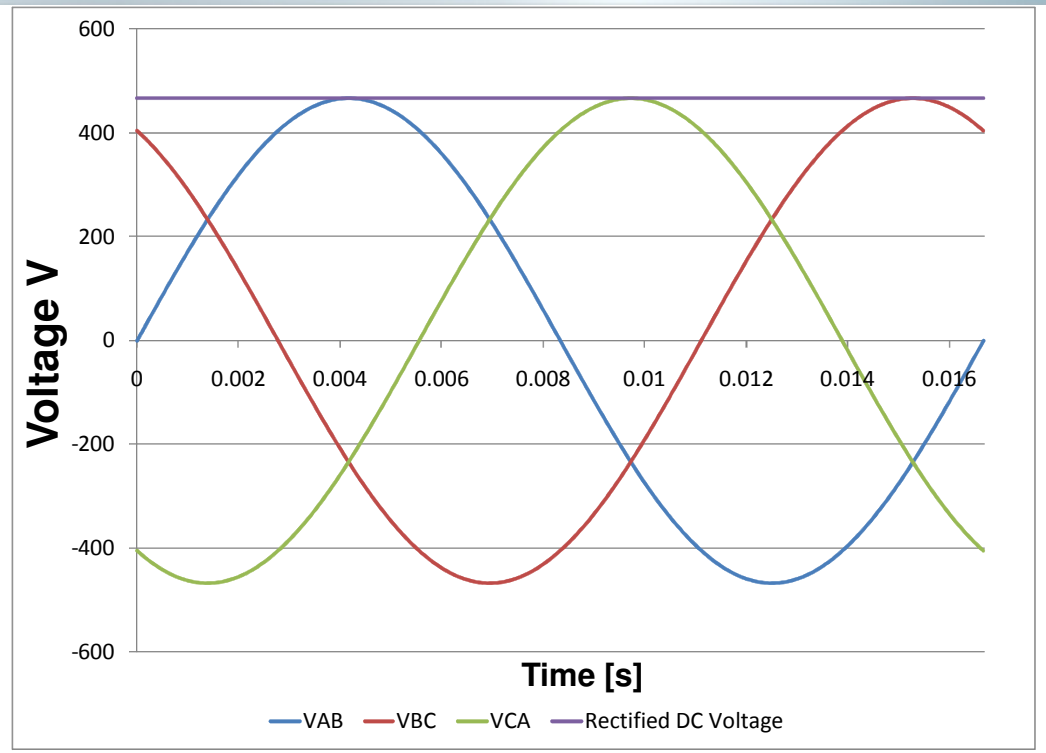


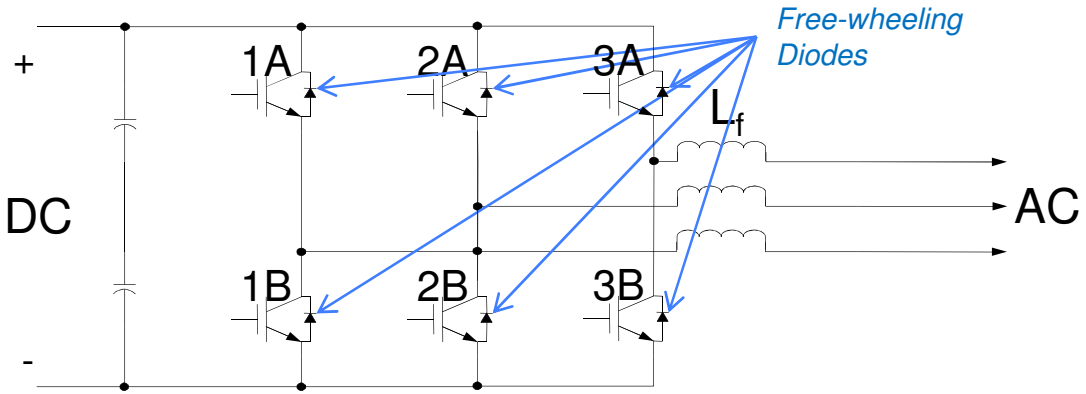
Inverter DC BUS Voltage Compliance Minimum Voltage

- Inverters have to keep a minimum DC bus voltage in order to sustain current control
- This is due to the inverter topology containing free-wheeling diodes
- If DC voltage happens to be lower than the peak of the line-line AC voltage, the diodes will start to conduct as they become forward biased
- This will create uncontrolled AC peak currents and loss of DC BUS voltage control
- Therefore, the following relationship has to be satisfied for current in/out of the inverter to be controllable:

Voltage Compliance Equation

$$V_{DC\text{-}BUS\ min} > V_{LL} * \sqrt{2} = Vpk_{LL}$$





SolarTie™ Inverter Power Curve
Flexible Output Power Range

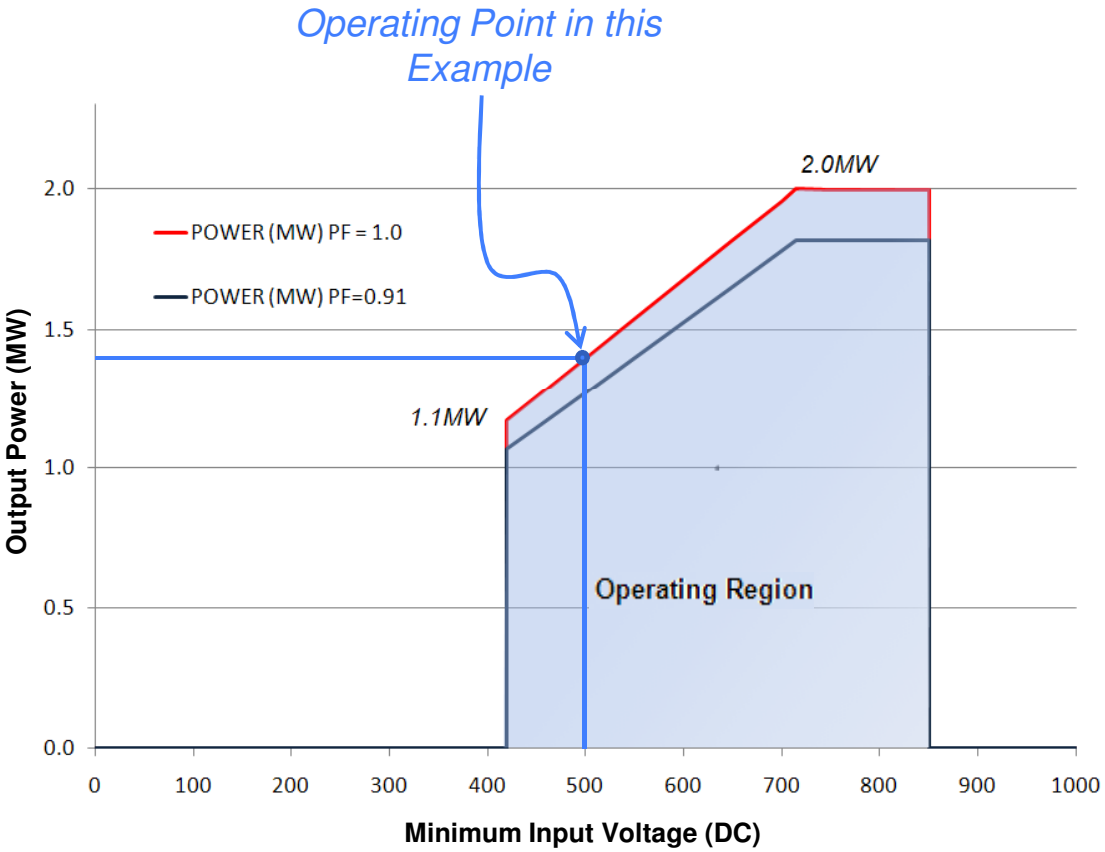
Based on the last several slides:

For example:

- If MPPT range is 500 VDC to 820 VDC, then
- AC voltage will be 330 VAC
- Therefore in this example, SolarTie™ output power is set to ~ 1.4 MW

- If other MPPT ranges are chosen, output power changes accordingly
- Watts and VARs prioritization is determined based on transient support and PF (settings pre-determined by study and customer)

1.4 MW ~ √3 x 2400 amps x 330 volts

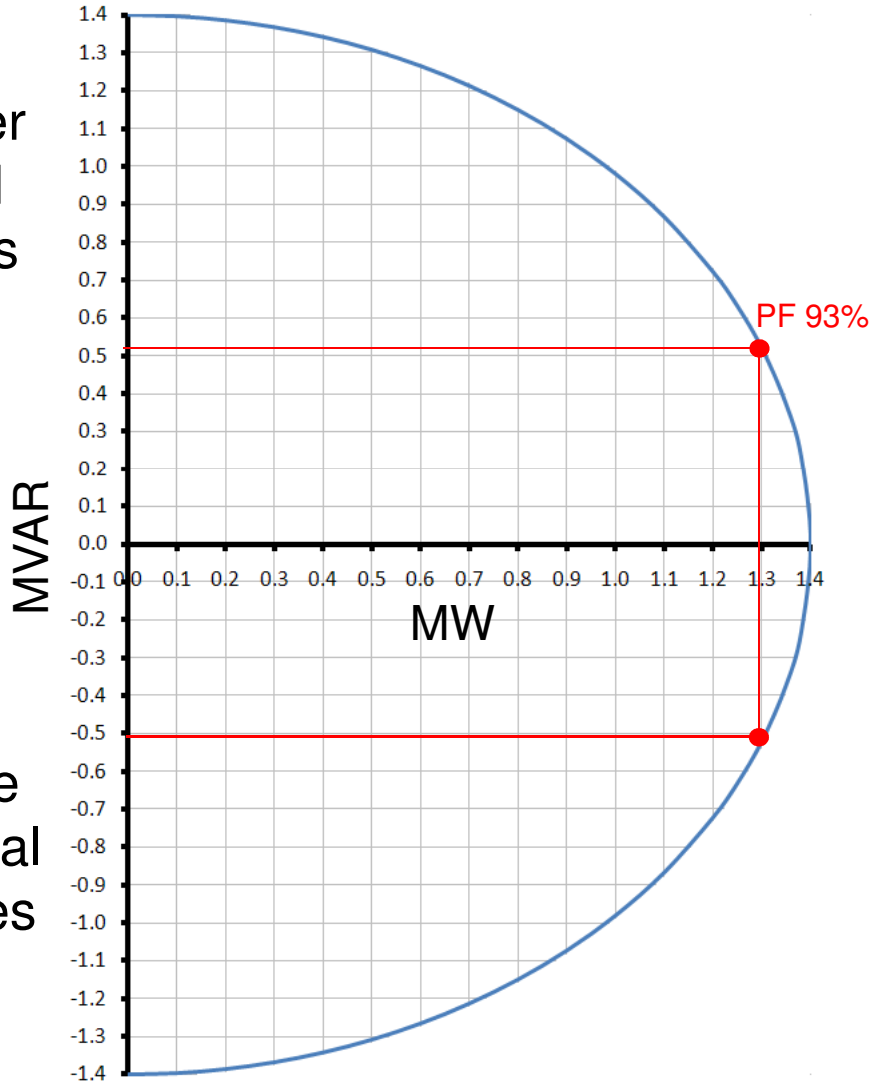


Solar Plant Inverter's Steady State Reactive Output Capability

The solar plant's inverter reactive output capability is dependent upon its real power output. For example, if an inverter is rated for 1.4 MVA operation, its VAR capability is shown in the table below

MW Output	MVAR Capability	Chosen PF
1.4	0.00	100%
1.3	±0.52	93%
1.2	±0.72	86%

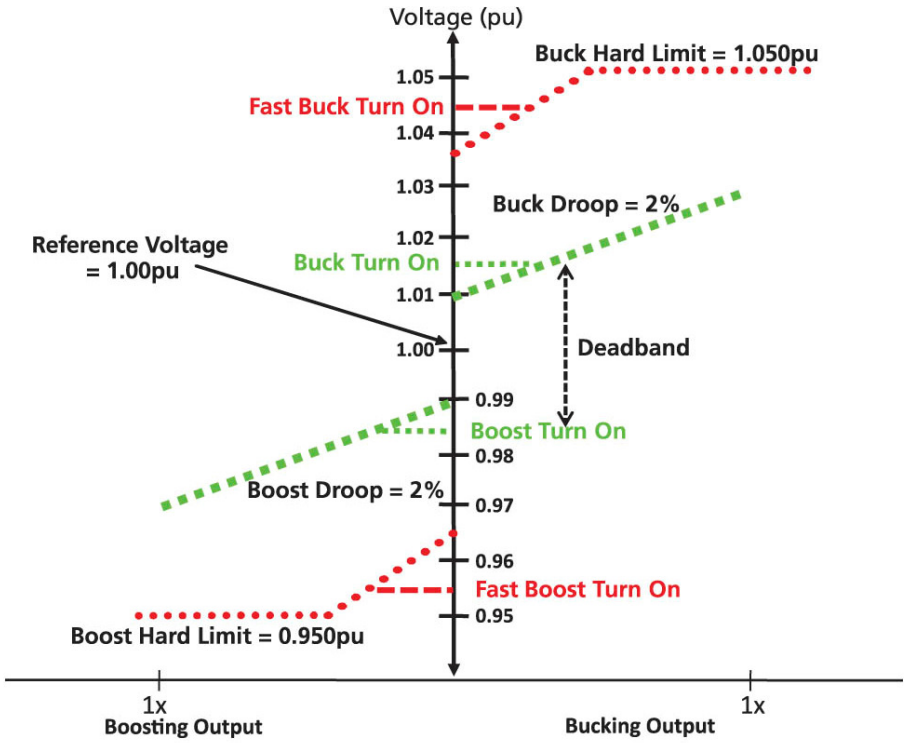
Thus, analysis needs to be done to determine the solar plant's internal reactive capability and whether it will need additional reactive resources from other shunt devices to meet the grid code requirements



SolarTie™ Grid Interconnection System
Unmatched Grid Voltage Support

- Highly configurable to meet a variety of interconnection requirements and grid codes
- Regulation at Point of Common Coupling (PCC) whether local or remote
- Steady-state and transient voltage regulation
- Voltage or PF control according to utility requirement

Voltage regulation and transient voltage support at PCC with adjustable deadband and droop



Integrated STATCOM Functionality, Utilizing Our Proprietary D-VAR® Technology

SolarTie™ Grid Interconnection System
Unmatched Grid Voltage Support

Powered by AMSC

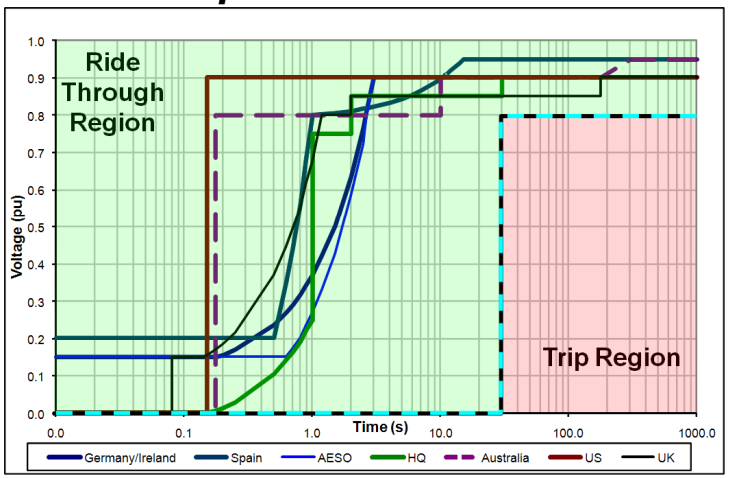
<u>Voltage Regulation on Cloudy Days:</u>
SolarTie inverters work harmoniously to maintain a consistent and smooth voltage profile during passing clouds

Integrated STATCOM Functionality, Utilizing Our Proprietary D-VAR® Technology

SolarTie™ Grid Interconnection System
Unmatched Grid Management Support

- **No disconnection from the grid** for low/ high voltage and frequency ride-through events
- **VAR injection assists post-fault voltage recovery** because dynamic VAR response helps recover the system voltage
- **Generation Power Management** with power curtailment during frequency disturbances and upon SCADA commands
- **Anti-islanding inverter shutdown** via adjustable frequency and voltage limits, and monitoring of "upstream" Circuit Breaker

LVRT Requirements World Wide

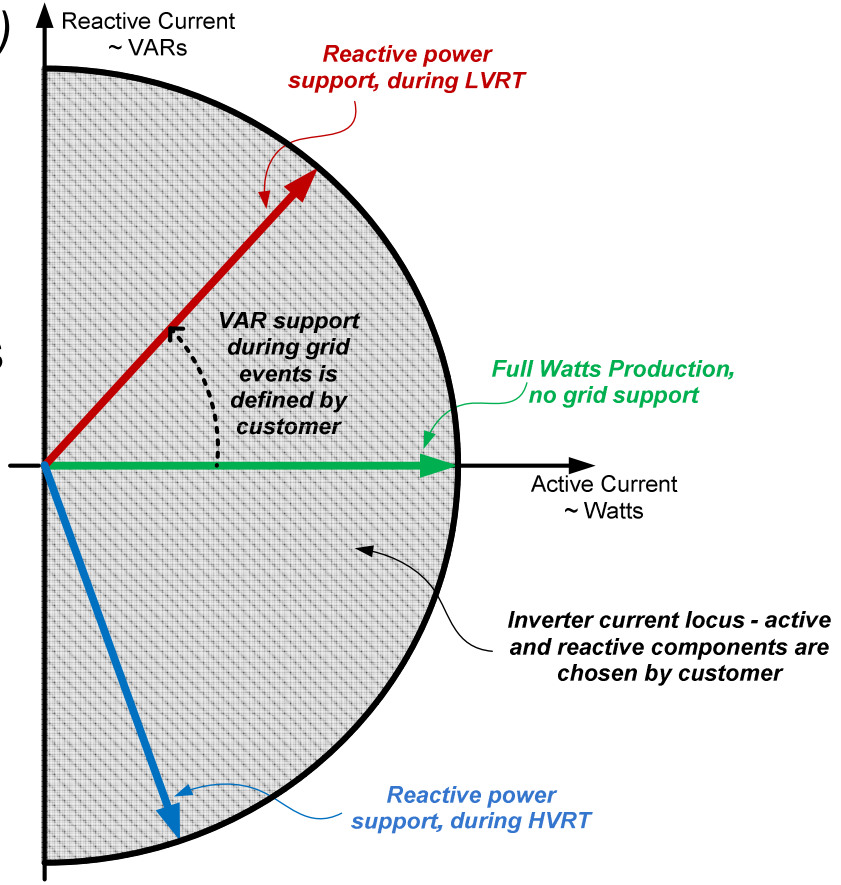


SolarTie™ PV Inverter's LVRT Capability

Ride Through Capability Gives Needed Support During Grid Events

SolarTie™ System Capability During Grid Events

- Smart Grid Interface sensors detect voltage disturbances in < *16 ms (~1 cycle[1])*
- In < *50 ms (~3 cycles[1])* after the fault, the system provides reactive support to help restore the voltage at the PCC
- SolarTie inverter reactive support priority is provided according to Watts and VARs prioritization set by customer during solar plant development
- If further support is needed, shunt banks and/or D-VAR® STATCOM support can be directed by the SGI Central Controller
- Once disturbance is mitigated the SolarTie inverters resume power production (watts)



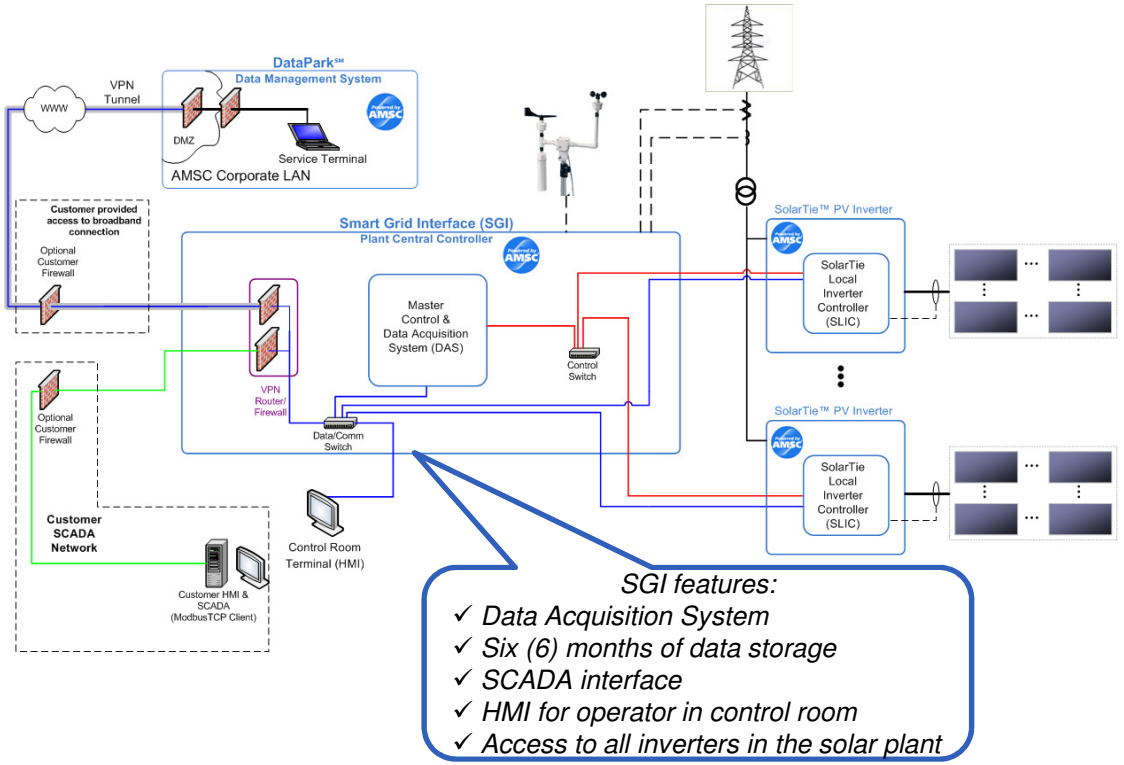
1: 60 Hz system

Configurable, Selectable, and Reliable Technology to Meet a Variety of Grid Codes

Smart Grid Interface (SGI) Communications

Highly configurable interface that provides a secure communication scheme

- ModbusTCP SCADA capability, uses industry common language (flexible customer interface)
- Built-in Data Acquisition System (DAS) collects solar plant information, faults, and transients for analysis
- Digital oscilloscope-like functionality for transient events
- Ethernet available for remote access with DataPark™ secure internet based monitoring system
- Remote access through secure communication channels with multiple layers of login security



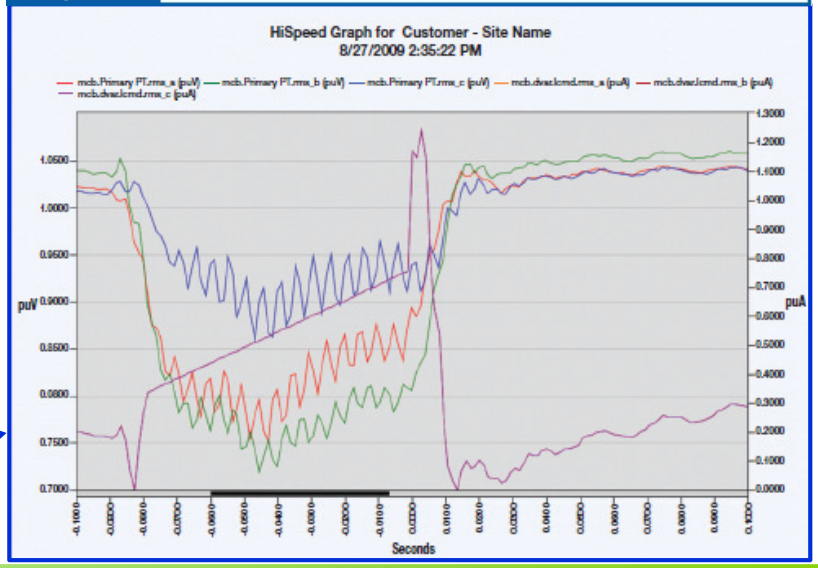
SGI features:
- ✓ *Data Acquisition System*
- ✓ *Six (6) months of data storage*
- ✓ *SCADA interface*
- ✓ *HMI for operator in control room*
- ✓ *Access to all inverters in the solar plant*

Secure Communication Scheme

DataPark^{SM} Data Management System

The SGI controller interfaces with DataPark data management system for secure and reliable data access and control

- **Low Speed Trend Data**
  - Once a minute
  - Logged to Enterprise server
  - Thermals, voltages, Watts and VARs, etc.
- **10 Hz Stream Data**
  - 2-week history stored on DAS-PC
  - Input/output voltage, current, power (CTs and PTs)
- **High Speed Event Triggered Capture**
  - AC waveforms @ 5 kHz
  - 0.5s pre-trigger, 3.5s post-trigger
  - Alarms trigger high speed capture



Captures the Intel Utilities Require

Utility Concerns with PV Plants

Utilities have many concerns about new generation on their transmission and distribution facilities. For PV plants, most of their concerns fall into the following categories:

- **System ACE**
  - PV Plant's ramp rates in the morning and evening along with their response to clouds are major utility concerns as they impact system ace and area voltages
- **System Normal and Contingency Operation (Slow Regulation)**
  - PV Plant's impact on system normal and contingency flows and voltage
- **Transient and Voltage Stability (Dynamic Events)**
  - The dynamic change in the PV plant's output along with other system events could cause unforeseen fast acting issues
- **Power Quality**
  - Electromagnetic transients, flicker, and harmonics impacts are all issues that PV Plants need to aware of and know that their plant is not causing system problems
- **HVRT, LVRT, and Islanding**
  - PV Plants along with all other generation must be able to handle correctly these newer issues that have come from the new interconnection grid codes
- **Fault Currents**
  - Additional PV Plant's impact on short circuit current ratings

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SolarTie™ Grid Interconnection System Summary

Reliable…

- Inverter technology proven world-wide in D-VAR® STATCOMs and wind turbines
- Unmatched fault ride through capability and grid voltage support
- Enables tight integration with grid operators' production management systems

Flexible…

- Optimization of AC voltage and power to PV array output
- Prioritization between Watts and VARs as required
- VAR compensation configurable via easily adjustable set of parameters
- Power factor or voltage regulation control at POI
- LVRT/HVRT capability with settable parameters
- Seamless integration with external switched shunt capacitor and reactor banks

Secure…

- Remote access through secure communication channels with multiple layers of login security that's already implemented for global D-VAR STATCOM installations

Contact Information

American Superconductor Corporation (AMSC®) is a leader in alternative energy, offering grid interconnection solutions as well as licensed wind energy designs and electrical systems.

www.amsc.com

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