# Distribution Grid Codes for High Penetration DER

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Advanced Grid Support Features Of Satcon Inverters

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# Utility Concerns About The Impact Of High Penetration DG on MV Feeders

- **Fluctuating real power output from renewable sources**
  - Increased switching operations for line regulators, tap changers, capacitors
  - Flicker due to fluctuating voltage
  - Transient voltage on sudden trip of DG station
- **Effect of new generation and reversible power flow at sub-stations**
  - Protective relay settings and operation
  - Conductor and equipment loading
  - Islanding of DG with residual load connected
  - Auto-reclosing feeder breaker onto energized DG

# Additional Concerns About Real Power In Island Grids With Limited Generator Rotational Inertia

- **Real power management for grid frequency regulation**
  - Rapid curtailment of real power sources on over-frequency
  - Rapid load-shedding or "spinning reserve" deployment on under-frequency
  - Ramping of real power from variable sources to minimize impact to the grid frequency
  - Transient frequency excursion on sudden trip of DG station

# Main Issues Delaying Or Blocking Interconnection Of PV Projects To the Grid

- **Short circuit capacity limitations on Transformer Stations (mainly in Ontario, Canada)**
- **Power/Distance limitations (Ontario)**
- **(Expensive) transfer trip requirements for PV plant**
  - Questioning effectiveness of anti-islanding with multiple PV units on one feeder
- **Uncertainty about impact of very high penetration of PV on feeder, relative to sub-station transformer rating or minimum load**
  - Flicker, line regulators, LTC, capacitor banks
- **Issues raised by interconnection requirements studies**
  - PV plant (ac output) grounding method
  - Transient over-voltage on islanding
  - Special custom requirements for reactive power deployment

# UL1741 / IEEE 1547 Does Not Address Concerns For Utility Scale Inverter-Based DR Connected To Distribution Systems

- **IEEE 1547 has served as a standard for single, small (<500 kW) DR units**
- **Main deficiencies for larger installations include**
  - Prohibition of autonomous local voltage control
  - No provision for LVRT
  - Multi-unit anti-islanding not addressed
  - No consideration of short term (1 to 5 cycles) performance
    - Fault current contribution
    - Transient voltage
  - Failure to distinguish between Inverter-Based DR and conventional rotating synchronous machine generators.

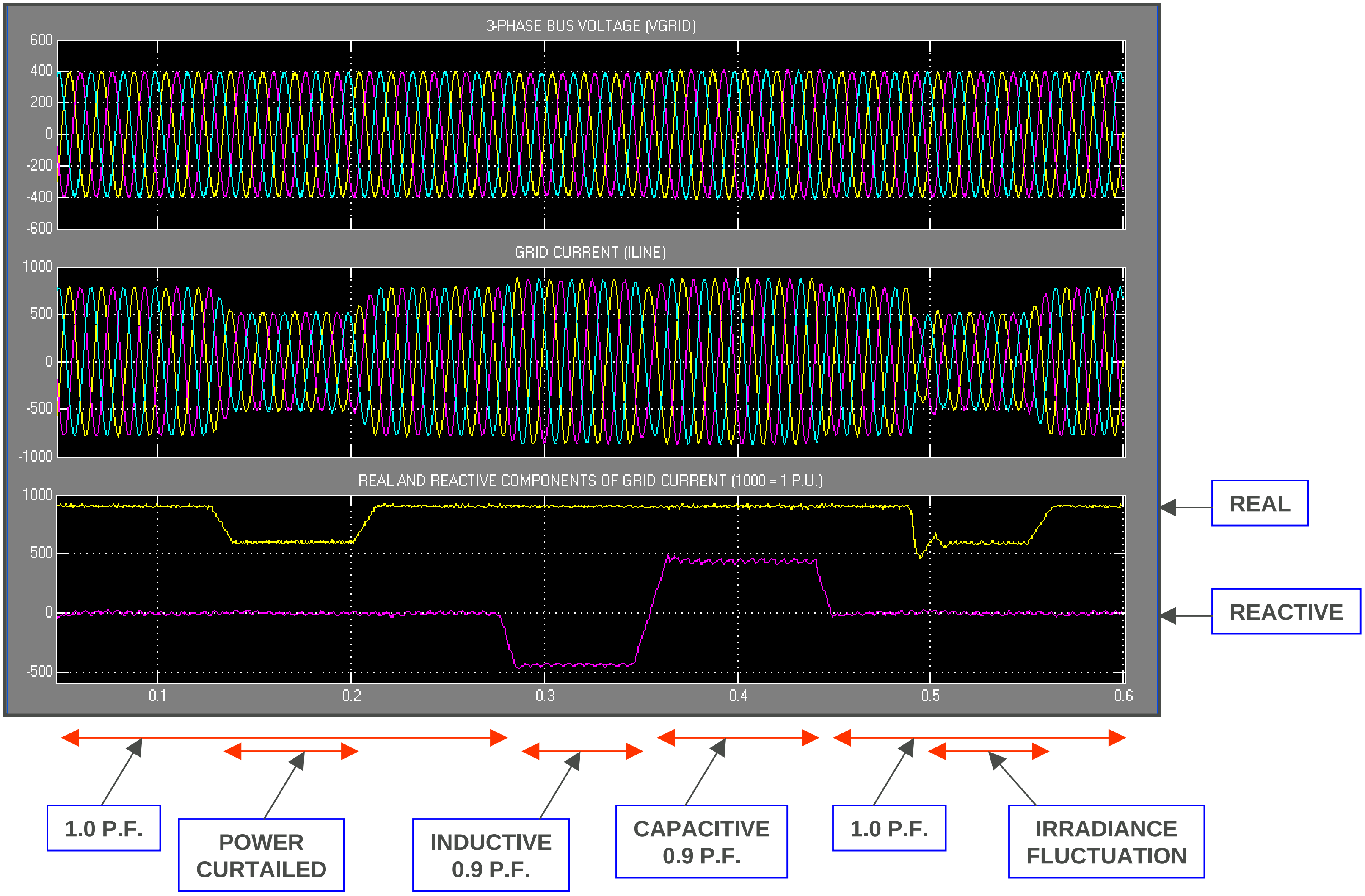
# DG Inverters Are Valuable Resources For The Grid

- **Inverters are capable of regulating voltage in distribution systems**
  - Inverters are the ultimate reactive power sources
  - Fast, controllable VARS at low incremental cost
  - Automatic voltage control at the DG plant can mitigate voltage concerns due to the plant itself
  - Real power ramping (with energy storage) can reduce concerns about fluctuating power
  - Inverters can improve “pre-existing” power quality on a feeder

# For DOE SEGIS Program Satcon Defined a New Set of Grid-Smart Inverter Features To Support The Future Grid

- **Local communication with site-level controller, providing utility SCADA communications and multi-unit control through:**
  - Control of real power limit (curtailment)
  - Controlled ramp rate for real power limit
  - Control of reactive power output **or** power factor
- **Ride-through capability for specified grid disturbances**
  - Adjustable tolerance for voltage and frequency deviation
  - Enhanced dynamic control (i.e. with unbalanced/distorted grid voltages during faults)
  - Un-interruptible power source for control
- **Bi-directional power flow to support DC energy store**
- **PLCC permissive – an alternative to transfer trip**

# Grid-Smart Inverter Model
# Illustration of Some Advanced Grid Support Control Features

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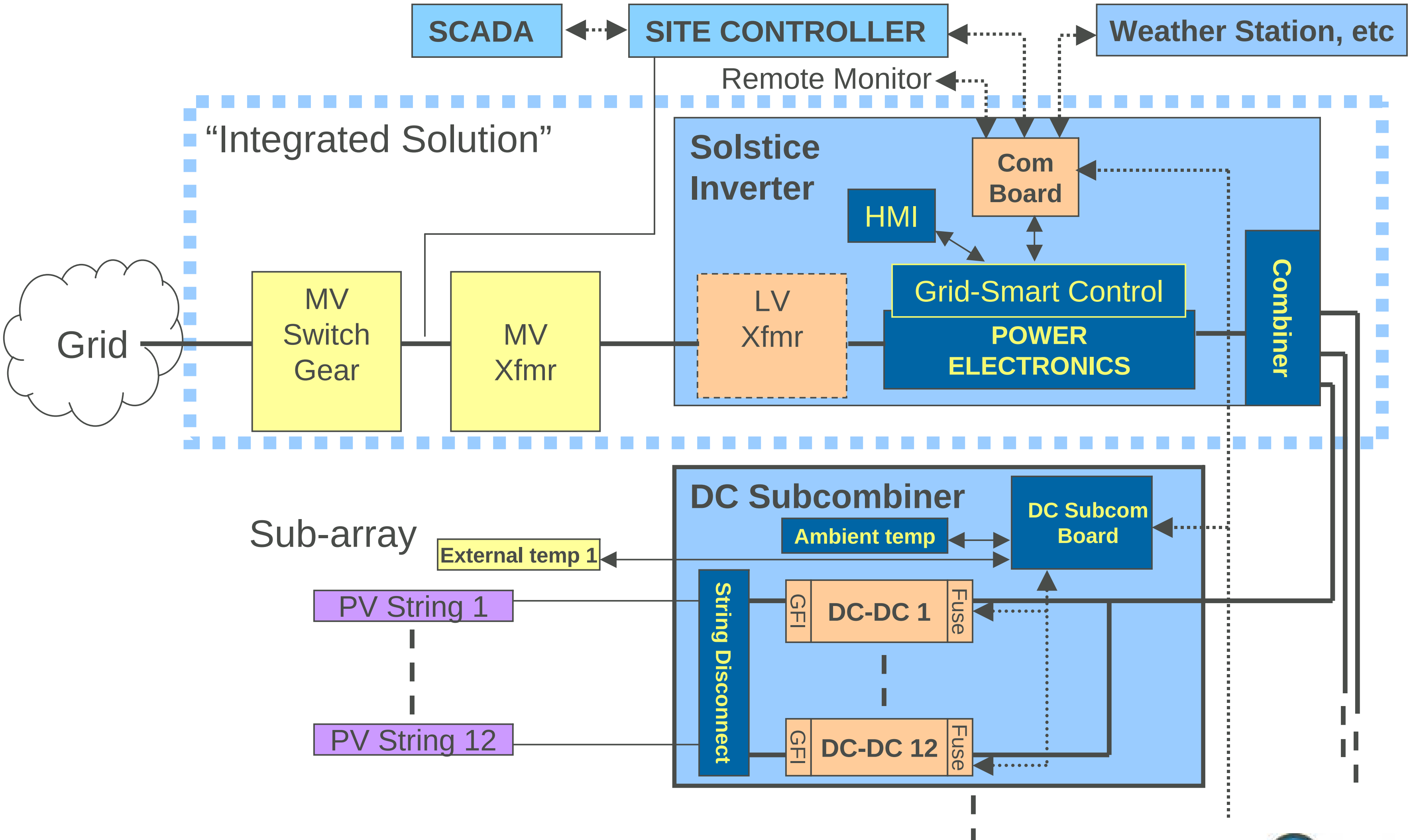
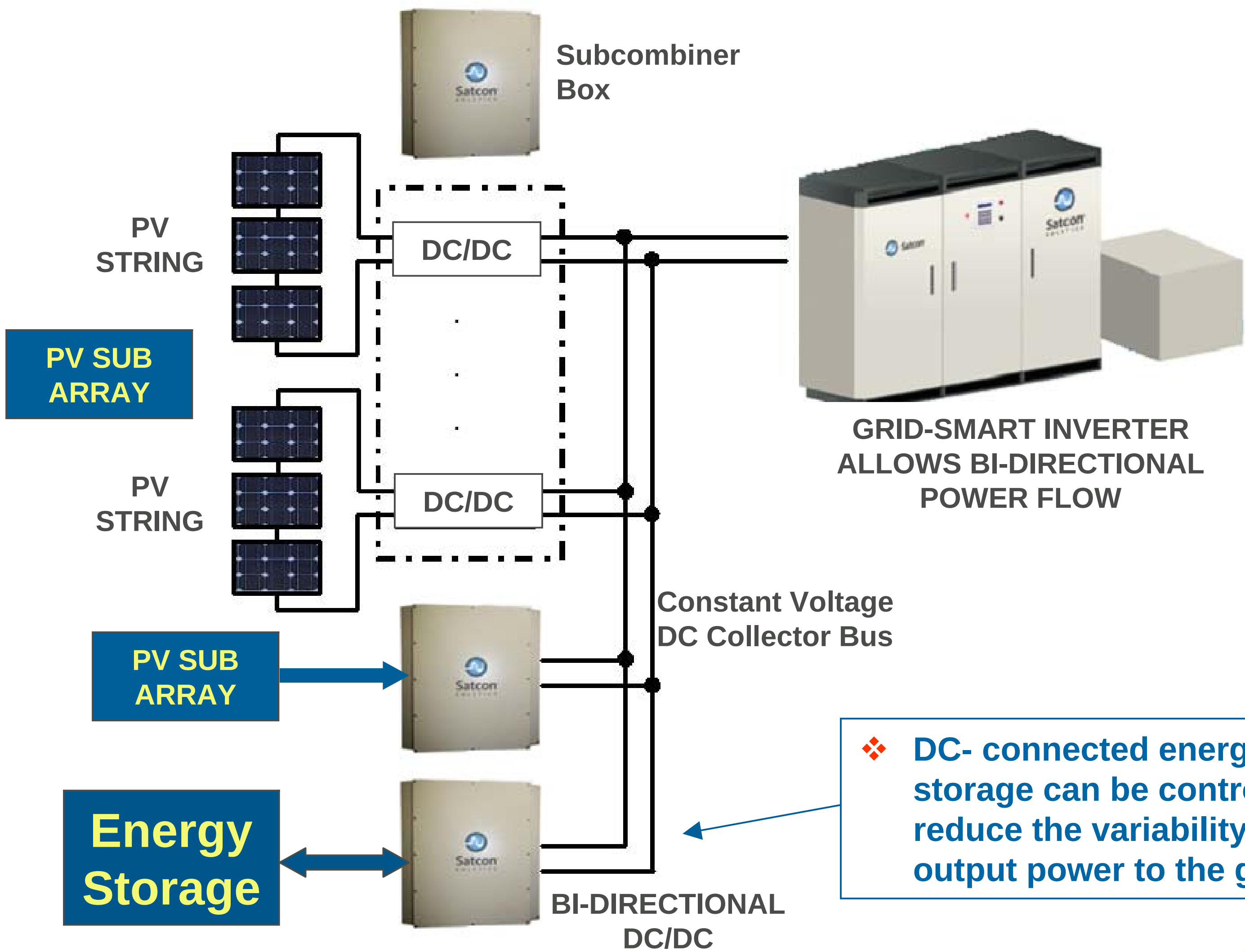
# Satcon Solstice Inverter Incorporates SEGIS Grid-Smart Control Features



# Satcon Solstice Two-Stage Architecture Facilitates Connection of DC Energy Storage

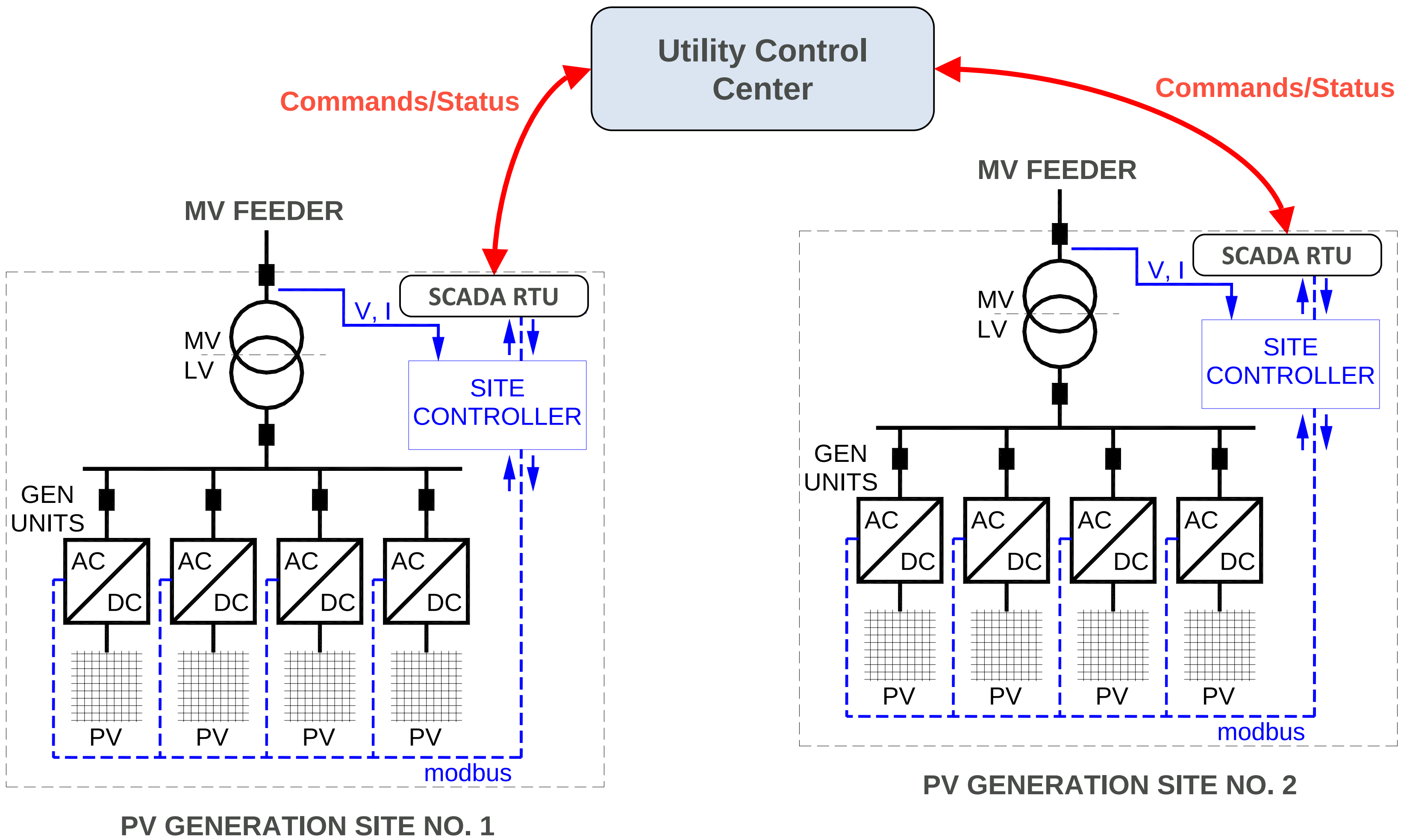



- DC- connected energy storage can be controlled to reduce the variability of AC output power to the grid

# Site Controller Complements The Features Of Each Inverter Unit With Aggregate Power Output Control

- For multi-inverter installations the *Site Controller* provides power management functions at the point of common coupling (PCC) with the utility.
  - Communicates with all inverters and the utility control center
  - Receives and processes real-time V,I measurements from PCC
  - Provides aggregate power factor control – accounting for site transformers – by issuing commands to the inverters
  - Provides automatic voltage control if required
  - Provides long duration real power ramping by means of curtailment commands to inverters

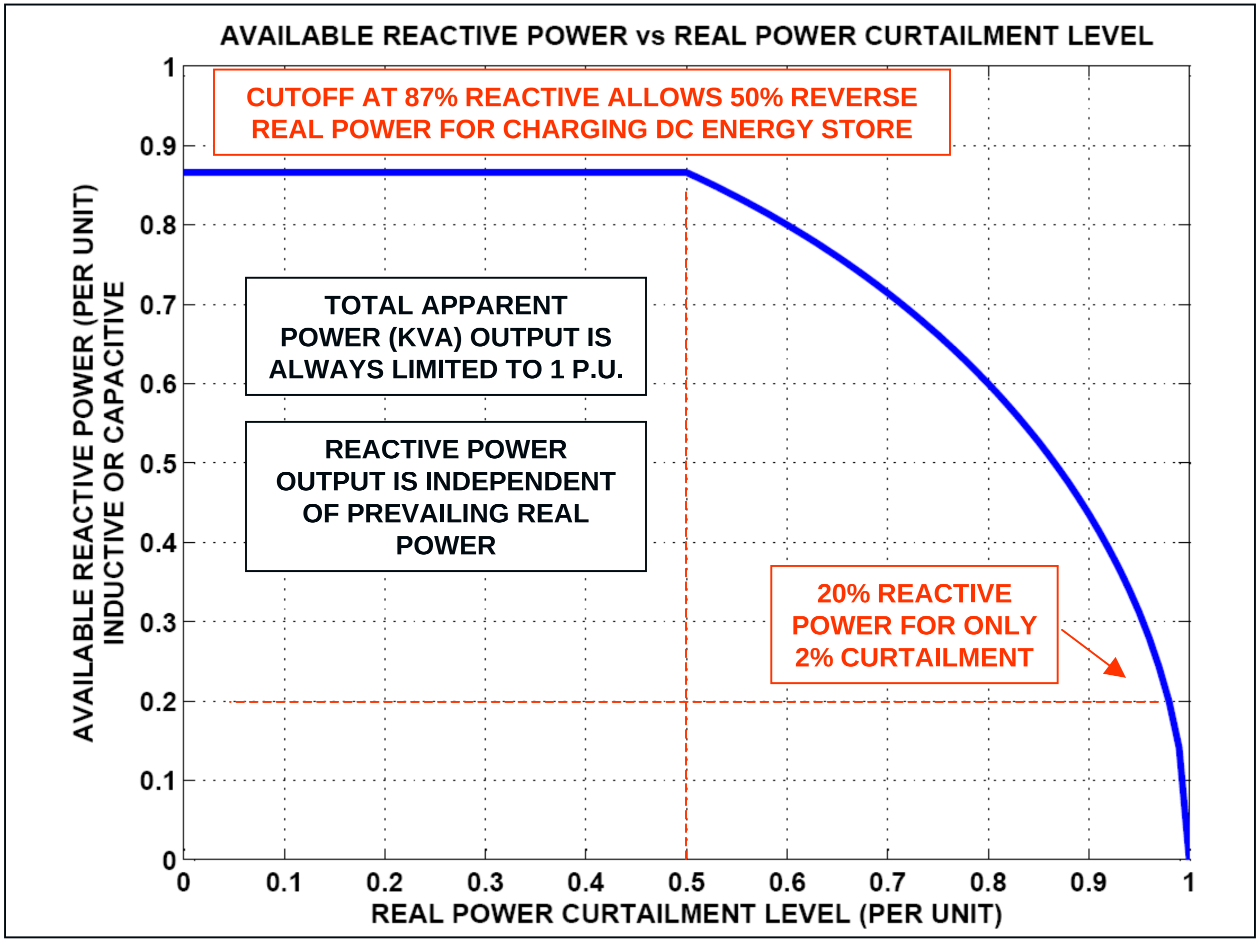
# Site Controller Provides Real And Reactive Power Management At the Point Of Common Coupling



# High Quality Reactive Power Generation At Low Incremental Cost With Two Alternative Reactive Power Control Modes

## 1. Independent Reactive Power Control Mode

- VAR reference from utility control center or local site controller

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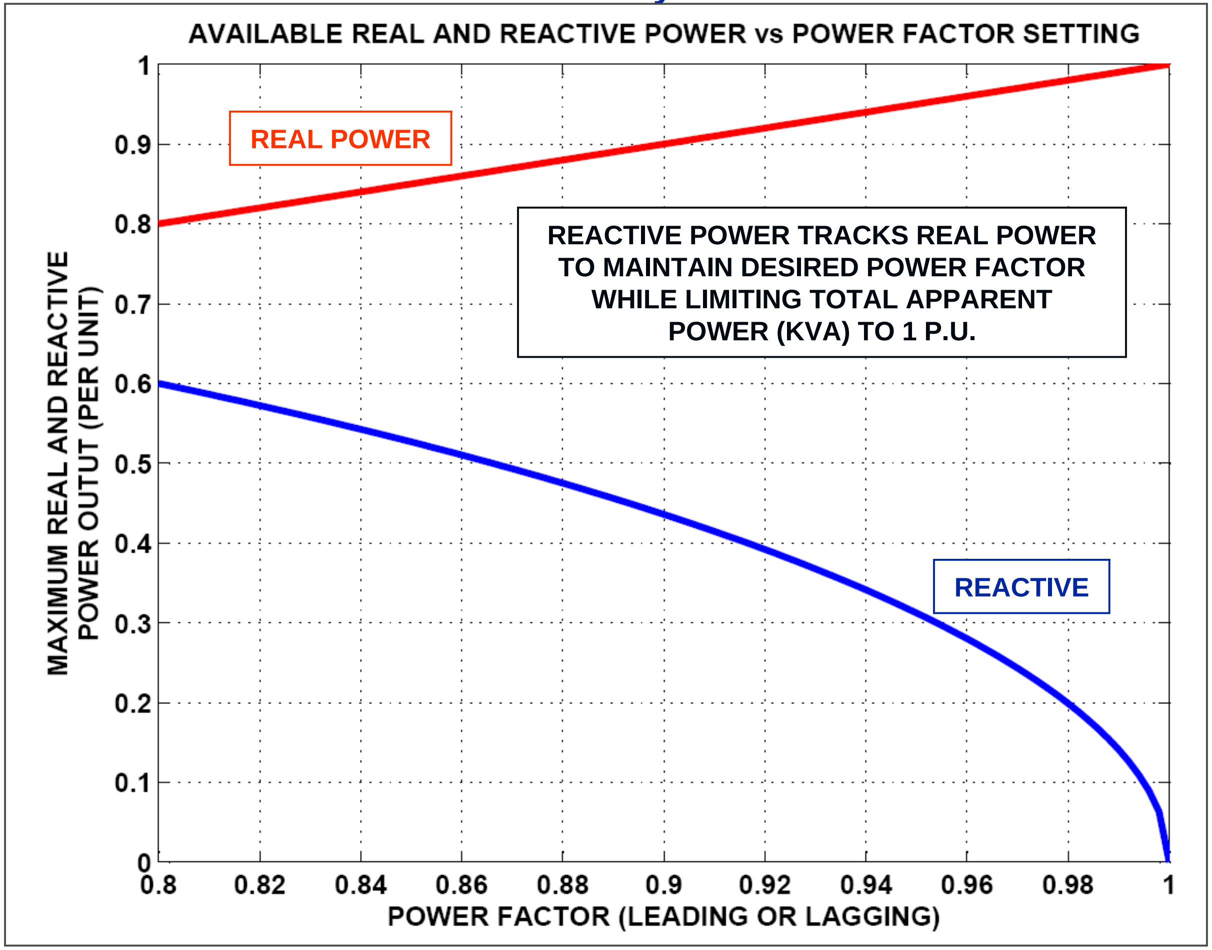
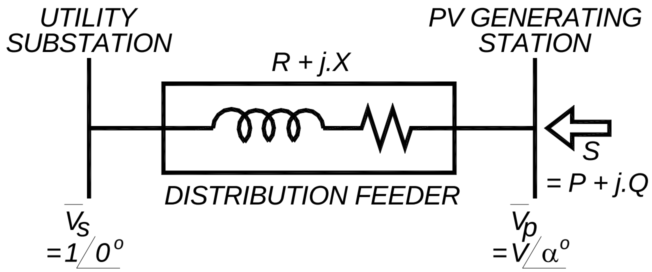
# Power Factor Control Mode Allows Dynamic Control Of Power Factor Without Exceeding Rated Apparent Power

## 2. Power Factor Control Mode

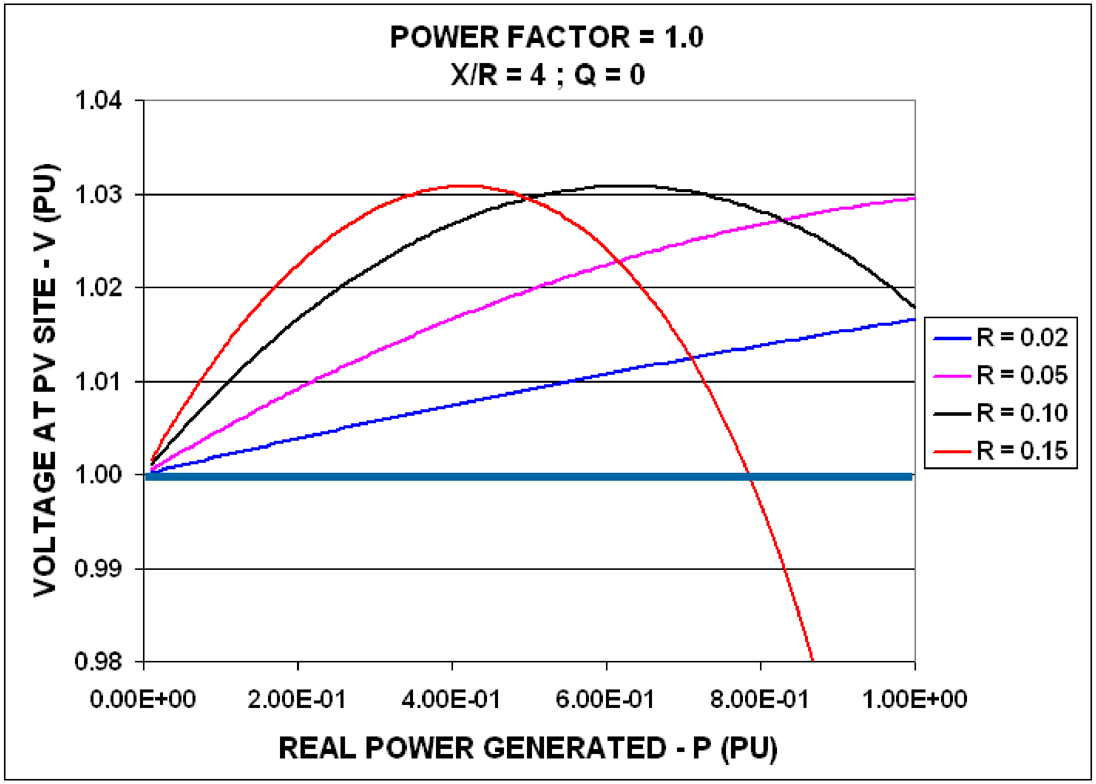
- Power Factor reference from utility control center or local site controller



# Voltage Impact At PCC With PV Plant Operating at Unity Power Factor

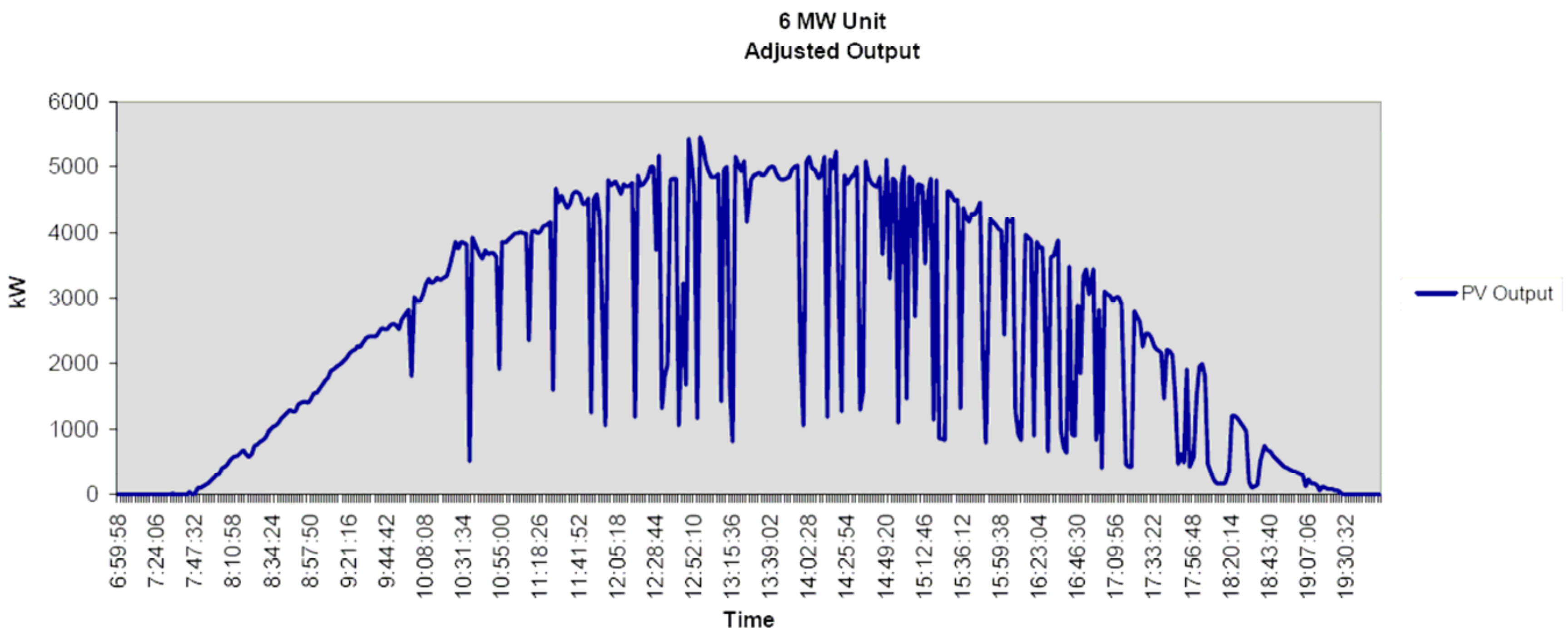



- Inverter generates real power (P)
- Reactive power (Q) = 0
- ΔV/ΔP can be positive or negative
- Lower X/R – higher max voltage
- Voltage collapse on very long feeder



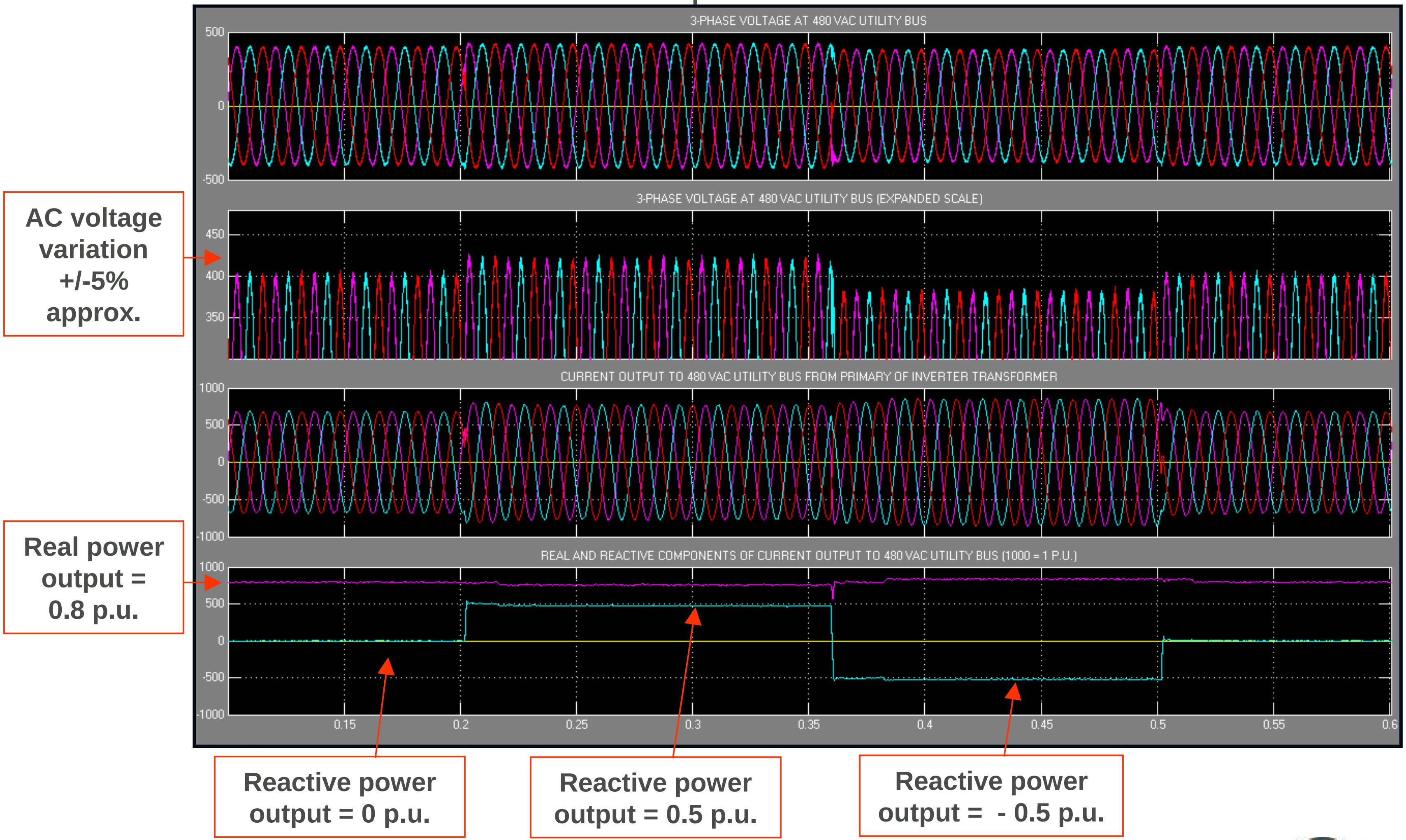

All per unit values based on the PV plant rating

# Real Power Output From PV Generating Station Fluctuates Due To Passing Cloud Cover

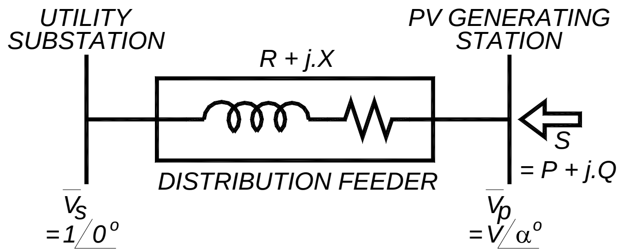


# PV Inverter Simulation Shows Fast VAR Step Response Capability And The Effect On Local Bus Voltage

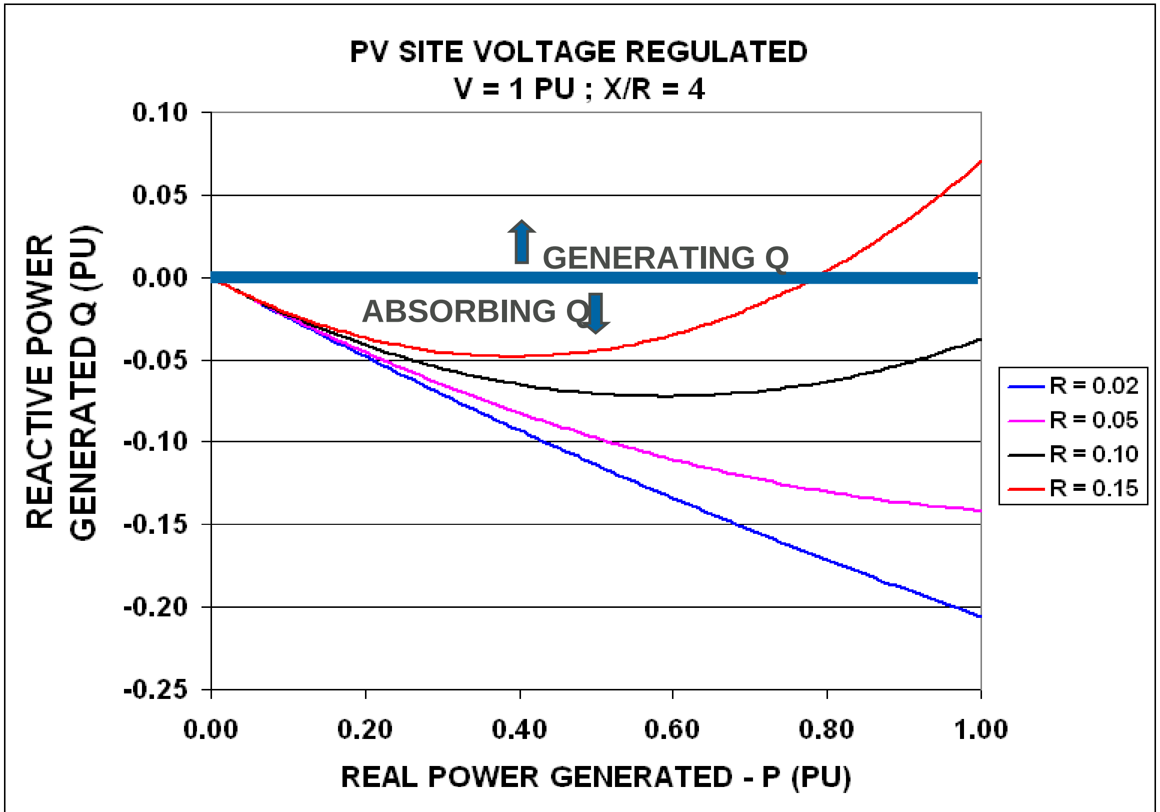
- Feeder X = 0.1 p.u. on inverter base



# Inverter VAR Output Can Be Used To Regulate Voltage At The PCC

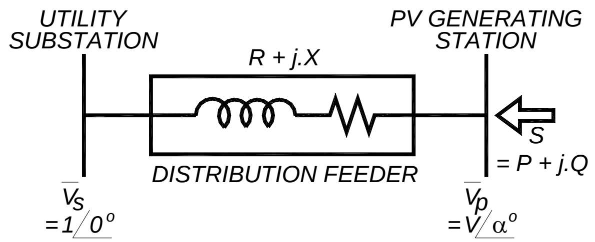



- Inverter generates P <u>and</u> Q
- Voltage at PCC maintained at 1 PU
- Closed loop control determines Q
- Relatively small Q requirement

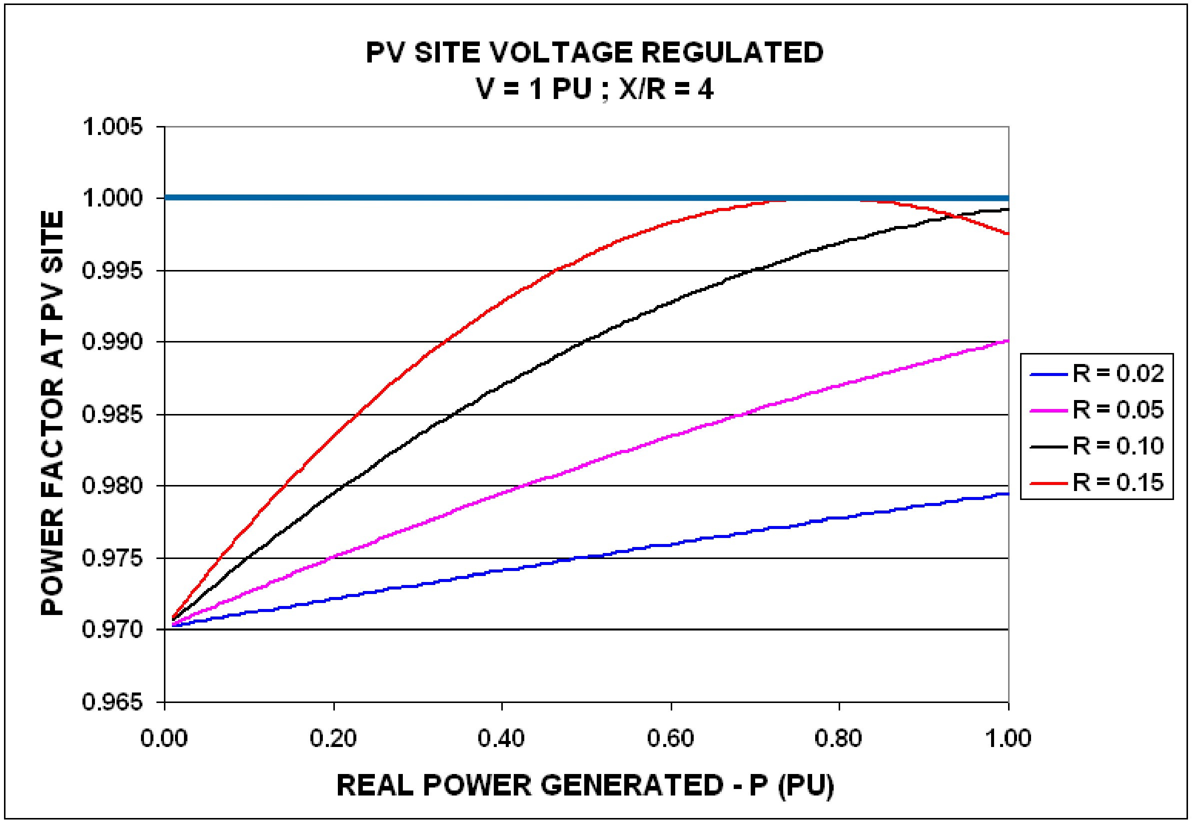



All per unit values based on the PV plant rating

# Wide Range Of Power Factors Required For Automatic Voltage Regulation at PV Station

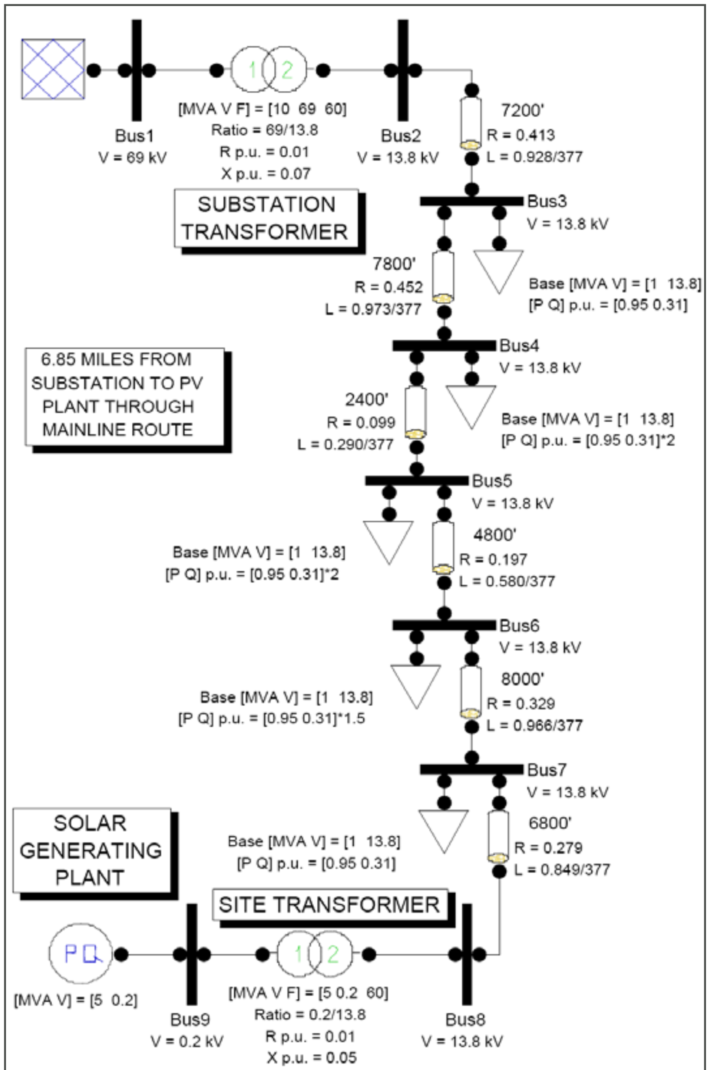



- Power factor is high at high P
- Small reduction in max P output

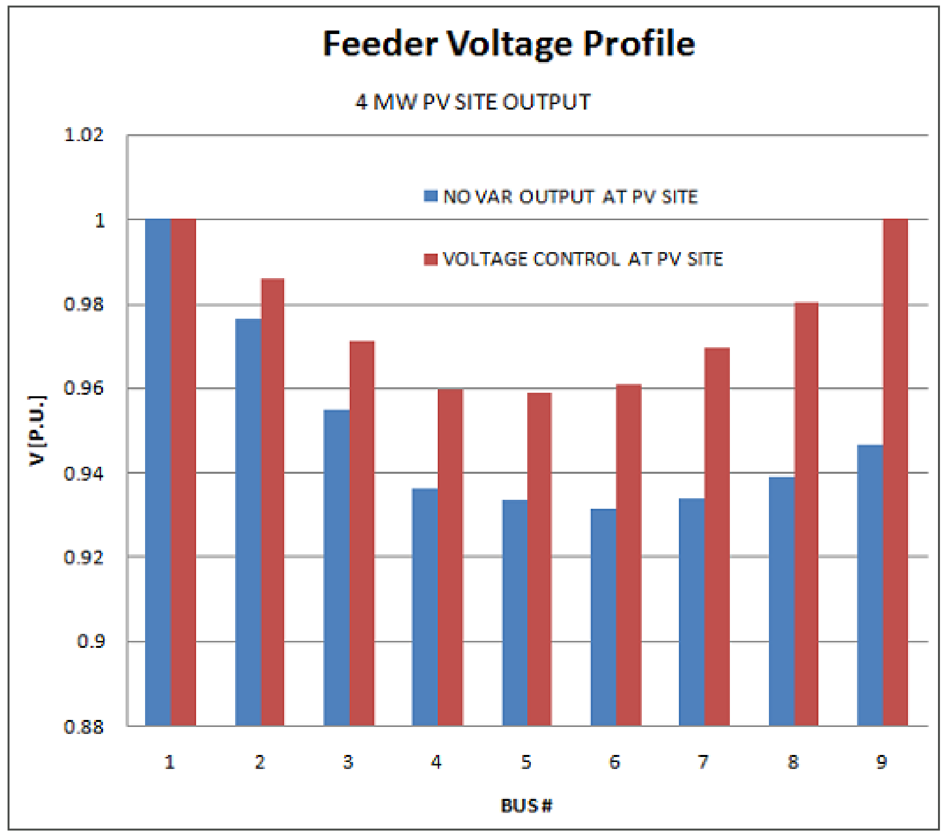



All per unit values based on the PV plant rating

# Illustration Of Automatic Voltage Control On a Long 13.8 kV, 10 MVA Feeder With 5 MVA PV Plant Connected




- No tap changers, line regulators, or capacitors
- Balanced feeder, balanced three-phase loads
- 9 buses - 7.5 MVA 0.95 p.f. constant power loads
- PV plant output, P = 4 MW

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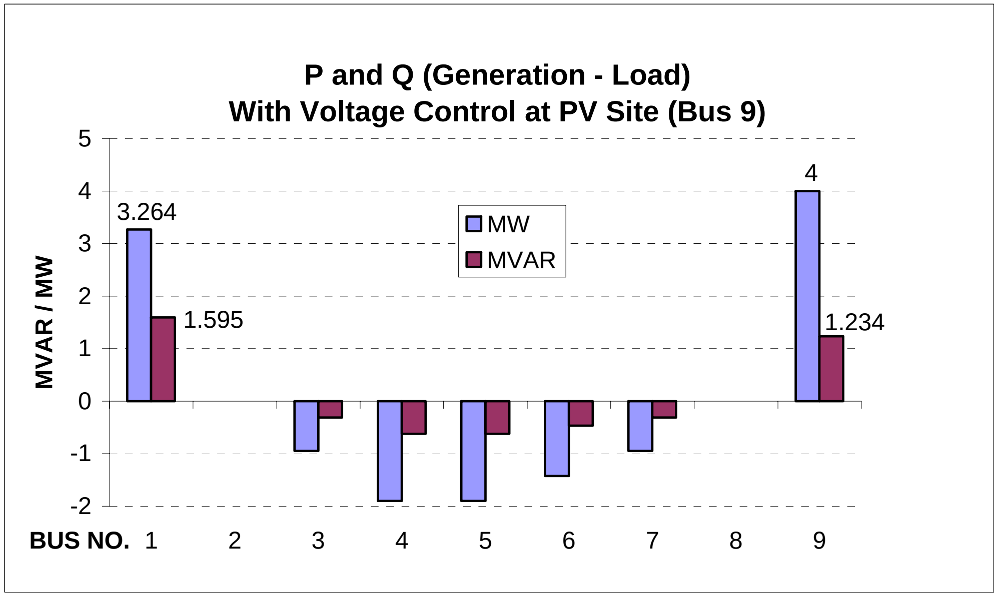
# Voltage Regulation At PV Plant Reduces Line Losses And Reactive Power Supplied From Substation




- PV site bus (#9) voltage regulated at 1 p.u.
- PV plant generating P = 4 MW and Q = 1.234 MVAR
- P.F. = 0.956
- Reactive power at bus #1 reduced from 2.949 MVAR to 1.595 MVAR
- Line loss reduced from 177 kW to 139 kW

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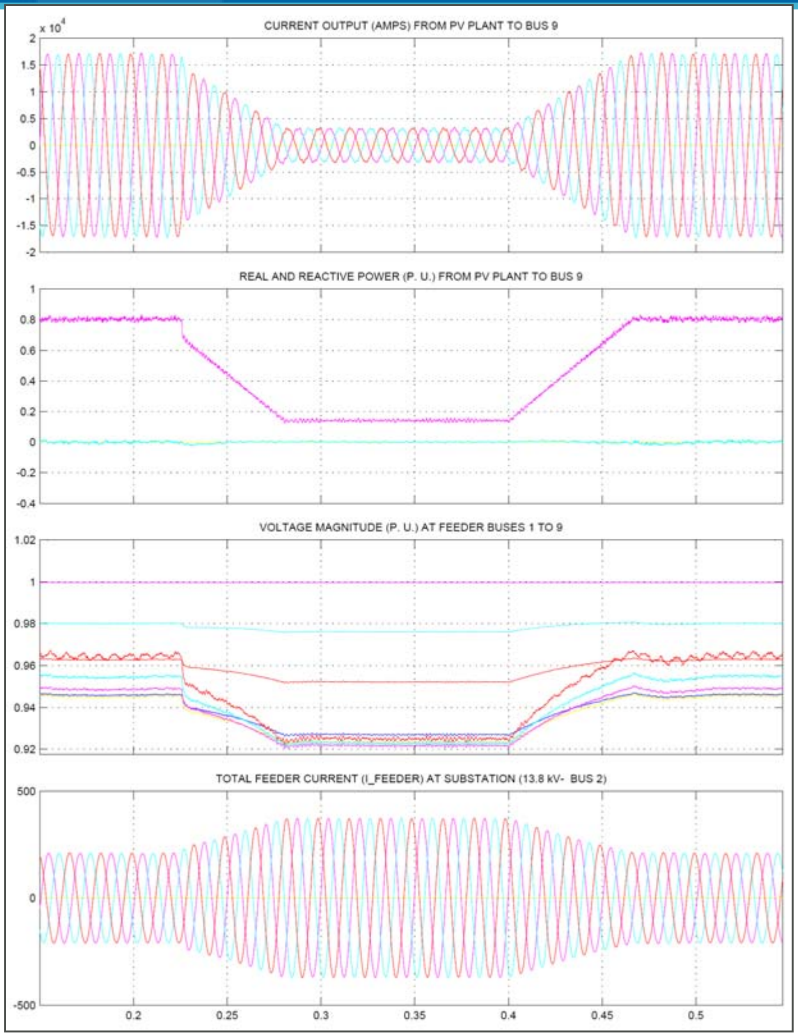
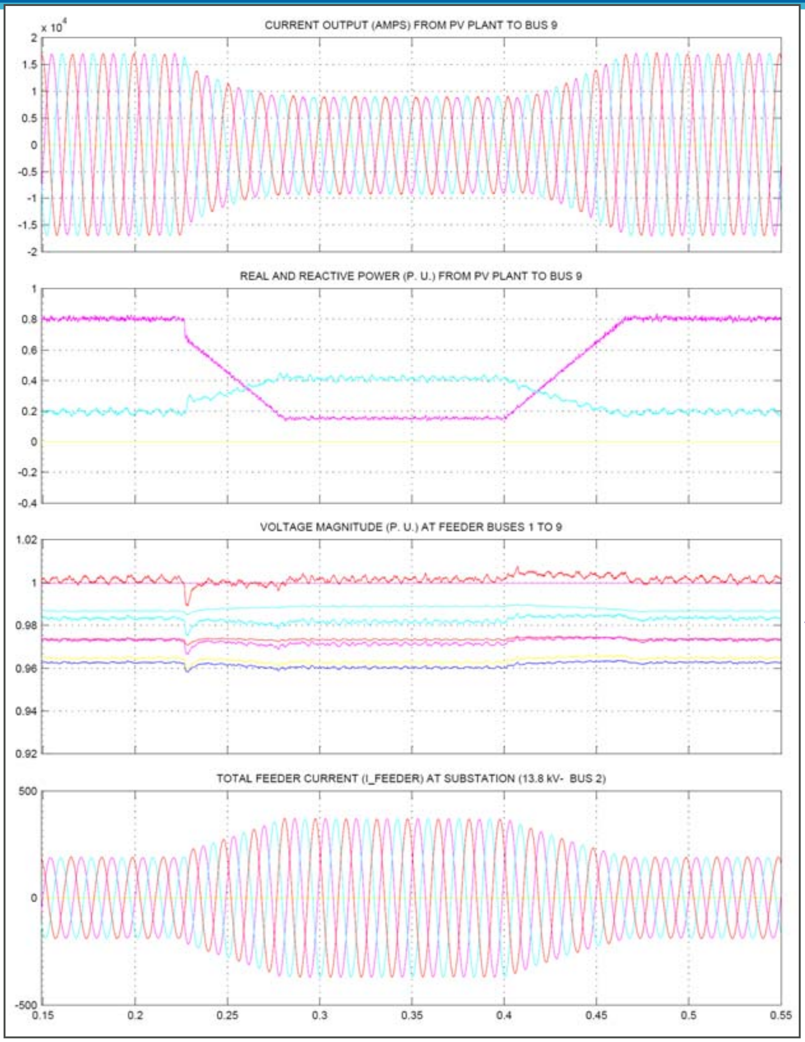
# Simulated Dip in Irradiance At PV Plant - Feeder Bus Voltages With / Without Fast Voltage Control

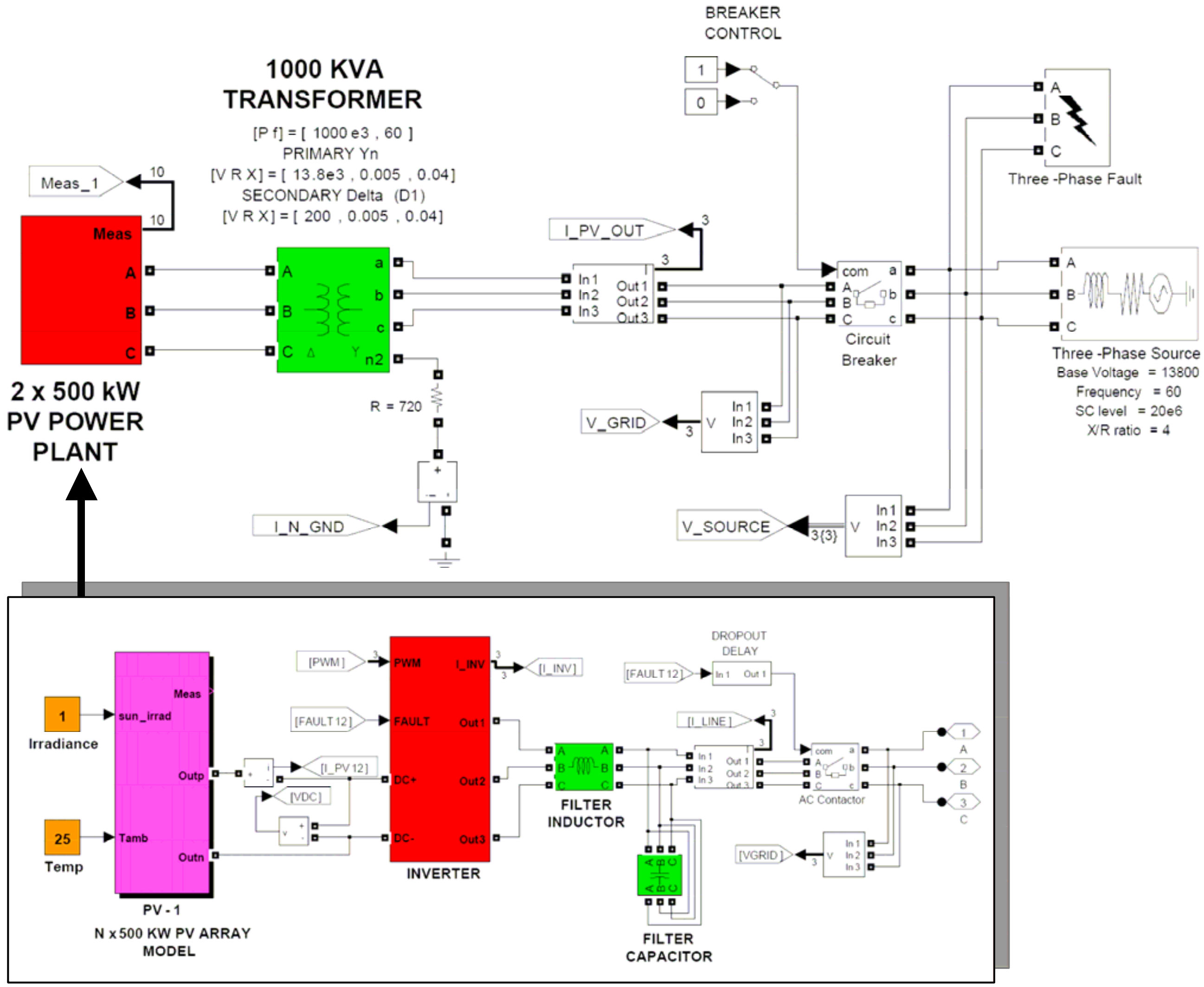



**Voltage Control Disabled**

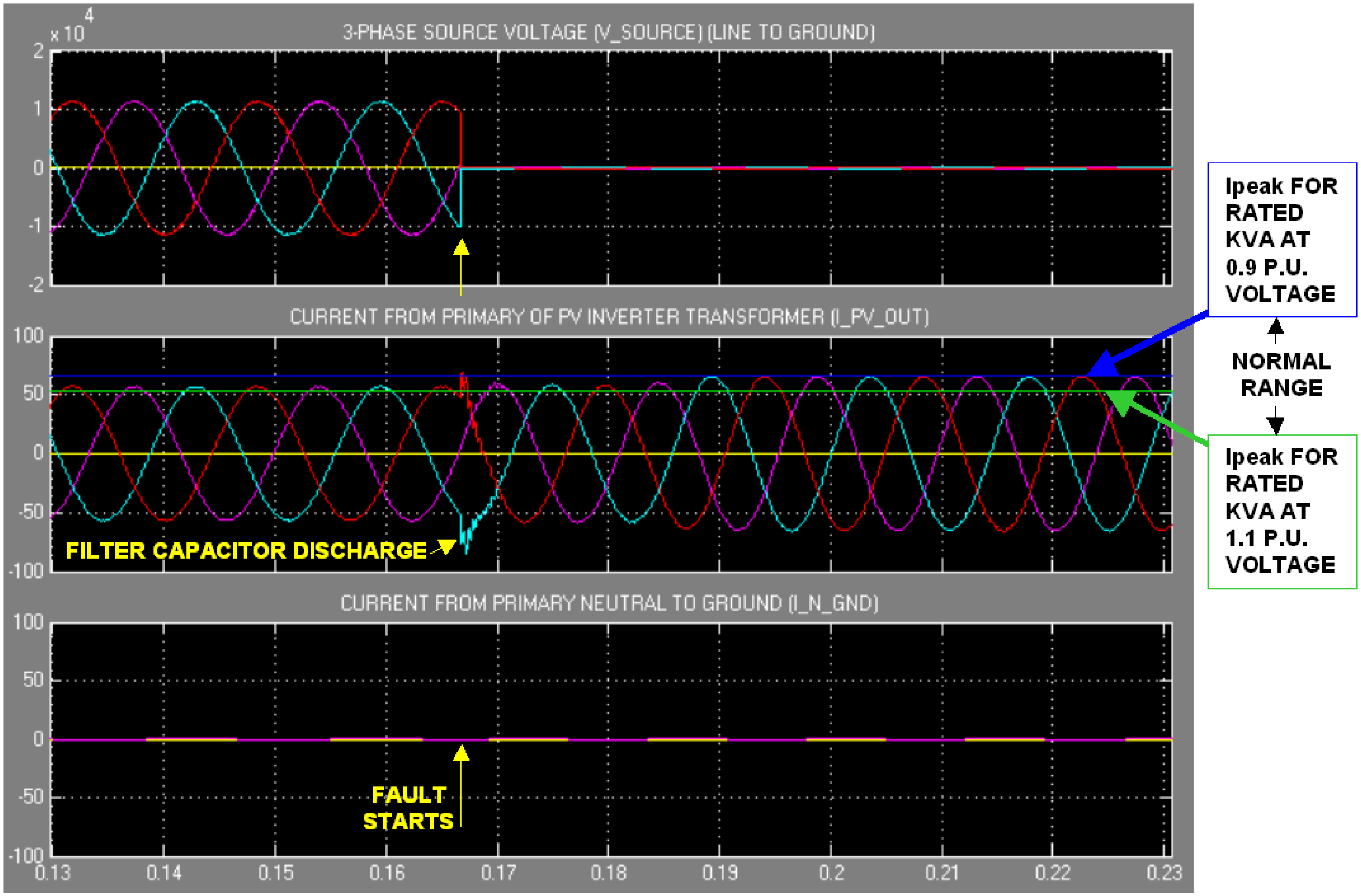



**Fast Voltage Control Enabled**

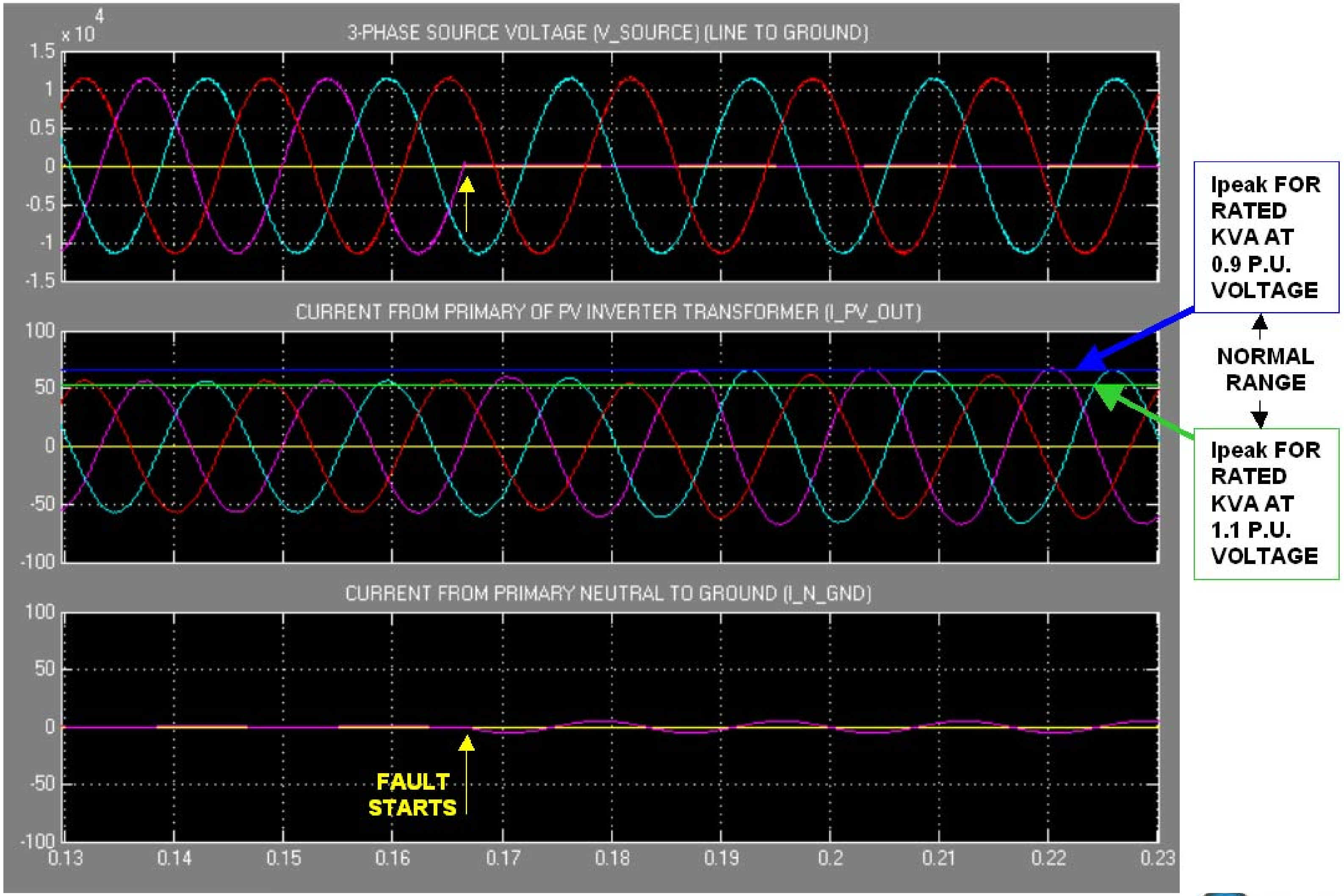
# Simulink Transient Model For Study of 1 MW PV Plant Fault Current Contribution



# 1 MW PV Plant
# Symmetrical Three Phase To Ground Fault



# 1 MW PV Plant
# Single Phase To Ground Fault

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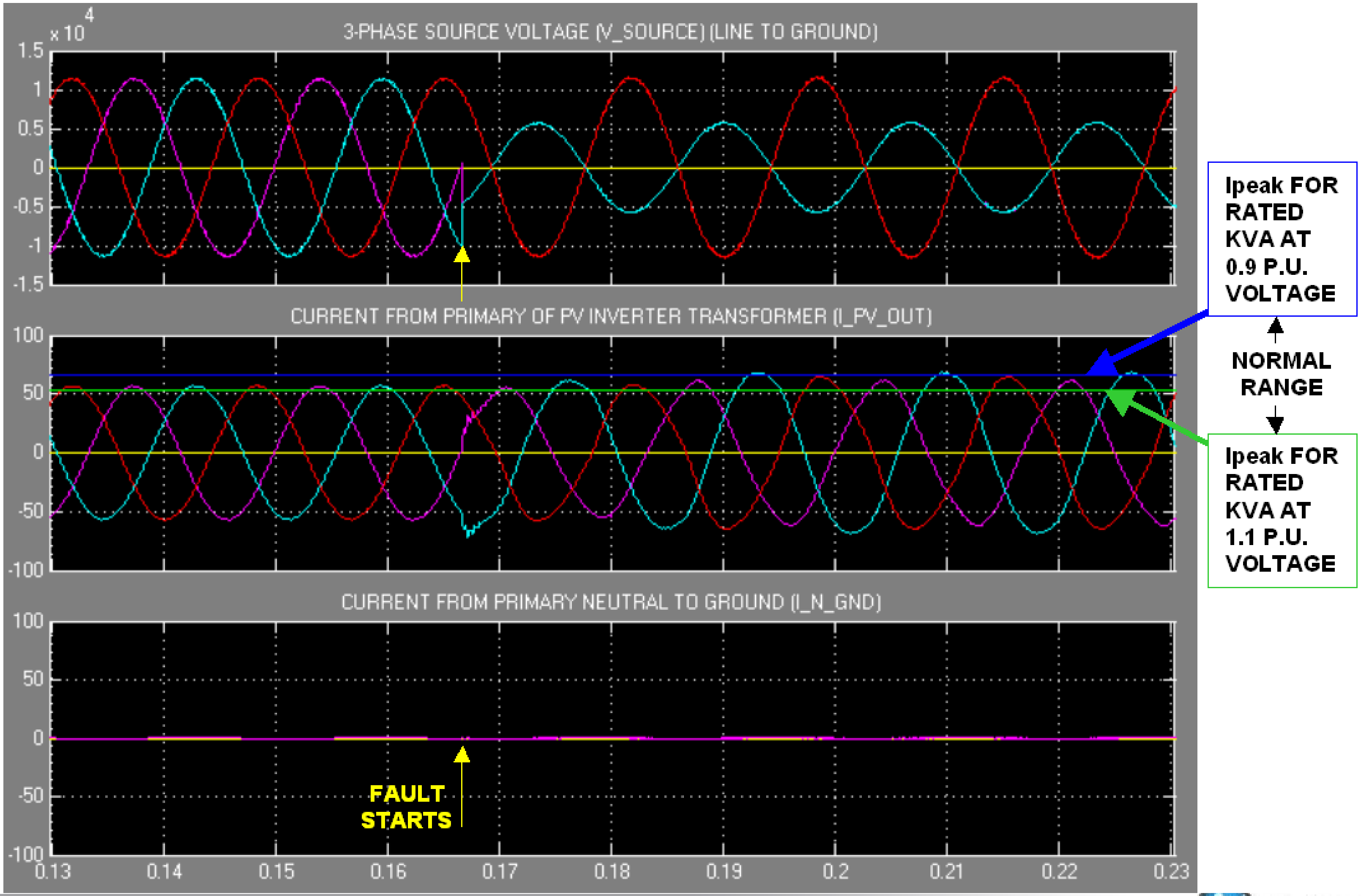
# 1 MW PV Plant
# Line To Line (A – B) Fault

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# Conclusions

- **Satcon inverters with advanced grid support features help to address utility concerns about high penetration DG**
  - Grid-smart inverter features enable PV generation to act as "hidden assets", providing *ancillary services* for the utility.
  - *Enhanced communication and control capabilities* allow the utility to regulate and monitor the generation of real and reactive power, and ensure reliable disconnection when necessary.
  - *Low voltage ride-through* (now mandated in several countries and for some installations in Hawaii) ensures that the PV plant is present to help support the system during and after voltage disturbances.
  - Ability to incorporate controlled *energy storage* in the inverter architecture facilitates the use of evolving storage technologies to mitigate the variability of PV power sources.