ADVANCED ENERGY®

A POWERFUL ADVANTAGE™

Advanced Power Controls
Case Studies
November 15, 2012

Advanced Power Controls

- Advanced Energy Introduction
- Why the need for advanced controls?
  - Curtailment
  - Reactive Power
- Temporary Over Voltage

AE Company

A leading, global supplier of:

- Power conversion and control technologies

To the world's most demanding markets:

- Renewable energy
- Thin film

By creating best-in-class products and services through:

- Innovative technology
- Life-cycle performance - quality, reliability and uptime

AE Solar Energy Global Footprint

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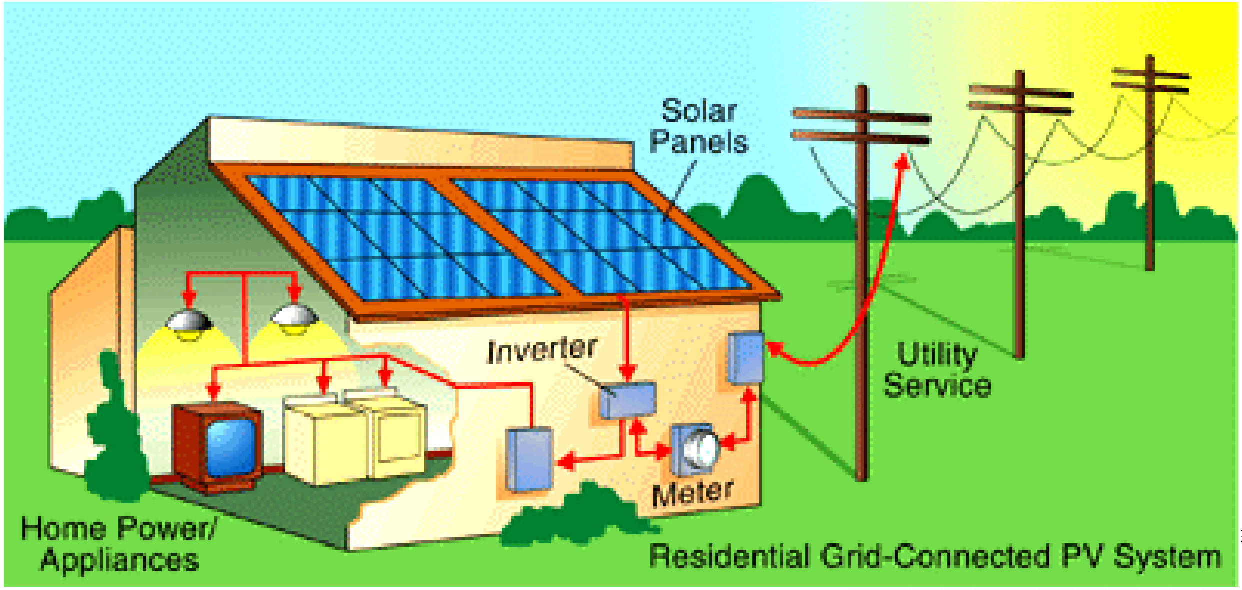
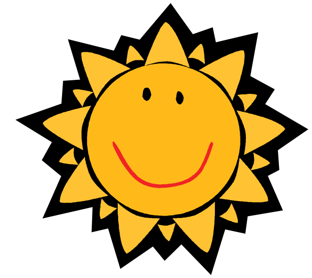
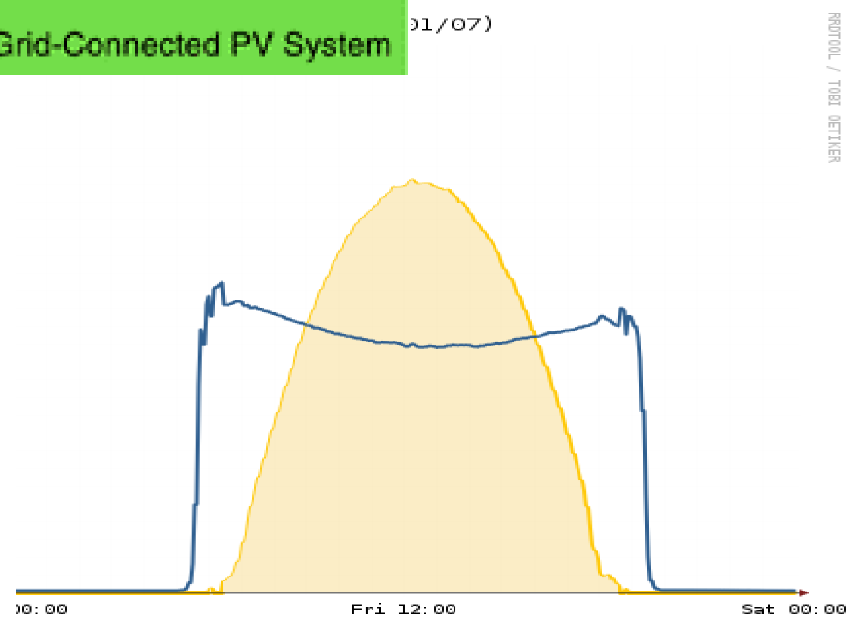
Renewable Energy Markets

Solar PV power conversion and architecture solutions aimed at lowest cost of energy through project life-cycle

“The Good Old Days”







<u>Requirements</u>

-IEEE1547, UL1741

Synchronization

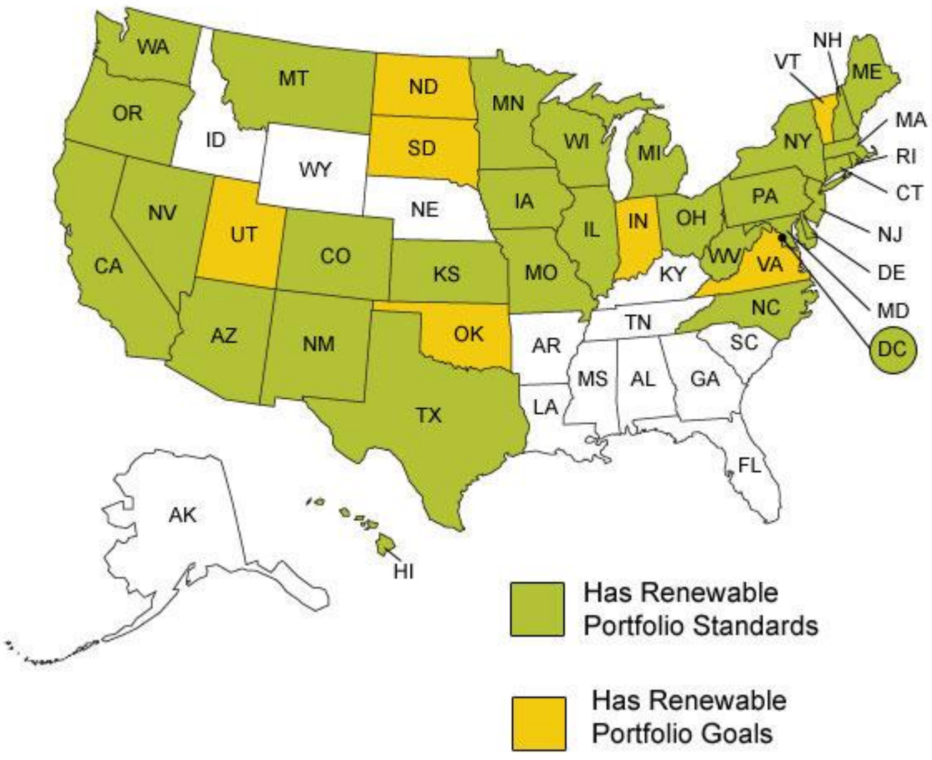
Response to Abnormal conditions

Non Islanding

-Assumed a minor player in the electrical system

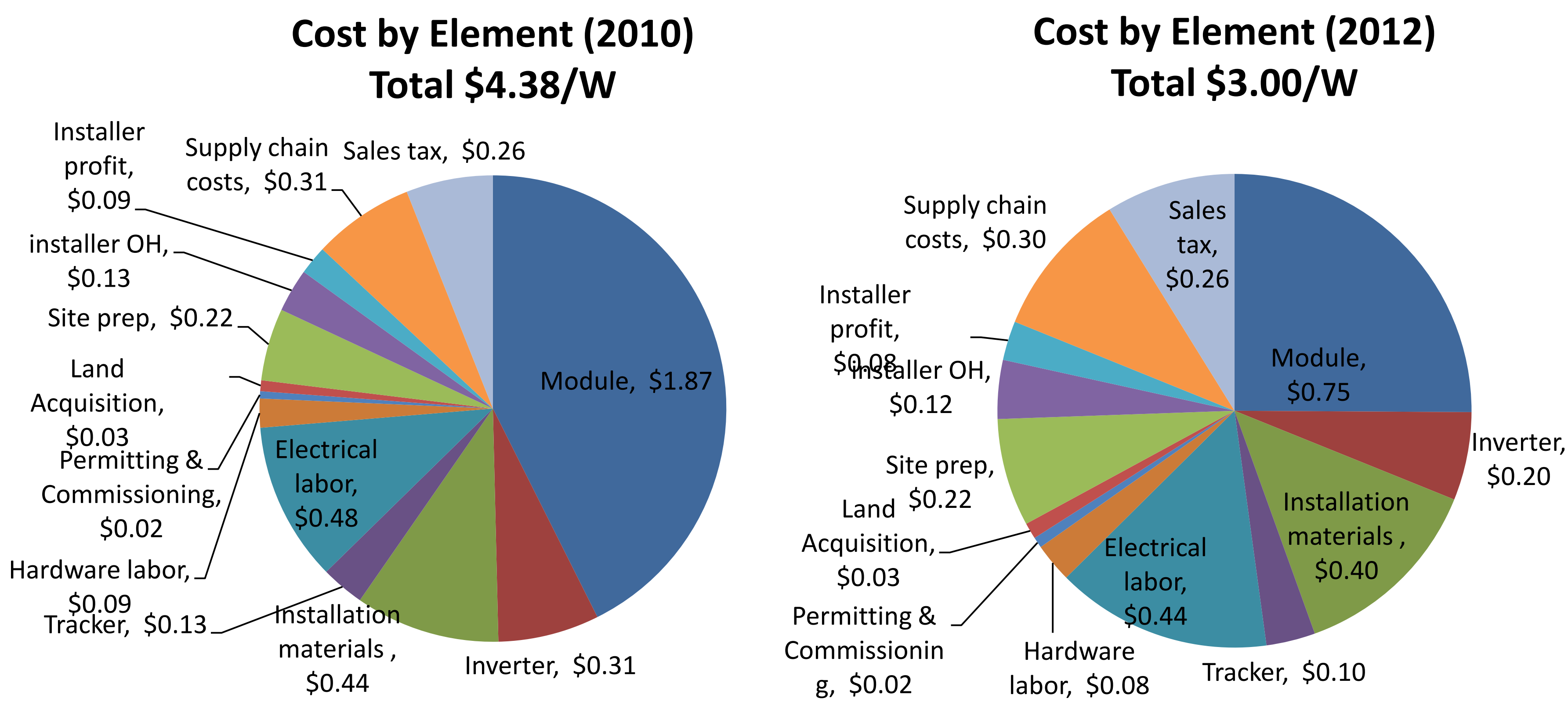
Photovoltaic Industry Growth

Most States Have Renewable Portfolio Standards or Goals



Source: N.C. Solar Center at N.C. State University, Database of State Incentives for Renewables & Efficiency (accessed July 2012).

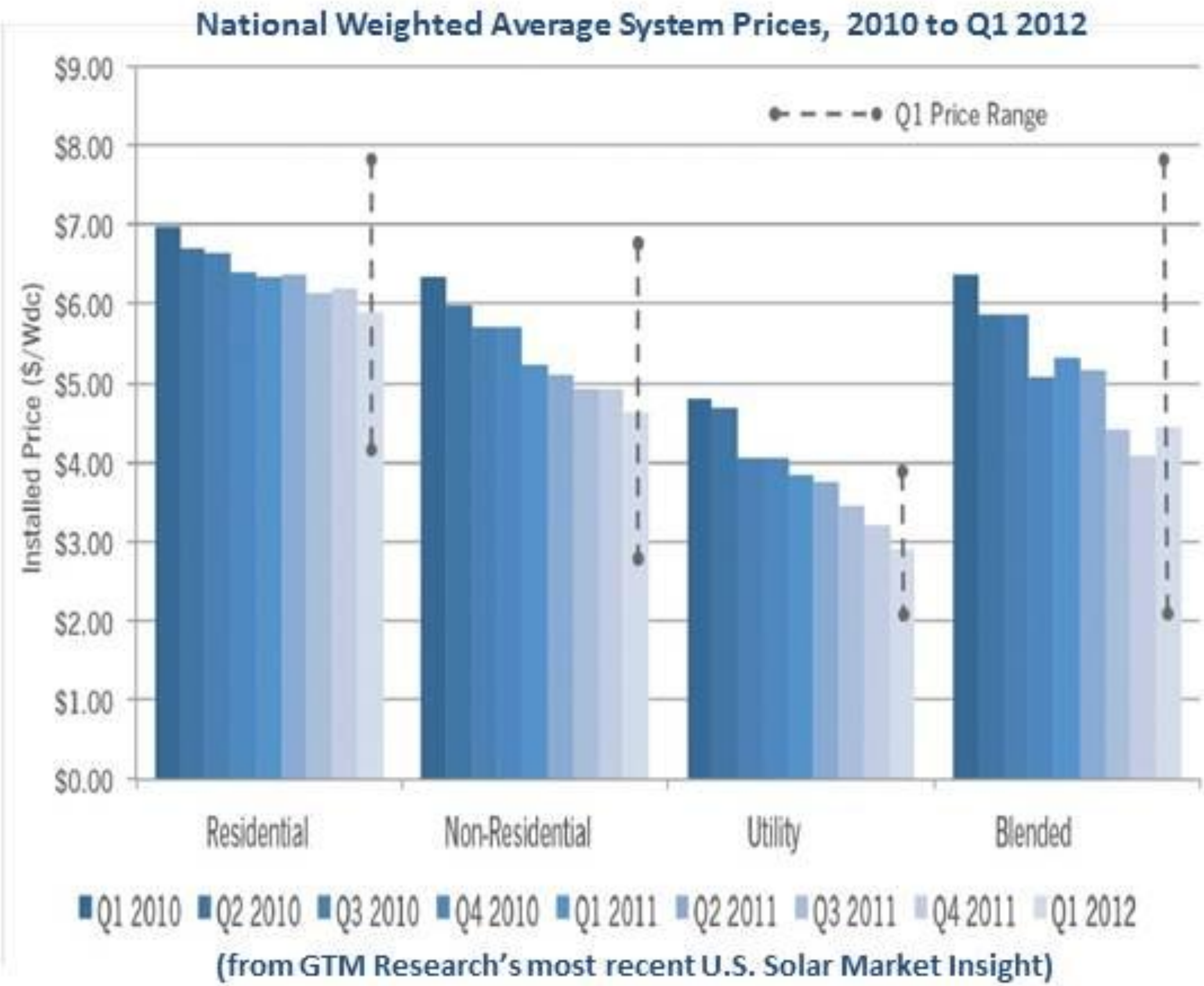
Decreasing Costs by System Element



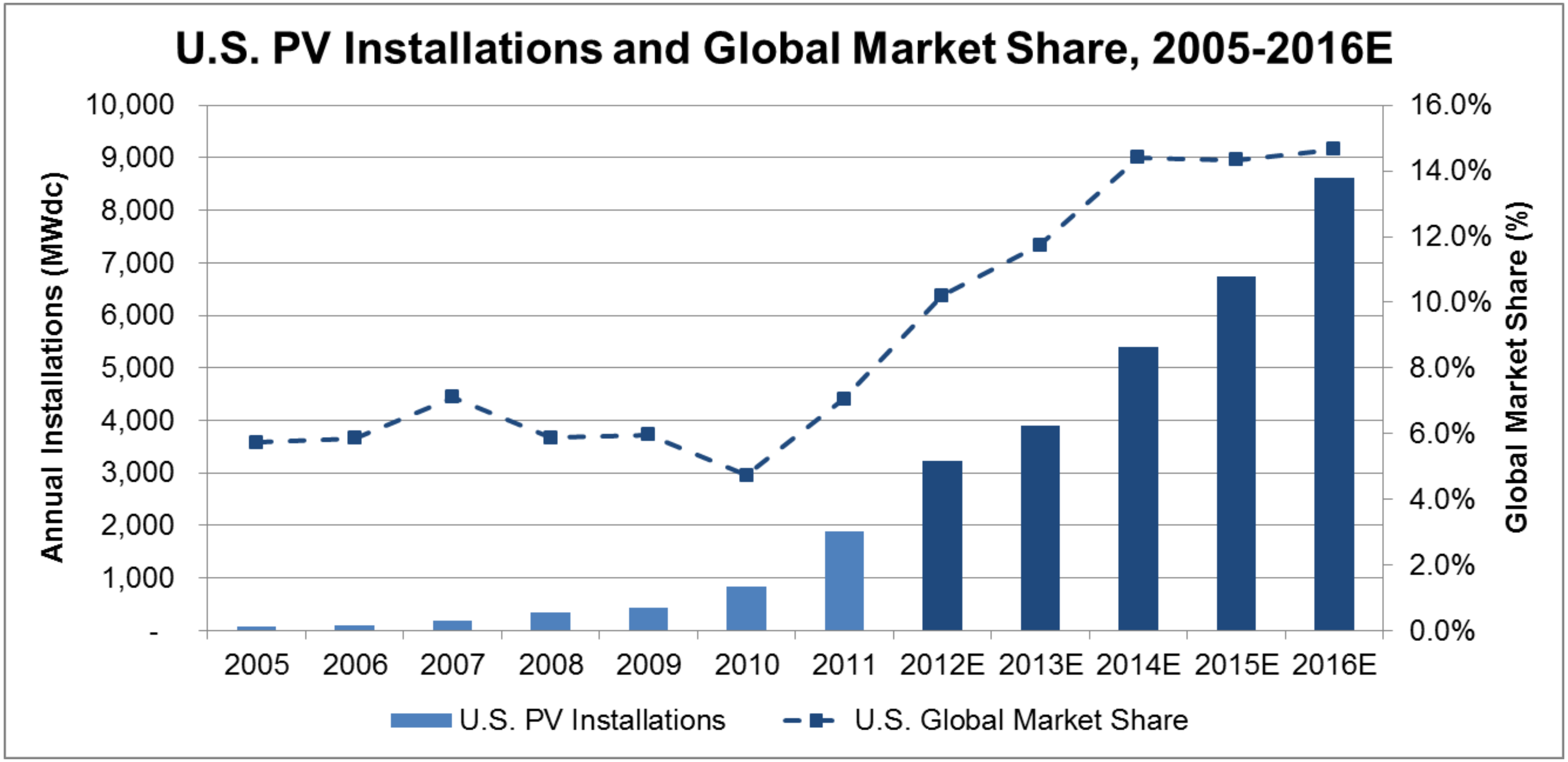
Sources: NREL- 2/12, GTM- 7/12

These are PV System costs only. Utility upgrades, line extensions, and interconnect costs are not included which **can be a substantial part of total project cost.**

Decreasing System Cost by Market Segment



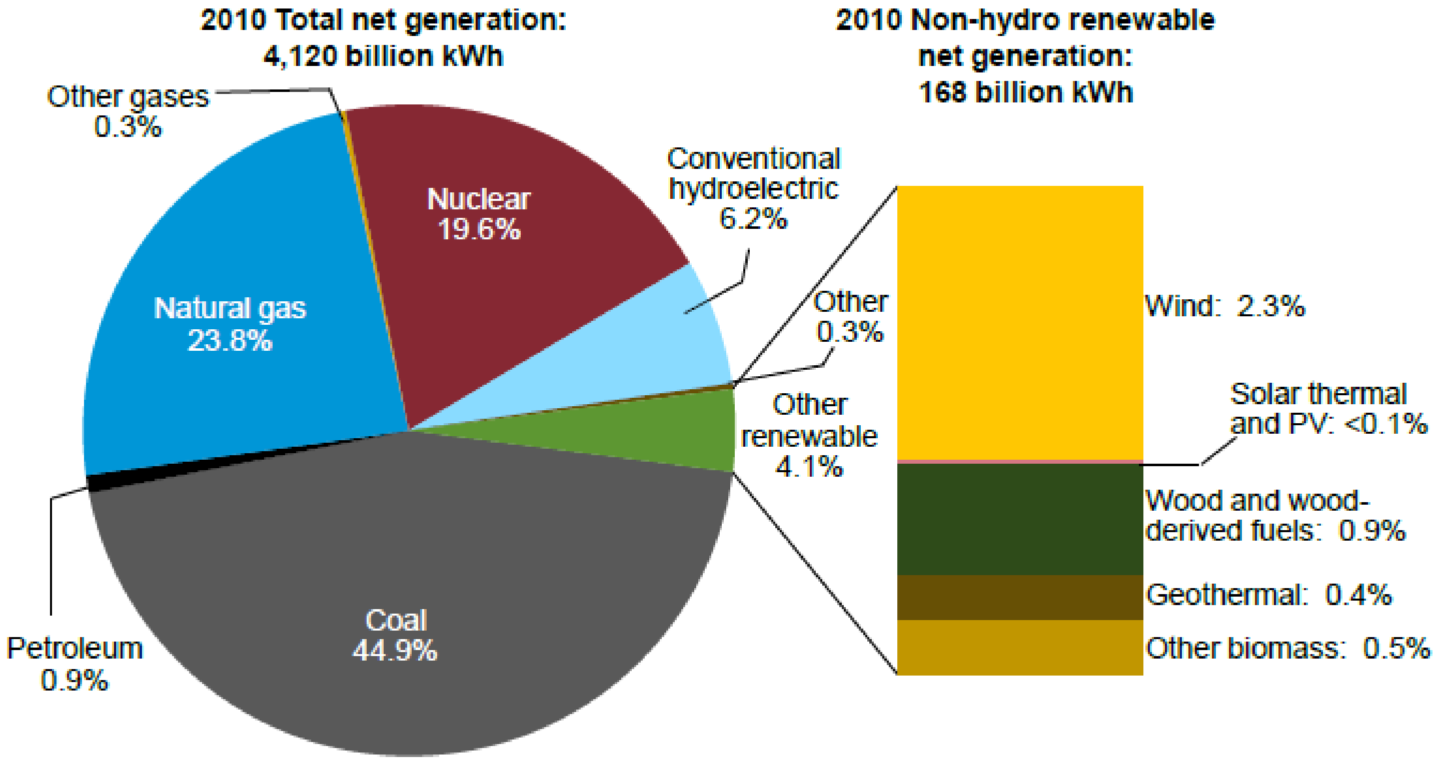
Photovoltaic Industry Growth



Source GTM 2012

- PV Industry experiencing year on year explosive growth
  - 40% historical growth, 42% annual growth expected through 2020
  - More states incenting solar, grid parity within reach

Photovoltaic Industry Growth



Source: EIA, Annual Energy Review, October 2011

- Nationwide PV remains a small portion of electrical generation
    - Is high penetration really a concern?

How do we get high penetration?

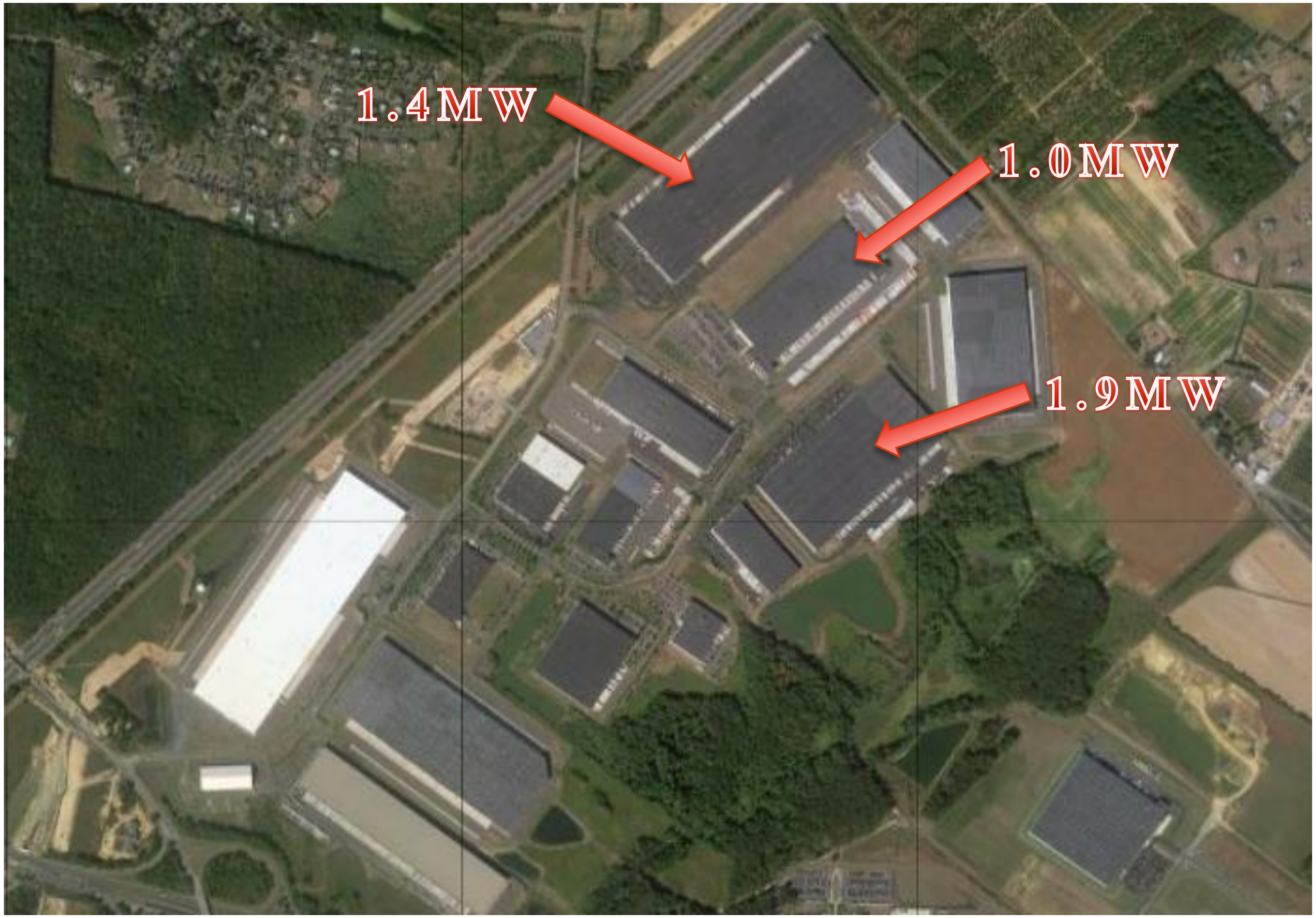
How do we get high penetration?

1 MW

How do we get high penetration?

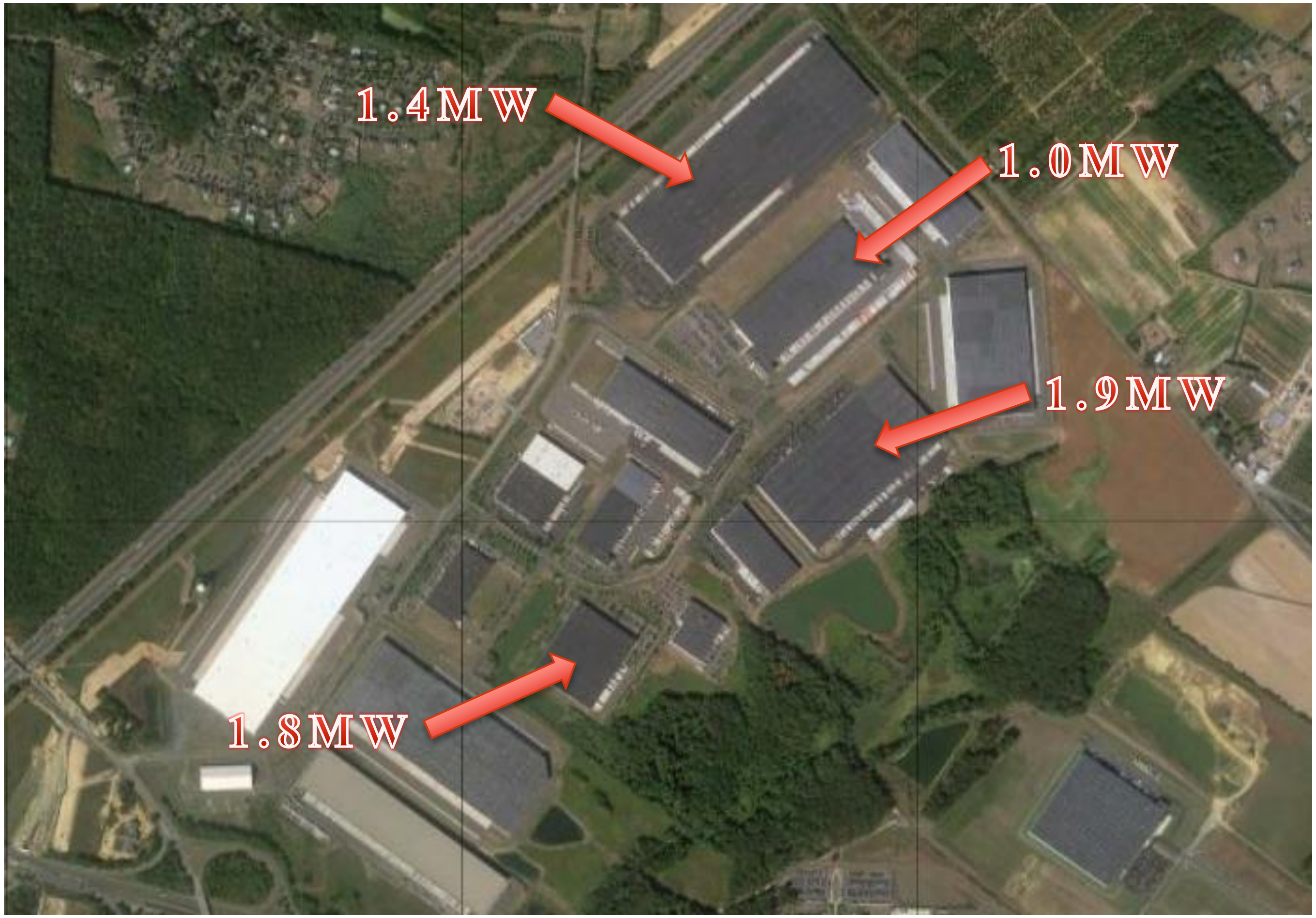
2.4 MW

How do we get high penetration?



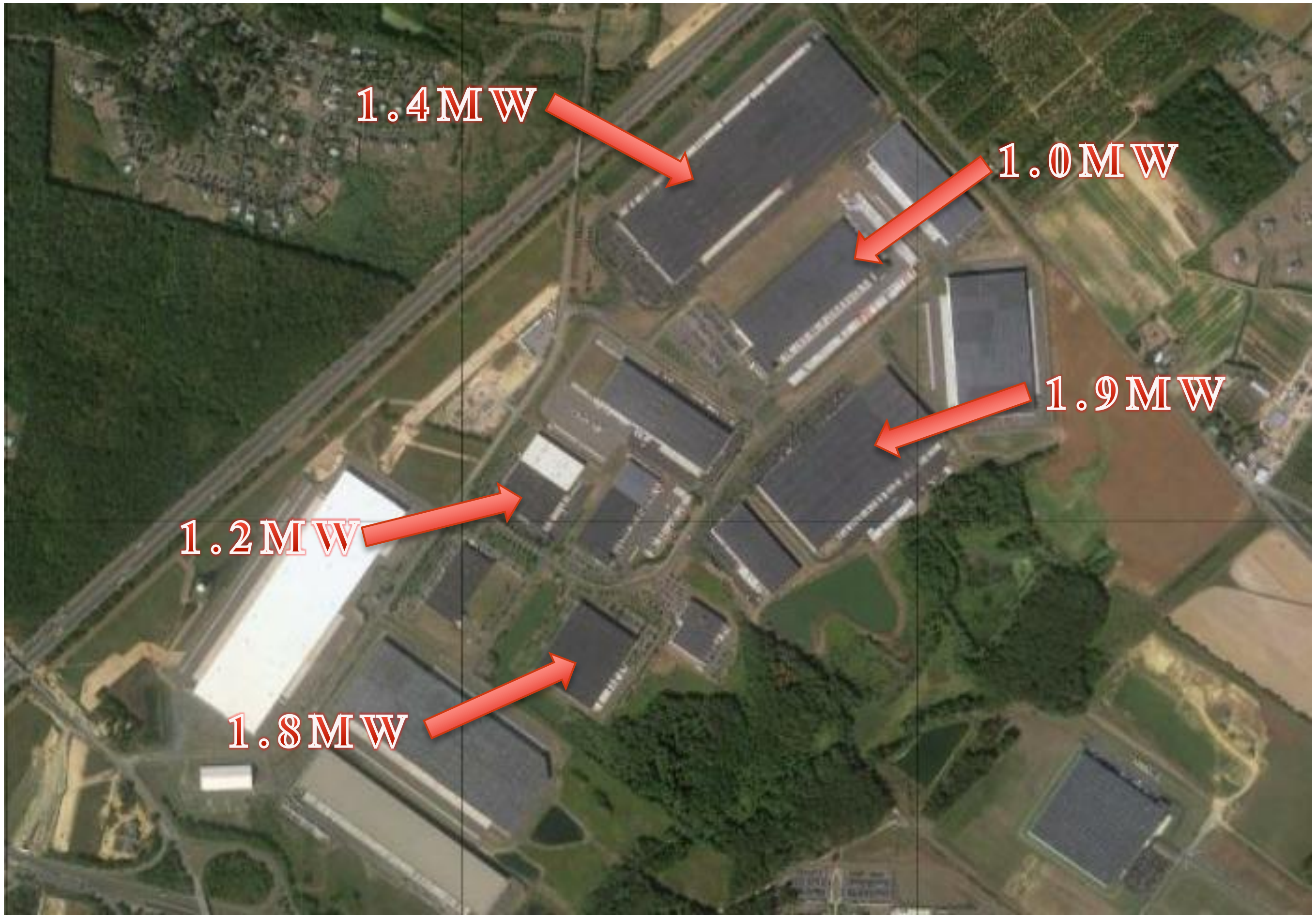
4.3 MW

How do we get high penetration?



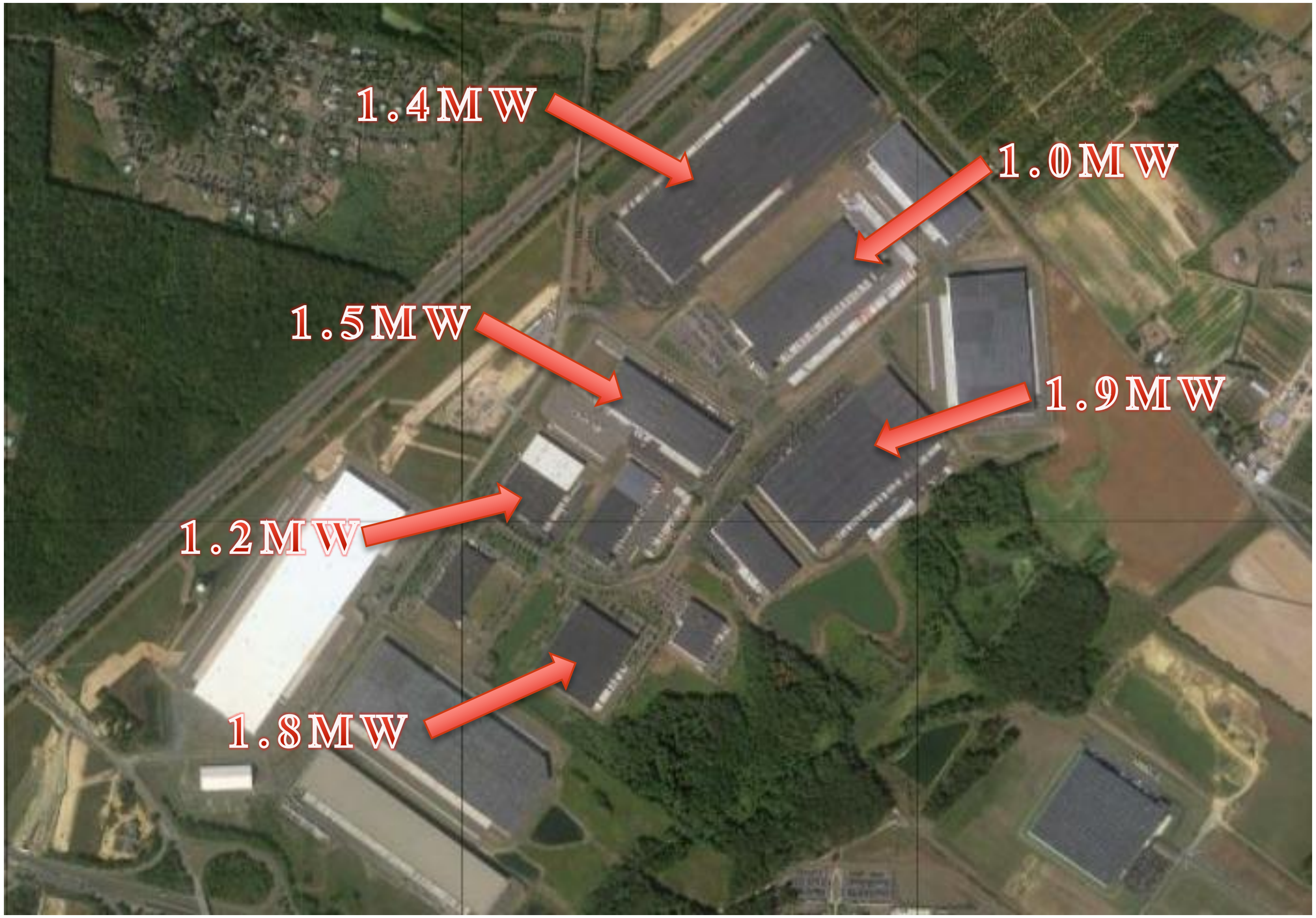
6.1 MW

How do we get high penetration?



7.3 MW

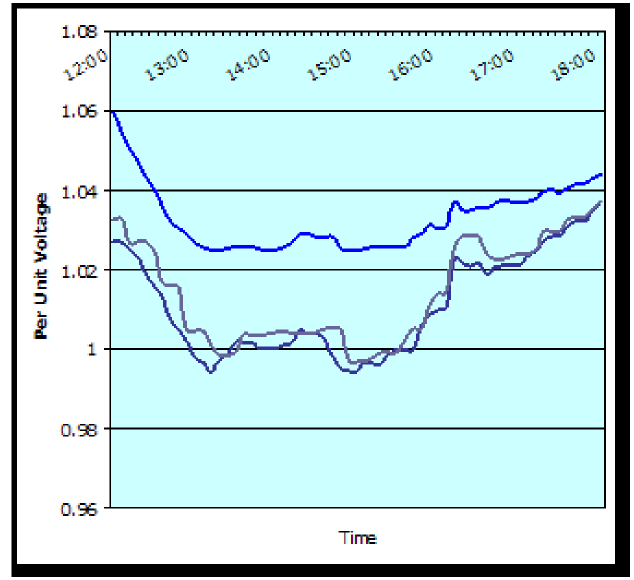
How do we get high penetration?



8.8 MW Total

Advanced Power Controls

Function	Range
Power Factor	0.9 leading to 0.9 lagging
Curtailment	5 –100% max kVA
Ramp Rate	1 – 50 kW/S
Action Delay	0 – 255 sec
Randomization	0 – 255 sec
Remote Enable/Disable	N/A



Stabilize grid voltage

Utility support functions

- Grid stability
- Meet interconnections requirements
- Adapt to site dynamics

All functions comply with UL1741/IEEE1547

Available on 75/100/250/260/500kW TX inverters

Advanced Power Control - Functions

Function	Description	Range
Power Factor	Sets the ratio of real power to apparent power. Allows for sourcing or sinking of VARs	0.9 to1.0 lead -0.9 to -0.99 lag
Curtailment	Specifies an upper limit for inverter output power by percent of max output or by absolute kVA.	5 –100% max kVA
Ramp Rate	Controls the maximum rate at which instantaneous power increases / decreases	1 – 50 kW/S
Action Delay	This feature enables pre-defined delays for set-point changes. Useful for multi-inverter sites.	0 – 255 sec
Randomization	This feature randomizes the start time of set-point change based on pre-defined thresholds	0 – 255 sec
Remote Enable/Disable	This feature allows for the system to be remotely turned on / off	N/A

All functions comply with UL1741/IEEE1547

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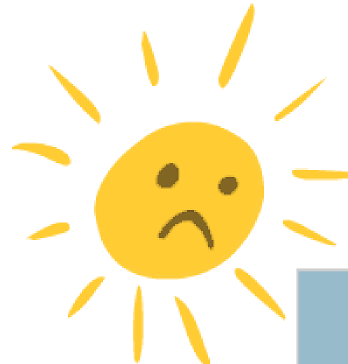
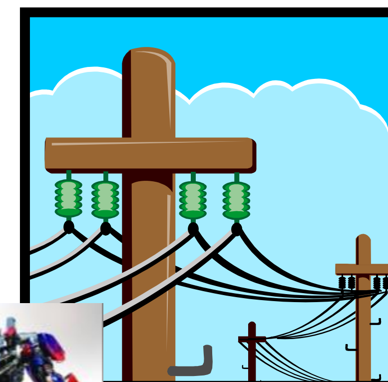
Inverter Curtailment

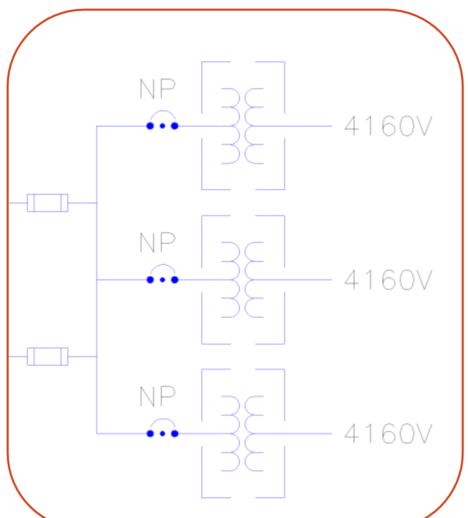
Inverter Curtailment

Why curtail?

- Service size
  - Service transformer size
- Network grid/spot network
  - No reverse power flow permitted
- Over subscribed feeder
  - Too much PV capacity already installed







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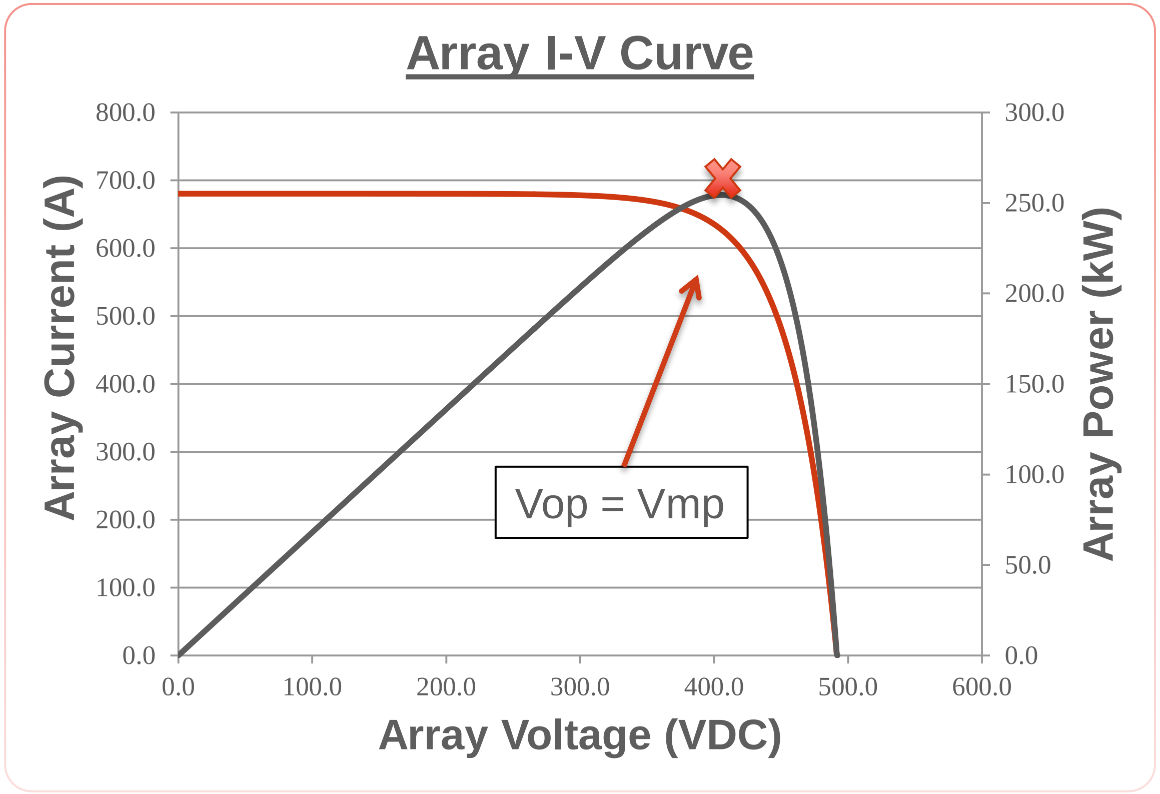
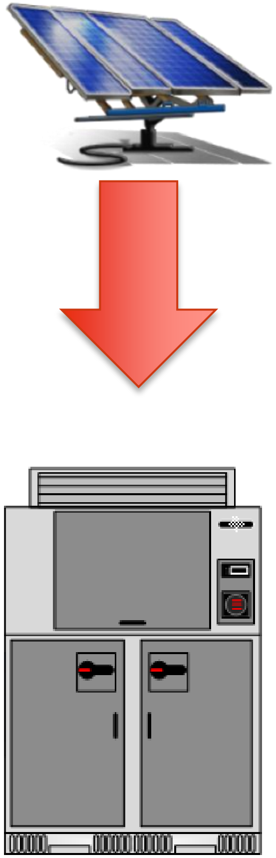
How is curtailment achieved?

Inverter stops maximum power point tracking, moves above Vmp
All available power is not drawn from array
No heat is expended in inverter





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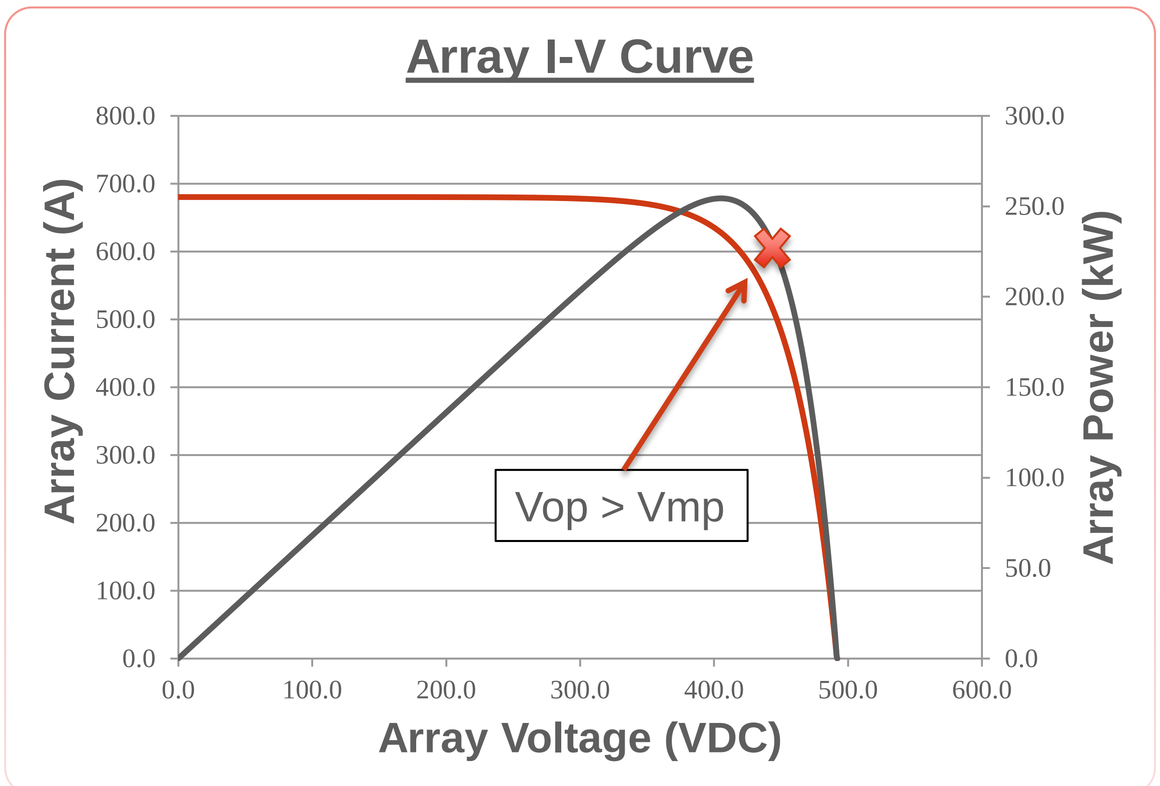
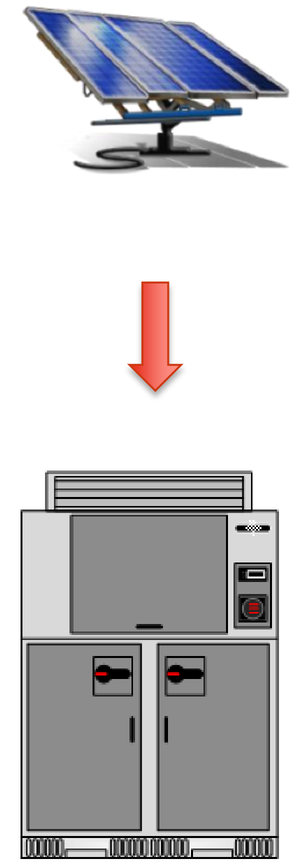
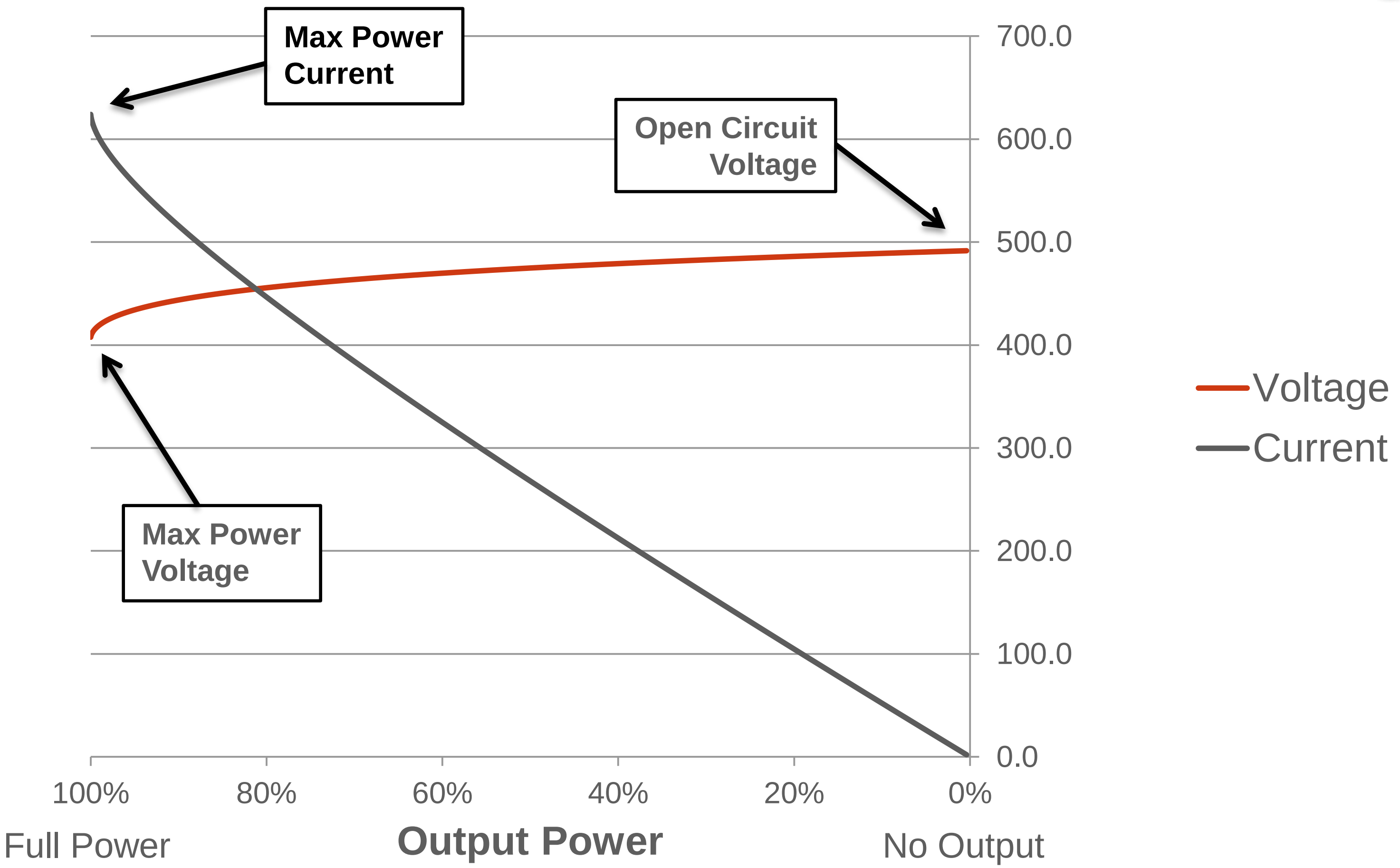




How is curtailment achieved?

Operating voltage is raised above maximum power voltage
Current decreases



Case Study: Fixed Curtailment

Location	Fair Lawn, NJ
Installation	412kW-DC
Products	AE 75TX AE 260TX

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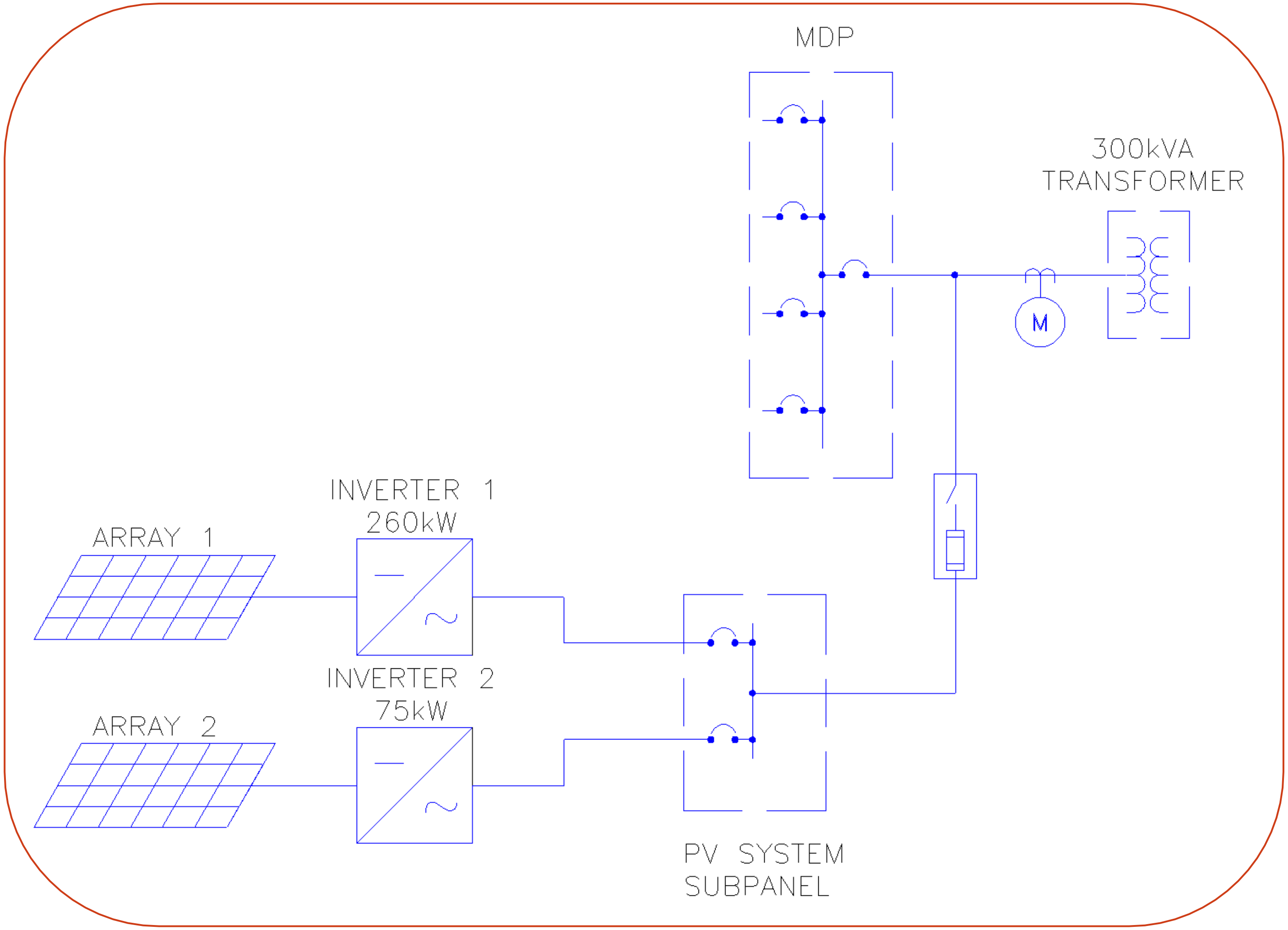
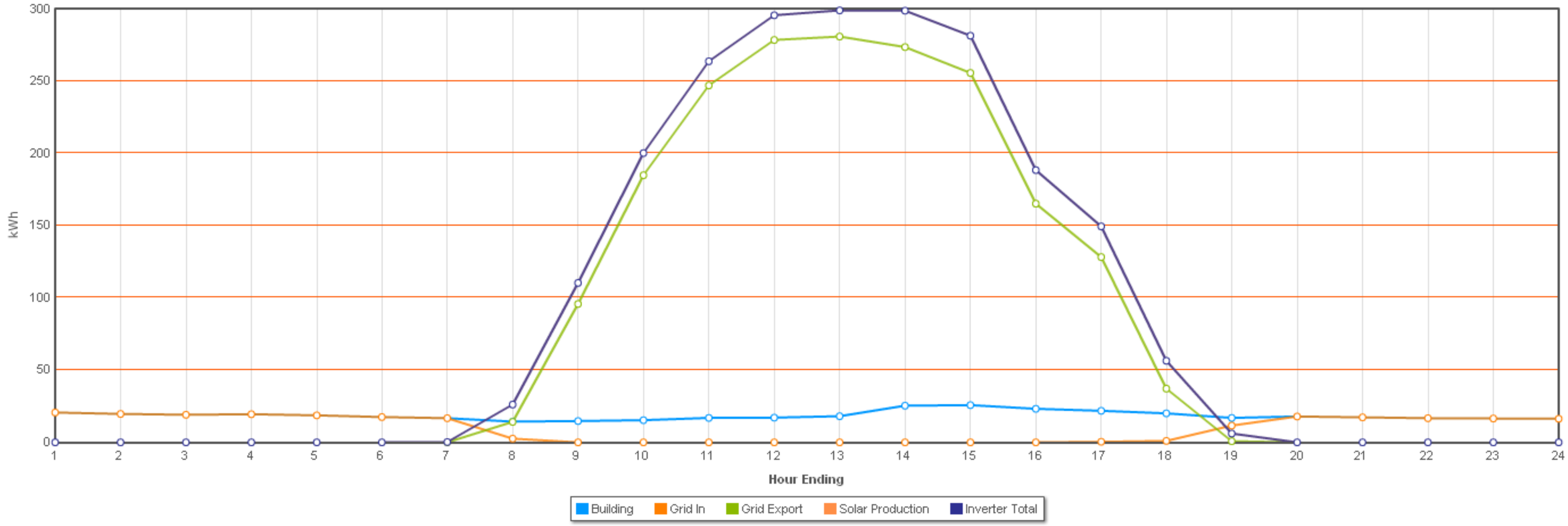
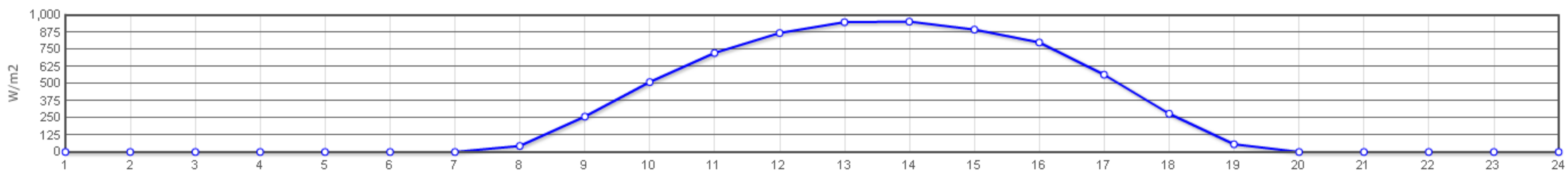
Case Study: Fixed Curtailment



335kW-AC System – 300kVA Service Transformer

Case Study: Fixed Curtailment



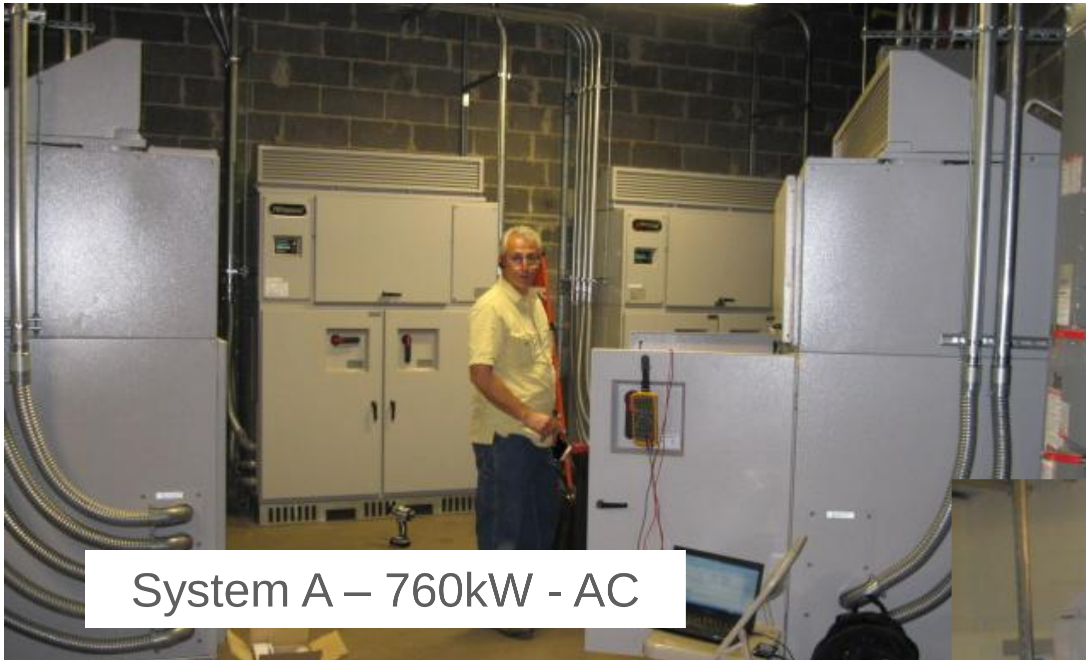


Inverter power output limited not to exceed transformer rating.
Inverters power limit at high irradiance.

Case Study: Scheduled Curtailment

Location	Paramus, NJ
Installation	1MW-DC
Products	AE 50TX AE 100TX AE 260TX

Case Study: Scheduled Curtailment

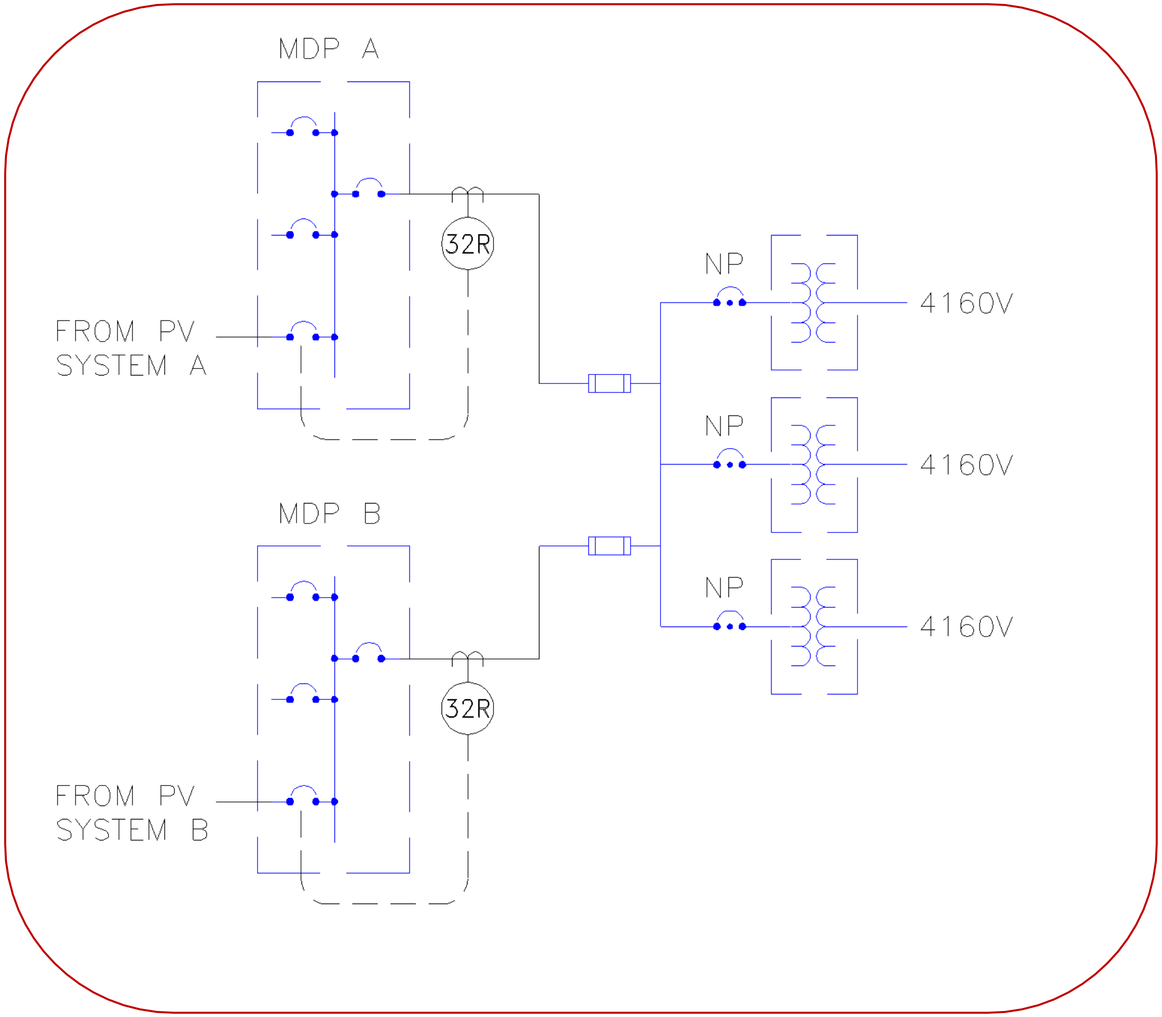


System A – 760kW - AC

System B – 150kW - AC

System split between Mall service entrances

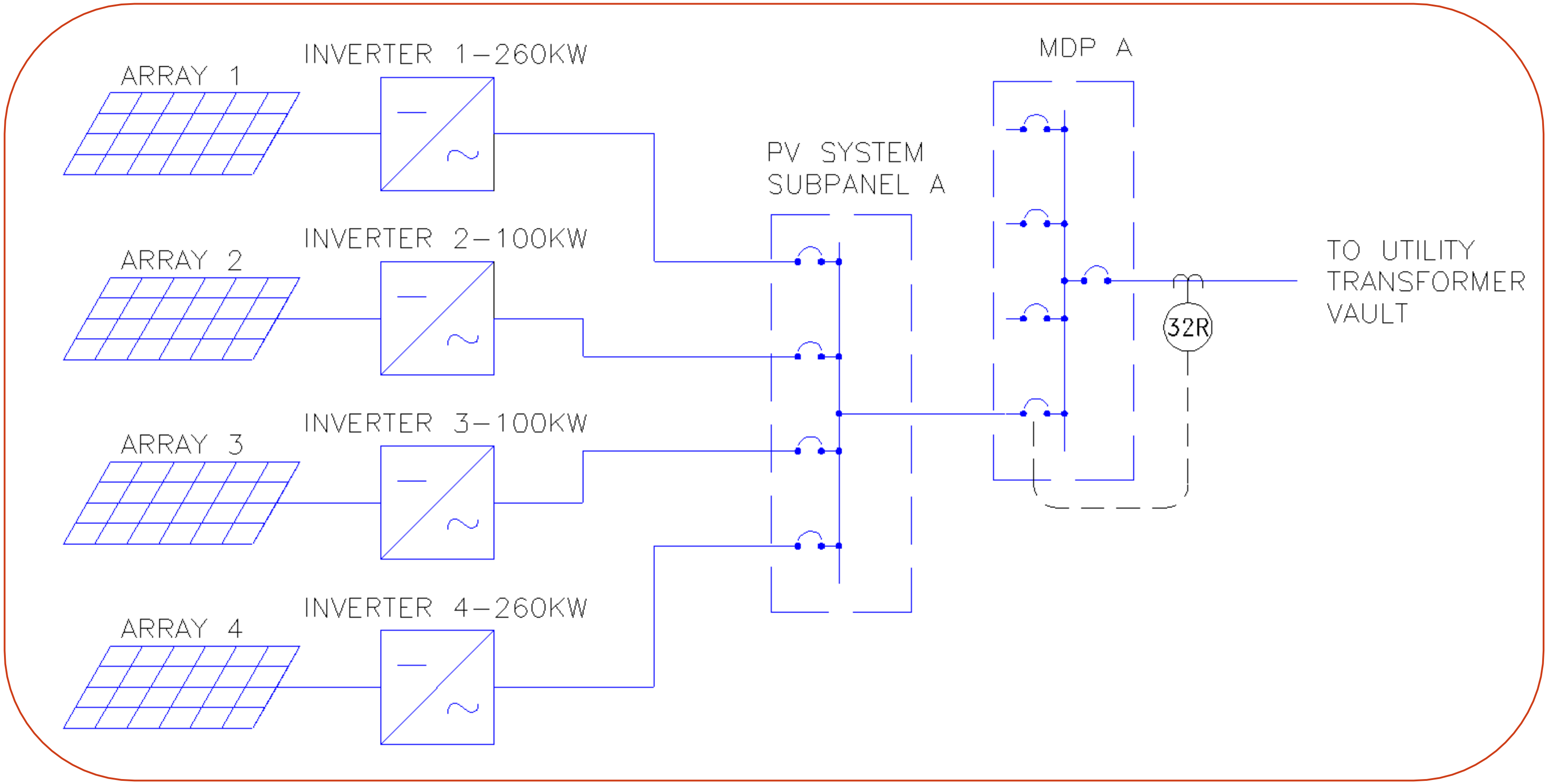
Case Study: Scheduled Curtailment



Reverse power flow not permitted on spot network

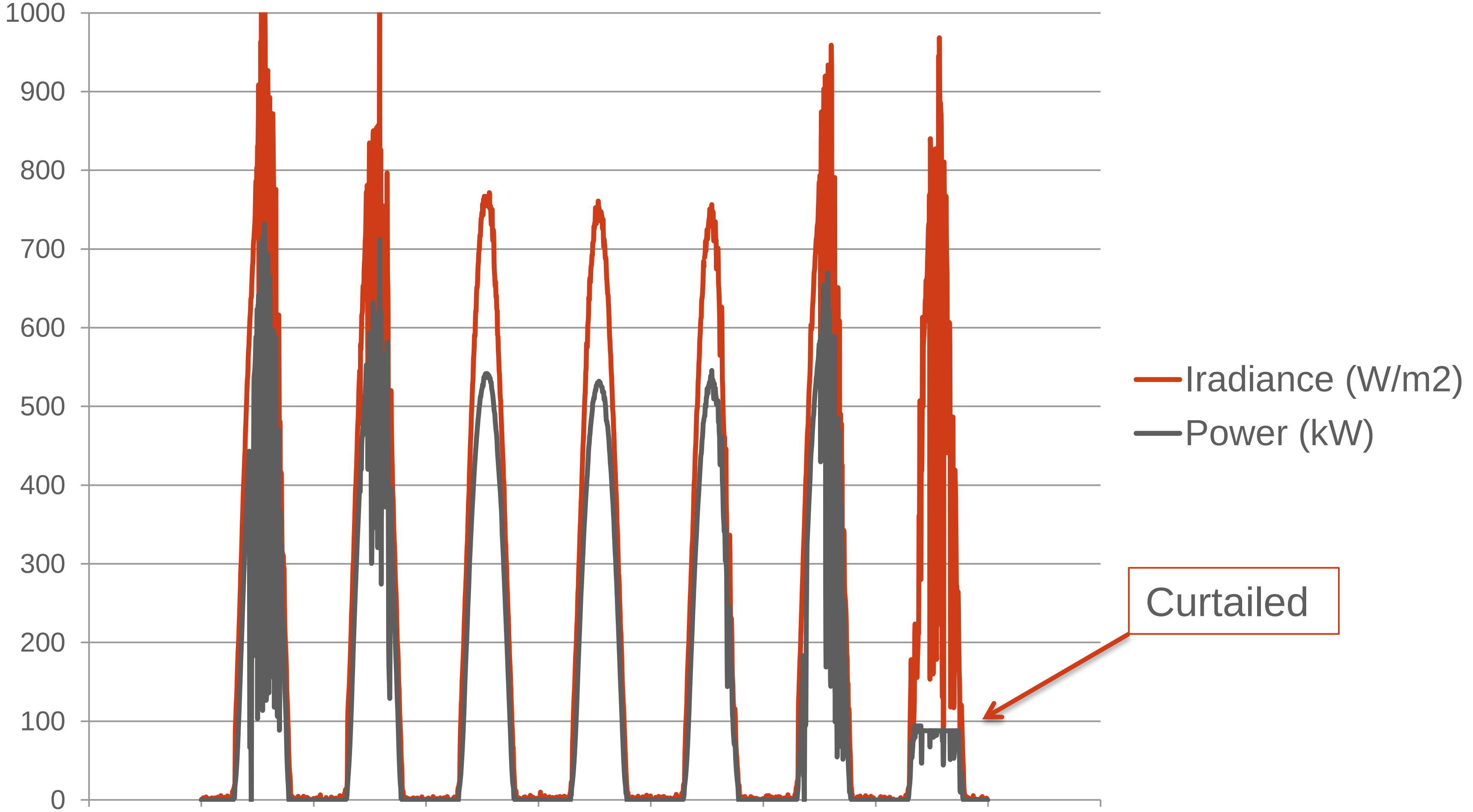
Minimal load on Sundays due to county blue laws

Case Study: Scheduled Curtailment



Scheduled curtailment eliminated need for site controller.
Backup protection provided by 32R.

Case Study: Scheduled Curtailment



Scheduled curtailment eliminated need for site controller.

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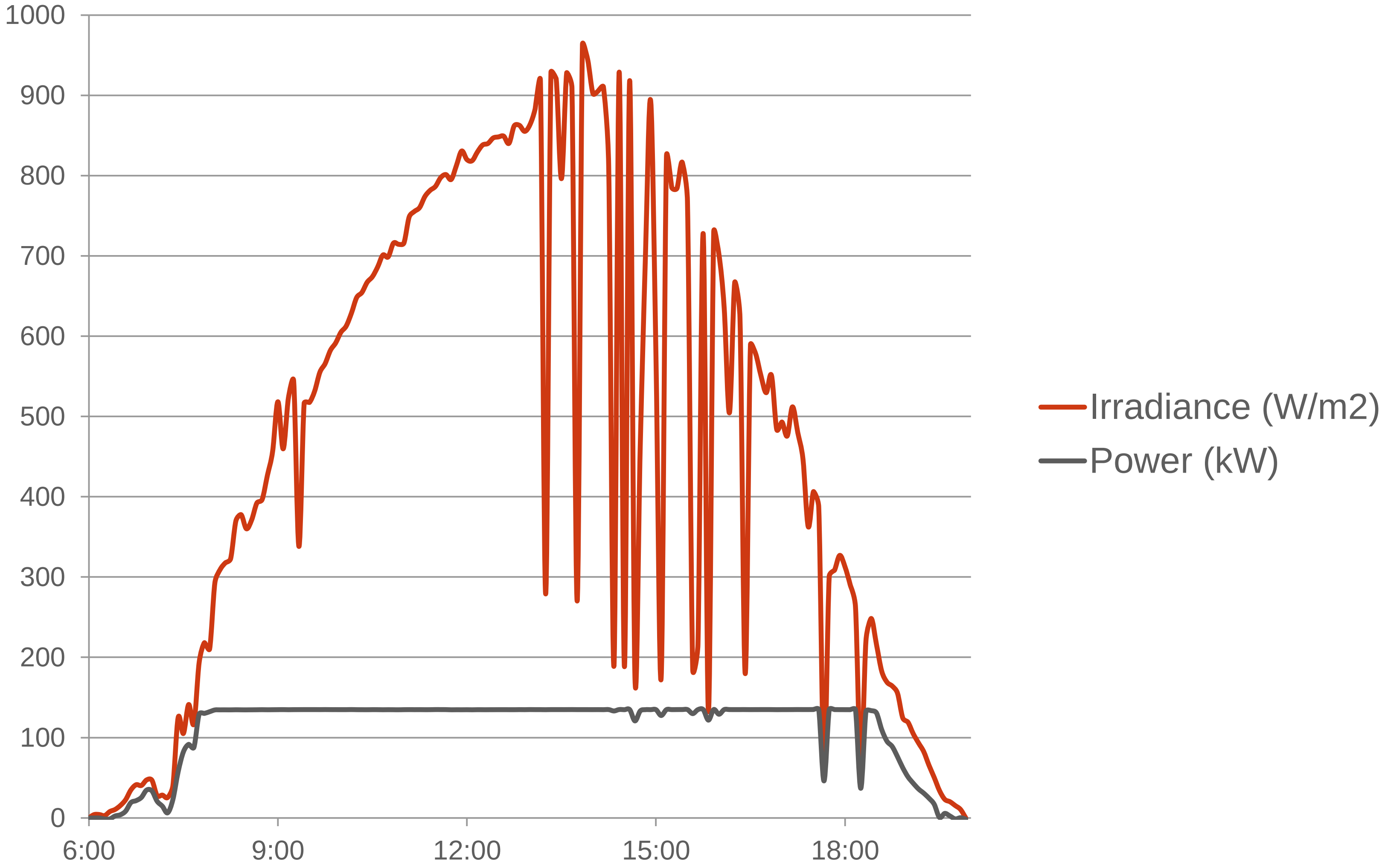
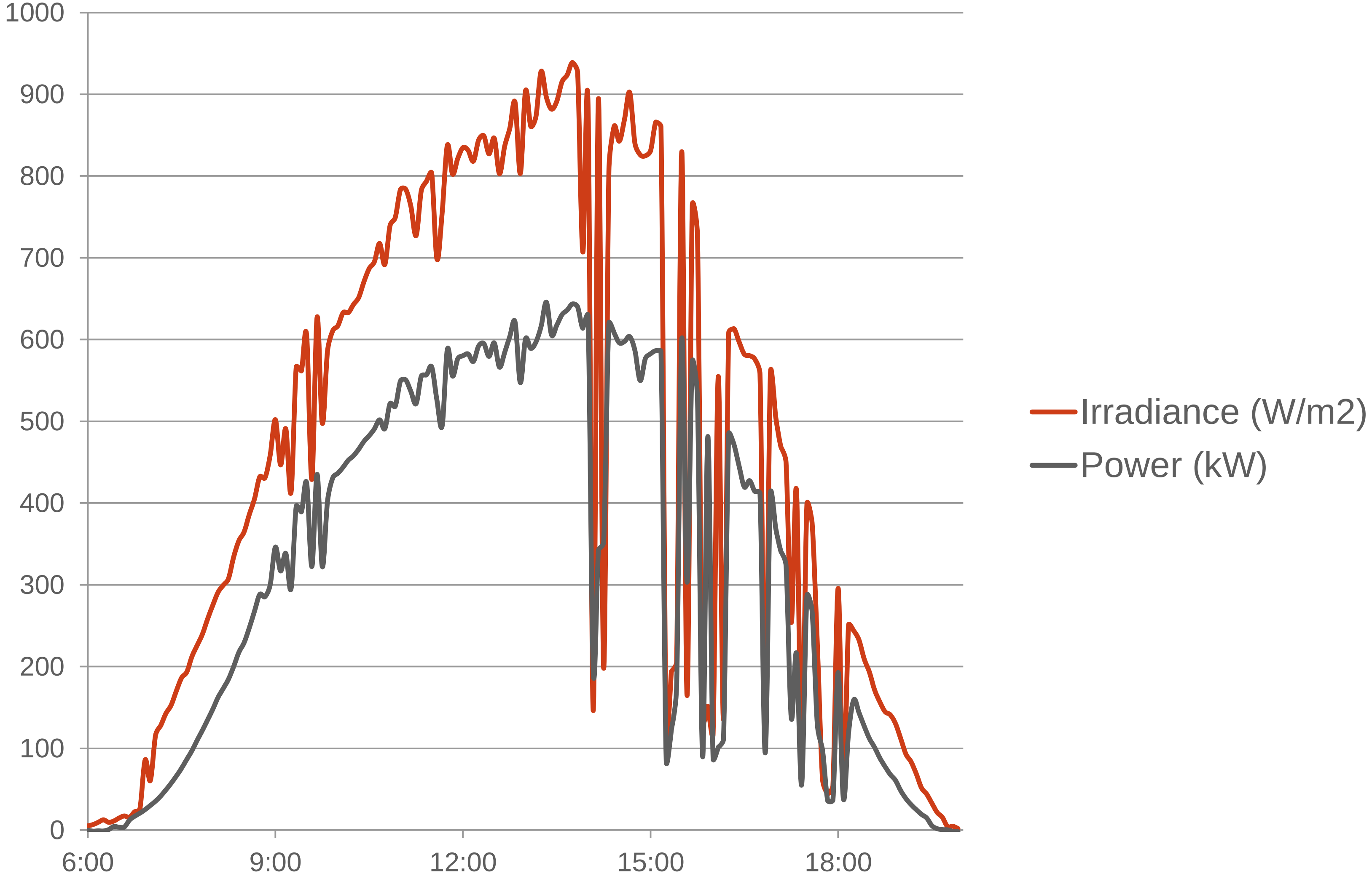
Case Study: Scheduled Curtailment



Sunday – system curtailed

Case Study: Scheduled Curtailment



Monday – normal operation

Case Study: Dynamic Curtailment

- High penetration area
- Over subscribed feeder
- Light load
- Only zero export installations permitted

Location	Cranbury, NJ
Installation	7MW, multiple buildings
Products	AE 260TX AE 100TX

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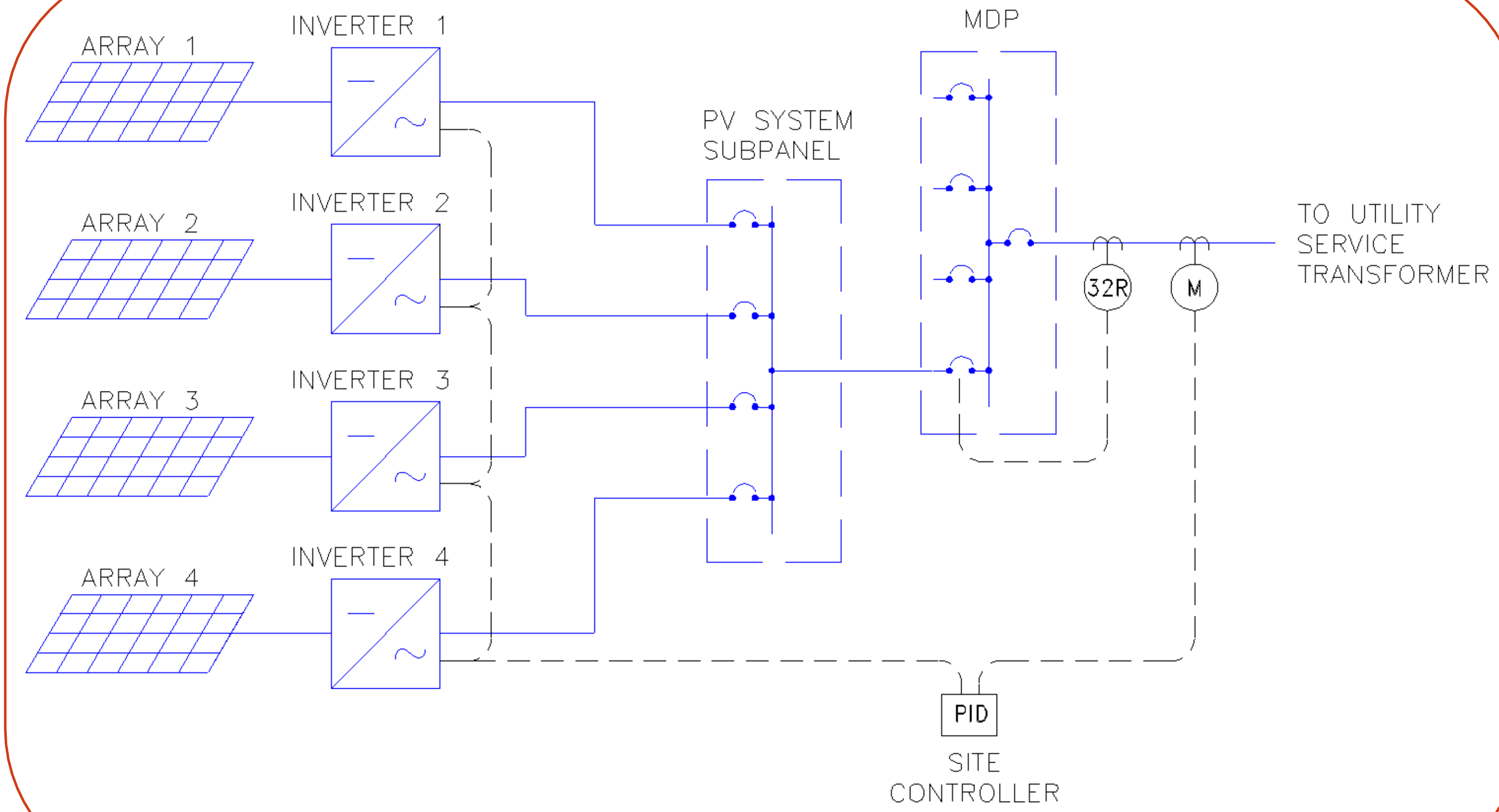
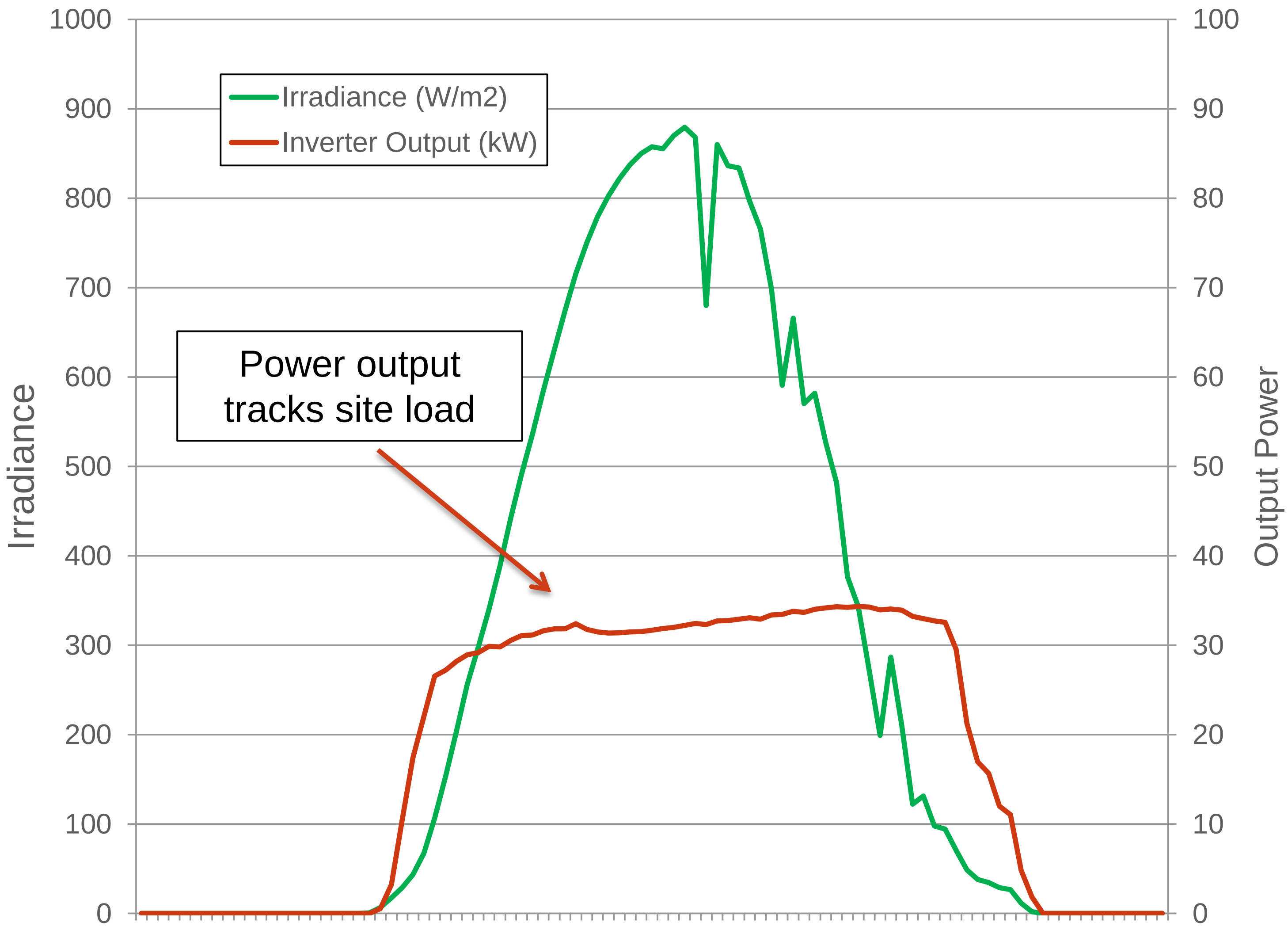
Case Study: Dynamic Curtailment

2 1MW PowerVaults

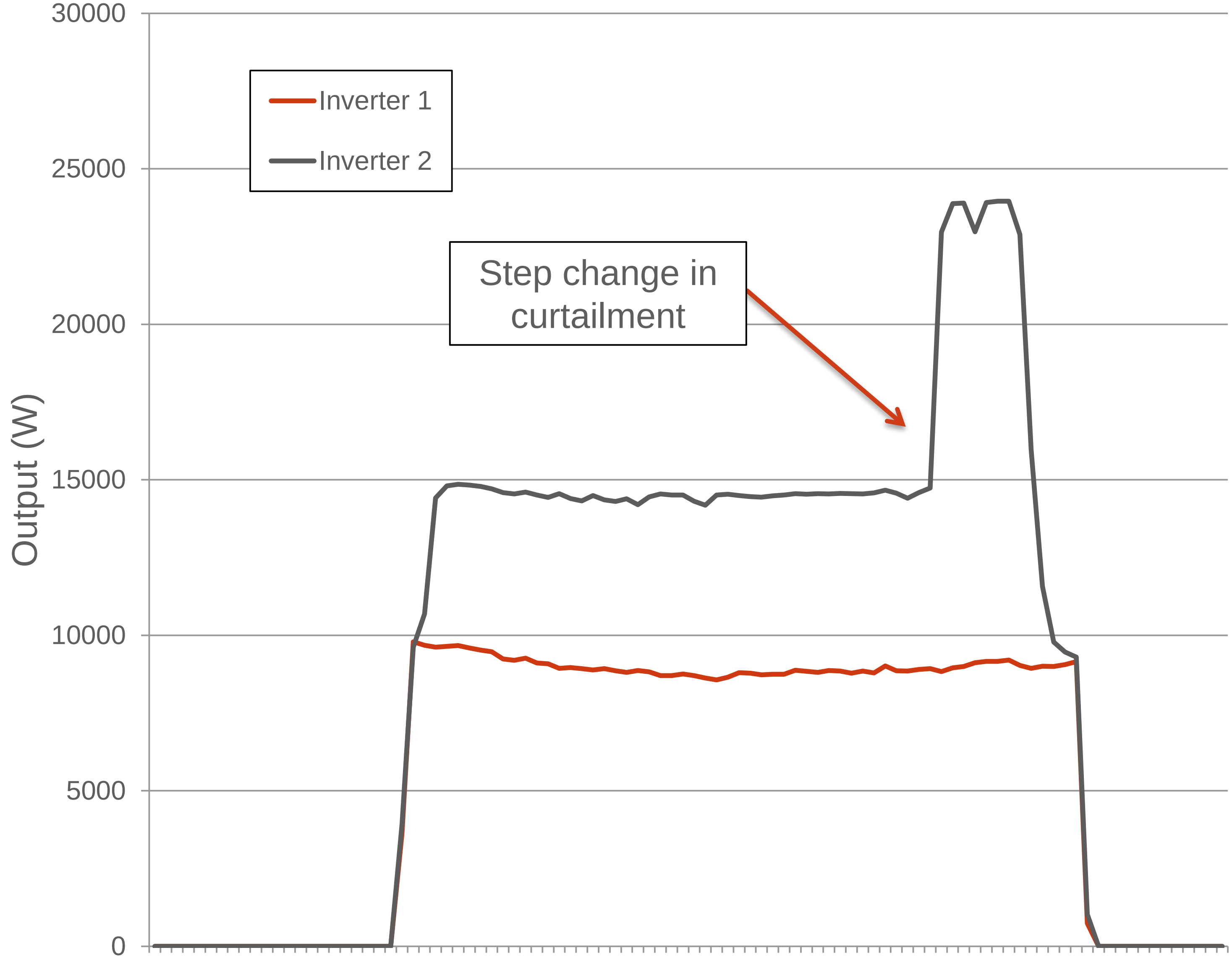
Case Study: Dynamic Curtailment



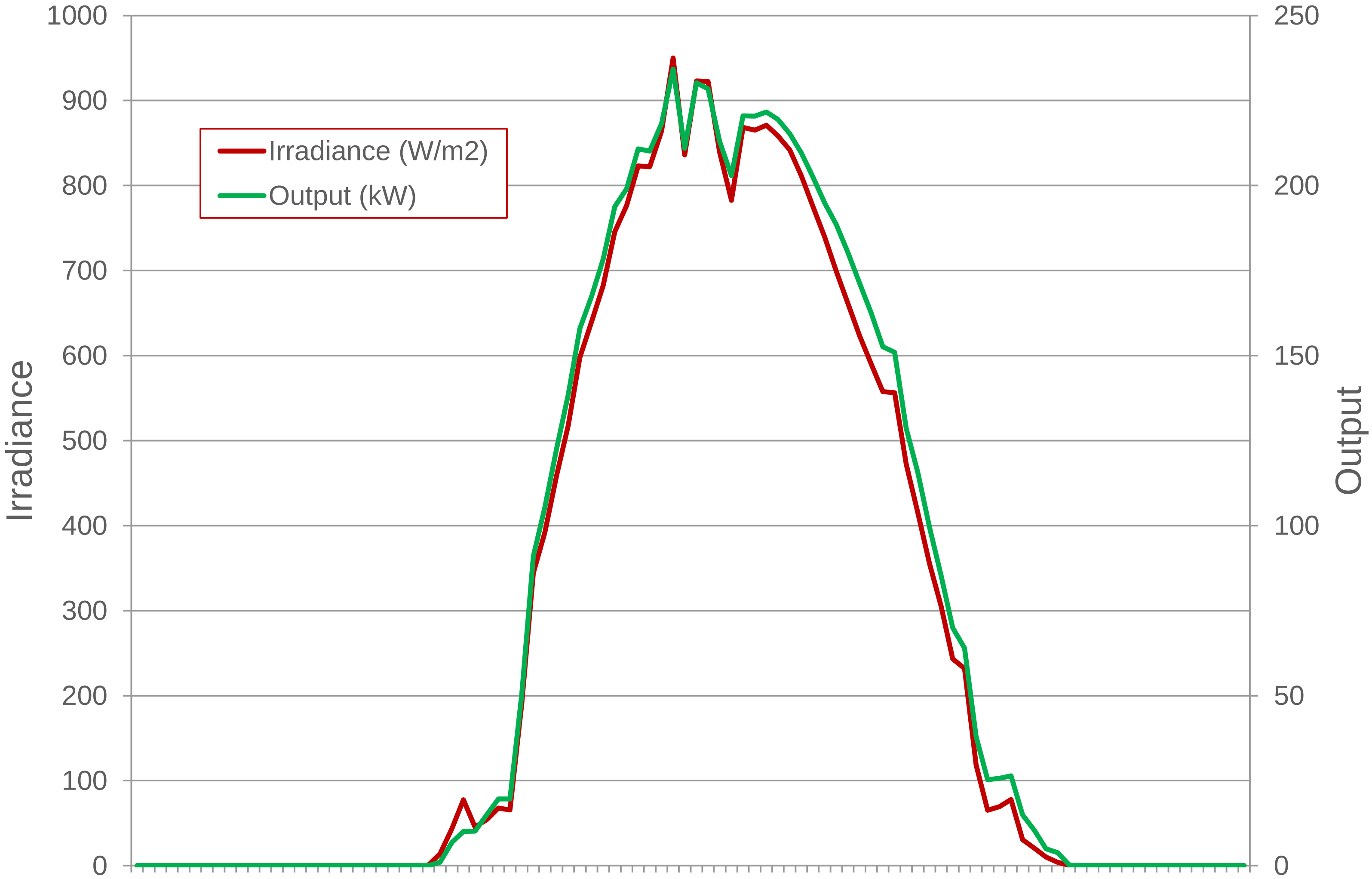
Case Study: Dynamic Curtailment



Case Study: Dynamic Curtailment



Case Study: Dynamic Curtailment



No curtailment

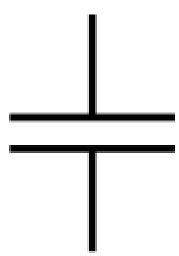
Inverter Power Factor

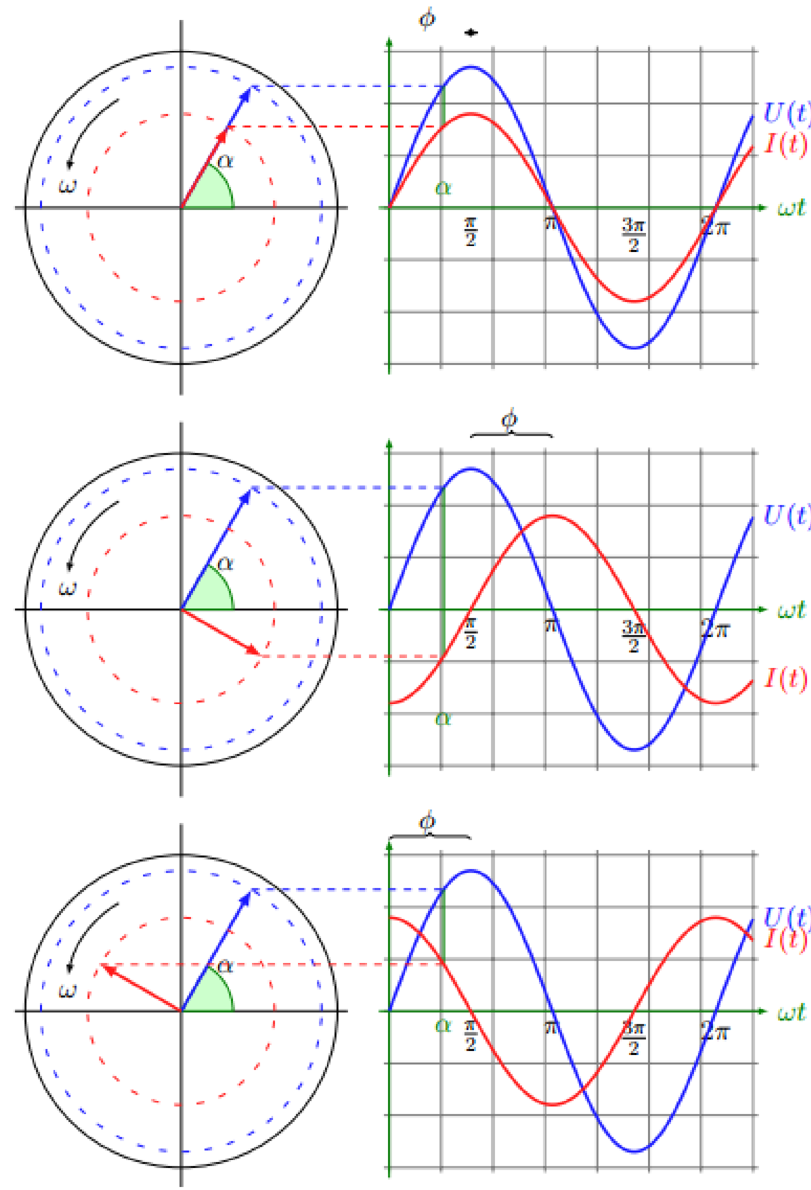
Inverter Power Factor

Historically, PV inverters have operated at unity power factor

Leading power factor may be used to mitigate voltage rise and flicker

Lagging power may be used to support system voltage and on site inductive loads





Urs Zellweger

Case Study: Scheduled Power Factor

Location	Pedricktown, NJ
Installation	1.5MW-DC
Products	AE 100TX AE 260TX

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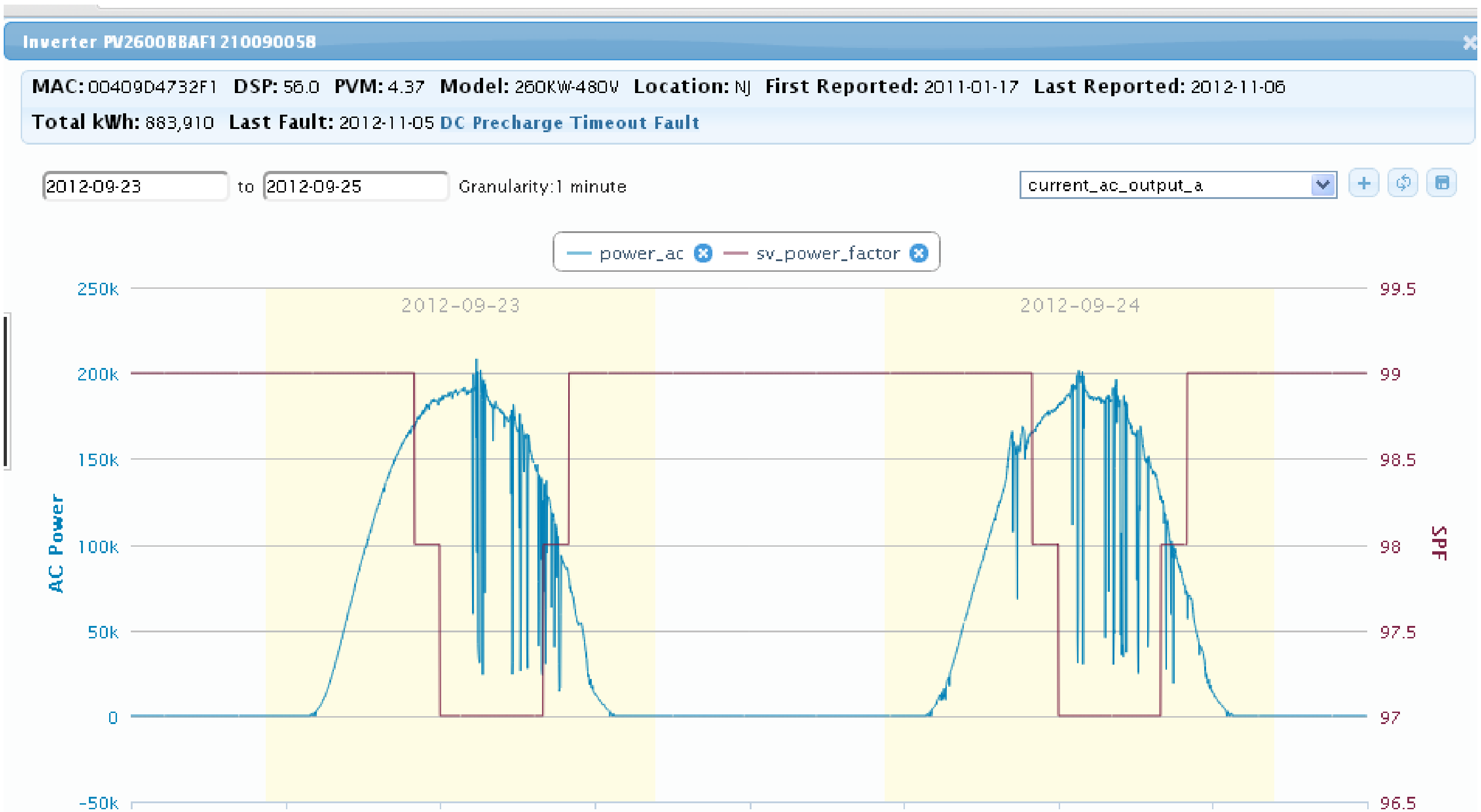
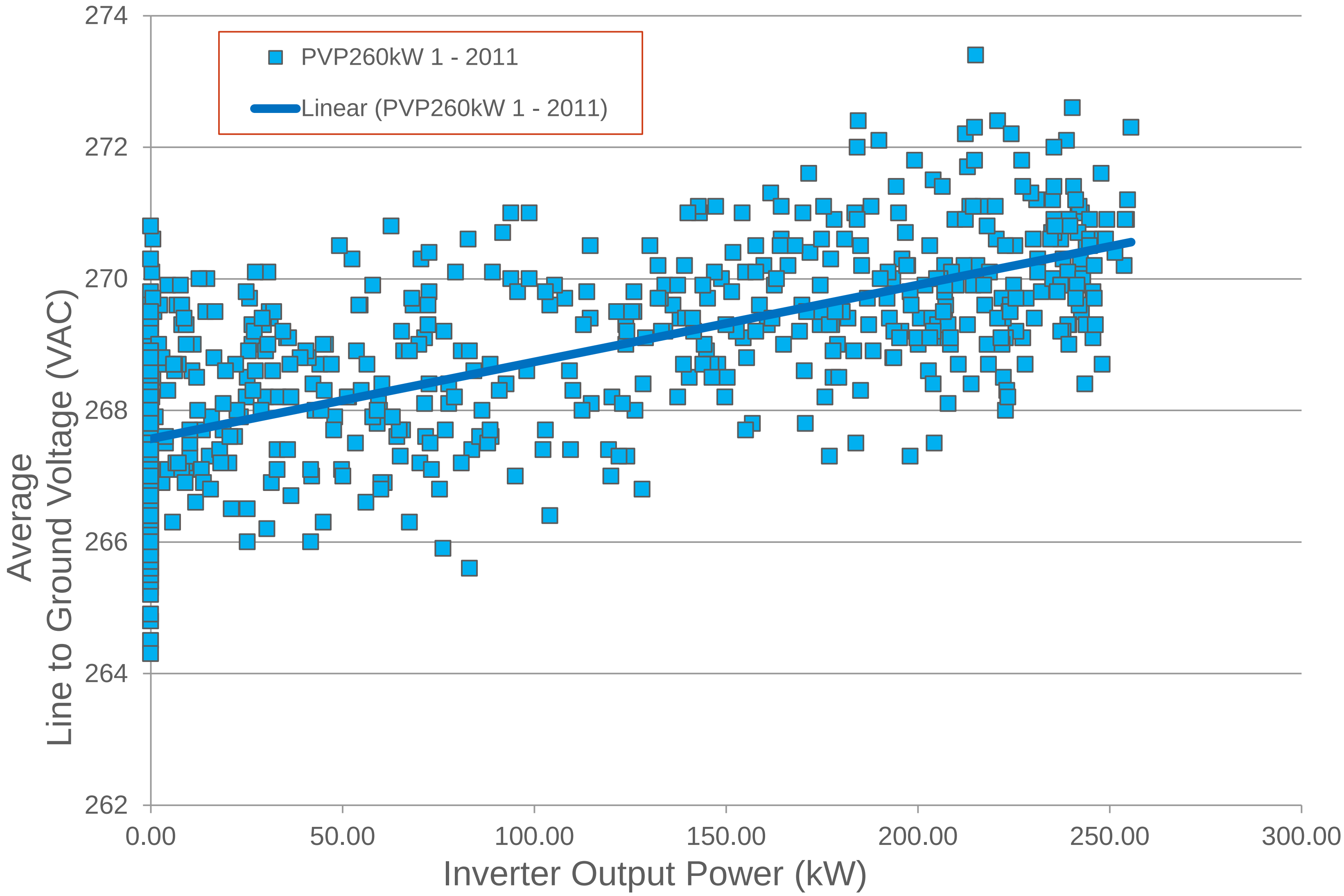
Case Study: Scheduled Power Factor



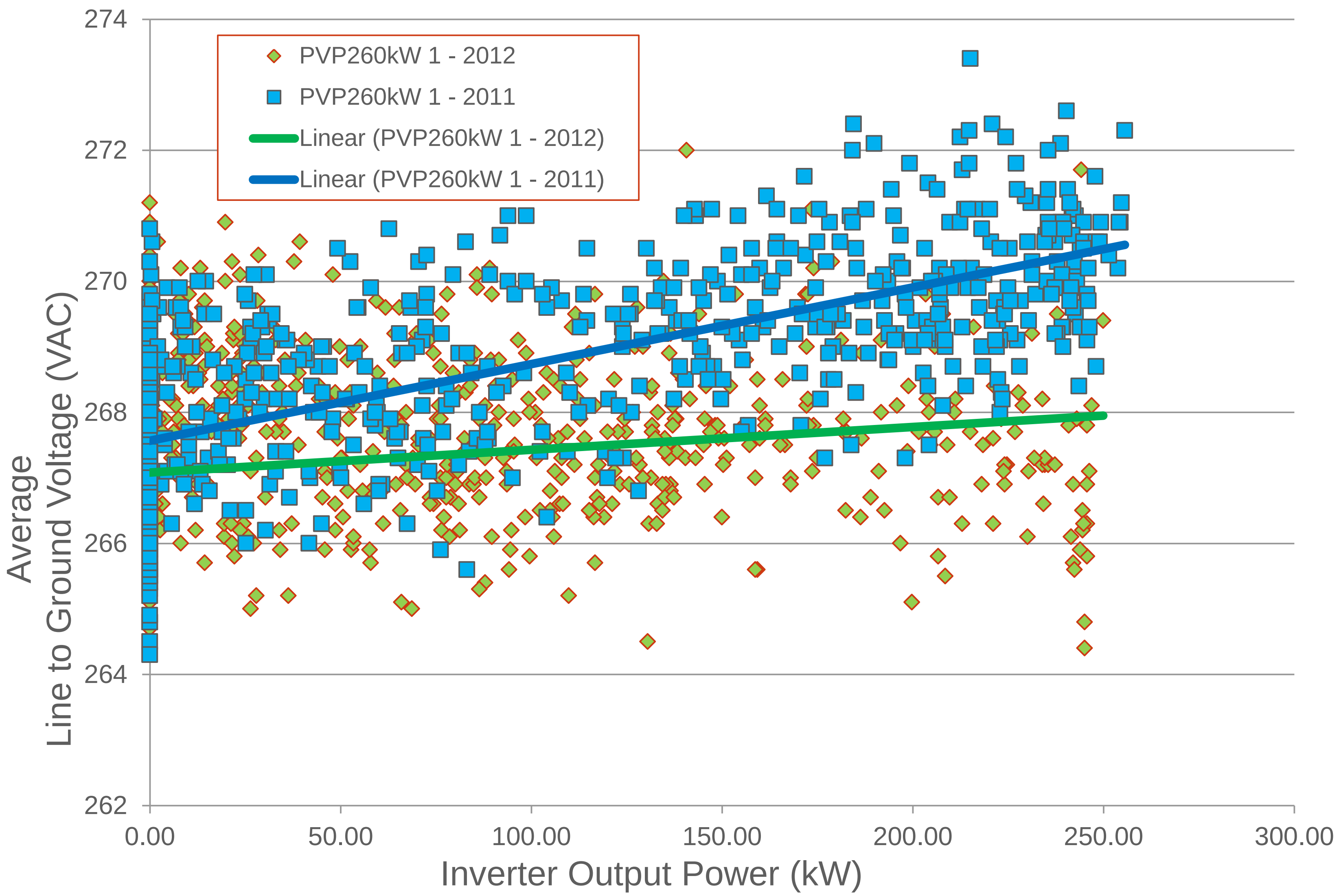
Case Study: Scheduled Power Factor

Location	Rockville, MD
Installation	700kW-DC
Products	AE 75TX AE 260TX

Case Study: Scheduled Power Factor



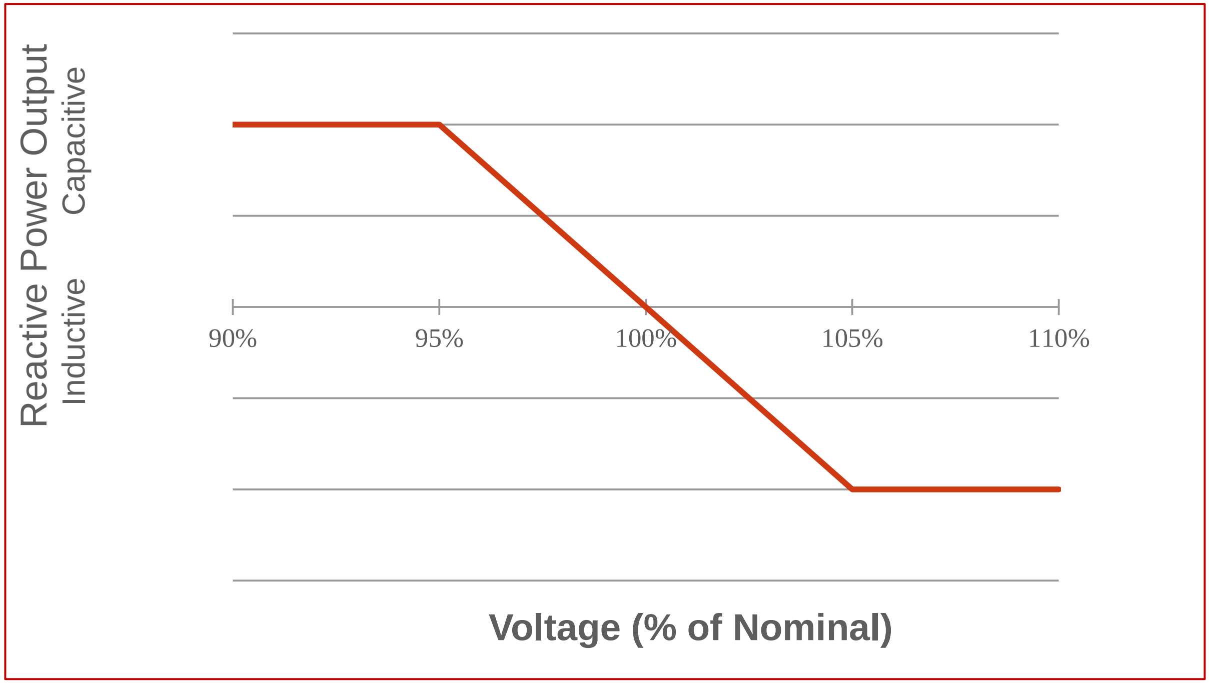
Case Study: Scheduled Power Factor



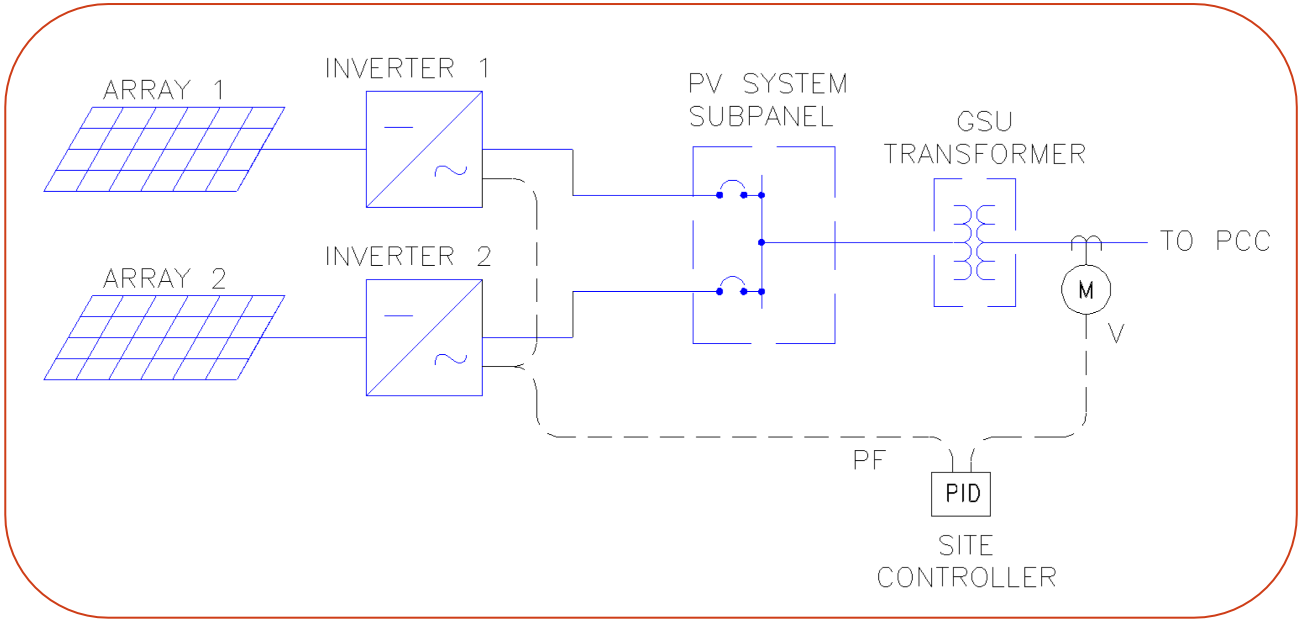
Case Study: Dynamic VAr Control

Dynamic Reactive Capability
- Active Volt/VAr Control
- Required by system operator
- *Disallowed by IEEE1547*

Location	Northern NJ
Installation	14MW
Products	AE 500NX *Under Construction*



Case Study: Dynamic VAr Control



Temporary Over Voltage

Temporary Over-Voltage (TOV)

TOV – a temporary condition where high, potentially damaging voltage can occur

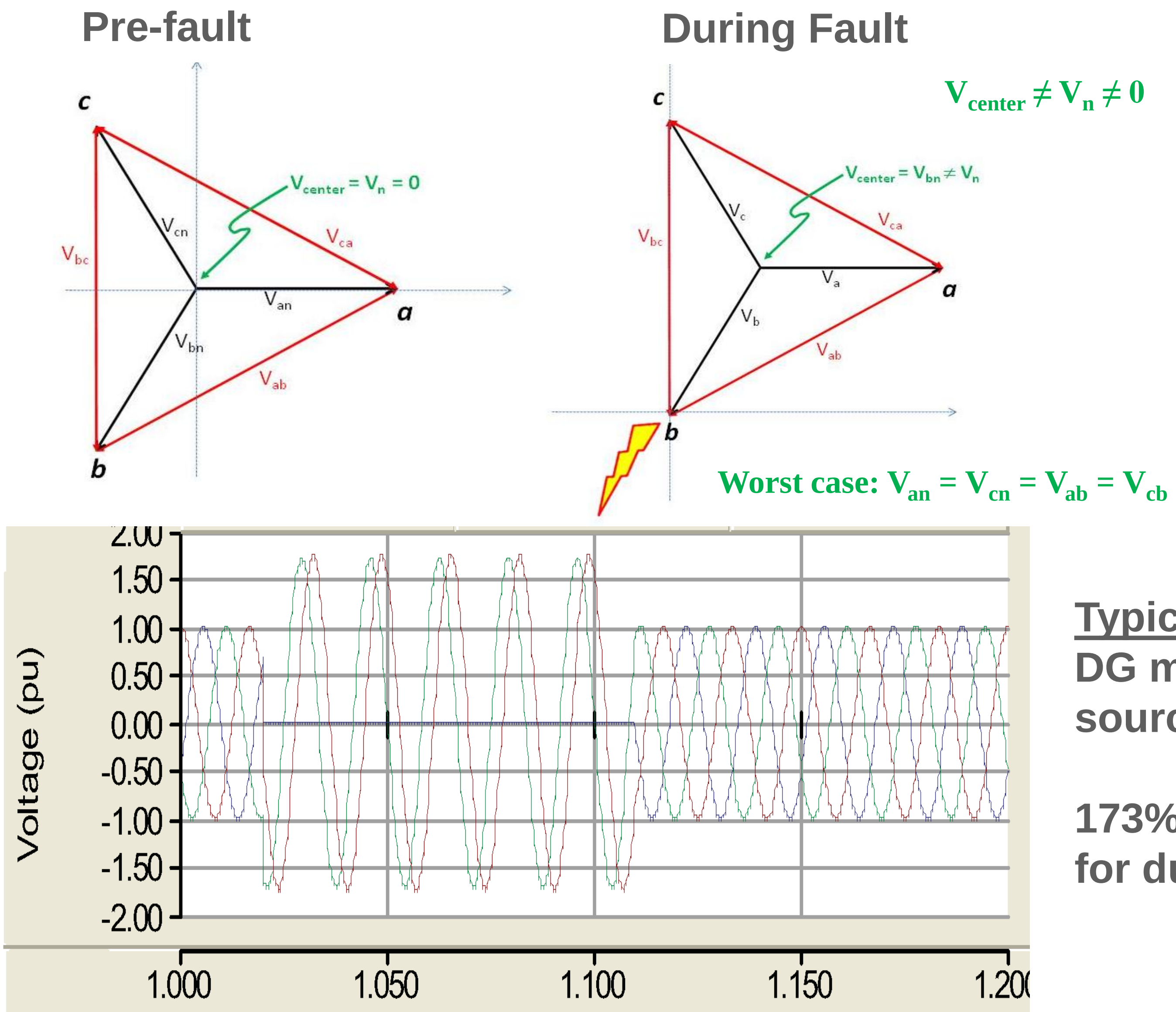
TOV mechanisms

1. *Derived Neutral Shift*
2. Ground Potential Rise
3. Inductive coupling of fault currents
4. Switching high generation into light load
5. Interruption of current through inductors
6. Over-modulation

Typical solution - Grounding inverter "neutral"

- Is this a safe solution?
- Is this an effective solution?

Derived Neutral Shift – Voltage Source DG



Typical prediction

DG modeled as voltage source

173% over-voltage for duration of fault

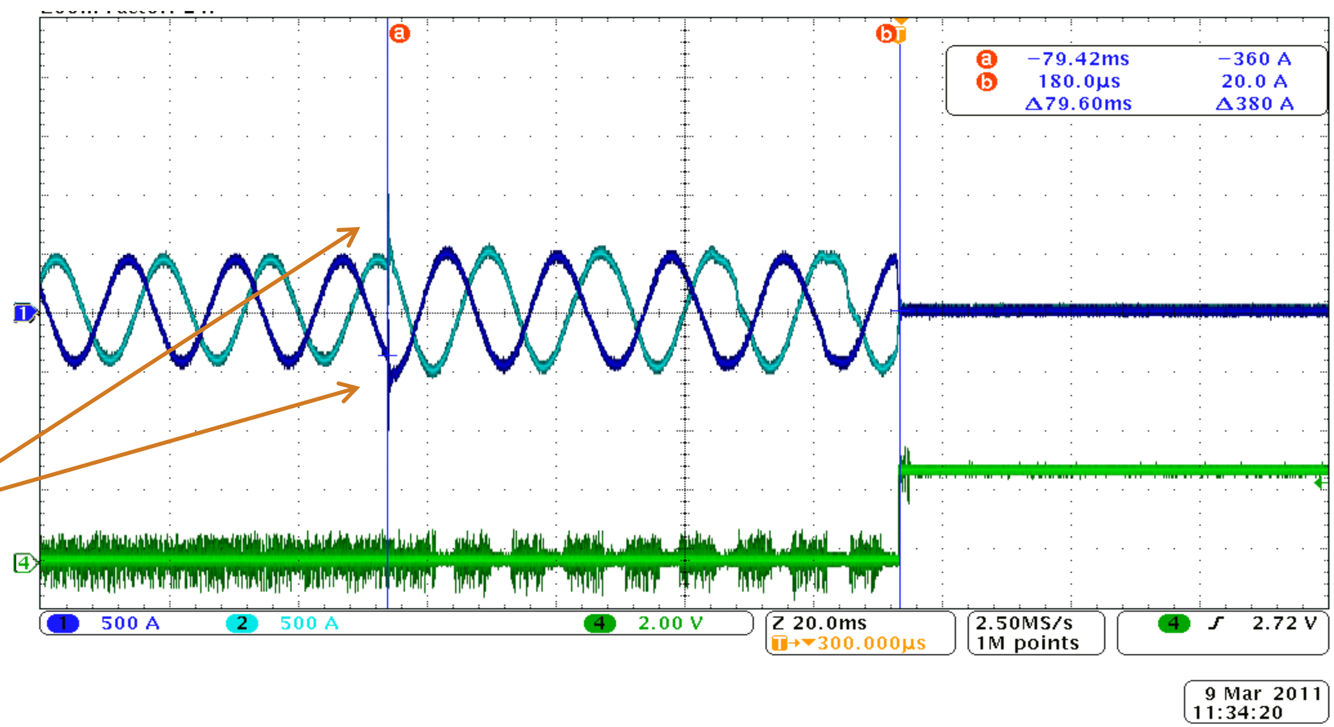
Inverter Behavior – Current Source

AE Inverter: Phase to Phase Short

-Current remains controlled

-Inverter detects O/U voltage

-Trips off after 79.6mS.



AC filter caps discharging

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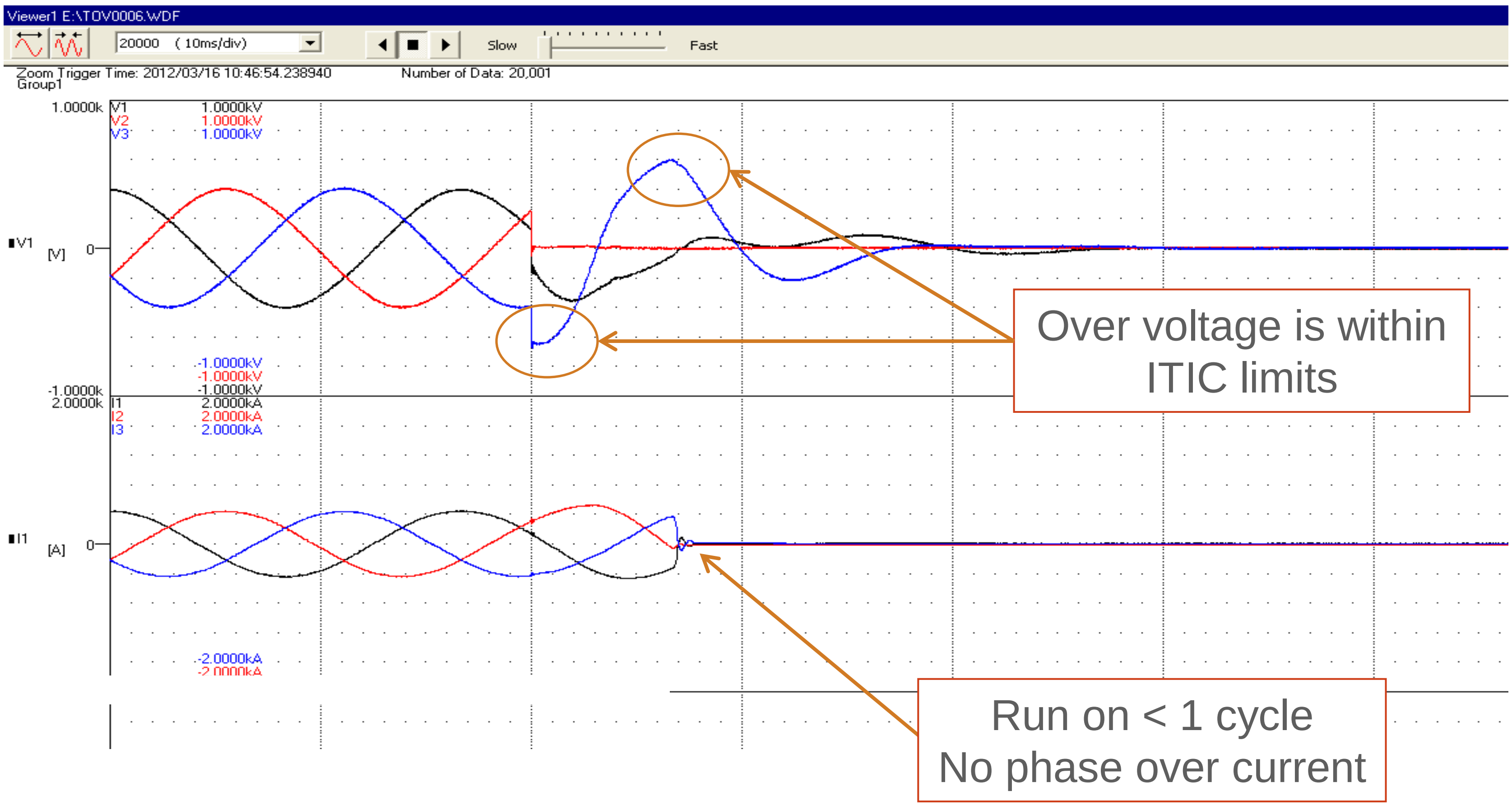
Inverter Behavior – Current Source

AE Inverter: Phase to Ground Short

-Current remains controlled



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Correct modeling of inverter based DG

Must properly represent inverter controls

- Need relatively short (<< 1 msec) time steps
- Should make sure that saturation is not artificially excluded

Must properly represent inverter power stage

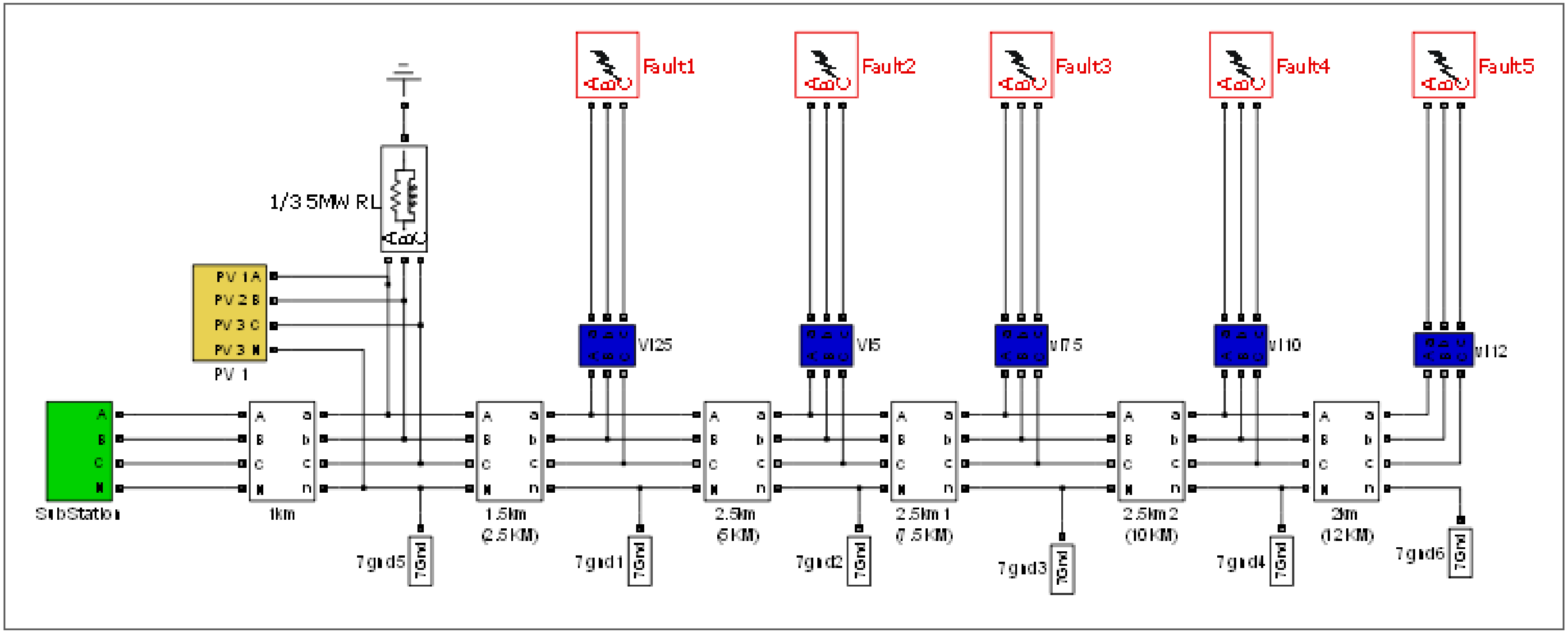
Must have inverter output filter components explicitly modeled

All transformers need to be modeled to see impact of DG on distribution system

Power-limited nature of DC source is important

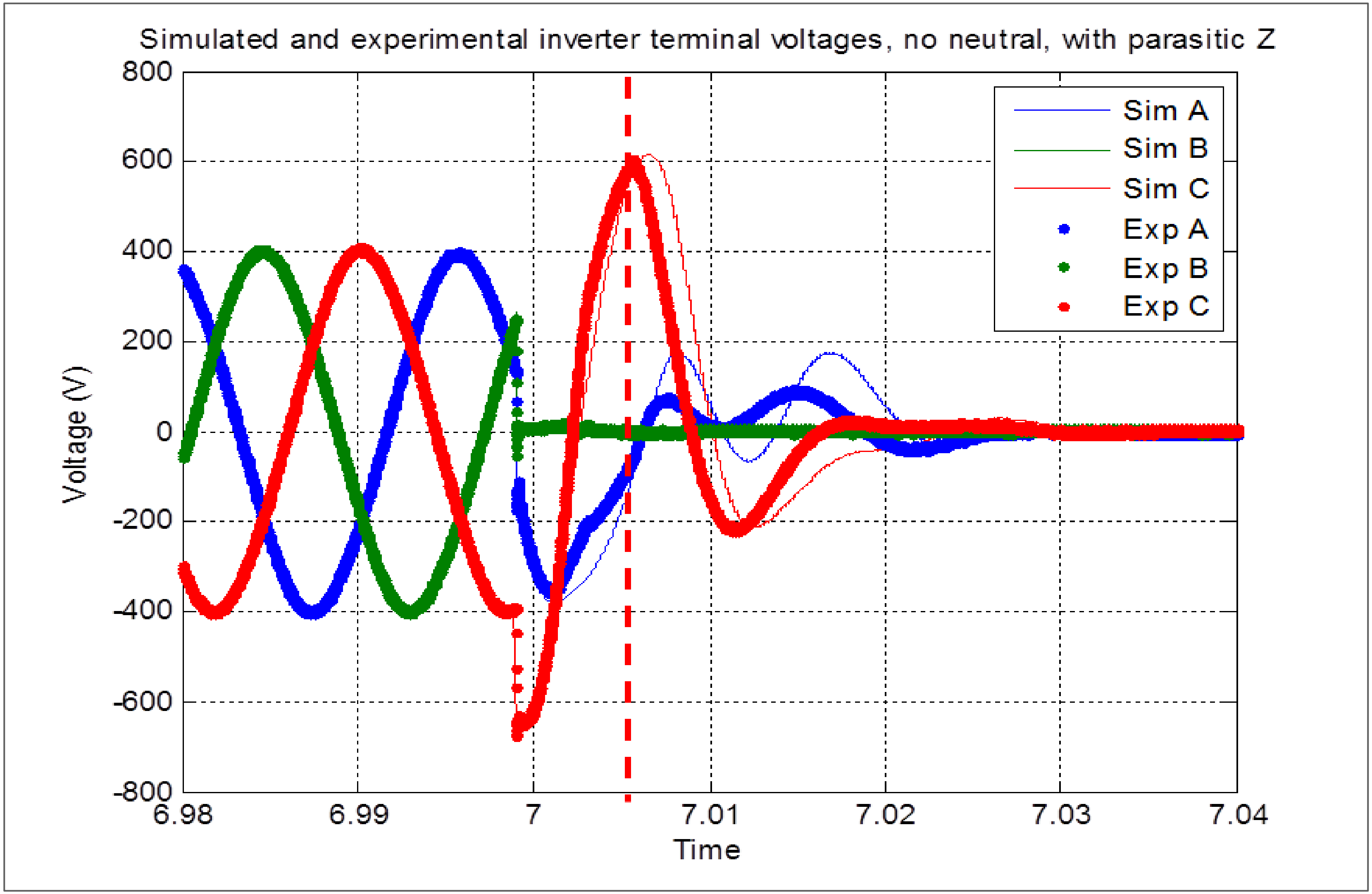
- Ideal DC voltage source models will not work

Correct modeling of inverter based DG



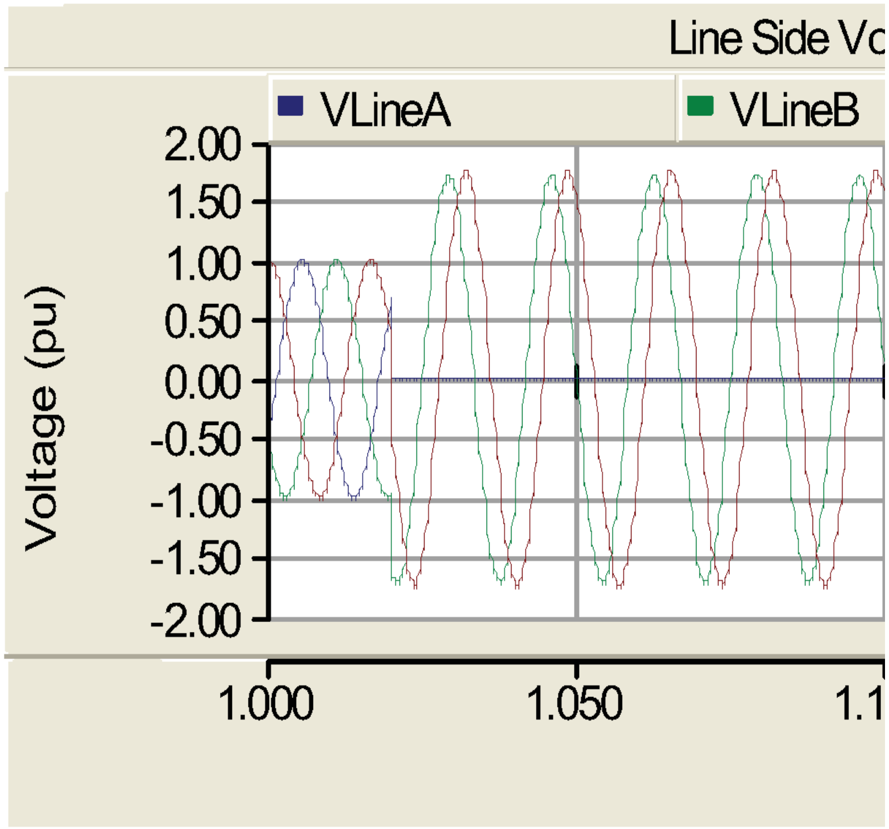
25 kV four-wire feeder, neutrals explicitly modeled, loads distributed, PV at head end. Faults modeled at multiple locations, including 480 V DG customer bus; impedance and aggregate loads used.

Correct modeling of inverter based DG

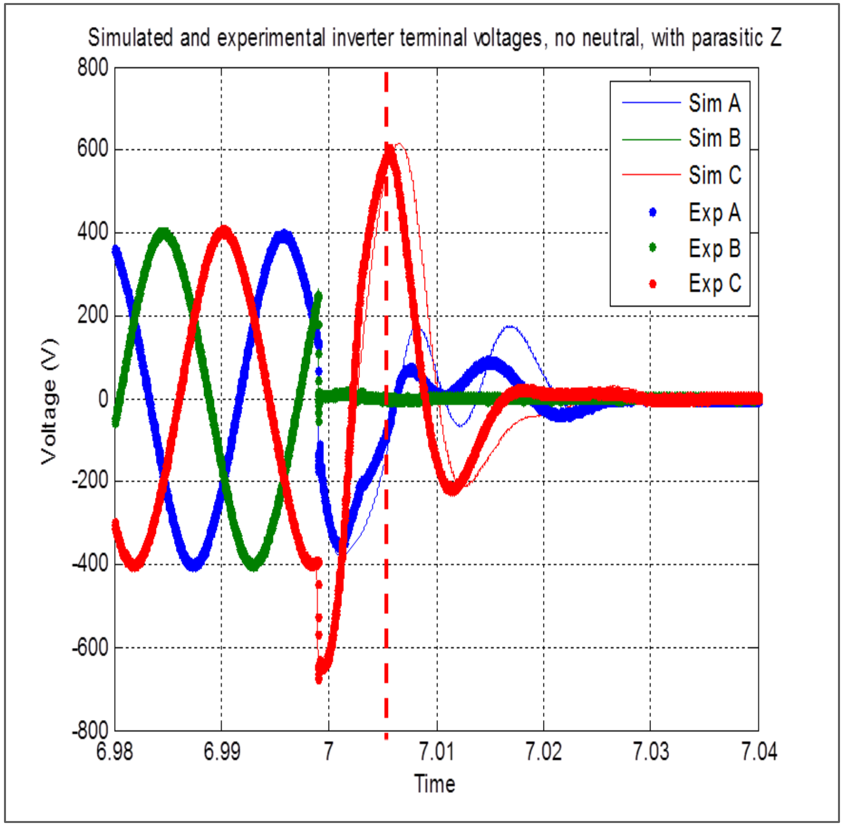


Correct modeling of inverter based DG

Voltage source modeling



Complete inverter modeling



Modeling Results:

Grounding inverter isolation transformer not effective at mitigating TOV

Yg on line side of distribution transformer is effective at mitigating TOV

High load : PV ratio is effective at mitigating TOV

Other protection strategies are being investigated by Advanced Energy

Solid neutral connection to inverter should not be permitted unless the inverter is actually tested and listed in that configuration

Proposal for near term solution: Grounding Banks

Add grounding bank near inverter(s)

Sized per modified IEEE 142 standard

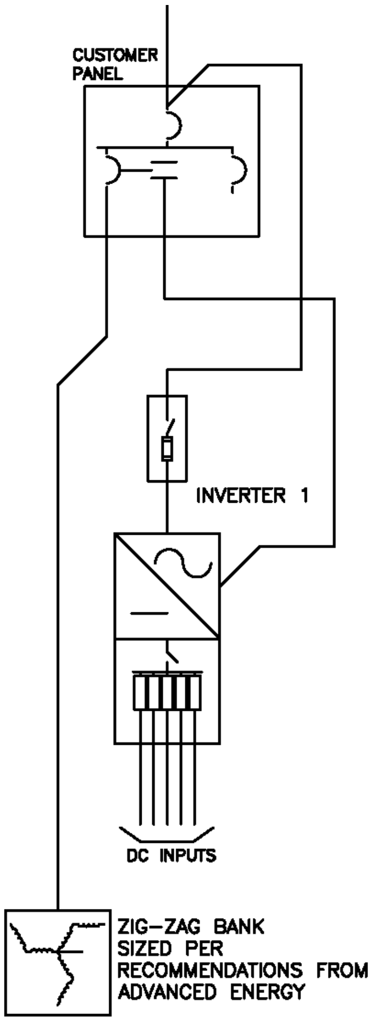
- Based on conservative assumptions about inverter fault current magnitude and duration
- Limits TOV magnitude to 1.25pu

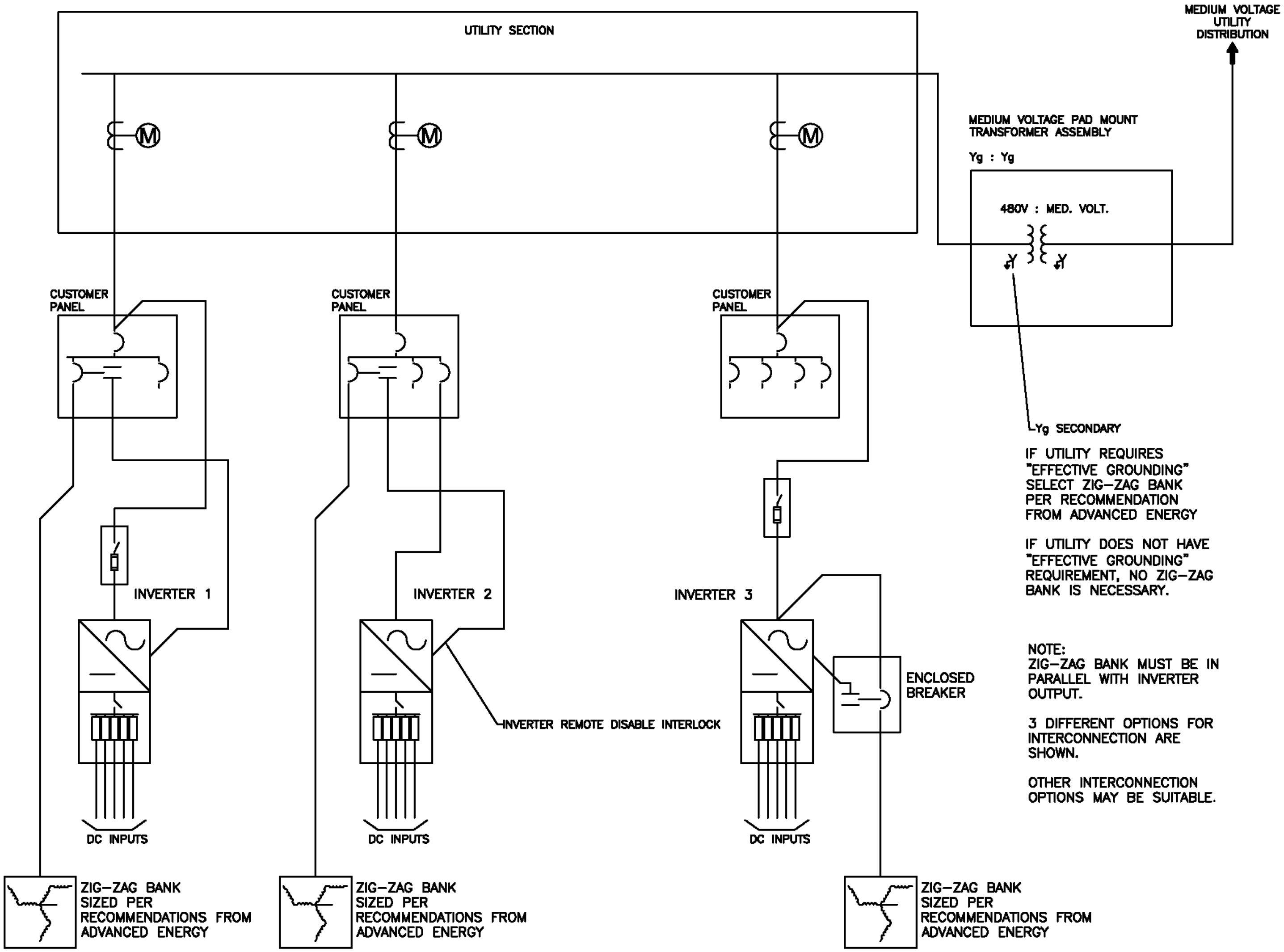
Grounding bank interlocked with inverter

- If grounding bank is off-line, inverter is disabled

De-couples grounding question from inverter design and UL 1741 listing

- Avoids potential problems with:
  - Harmonics
  - Response during faults





UTILITY SECTION
MEDIUM VOLTAGE UTILITY DISTRIBUTION
MEDIUM VOLTAGE PAD MOUNT TRANSFORMER ASSEMBLY
Yg : Yg
480V : MED. VOLT.
Yg SECONDARY
CUSTOMER PANEL
CUSTOMER PANEL
CUSTOMER PANEL
INVERTER 1
INVERTER 2
INVERTER 3
INVERTER REMOTE DISABLE INTERLOCK
ENCLOSED BREAKER
DC INPUTS
DC INPUTS
DC INPUTS
ZIG-ZAG BANK SIZED PER RECOMMENDATIONS FROM ADVANCED ENERGY
ZIG-ZAG BANK SIZED PER RECOMMENDATIONS FROM ADVANCED ENERGY
ZIG-ZAG BANK SIZED PER RECOMMENDATIONS FROM ADVANCED ENERGY
IF UTILITY REQUIRES "EFFECTIVE GROUNDING" SELECT ZIG-ZAG BANK PER RECOMMENDATION FROM ADVANCED ENERGY
IF UTILITY DOES NOT HAVE "EFFECTIVE GROUNDING" REQUIREMENT, NO ZIG-ZAG BANK IS NECESSARY.
NOTE:
ZIG-ZAG BANK MUST BE IN PARALLEL WITH INVERTER OUTPUT.
3 DIFFERENT OPTIONS FOR INTERCONNECTION ARE SHOWN.
OTHER INTERCONNECTION OPTIONS MAY BE SUITABLE.

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