NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Integration of Renewables: Challenges and Solutions

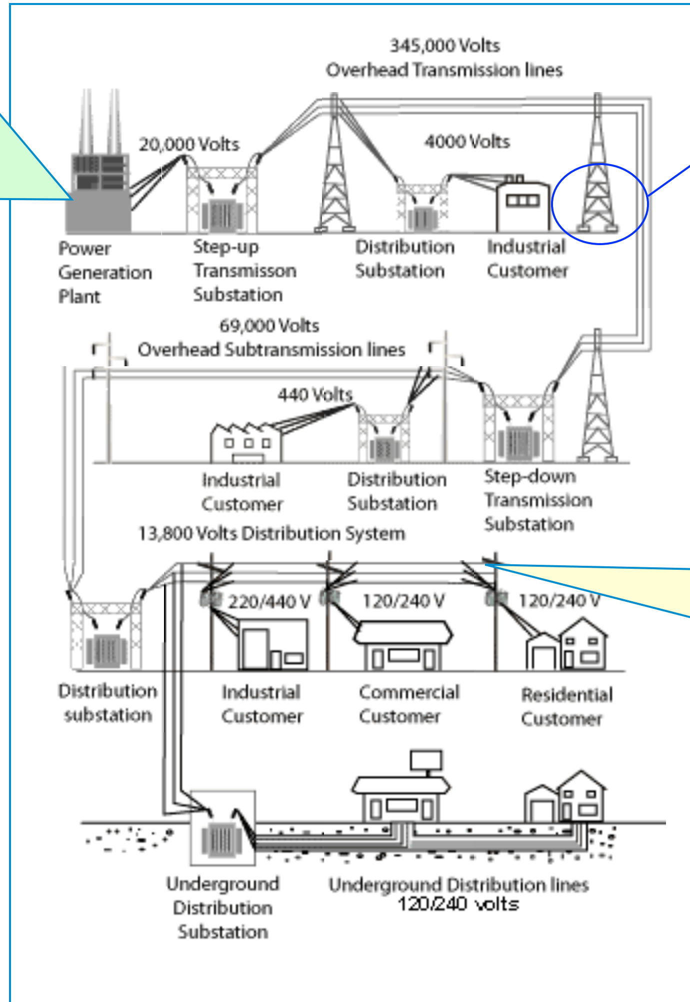
Blake Lundstrom

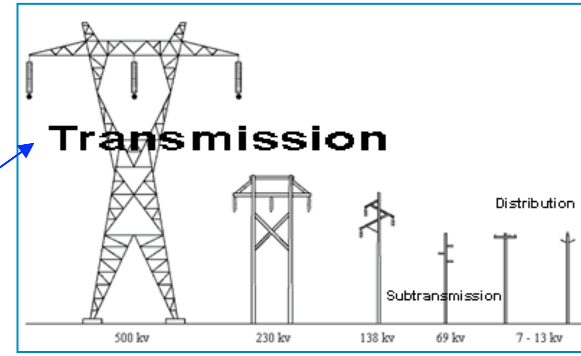
Renewable Energy Resources Interconnection

Central Station

Large
wind farms, CSP,
large PV, biopower,
hydro, geothermal,
hydrokinetic,
interconnect at
transmission and
sub-transmission
levels

Electric Power System





Distributed

PV, small
wind, and fuel cells
interconnect at the
distribution level

Utility Concerns for Distributed Generation

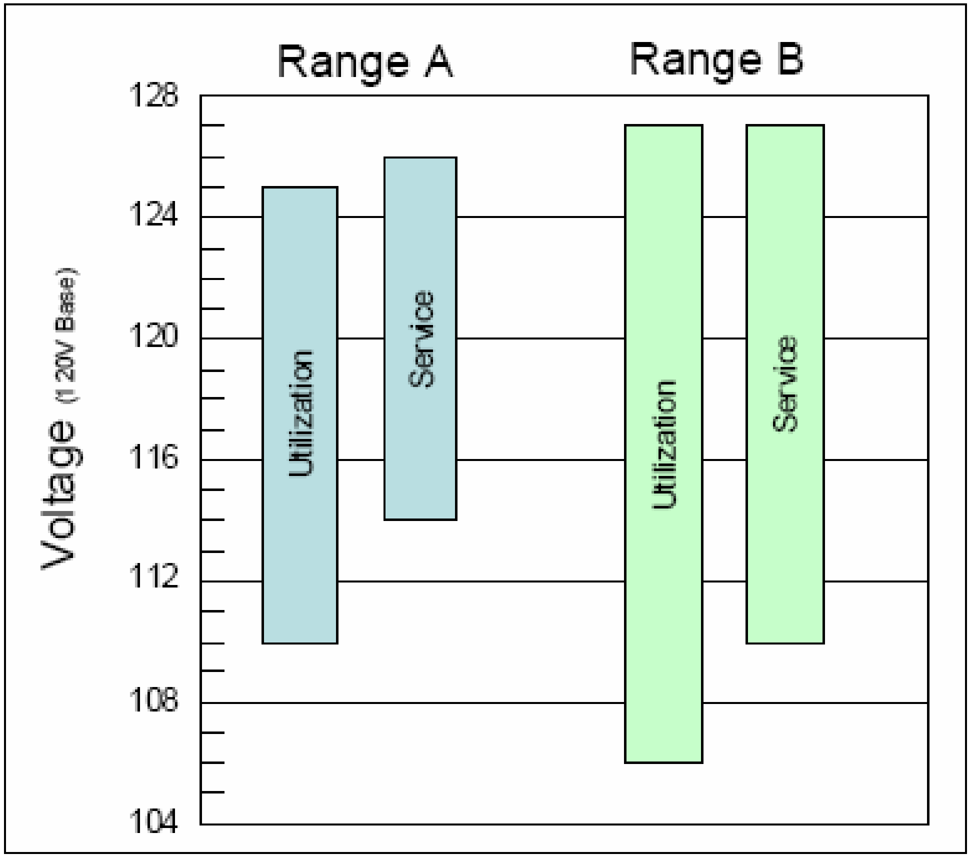
Identified Issues	Relative Priority	Identified Issues	Relative Priority
Voltage Control	High	Equipment Specs	High
Protection	High	Interconnection Handbook	Medium
System Operations	High	Rule 21 and WDAT	Medium
Power Quality	High	IEEE 1547/ UL 1741	Medium
Monitoring and Control	Medium	Application Review	High
Feeder Loading Criteria	High	Clarification of Responsibilities	High
Transmission Impact	Medium	Integration with Tariffs	Medium
Feeder Design	Medium	Coordination with Other Initiatives	Medium
Planning Models	Medium		

Source: Southern California Edison

ANSI C84.1 Voltage Limits

ANSI C84.1
Standard for Electrical Power Systems and Equipment-Voltage Ratings (60 Hz)

- Service Voltage – Voltage at the point of delivery.
- Range A (114-126V) is favorable, Range B (110-127V) is tolerable.



Voltage Regulation Devices

Load Tap Changers (LTCs)

Voltage Regulators (VREGs)

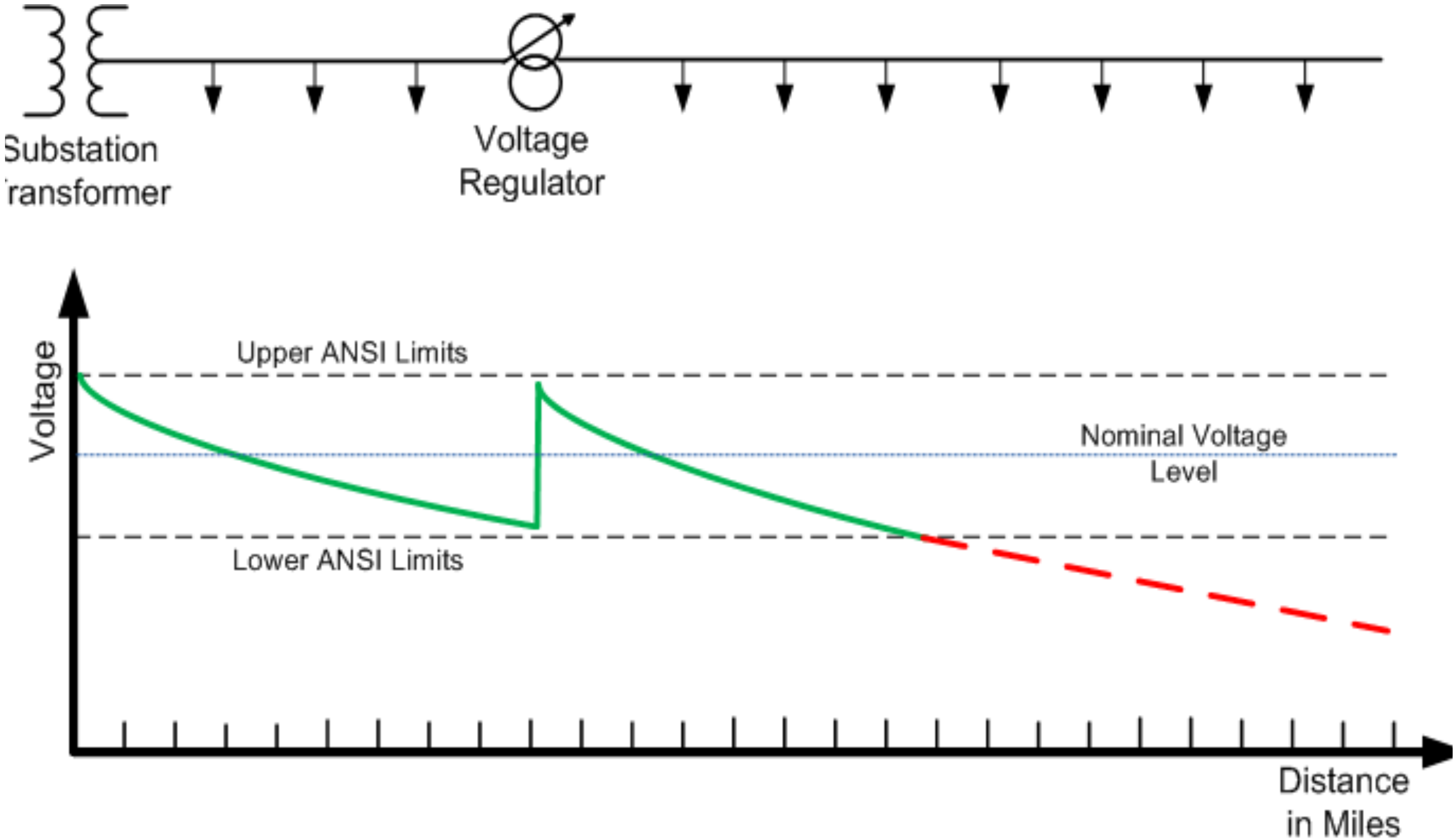
Photos Courtesy Ravel Ammerman, Colorado School of Mines

Voltage Regulation Devices

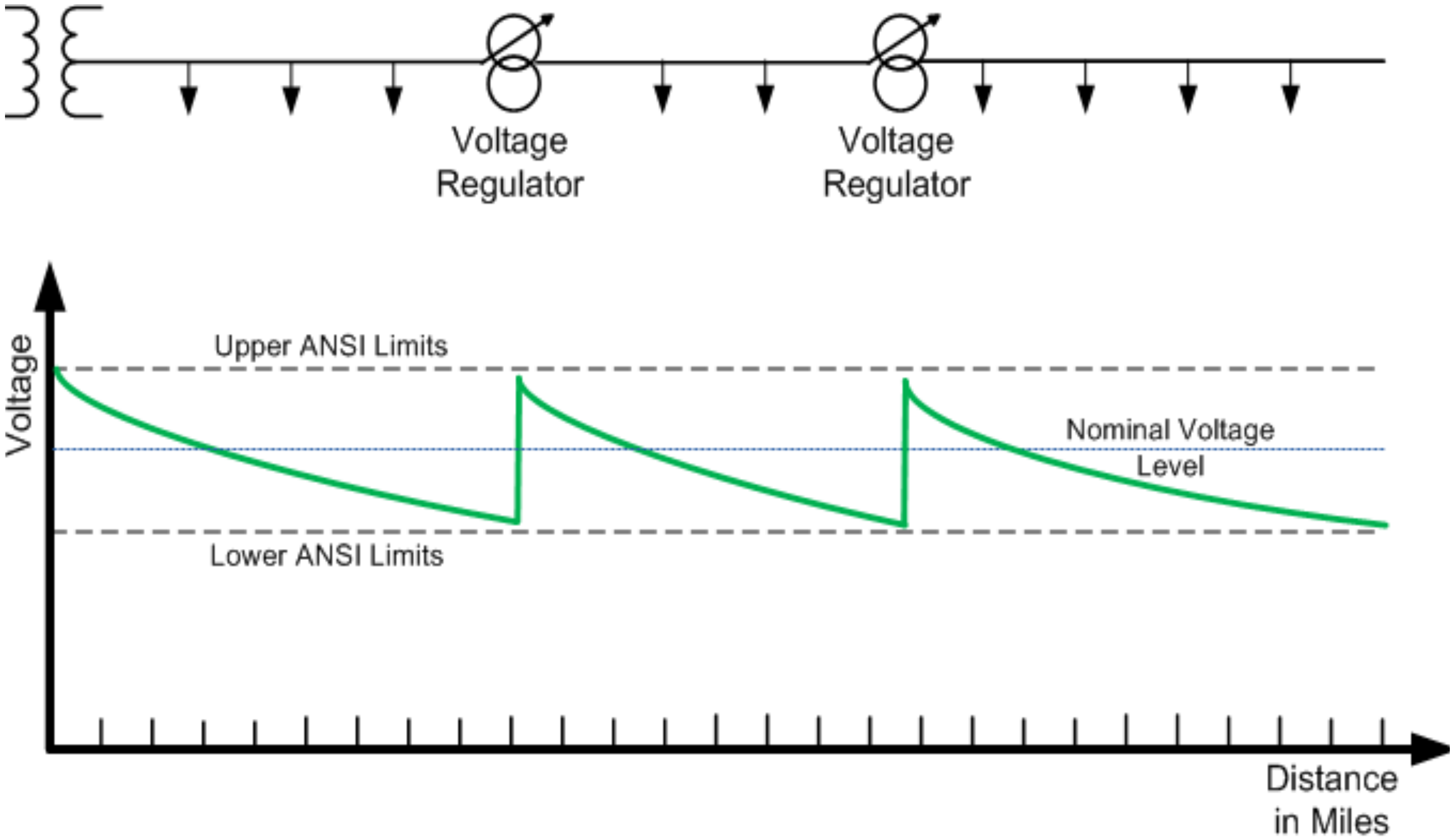
- **Switched Capacitor Banks**
  - Defined by kVAr rating of bank.
  - Voltage rise proportional to rating.

Source: http://www.energyinnovationcorridor.com/page/wp-content/uploads/2011/01/IMG_0574.jpg

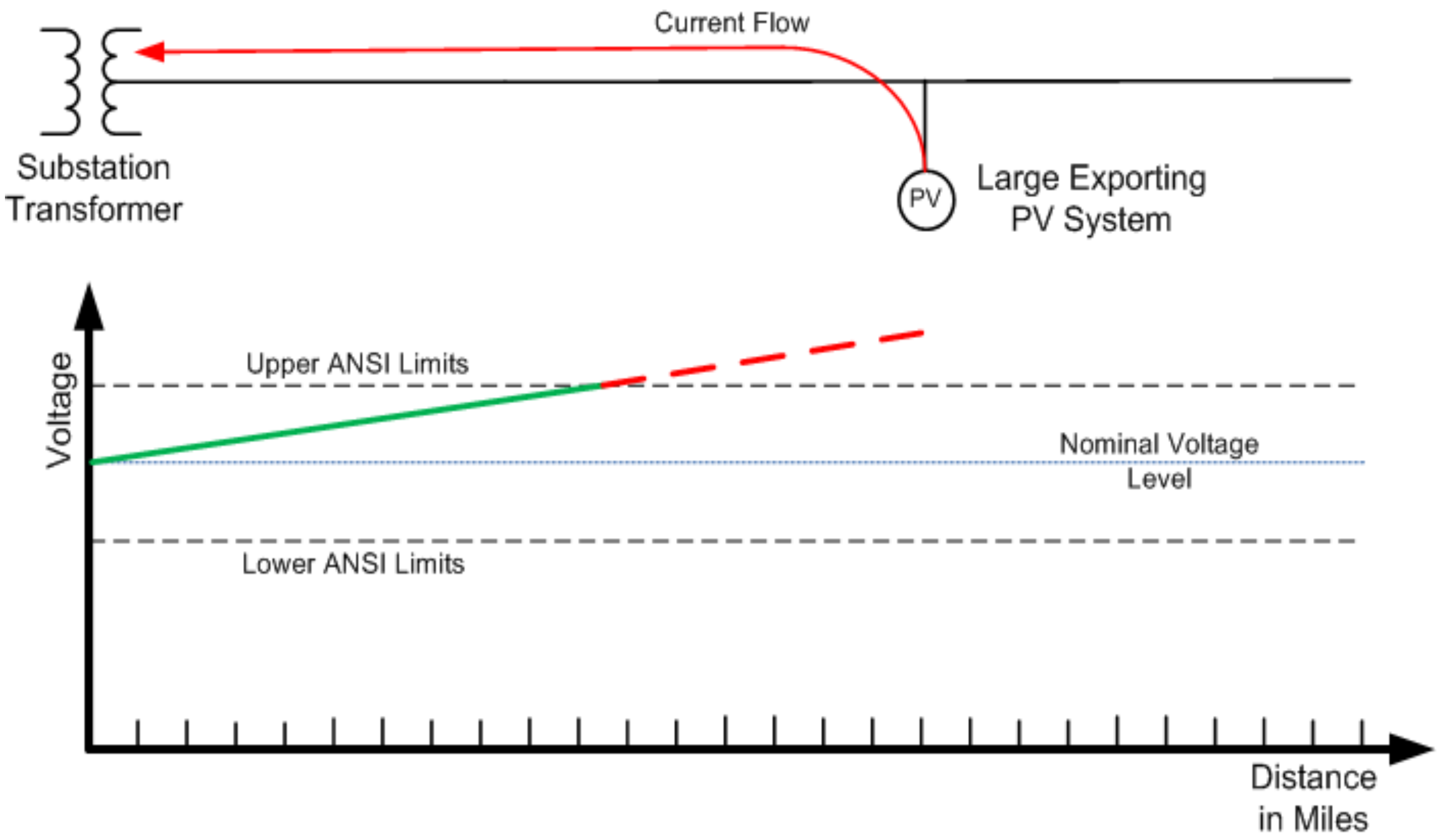
Distribution System Voltage Profile



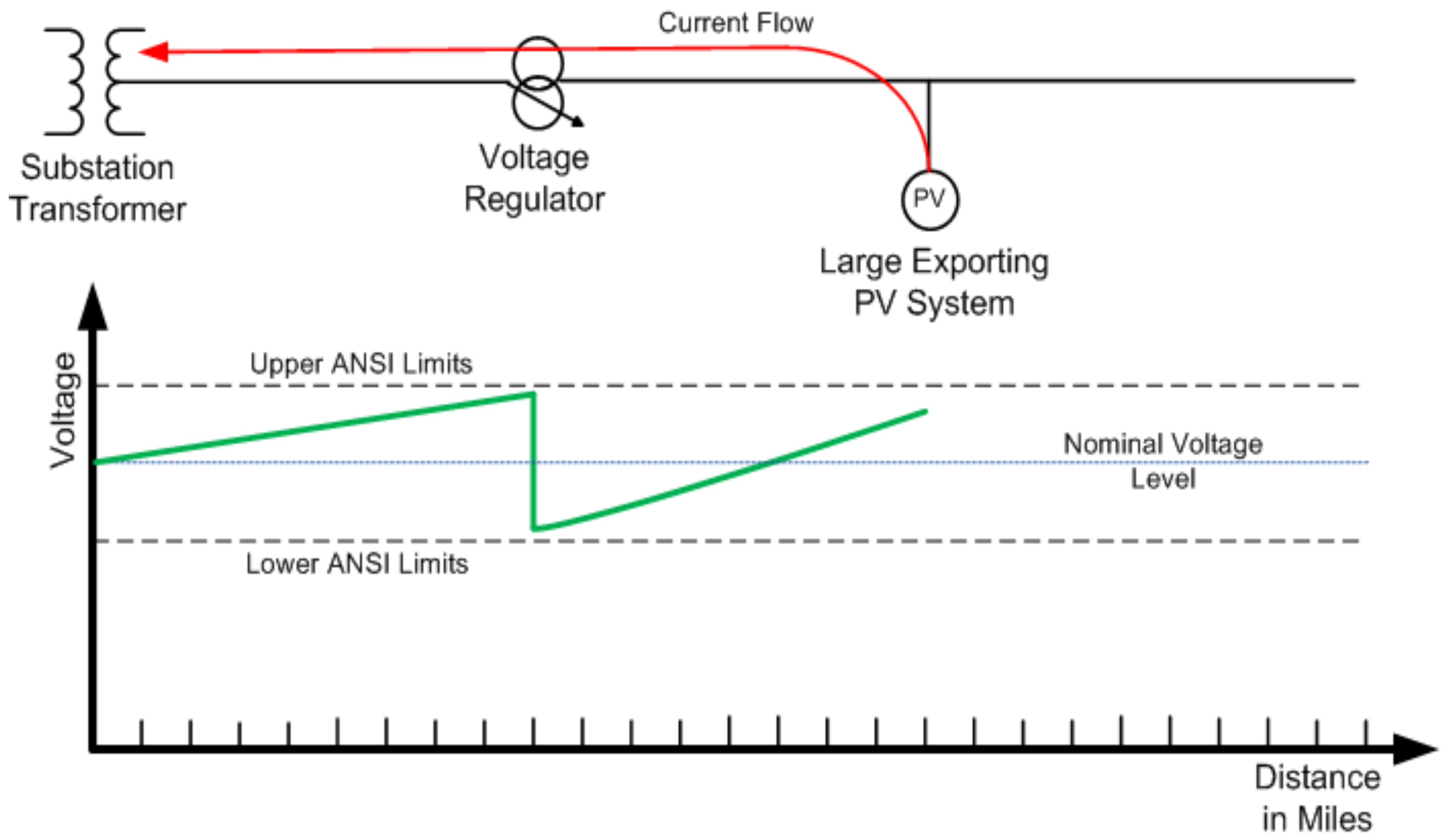
Distribution System Voltage Profile



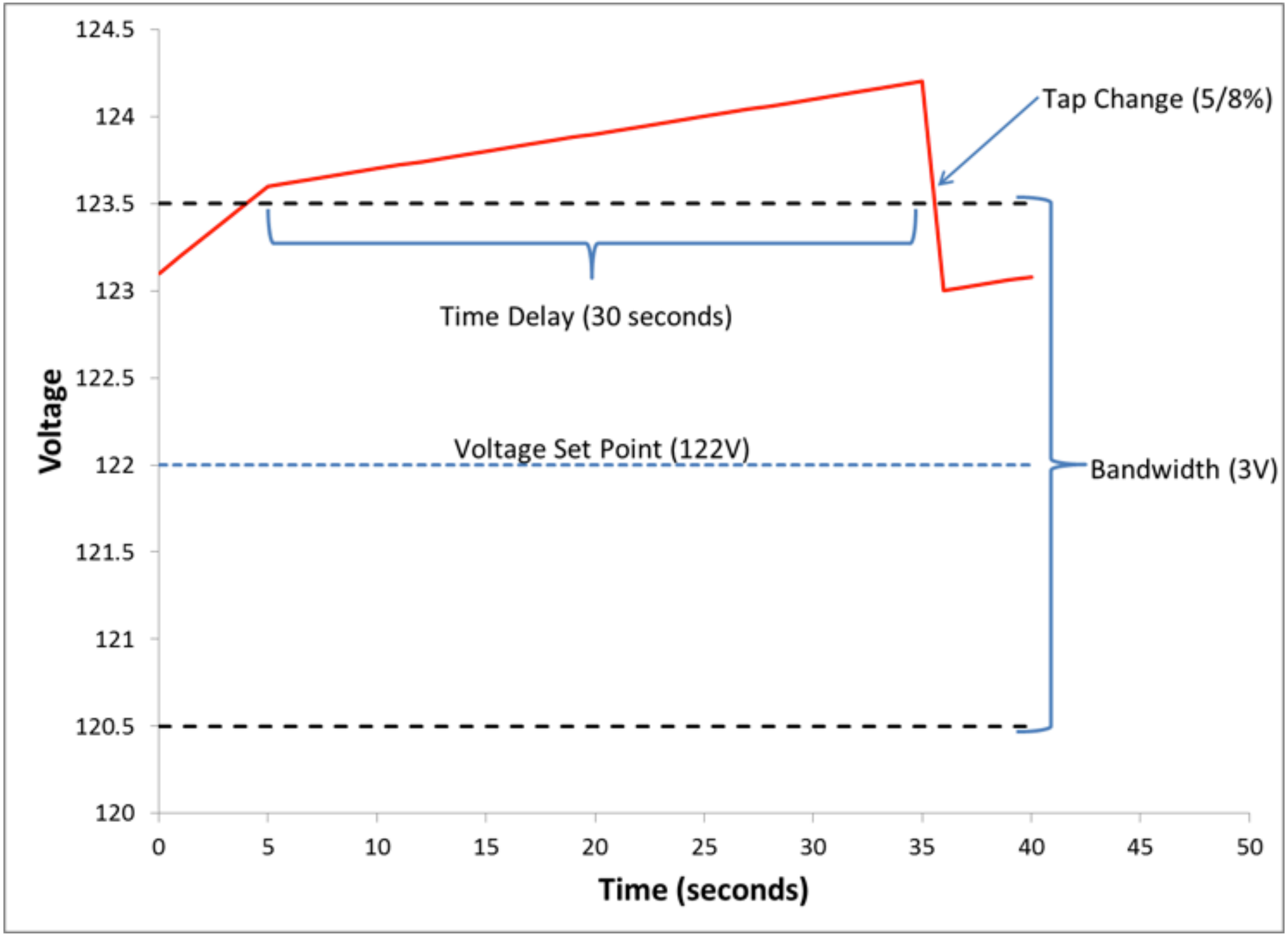
Distribution System Voltage Profile – Large PV



Distribution System Voltage Profile – Large PV



LTCs and VREGs Basic Settings



Courtesy: Jimmy Quiroz, SNL

Device Controls and Modes

VREG Reverse Power Operation Modes

- Locked Forward Mode – Always operates with the forward direction settings and monitoring. If reverse power is sensed, tap position remains on last position regardless of reverse current level.
- Neutral Idle Mode – When the reverse current threshold is exceeded for 10 continuous seconds, the control will tap to neutral and holds there until forward current threshold is exceeded again.
- Bi-directional Mode – Uses reverse power settings when reverse current exceeds the reverse power threshold, and returns to forward settings when forward power threshold exceeded.
- Cogeneration Mode – Focuses voltage regulation on cogeneration side of VREG, even under reverse power, by always using forward power metering and only changing LDC settings to account for changes in power flow direction.

Source: http://www.cooperindustries.com/content/dam/public/powersystems/resources/library/225_VoltageRegulators/S225701.pdf

Device Controls and Modes

- **Switched Capacitor Control Modes and Settings**
  - Time Schedule – Time on and time off.
  - Voltage – Voltage threshold on and voltage threshold off, time delay.
  - VAr (PF) – PF/VAr threshold on and PF/VAr threshold off, time delay.
  - Current – Current threshold on and current threshold off, time delay.

Source: http://www.abb.us/product/db0003db004279/9b04ded0266732fac1257af700221a88.aspx

Other Voltage Regulation Methods

- Increasing the feeder conductor size
- Transferring of loads to other feeders
- Increase of primary voltage levels
- Changing the feeder sections from single-phase to three-phase
- Installing new substations and primary feeders

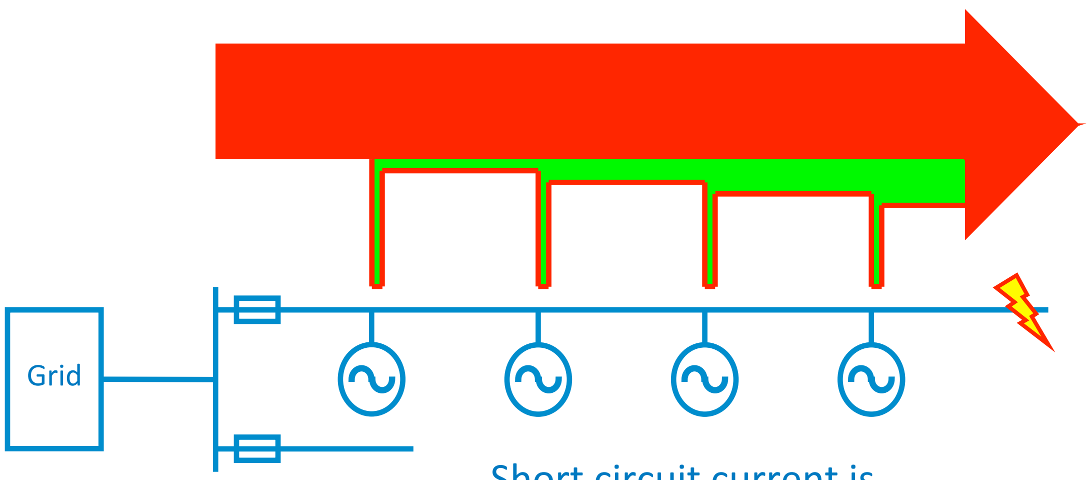
Technical Concerns: System Protection

Potential Impact of DG on Protection

- Improper protective device coordination
- Nuisance fuse blowing
- Relay desensitization
- Sectionalizers will not count w/o loss of voltage, therefore DG's can cause sectionalizing misoperations
- DG's can cause reverse power relay malfunctions - also non-directional relay malfunctions
- As additional DG units are added on a circuit, switchgear ratings (on existing DG units) could be exceeded

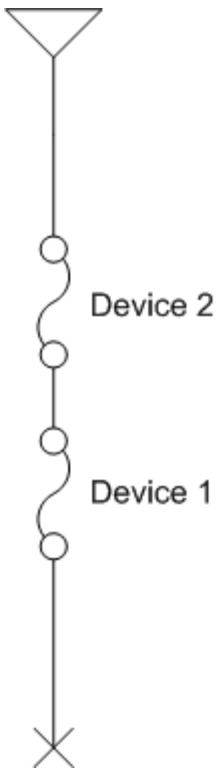
Issue with Fault Current and DG

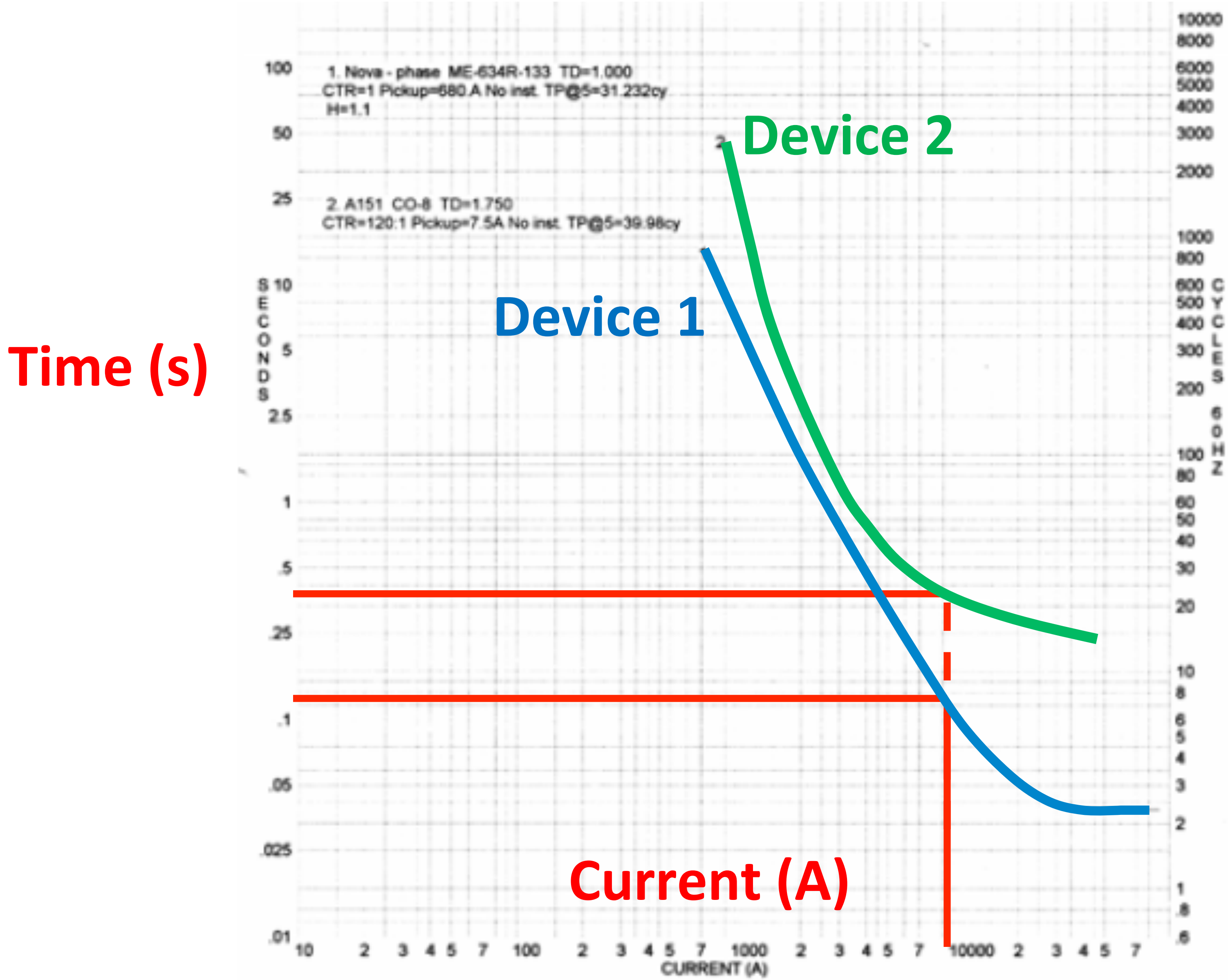
- **Problem:**
  - Power system is designed for top-down power flow: Generation → Transmission → Distribution → End users
  - Local source contributes to the short-circuit current in case of fault
    - Fault effects more severe
    - Difficult to isolate fault location



Short circuit current is added up by DG units

Time – Current Coordination of Two Devices

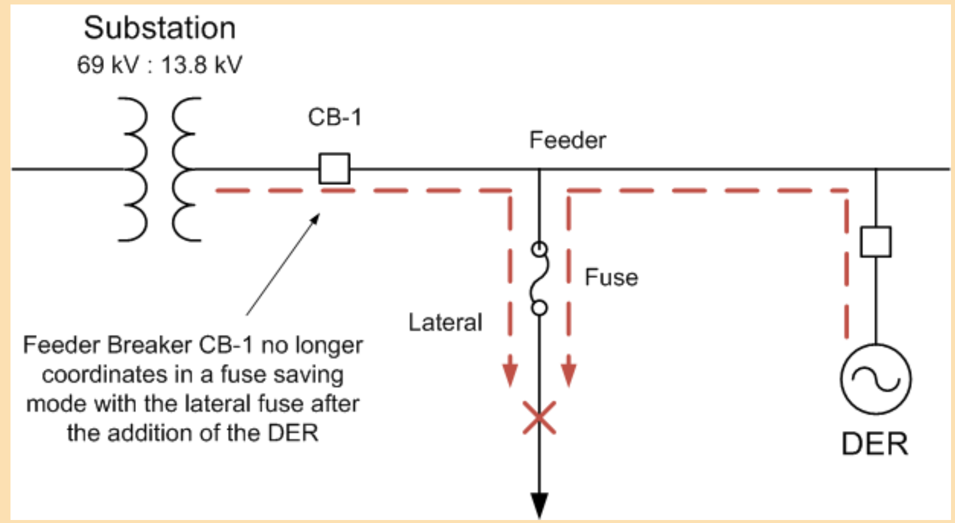


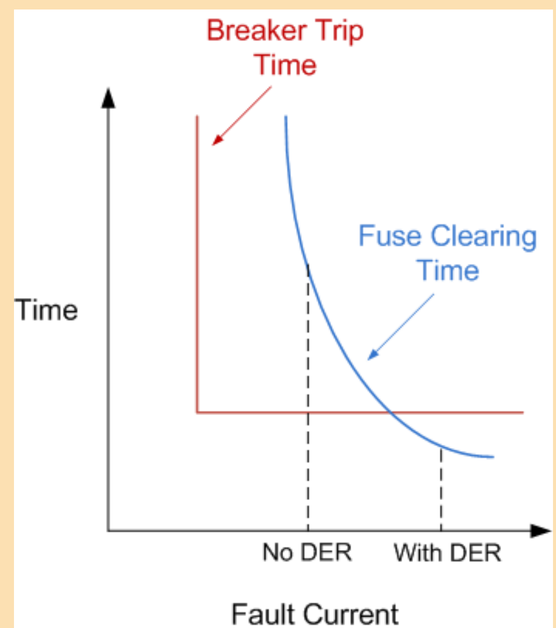


Nuisance Fuse Operations

Short-circuit Current Coordination

- DG can provide a variety of levels of short circuit current
- This may impact the short-circuit coordination between fuses and circuit breakers in the distribution system
- In the example to the right, the DG increases short-circuit current seen by the fuse and is no longer coordinated with the breaker CB-1 opening

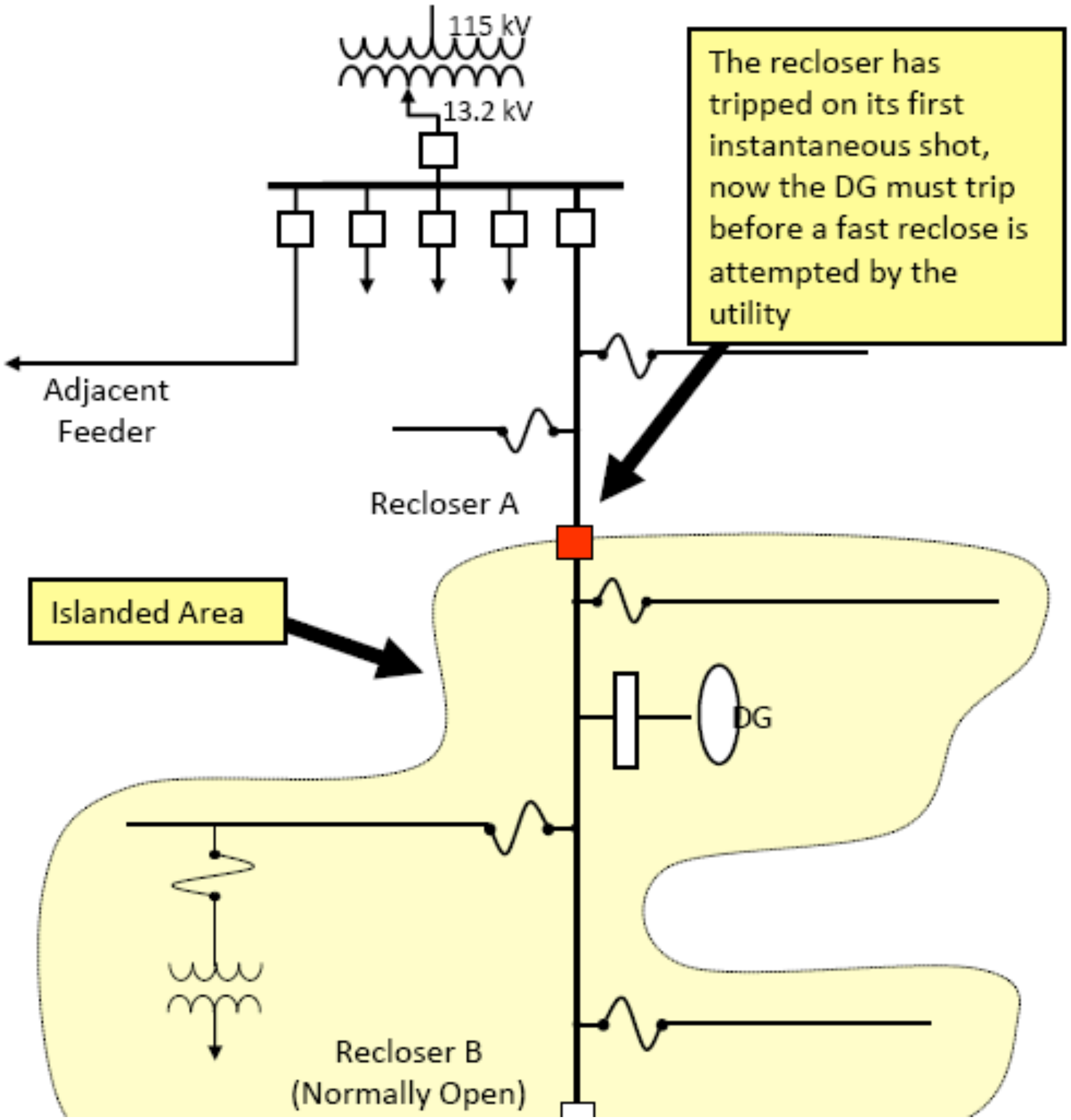





Islanding

Unintentional DG Islanding Issues

- **Safety**
  - Incidents of energized downed conductors
  - Utility system reclosing into live island
  - Damaging overvoltages can occur during some conditions
- Service restoration will be delayed and more dangerous for crews
- Islands may not maintain suitable power quality



Source: Nova Energy Specialists, LLC, *Rule 14H Informational Session B*, July 1, 2010

IEEE 1547: Unintentional Islanding

Unintentional Islanding Requirement

- For an unintentional island in which the DR energizes a portion of the Area EPS through the PCC, the DR interconnection system shall detect the island and **cease to energize the Area EPS within two seconds** of the formation of an island.

Mitigating Integration Challenges

Inability to Dispatch
- Weather determines output

Uncertainty
- Can be forecasted to a large extent

→ Forecasting

Variability
- Increases difficulty to balance load

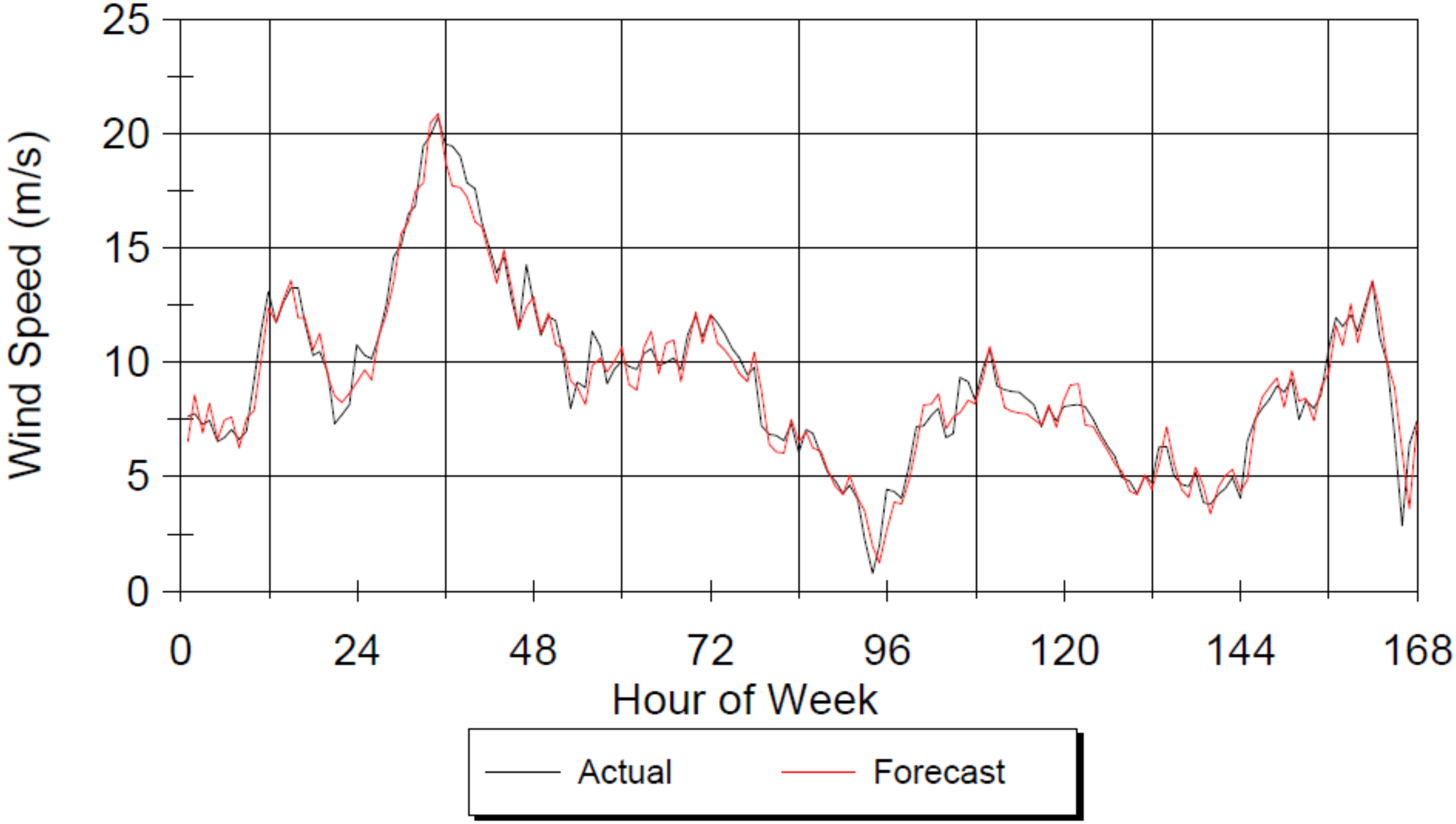
→ Aggregation & Geographic Dispersion

Different Electrical Characteristics
- Lower inertia, voltage tolerance, reactive controls
- Still compatible with the grid

→ Advanced PE

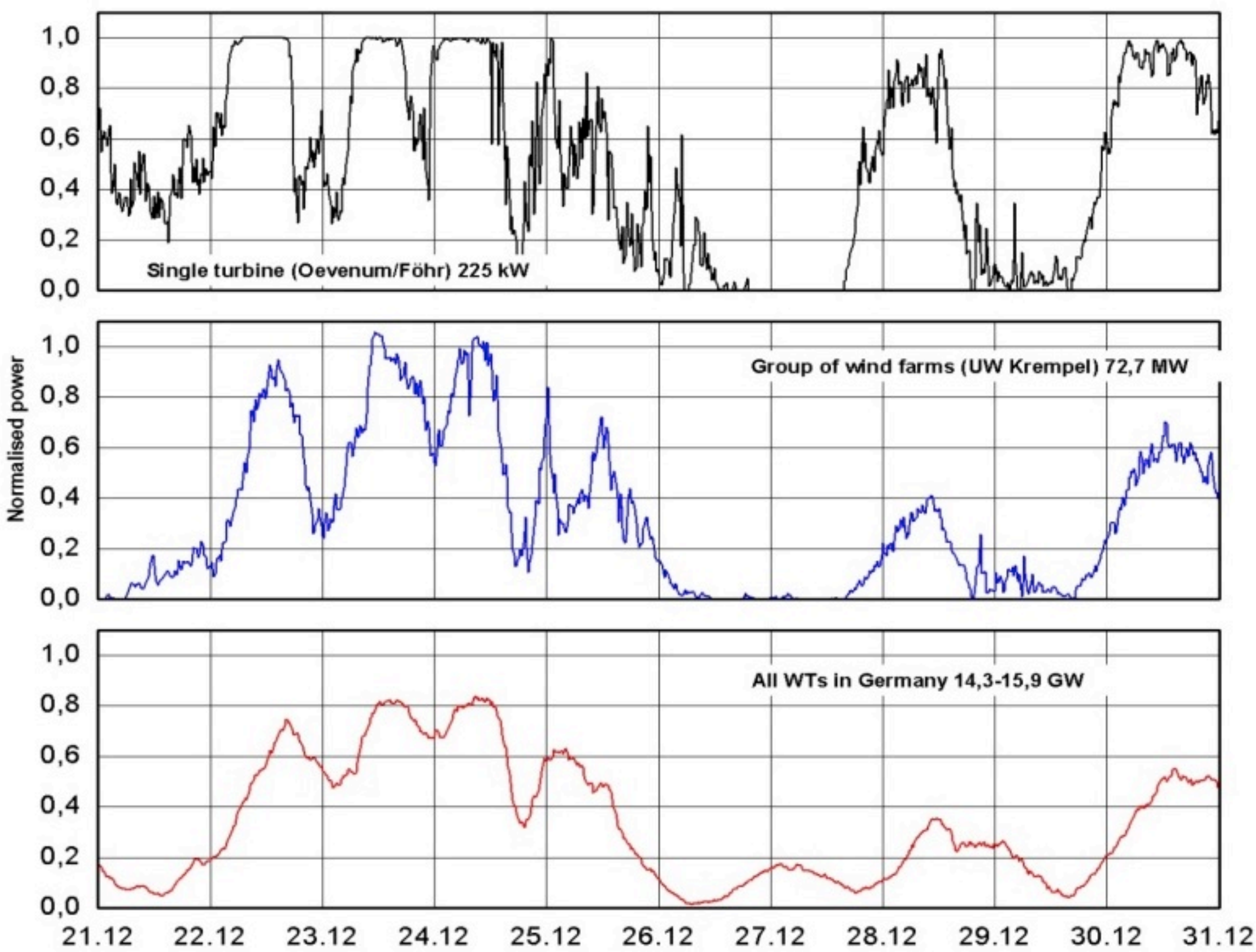
(All of the above) → Energy Storage

Wind Forecasting – Hour Ahead

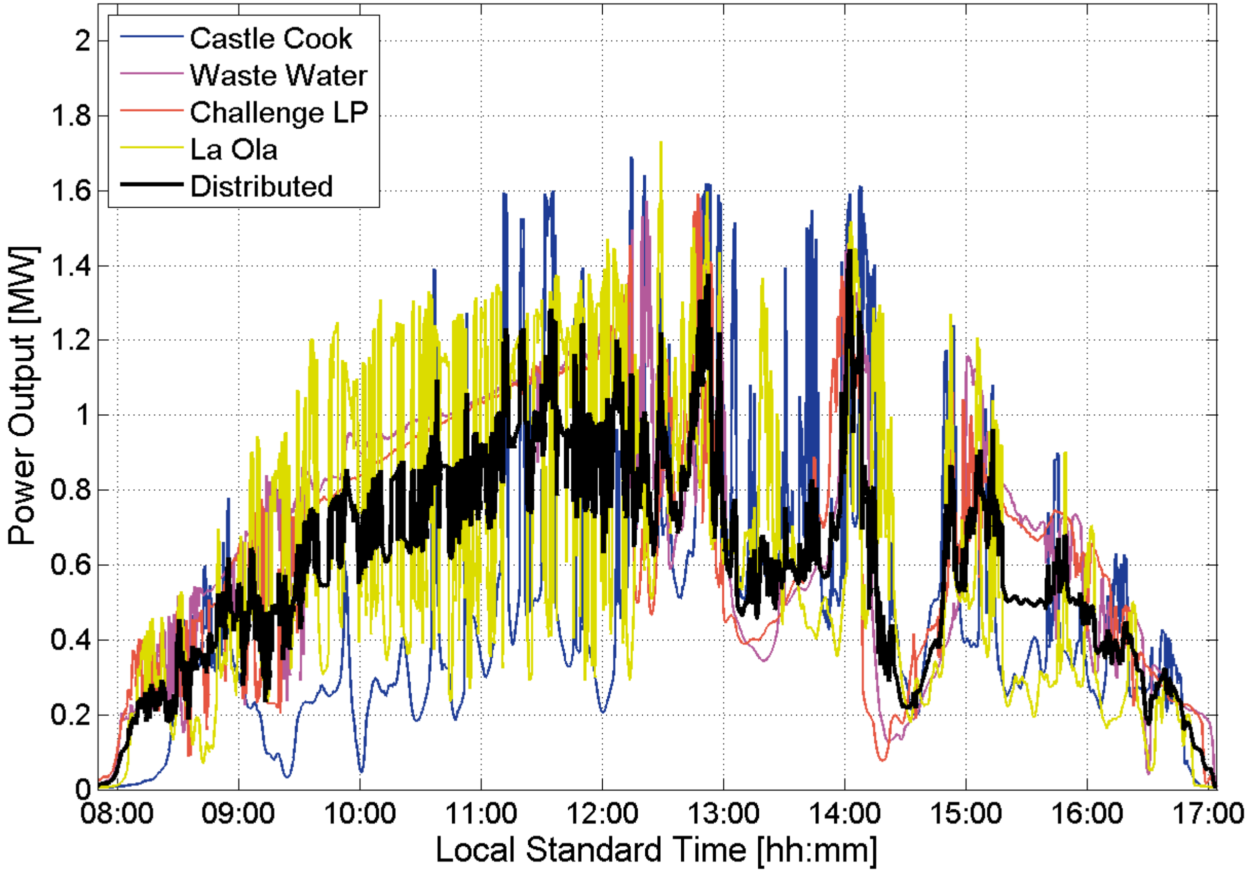


M. Milligan, NREL

Aggregation - Wind

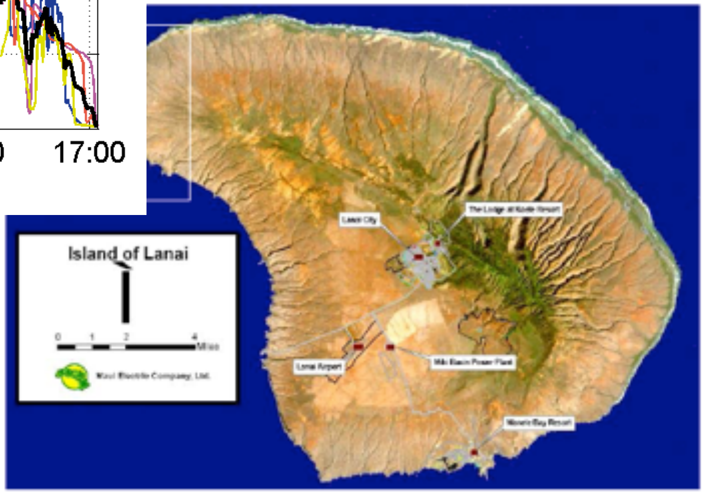


PV Variability & Geographic Smoothing



variability is reduced as PV arrays are spread over a larger area

Hawaiian Island of Lanai



Source: Sengupta & Urquhart, NREL

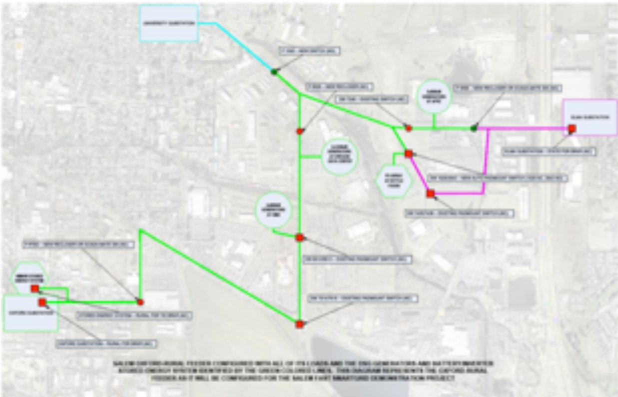
Energy Storage

Mode of Operation	Control Driver(s)
Basic Grid Support: Wind	**Wind Farm Output** (Charging) + **Time of Day** (Discharging)
Basic Grid Support: Wind + Grid	**Wind Farm Output + Grid When Needed** (Charging) and **Time of Day** (Discharging)
Economic Dispatch	**Operating System Price Signals** (Charging and Discharging)
Frequency Regulation	**Operating System Regulation** (Charging and Discharging)
Wind Smoothing – Ramp Rate Control	**Wind Farm Output + Wind Farm Output Rate of Change Limiter** (Charging and Discharging)
Wind Leveling – Steady Output Control	**Wind Farm Output** (Charging) and **Fixed Set Point for Combined Output** (Discharging)

Table directly from: F. Novachek, "Energy Storage for Wind Energy Integration", *Xcel Energy,* June 4, 2009.

Portland General Electric HRZ Testing

High Reliability Zone Map



Smart Inverter

Energy Storage

HRZ Map and Connection Diagram directly rom: J. Barra, "PGE Smart Feeder Project: Advancing Smart Grid Implementation", *Portland General Electric,* 2010.
Photos Courtesy Blake Lundstrom, NREL

Early US PV Inverter Interconnection Features

- **Design to meet IEEE 1547-2003**
- **Based on low penetration installations from California Rule 21 which is 15%**
- **Listed to UL-1741 (harmonized with IEEE 1547)**
  - Anti-Islanding
    - Stop Operation if grid voltage goes away
  - Tight over/under voltage and frequency trip settings
  - Unity Power Factor
    - AC voltage regulation not allowed
- **Purpose is to get out of the way in fault condition and let existing utility protection scheme operate**
- **Solar developers are compensated for real power**

Utility-Friendly Inverter Features

- **Operate like a traditional synchronous generator**
- **VAR Control**
  - Non-Unity Power Factor
  - Regulate PV plant voltage
- **Low Voltage Ride Through**
  - Stay on-line during grid Voltage dip
  - In contrast to Anti-Islanding
  - Help improve system stability
- **Dynamic Control**
  - Ramp rate and curtailment of real power
  - Communication allows PV to be part of the utility system
- **Purpose is to <u>help</u> with grid stability**

Source: Ray Hudson (BEW)

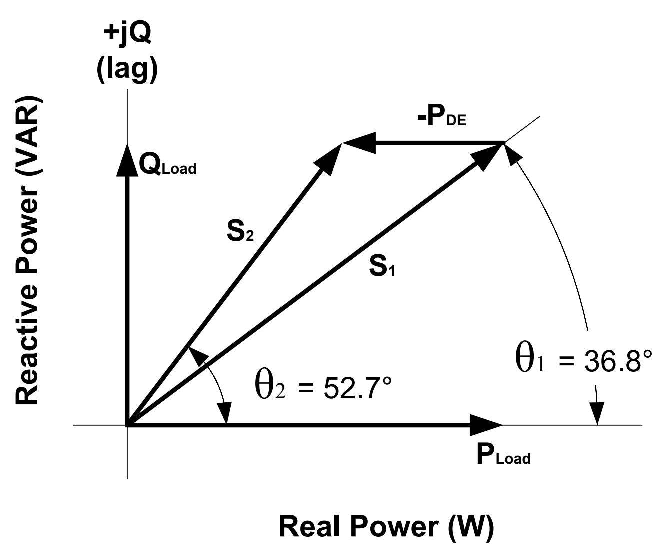
"Common Functions for Smart Inverters"

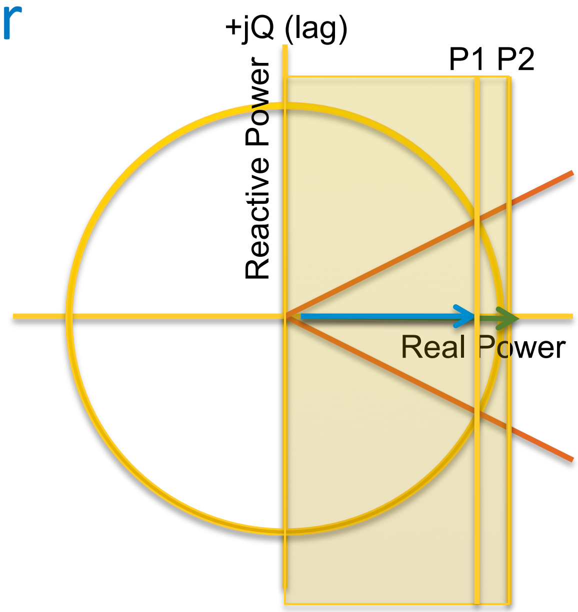
- Connect / Disconnect from Grid
- Maximum Generation Limit
- Battery Storage: Direct charge/ discharge management
- Battery Storage: Price-based charge/discharge
- Battery Storage: Coordinated charge-discharge
- **Fixed Power Factor**
- **Intelligent Volt-Var Control**
- **Volt-Watt**
- **Frequency-Watt**
- Watt-Power Factor
- Price or Temperature Driven Functions
- **Low/High Voltage Ride-through**
- **Low/High Frequency Ride-through**
- Dynamic Reactive Current Support
- Real Power Smoothing
- Dynamic Volt-Watt
- Peak Power Limiting
- Load and Generation Following
- Event/History Logging
- Status Reporting /Reading
- Time-sync

Source: "Common Functions for Smart Inverters, Version 3," *Electric Power Research Institute (EPRI)*, Report 3002002233, Feb. 2014.

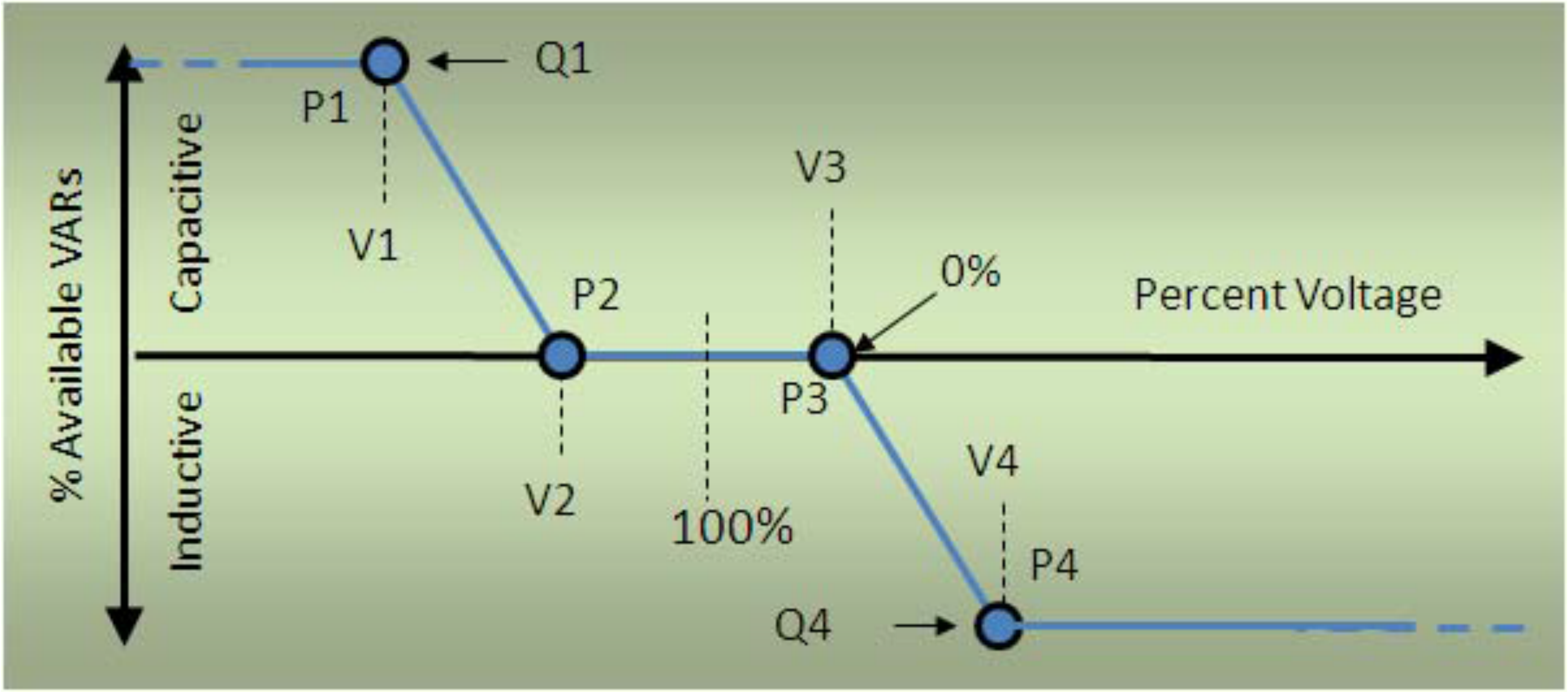
Inverter-based VAR Support

- Most inverters for DE systems are self-commutated and can produce an AC voltage of an arbitrary amplitude and phase
- This allows the DE systems to produce any power at any power factor
- PE interface has a wider operating power factor range than a synchronous generator



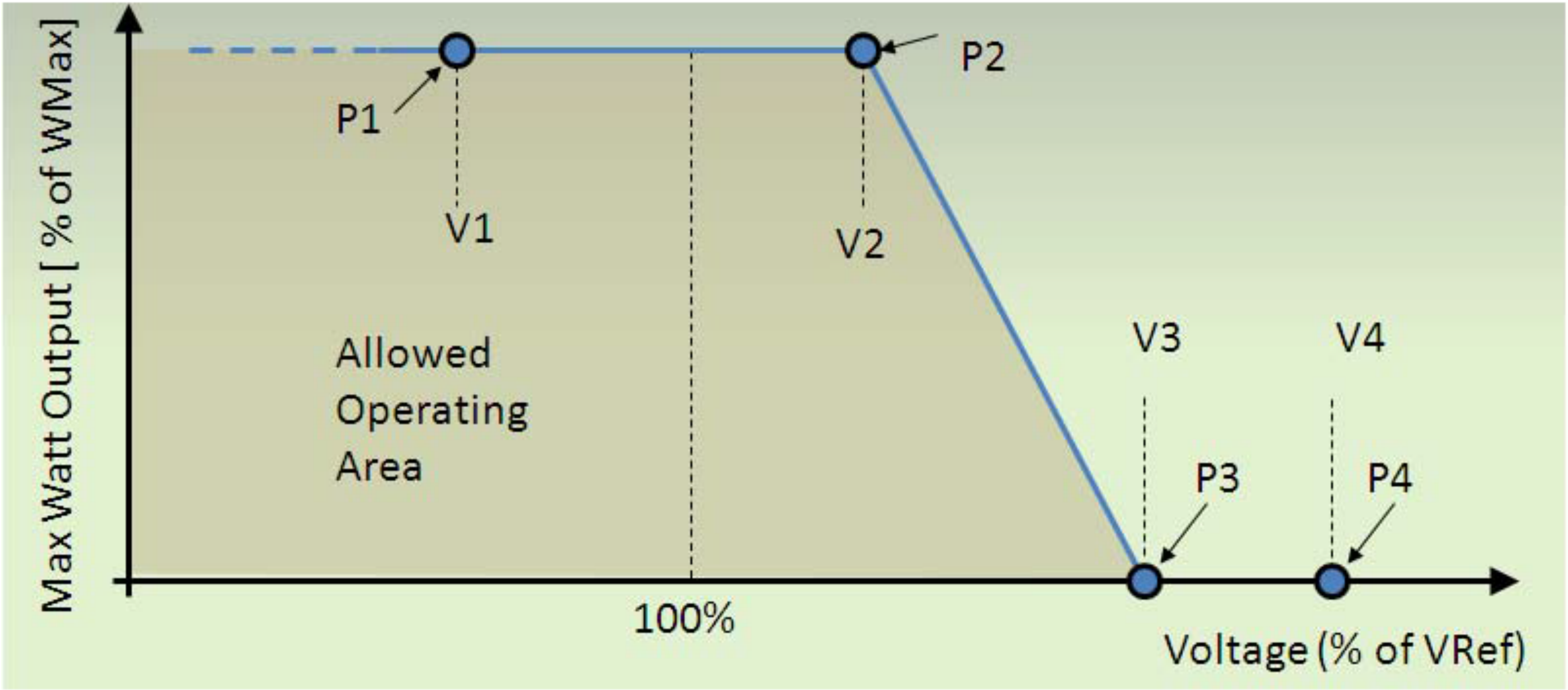


Reactive Power (Volt-VAR) Control Function



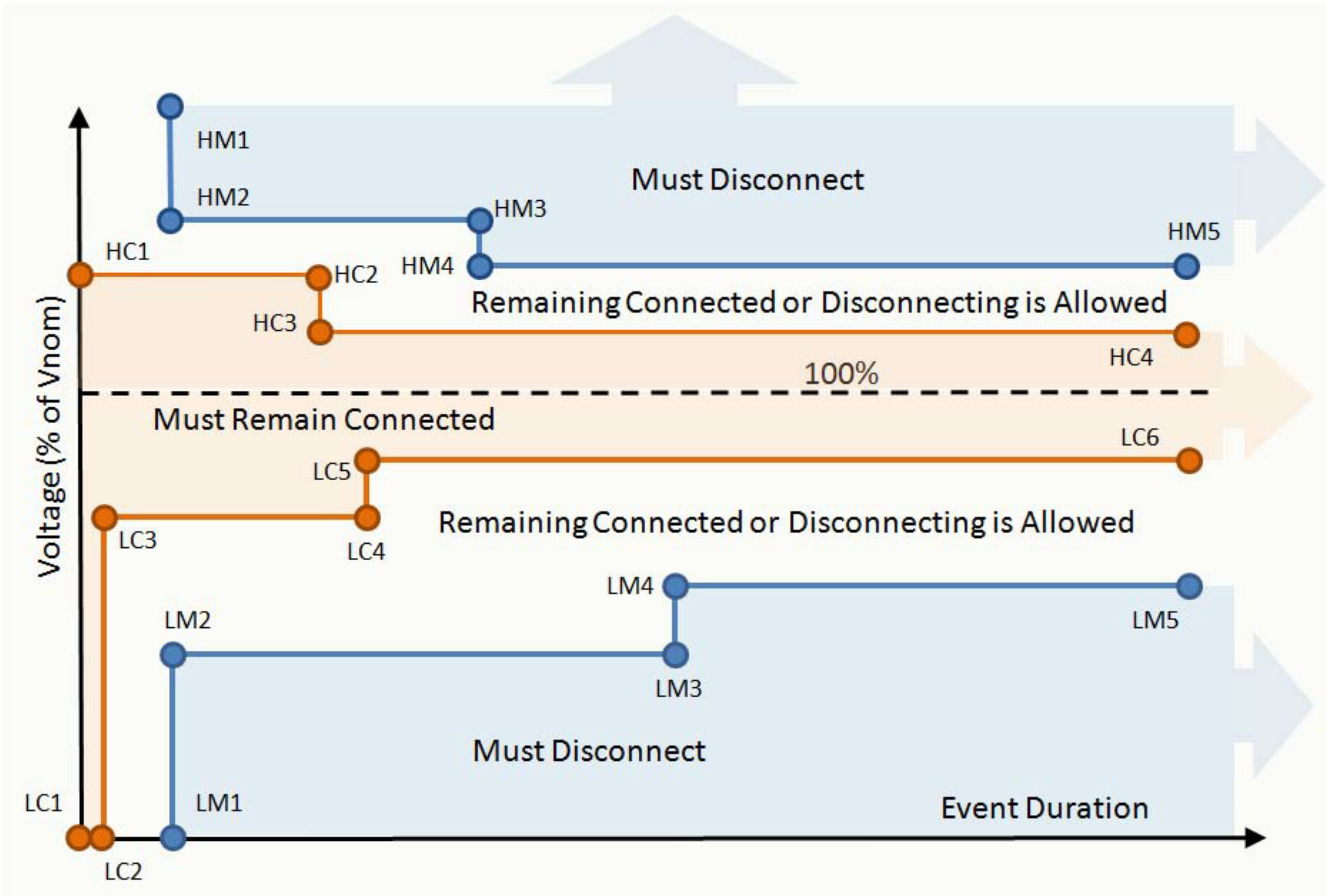
Source: “Common Functions for Smart Inverters, Version 3,” *Electric Power Research Institute (EPRI)*, Report 3002002233, Feb. 2014.

Real Power Control (Volt-Watt) Function



Source: "Common Functions for Smart Inverters, Version 3," *Electric Power Research Institute (EPRI)*, Report 3002002233, Feb. 2014.

L/H Voltage Ride-through



Source: "Common Functions for Smart Inverters, Version 3," *Electric Power Research Institute (EPRI)*, Report 3002002233, Feb. 2014.

Solar PV Inverters: Advanced Features

Advanced Feature	Benefits
Ramp Rates	Prevent local overvoltages during low-load/high-gen
Voltage Ride-through	• Support transmission system: prevent unnecessary disconnection and potentially longer voltage recovery • Limit/define fault-current contribution
Frequency Ride-through	Support transmission system
Watts-Hz Dynamic Support	Supports grid during over generation conditions
Voltage (VAR) Support (Phase Independent)	Supports local voltage Support voltage imbalance due to 1Φ load/generation
Voltage support at night time	Supports grid especially during high load conditions
10% above rating for grid	Owner not lose revenue during grid support
Standard communications	Owners/utility
Auxiliary power supply	Provide owners emergency power

Source: Richard Bravo, SCE