Smart Inverters and Grid Support Requirements

IEEE 1547-2018

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Disclaimer & Acknowledgements

- *This presentation on IEEE P1547 are the author's views and are not the formal position, explanation or position of the IEEE.*

- *Many thanks to Project 1547 Officers, Working Group members, and balloters who contributed their time and efforts to develop this standard.*

Outline

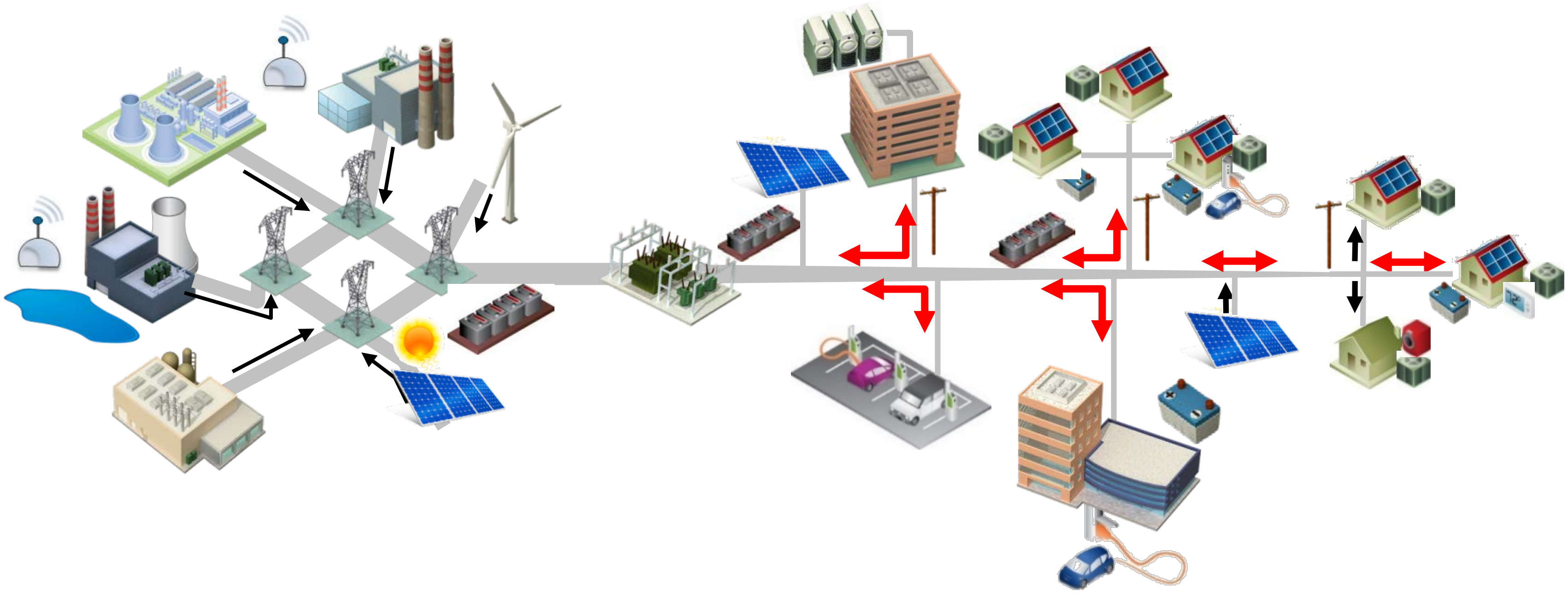
1. Smart Inverter – What it is?

2. Voltage Management Support Functions

3. Voltage and Frequency Ride Through

DER - Reshaping the Power System

- Consumers becoming energy producers
- Loads becoming more interactive and dynamic
- Generation becoming more flexible
- T&D becoming more controllable and resilient



Sharing the same power system – need more coordination and shared responsibility

Challenges with High Penetration of PV

Voltage

- Overvoltage
- Voltage variations

Equipment Operation

- Feeder regulators,
- Load tap changers
- Switched capacitor banks

Demand/Energy

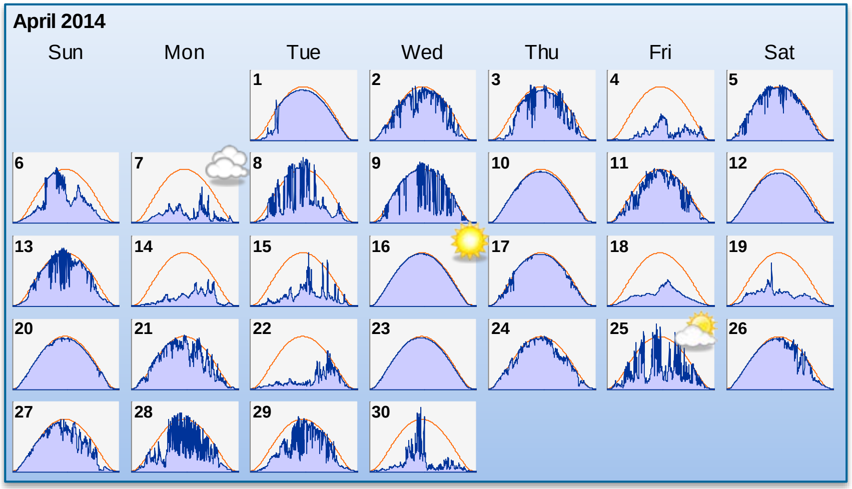
- “Masking” peak demand
- Unbalancing supply and demand

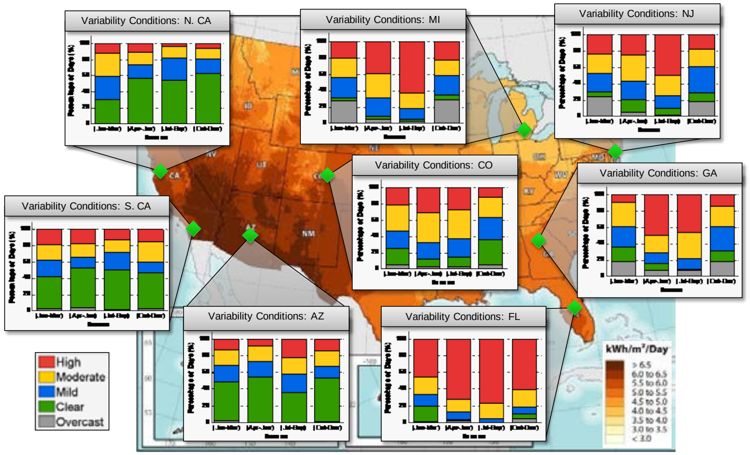
System Protection

- Relay desensitization, networks
- Breaker reduction of reach
- Unintentional islanding

Power Quality

- Harmonic generation
- Flicker worries

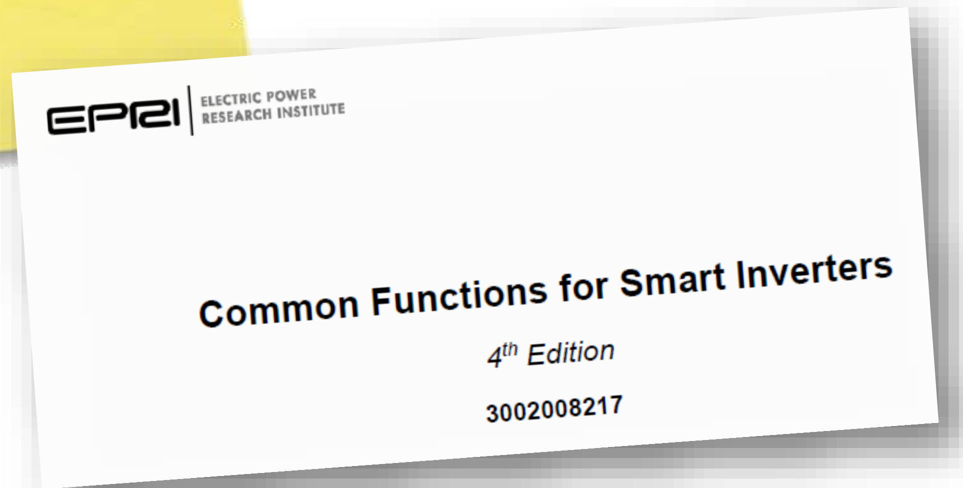




What is Smart Inverter?

What is a Smart Inverter?

- Inverter that can modify it's real and reactive power output to provide grid support
- Can respond autonomously to V/F changes or can respond to communicated signal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Common Functions for Smart Inverters

4th Edition

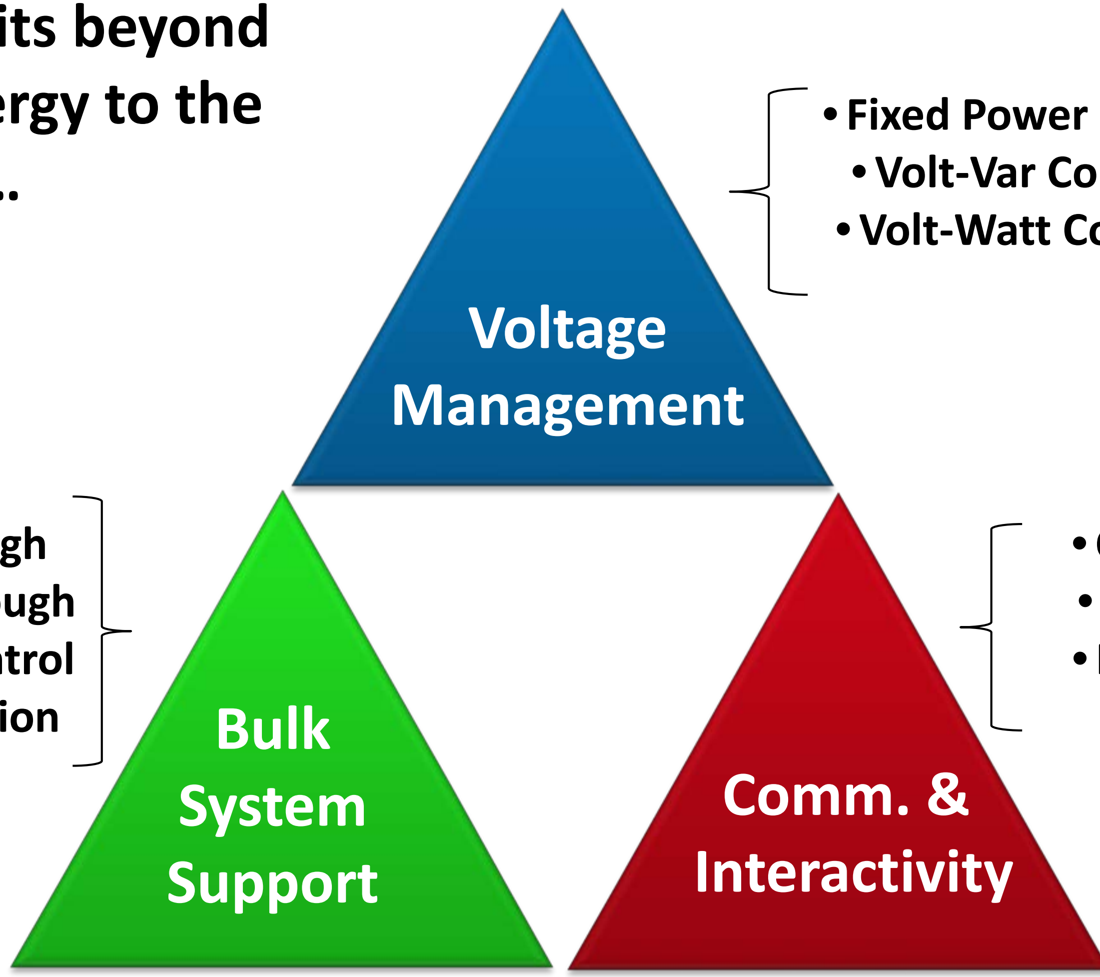
3002008217

Go to www.epri.com and search **3002008217**

What Can a Smart Inverter Do?

Provide benefits beyond delivering energy to the grid…

- Fixed Power Factor
- Volt-Var Control
- Volt-Watt Control



- Voltage Ride-through
- Frequency Ride-through
- Frequency-Watt Control
- Active Power Injection

- Configuration
- Coordination
- R/T Feedback

Outline

1. Smart Inverter – What it is?

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Changes in IEEE – 1547 Requirements

IEEE 1547-2003
DER **shall not** actively regulate the voltage at PCC

IEEE 1547a-2014
DER **may** actively participate to regulate the voltage by changes of real and reactive power

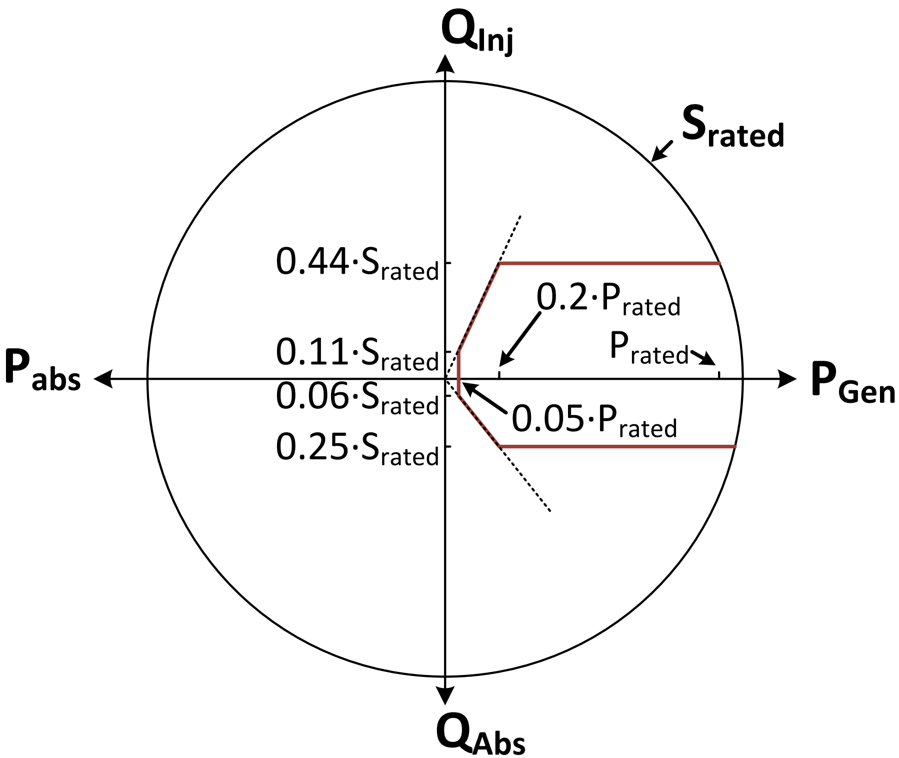
IEEE 1547-2018
DER **shall provide** voltage regulation capability by changes of active and reactive power

Minimum Reactive Power Capability

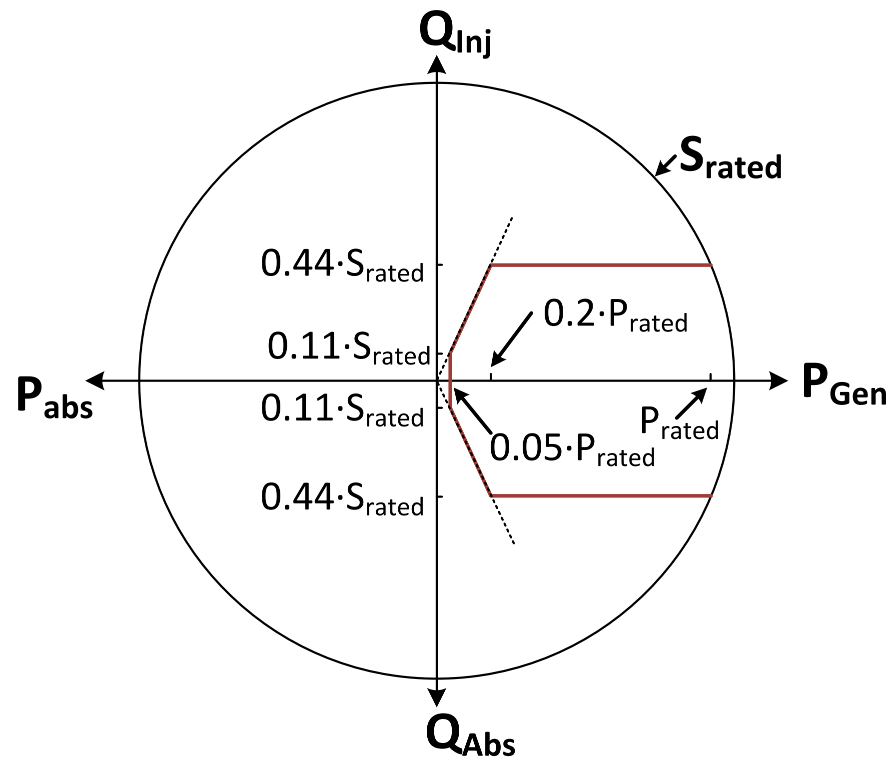
- DER shall be capable of injecting and absorbing reactive power for active power levels greater than or equal to the minimum steady state active power capability or 5% of rated power of the DER, whichever is greater.
- Operation at any active power above 20% of DER rated power shall not constrain the DER reactive power absorption and injection capability up to the limit specified in the below table:

Category	Injection Capability as % of Nameplate Apparent Power (kVA) Rating	Absorption Capability as % of Nameplate Apparent Power (kVA) Rating
A (at DER rated voltage)	44	25
B (over the full extent of ANSI C84.1 range A)	44	44

Minimum Reactive Power Capability



Category A



Category B

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Voltage Regulation Support Functions in IEEE 1547-2018

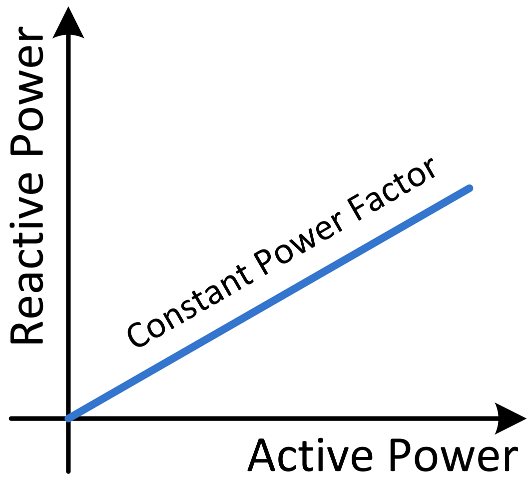
DER Category	Cat A	Cat B
Voltage regulation by reactive power (Q) control		
Constant power factor mode	mandatory	mandatory
Voltage – reactive power (volt-var) mode	mandatory	mandatory
Active power – reactive power (watt-var) mode	not required	mandatory
Constant reactive power mode	mandatory	mandatory
Voltage regulation by active power (P) control		
Voltage – active power (volt-watt) mode	not required	mandatory

Notes

- It is Area EPS operator’s responsibility to specify the required DER performance category (A or B).
- Unless otherwise specified by the Area EPS operator, constant power factor mode with unity power factor setting shall be the default mode of the installed DER.
- Reactive power capability and voltage/power control requirements apply to the continuous operation region when the voltage is between 0.88 p.u. to 1.1 p.u.
- Continued operation of voltage regulation support functions outside the continuous operation region may be acceptable to support functions covered in response to abnormal voltage condition section.
- Under mutual agreement between Area EPS operator and DER operator, requirements other than those specified in the IEEE 1547 revision are also permitted.

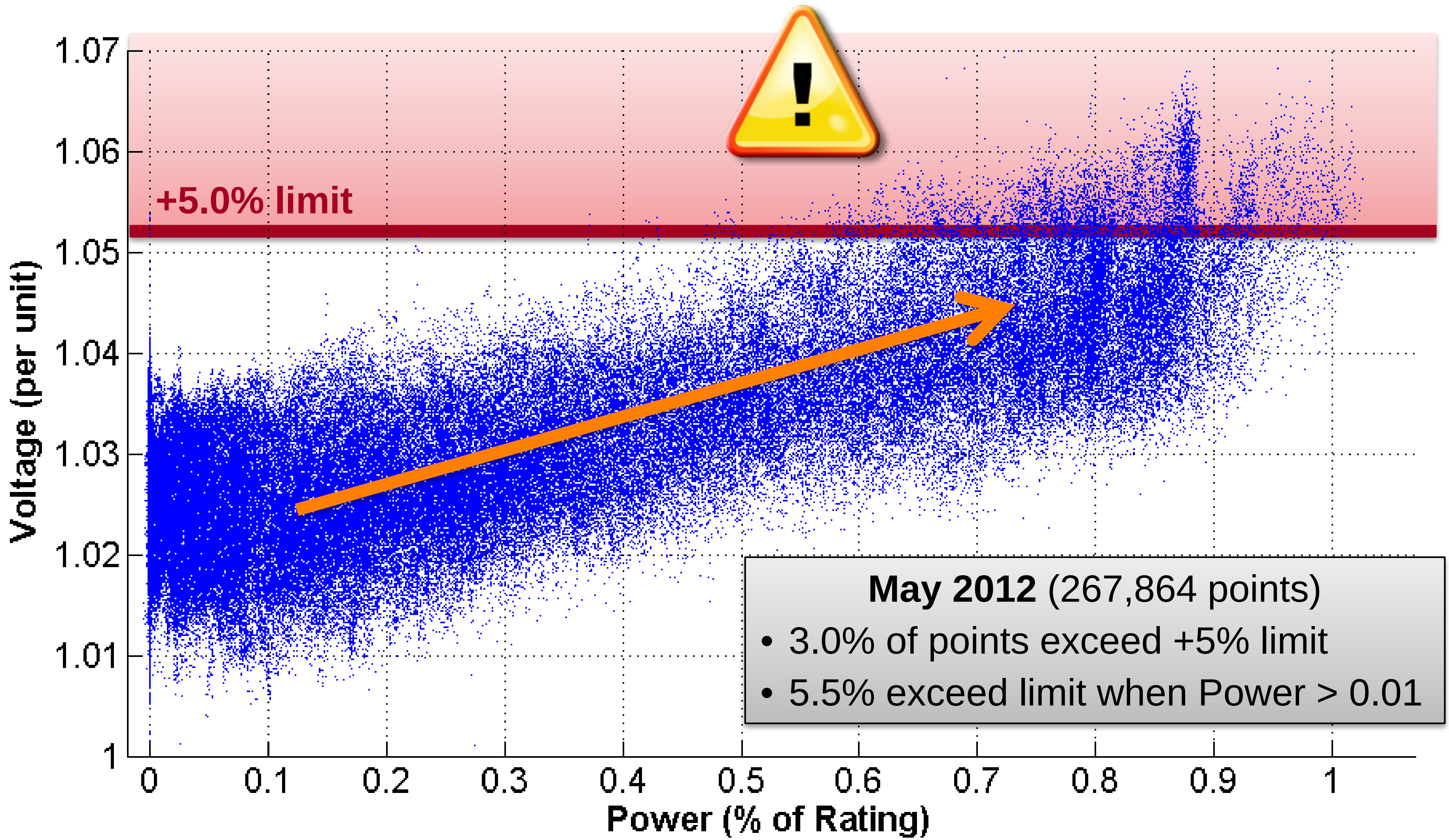
Constant Power Factor Mode

- This function allows DERs to operate at a fixed power factor (PF) (ratio of active to reactive power), regardless of voltage or active power generation.
- Although this control mode does not directly regulate the voltage, it does adjust the reactive power based upon the level of active power generation, thus providing a form of voltage-regulation support.
- Maximum DER response time to maintain constant power factor shall be 10s or less.
- Area EPS operation shall specify the target power factor and shall not require reactive power exceeding the minimum reactive power requirements.
- Settings are allowed to be adjusted local and/or remotely as specified by the EPS operator.



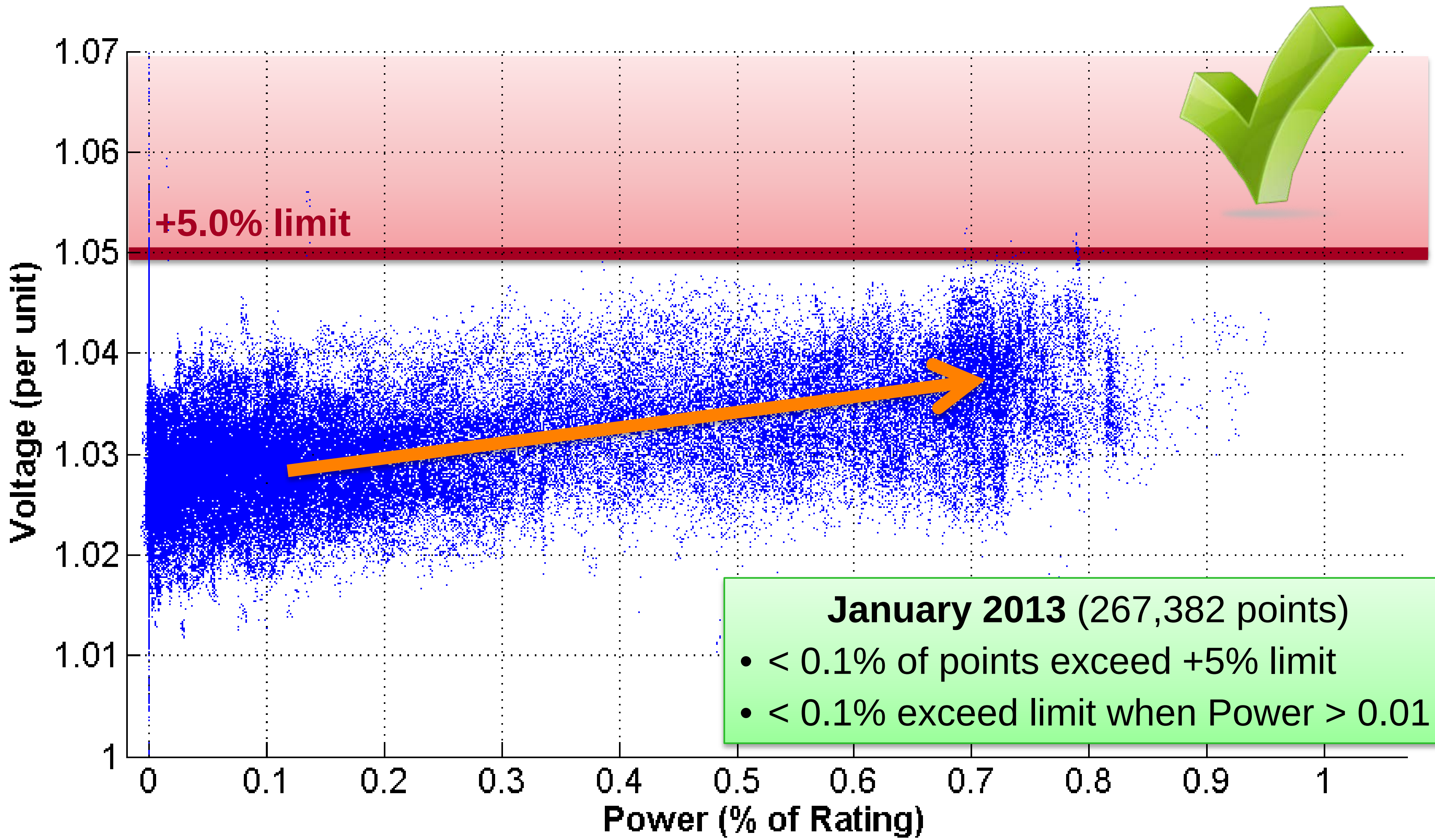
Voltage Exceeds Planning Limit

10-second average PV plant service voltage often above +5% at midday



Voltage after Power Factor Adjustment

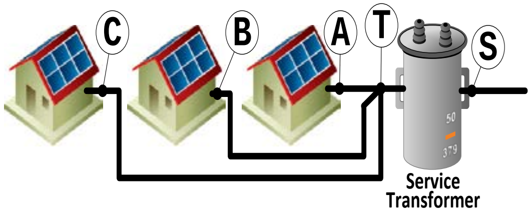
January 2013

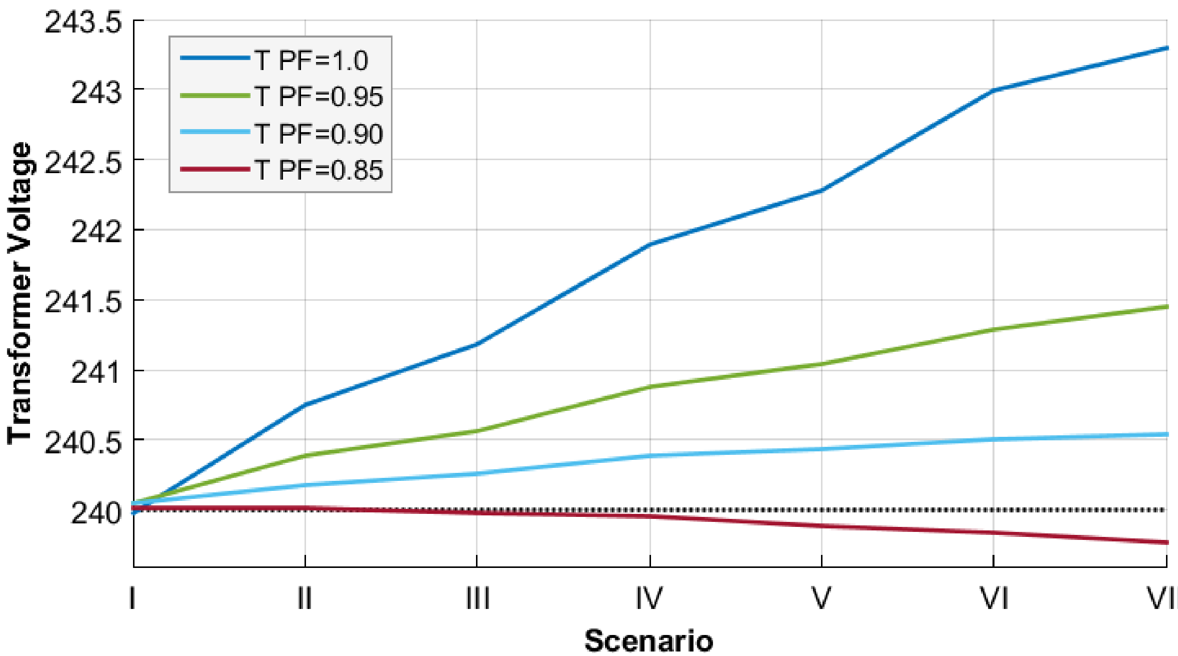


January 2013 (267,382 points)

- < 0.1% of points exceed +5% limit
- < 0.1% exceed limit when Power > 0.01

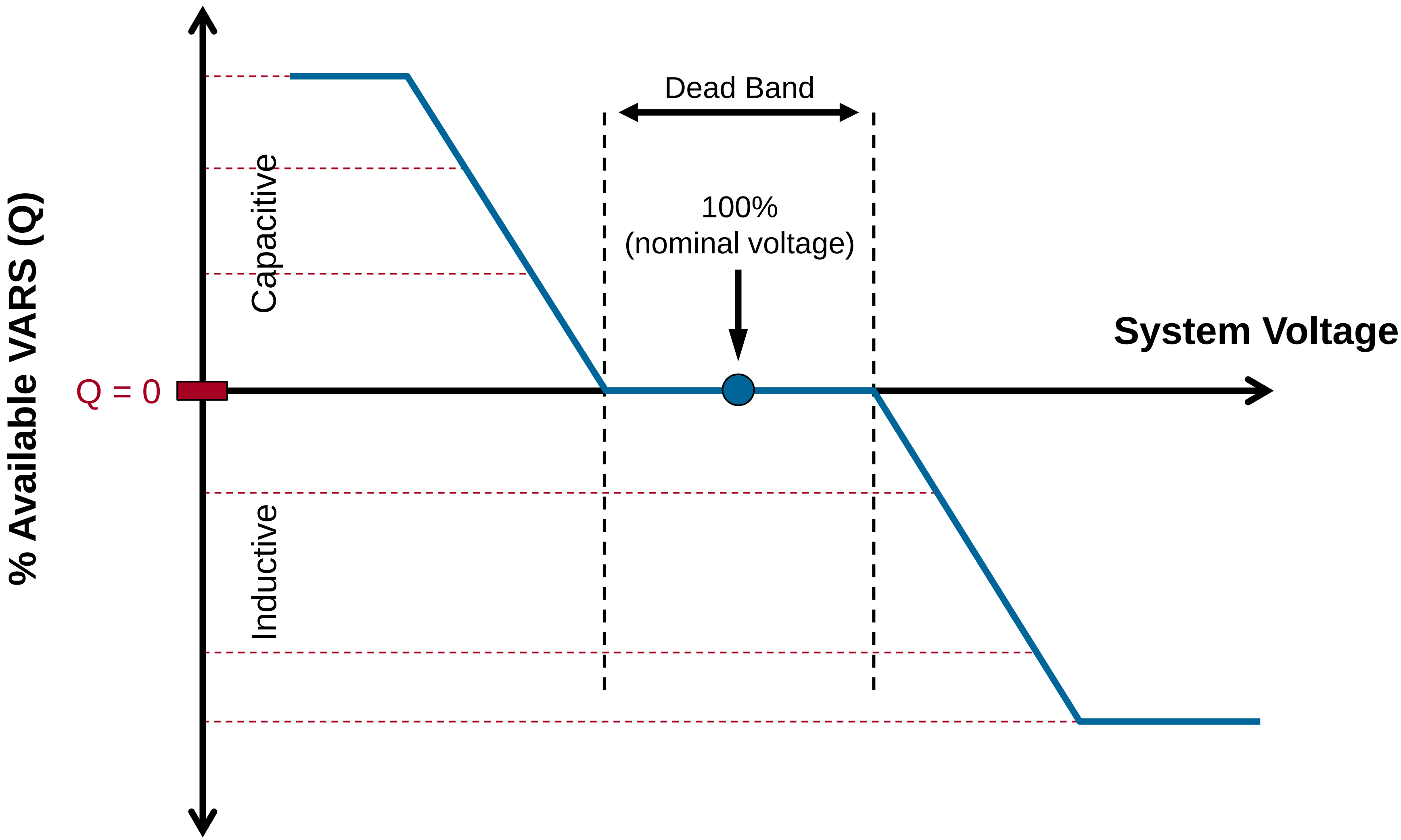
Non-Unity Power Factor Impact on Service Transformer Secondary Voltage





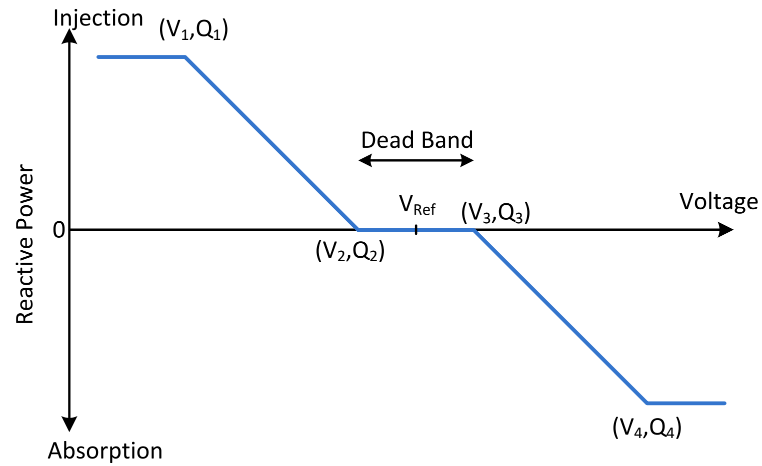
Scenarios	I	II	III	IV	V	VI	VII
House A PV Power	0	0	0	0	0	3.0kW	4.8kW
House B PV Power	0	0	0	3.0kW	4.8kW	4.8kW	4.8kW
House C PV Power	0	3.0kW	4.8kW	4.8kW	4.8kW	4.8kW	4.8kW

Voltage – Reactive Power (Volt-Var) Function



Voltage – Reactive Power (Volt-Var) Function

- In this mode, the DER shall actively regulate its reactive power output as a function of voltage, following a voltage – reactive-power characteristic.
- This control mode tries to actively regulate voltage by controlling the injection or absorption of reactive power.
- The volt-var characteristics are allowed to be adjusted locally and/or remotely as specified by the area EPS operator.



Voltage-reactive power parameters	Default settings		Ranges of allowable settings	
	Category A	Category B	Minimum	Maximum
V_{Ref}	V_N	V_N	$0.95\ V_N$	$1.05\ V_N$
V_2	V_N	$V_{Ref} - 0.02\ V_N$	Category A: V_{ref} Category B: $V_{Ref} - 0.03\ V_N$	V_{Ref} [c]
Q_2	0	0	100% of nameplate	100% of nameplate reactive power

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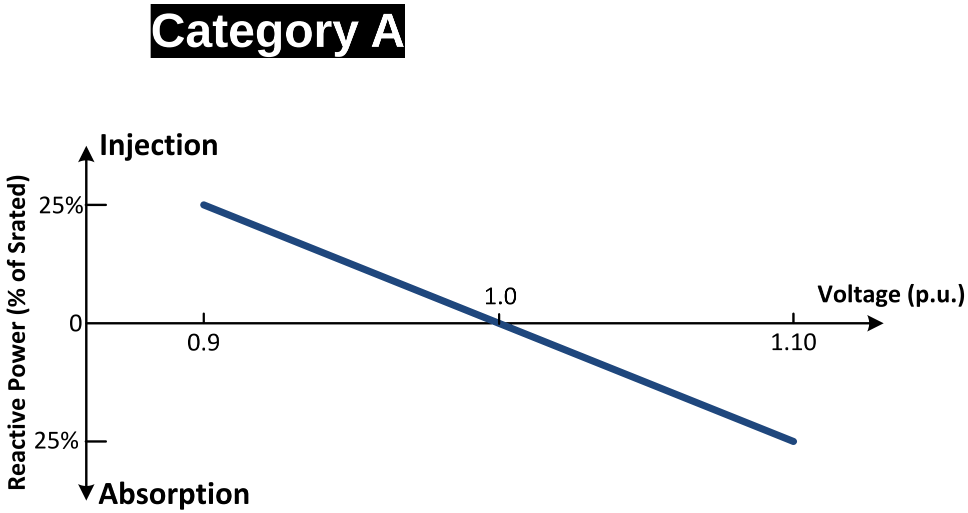
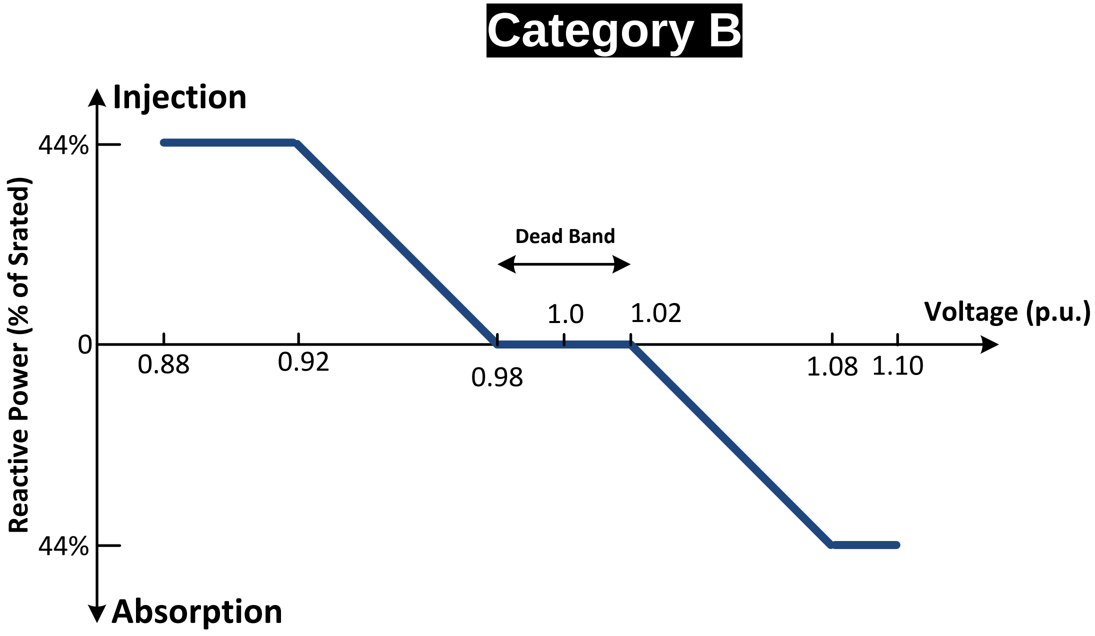
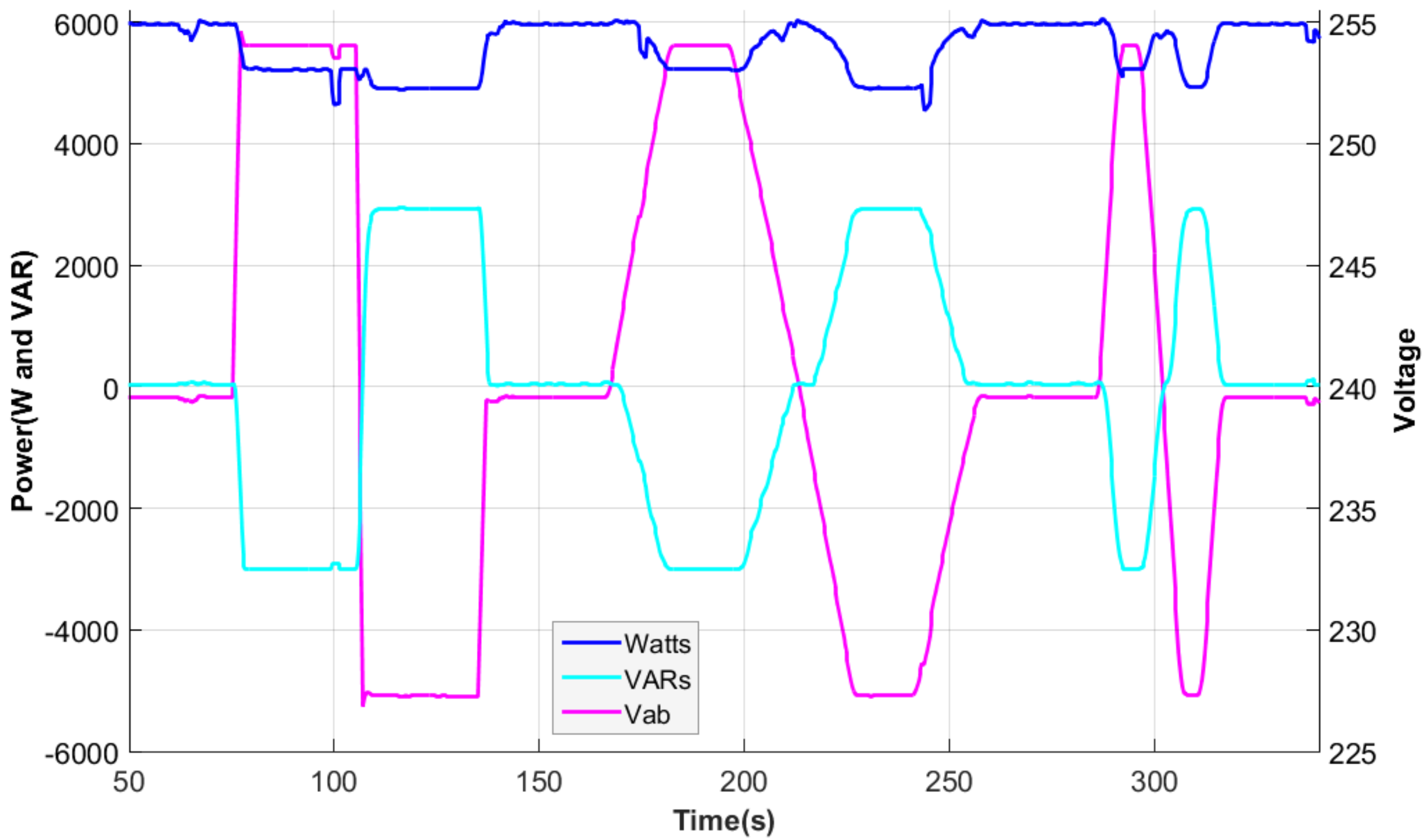
Cat A and Cat B Default Volt-Var Characteristics



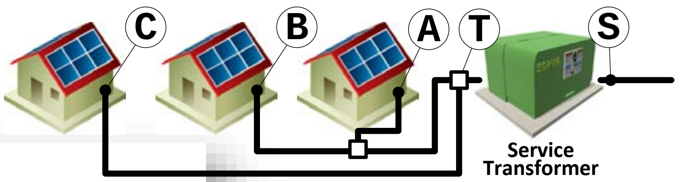


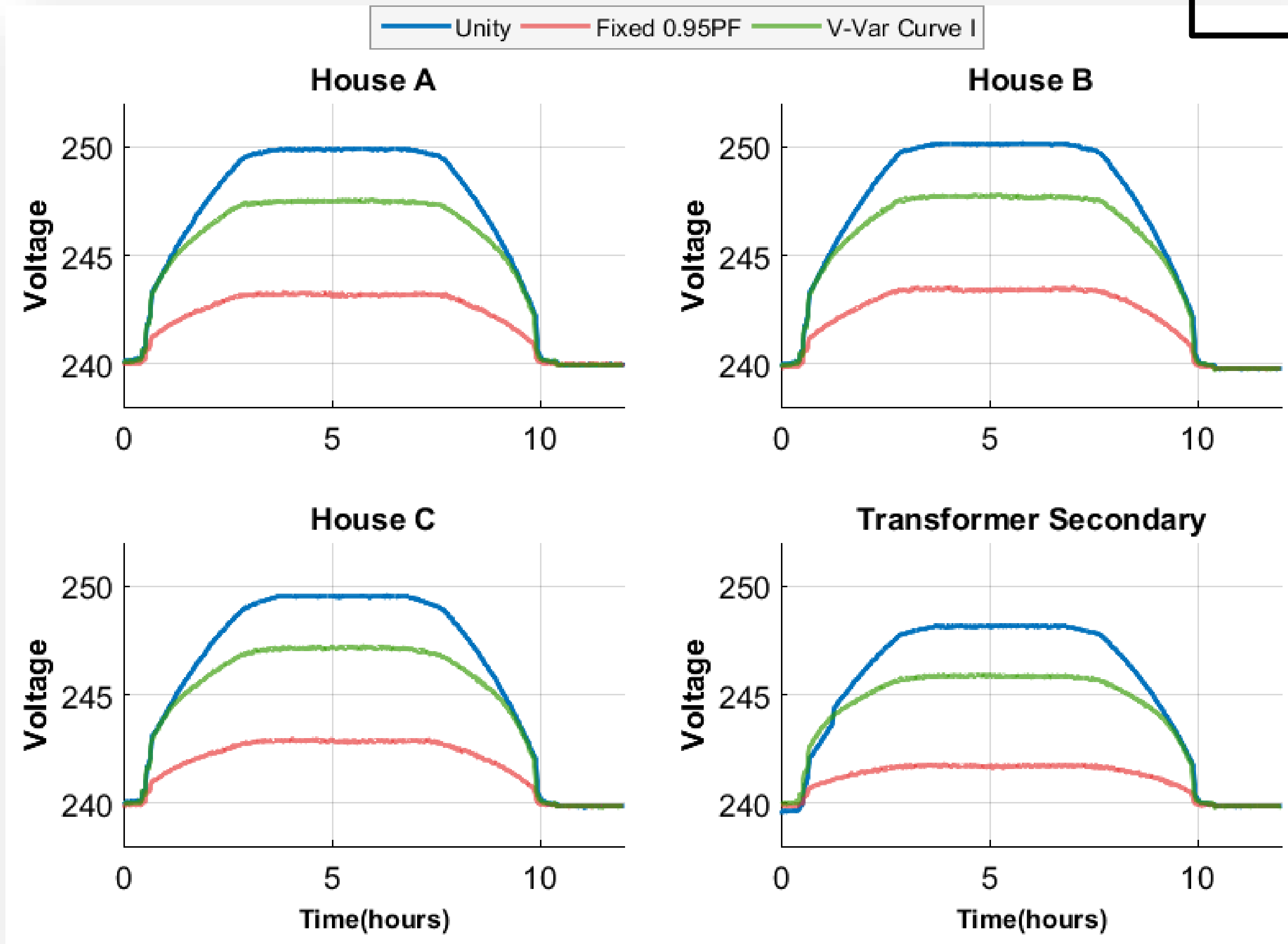
Volt-Var Function – Responding to Voltage Variation



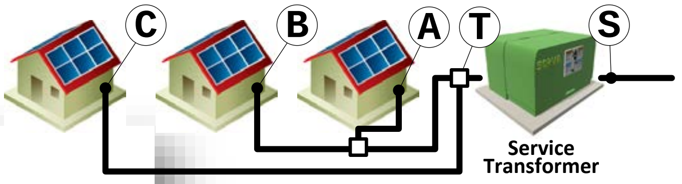
- DER is changing the polarity and magnitude of reactive power in response to the voltage variation following the volt-var characteristics.
- In constant PF mode, DER cannot change the polarity of reactive power autonomously.

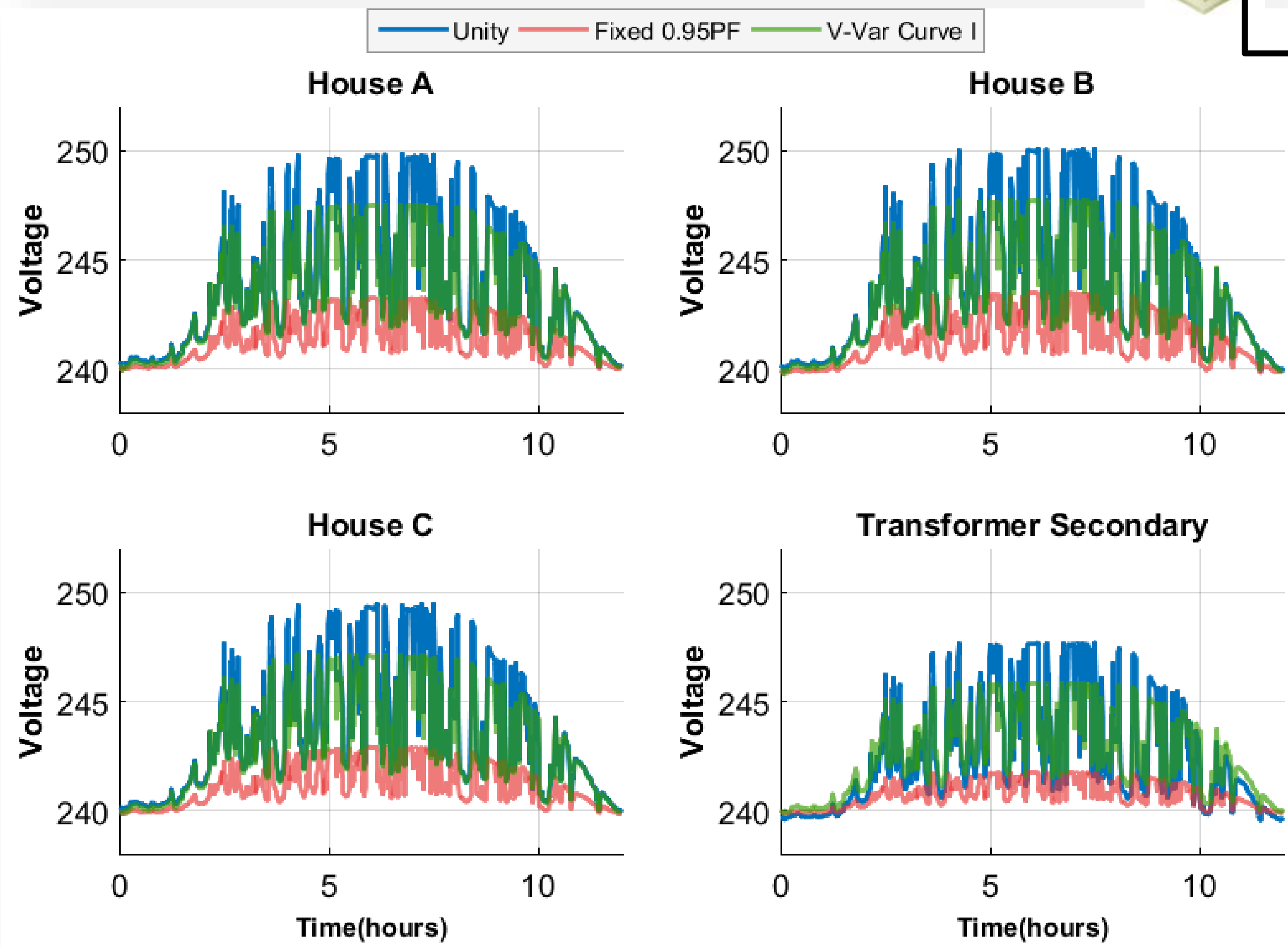
PF and Volt-Var Function Impact on Voltage





PF and Volt-Var Function Impact on Voltage on a Highly Variable Day





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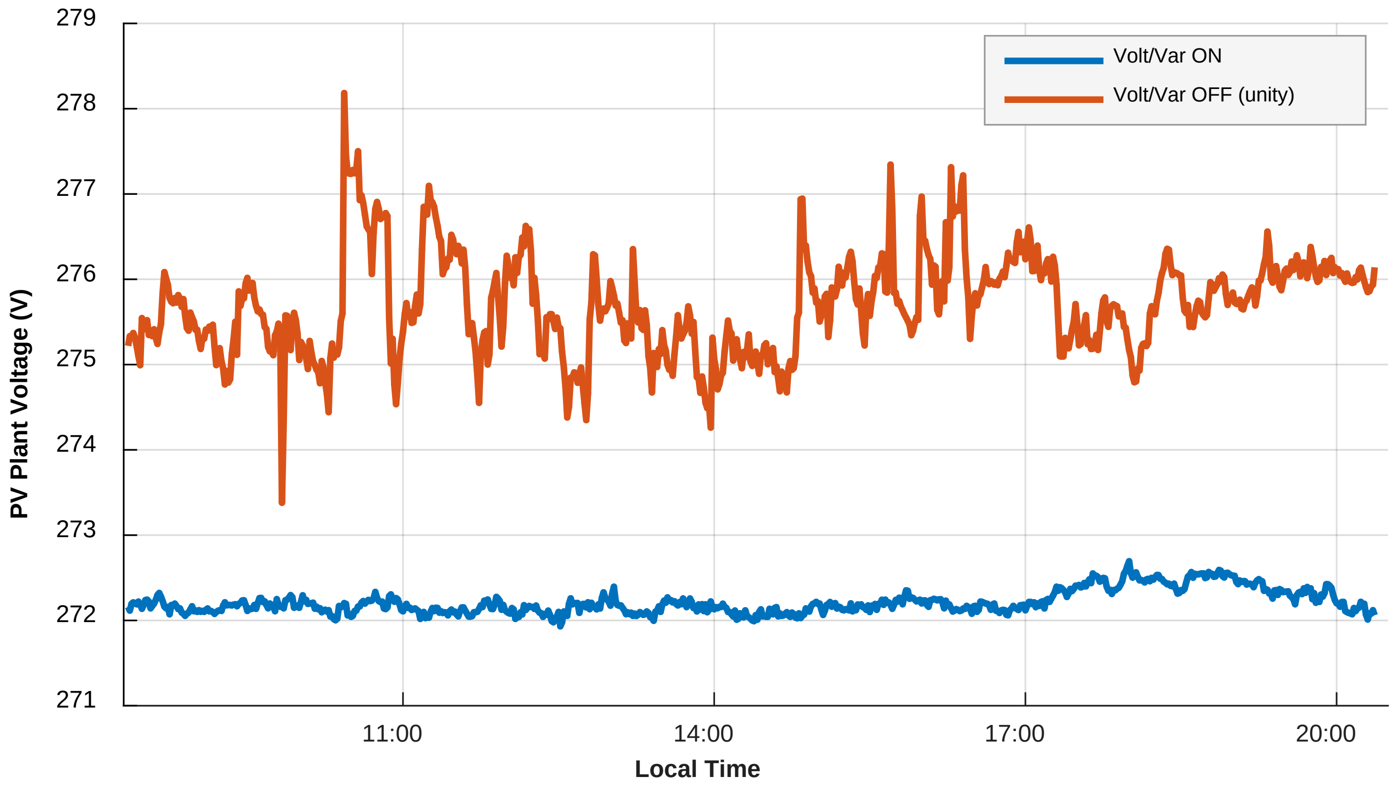
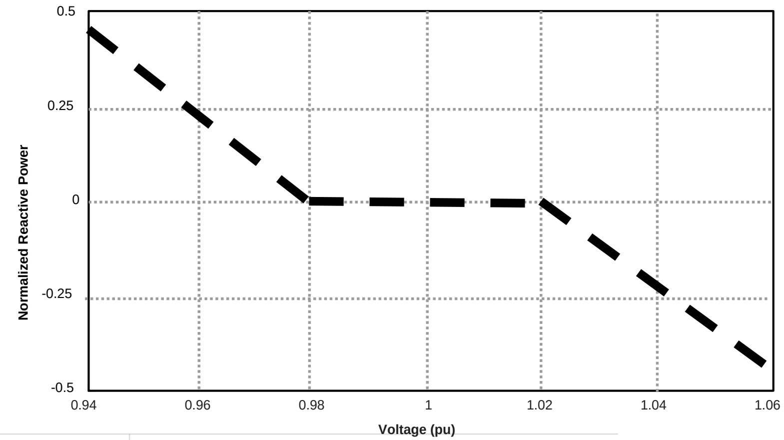
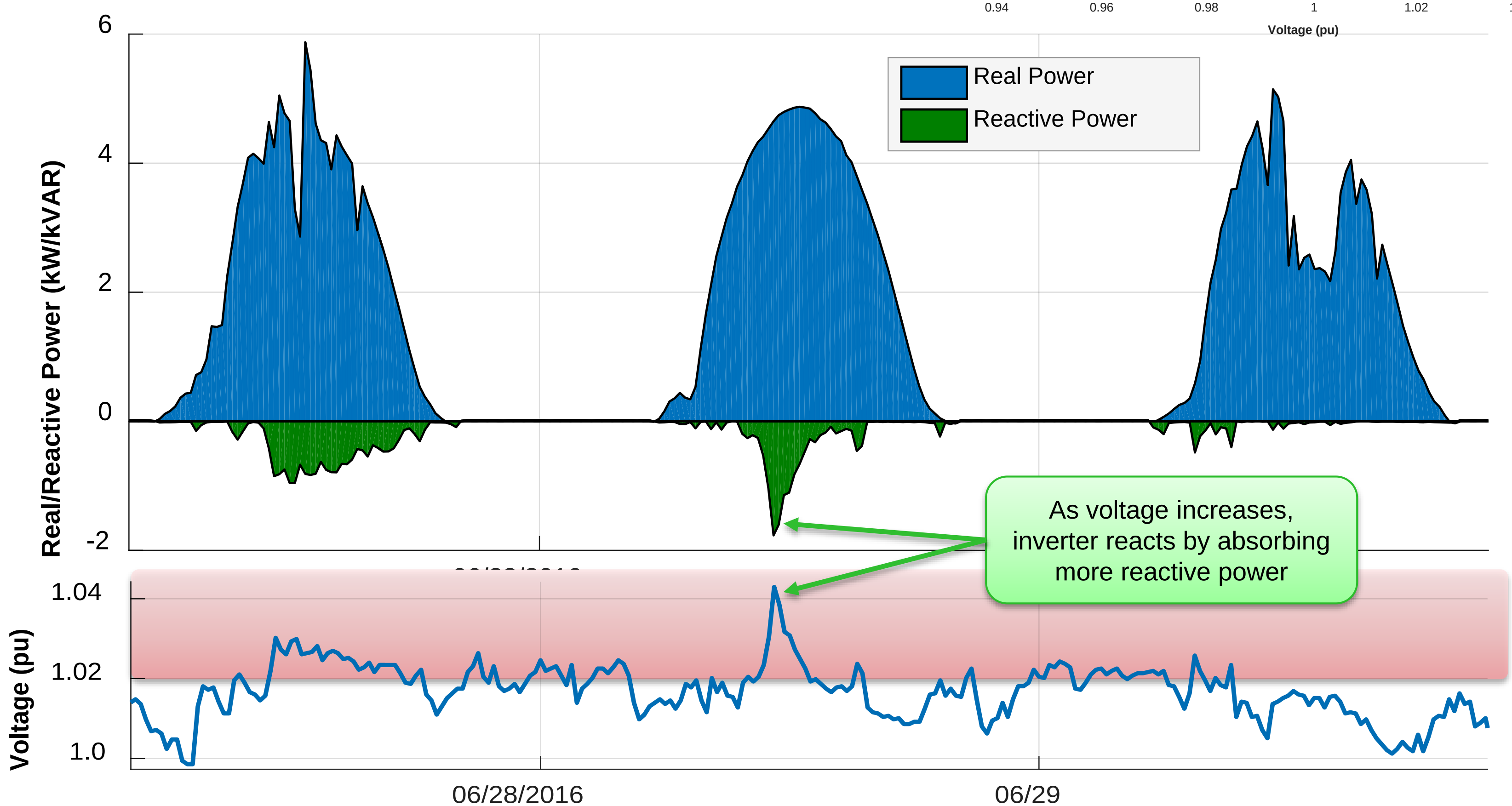
Volt-Var Function – Field Demonstration Result

- Two similar days in terms of solar variability, load, and temperature.
- PCC voltage of 1-MW PV plant



Volt-Var – Real World Example

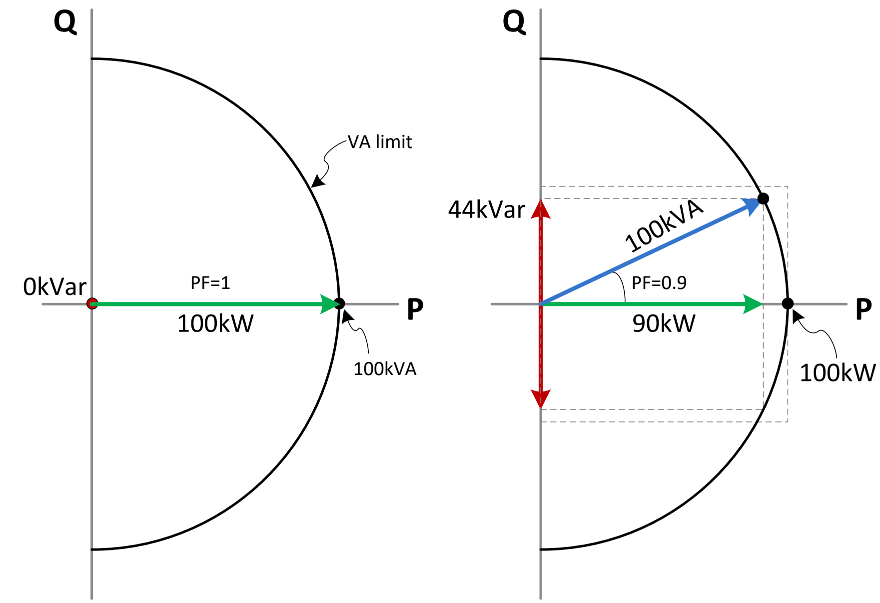




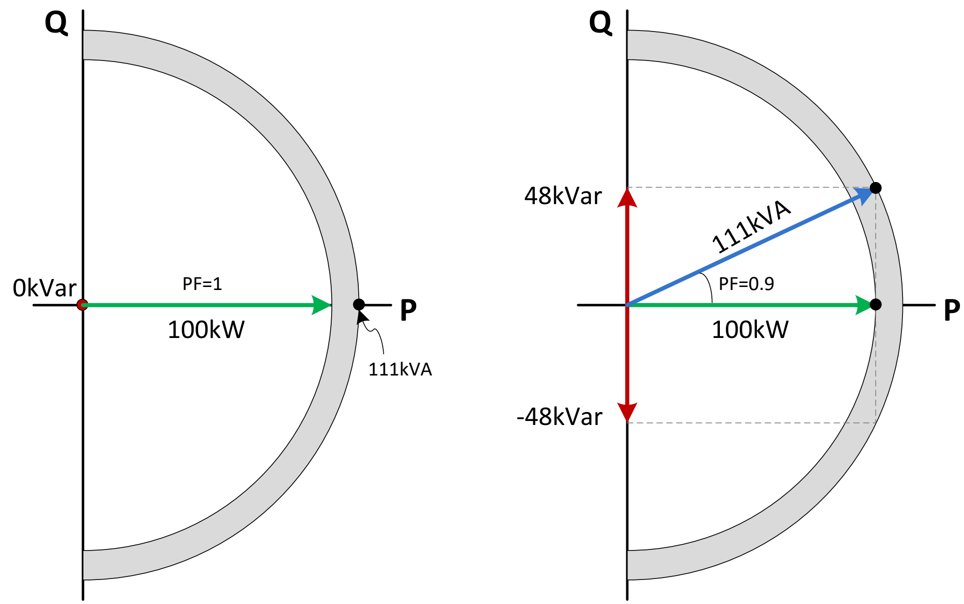
Constant PF and Volt-Var Impact on Active Power

- Depending on the inverter design (kW vs KVA rating), constant power factor and volt-var function can impact the DER active power generation.

$P_{rated} = S_{rated}$

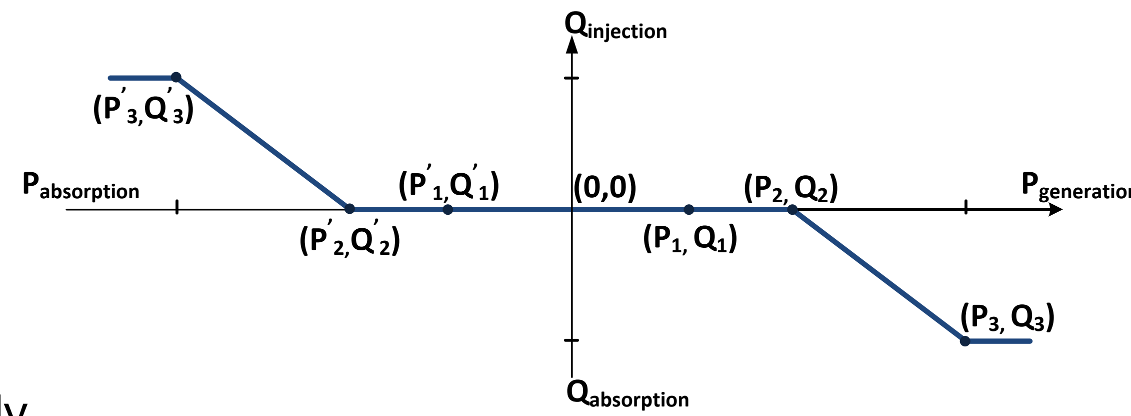


$P_{rated} < S_{rated}$



Active Power – Reactive Power (Watt-Var) Mode

- In this mode, DER shall actively control the reactive power output as a function of the active power output following a target active power–reactive power characteristic.
- The response time shall not be greater than 10 s.
- The left-hand side of the characteristics shall only apply to DER capable of absorbing active power.
- The Watt-Var characteristics are allowed to be adjusted locally and/or remotely as specified by the Area EPS Operator.



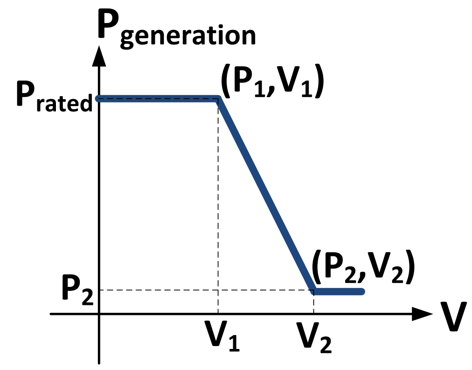
Active power-reactive power parameters	Default settings		Ranges of allowable settings	
	Category A	Category B	Minimum	Maximum
P_3	P_{rated}		$P_2 + 0.1\ P_{rated}$	P_{rated}
P_2	$0.5\ P_{rated}$		$0.4\ P_{rated}$	$0.8\ P_{rated}$
P_1	The greater of 0.2 P_{rated} and P_{min}		P_{min}	$P_2 - 0.1\ P_{rated}$

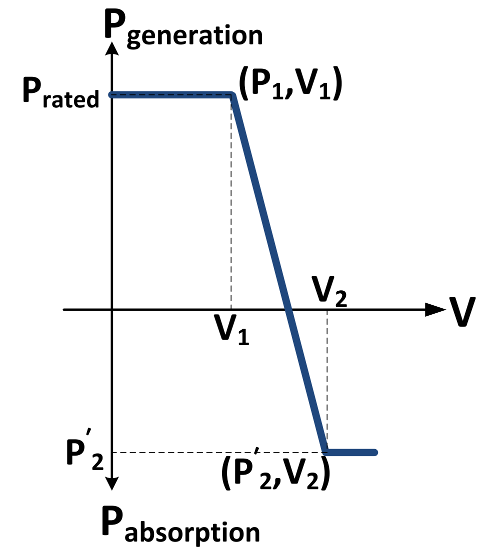
Constant Reactive Power (Var) Mode

- In this mode the DER shall maintain a constant reactive power.
- The target reactive power magnitude and mode (injection or absorption) shall be specified by the Area EPS Operator and shall be within the minimum required reactive power range.
- The reactive power settings are allowed to be adjusted locally and/or remotely as specified by the Area EPS Operator.
- The maximum DER response time to maintain constant reactive power shall be 10 s or less.

Voltage – Active Power (Volt-Watt) Mode

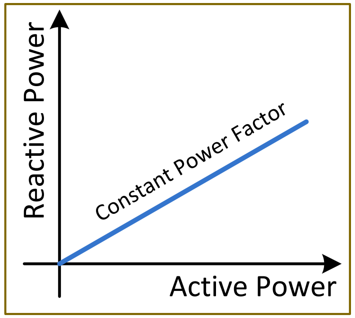
- This control mode limits the maximum active power under high voltage conditions, following a volt-watt characteristic.
- Limiting active power output limits the voltage rise.
- The voltage threshold above which this control mode limits the active power needs to be selected carefully to avoid frequent power limiting.
- This control mode is expected to trigger power limiting only to address excessive voltage levels that might be caused by DER power export.





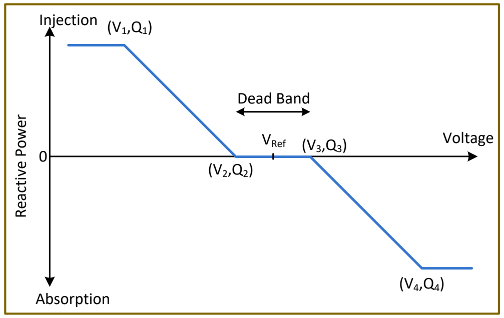
Active power-reactive power parameters	Default settings		Ranges of allowable settings	
	Category A	Category B	Minimum	Maximum
P_3	P_{rated}		$P_2 + 0.1\ P_{rated}$	P_{rated}
P_2	$0.5\ P_{rated}$		$0.4\ P_{rated}$	$0.8\ P_{rated}$
P_1	The greater of $0.2\ P_{rated}$ and P_{min}		P_{min}	$P_2 - 0.1\ P_{rated}$

Common Voltage Regulation Support Functions



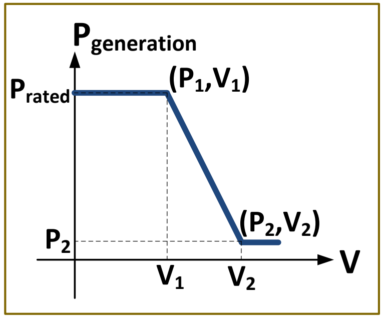
Constant Power Factor (PF)

- Operates at a fixed PF, regardless of voltage and power
- Reactive power is in proportion to active power
- Not directly respond to voltage change



Volt-Var

- Regulates reactive power in response to voltage variation
- Tries to bring voltage close to the reference voltage
- Not directly respond to active power generation change



Volt-Watt

- Limits max active power injection above certain voltage
- Can work in conjunction with volt-var function
- Objective is to limit excessive voltage increase

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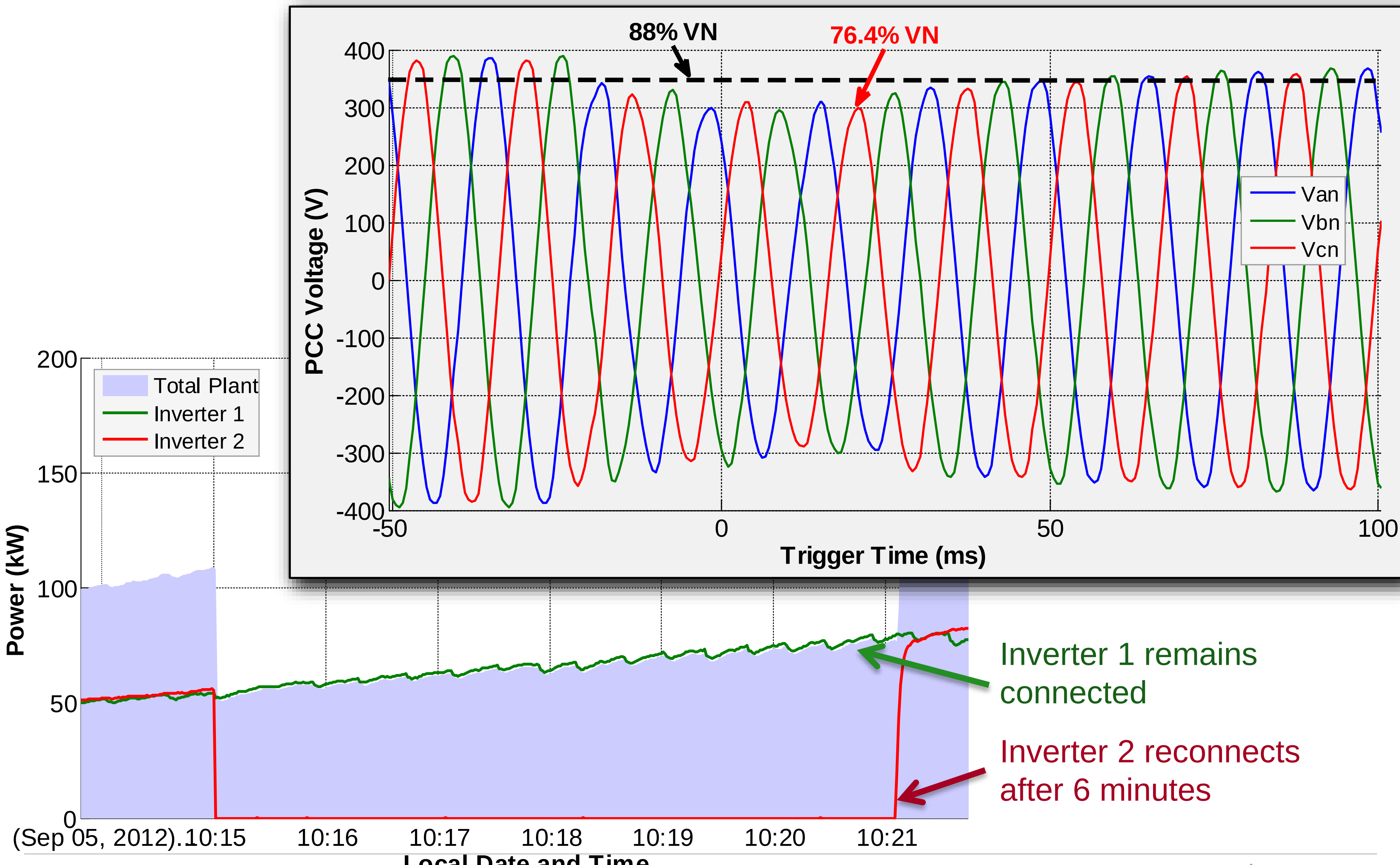
Abnormal Voltage and Frequency Conditions - Performance Categories

Category	Objective	Foundation
I	Essential bulk system needs and reasonably achievable by all current state-of-art DER technologies	German grid code for synchronous generator DER
II	Full coordination with bulk power system needs	Based on NERC PRC-024, adjusted for distribution voltage differences (delayed voltage recovery)
III	Ride-through designed for distribution support as well as bulk system	Based on California Rule 21 and Hawaii Rule 14H

Category II and III are sufficient for bulk system reliability.

Low Voltage Ride Through

What does it mean?



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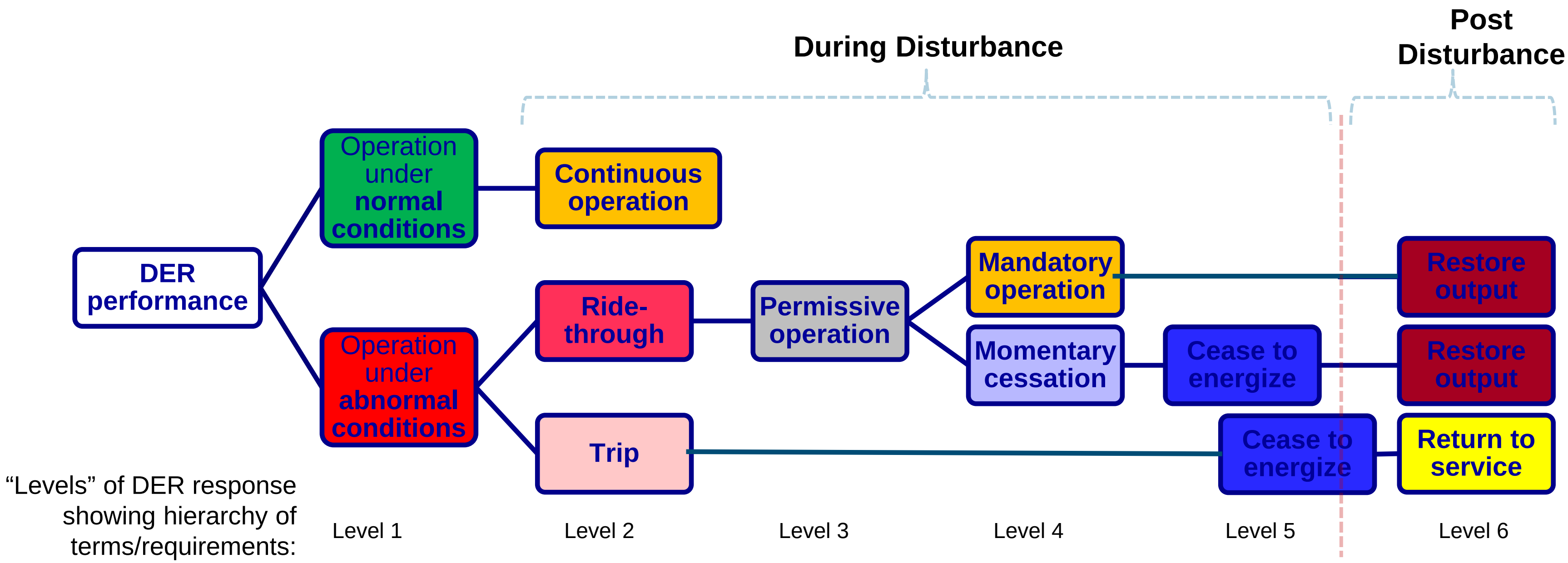
Disturbance performance terminology

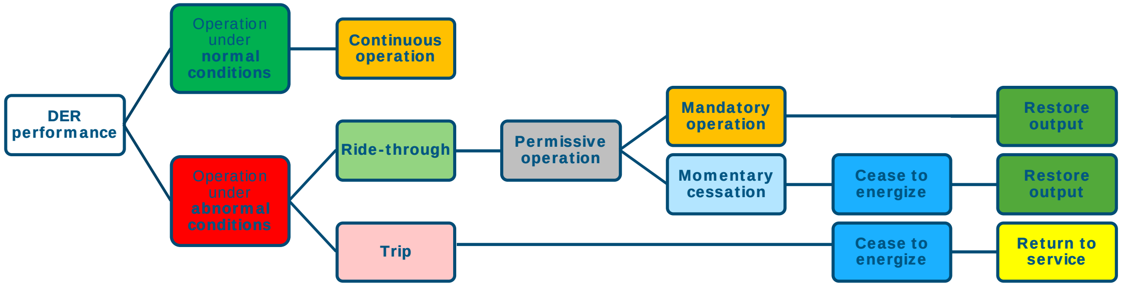


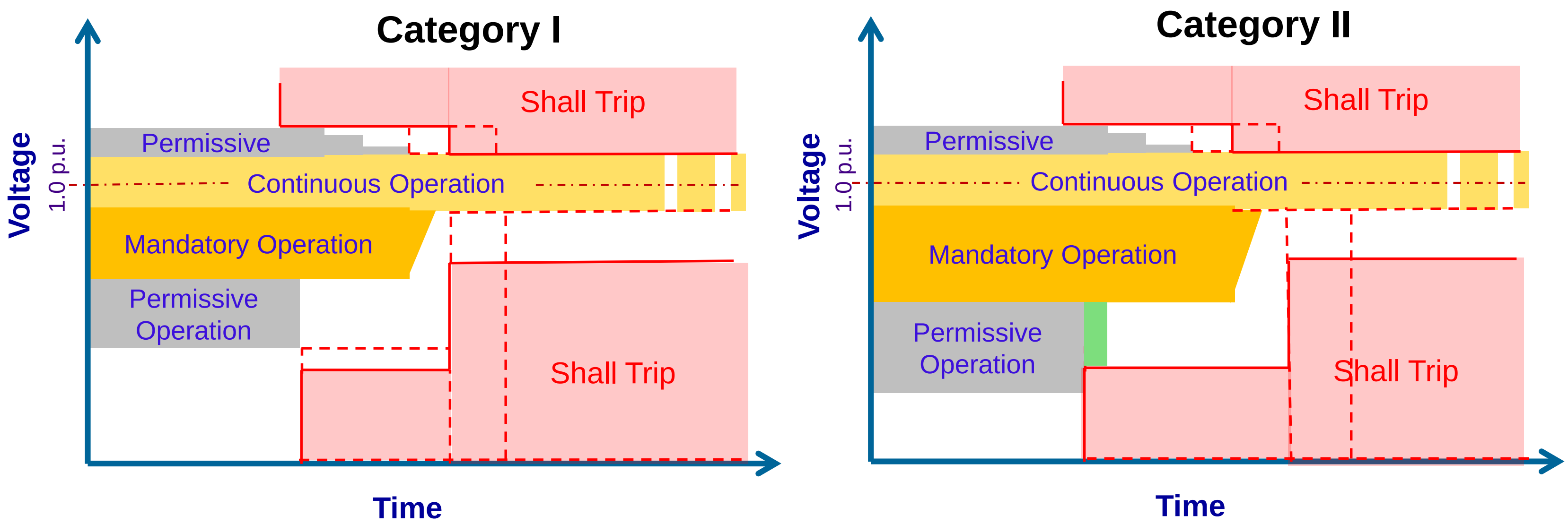
- **Ride-through** – ability to withstand voltage or frequency disturbances
  - **Permissive operation** – DER may either continue operation or may cease to energize, at its discretion
    - **Mandatory operation** – required active and reactive current delivery
    - **Momentary cessation** – cessation of energization for the duration of a disturbance with rapid recovery when voltage or frequency return to defined range
  - **Restore output** – DER recovery to normal output following a disturbance that does not cause a ***trip***.
- **Trip** – cessation of output without immediate return to service; not necessarily disconnection
  - **Return to service** – re-entry of DER to service following a trip; equivalent to start-up of DER

Clarification of "Cease to Energize"

- **Cease to energize**
  - Refers to Point of DER Connection (PoC) of individual DER unit(s)
  - No active power delivery
  - Limitations to reactive power exchange
  - Does not necessarily mean physical disconnection
  - Used either for *momentary cessation* or *trip*

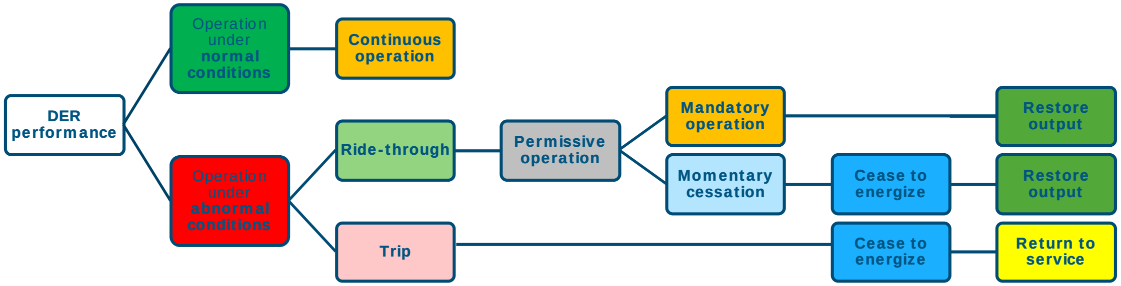
Structure of VRT – Cat. I and II



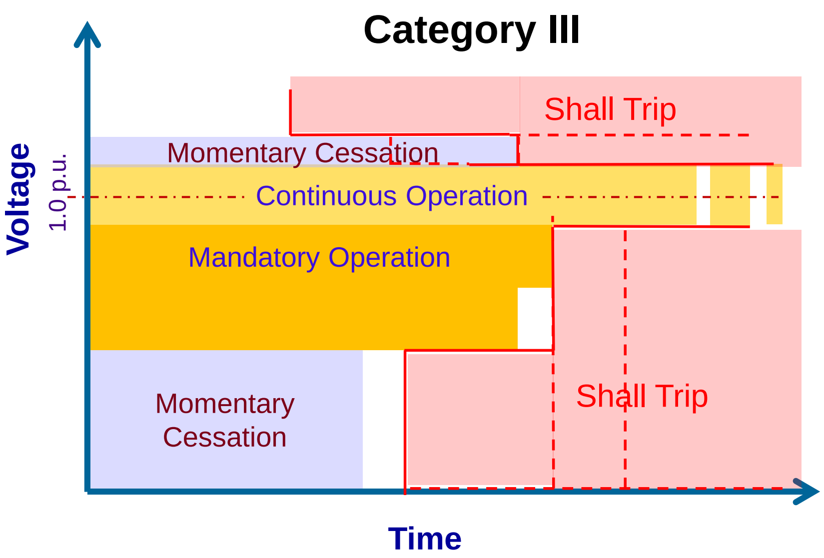


Dashed lines indicate permissible range of trip adjustment, solid lines indicate default settings.
Figure are approximate and solely for illustration, refer to IEEE P1547-2018 for actual requirements

Structure of VRT – Cat. III



- Category III introduces *momentary cessation* requirement
- Requires a relatively long zero voltage ride-through requirement (in *momentary cessation* mode)
- If feeder is faulted and tripped at the substation, then DER in momentary cessation will not energize the islanded feeder
  - Voltage will remain zero and DER will eventually trip off



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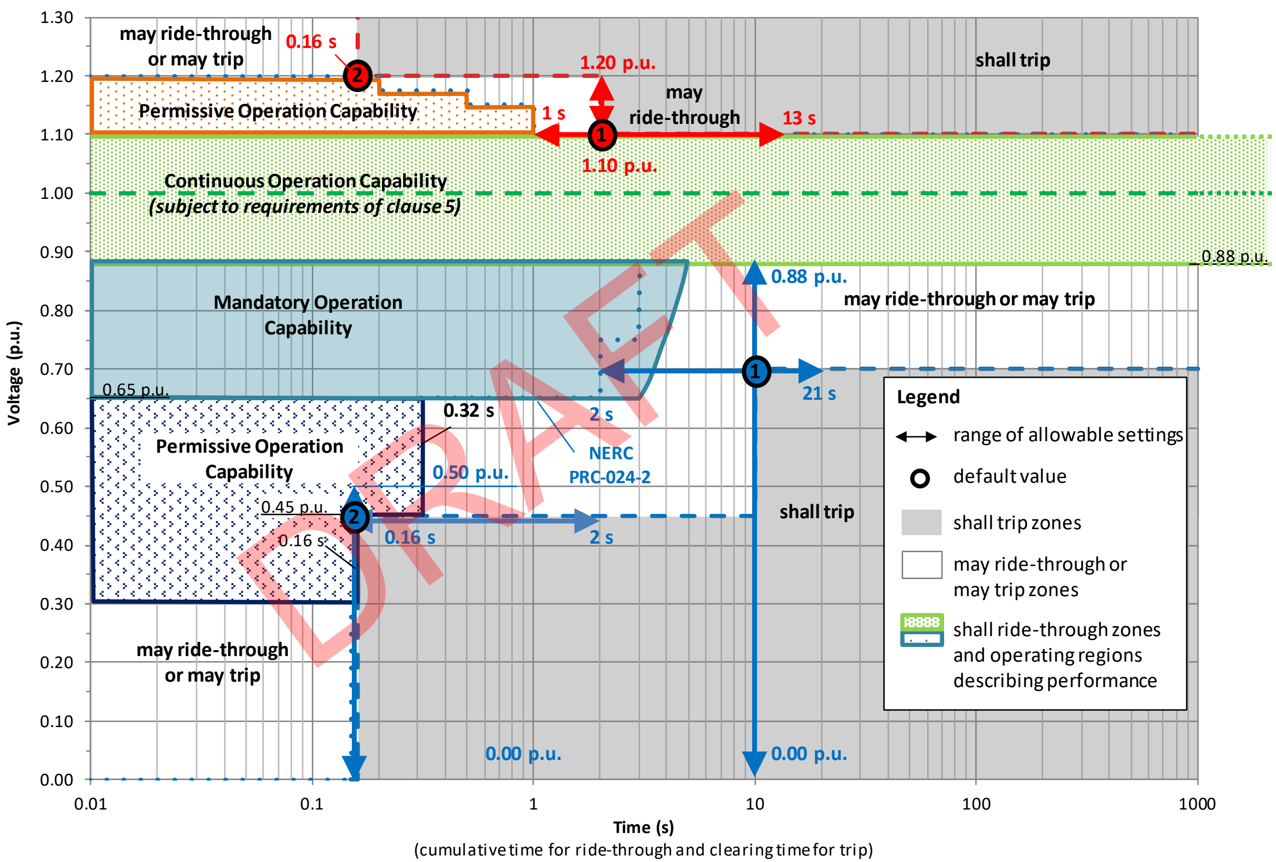
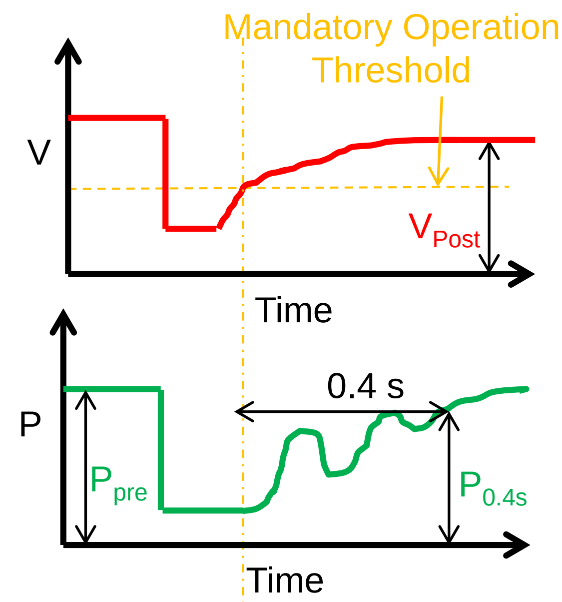
IEEE 1547-2018 Abnormal Performance Category II



- **mandatory operation:**
  - Continuance of active current and reactive current exchange
- **momentary cessation**:
  - Temporarily cease to energize the utility's distribution system
  - Capability of immediate restore output of operation
- **permissive operation**:
  - Either mandatory operation or momentary cessation.

Restore Output after Ride-through Performance

- DER must restore output to 80% of pre-disturbance active current within 0.4 s
- Time begins when applicable voltage returns to mandatory operation or continuous operation ranges
- Oscillatory power output is acceptable if positively damped (accommodates rotor angle swings of synchronous generators and imperfect control of inverters)
- If DER provides dynamic reactive power support (not mandatory), dynamic support must continue for 5 seconds before returning to pre-disturbance reactive control mode.

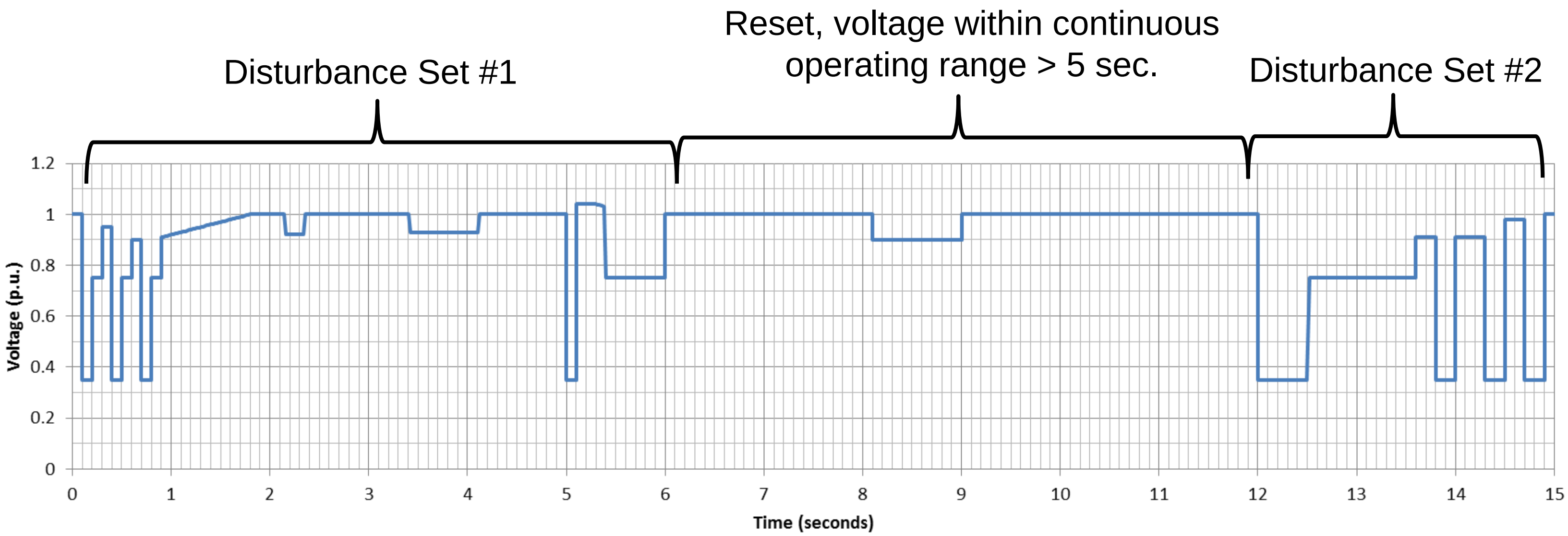


$P_{0.4s} \geq 0.8 \text{ x } P_{pre} \text{ x } V_{post}(\text{p.u.})$

Ride-through of recurring voltage disturbances

- IEEE P1547 mandates ride-through of multiple consecutive disturbances in order to accommodate:
  - Unsuccessful reclose attempts (transmission or other feeder)
  - Rapidly occurring fault events (e.g., during a severe storm)
  - Dynamic oscillations of bulk system causing voltage to swing in and out of normal range
- Ride-through of multiple events in a disturbance set are defined by cumulative undervoltage (or overvoltage) duration – number of events not limited
- Voltage within the continuous operating range for a prescribed period (5 s – 20 s, depending on category) resets cumulative timers and any further disturbance is a new disturbance set.
- Maximum number of sets = 2 to 3, depending on category
- Disturbance set count reset after a period of 20 to 60 minutes

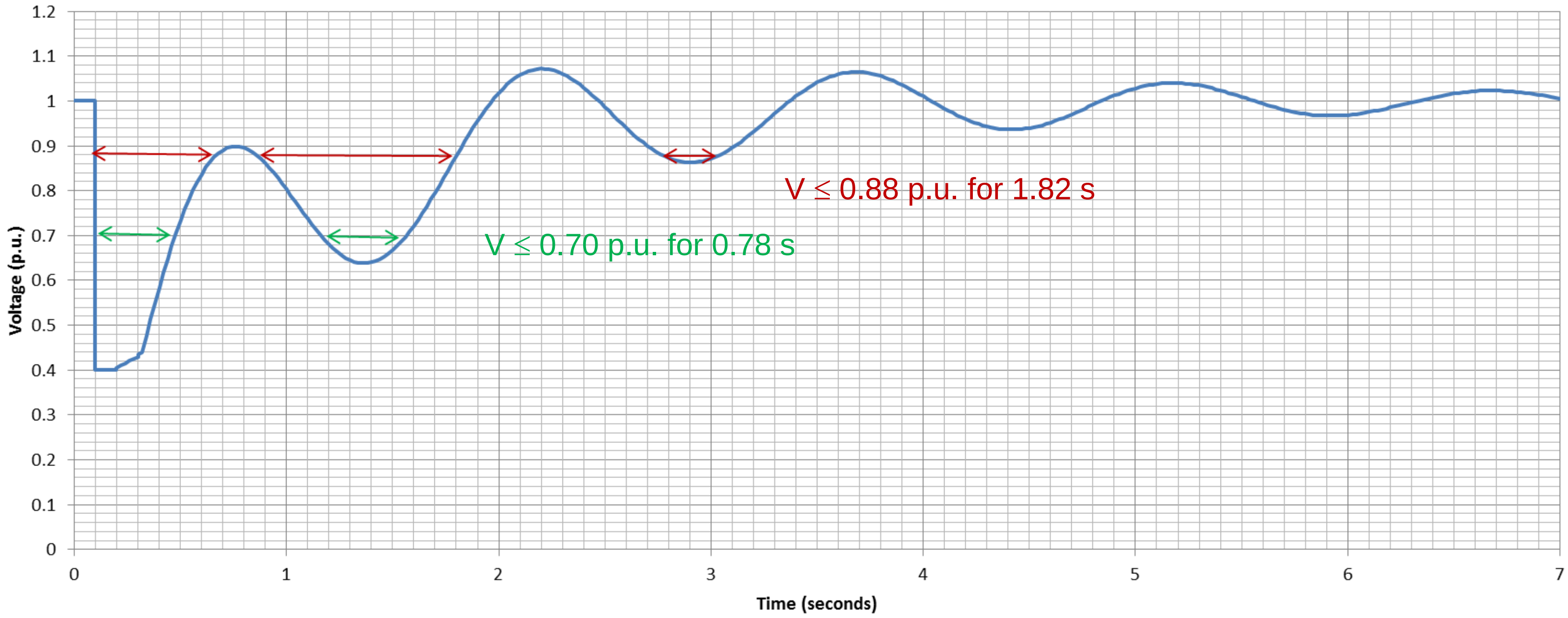
Consecutive disturbance rule example



Disturbance Set #1: V ≤ 0.75 p.u. for 1 s, V ≤ 0.35 p.u. for 0.4 s

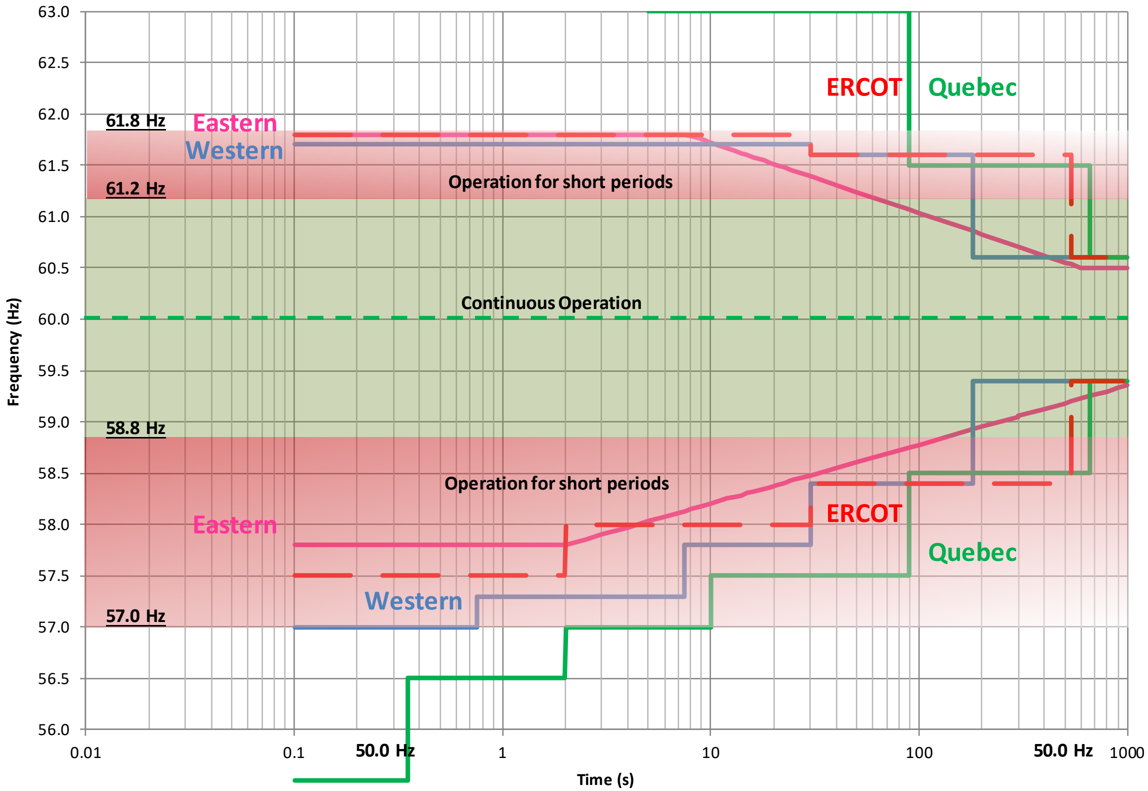
Disturbance Set #2: V ≤ 0.75 p.u. for 2.2 s, V ≤ 0.35 p.u. for 1.1 s

Bulk system post-fault dynamic swing example



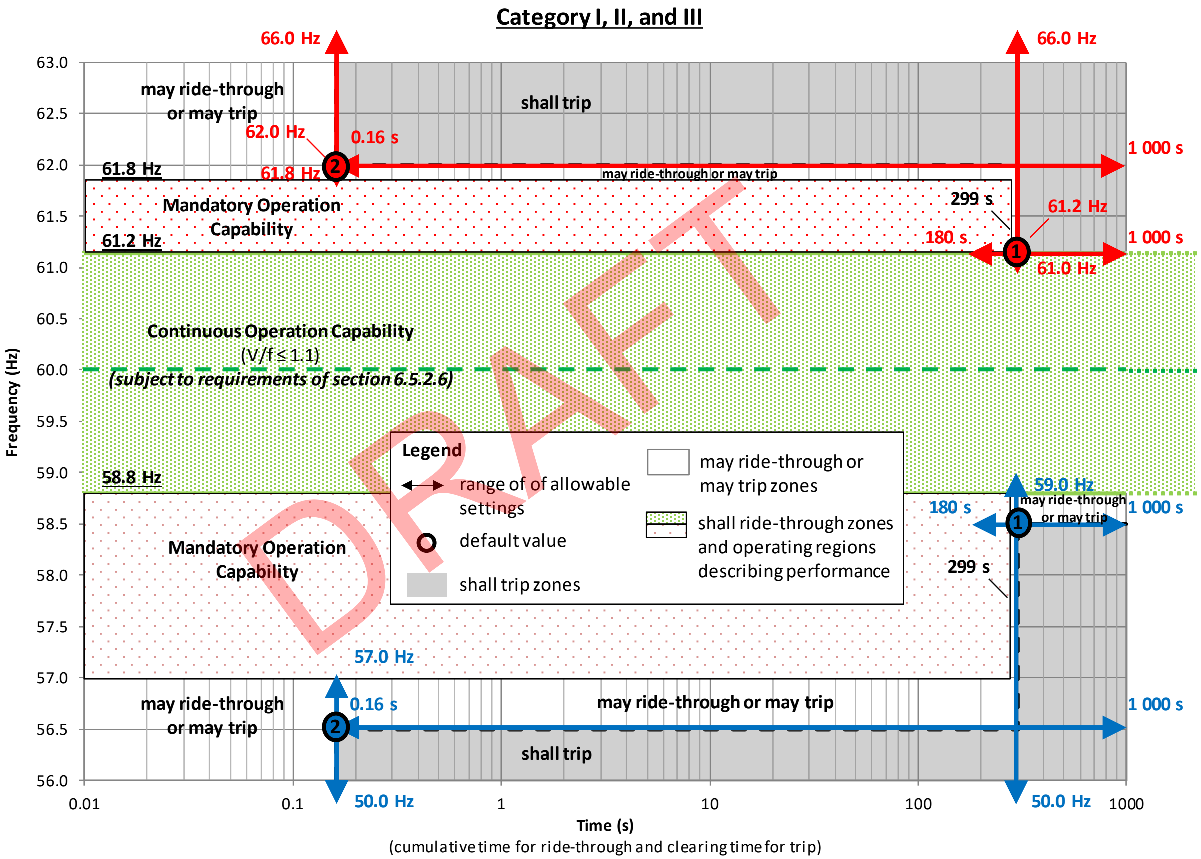
ELECTRIC POWER RESEARCH INSTITUTE

Comparison with IEEE Std C50.13 and NERC PRC-024-2



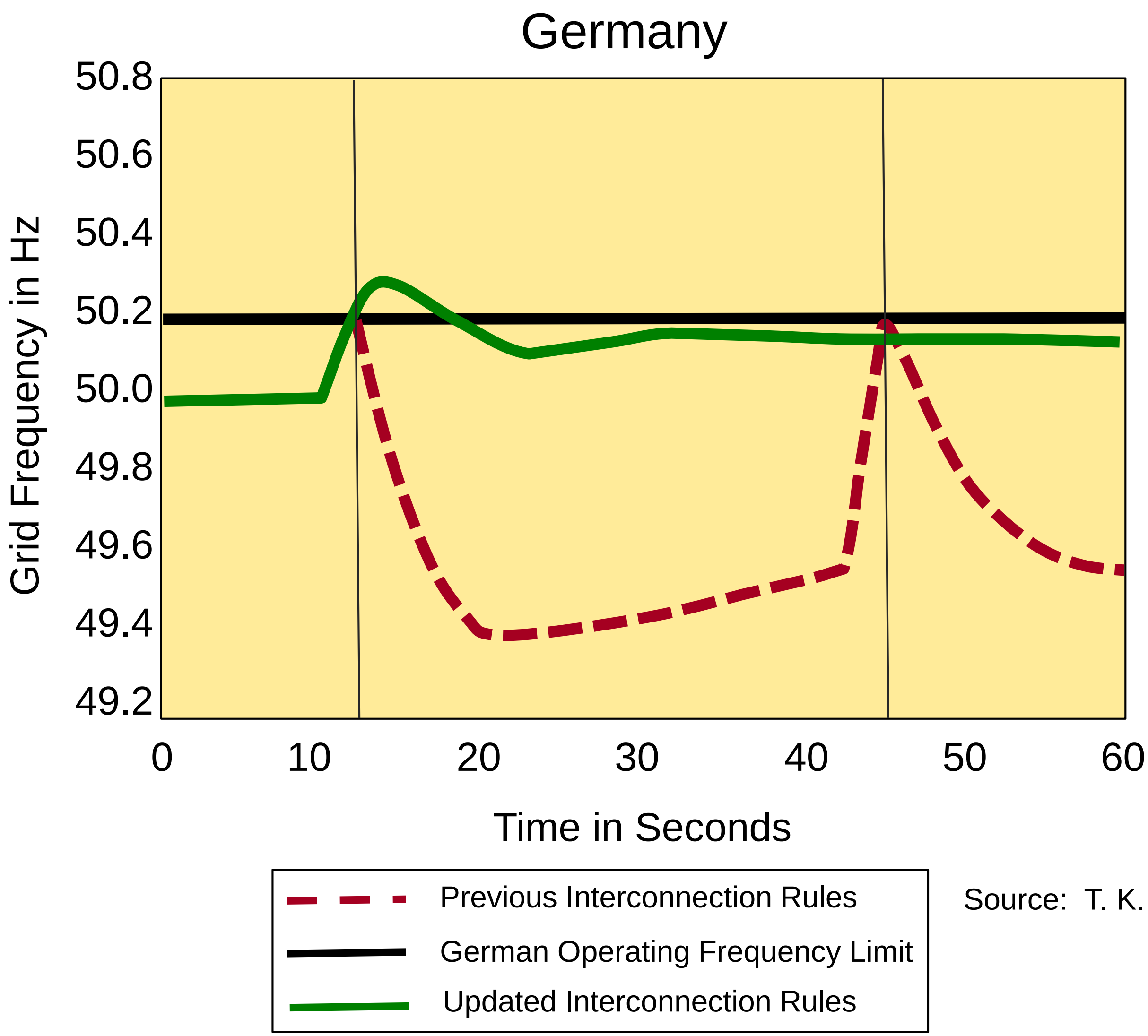
- Shaded areas indicate design specifications of IEEE Std C50.13 for synchronous generators ≥ 10 MVA
- Lines indicate frequency settings envelopes specified by NERC PRC-024-2

IEEE 1547-2018 Frequency Ride-Through and Trip



- **continuous operation:**
  - Exchange of current between the DER and an EPS within prescribed behavior while connected to the Area EPS and
  - while the *applicable voltage* and the system frequency is within specified parameters.
- **mandatory operation:**
  - Continuance of active current and reactive current exchange

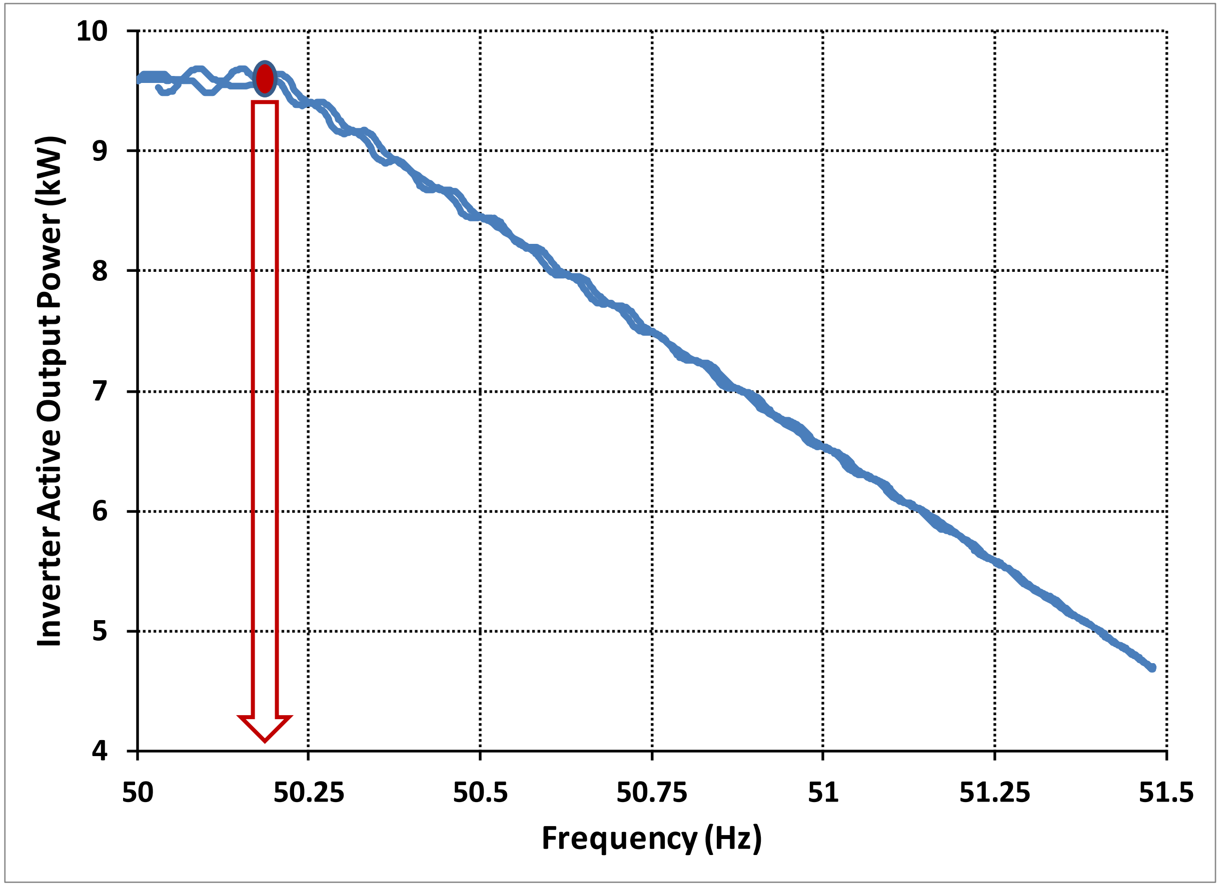
Risk of Frequency Instability



Source: T. K. Vrana (2011)

Frequency – Droop (Watt-Frequency)

"50.2 Hz" frequency trip setting retrofit in Germany!



Retrofitting

315,000 PV systems

Sized 10kW+

9 GW Nominal Power

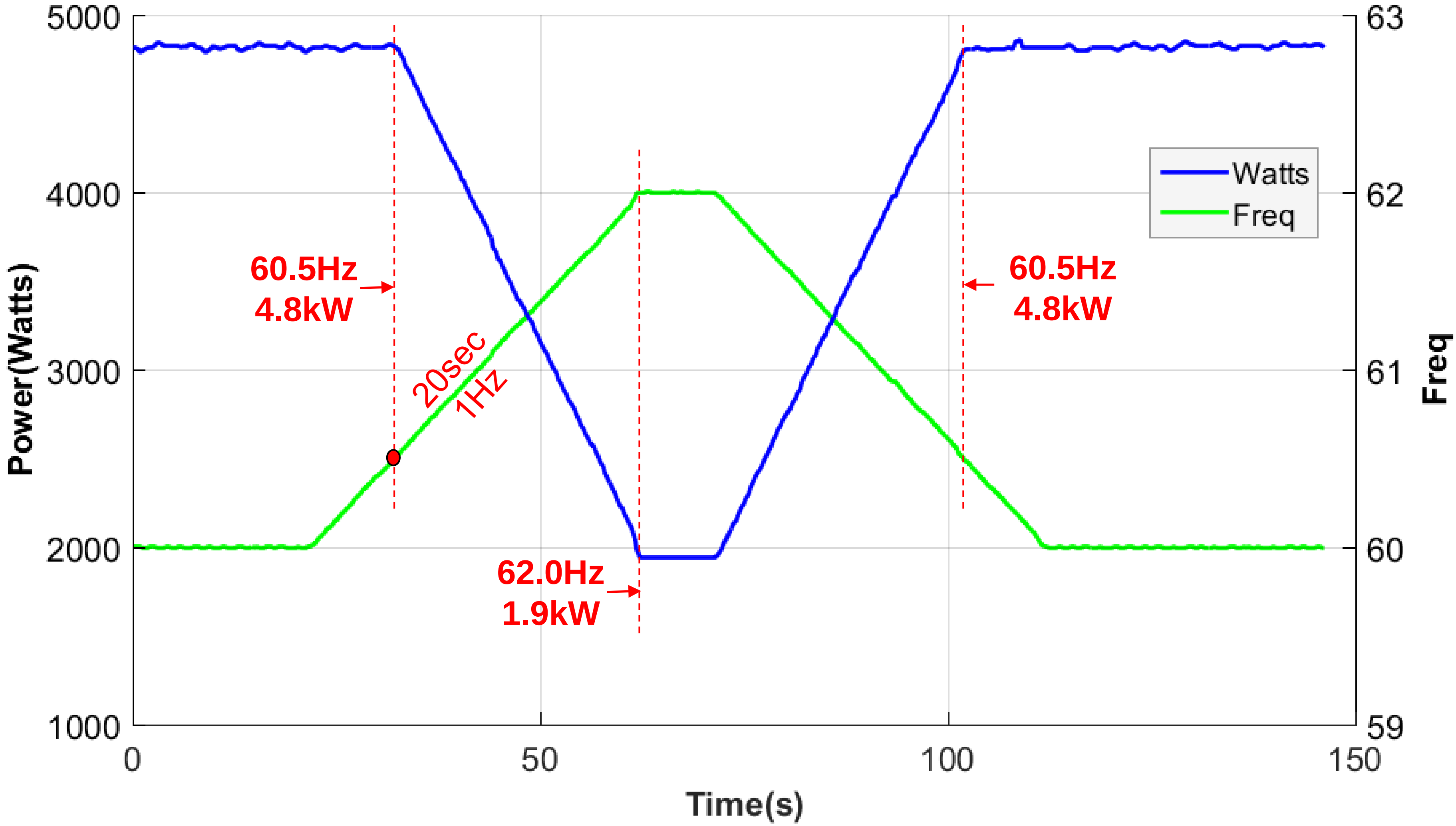
Over 3 – 4 years

Costing €65 – 175 Million

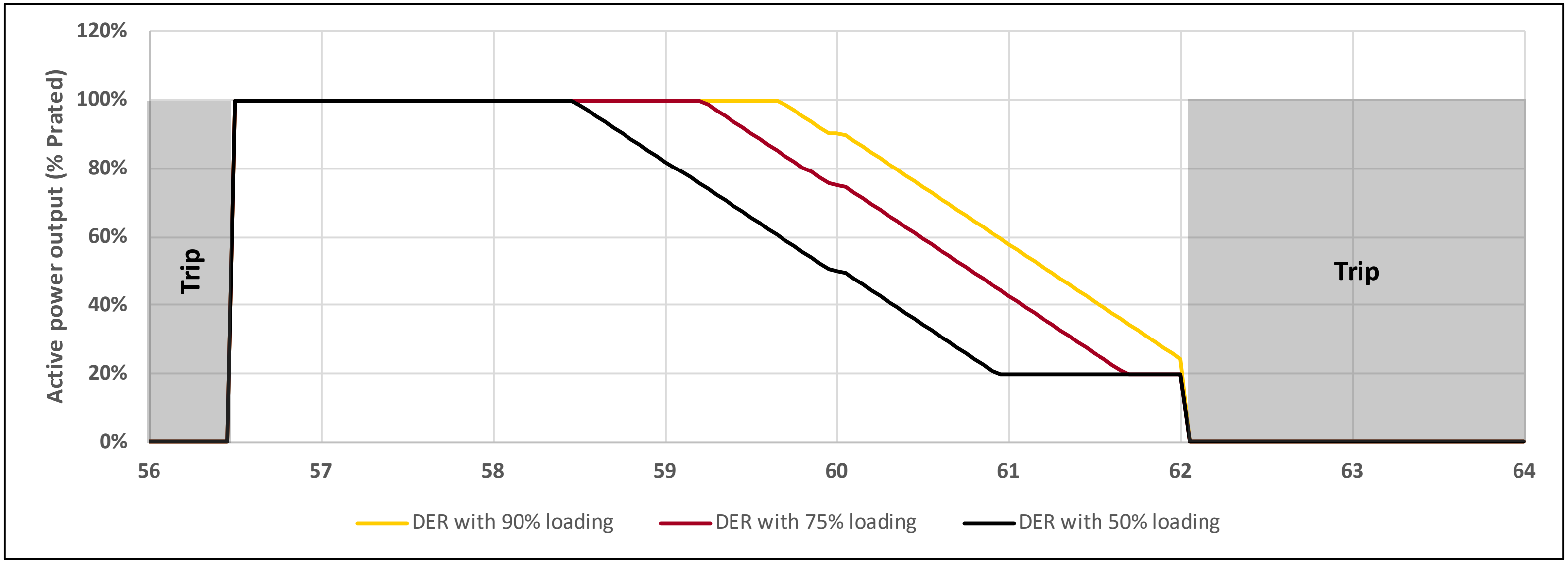
Source: ECOFYS

Frequency-Watt

Frequency sweep (60Hz → 62Hz → 60Hz)



Frequency – Droop (Watt-Frequency) in IEEE 1547 Revision



- DER response during low-frequency may be subject to *available active power* and the pre-disturbance power output level.

Frequency rate-of-change ride-through

- During severe grid disturbances, frequency can change rapidly
  - Rate-of-change of frequency (ROCOF) can be greater in low-inertia grids
  - Displacement of synchronous generators by inverter-coupled resources decreases inertia

- If frequency remains in the continuous operation or ride-through frequency range, DER shall not trip for ROCOF < criterion
  - Category I: ROCOF ≤ 0.5 Hz/s
  - Category II: ROCOF ≤ 2.0 Hz/s
  - Category III: ROCOF ≤ 3.0 Hz/s

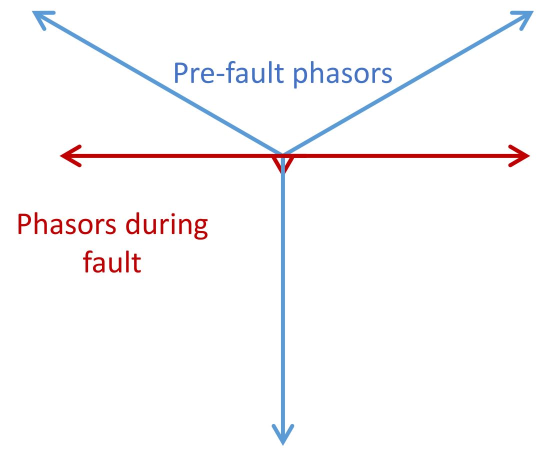
- Some DER anti-islanding schemes have been based on sensitive ROCOF detection

- ROCOF ride-through requirement places limit on such schemes
  - Manufacturers using this scheme may need to adopt alternative approaches

Phase jump

- A phase jump is theoretically an infinite frequency for an infinitesimal period
  - Without a phase-jump ride-through requirement, a phase jump is a loophole
- Positive sequence voltage phase angle jumps occur from:
  - Large abrupt load changes (load tripping)
  - Generator tripping
  - Change in impedance – line tripping
  - Faults – to a relatively small degree
- Individual phase voltage phase angle jumps are caused by unbalanced faults
- IEEE P1547 ride-through requirements:
  - Up to 20° positive-sequence voltage phase angle step
  - Up to 60° individual phase voltage phase angle step
  - Damped power oscillations or momentary cessation < 0.5 seconds allowed

Distribution voltages for transmission phase-to-phase fault



Together…Shaping the Future of Electricity

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