Multifunctional active front-end converter

Lecture 4 – Smart Inverters and Ancillary services

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May 2021

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(*TESLA – Power Engineering*)

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Active Front End Converter

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Timetable

Monday 03/05/21,	from 14:00 to 16:00	Lect. 1: Introduction and MatLab implementation
Tuesday 04/05/21,	from 14:00 to 16:00	Lect. 2: current controlled inverter and current control design
Wednesday 05/05/21,	from 14:00 to 16:00	Lect. 3: Multifunctionalities and Matlab implementation
Thursday 06/05/21,	from: 14:00 to 16:00	Lect. 4: Ancillary services and Matlab implementation

Teams link:

https://teams.microsoft.com/l/meetup-join/19%3ameeting_NWJlNTZjY2MtMDBlNi00NTE4LTg3NGEtZGJhYzIyNTg5Nzcx%40thread.v2/0?context=%7b%22Tid%22%3a%2264126139-4352-4cd7-b1fb-2a971c6f69a6%22%2c%22Oid%22%3a%226c92d539-4c94-4e3a-bc6c-a1422cc5962c%22%7d

References:

S. Buso, P. Mattavelli, “Digital Control in Power Electronics”, Morgan & Claypool, 2nd edition, 2015. (Lecture 2);

Marafao, F. P., Brandao, D. I., Costabeber, A., Paredes, H. K. M., “Multi-task control strategy for grid-tied inverters based on conservative power theory," IET Renewable Power Generation, v. 9, n. 2, 2015. (Lecture 3).

IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003) , vol., no., pp.1-138, 6 April 2018. (Lecture 4);

Common functions for smart inverters, 4th edition, 3002008217, Dec. 2016. (Lecture 4);

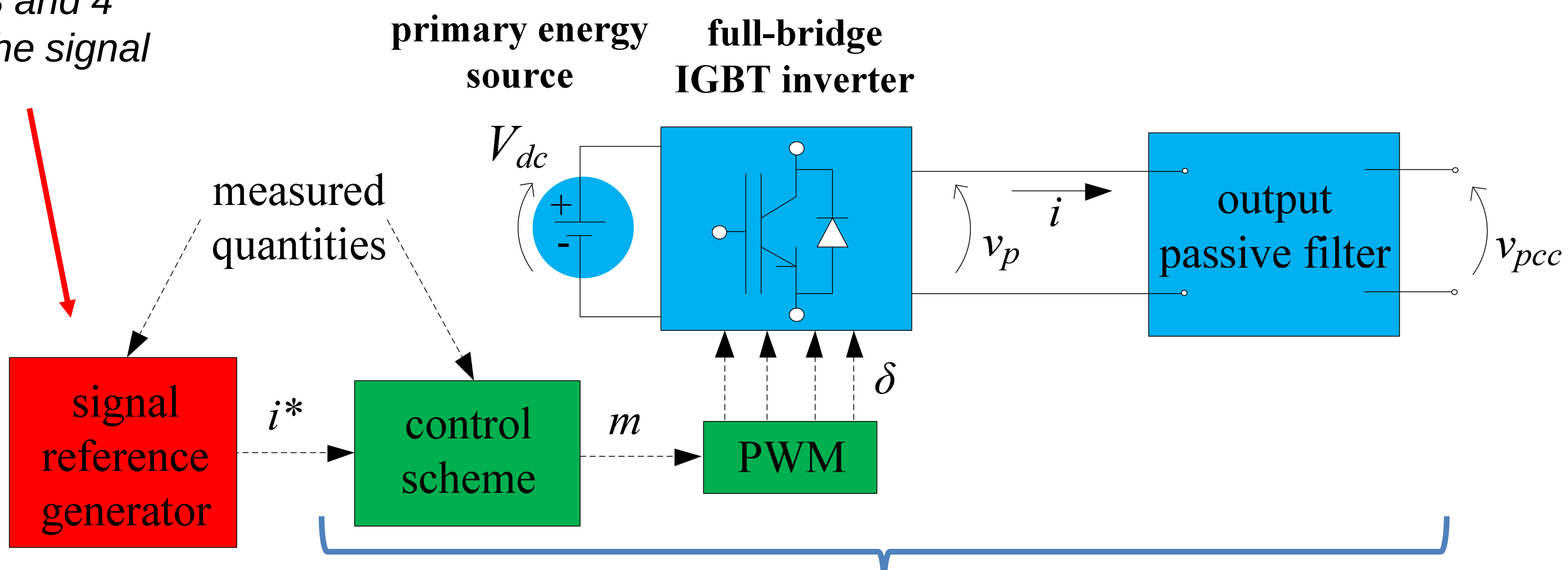
Active front end converter

Structure

- An active front end (AFE) converter comprises of: 1) **power electronics and instrumentation**, 2) **control scheme and modulator**, and 3) **generator of signal references**.

- The most applied modulators for AFE converter are those based on pulse-width modulation (PWM), in which the controlled **converter can synthetize any voltage waveform tracking a signal reference** (i.e., one period average of v_p is equal to modulation signal, m).

Lectures 3 and 4 focus on the signal reference generator



Current controlled mode converter

PHONES

Cell phone

Allows one to only:

- make a phone calls

Smart phone

Allows one to:

- access internet;
- listen to music;
- watch movies;
- read books;
- play games;
- take pictures;
- record videos;
- send e-mails;
- etc.

In addition to:

- make a phone calls.

INVERTERS

Conventional inverter

Is used to only:

- generates active power with constant power factor, *typically unity power factor*.

First generation of grid-tied inverters

Grid-support functions (*second generation of grid-tied inverters*)

Microgrid functions (*third generation of grid-tied inverters*)

Smart inverter

Is used to:

- generates active power;
- modulates active power;
- exchanges reactive power (inductive / capacitive);
- compensates harmonics (*in future*)

Performs in response to system conditions:

- **autonomously** (response to local voltage/frequency deviations);
- **remotely** (per communicated commands).

INVERTERS

Motivations:

- Increase the *hosting capacity* of the power system (i.e., increase the amount of distributed generation);
- Enhance the system power quality;
- Fully exploit the distributed inverters capability.

Grid-support functions (*second generation of grid-tied inverters*)

Microgrid functions (*third generation of grid-tied inverters*)

Smart inverter

Is used to:

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- **autonomously** (response to local voltage/frequency deviations);

- **remotely** (per communicated commands).

Autonomous ancillary services:

Not requiring communication

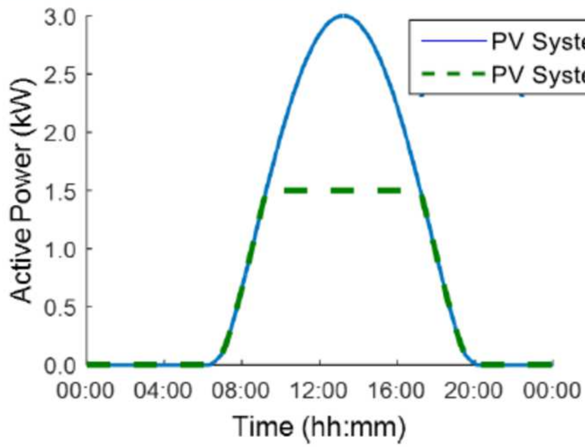
- Limit DER power output function
- Fixed power factor (non-unity PF)
- Volt/VAR function
- Volt/Watt function
- Volt/Freq function
- Low/high voltage ride through
- Low/high frequency ride through
- Peak power limiting
- Dynamic reactive current support
- Energy storage charge/discharge management function
- ***Electrical disturbances compensation (reactive, unbalance and harmonic)***

[1] Common functions for smart inverters, 4^{th} edition, 3002008217, Dec. 2016.

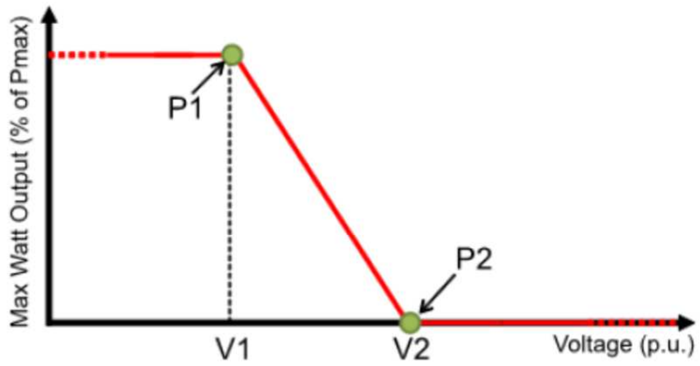
Autonomous ancillary services:

These curves are implemented into the signal reference generator block

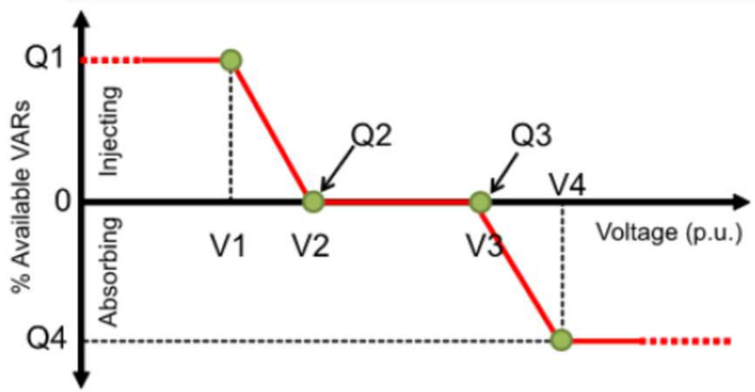
1. Active Power Limit Function



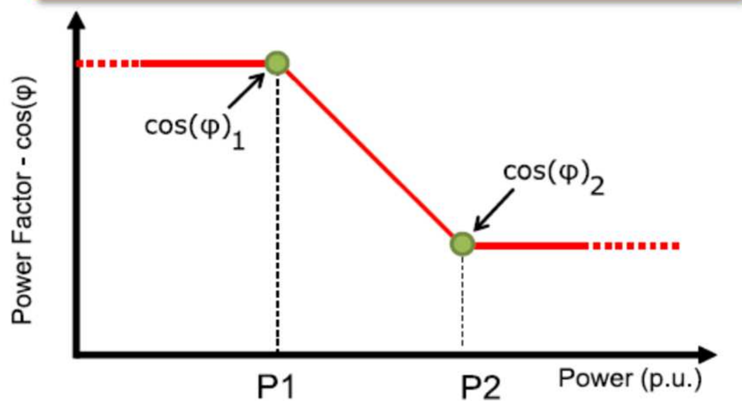
2. Volt-Watt Control Function



3. Volt-var Control Function



4. Watt-PF Control Function



Ancillary Services

Connect/disconnect function

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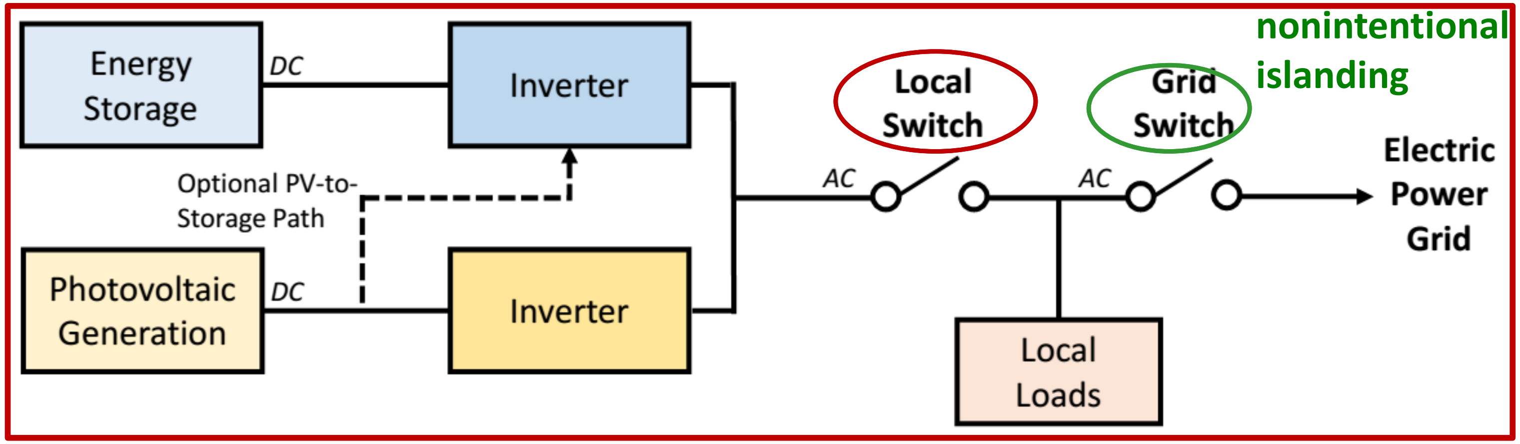
Provide a flexible mechanism to disconnect inverters in case of: emergency reduction of DGs, malfunctioning of DERs, and grid maintenance



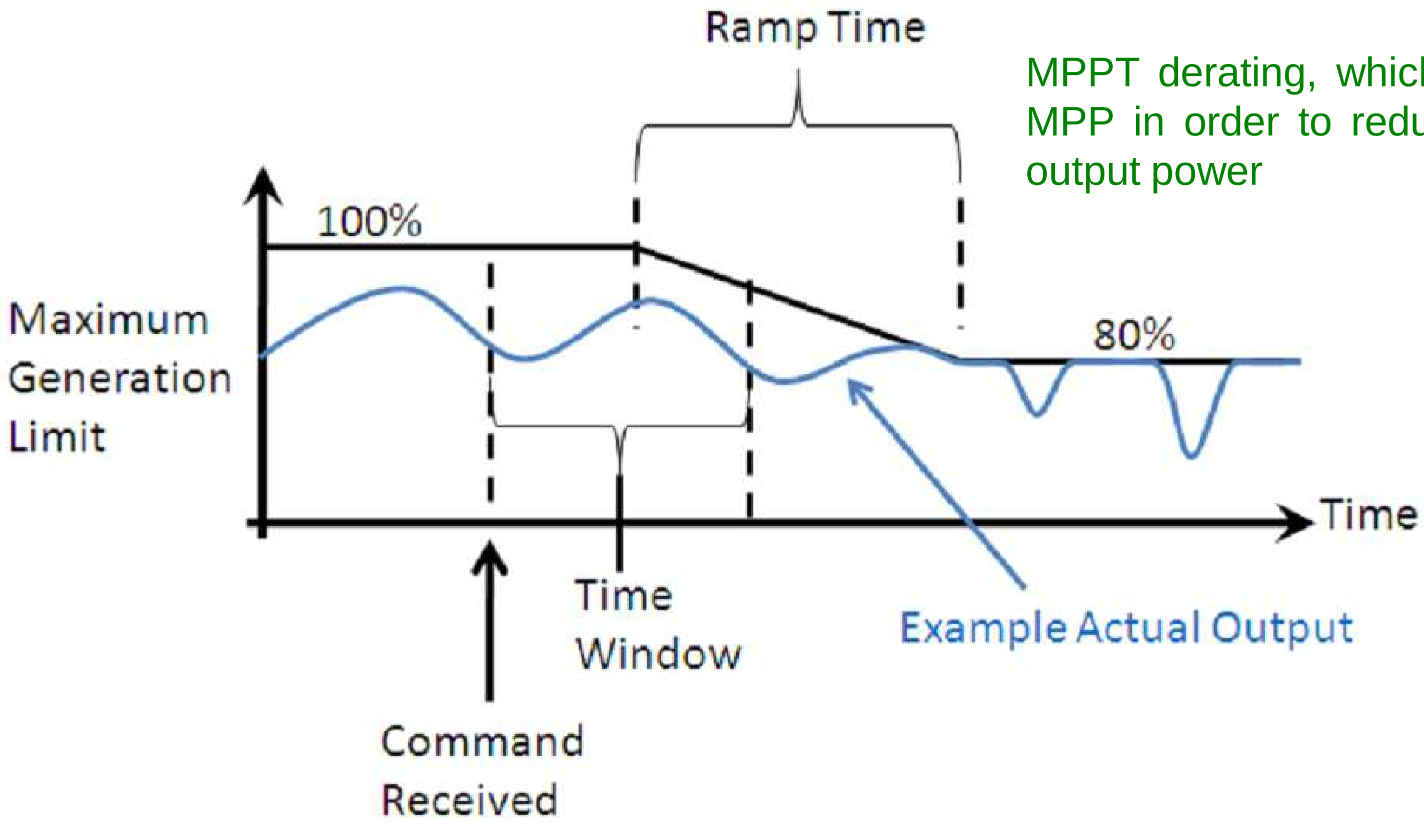
State of the Virtual Disconnect Parameter	State of the Physical Disconnect Parameter	Action from DER
Connect	Connect	Connect to the grid and energize.
Connect	Disconnect	Perform a physical disconnect but may remain energized and provide active and reactive power to devices on the same size of the disconnect switch as the inverter such as in an islanding scenario.
Disconnect	Connect	Perform a virtual disconnect but may remain galvanically connected to the grid.
Disconnect	Disconnect	Set both active and reactive power to zero but also operate disconnect switch to provide galvanic isolation.

Ancillary Services

Limit DER power output function

Provide a flexible mechanism through which the output power of DERs may be self-limited because: localized overvoltage condition, prevent overloading of transformer, feeder overvoltage condition

MPPT derating, which is detuning the MPP in order to reduce the inverter´s output power

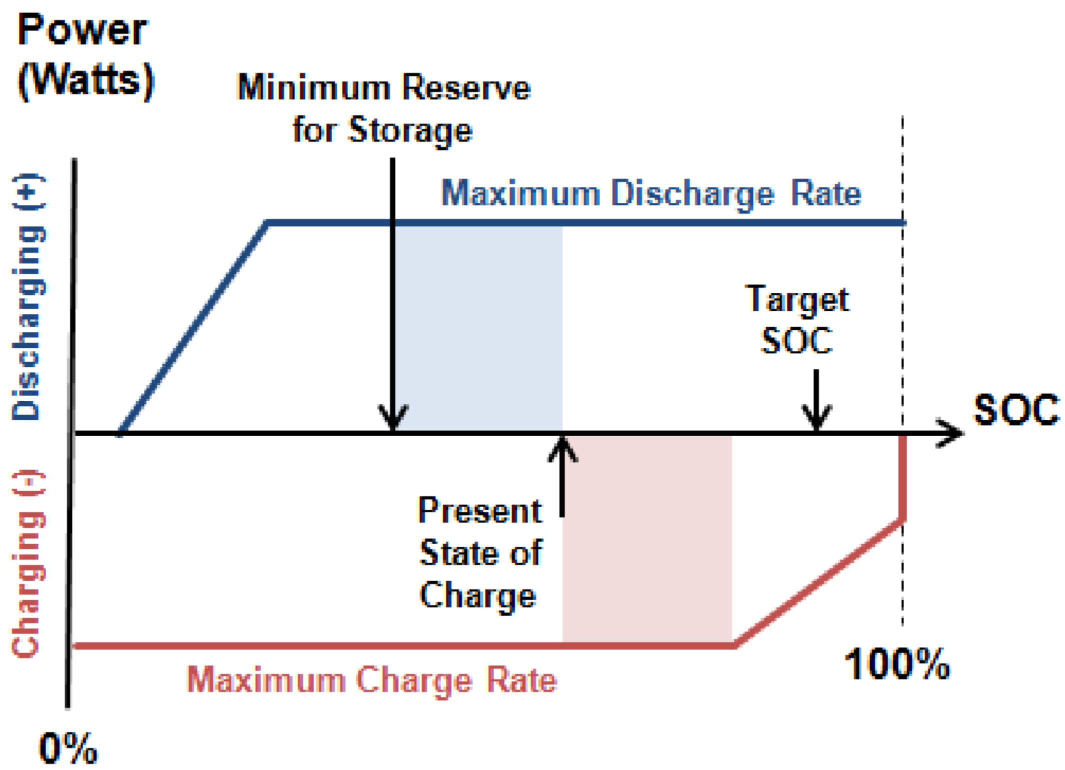


Ancillary Services

Energy storage charge/discharge management function

They are divided into: 1) direct control; 2) price-based control; and 3) coordinated control.

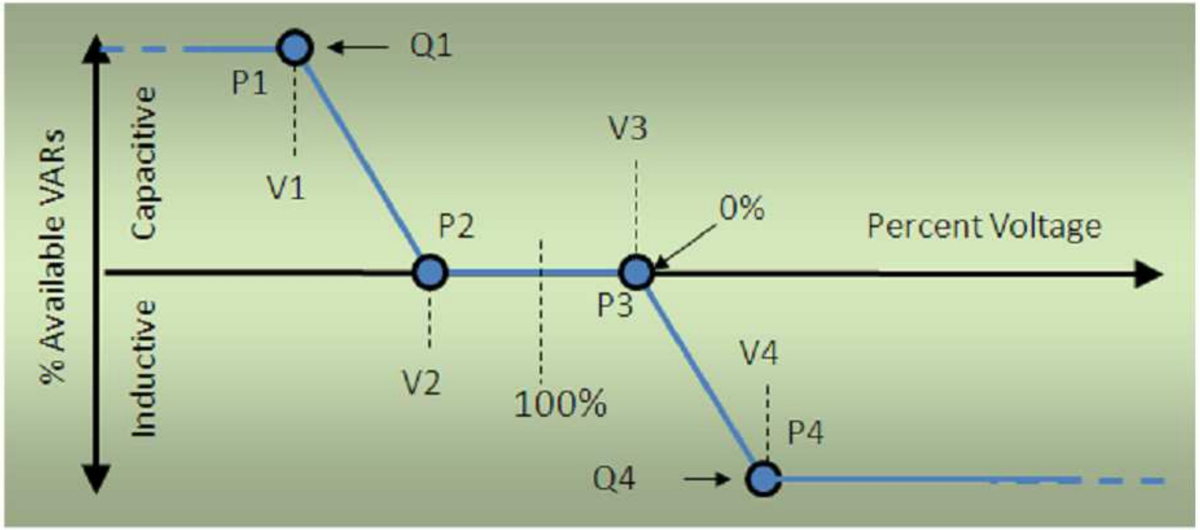
Provide a flexible mechanism to set the maximum power rate that storage system can charge or discharge, minimum state-of-charge (SOC), etc..



Ancillary Services

Volt/VAR function

It intends to provide a mechanism through which DERs may be configured to manage its own reactive power in response to local voltage level



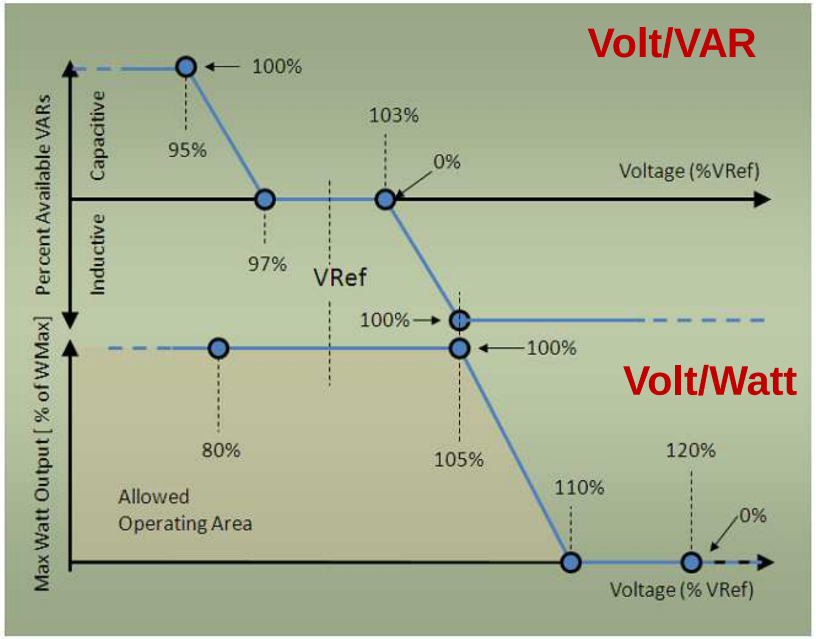
- Sometimes manufactures consider *limits on VARs that are smaller than VA*;
- **VARs precedence** means that inverter *will sacrifice* watts to provide the requested VARs if its limit is exceeded;
- **Watts precedence** means that inverter *will not sacrifice* watts to provide the requested VARs if its limit is exceeded.

The Volt/Watt function follows the same concept by acting on the active power in response to local voltage level.

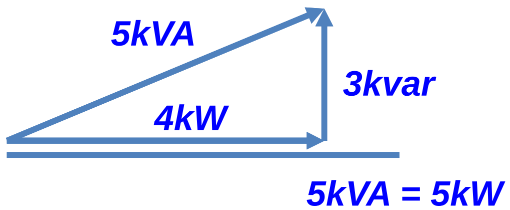
Ancillary Services

Volt/VAR and Volt/Watt function

Combining the Volt/VAR with the Volt/Watt function

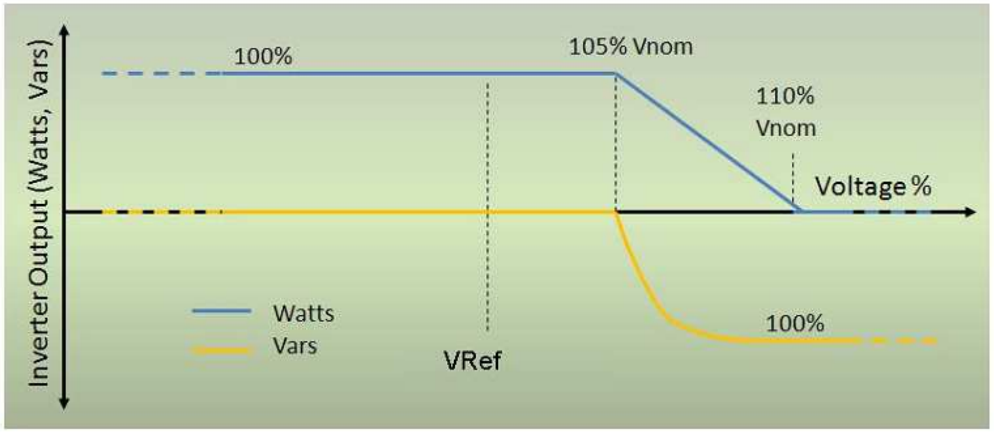


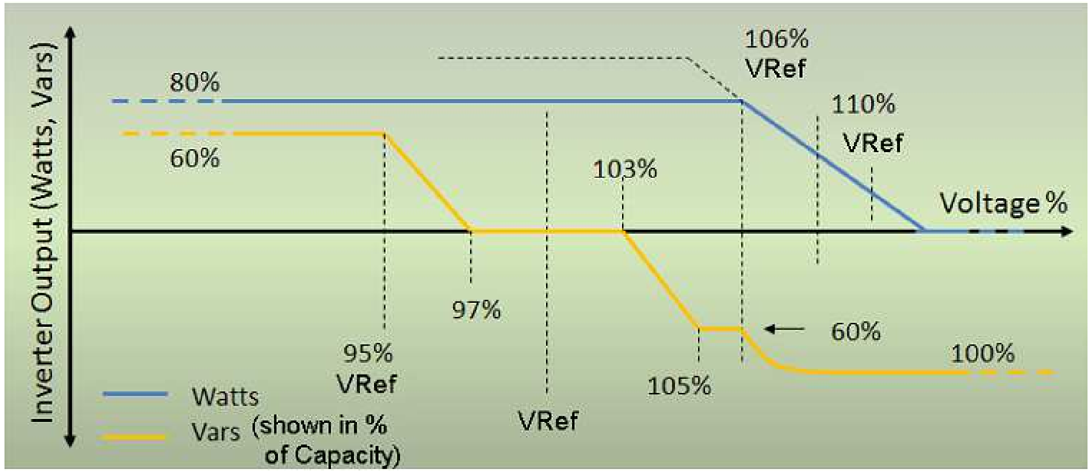
Watts precedence



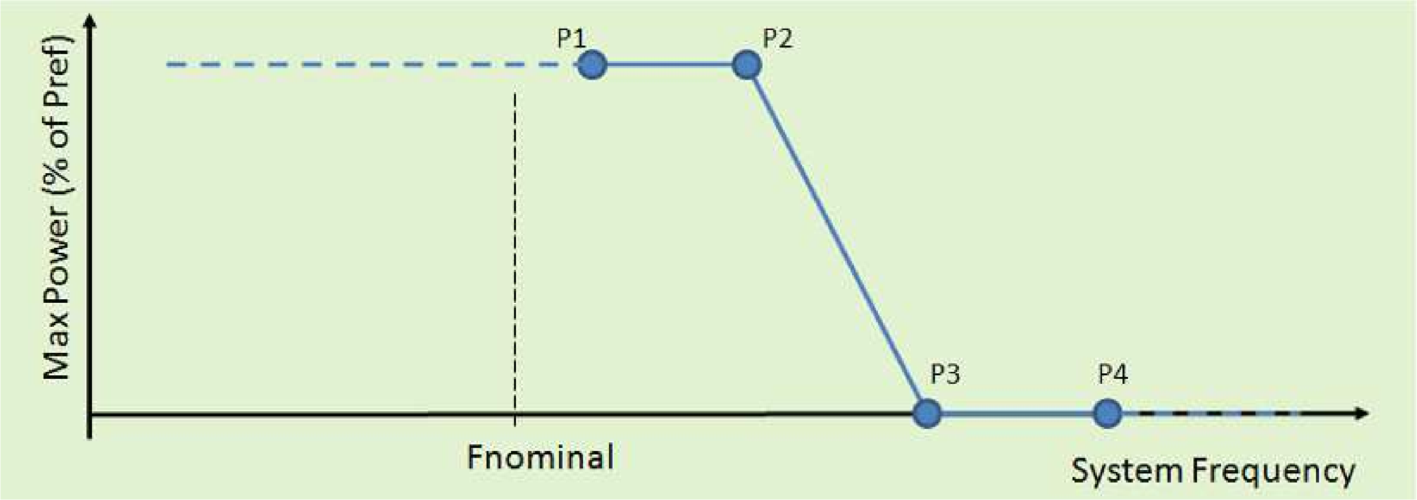
PV panel output at 100%

PV panel output at 80%

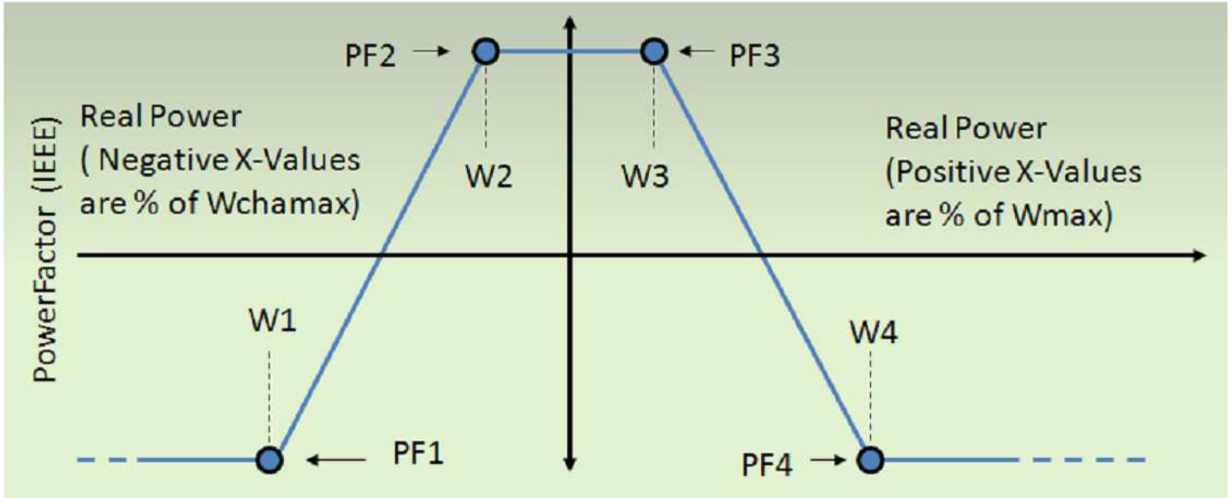




Frequency-Watt function



Watt-Power factor function



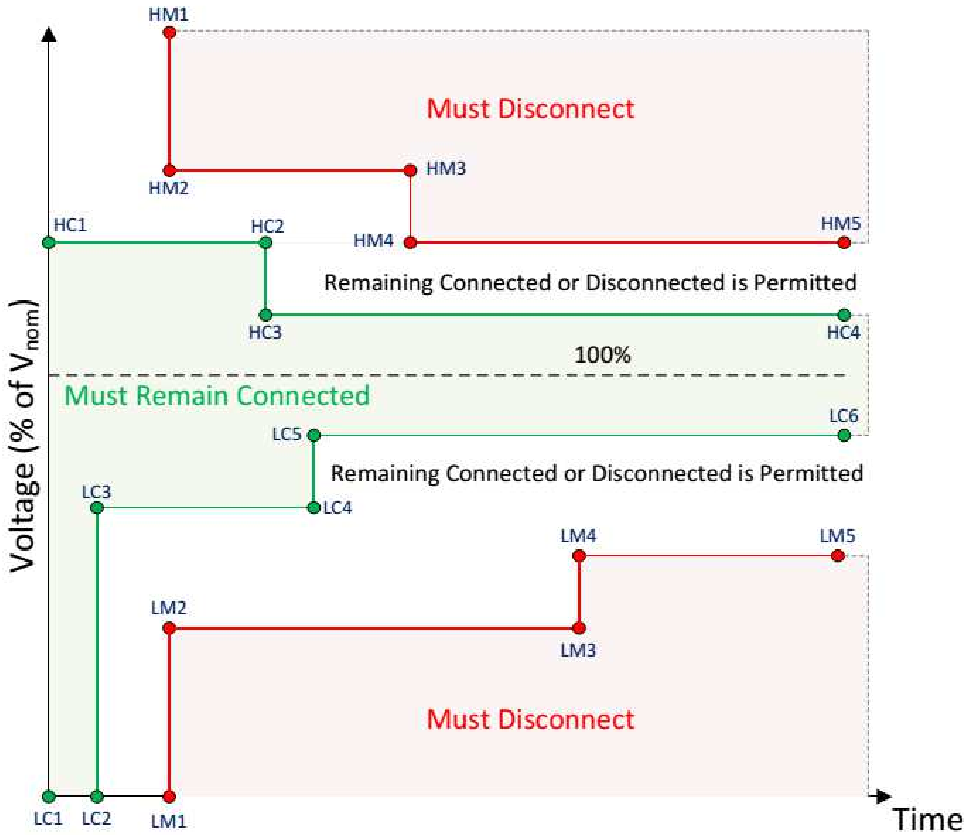
Ancillary Services

Low/high voltage/frequency ride through

Refers only to connect/disconnect behavior of the DERs under voltage disturbances

- Fast disconnection during voltage disturbances may not be desirable, because it may lead to power outages;
- Defining dynamic connect/disconnect behavior may be beneficial under islanded operation, or in weak grids.

Typical function in which the voltage and time coordinates for each point are provided by the system operator or utility based on the grid codes and interconnection standards



Ancillary Services

Low voltage ride through with reactive power injection

VAR support during fault ride through is possible associating with volt-VAR function or dynamic reactive current support.

VARs precedence

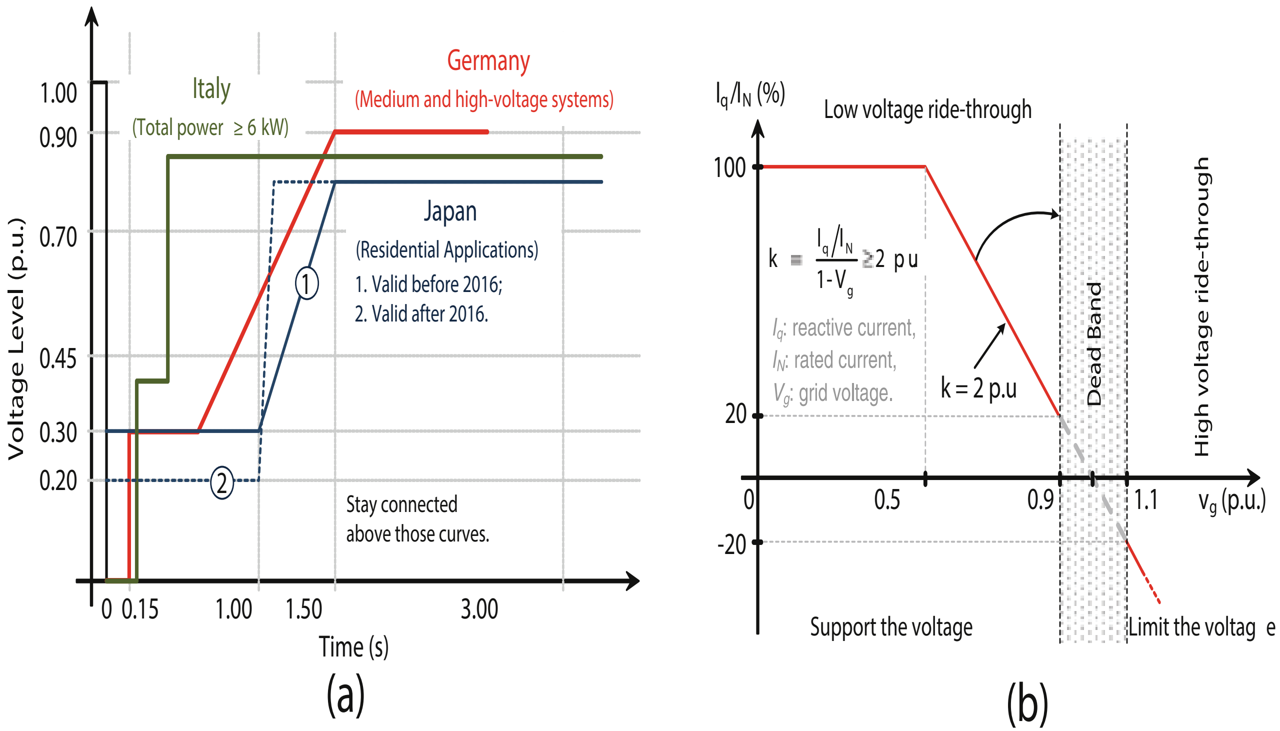


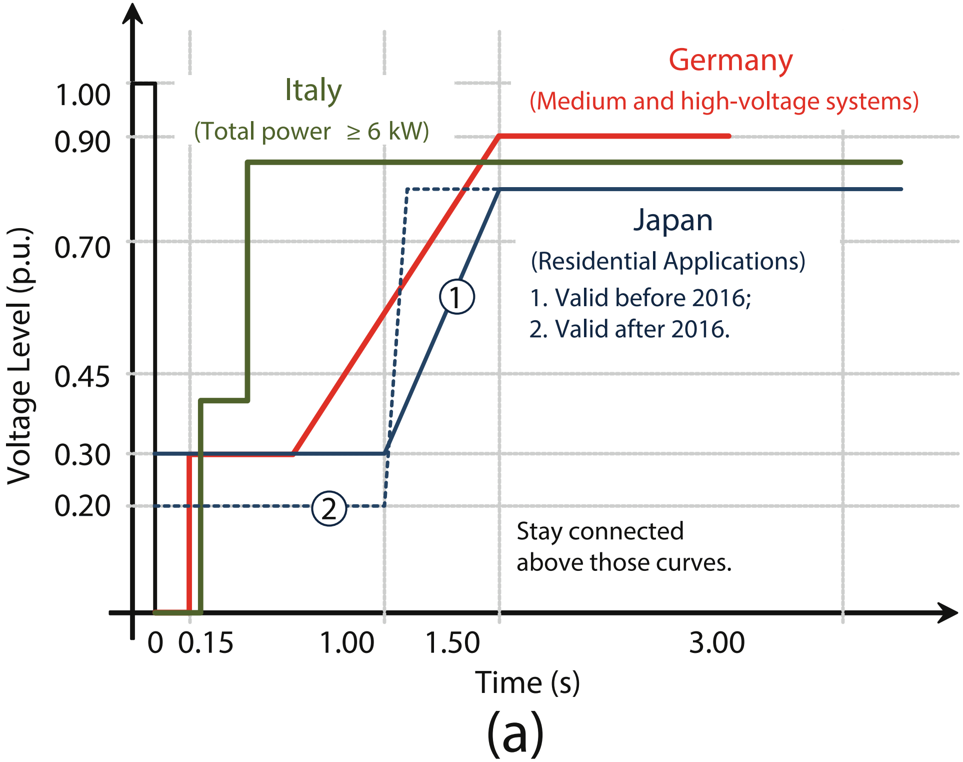
Fig. 2 ***a*** Low voltage ride-through requirements in different counties and ***b*** reactive current injection requirements during low voltage ride-through defined in E.ON grid code for medium and high voltage systems .

Reactive power injection

Other grid codes with LVRT and concomitantly reactive power injection

In Germany, medium and high voltage systems must have LVRT capability with reactive power injection.

VARs precedence



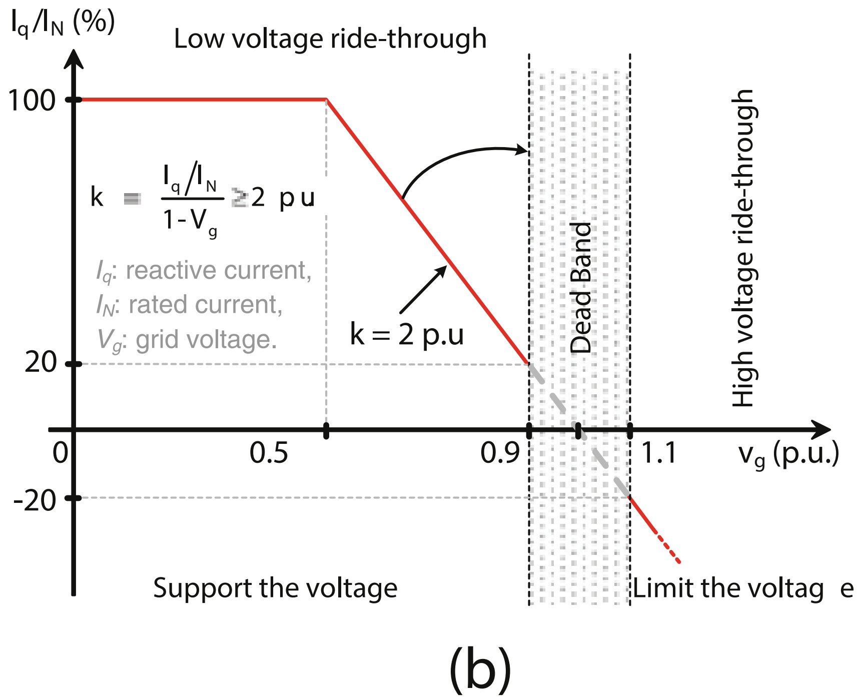


Fig. 2 ***a*** Low voltage ride-through requirements in different counties and ***b*** reactive current injection requirements during low voltage ride-through defined in E.ON grid code for medium and high voltage systems .

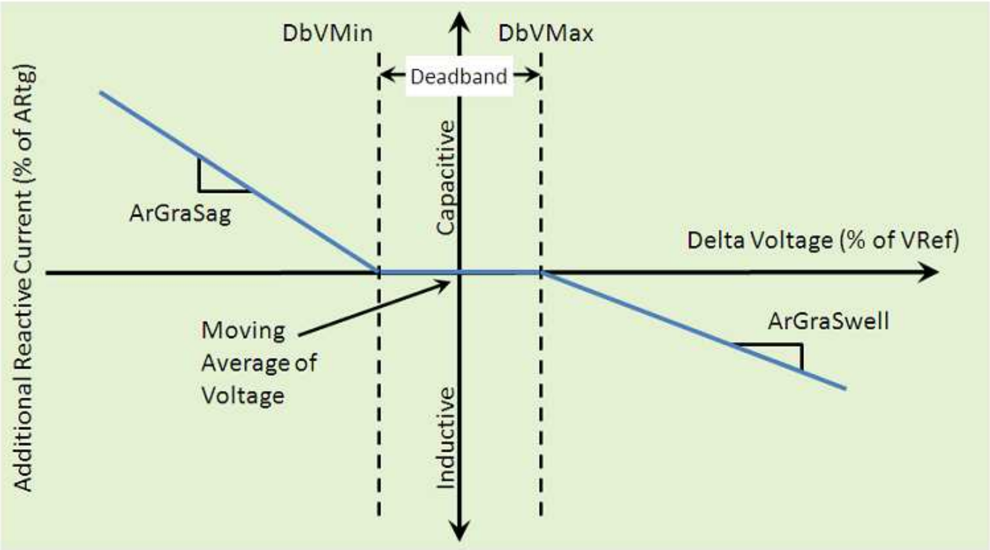
Ancillary Services

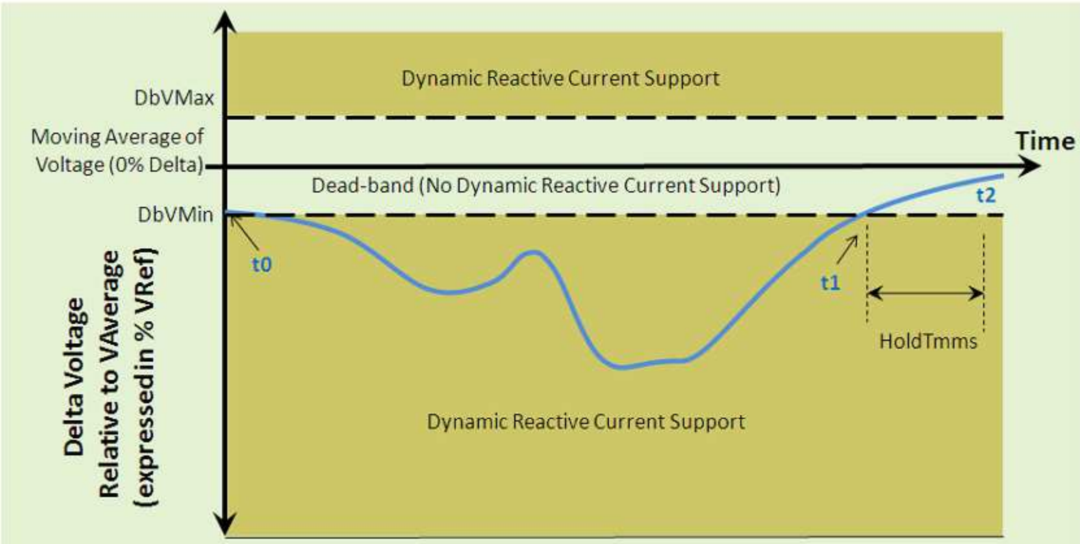
Dynamic reactive current support

Provides reactive current in response to dynamic variations on voltage

- Exchange appropriate reactive current with the grid in response to **voltage deviation** instead of **absolute value of voltage**;
- Such function creates an effect that is in same ways similar to <u>inertia</u>;
- May improve <u>flicker</u> problems.

The dynamic real-power support and dynamic volt-Watt functions follow the same concept by acting on the active power in response to dynamic voltage level.

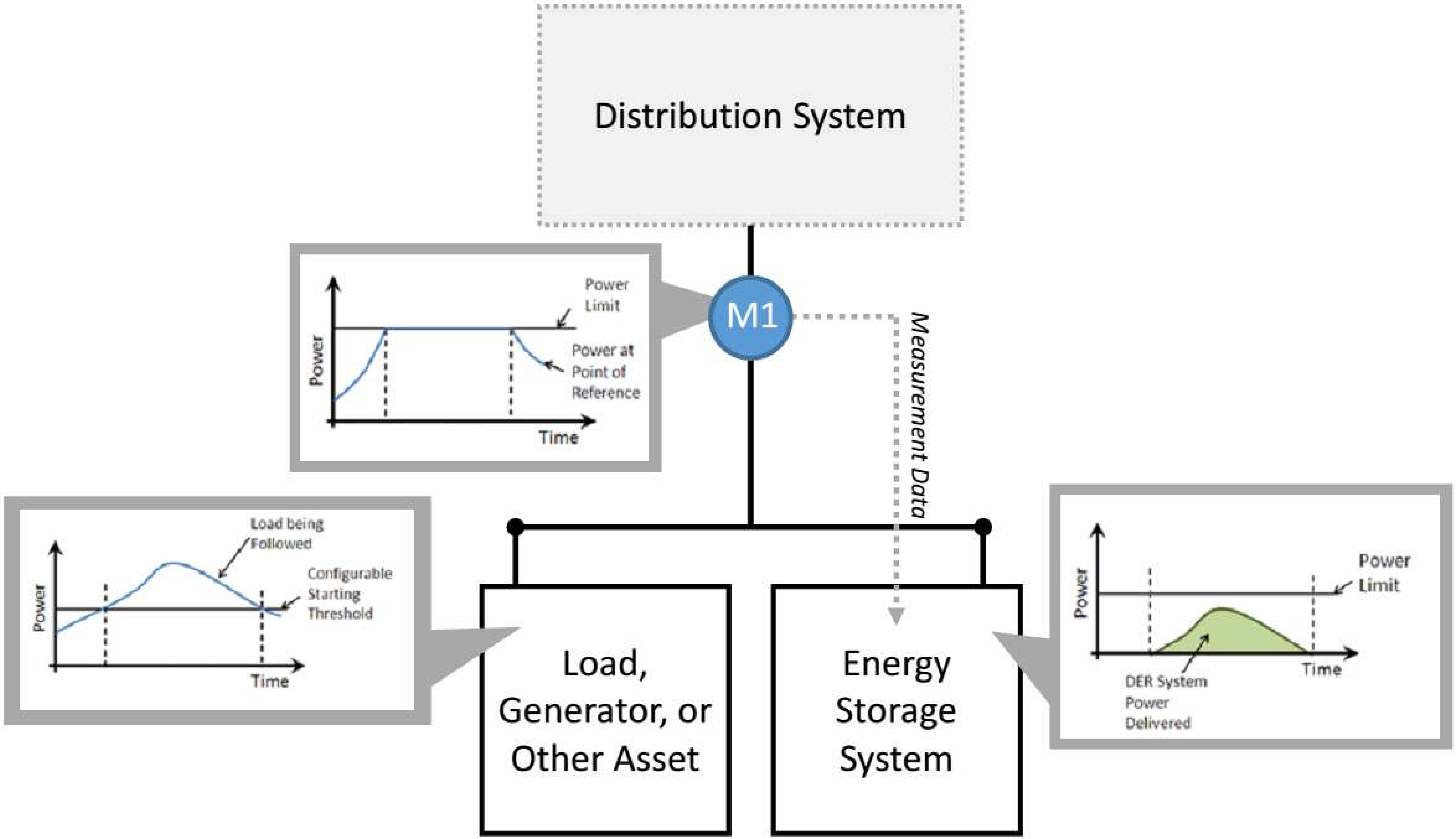




Ancillary Services

Peak power limiting

This function involves the variable dispatch of power/energy in DERs

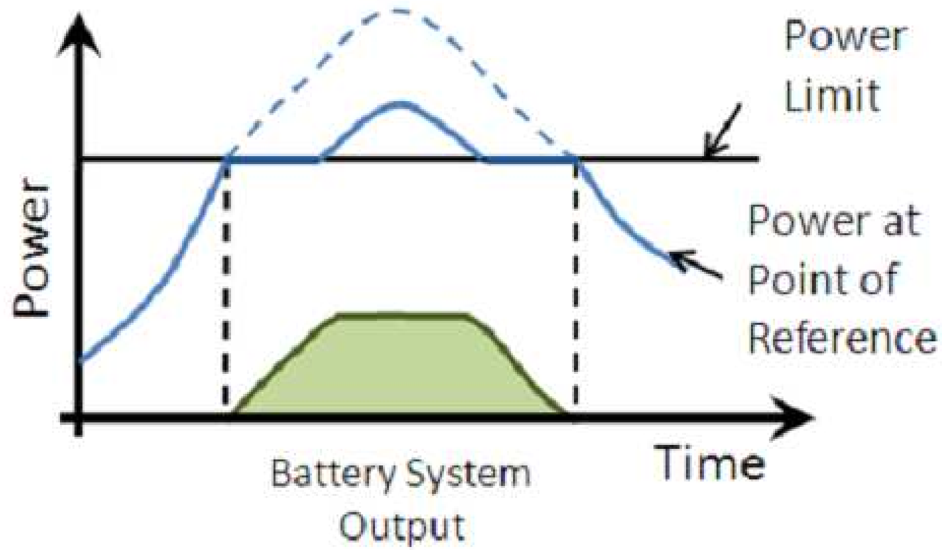


Ancillary Services

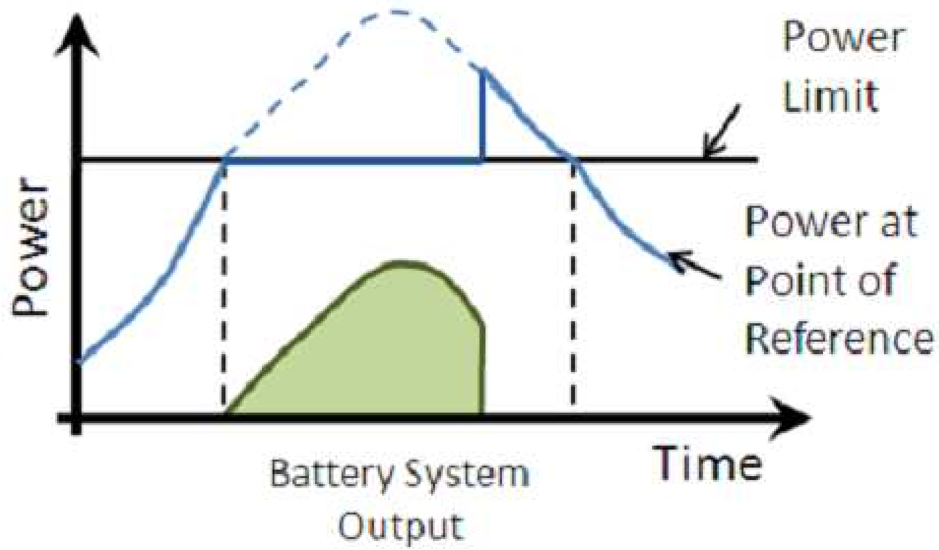
Peak power limiting

As with all functions, DER will operate within self-imposed limits and will protect their own components. These limits vary depending on many factors (e.g. state of maintenance, damage, temperature)

Watt limit



Energy storage capacity limit

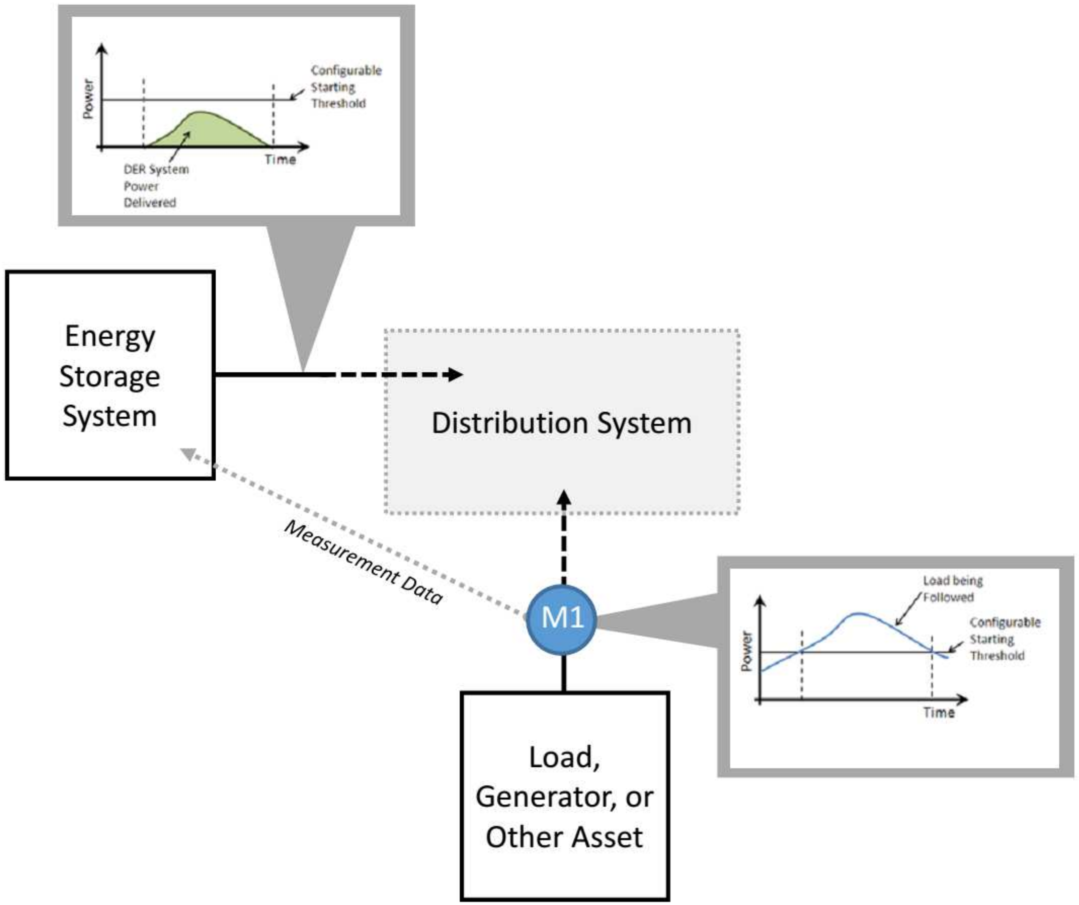


Ancillary Services

load and generation following function

Peak power limiting ≠ load and generation following function

- Load following does not include the effect of the inverter at the metering location;
- Peak power limiting does include the effect of the inverter at the metering location.



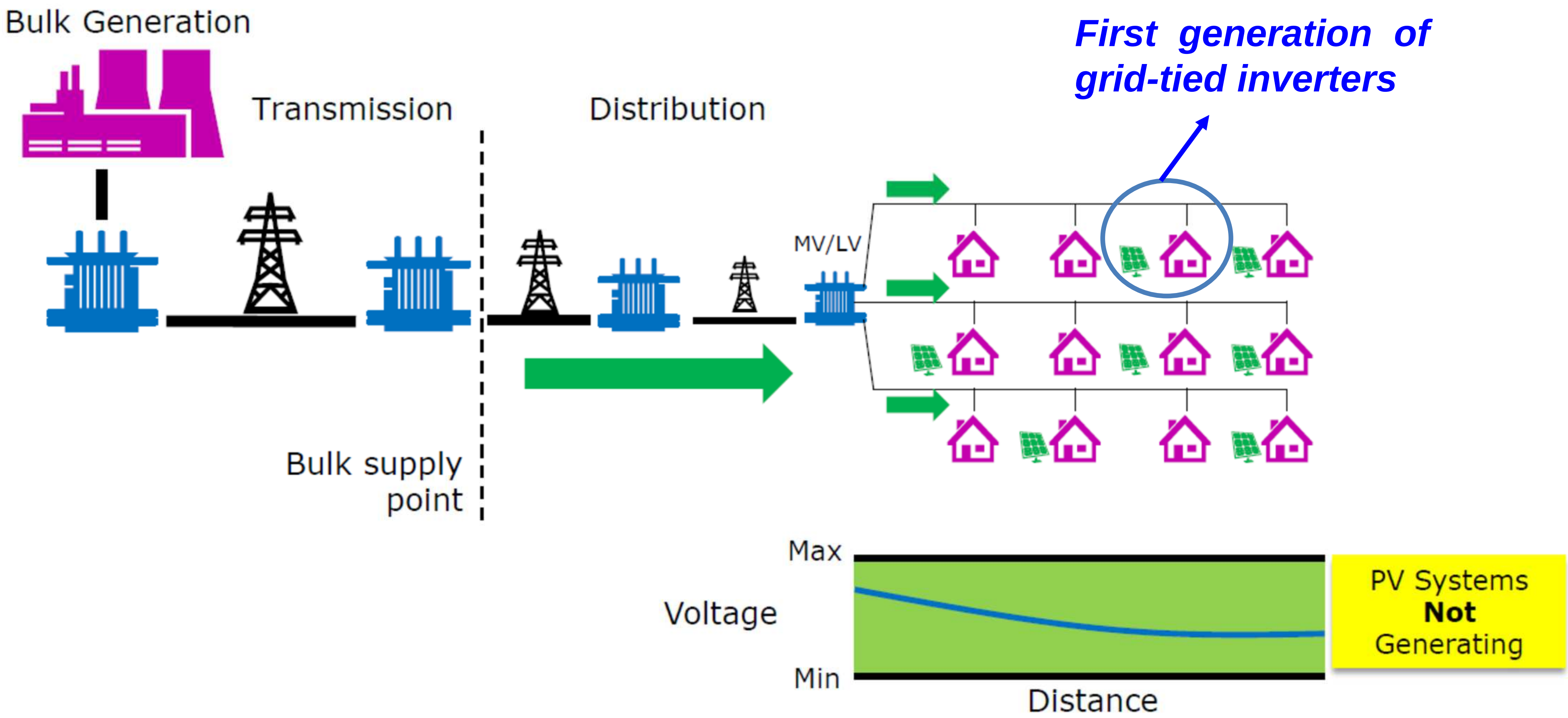
Utility benefits from smart inverters:

- Prevention of overvoltages and improvement of voltage profile
- Reduction in capacitor switchings
- Decrease in LTC tap change operations
- Reduction in distribution line losses
- Mitigation of voltage flicker
- Deferment of line regulators
- Increase in penetration of DG systems (**rise the hosting capacity**)

[2] R. Bravo, B. Enayati, M. Coddington, M. Morjaria, B. York, R. Varma, “Smart Inverters for Distributed Generators”, Tutorial of IAS, 2017

Smart Inverters

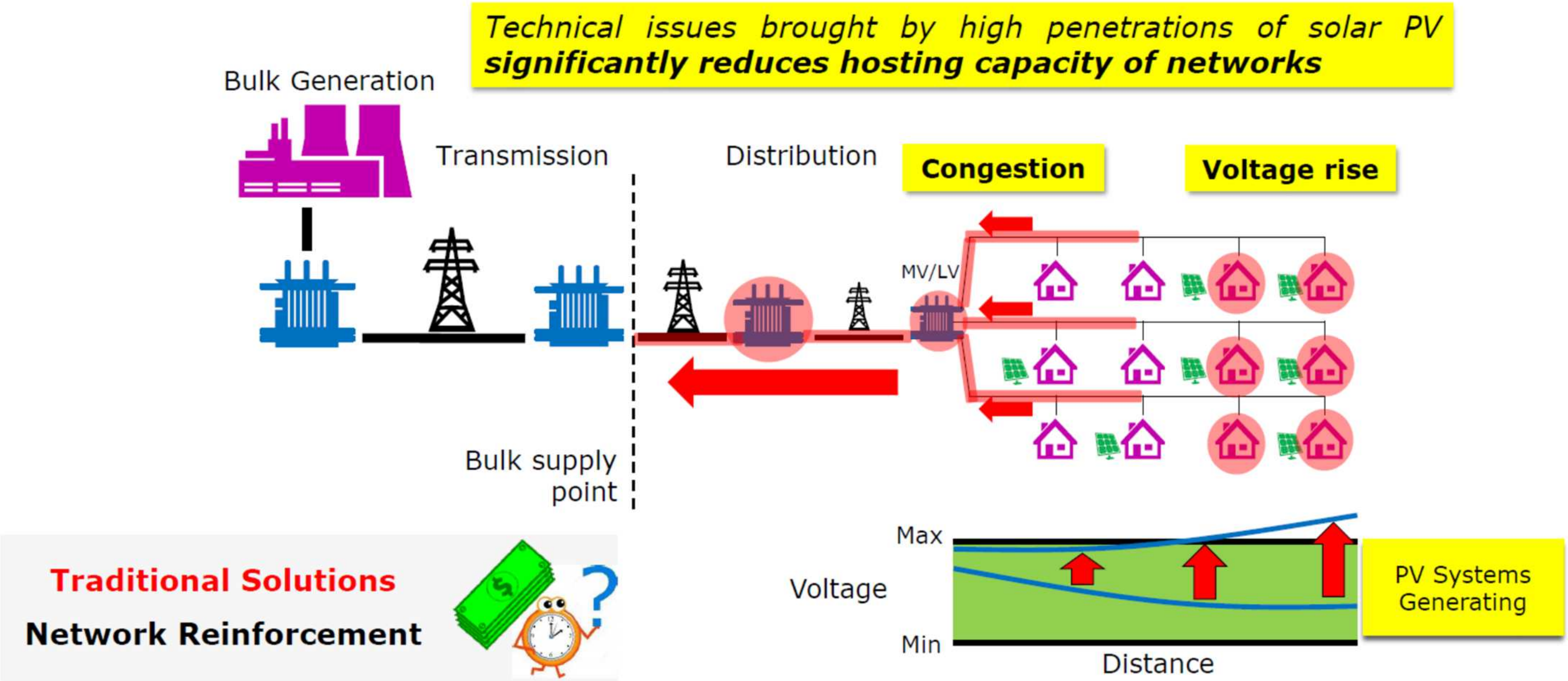
Hosting capacity enhancement



Slides from Dr. Andreas T. Procopiou - Watts Battery Inc

Smart Inverters

Hosting capacity enhancement



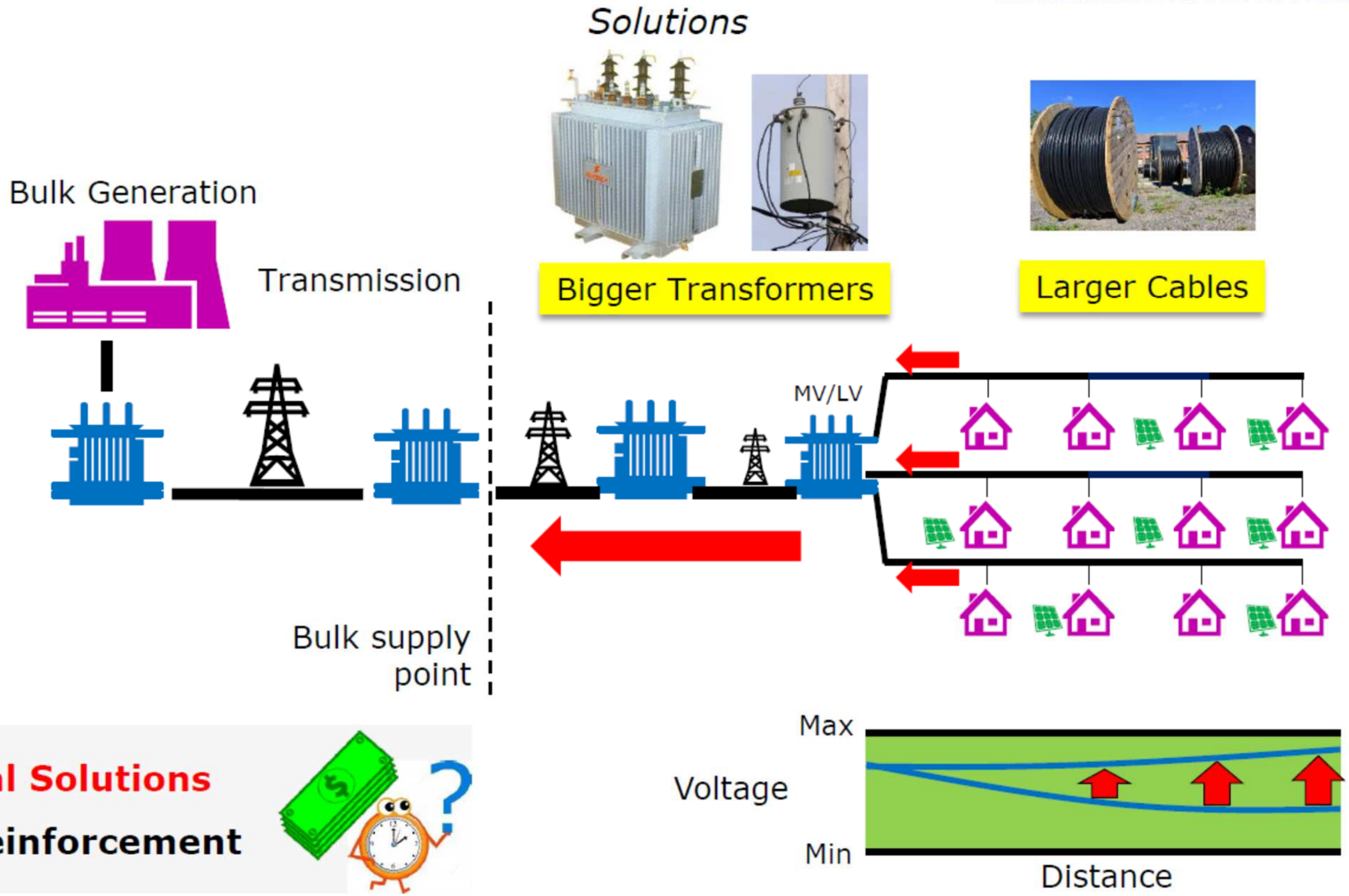
HC about <u>20%</u> of the MV/LV transformer rated power considering only 1^{st} generation inverter (i.e., unity power factor)

R. Torquato, D. Salles, C. O. Pereira, P. C. M. Meira, and W. Freitas, "A Comprehensive Assessment of PV Hosting Capacity on Low-Voltage Distribution Systems," *IEEE Trans. Power Deliv.*, vol. 33, no. 2, pp. 1002–1012, 2018.

Sherif M. Ismael, Shady H.E. Abdel Aleem, Almoataz Y. Abdelaziz, Ahmed F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," Renewable Energy, Vol.130, pp 1002-1020, 2019.

Smart Inverters

Hosting capacity enhancement



Traditional Solutions

Network Reinforcement

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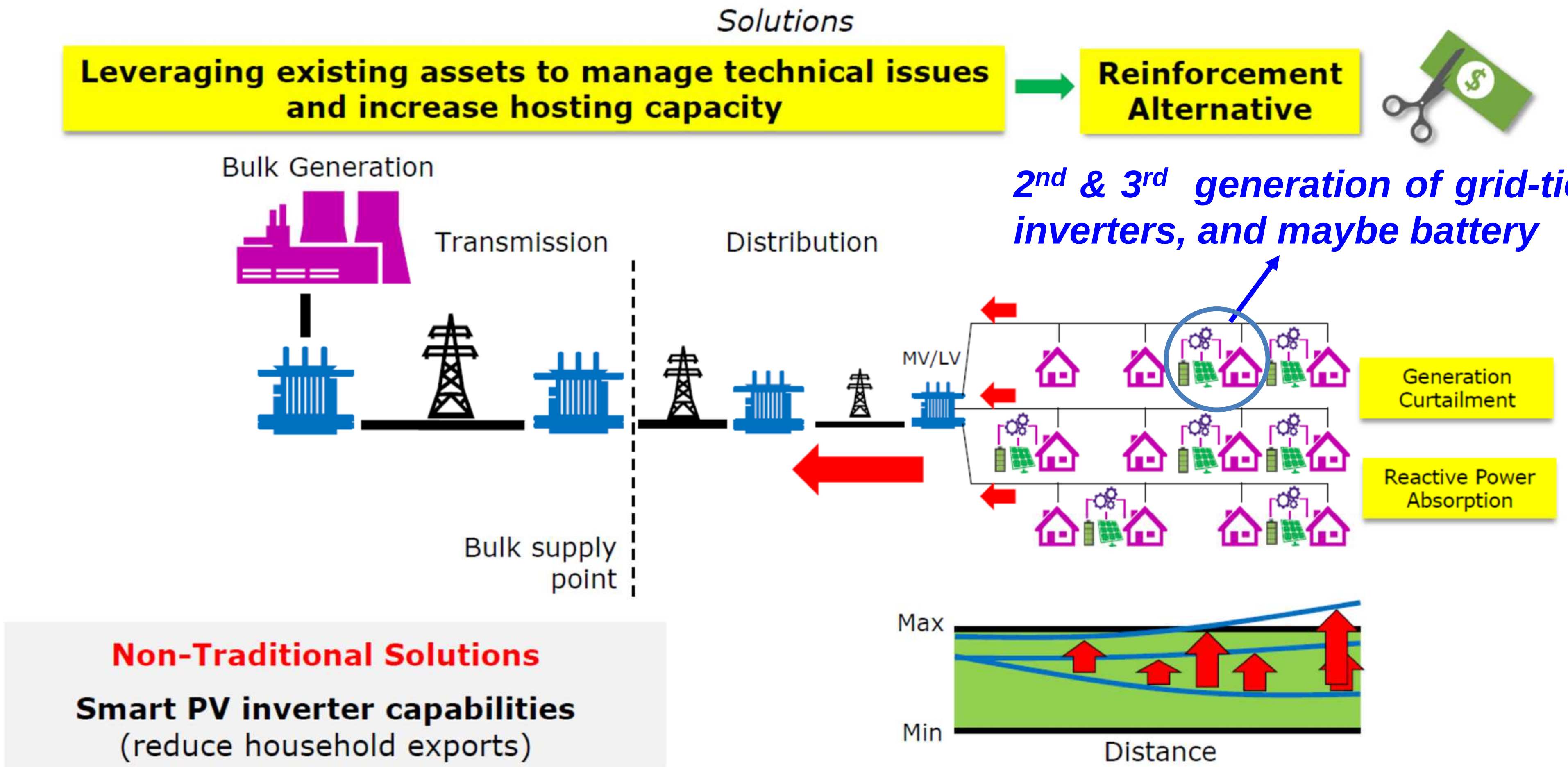
Smart Inverters

Hosting capacity enhancement



Functions related to reactive power may raise the HC by <u>a factor of 1.5 to 2</u>.

T. Degner, G. Arnold, T. Reimann, B. Engel, M. Breede, P. Strauss, "Increasing the photovoltaic-system hosting capacity of low voltage distribution networks," in: 21st Int. Conf. Exhib. Electr. Distrib., 2011.

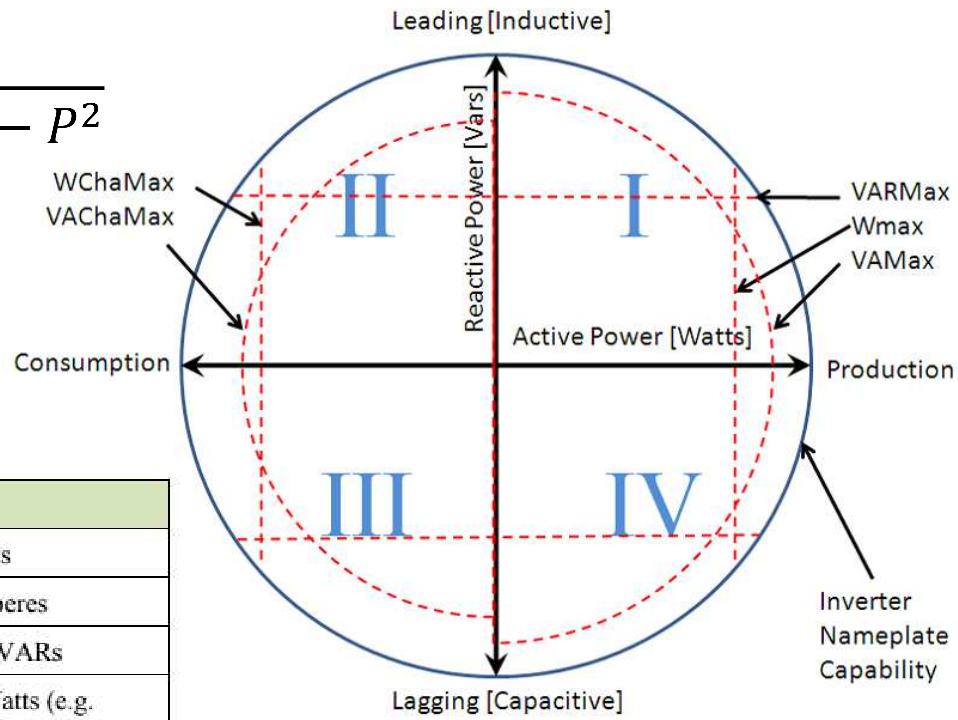
Ancillary Services

Constraints of power electronics

Smart inverters must comply with grid code and power electronics constraints

- DER can operate in quadrants I and IV with no energy storage, but can operate in all four quadrants with energy storage.

Idle power capacity avaliable: $\Delta Q = \sqrt{A^2 - P^2}$



Name	Description
WMax	The maximum real power that the DER can deliver to the grid, in Watts
VAMax	The maximum apparent power that the DER can conduct, in Volt-Amperes
VARMax	The maximum reactive power that the DER can produce or absorb, in VARs
WChaMax	The maximum real power that the DER can absorb from the grid, in Watts (e.g. energy storage charging). Note that WChaMax may or may not differ from WMax.
VAChaMax	The maximum apparent power that the DER can absorb from the grid, in Volt-Amperes (e.g. energy storage charging). Note that VAChaMax may or may not differ from VAMax.
ARtg	A nameplate value, the maximum AC current level of the DER, in RMS Amps.

R. Bravo, B. Enayati, M. Coddington, M. Morjaria, B. York and R. Varma, "Smart Inverter for Distributed Generators," *IEEE Power and Energy Society*, 2018.

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Smart inverters must comply with grid code and power electronics constraints

- DER can operate in quadrants I and IV with no energy storage, but can operate in all four quadrants with energy storage.

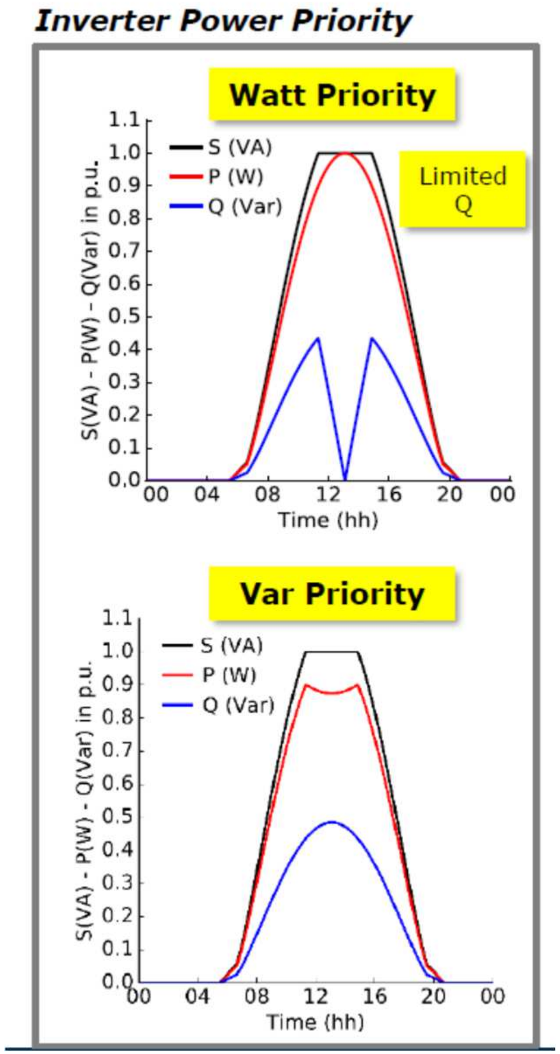
Idle power capacity avaliable: $\Delta Q = \sqrt{A^2 - P^2}$

- **Active power injection takes precedence over reactive power exchange (i.e, Watt priority)**

  (***usually under normal operation condition***)

- **Reactive power injection takes precedence over active power exchange (i.e, var priority)**

  (***usually under abnormal operation condition***)

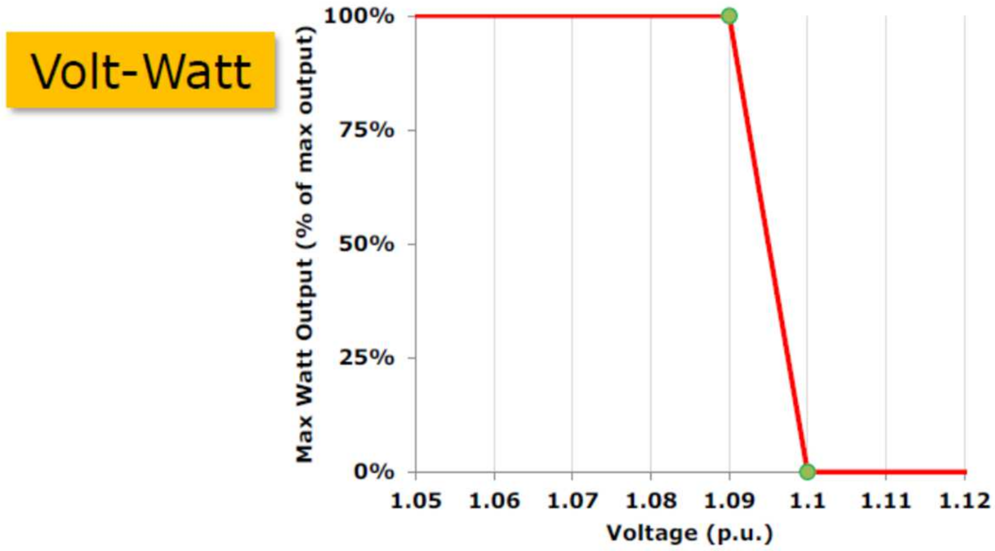


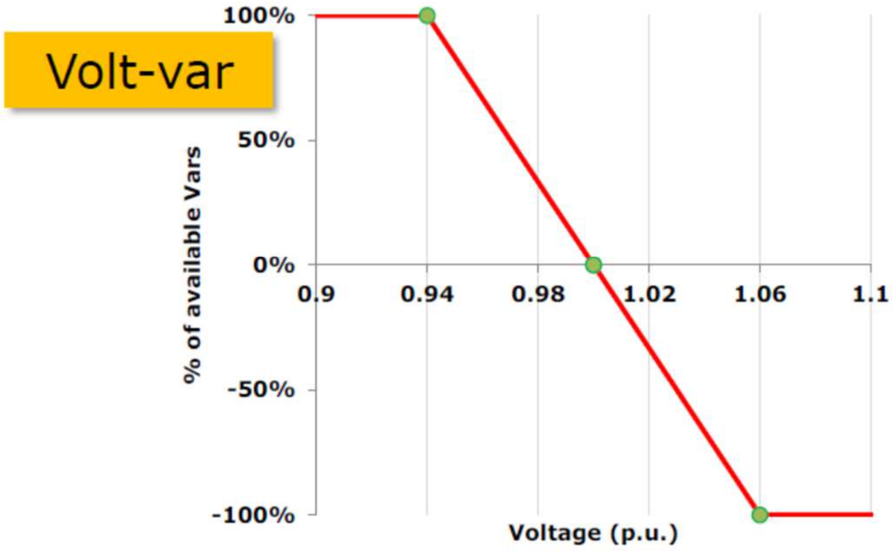
Slides from Dr. Andreas T. Procopiou - Watts Battery Inc

Smart Inverter

Control function examples

Example setting used for demonstration purposes:



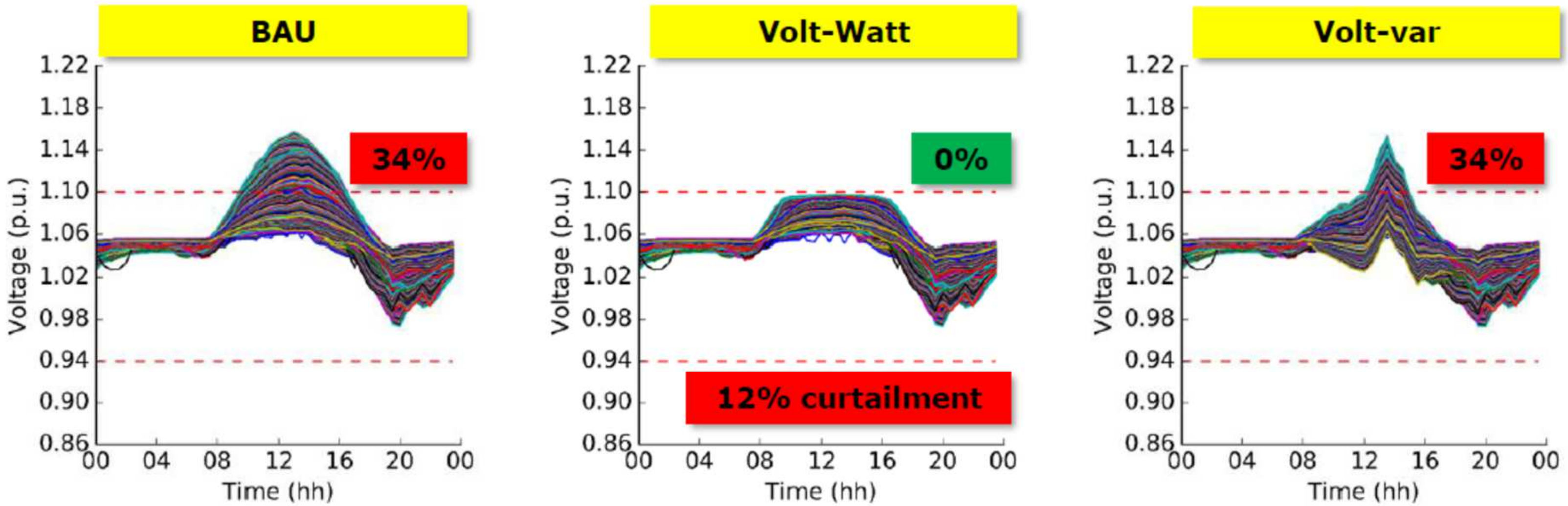


A. Procopius, “Active Management of PV-Rich Low Voltage Network,” PhD Thesis, Univ. of Manchester, 2017.
www.escholar.manchester.ac.uk/item/?pid=uk-ac-man-scw:310939

Smart Inverter

Voltage Issues

60% PV penetration on the Australian HV-LV network



- **Volt-Watt control effective** at the expense of energy curtailment
- **Volt-var control ineffective** due to limited Q when needed

A. Procopius, "Active Management of PV-Rich Low Voltage Network," PhD Thesis, Univ. of Manchester, 2017.
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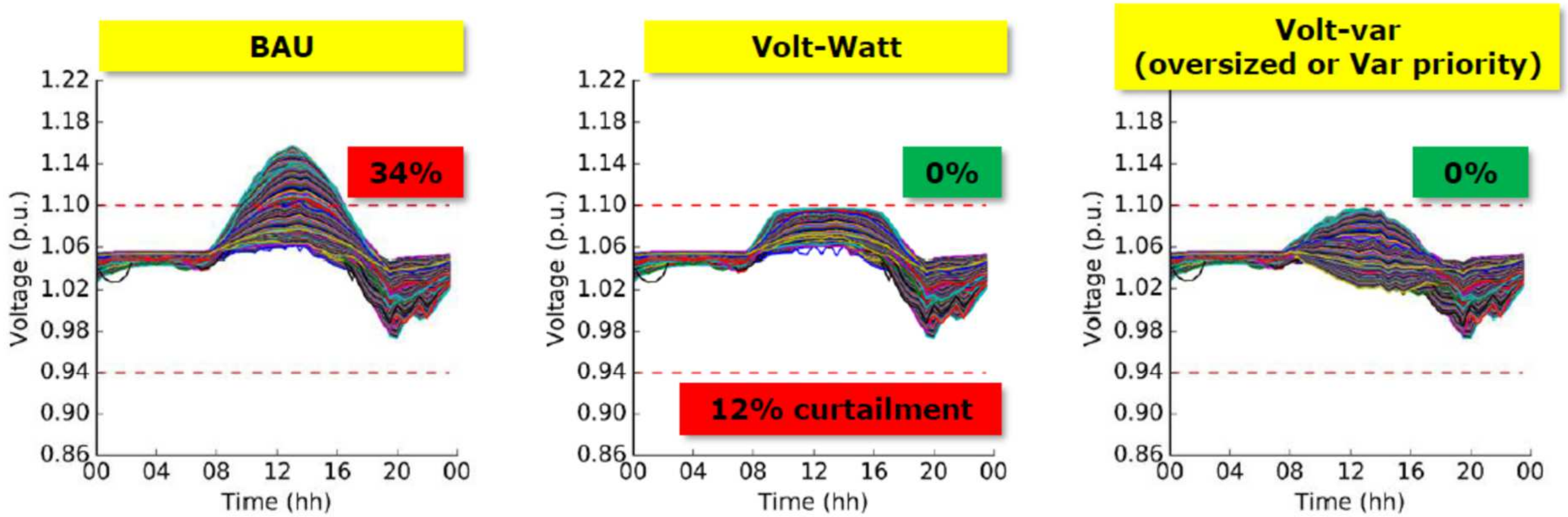
60% PV penetration on the Australian HV-LV network



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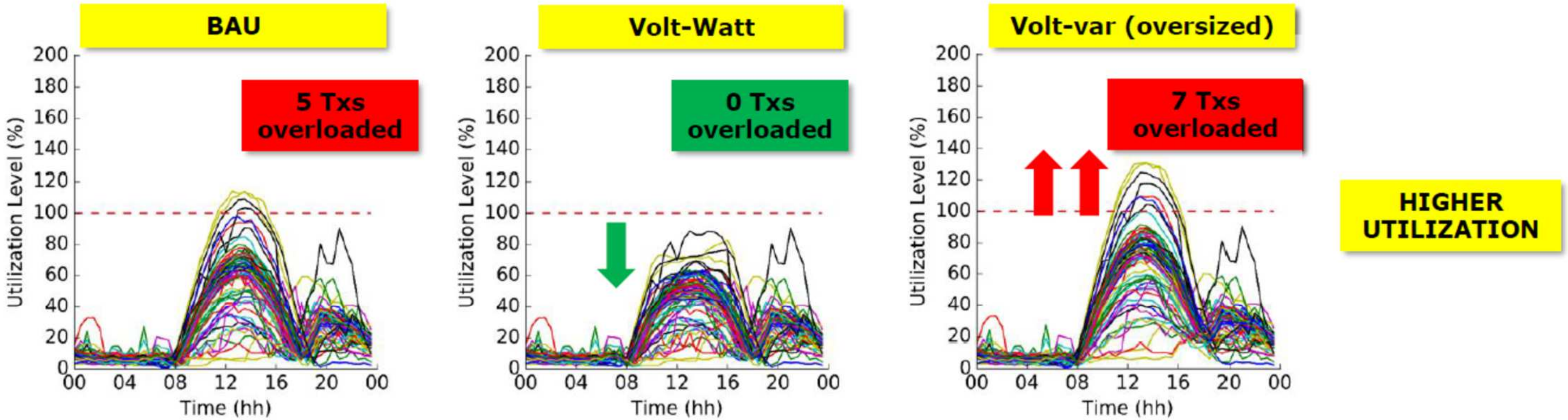
Smart Inverter

Thermal Issues

60% PV penetration on the Australian HV-LV network

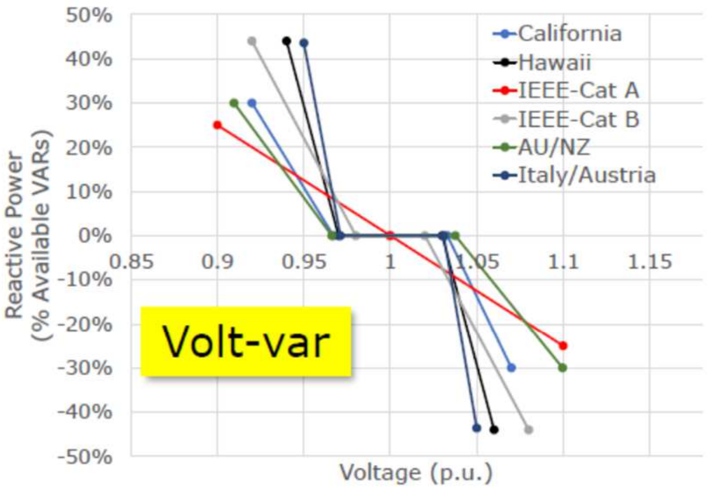


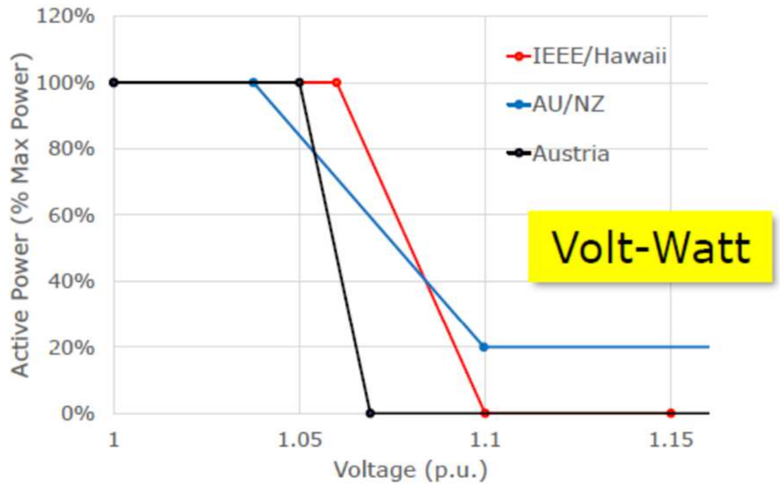
- Curtailment from Volt-Watt eliminates Tx overloads
- **Q from Volt-var creates more overloads**

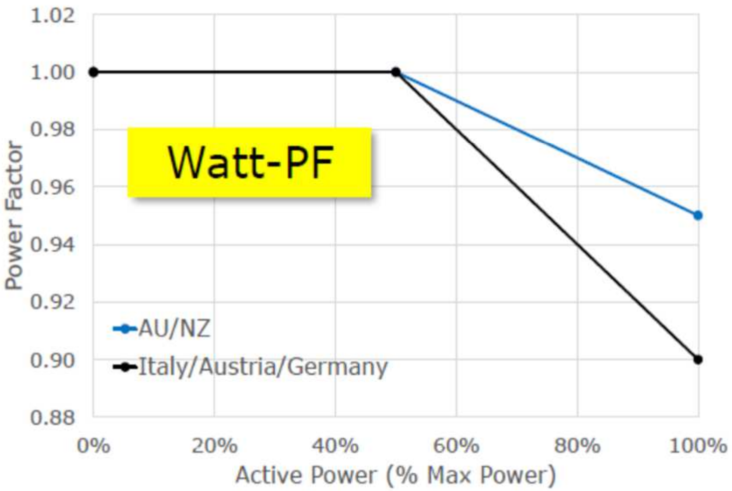
A. Procopius, “Active Management of PV-Rich Low Voltage Network,” PhD Thesis, Univ. of Manchester, 2017.
www.escholar.manchester.ac.uk/item/?pid=uk-ac-man-scw:310939

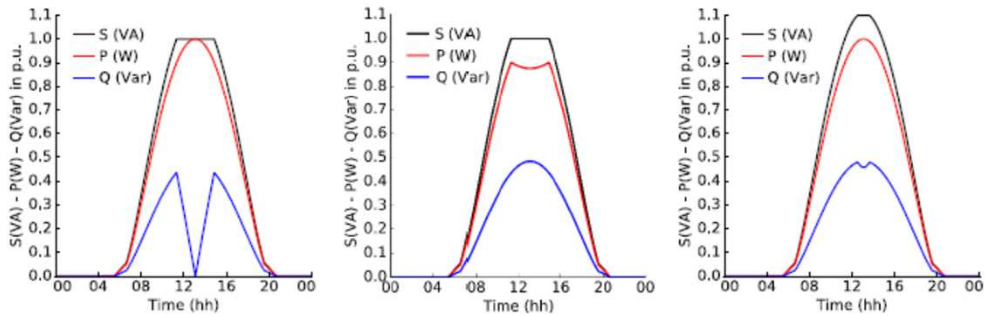
Smart Inverter

Control function setting and options







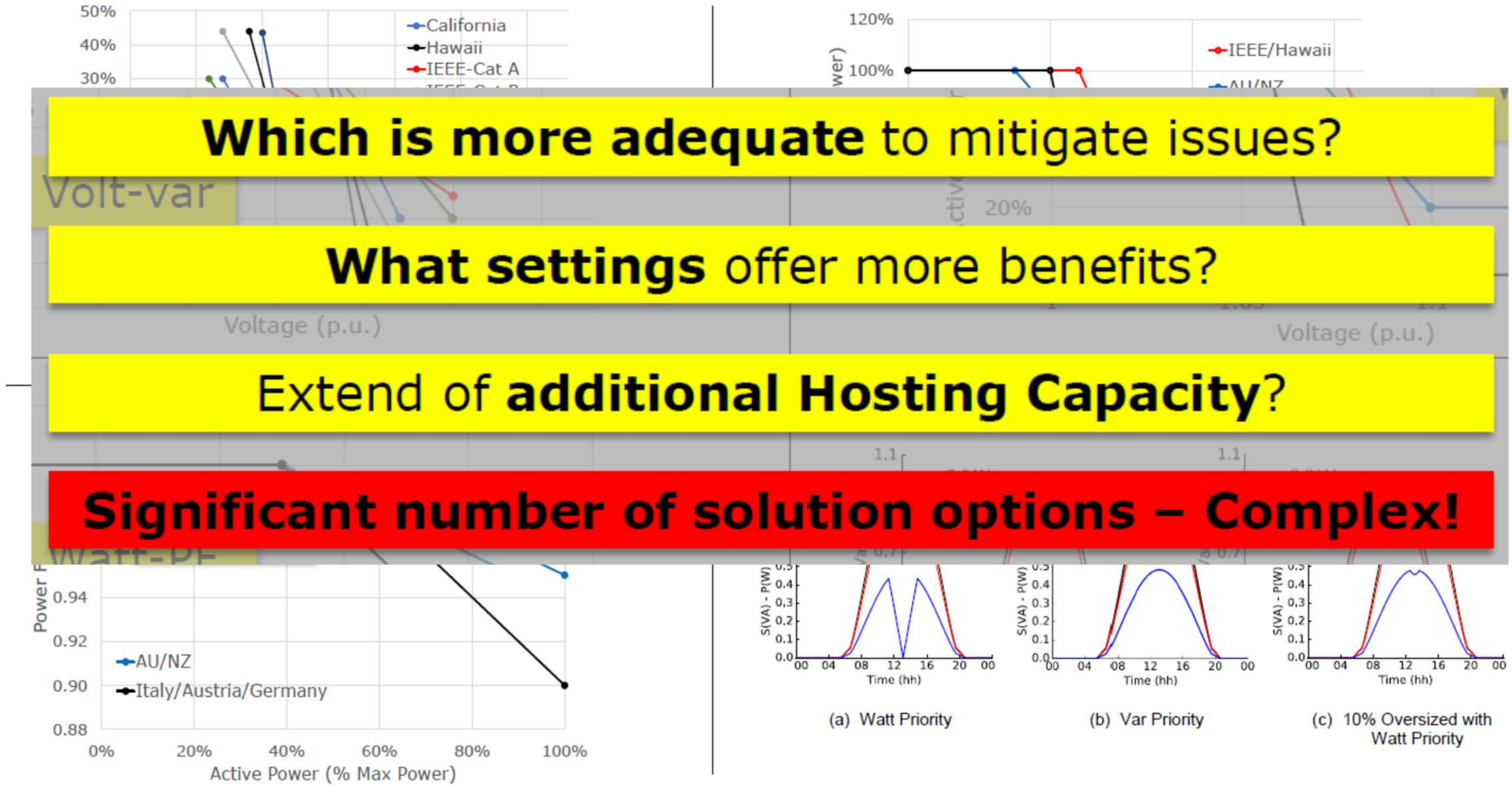


(a) Watt Priority (b) Var Priority (c) 10% Oversized with Watt Priority

A. Procopius, “Active Management of PV-Rich Low Voltage Network,” PhD Thesis, Univ. of Manchester, 2017. www.escholar.manchester.ac.uk/item/?pid=uk-ac-man-scw:310939

Smart Inverter

Control function setting and options



Which is more adequate to mitigate issues?

What settings offer more benefits?

Extend of **additional Hosting Capacity**?

Significant number of solution options – Complex!

A. Procopius, "Active Management of PV-Rich Low Voltage Network," PhD Thesis, Univ. of Manchester, 2017.
www.escholar.manchester.ac.uk/item/?pid=uk-ac-man-scw:310939

Smart Inverters

Introduction

Categories A/B and I/II/III for DGs based on *Std. IEEE 1547-2018*

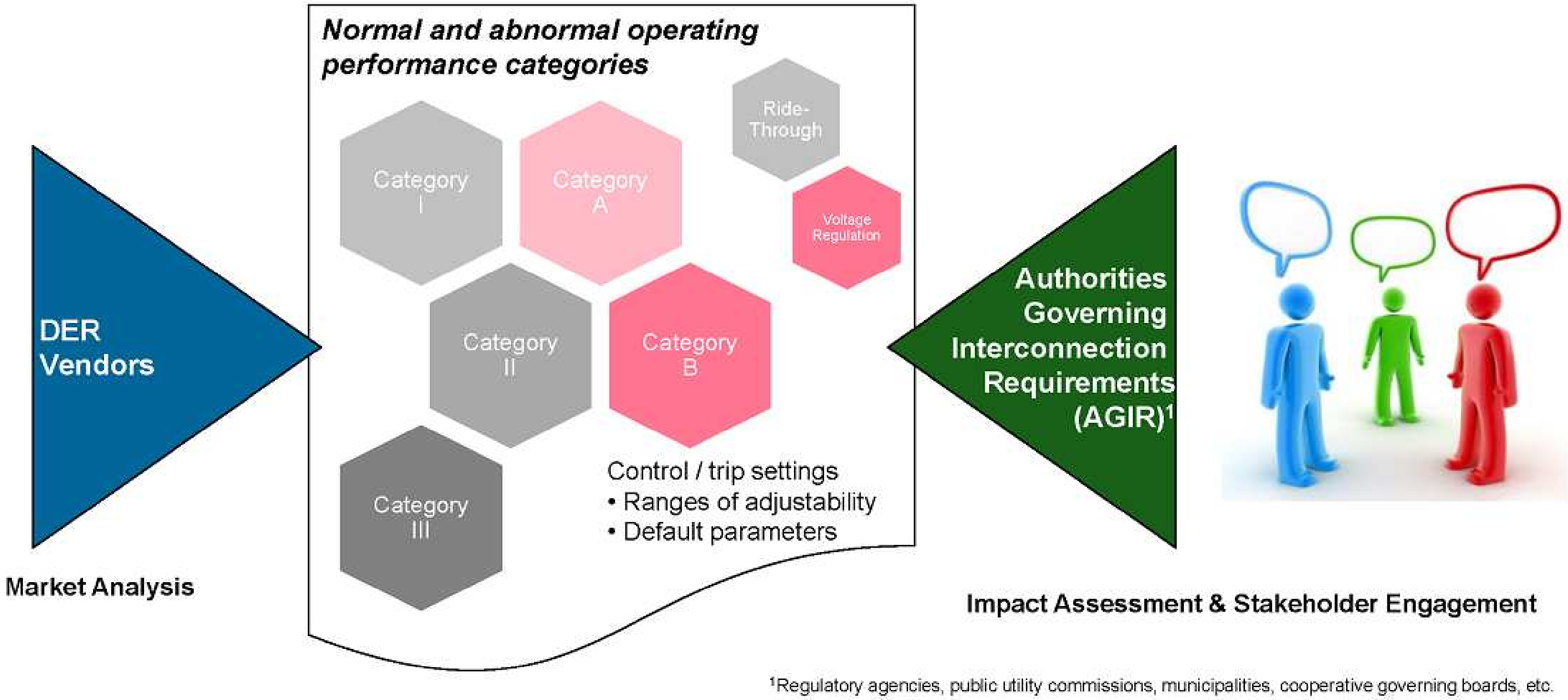


Figure B.1—High-level overview of performance-based category approach

— Categories A and B for voltage regulation performance and reactive power capability requirements (Clause 5)

— Categories I, II, and III for disturbance ride-through requirements (Clause 6)

Categories A/B and I/II/III for DGs based on *Std. IEEE 1547-2018*

Table 6—Voltage and reactive/active power control function requirements for DER normal operating performance categories

DER category	Category A	Category B
Voltage regulation by reactive power control		
Constant power factor mode	Mandatory	Mandatory
Voltage—reactive power mode[a]	Mandatory	Mandatory
Active power—reactive power mode[b]	Not required	Mandatory
Constant reactive power mode	Mandatory	Mandatory
Voltage and active power control		
Voltage—active power (volt-watt) mode	Not required	Mandatory

[a]Voltage-reactive power mode may also be commonly referred to as "volt-var" mode.
[b]Active power-reactive power mode may be commonly referred to as "watt-var" mode.

Table 7—Minimum reactive power injection and absorption capability

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

Reference reading

1. IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003) , vol., no., pp.1-138, 6 April 2018.

2. Common functions for smart inverters, 4th edition, 3002008217, Dec. 2016.

3. R. Bravo, B. Enayati, M. Coddington, M. Morjaria, B. York and R. Varma, "Smart Inverter for Distributed Generators," *IEEE Power and Energy Society*, 2018.

4. A. Procopius, "Active Management of PV-Rich Low Voltage Network," PhD Thesis, Univ. of Manchester, 2017.
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