Presentation @ KIOS Research Center

University of Cyprus, Cyprus
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Advanced Control Strategies for Grid-Friendly Photovoltaic Systems

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AALBORG UNIVERSITY
DENMARK

Agenda

I. Introduction

- Energy Technology (E.T.) at Aalborg University
- Background and motivation

II. Advanced Control Strategies

- Harmonic control
- Low voltage ride-through operation
- Constant power generation concept

III. Conclusions

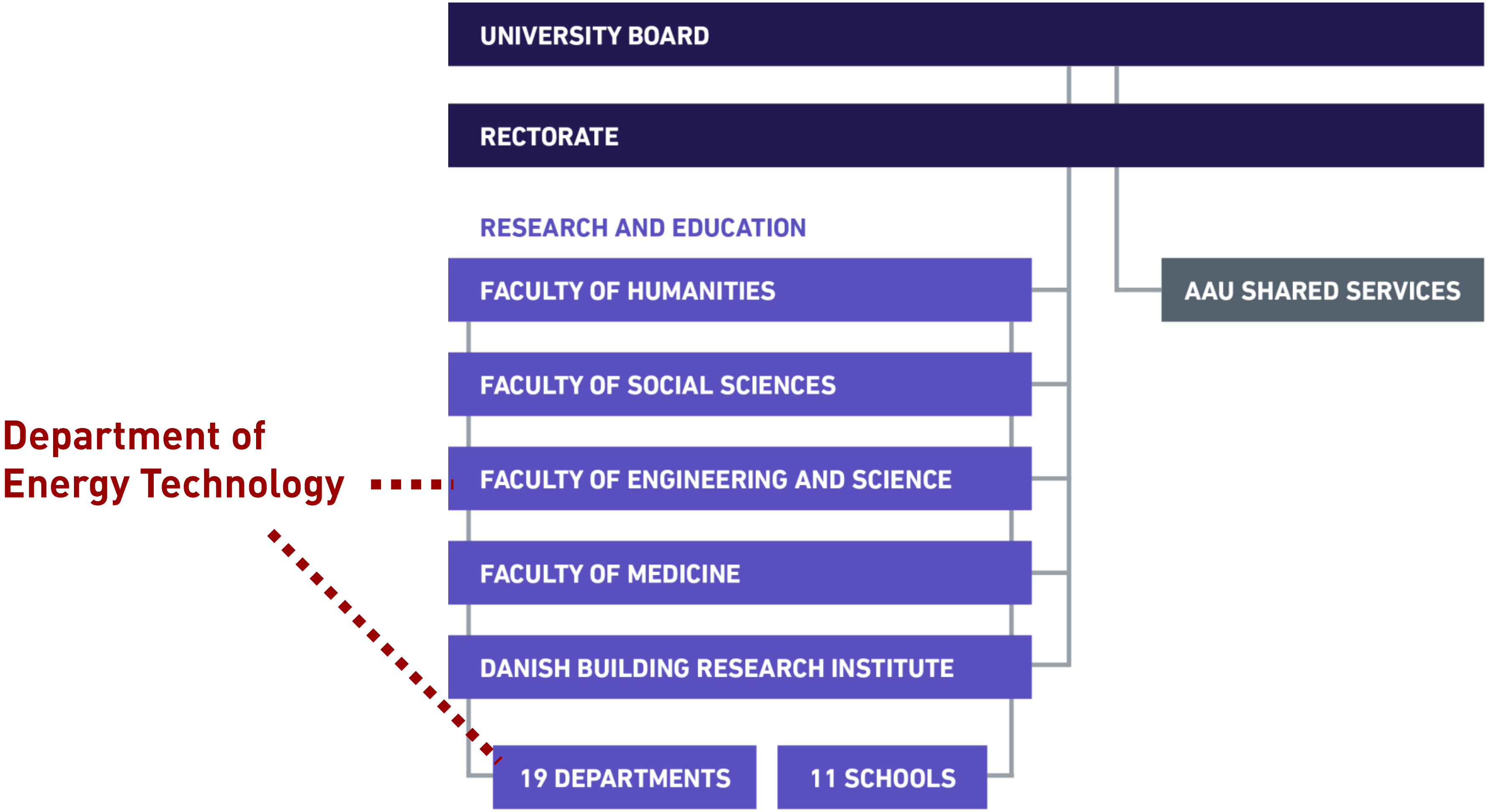
- Summary and outlook

Aalborg University (AAU)

Inaugurated in 1974
15,000+ students
2,000+ faculty

PBL-Aalborg Model (Project-organized and problem-based)

Aalborg University (AAU)



Department of Energy Technology (E.T.)

E.T.

Presentation at KIOS Research Center

Research and Education Sections at Department of Energy Technology, Aalborg University

- Electric Power Systems
- Power Electronic Systems
- Electrical Machines
- Fluid Power and Mechatronic Systems
- Fluid Mechanics and Combustion
- Thermal Energy Systems

Multi-disciplinary Research Programs

Core power electronics research program
- Efficient and Reliable Power Electronics

Programs of power electronics intensive applications
- Wind Turbine Systems
- Photovoltaic Systems and Microgrids
- Automotive and Industrial Drives

Programs of power electronics related applications
- Fuel Cell and Battery Systems
- Smart Grids and Active Networks
- Modern Power Transmission Systems
- Green Buildings
- Thermoelectrics

- Fluid Power in Wind and Wave Energy
- Biomass

Department in total
- 40+ Faculty members
- 100+ PhD students
- 30+ Research assistants and postdocs
- 30+ Visiting scholars and students
- 20+ Technical and administrative staff
- 4 In-house company divisions

60%+ of the above manpower are in power electronics and its applications.

3 in-house company divisions heavily involve in power electronics.

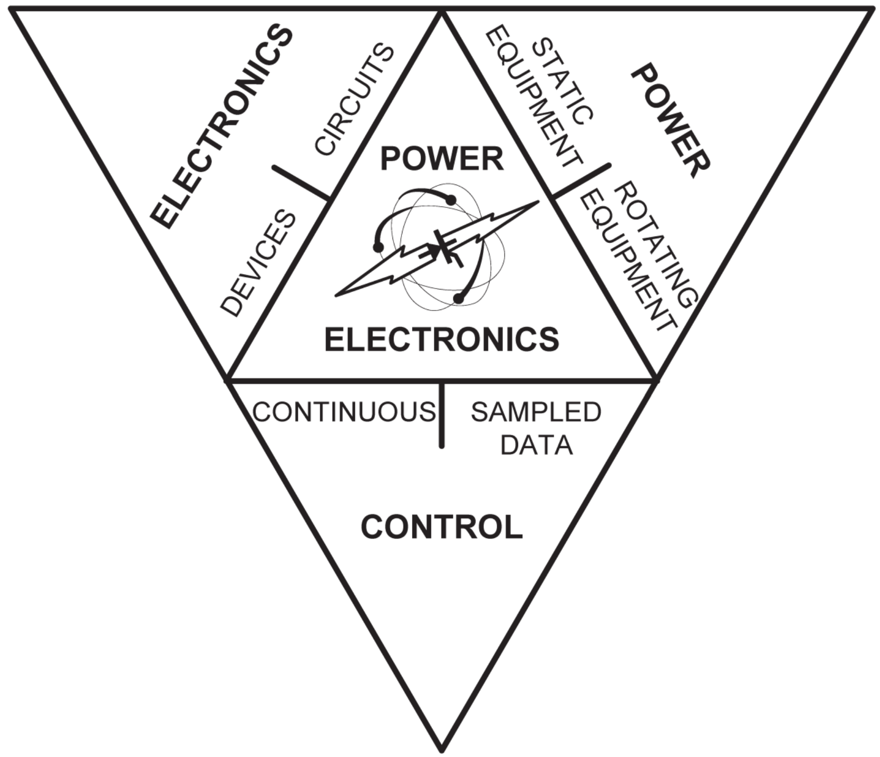
Energy Production – Energy Distribution – Energy Consumption – Energy Control

Selected Ongoing Research Projects

Example of Ongoing Projects funded by European Research Council and Danish Government, Heavily Involved also Industry Companies

- HARMONY - Harmonic identification, mitigation and control in power electronics based power systems (2013-2018, ERC Advanced Grant, first of its kind in power electronics)
- IEPE - Intelligent and Efficient Power Electronics (2012-2017, Danish National Advanced Technology Foundation)
- CORPE - Center of Reliable Power Electronics (2011-2016, Danish Council for Strategic Research)
- ReliaCap - Reliability of capacitors in power electronic systems (2013-2014, Danish Council for Independent Research, first of its kind in power electronics)
- Highly efficient, low-cost energy generation and actuation using disruptive DEAP technology (2011-2015, Danish National Advanced Technology Foundation)
- SEMPEL - Semiconductor Materials for Power Electronics (2014-2019, Danish Council for Strategic Research)
- REST - Reliability ESTimation of hydrogen and fuel cell systems (2014-2017, EUDP)
- Power-2-Electrolysers (2013-2016, EUDP)
- DSO challenges from introduction of heat pumps (2014-2016, Energinet)
- NHTD - New Harmonic Reduction Techniques for Motor Drives (2014-2017, Højteknologifonden) ← <u>which I am working on</u>
- PV2GRID – A next generation grid side converter with advanced control and power quality capabilities (2015-2018, SOLAR-ERA.NET Project, EU's Seventh Framework Program)

Power Electronics Scope in 1970s



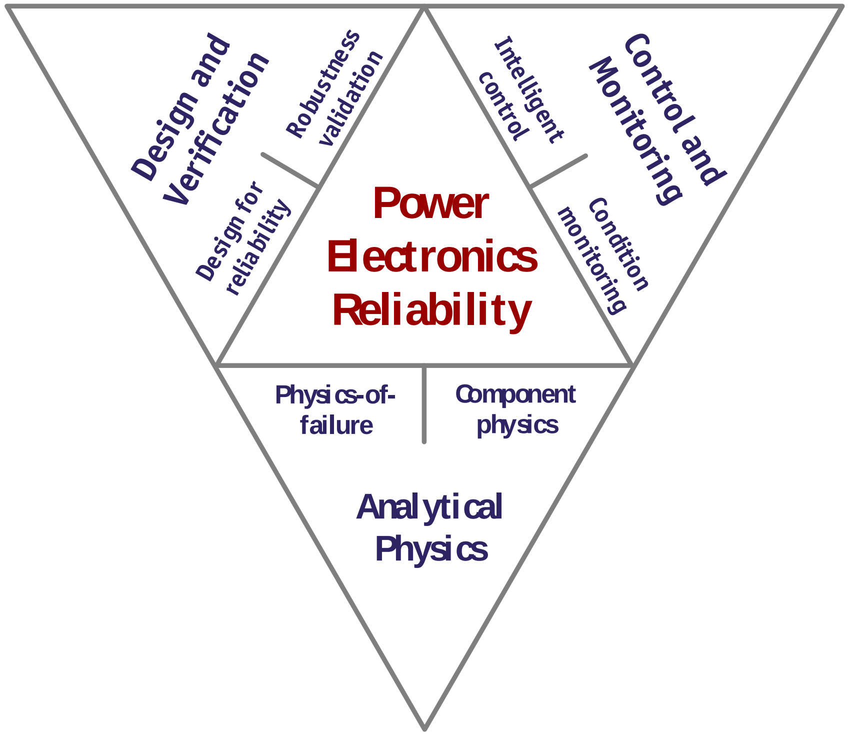
Power electronics refers to efficient control and conversion of electrical power by power semiconductor devices

Interdisciplinary application-oriented technology

William E. Newell, "Power Electronics-Emerging from Limbo," *IEEE Trans. Ind. Appl.*, vol. IA-10, no. 1, pp. 7-11, Jan./Feb.. 1974.

The Scope of Reliability of Power Electronics

A multi-disciplinary research area – by CORPE



Paradigm Shift

- From components to failure mechanisms
- From constant failure rate to failure level with time
- From reliability prediction to robustness validation
- From microelectronics to also power electronics

I. Introduction

- Background and motivation

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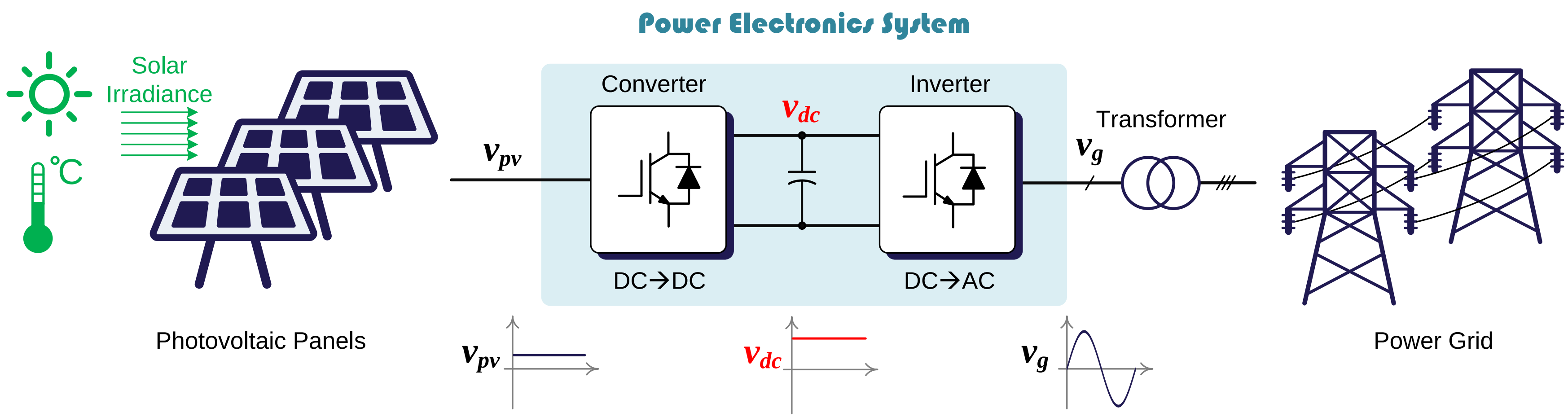
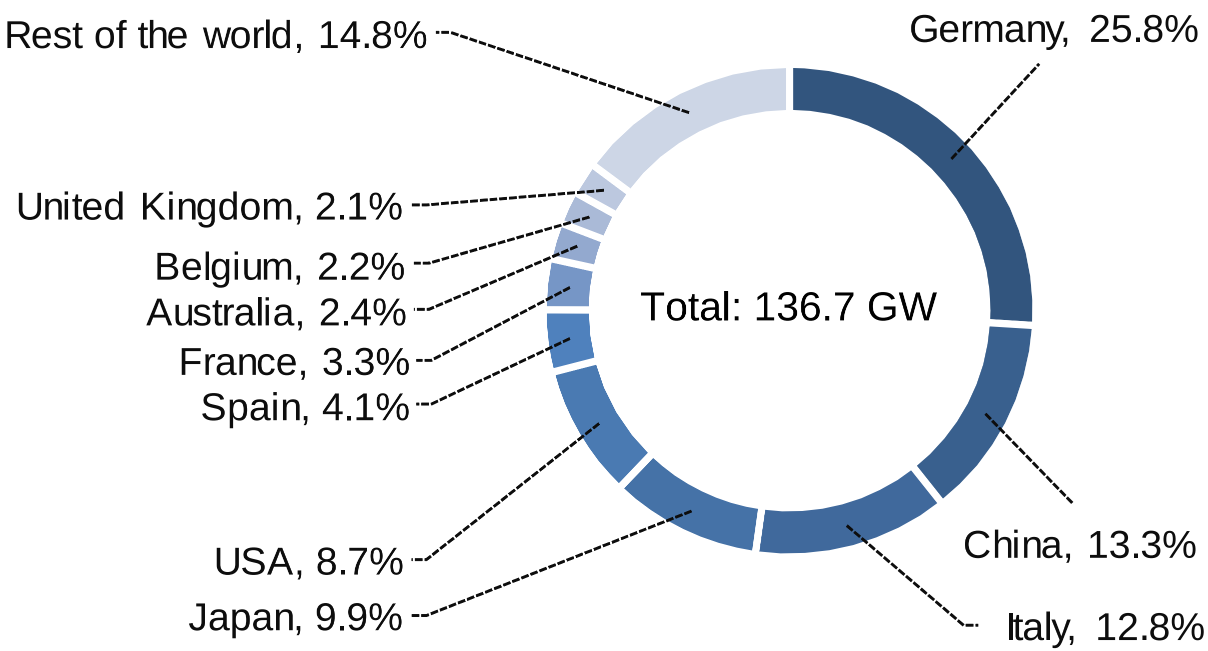
III. Conclusions



Opportunities enabled by PV systems

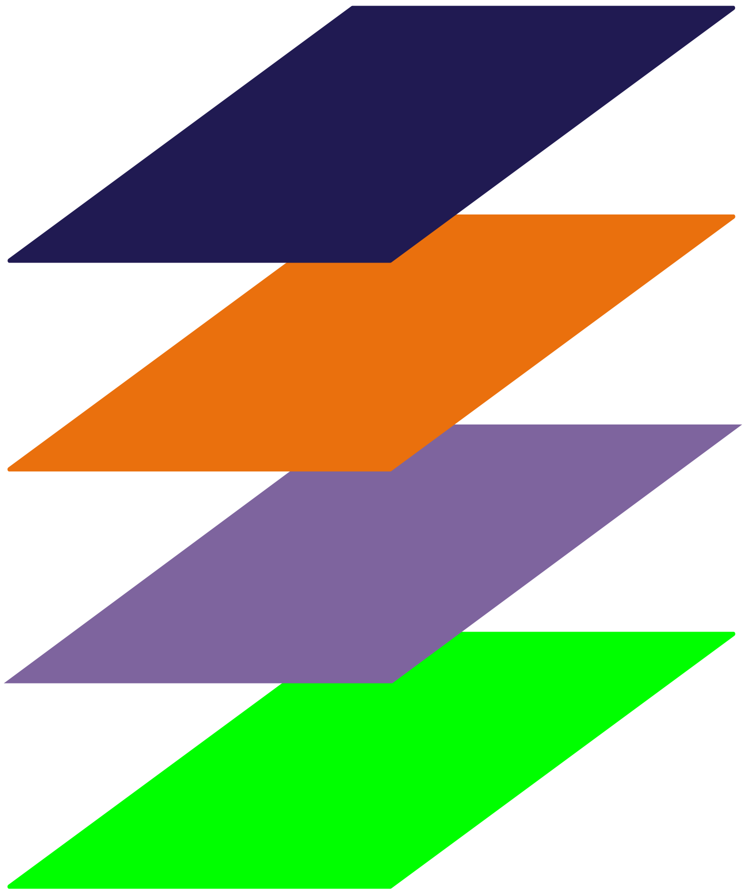


Source: EPIA

PV cumulative installation capacity world-wide share in 2013 (%)

Codes/requirements evolution for PV systems

Codes/requirements evolution for PV systems



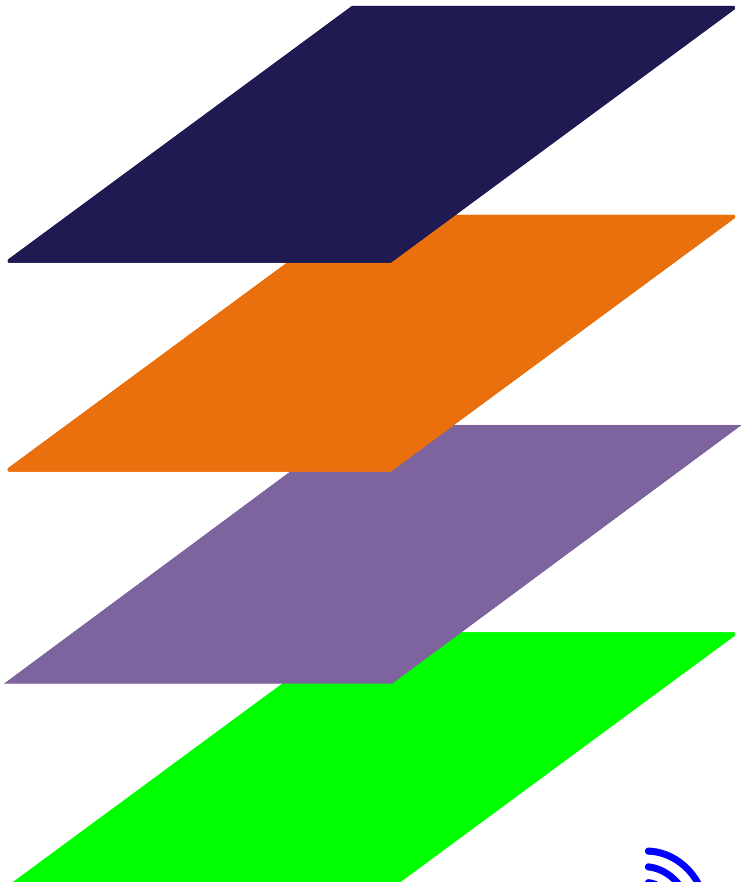
Transmission Level (EHV, HV) –
Response to faults, Grid stability,
Power quality, Reactive power, ...

Distribution Level (HV, MV) –
Local stability (voltage), Power flow,
P/*Q* provision to HV, ...

Converter System Level (LV) –
Voltage rise, Fault ride-through (*V* and/or *f*),
Anti-islanding, Efficiency, Cost, Reliability,
Power controllability, Power factor,...

Generator Level (PV modules) –
Efficiency, Cost, Safety, ...

Codes/requirements evolution for PV systems



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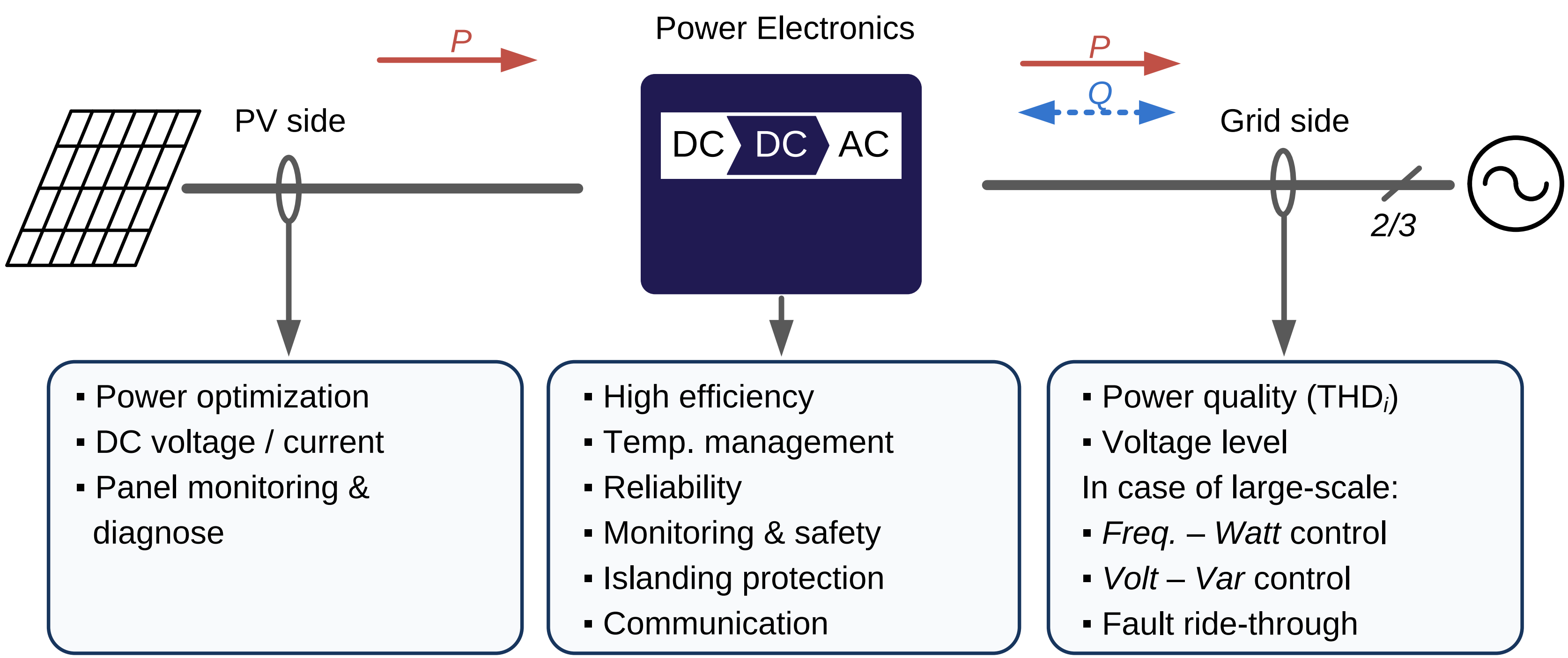
Efficiency, Cost, Safety, ...

Monitoring, Forecasting, and Communication

Challenges brought by further increasing PV capacity



Demands (challenges) for a grid-connected PV system

What else benefits to the grid and the costumers ?

- How to better fulfil the requirements (grid & customer demands)?
- Any solutions to further reduce the cost of PV energy?

Background and Motivation

Suggestions on grid requirement modifications:

- ➢ Active power control (power curtailment)
- ➢ Reactive power control (Volt-VAR control)
- ➢ Freq. control through active power control (Freq.-Watt control)
- ➢ Dynamic grid support (fault ride-through capability)
- ➢ High reliability
- ➢ High efficiency

...

Y. Yang, P. Enjeti, F. Blaabjerg, and H. Wang, "Suggested grid code modifications to ensure wide-scale adoption of photovoltaic energy in distributed power generation systems," *IEEE Ind. Appl. Mag.*, 2015.

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- Low voltage ride-through
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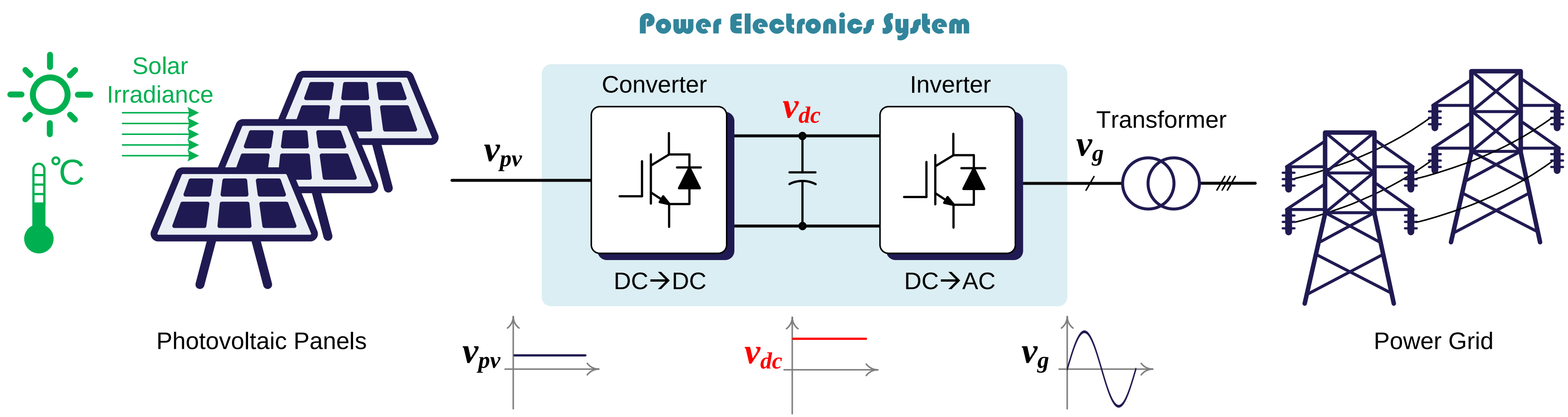
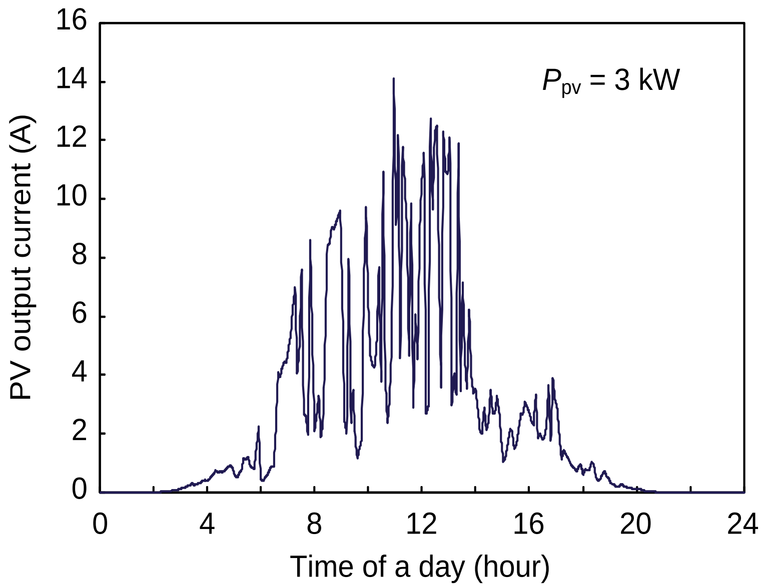


Harmonic emissions from PV inverters

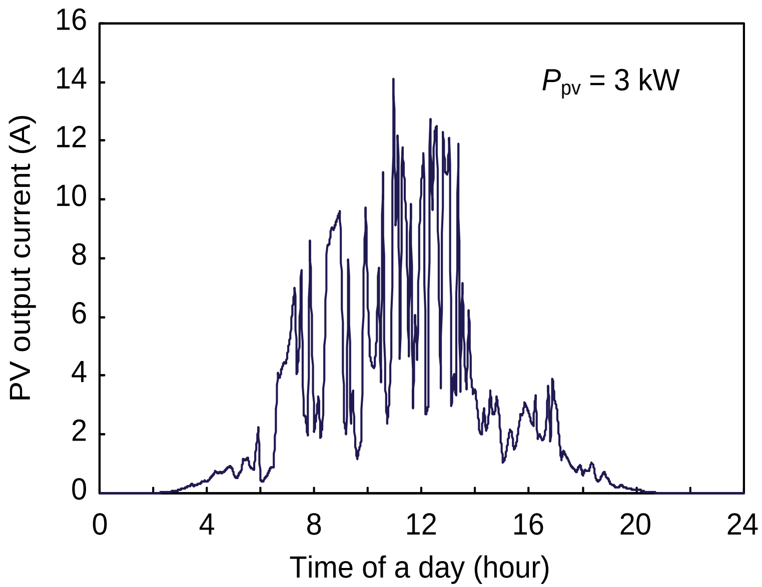


PV power weather-dependency

Y. Yang, K. Zhou, and F. Blaabjerg, "Harmonics suppression for single-phase grid-connected PV systems in different operation modes," in *Proc. of APEC*, pp.889-896, Mar. 2013.

Harmonic Control

Harmonic emissions from PV inverters



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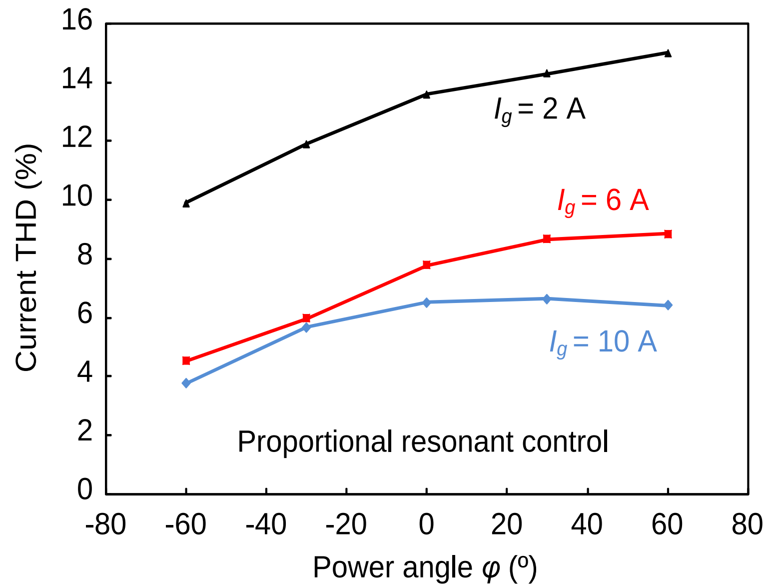

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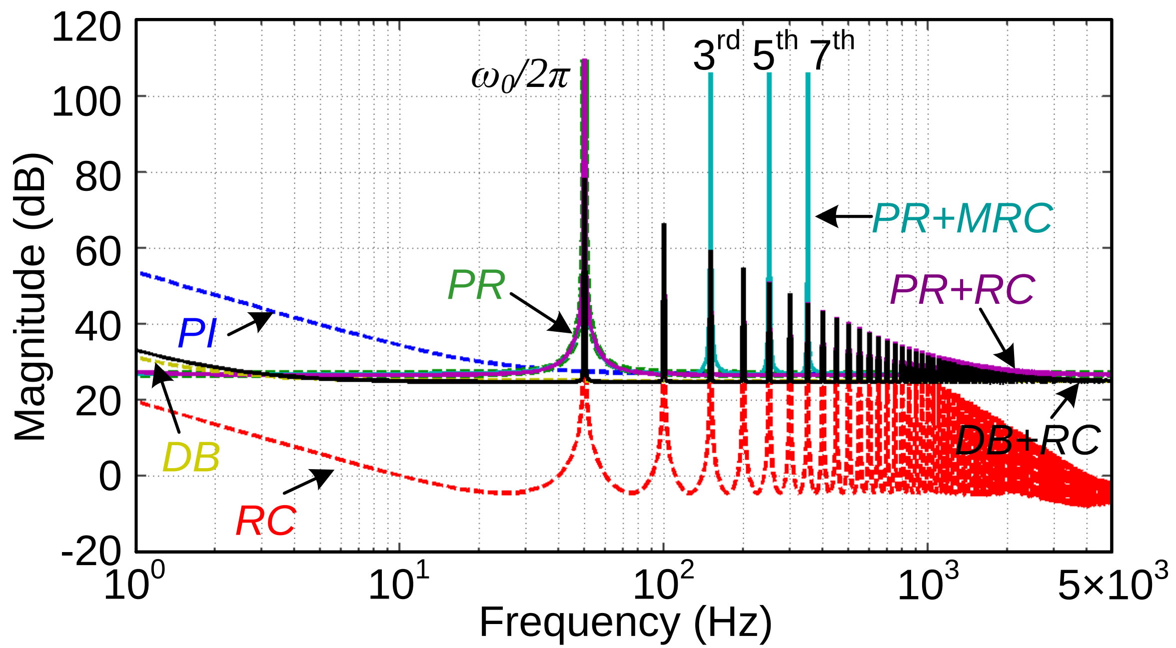
Harmonic control – current controllers in the *αβ*-frame

Controllers	Transfer functions, G_c	Remarks
DB	$G_{DB}(z) = \dfrac{1}{G_f(z)(z-1)}$	Simple and very fast response (approximately one sampling period). High model-dependency (i.e. poor robustness).
PR	$G_{PR}(s) = k_p + \dfrac{k_i s}{s^2 + \omega_0^2}$	Fundamental frequency controller. Harmonic compensators (e.g. MRC) are required for the power quality concern.
PR+MRC	$G_{PR}(s) + \sum \dfrac{k_{ih} s}{s^2 + (h\omega_0)^2}$	Fast response. Good harmonic rejection capability at the resonant frequencies. Heavy parallel computation burden, when higher-order harmonics (e.g. 11^{th}, 13^{th}, 15^{th}, and 17^{th}) should be compensated. Also increased complexity.
PR+RC	$G_{PR}(s) + \dfrac{k_{rc} e^{-s \cdot 2\pi/\omega_0} Q(s)}{1 - e^{-s \cdot 2\pi/\omega_0} Q(s)} e^{sT_f}$	Easy implementation, which can compensate all harmonics, but only one control gain k_{rc} for the harmonic control is adjustable. Moderate response speed compared to PR+MRC due to its compact recursion property.
DB+RC	$G_{DB}(z) + \dfrac{k_{rc} z^{-N} Q(z)}{1 - z^{-N} Q(z)} z^m$	Takes advantage of the strengths of both DB and RC. Simple implementation, good harmonic rejection capability, and less computational burden.

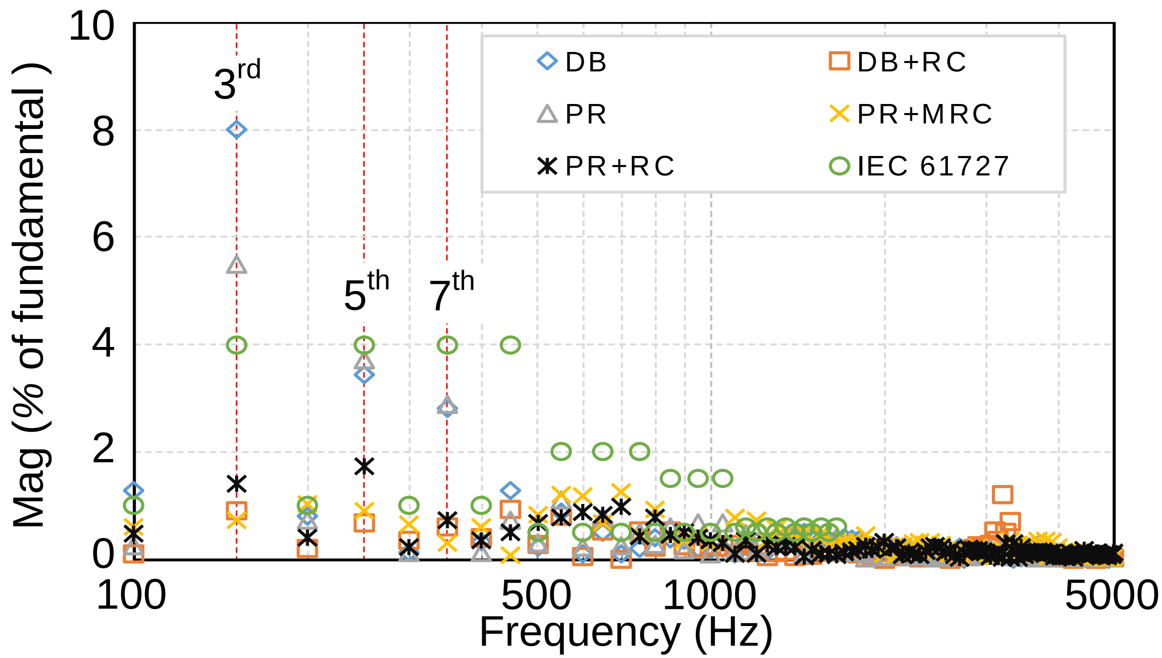
Current controllers for single-phase PV inverters with or w/o harmonic compensation

Harmonic control – current controllers



Magnitude responses of different current controllers

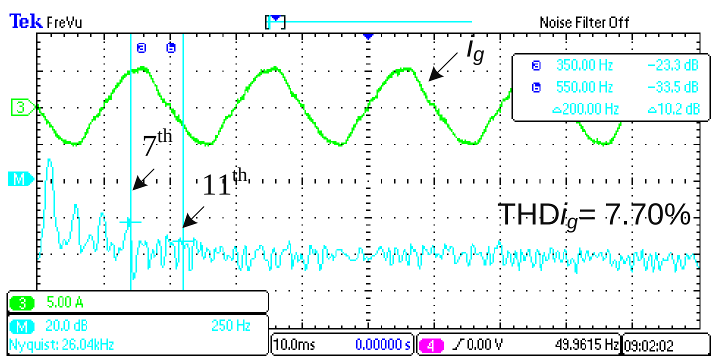
Harmonic control – current controllers



Harmonic distributions of the grid current using different current controllers

Test results – harmonic comp. in single-phase inverters

PR w/o HC



Y. Yang, K. Zhou, and F. Blaabjerg, "Harmonics suppression for single-phase grid-connected PV systems in different operation modes," in *Proc. of APEC*, pp.889-896, Mar. 2013.
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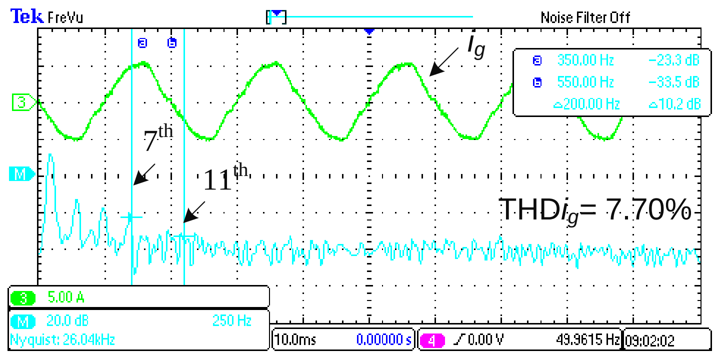
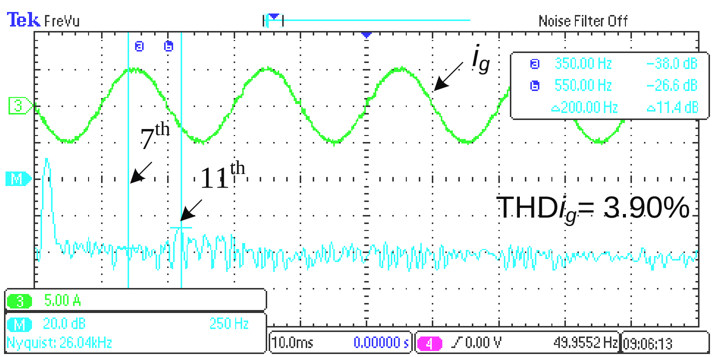
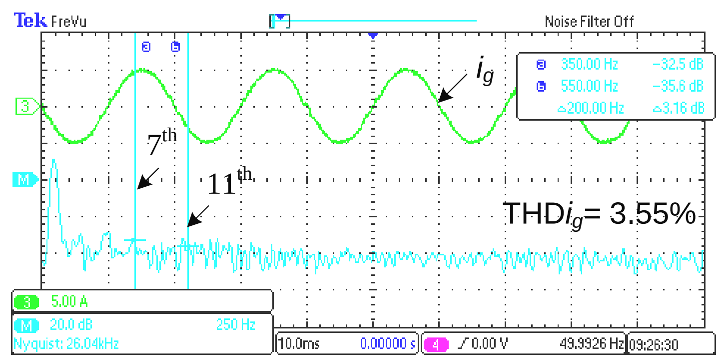


PR with MRC



PR with RC



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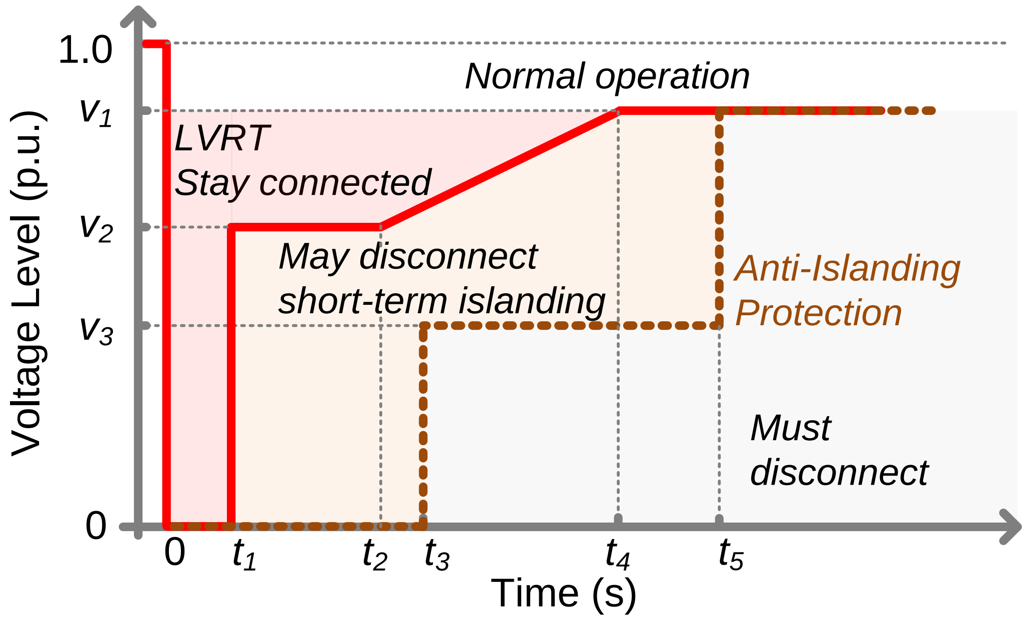
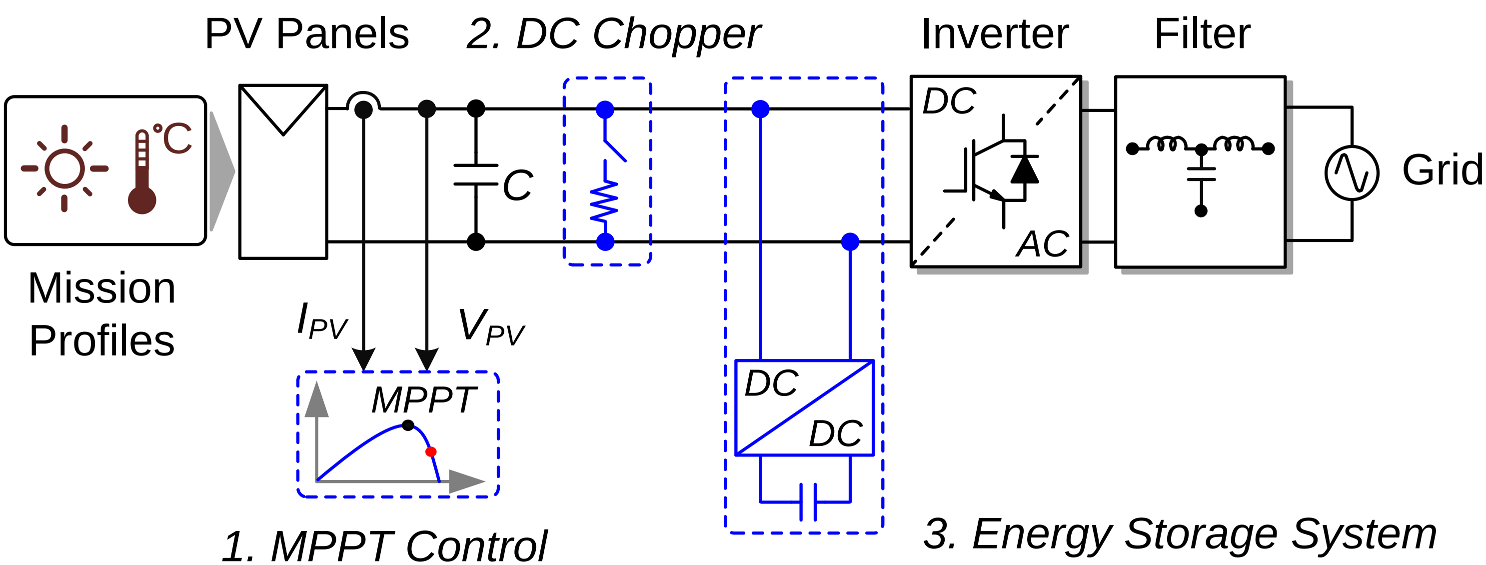
LVRT requirements



Compatible implementation of low voltage (and zero voltage) ride-through and anti-islanding requirements

Y. Yang, P. Enjeti, F. Blaabjerg, and H. Wang, "Suggested grid code modifications to ensure wide-scale adoption of photovoltaic energy in distributed power generation systems," *IEEE Ind. Appl. Mag.*, 2015.
Y. Yang, H. Wang, and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," *IEEE Trans. Ind. Appl.*, 2014.

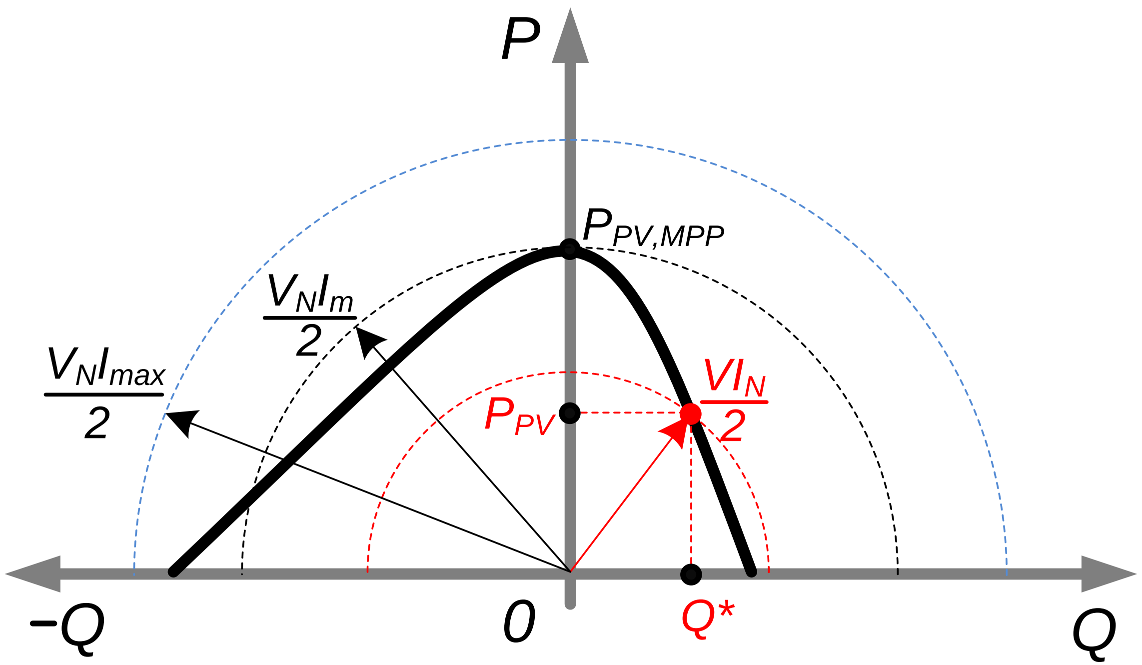
LVRT implementation - 1



Implementation possibilities of LVRT in single-phase PV inverters

Y. Yang, P. Enjeti, F. Blaabjerg, and H. Wang, "Suggested grid code modifications to ensure wide-scale adoption of photovoltaic energy in distributed power generation systems," *IEEE Ind. Appl. Mag.*, 2015.

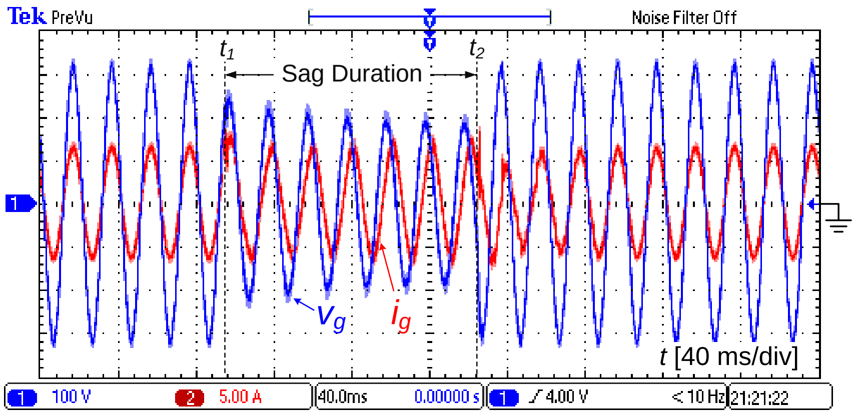
LVRT implementation - 2

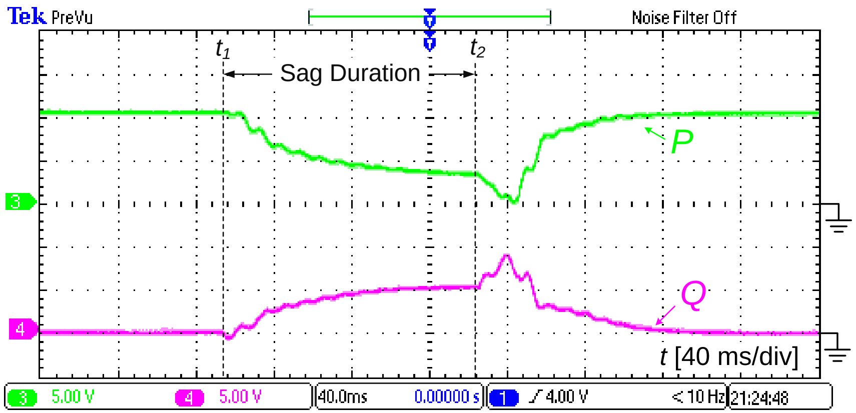


Implementation of LVRT by modifying the MPPT control

Y. Yang, F. Blaabjerg, and Z. Zou "Benchmarking of grid fault modes in single-phase grid-connected photovoltaic systems," *IEEE Trans. Ind. Appl.*, 2013.

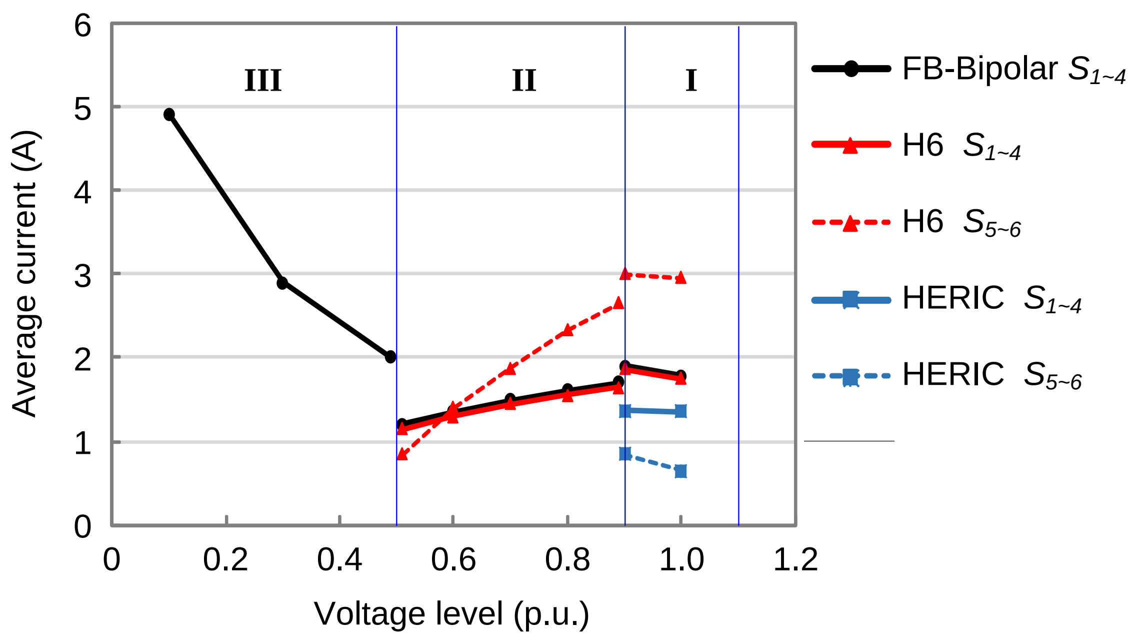
Tests of single-phase FB inverters in LVRT





Y. Yang and F. Blaabjerg, "Low voltage ride-through capability of a single-stage single-phase photovoltaic system connected to the low-voltage grid," *Int'l J. Photoenergy*, vol. 2013, pp. 1 - 9, 2013.
Y. Yang, F. Blaabjerg, and H. Wang, "Low voltage ride-through of single-phase transformerless photovoltaic inverters," *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 1942–1952, May-Jun. 2014.

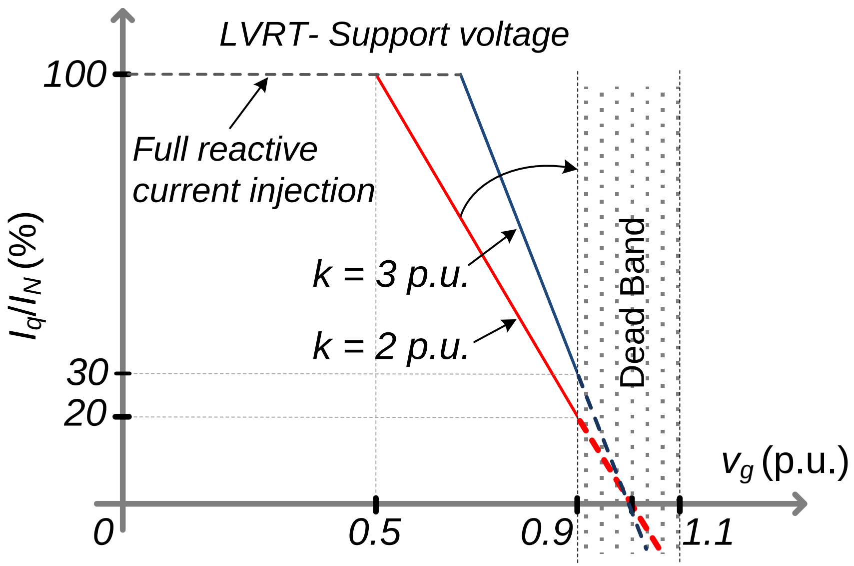
Tests of single-phase transformerless inverters in LVRT



Current stress vs. voltage level (transformerless inverters)

Y. Yang, F. Blaabjerg, and H. Wang, "Low voltage ride-through of single-phase transformerless photovoltaic inverters," *IEEE Trans. Ind. Appl.*, 2014.

Reactive Power Injection (RPI) requirements



Reactive current profile during LVRT

Y. Yang, H. Wang, and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," *IEEE Trans. Ind. Appl.*, 2014.

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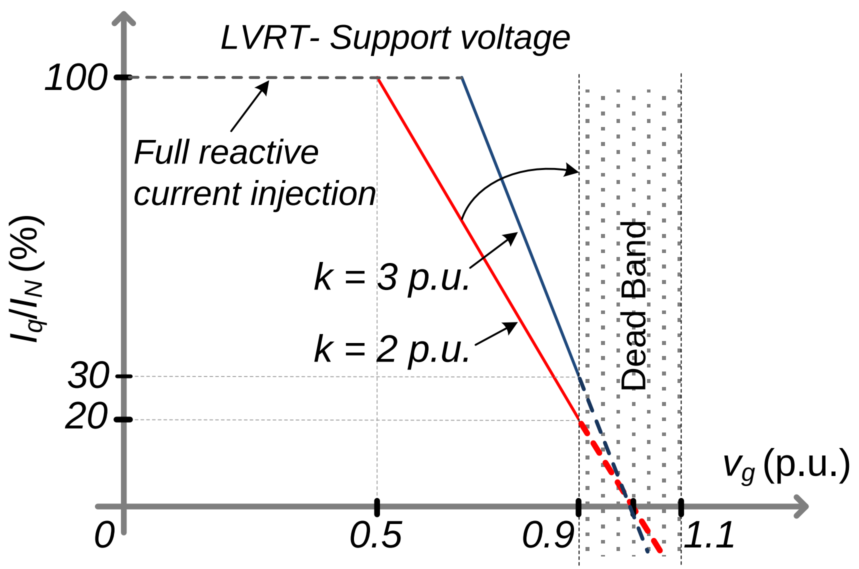
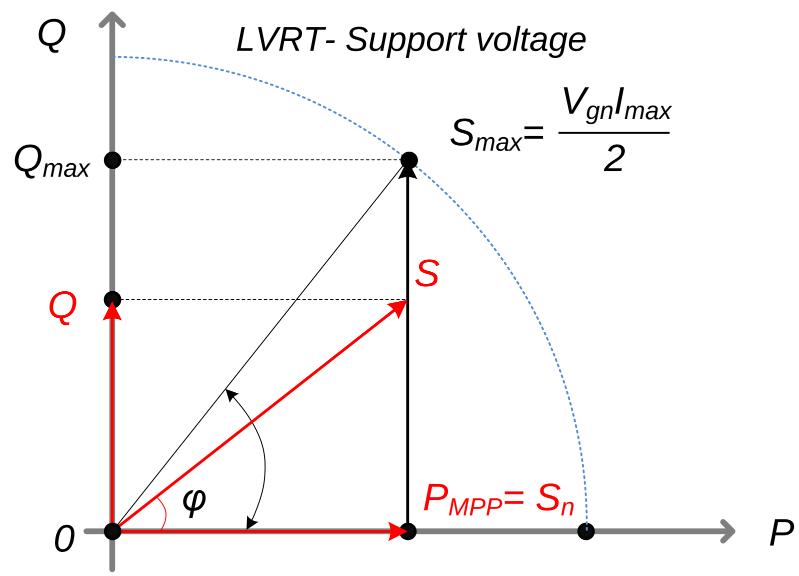


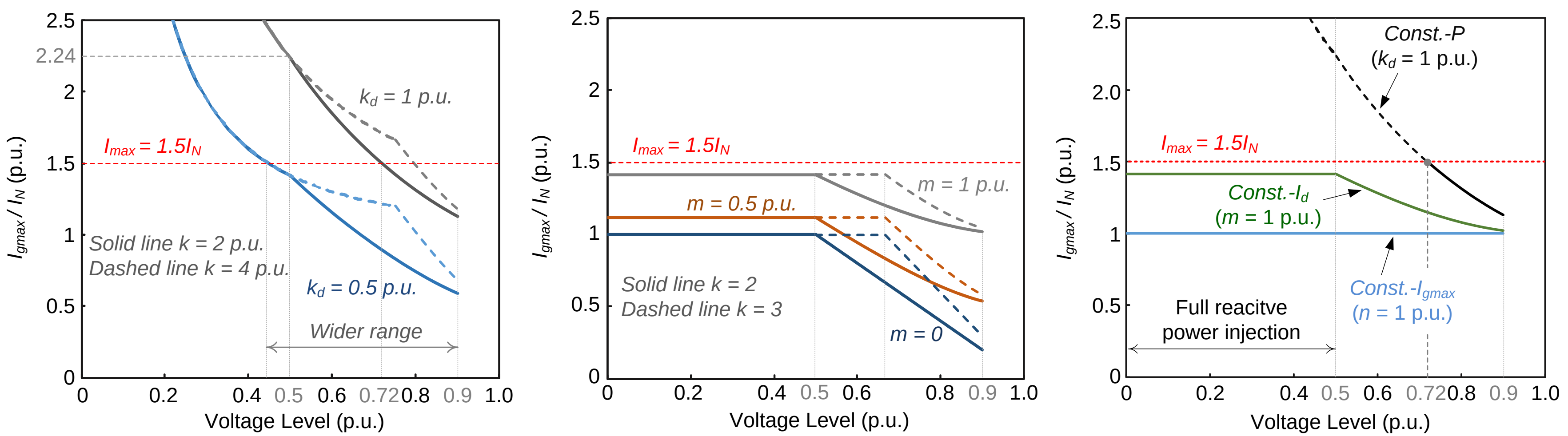
Reactive current profile during LVRT



Inverter *Q* capability

Y. Yang, H. Wang, and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," *IEEE Trans. Ind. Appl.*, 2014.

Reactive power injection strategies (proposed)



Const. - P Const. - I_d Const. - I_{gmax}

Y. Yang, H. Wang, and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," *IEEE Trans. Ind. Appl.*, 2014.

RPI tests of single-phase PV inverters in LVRT

Const. - I_{gmax}

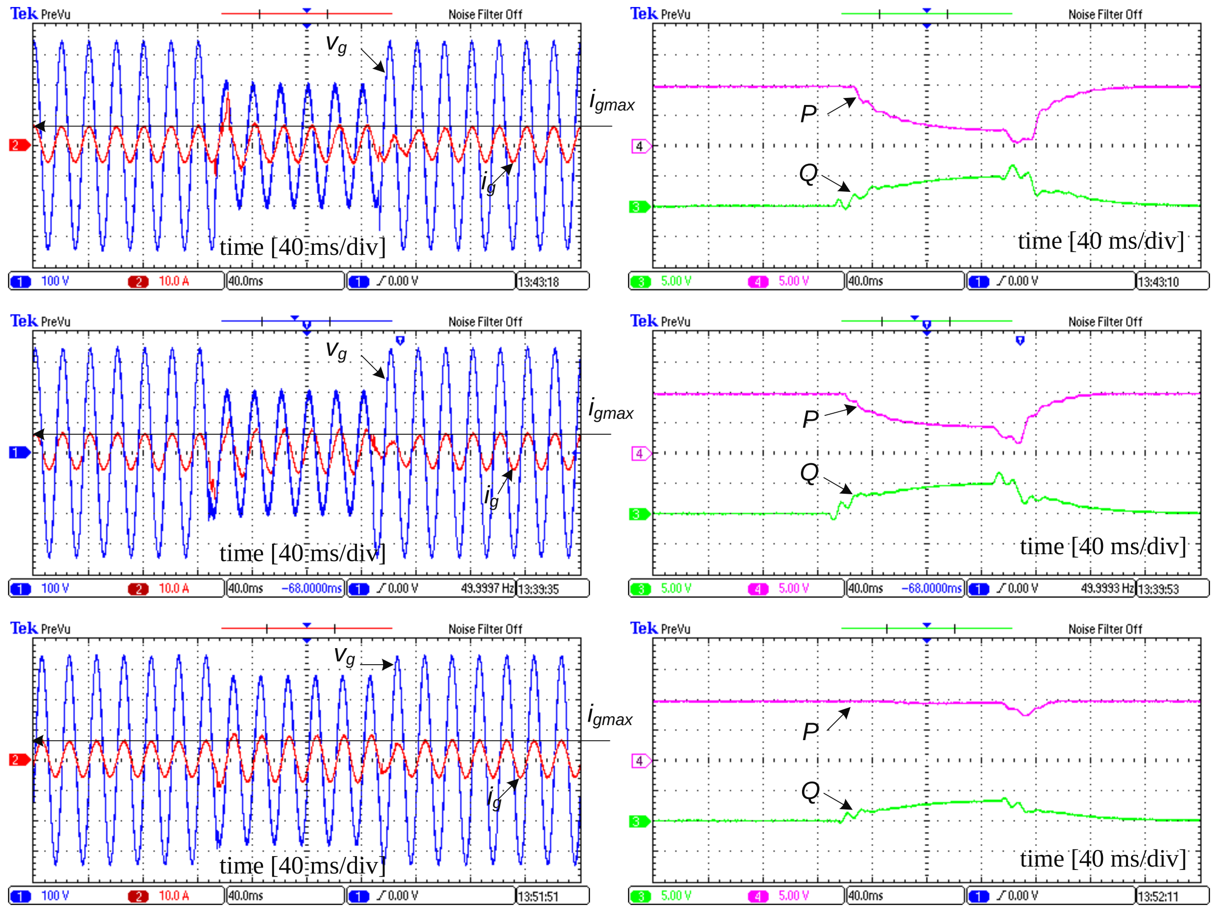
(45 % drop)

Const. - I_d

(45 % drop)

Const. - P

(20 % drop)



Y. Yang, H. Wang, and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," *IEEE Trans. Ind. Appl.*, 2014.

Constant Power Generation (CPG) Concept

Challenges increase with an even wide-scale PV adoption:

- **Overloading** at peak power generation (voltage rise, transformer saturation)
- **Limited utilization** of PV inverters
- **High temperature peaks and variations** due to intermittency

Y. Yang, H. Wang, F. Blaabjerg, and T. Kerekes, "A hybrid power control concept for PV inverters with reduced thermal loading," *IEEE Trans. Power Electron.*, 2014.

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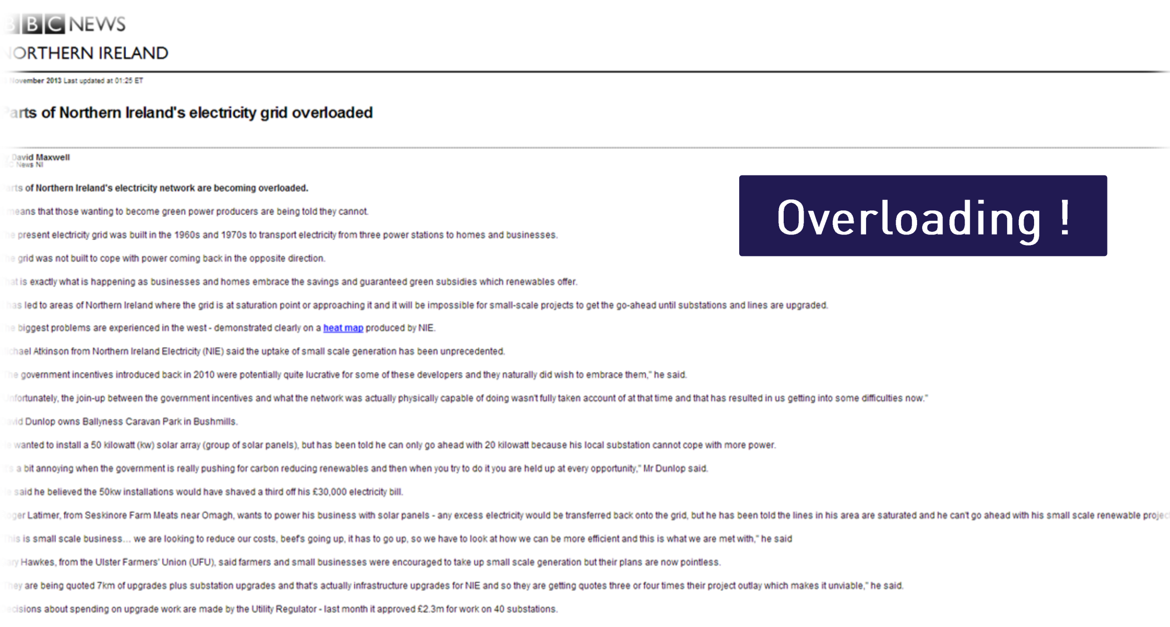

BBC NEWS
ORTHERN IRELAND

ovember 2013 Last updated at 01:25 ET

arts of Northern Ireland's electricity grid overloaded

avid Maxwell
News NI

rts of Northern Ireland's electricity network are becoming overloaded.

eans that those wanting to become green power producers are being told they cannot.

present electricity grid was built in the 1960s and 1970s to transport electricity from three power stations to homes and businesses.

grid was not built to cope with power coming back in the opposite direction.

at is exactly what is happening as businesses and homes embrace the savings and guaranteed green subsidies which renewables offer.

as led to areas of Northern Ireland where the grid is at saturation point or approaching it and it will be impossible for small-scale projects to get the go-ahead until substations and lines are upgraded.

biggest problems are experienced in the west - demonstrated clearly on a heat map produced by NIE.

chael Atkinson from Northern Ireland Electricity (NIE) said the uptake of small scale generation has been unprecedented.

e government incentives introduced back in 2010 were potentially quite lucrative for some of these developers and they naturally did wish to embrace them," he said.

fortunately, the join-up between the government incentives and what the network was actually physically capable of doing wasn't fully taken account of at that time and that has resulted in us getting into some difficulties now."

vid Dunlop owns Ballyness Caravan Park in Bushmills.

wanted to install a 50 kilowatt (kw) solar array (group of solar panels), but has been told he can only go ahead with 20 kilowatt because his local substation cannot cope with more power.

s a bit annoying when the government is really pushing for carbon reducing renewables and then when you try to do it you are held up at every opportunity," Mr Dunlop said.

said he believed the 50kw installations would have shaved a third off his £30,000 electricity bill.

ger Latimer, from Seskinore Farm Meats near Omagh, wants to power his business with solar panels - any excess electricity would be transferred back onto the grid, but he has been told the lines in his area are saturated and he can't go ahead with his small scale renewable proje

is is small scale business... we are looking to reduce our costs, beef's going up, it has to go up, so we have to look at how we can be more efficient and this is what we are met with," he said

y Hawkes, from the Ulster Farmers' Union (UFU), said farmers and small businesses were encouraged to take up small scale generation but their plans are now pointless.

ey are being quoted 7km of upgrades plus substation upgrades and that's actually infrastructure upgrades for NIE and so they are getting quotes three or four times their project outlay which makes it unviable," he said.

cisions about spending on upgrade work are made by the Utility Regulator - last month it approved £2.3m for work on 40 substations.

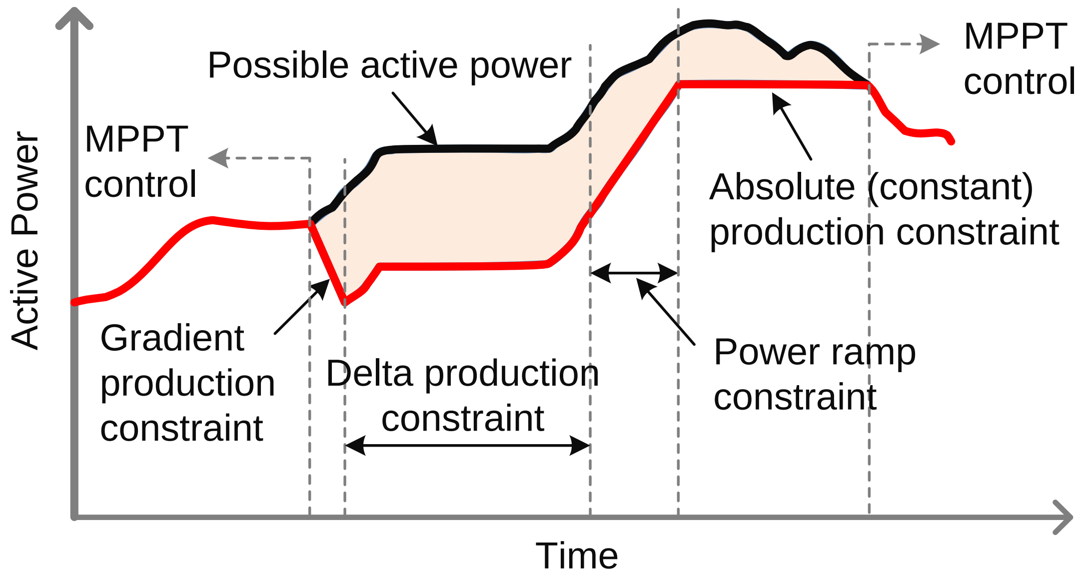
Michael Atkinson from NIE admitted that many connections still will not be able to go ahead.

Overloading !

<u>Y. Yang</u>, H. Wang, F. Blaabjerg, and T. Kerekes, "A hybrid power control concept for PV inverters with reduced thermal loading," *IEEE Trans. Power Electron.*, 2014.

Constant Power Generation (CPG) Concept

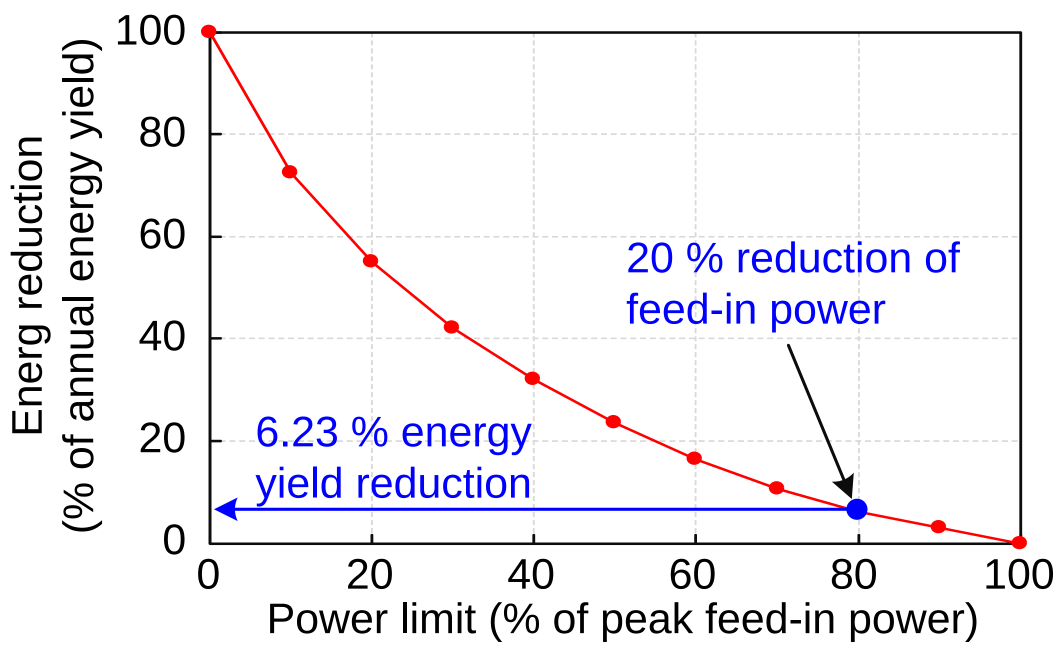
CPG – one of the Active Power Control (APC) functions



Extend the CPG function for WTS in Denmark to wide-scale PV applications?

Y. Yang, F. Blaabjerg, and H. Wang, "Constant power generation of photovoltaic systems considering the distributed grid capacity," in *Proc. of APEC*, pp. 379-385, 16-20 Mar. 2014.

Feasibility of CPG for PV systems



Energy reduction vs. limiting feed-in power

Y. Yang, H. Wang, F. Blaabjerg, and T. Kerekes, "A hybrid power control concept for PV inverters with reduced thermal loading," *IEEE Trans. Power Electron.*, 2014.

Implementation of CPG in single-phase PV systems - 1

- Energy "reservoir" – storage elements
- Power management/balancing control
- Modifying the MPPT

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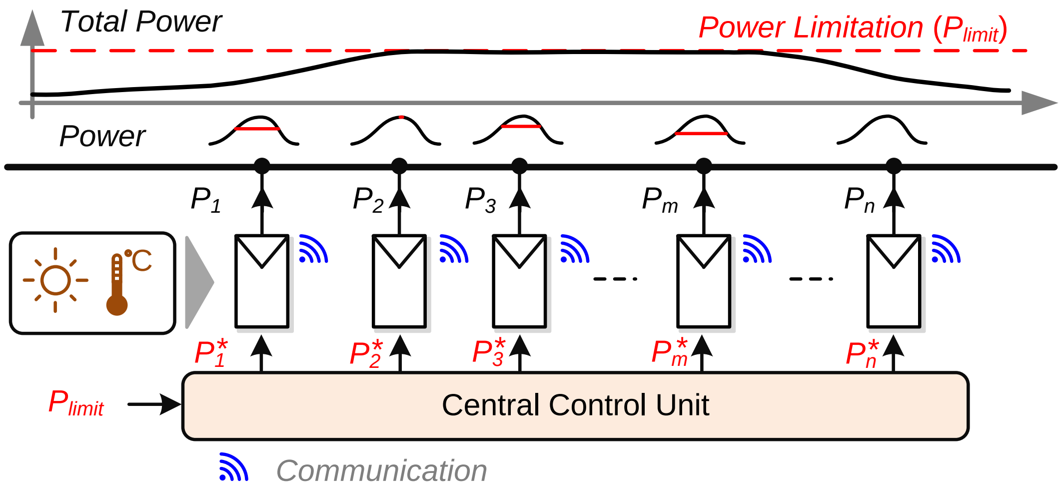
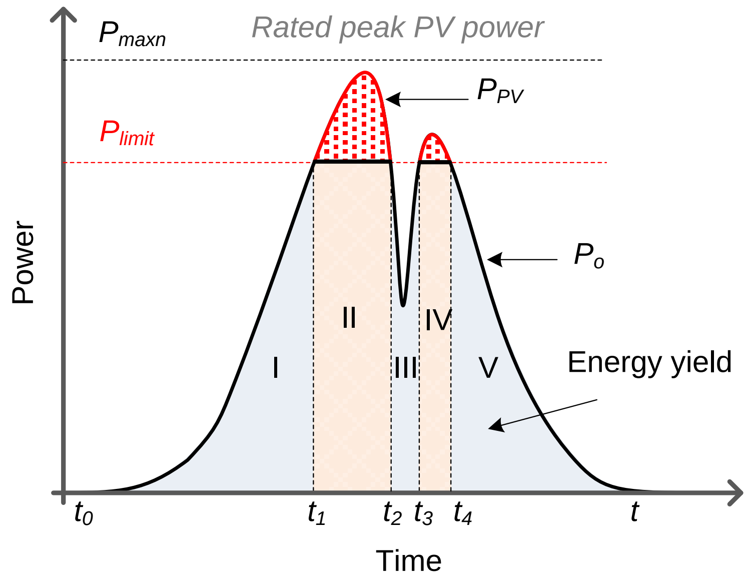
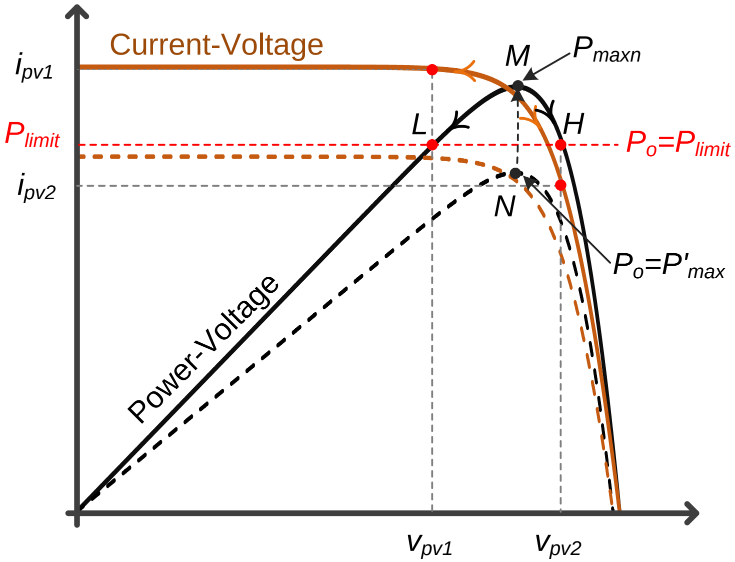
- Energy "reservoir" – storage elements
- Power management/balancing control
- Modifying the MPPT



Implementation of CPG in single-phase PV systems - 2

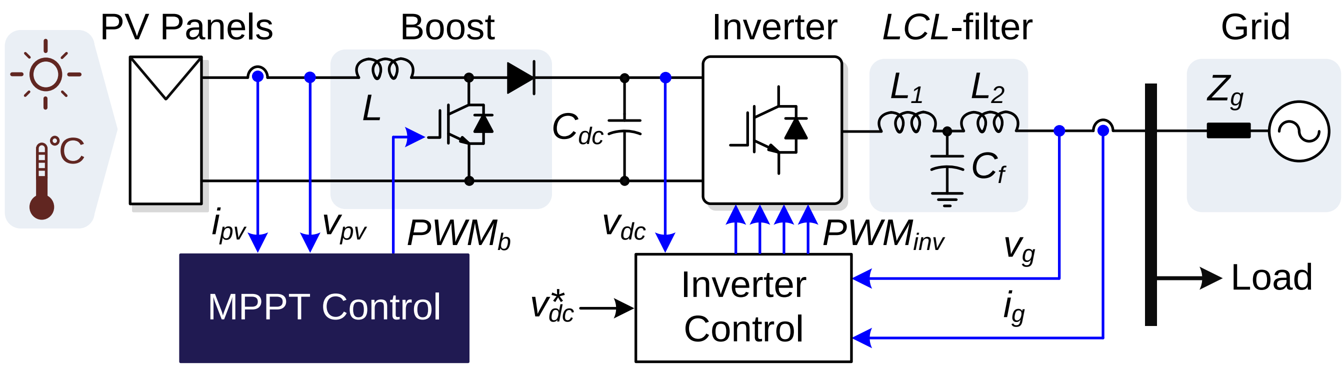
- Energy "reservoir" – storage elements
- Power management/balancing control
- Modifying the MPPT





Constant Power Generation (CPG) Concept

Entire implementation of CPG in double-stage systems



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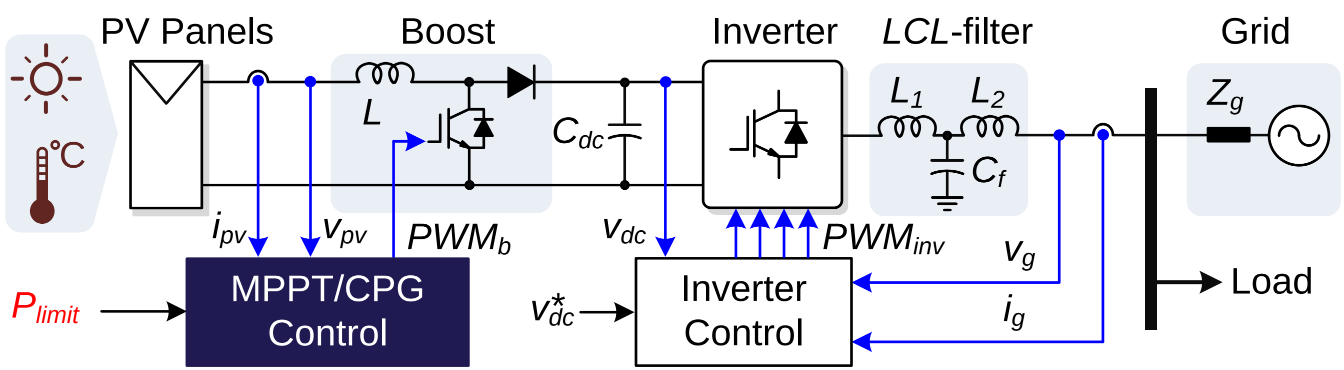
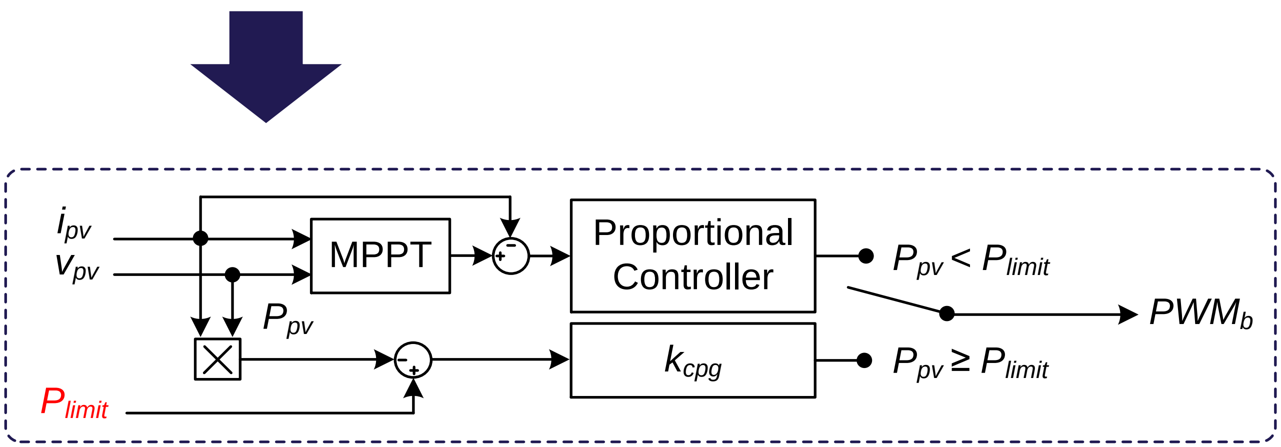
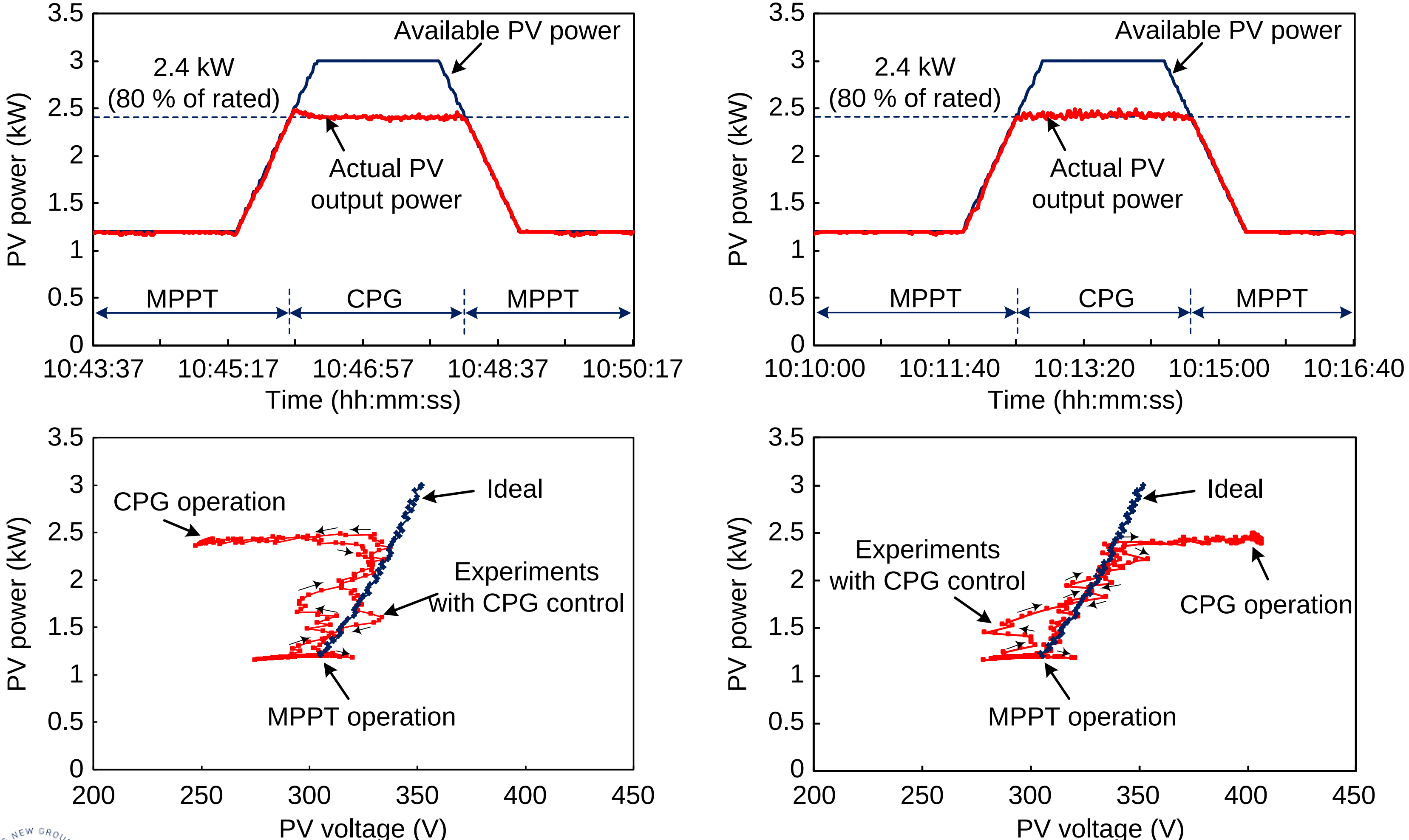


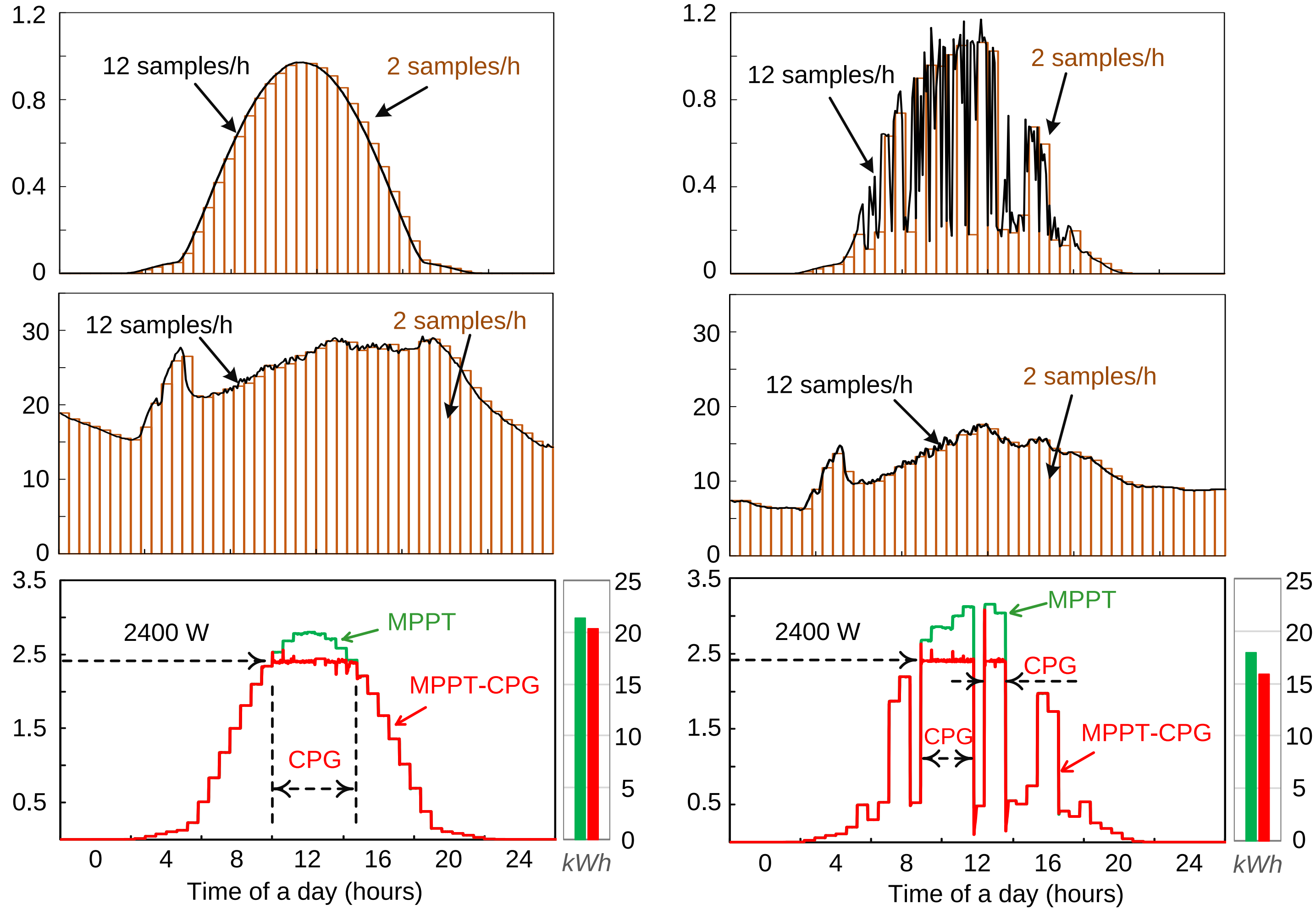


Constant Power Generation (CPG) Concept

Operation examples of CPG control (experiments) - 1

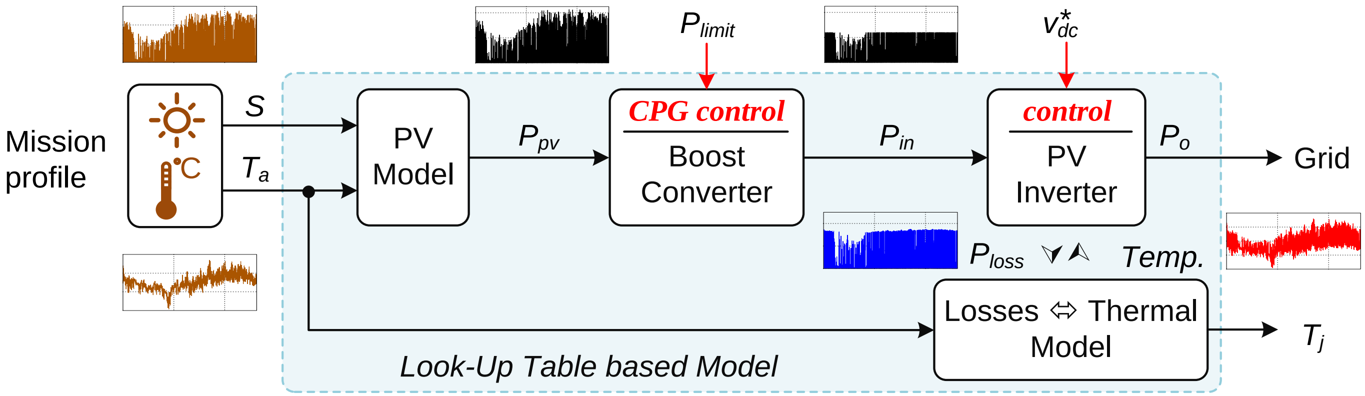


Operation examples of CPG control (simulations) - 2

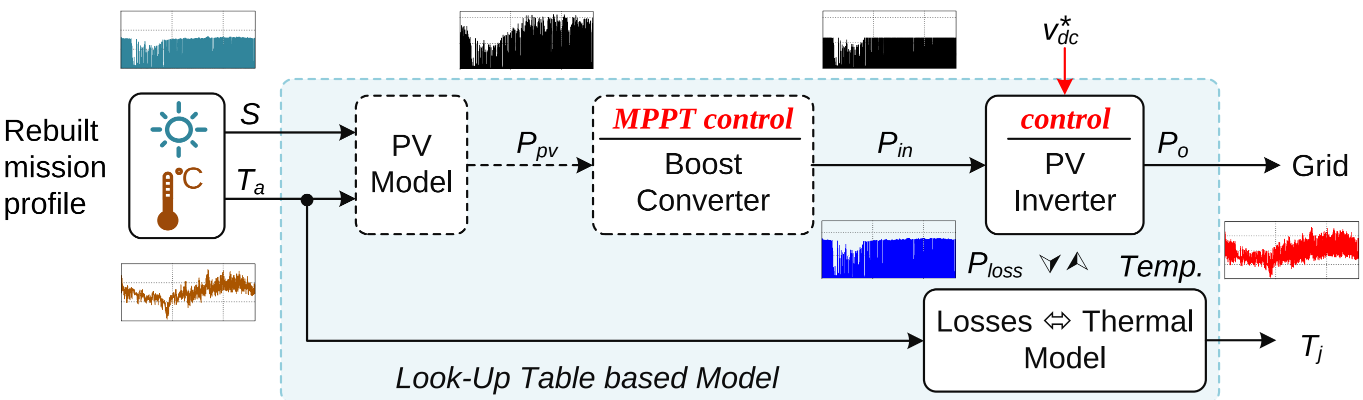


Reduced thermal loading enabled by CPG control

Direct CPG

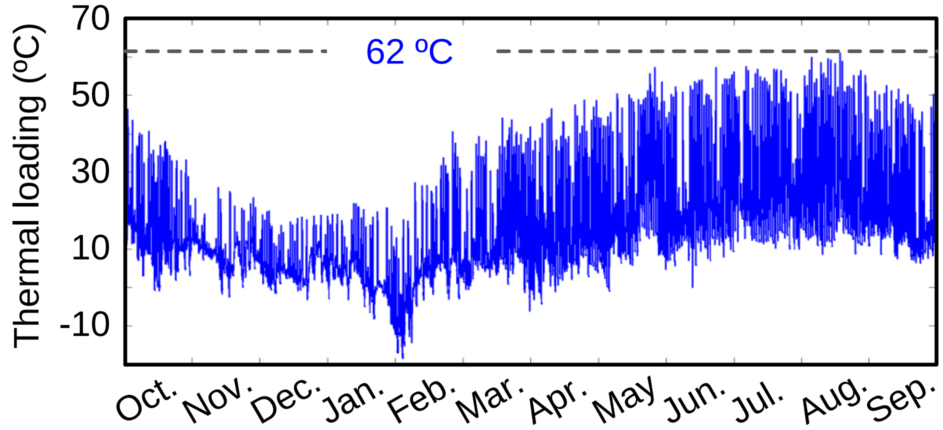


Rebuilt MP

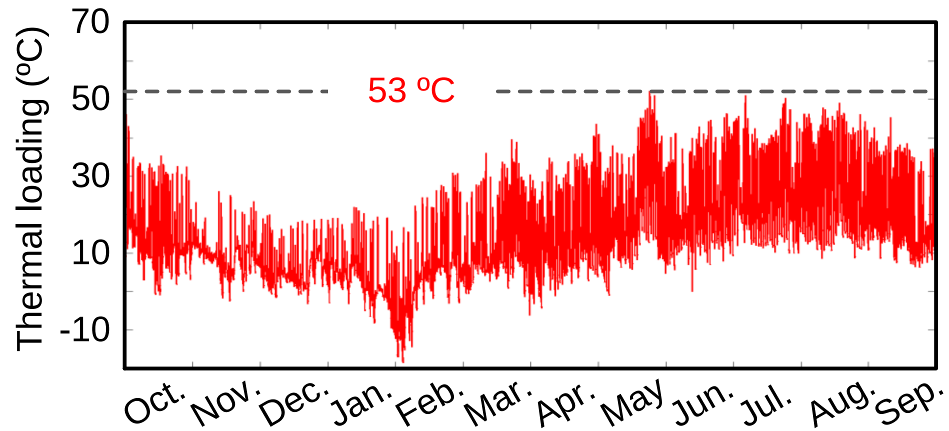


Results – thermal loading with and w/o CPG control

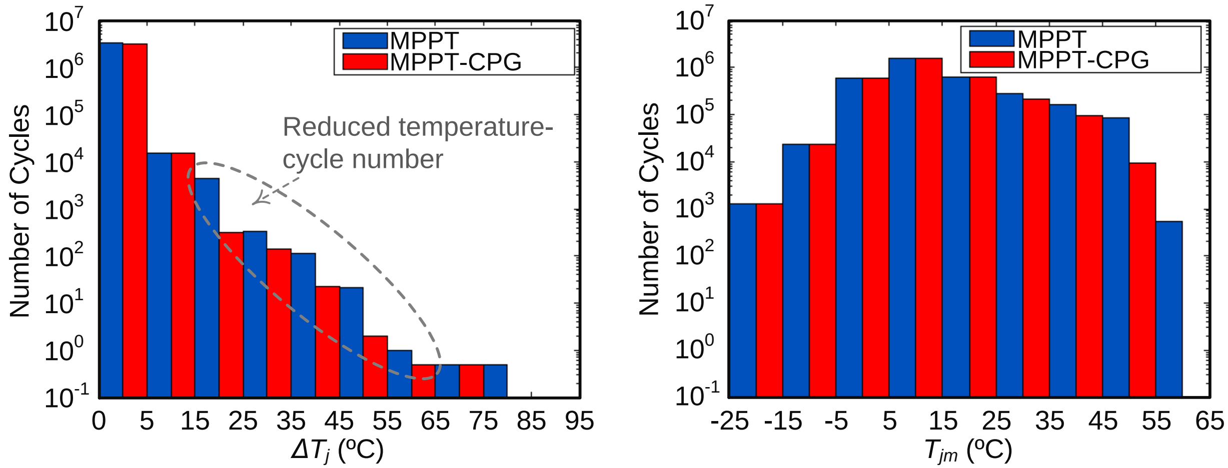
MPPT control



CPG control (80%)



Results – reliability (application of the evaluation approach)



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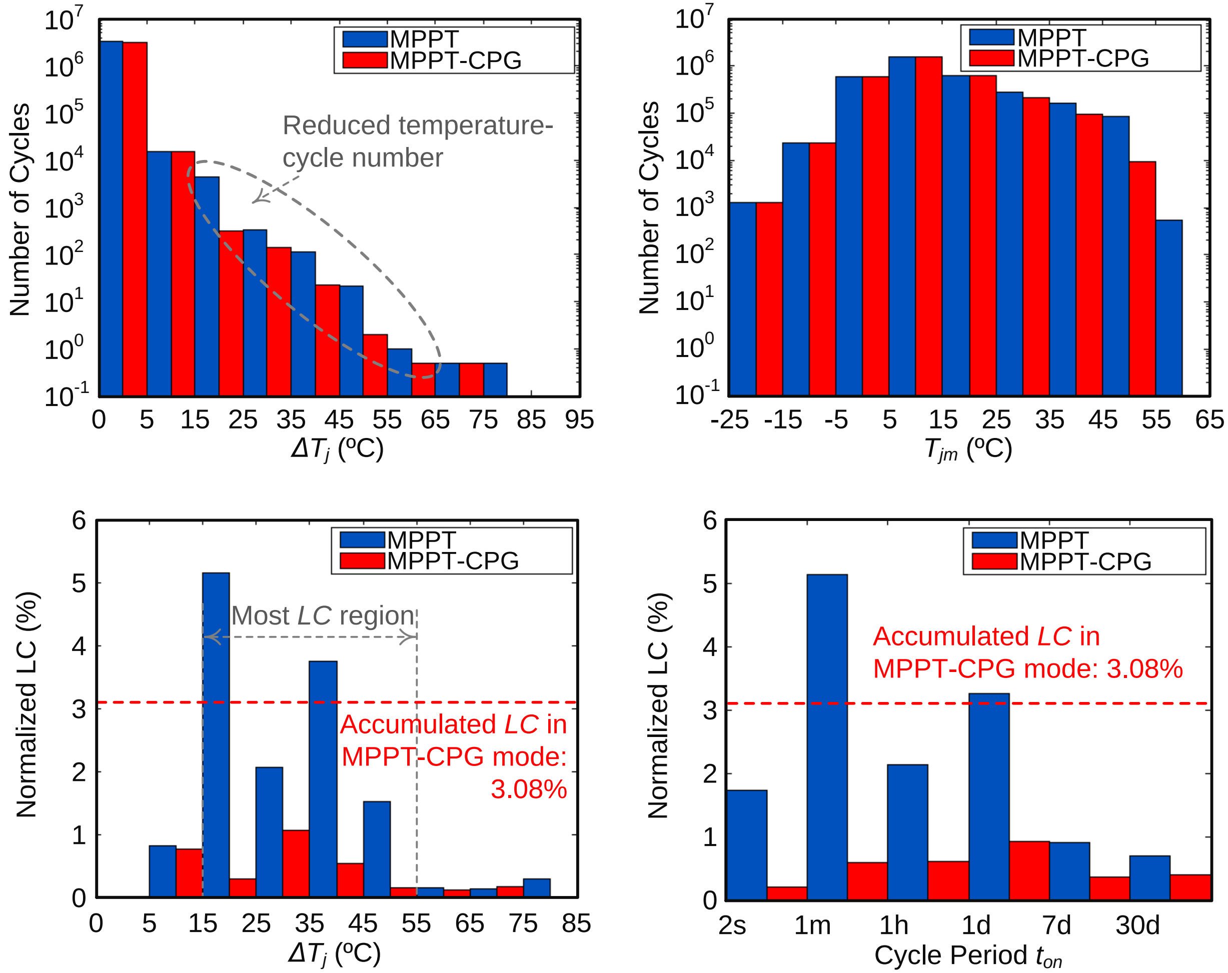
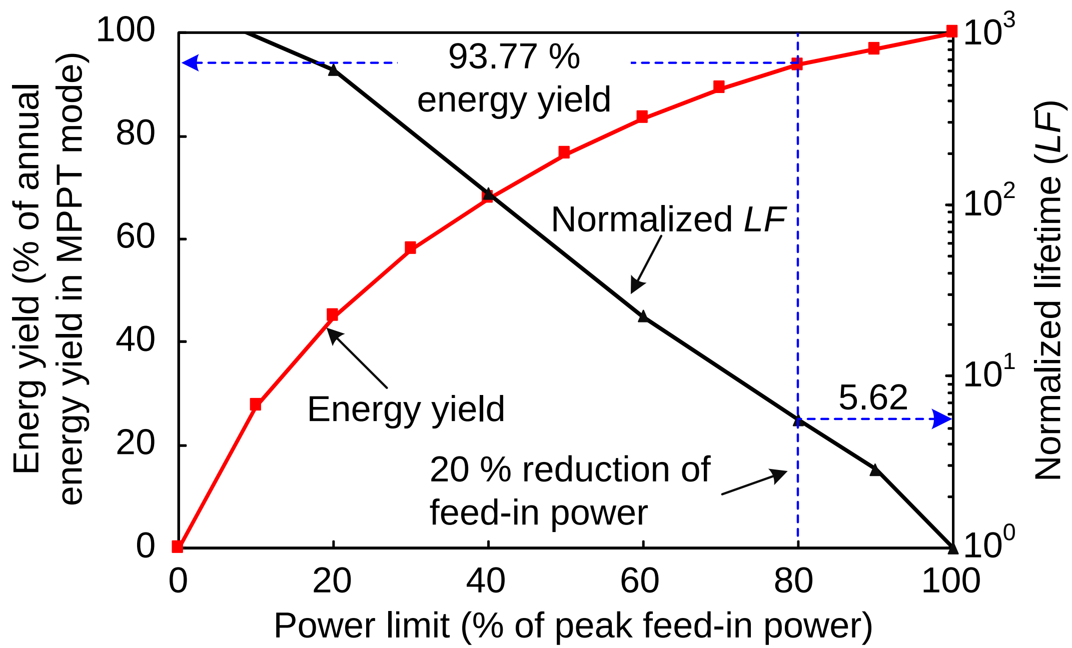


Benefits from CPG control



Energy yield and lifetime improvement (single device)
under different power limits (CPG control)

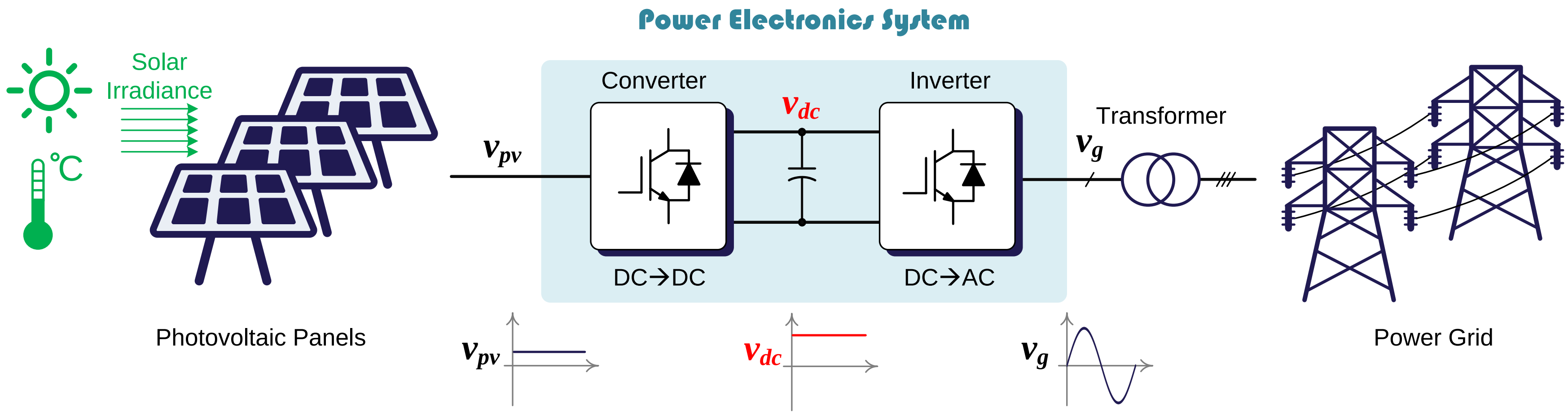
Y. Yang, F. Blaabjerg, and H. Wang, "Constant power generation of photovoltaic systems considering the distributed grid capacity," in *Proc. of APEC*, pp. 379-385, 16-20 Mar. 2014.

I. Introduction

II. Advanced Control Strategies

III. Conclusions

- Summary and outlook



Summary

Main contributions of the PhD project

- Comprehensive comparison of transformerless inverters

- Proposed grid code/requirement modifications

- Developed advanced control strategies
  - Harmonic control
  - Low voltage ride-through control
    with proposed reactive power injection strategies
  - Constant power generation control

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Ultimate Solutions?

Outlook

Advancing Grid-Friendly PV Systems

Research perspectives enabled by this project

- Evaluation of grid-side filters (also power losses) and current controllers in different operation modes
- Reactive power injection (thermal performance and cost of reactive power)
- System integration with e.g. storage systems and electrical vehicles, and thus grid code modifications
- More detailed investigations of the constant power generation control
- Developing analytical method/model of junction temperature control
- Application of advanced power devices (SiC, GaN) in those inverters

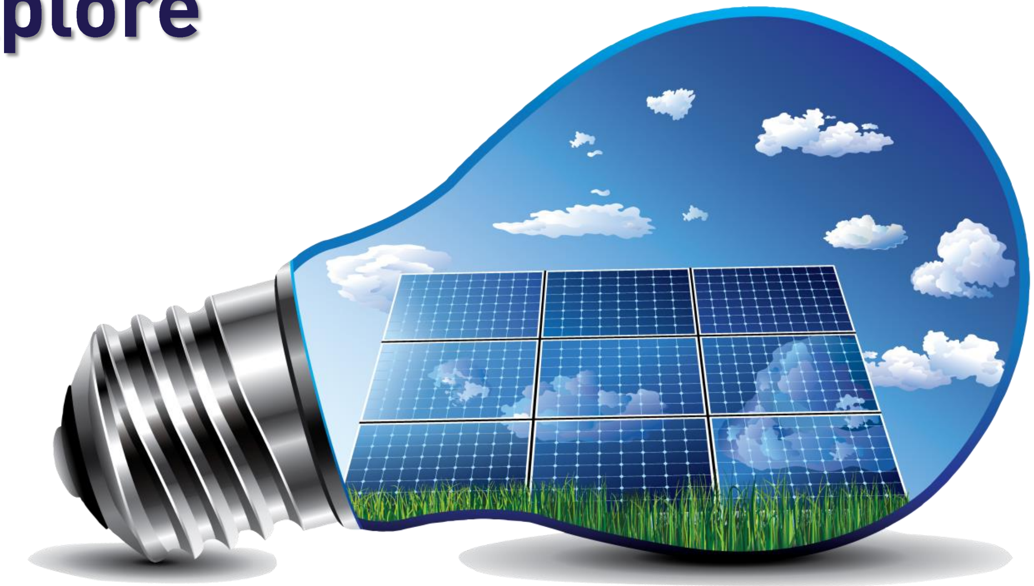
Advancing Grid-Friendly PV Systems

"Prediction is very difficult, especially about the future"

Niels Bohr

Danish physicist (1885 - 1962)

A brighter future for grid-friendly PV is waiting for us to explore



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Thank you all!

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