Photovoltaic Systems as Virtual Energy Storage for Frequency Support

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About the Presenter

Yongheng YANG ZJU100 Professor at Zhejiang University, China

He received the B.Eng. degree from Northwestern Polytechnical University, China, in 2009 and the Ph.D. degree from Aalborg University (AAU), Denmark, in 2014. He was a Postgraduate Student with Southeast University, China, from 2009 to 2011. In 2013, he spent three months as a Visiting Scholar at Texas A&M University, USA. Since 2014, he has been with the Department of Energy Technology, AAU, where he became a tenured Associate Professor in 2018. In January 2021, he joined Zhejiang University, China, where he is currently a ZJU100 Professor with the Institute of Power Electronics.

His current research is focused on the grid-integration of photovoltaic systems and control of power converters, particularly, the mechanism and control of grid-forming systems.

Dr. Yang was the Chair of the IEEE Denmark Section (2019– 2020). He is an Associate Editor for several IEEE Transactions/Journals. He is a Deputy Editor of the IET Renewable Power Generation (RPG). He was the recipient of the 2018 IET RPG Premium Award and was an Outstanding Reviewer for the IEEE TPEL in 2018. He was the recipient of the 2021 Richard M. Bass Outstanding Young Power Electronics Engineer Award from the IEEE PELS. In addition, he has received two IEEE Best Paper Awards. He is currently the Secretary of the IEEE PELS Technical Committee on Sustainable Energy Systems.

About the Presentation

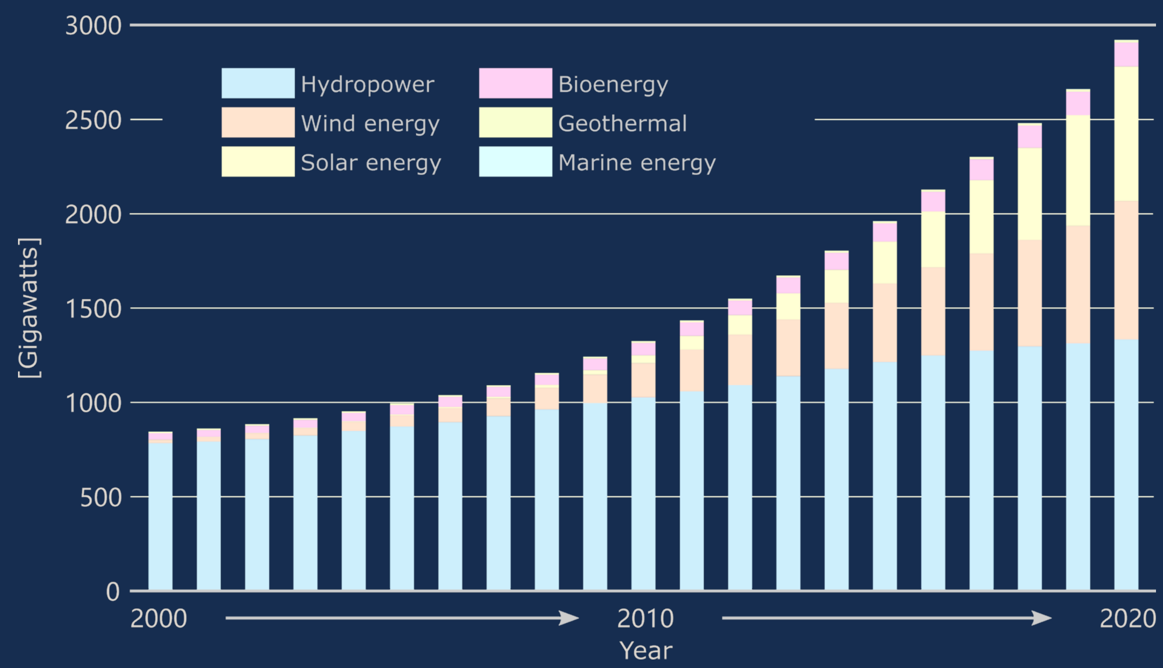
Background and Motivation

Virtual Energy Storage

Frequency Support Operation

Summary and Discussion

Renewable Evolution



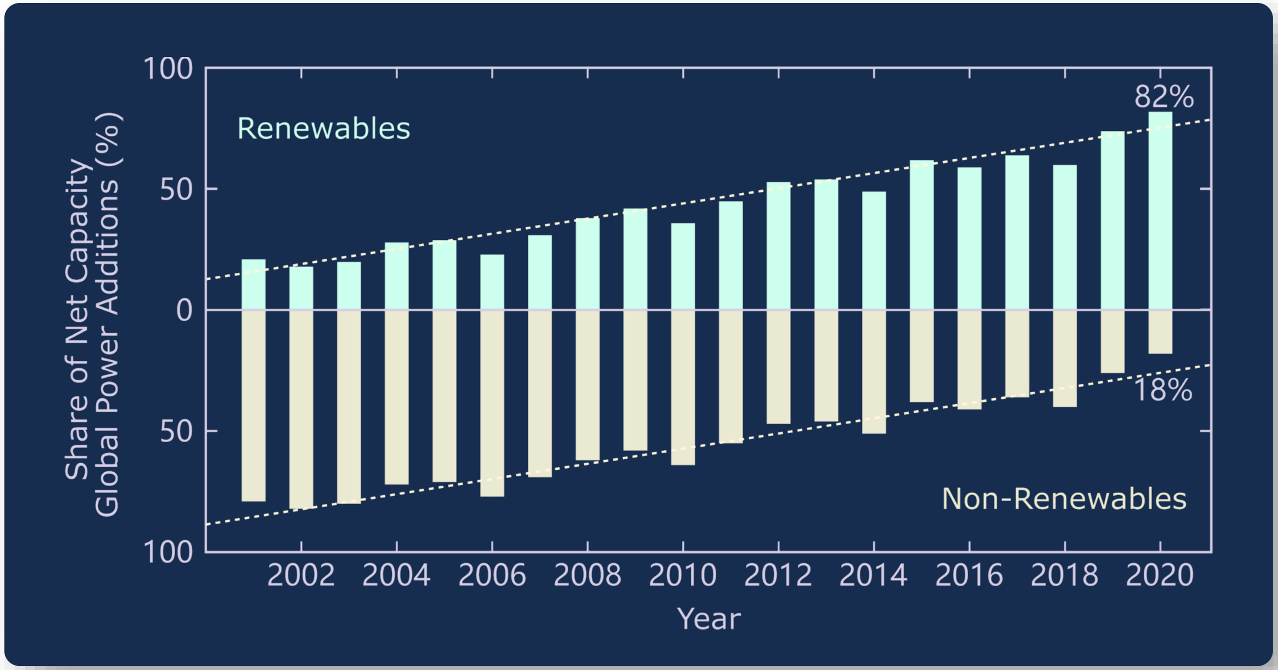
Global Renewable Energy Annual Changes in Gigawatt (2000-2020)

~3000 GW in total

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy
3. Solar includes photovoltaics and solar thermal
4. Wind includes both onshore and offshore wind energy

(Source: IRENA, "Renewable energy capacity statistics 2021", http://www.irena.org/publications, March 2021)

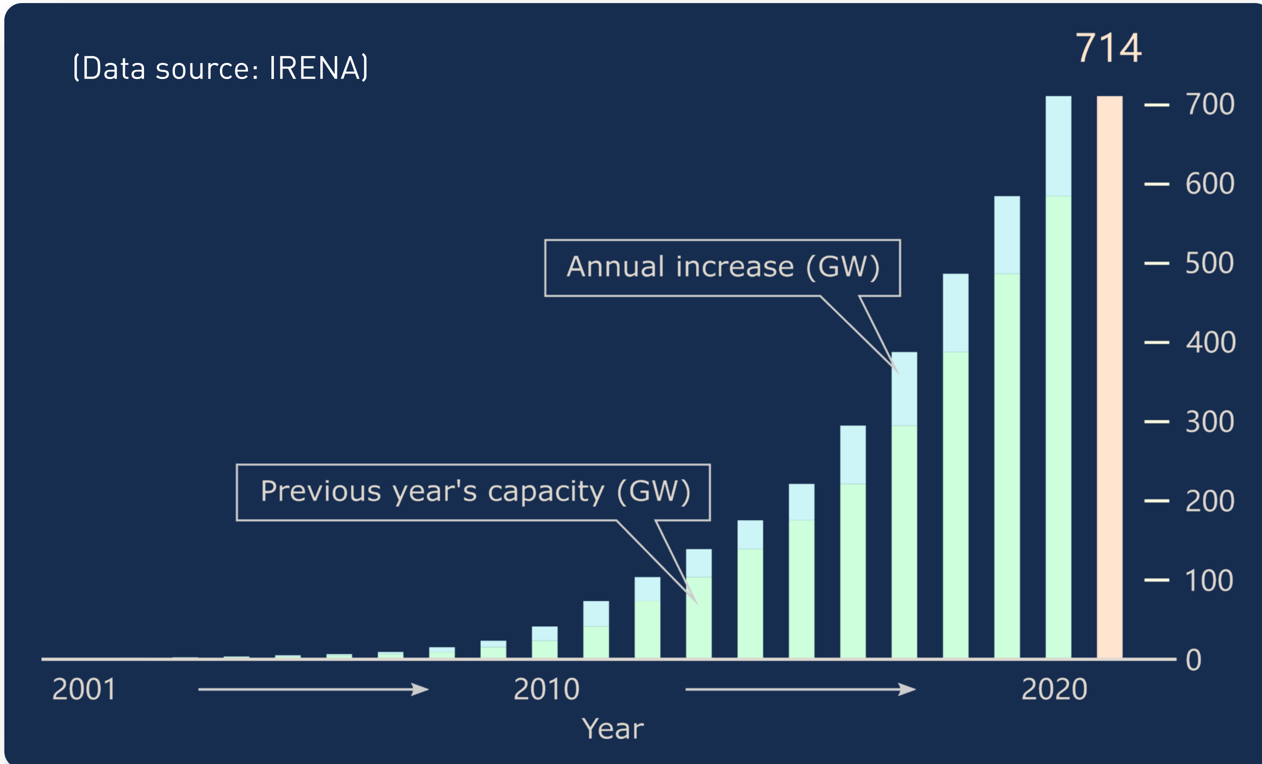
Net Total Annual Additions



RES and Non-RES as A Share of The Net Total Annual Additions

(Source: IRENA, "Renewable Capacity Highlights", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_-RE_Capacity_Highlights_2021.pdf?la=en&hash=1E133689564BC40C2392E85026F71A0D7A9C0B91, March 2021)

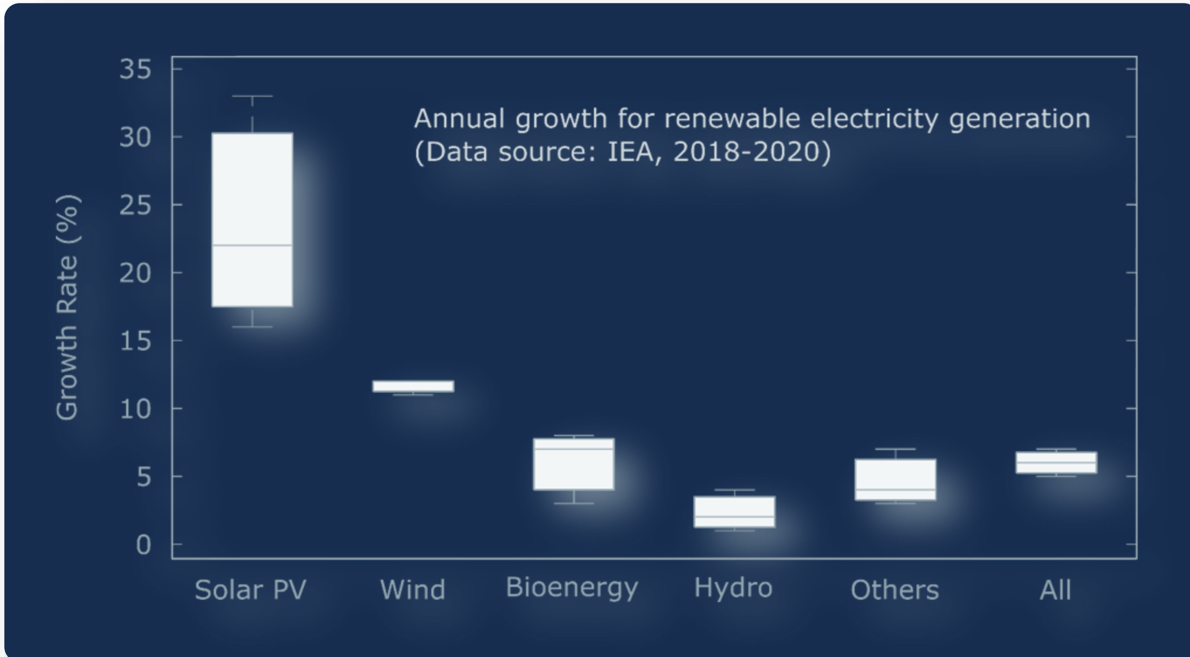
Photovoltaic Capacity



Global installed solar PV capacity (until 2020): **714 GW**, 2020: **127 GW**

- More significant total capacity (45% non-hydro renewables; ~1/4 total incl. hydro).
- Fastest growth rate (22% between 2018-2020, 33% in 2018).

Photovoltaic Development



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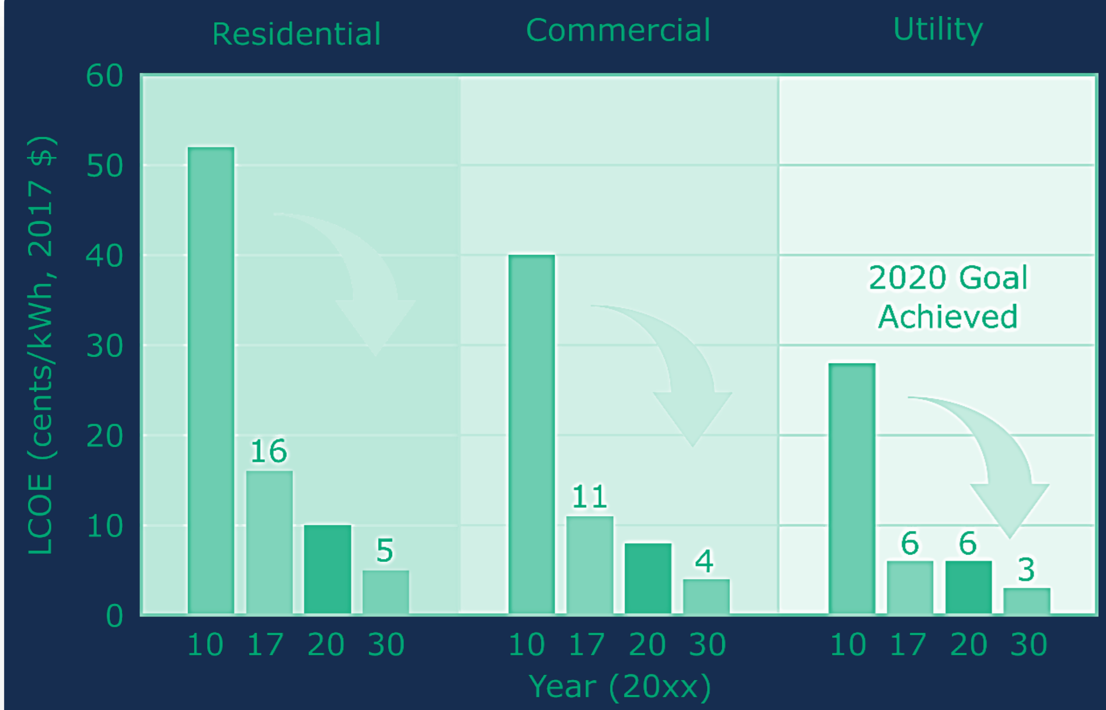
More Expected

Increasing competitiveness by lowering Cost of Energy



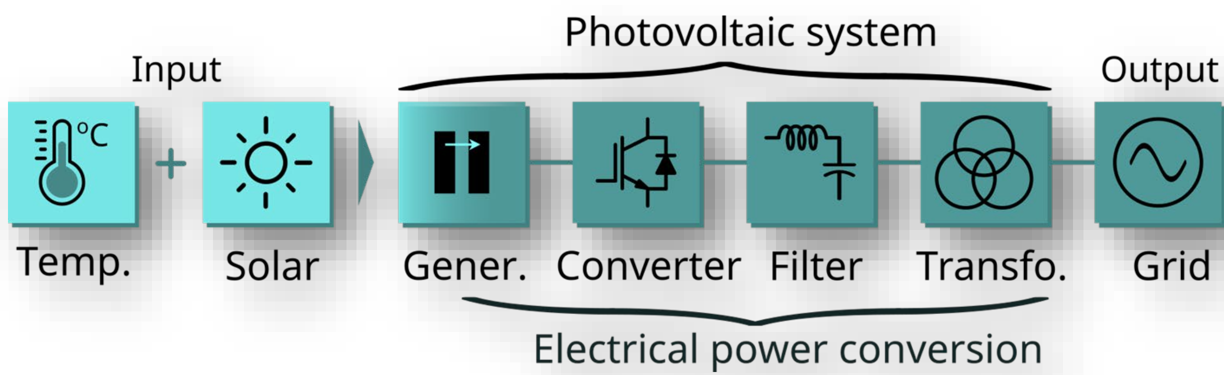
In 2017, DOE's Solar Energy Technologies Office (SETO) announced that the industry had achieved the 2020 cost goal for utility-scale solar of **6¢/kWh**.

*Levelized cost of electricity (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010–17.

U.S. DOE - https://www.energy.gov/sites/prod/files/2018/05/f51/SunShot%202030%20Fact%20Sheet.pdf

How to Integrate?

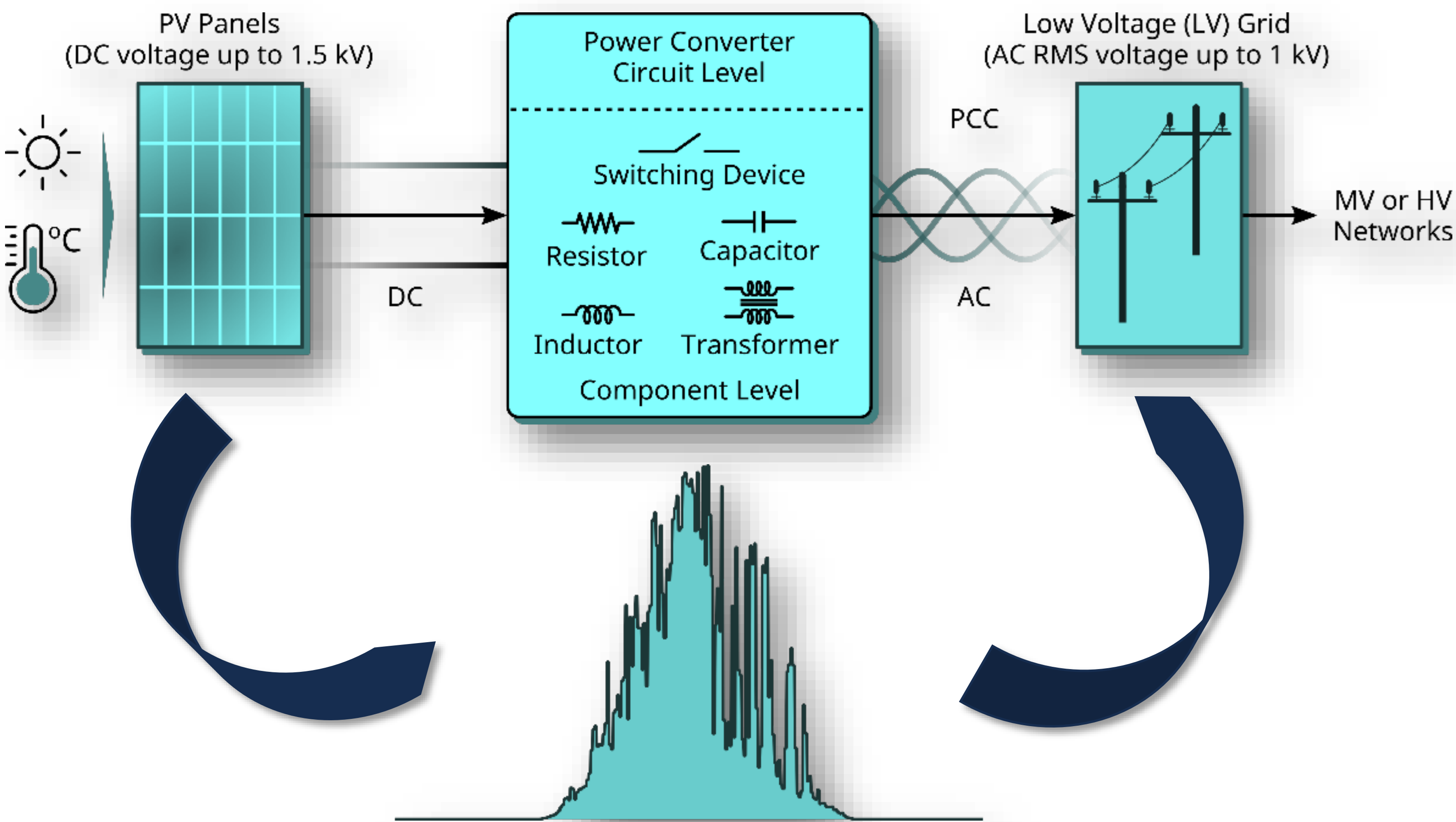
General Photovoltaic power conversion (grid integration)



- **Photovoltaic Effect**
  Power generation is dependent on the ambient conditions
- **Power Electronics**
  Power converters are essential to realize the power transfer
- **Power Grid**
  Synchronous generator governed system with fixed frequency and voltage

PV Makes Trouble

A Double-Edged sword



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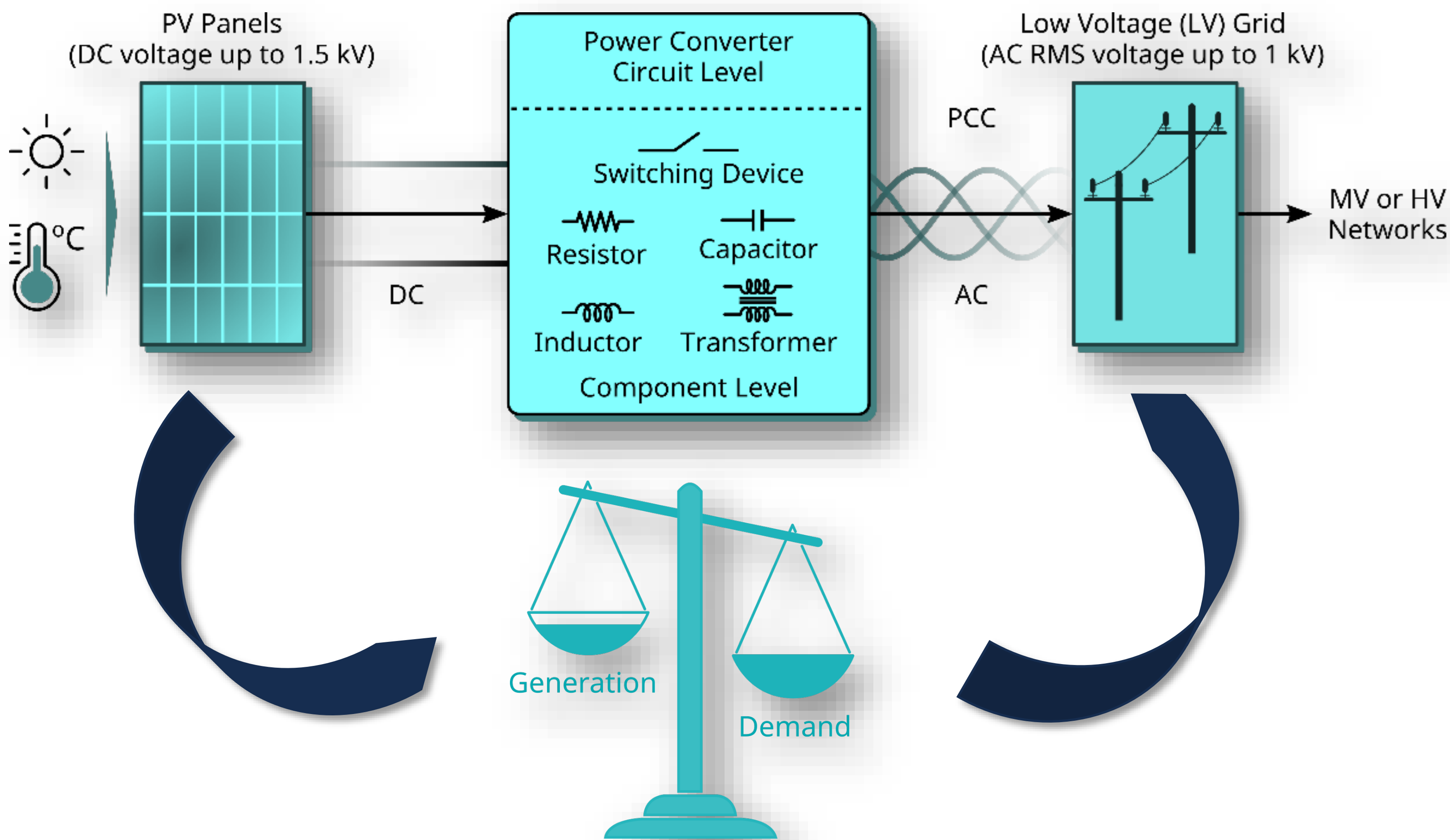


More Challenges

Challenges with a high penetration of PV systems

- Overloading at peak power generation (voltage rise, transformer saturation)
- Equipment operation failures/issues (feeder regulation, load tap changes, switched capacitor banks, etc.)
- Demand and energy management (masking peak demand, unbalancing)
- System protection (relay desensitization, breaker, unidirectional islanding)
- Power quality (harmonics, flickers)
- ...

BBC NEWS

ORTHERN IRELAND

ovember 2013 Last updated at 01:25 ET

arts of Northern Ireland's electricity grid overloaded

avid Maxwell
C 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.

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

e 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.

e 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.

nfortunately, 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.

e 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

ry 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.

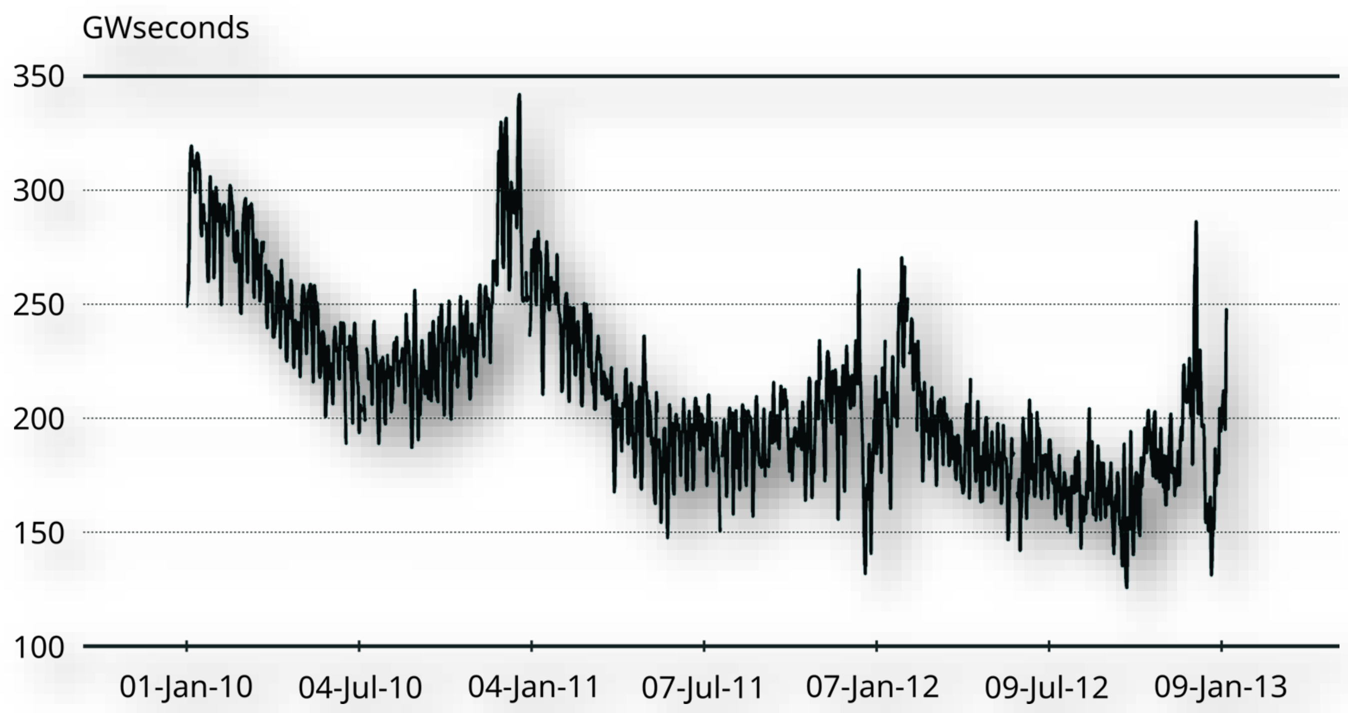
t Michael Atkinson from NIE admitted that many connections still will not be able to go ahead.

Overloading !

Y. Yang, et al, "A hybrid power control concept for PV inverters with reduced thermal loading," IEEE Trans. Power Electron., 2014.

Reduction of Inertia

Reduction of synchronous inertia in the National Grid (UK)



G. Stein and T. Derry, "Presentation: Rapid Frequency Response - BSSG/CBSG," National Grid, 4 Sept 2013.

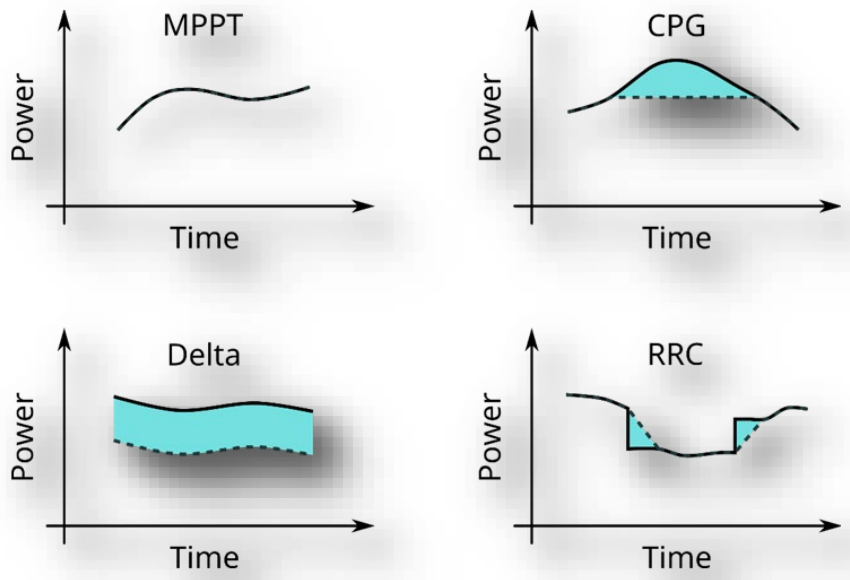
Demands on PV Systems

Grid-Connected PV Systems ranging from several kWs to even a few MWs are being developed very fast and will soon take a major part of electricity generation in some areas. PV systems must comply with much tougher requirements than ever before - a combination of **standardized PV features and advanced demands** for a grid-friendly integration.

- ▶ Flexible power controllability
- ▶ Reactive power control
- ▶ Frequency regulation through active power
- ▶ Harmonic compensation or control
- ▶ Dynamic grid support
- ▶ Further enhancing reliability and efficiency

More Stringent Requirements

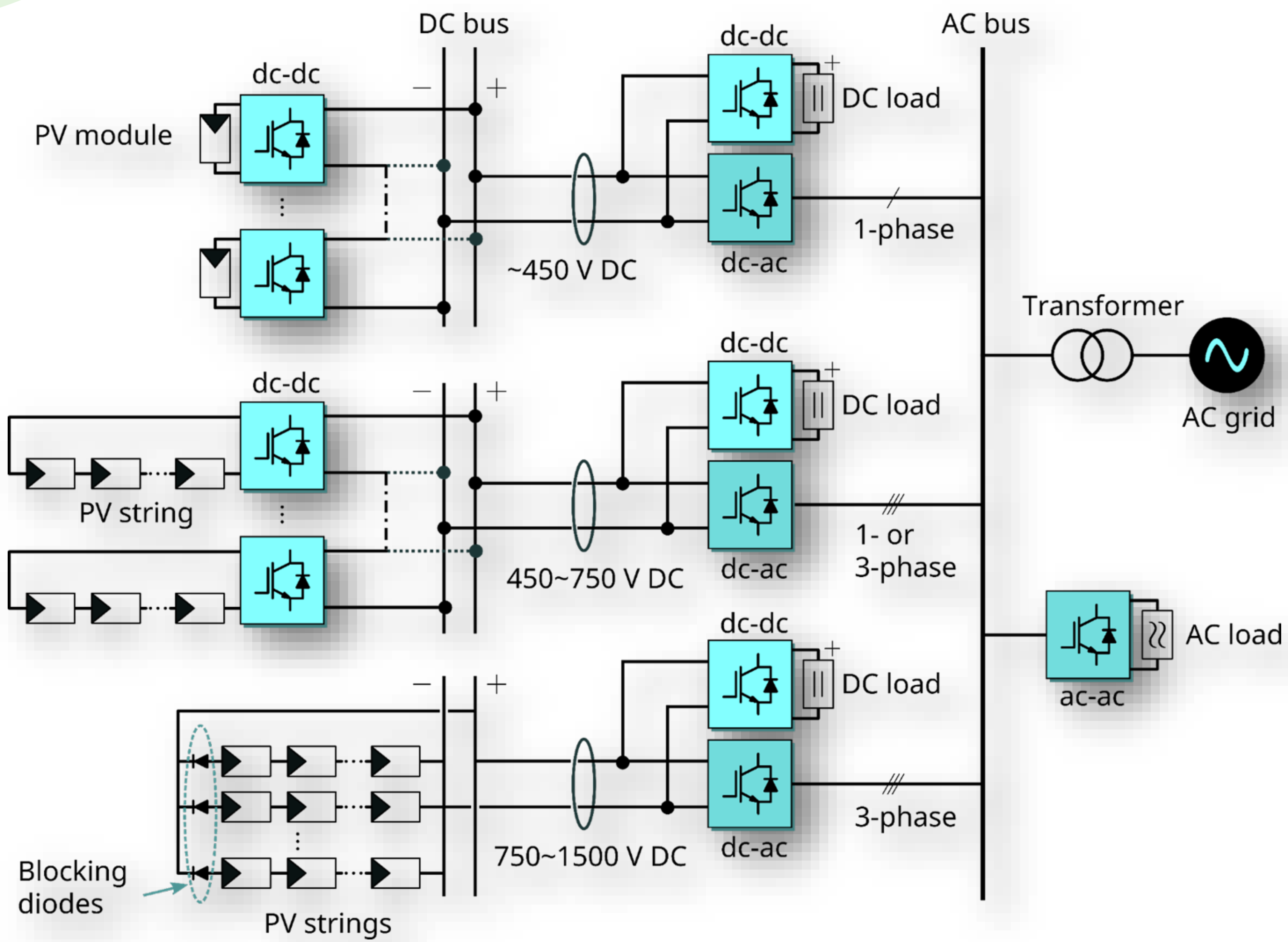
Not just a generator, PV should be **More Active** in grid regulation



- New demands for grid integrations, communications, power flow control, and protection are needed to accept more renewables.
- Power electronic converters are important in this technology transformation.

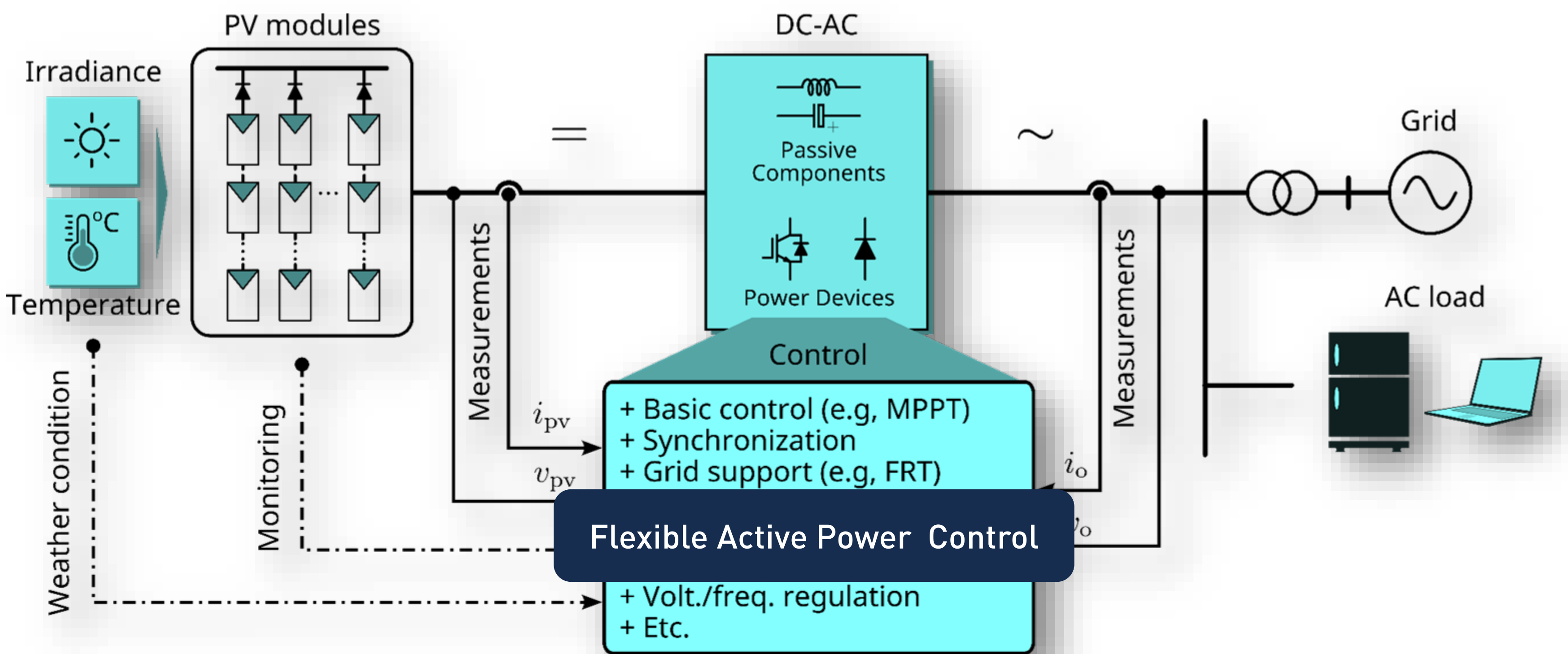
Flexible Power (Virtual Energy Storage) Control →

PV System Configurations



General Control Structure

The general Control

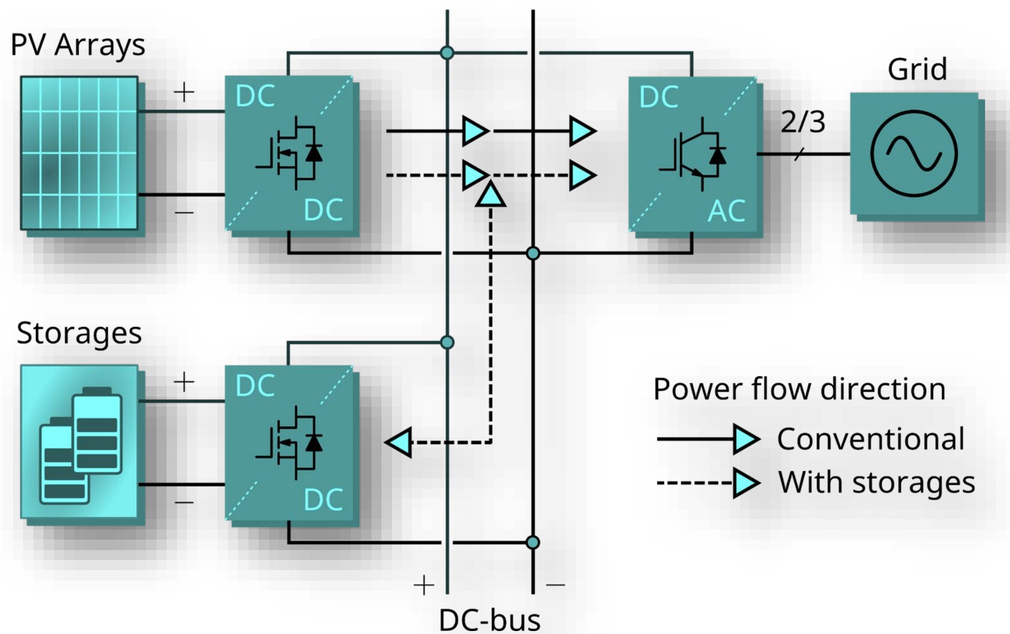


Almost all demands → Controlling PV converters

Active Power Control Solutions

Meet the Demands by integrating storages

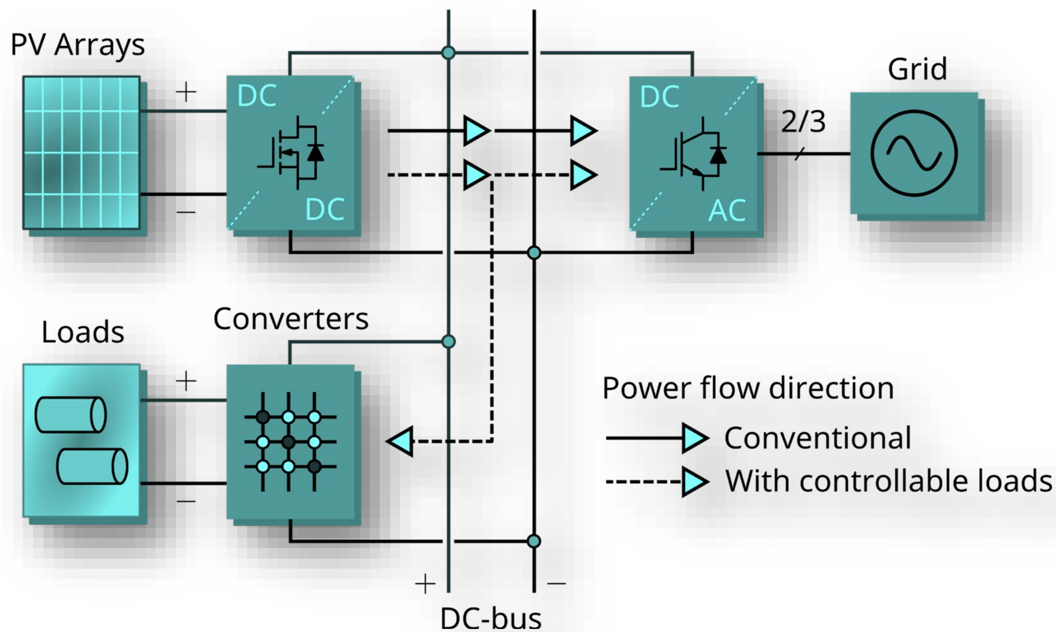
- Effective and flexible
- Increased cost and control
- Limited lifetime



Active Power Control Solutions

Meet the Demands using dummy controllable loads

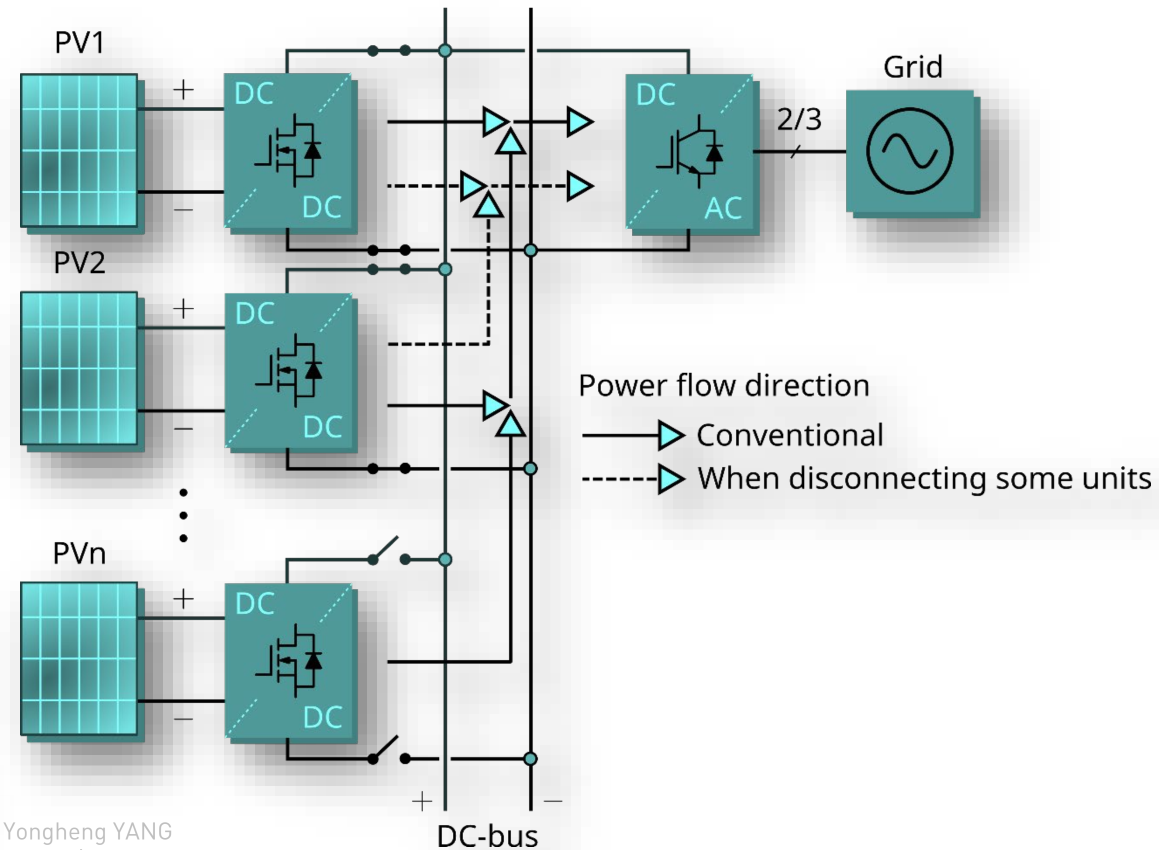
- Cheap but not very flexible
- Complicated control, relying on communication
- Unidirectional (not possible to inject power)



Active Power Control Solutions

Meet the Demands by switching multiple units

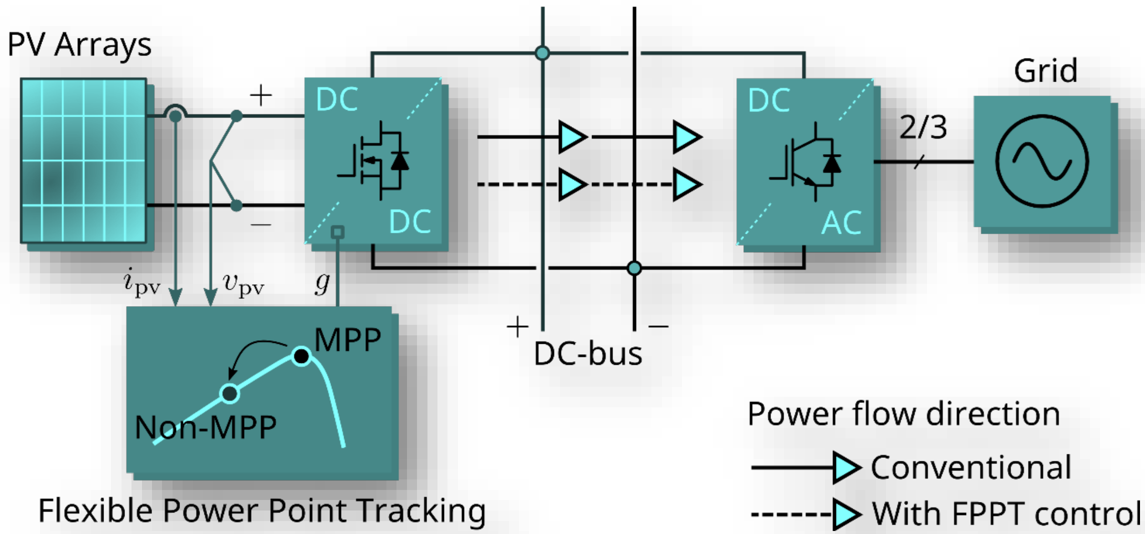
- Not very flexible – limited by configuration
- Complicated control, relying on communication – challenging stability
- Unidirectional (not possible to inject power)



Active Power Control Solutions

The solution – Flexible Power Point Tracking (FPPT)

- No hardware modification, and easy to implement
- Universal solution to all PV systems
- Not able to provide power (unidirectional)



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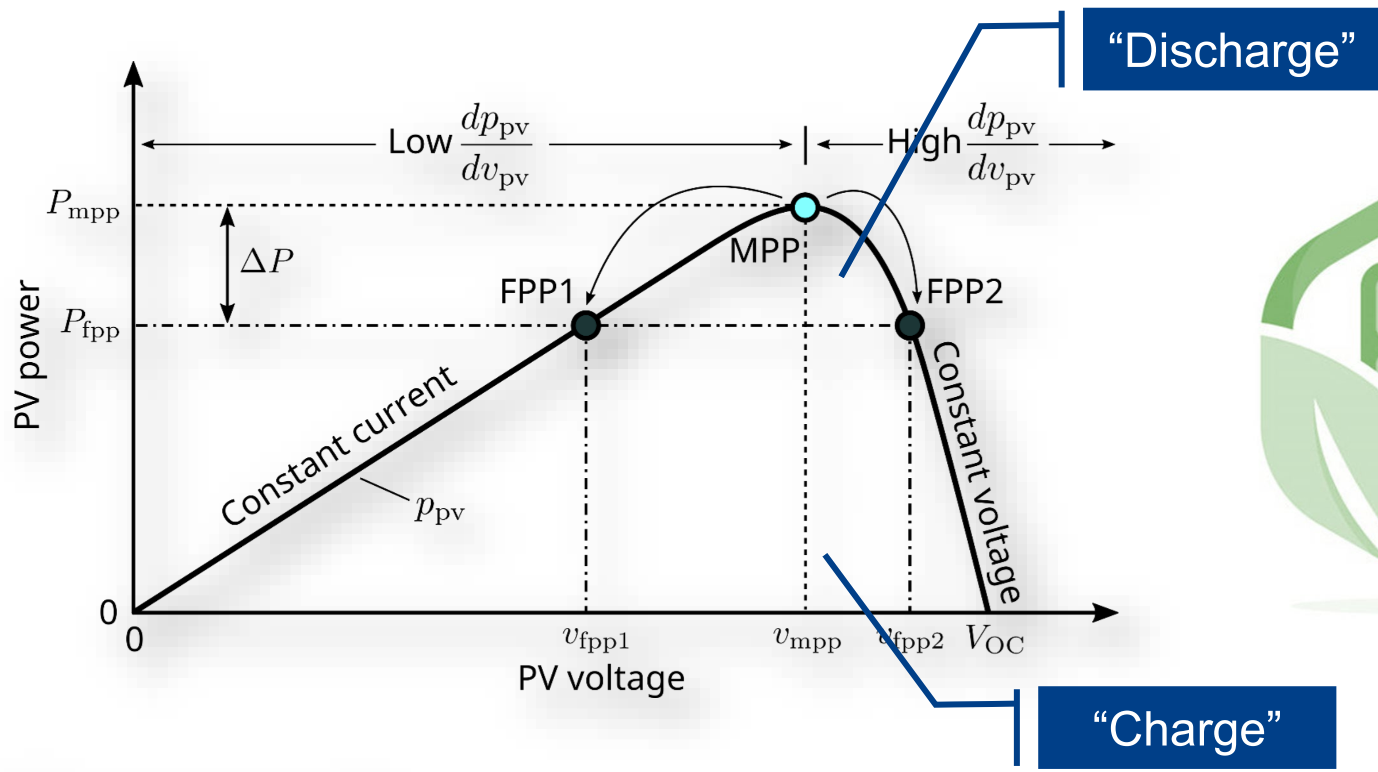
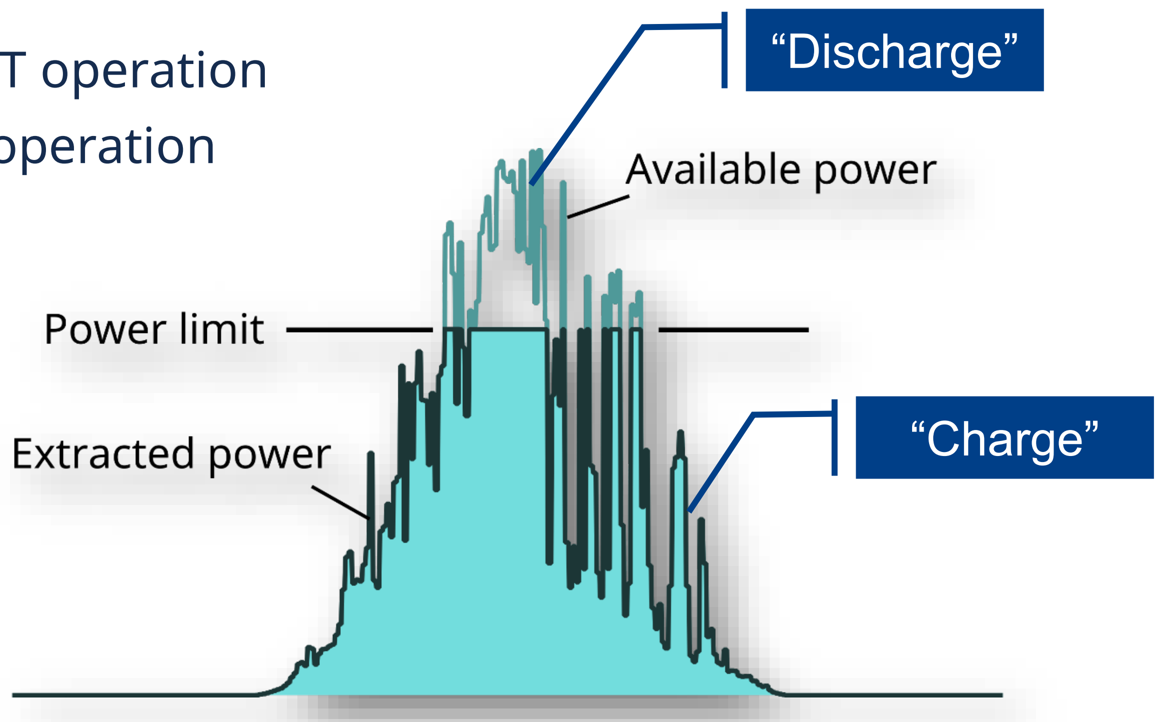


Constant Power Generation

Also referred to as **Power Limiting Control** (PLC)

- Direct power control
- Current limiting scheme
- Modified MPPT algorithm (FPPT)

$$P_{out} = \begin{cases} P_{ava} \rightarrow \text{MPPT operation} \\ P_{lim} \rightarrow \text{PLC operation} \end{cases}$$



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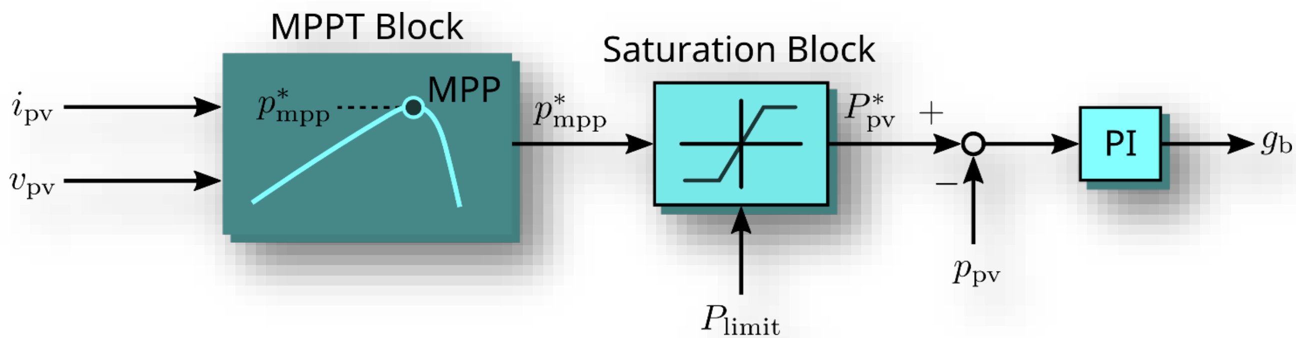

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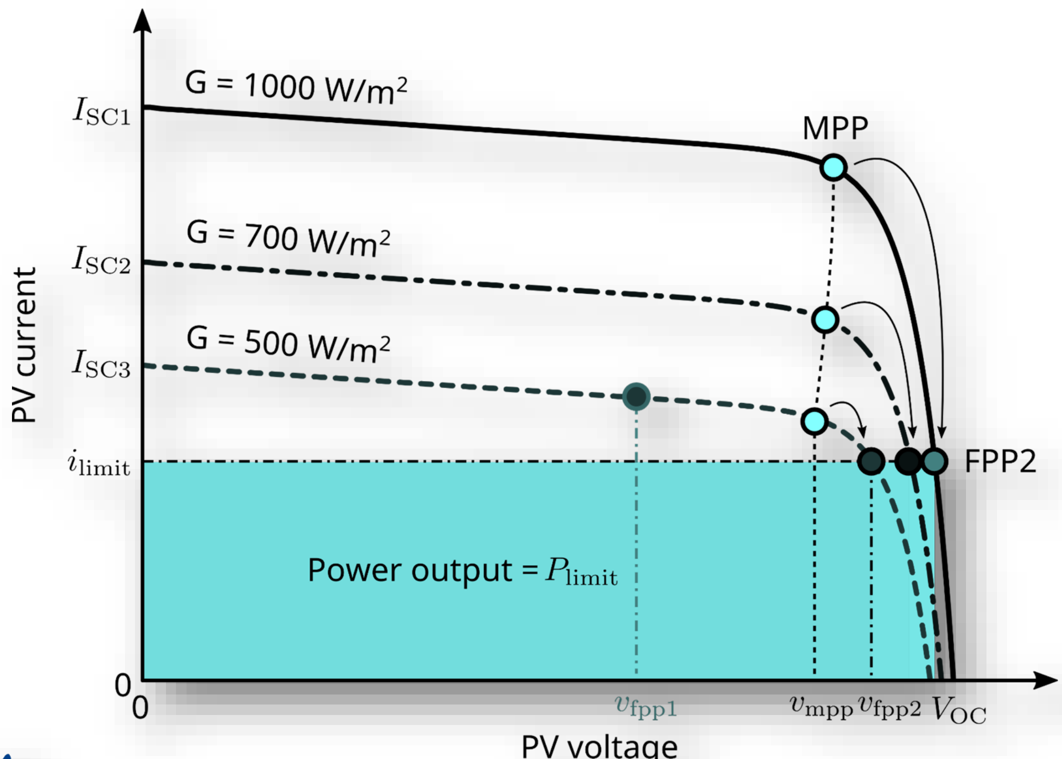

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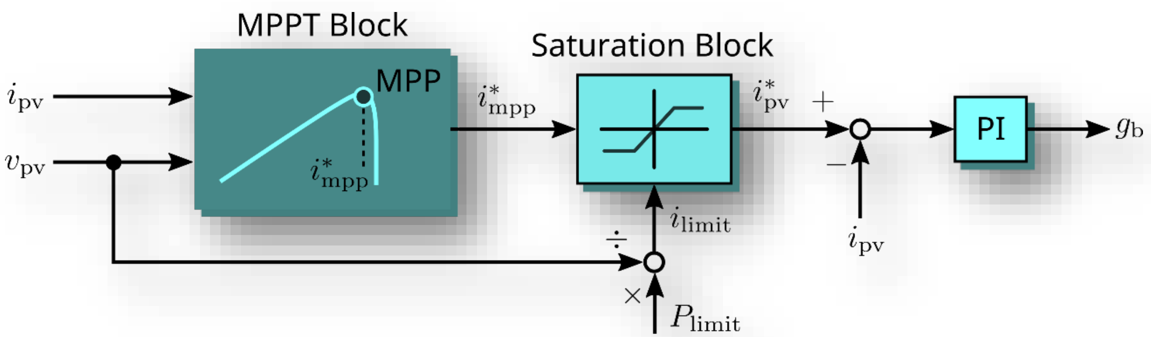
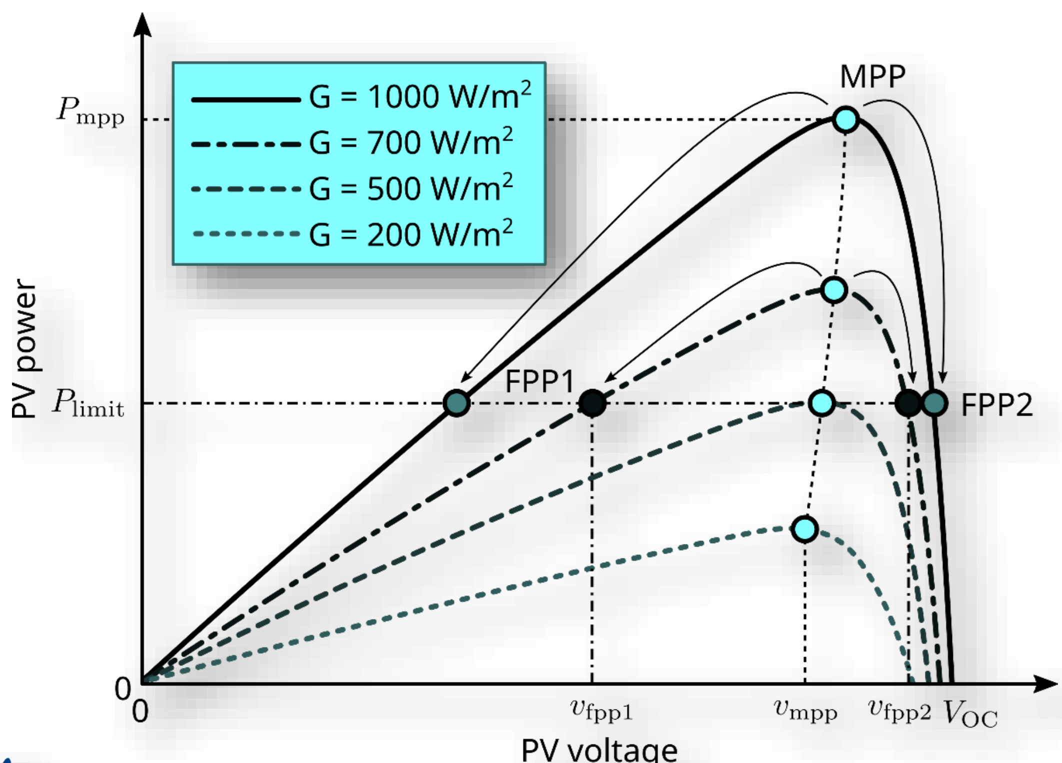


$$i_{\text{limit}} = \frac{P_{\text{limit}}}{V_{\text{pv}}}$$

Constant Power Generation

Also referred to as Power Limiting Control (PLC)

- Direct power control
- Current limiting scheme
- **Modified MPPT algorithm (FPPT)**



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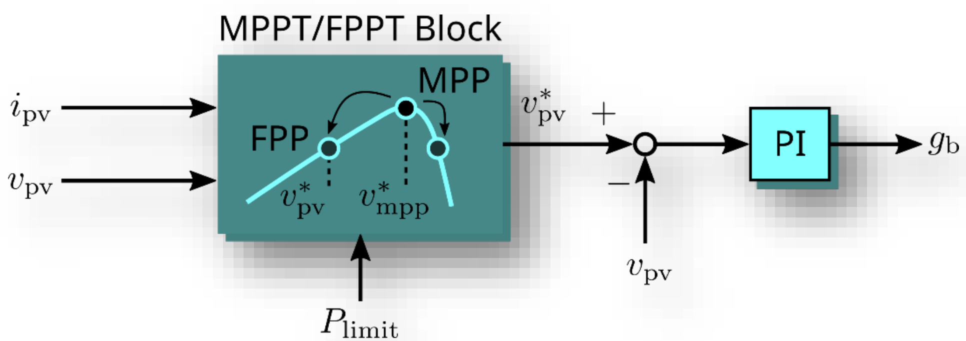
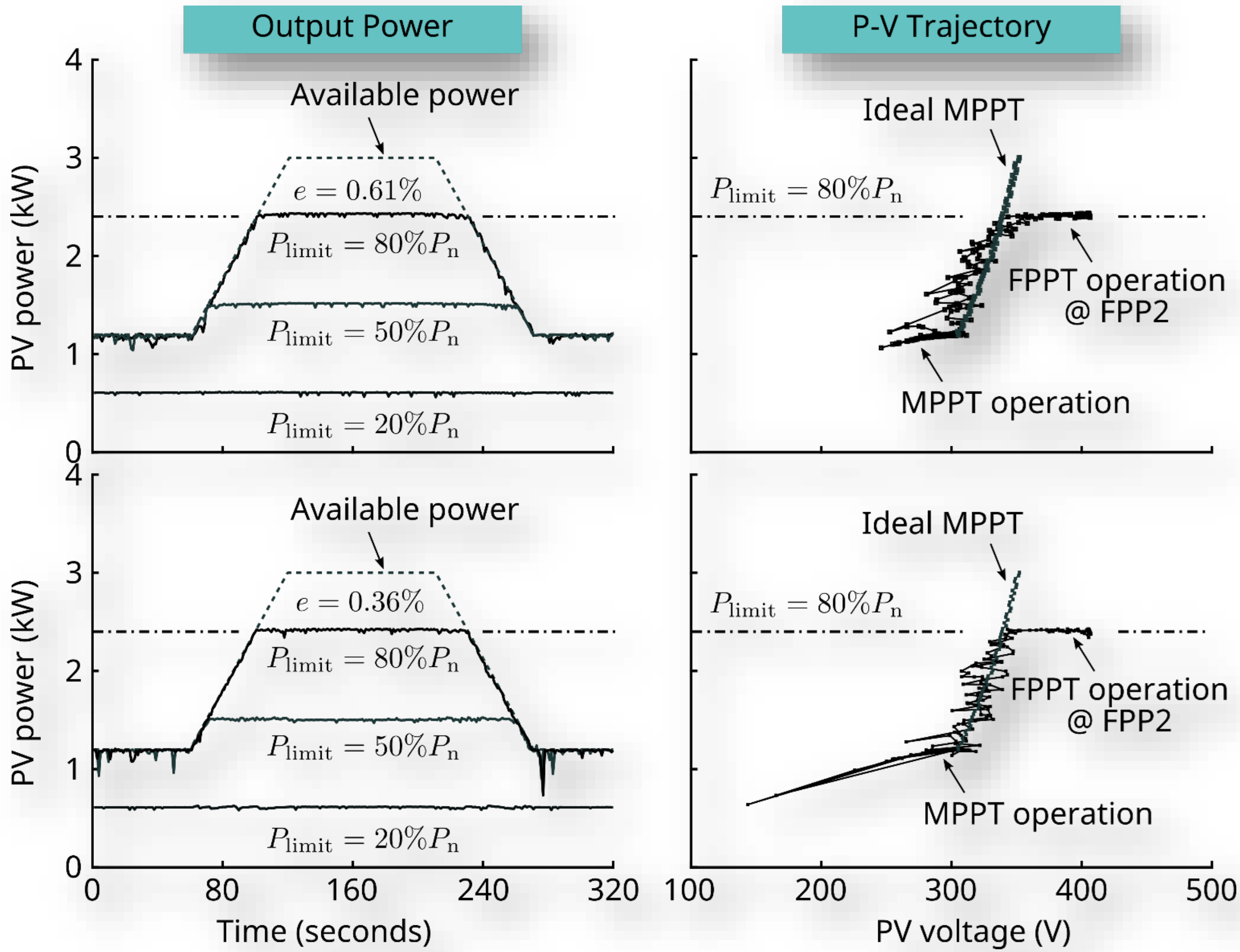


Results – Power Limiting Control



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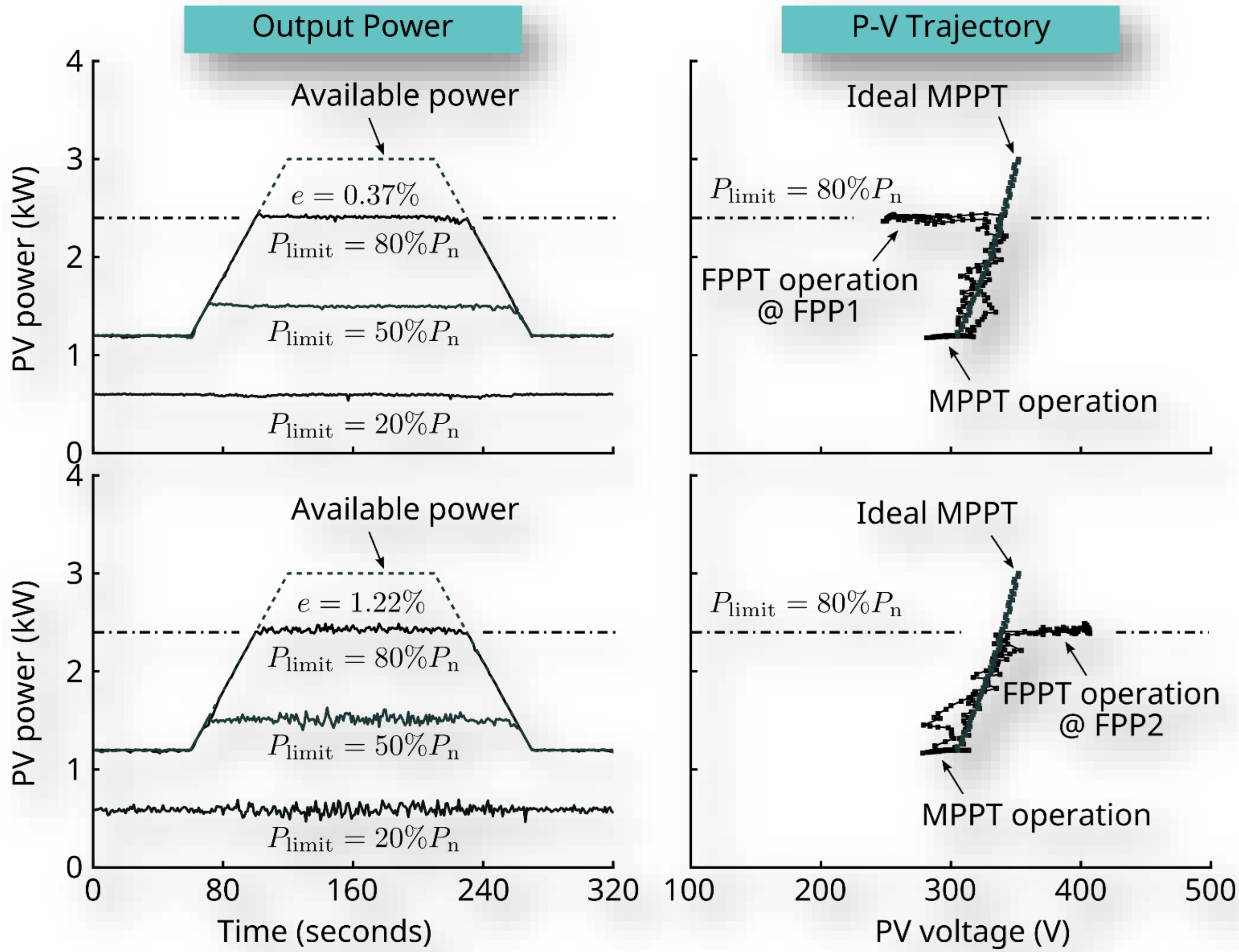
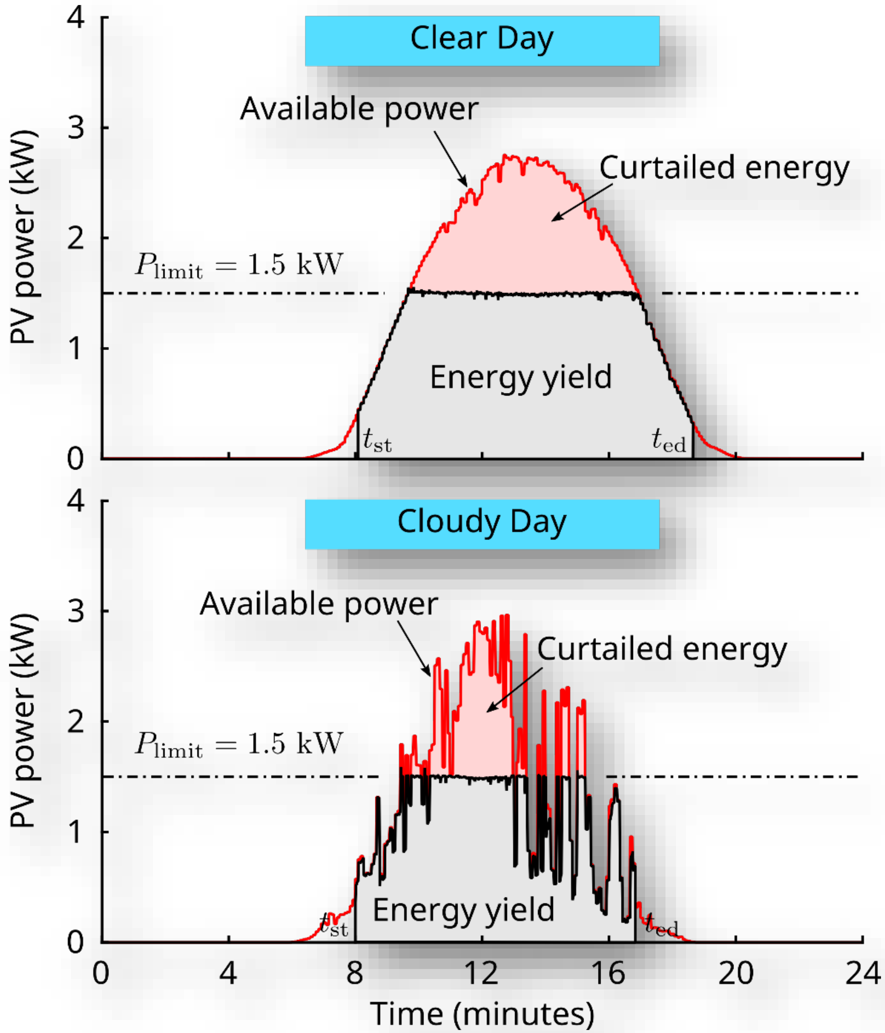


Results – Power Limiting Control

FPPT enables flexible active power control



Power Reserve Control

Power Reserve Control (PRC) is demanded today

- Grid stability, e.g., due to frequency excursions
- Frequency-dependent active power control – regulate frequency
- Power should be reserved (also called delta power control) and in case needed, release power to support the frequency control

$$P_{out} = P_{ava} - \Delta P$$

⬇

$$P_{limit} = P_{ava} - \Delta P$$

⬇

Flexible Power Point Tracking

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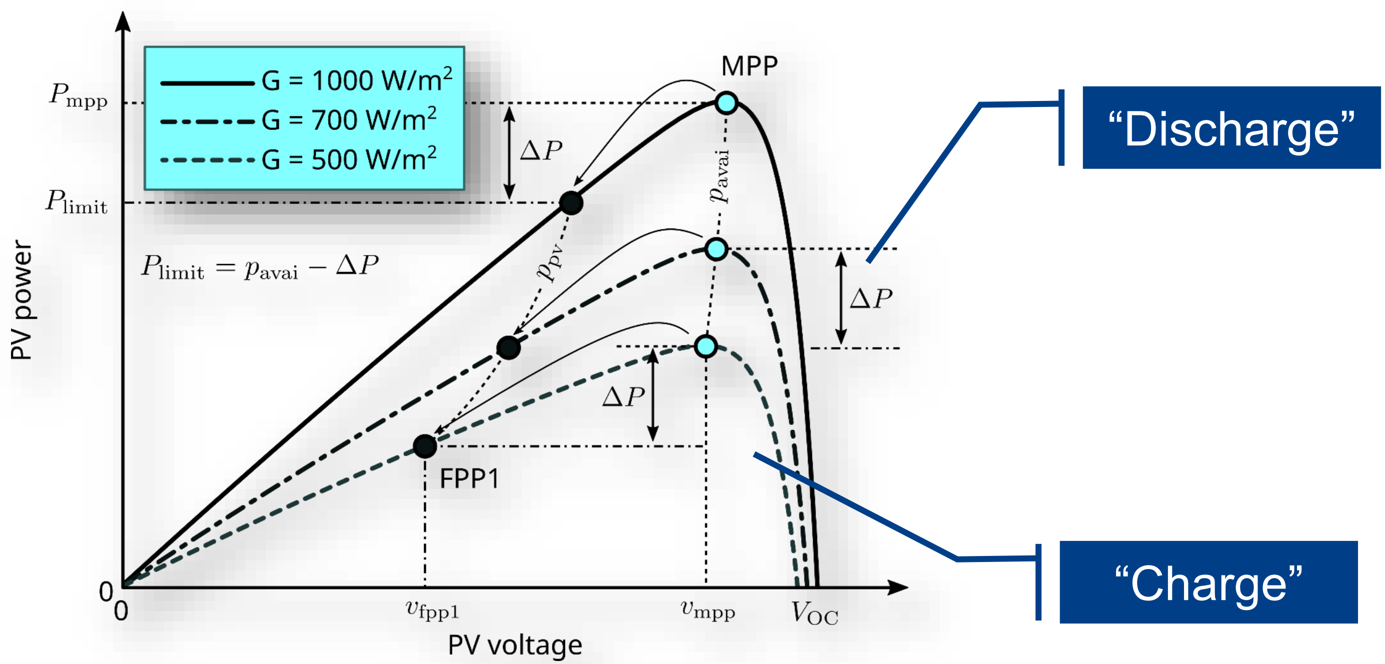


Power Reserve Control

Challenges of PRC is how to measure the available

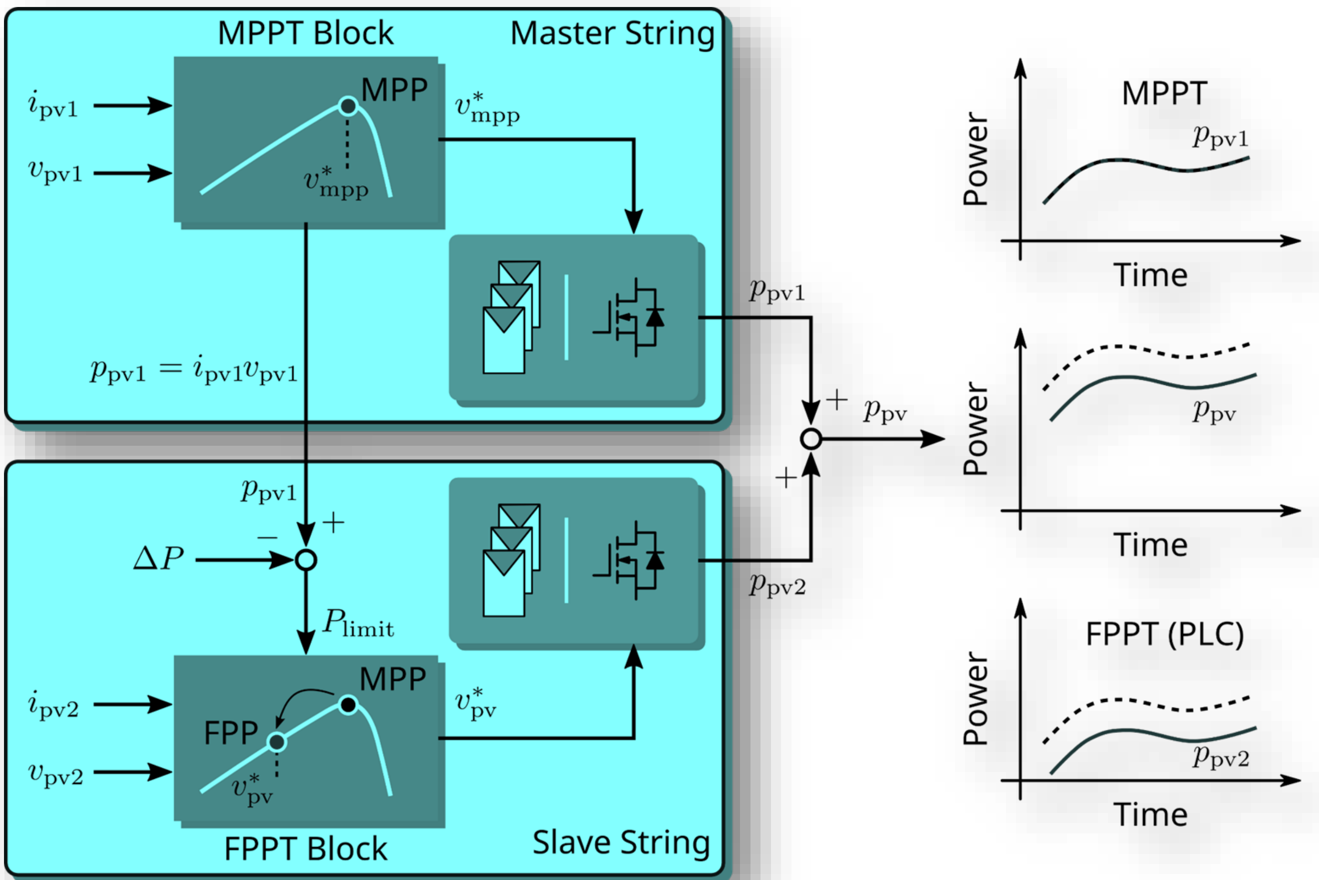
- Installing solar irradiance measurement or using solar irradiance forecasting data together with the PV array characteristic model.
- Using artificial intelligence (AI) techniques to predict the maximum available power based on historical operation and meteorological data.
- Applying the curve-fitting approximation of the P-V characteristic of the PV panels used in the system.
- Employing a small PV unit to operate in the MPPT mode and use the output power to approximate the total power of the entire system (assuming that the solar irradiance is similar and evenly distributed for all the PV arrays in the system).
- Adopting a hybrid operation between the MPPT and the PRC mode in one single PV system.

Master-slave PRC strategy

Sensorless PRC strategy →

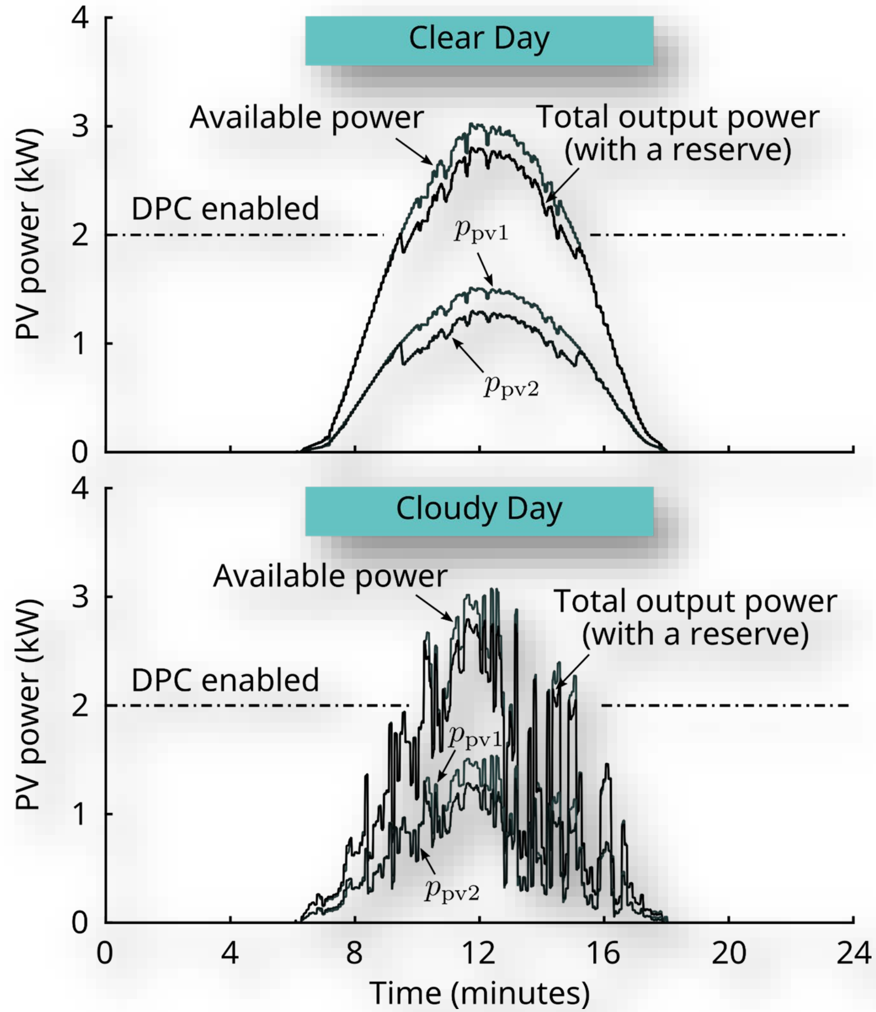
Power Reserve Control

Master-slave PRC exemplified on a two-string system



Results – Power Reserve Control

Master-slave PRC for a two-string system (ΔP = 200 W)



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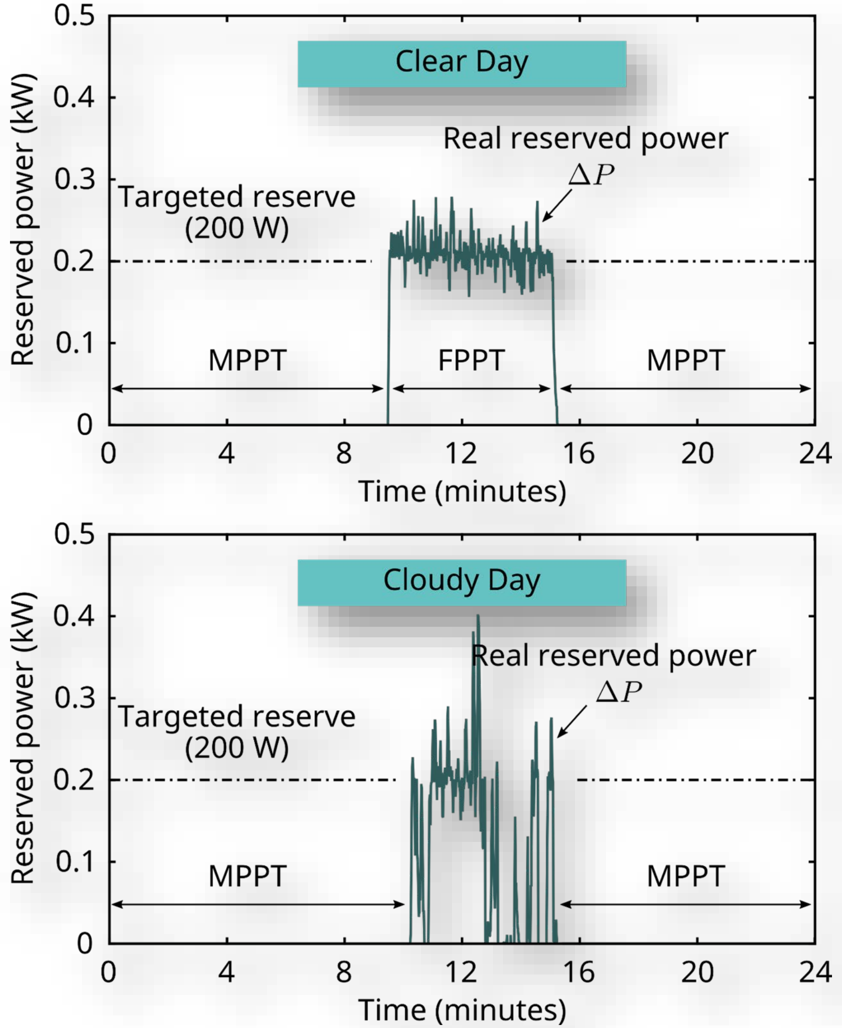
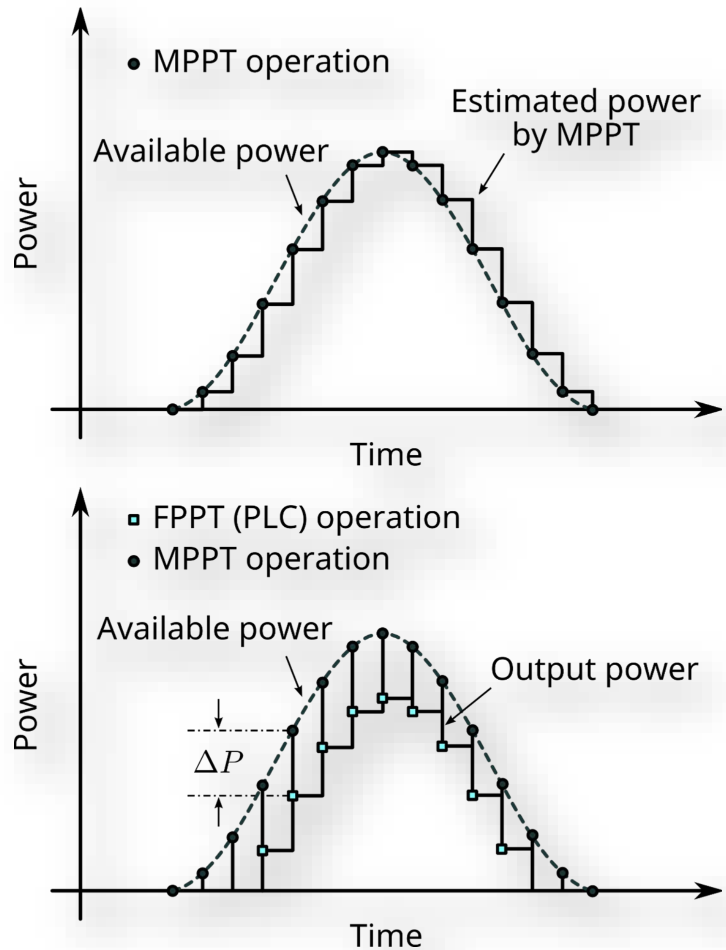


Power Reserve Control

Sensorless PRC for two-stage systems with capacitors

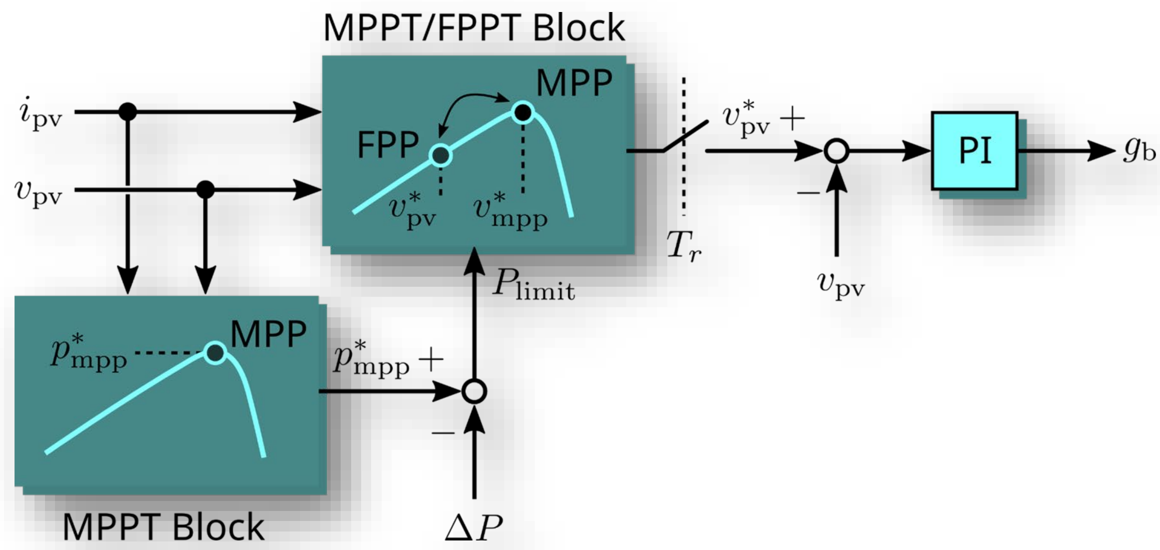
Routinely operate at MPPT to estimate the available



Power Reserve Control

Sensorless PRC for two-stage systems with capacitors

- When measured, operate at the power limiting control
- Excessive energy is stored at the DC-link capacitor



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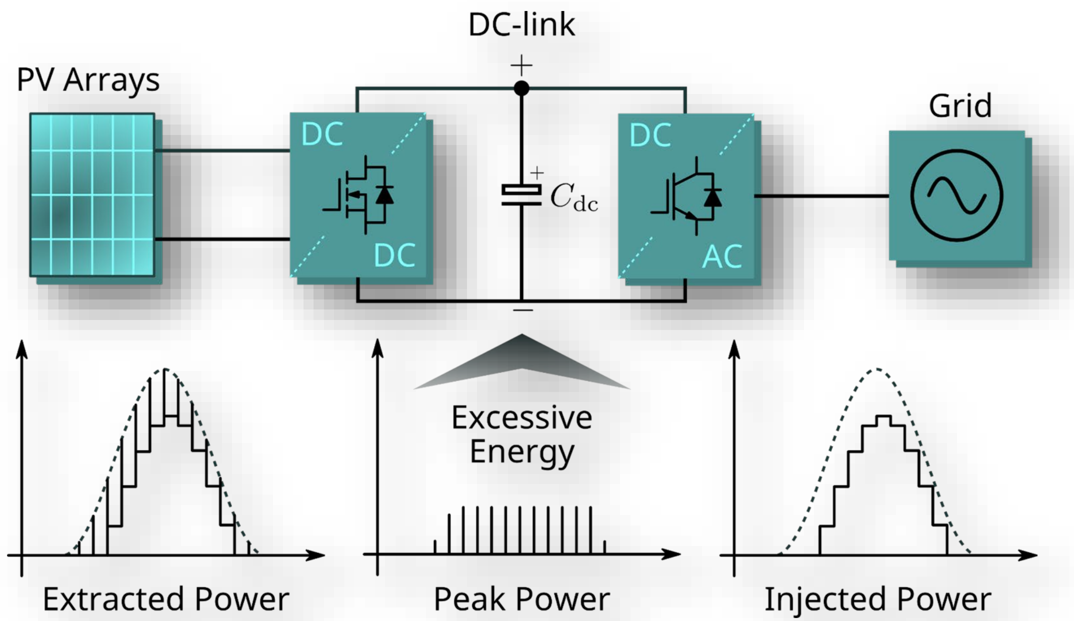

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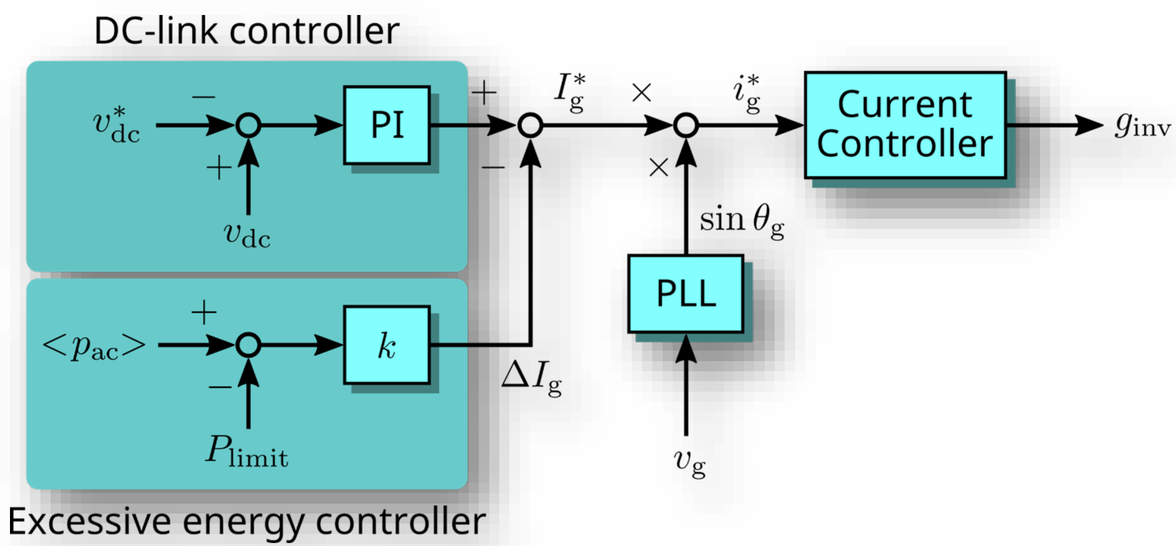
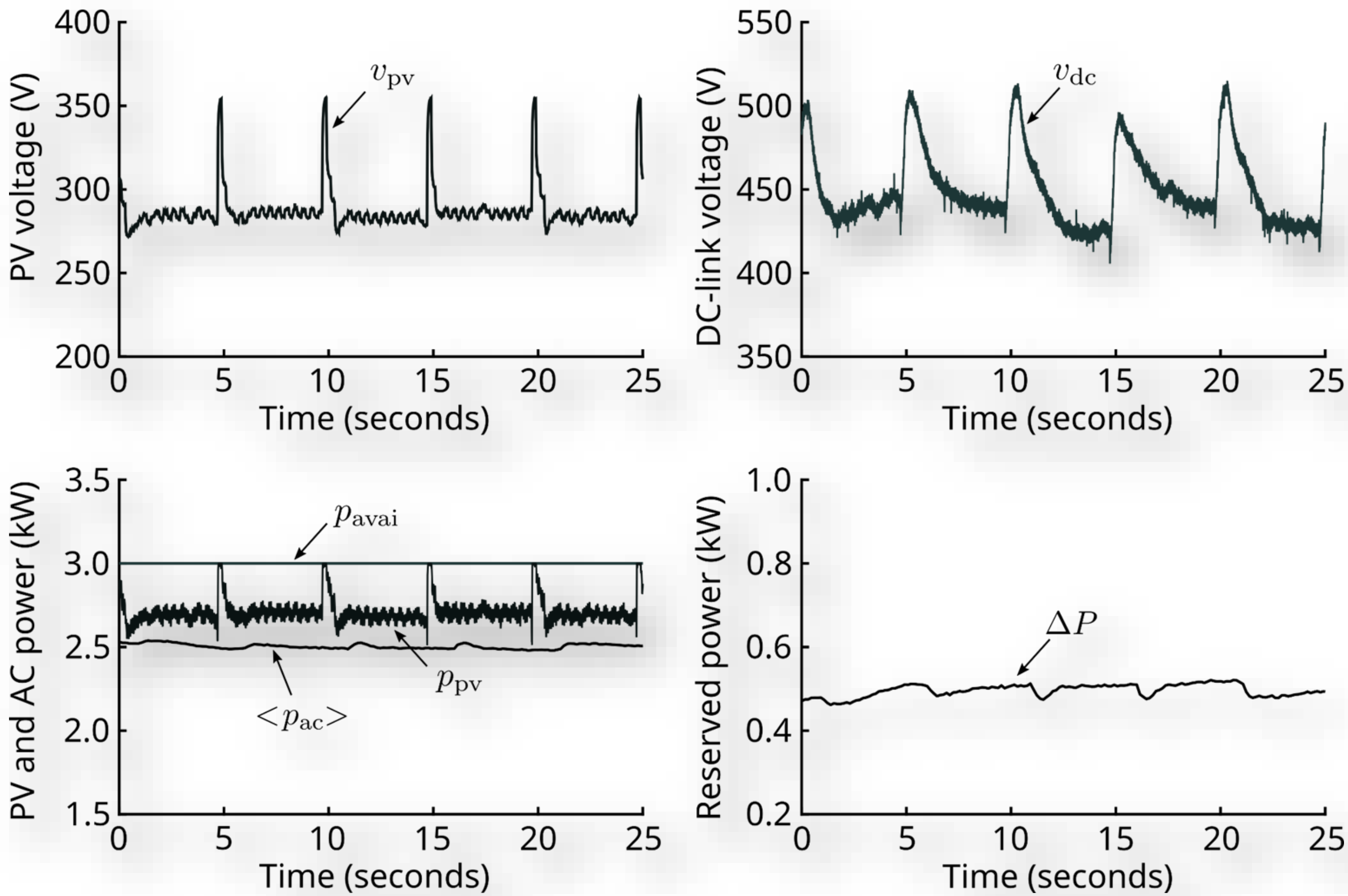


Results – Power Reserve Control

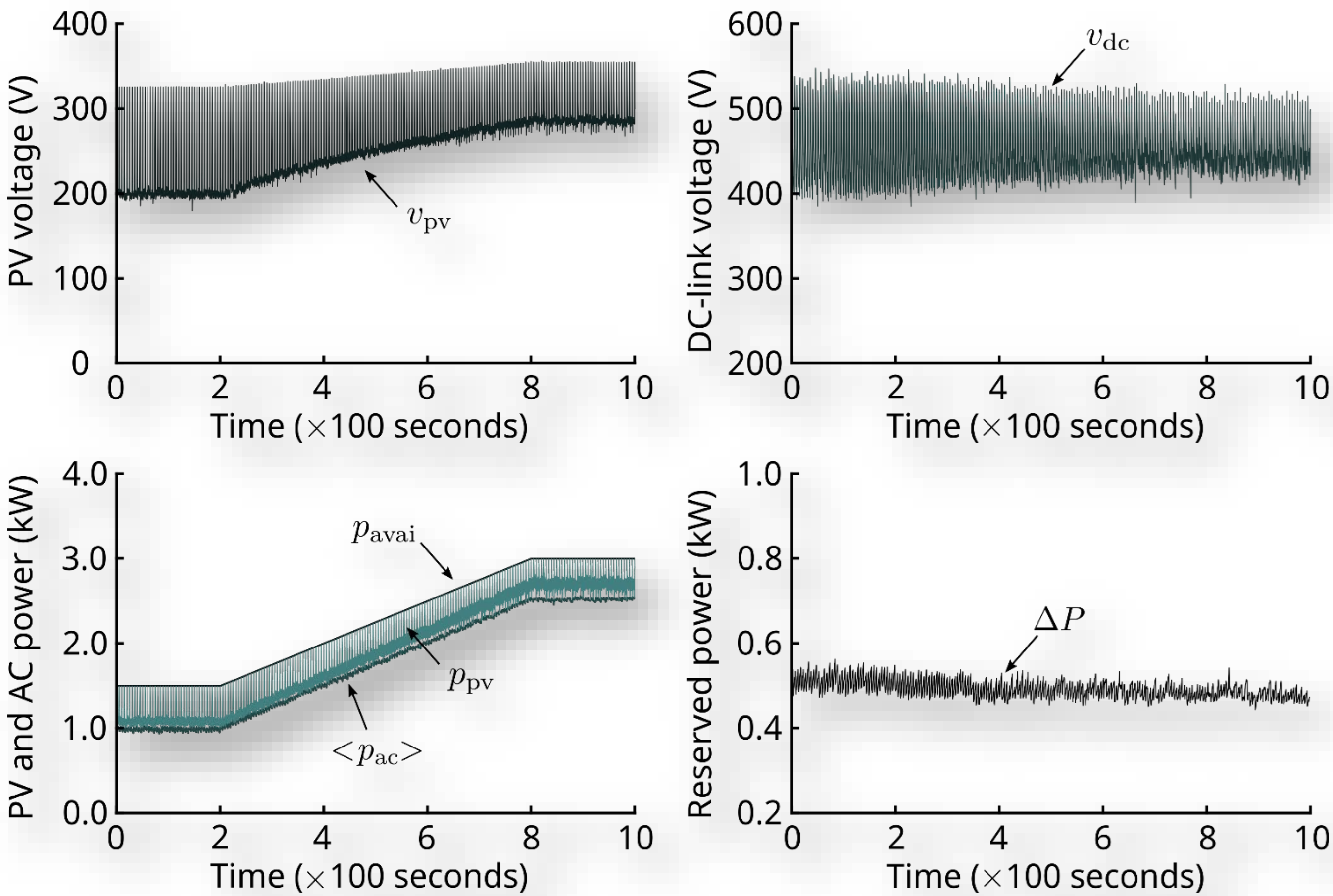
Sensorless PRC – a cost-effective solution



Constant irradiance condition (ΔP = 500 W)

Results – Power Reserve Control

Sensorless PRC – a cost-effective solution

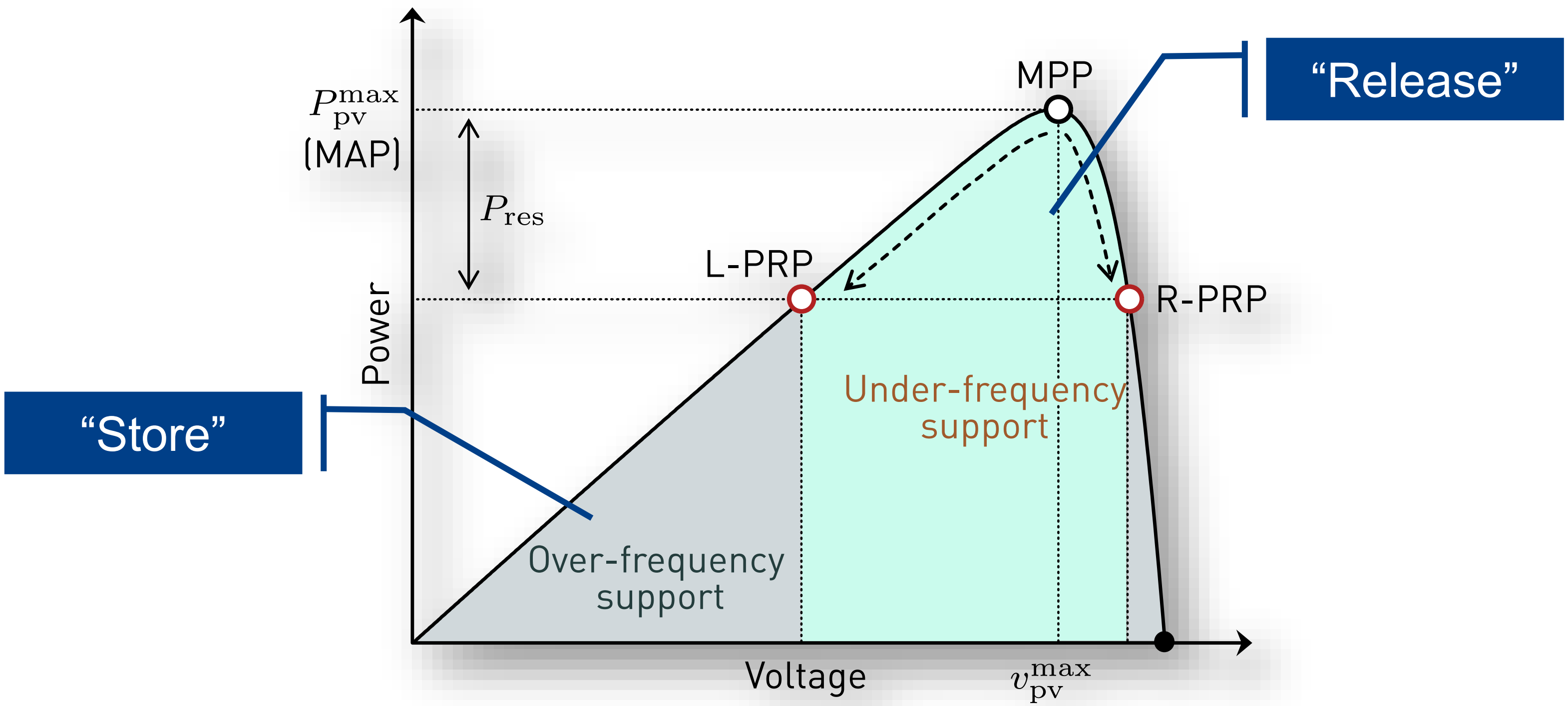


Changing irradiance condition (ΔP = 500 W)

Flexible Frequency Support from PV Systems

Inertia Provision and Frequency Damping

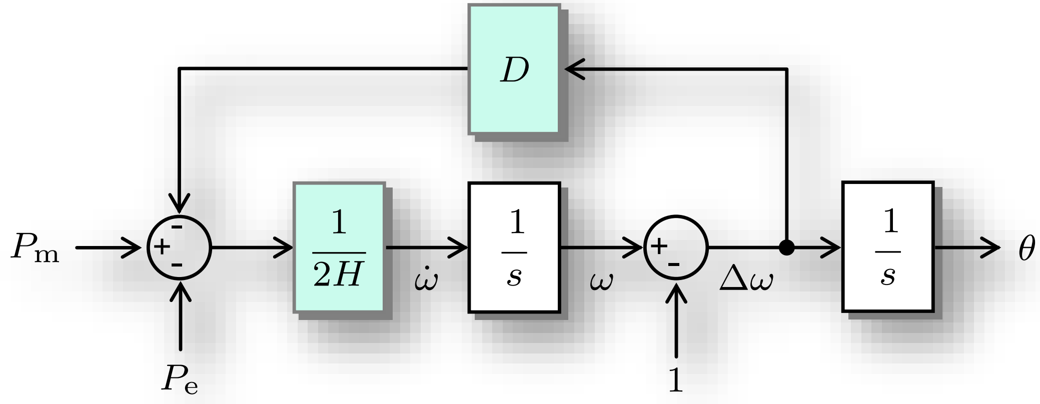
- Over-frequency issue: PV system shall reduce the output power
- Under-frequency issue: PV system should increase the output power
- Solution: Power reserve control



Flexible Frequency Support from PV Systems

Full-range Frequency Regulation

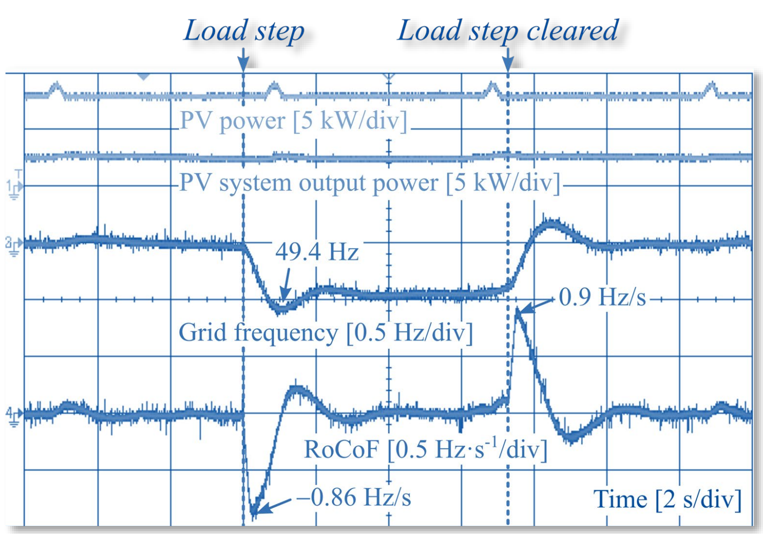
- Virtual inertia: In proportion to the derivative of frequency
- Frequency damping: In proportion to the frequency deviation
- Solution: Coordination of power reserve

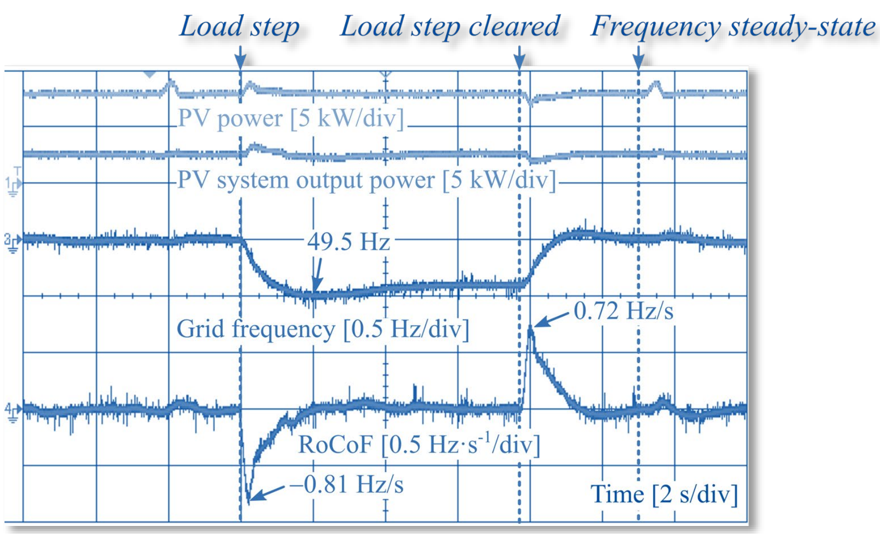


Experimental Results

Virtual Inertia Control to enhance the grid integration

- Rate of Change of Frequency (ROCOF)
- Frequency Nadir





Without VIC

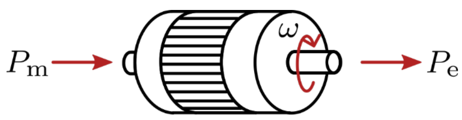
With VIC

Virtual Inertial Control with Internal Storage

Virtual Inertia Provision from DC-link capacitors

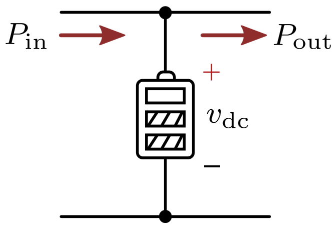
- Universal solutions (physical storage)
- Limited inertia (due to the stability concern)

Synchronous Generator



$$P_m - P_e = 2H\frac{d\omega}{dt}$$

DC-Link Capacitor



$$P_{in} - P_{out} = C_{dc}v_{dc}\frac{dv_{dc}}{dt}$$

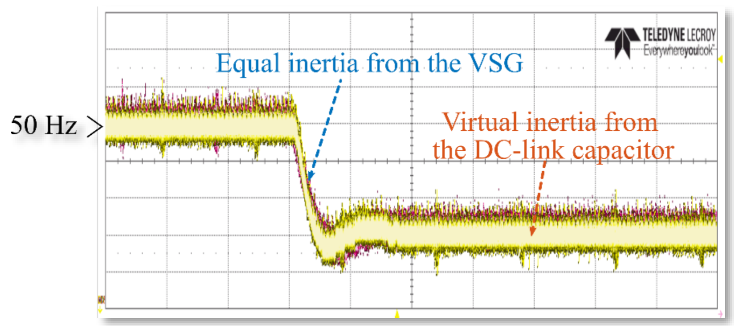
When $v_{dc} = k_{\omega v}\omega$, $P_{in} - P_{out} = C_{dc}v_{dc}^{*}k_{\omega v}\frac{d\omega}{dt}$

$$H_v = \frac{1}{2}C_{dc}v_{dc}^{*}k_{\omega v}$$

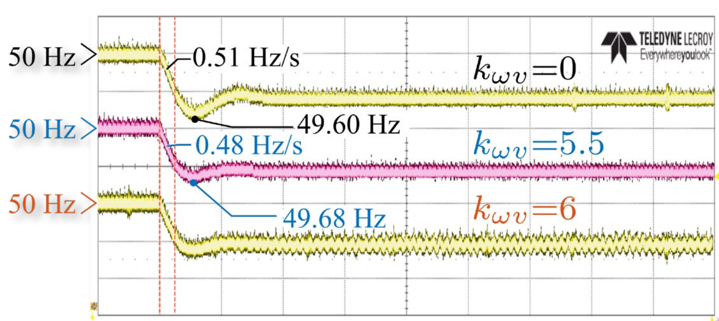
Virtual Inertial Control with Internal Storage

Virtual Inertia Provision from DC-link capacitors

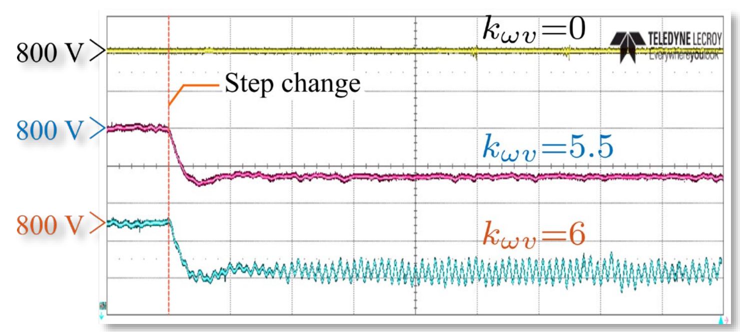
- Universal solutions (physical storage)
- Limited inertia (due to the stability concern)



Emulated Inertia



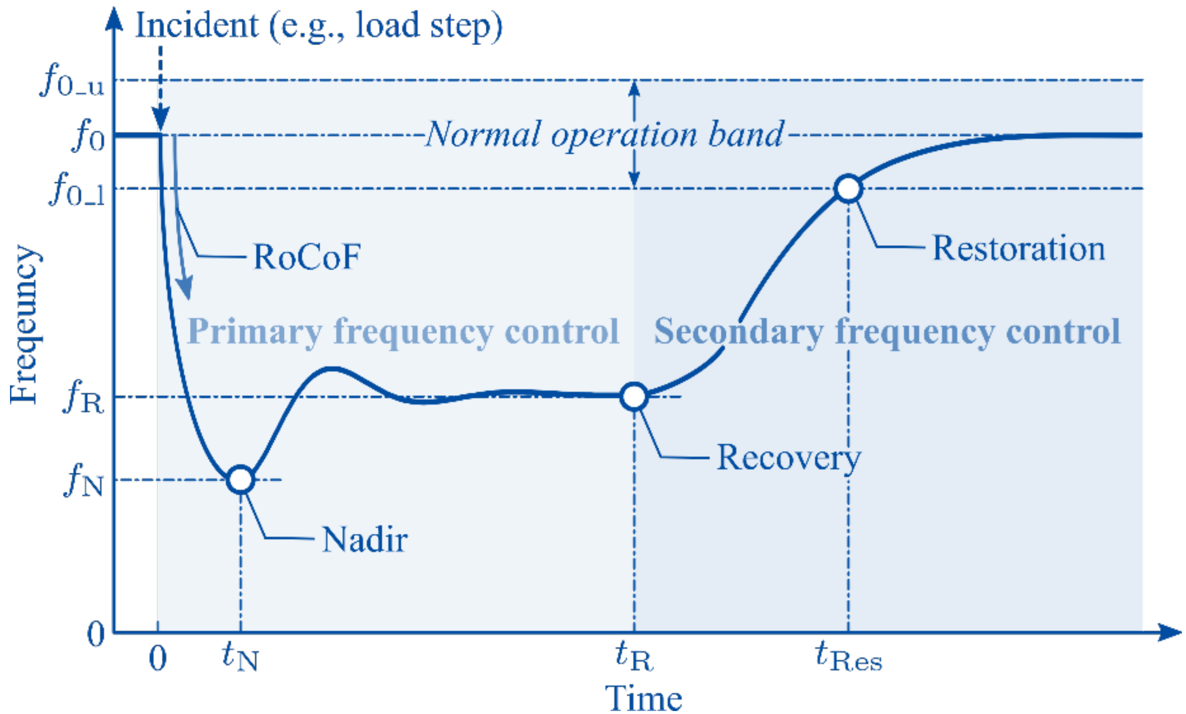
Frequency



DC-link Voltage

Flexible Frequency Support from PV Systems

Coordination for inertia emulation and frequency damping



- Crucial indices
  - Frequency nadir
  - RoCoF (Rate of Change of Frequency)
  - Steady-state frequency deviation

Flexible Frequency Support from PV Systems

Coordination for inertia emulation and frequency damping

GRID CODE FOR THE NORTHERN EUROPE GRID ON THE FREQUENCY QUALITY.

Description	Requirement
Rated grid frequency	50 Hz
Thresholds of normal operation	$\pm$ 0.1 Hz
Maximum instantaneous frequency deviation	$\pm$ 1 Hz
Maximum steady-state frequency deviation	$\pm$ 0.5 Hz
Frequency restoration range	$\pm$ 0.1 Hz
Time to recover frequency	Not required
Time to restore frequency	$\pm$ 15 minutes
RoCoF withstanding capability*	$\pm$ 2.5 Hz/s

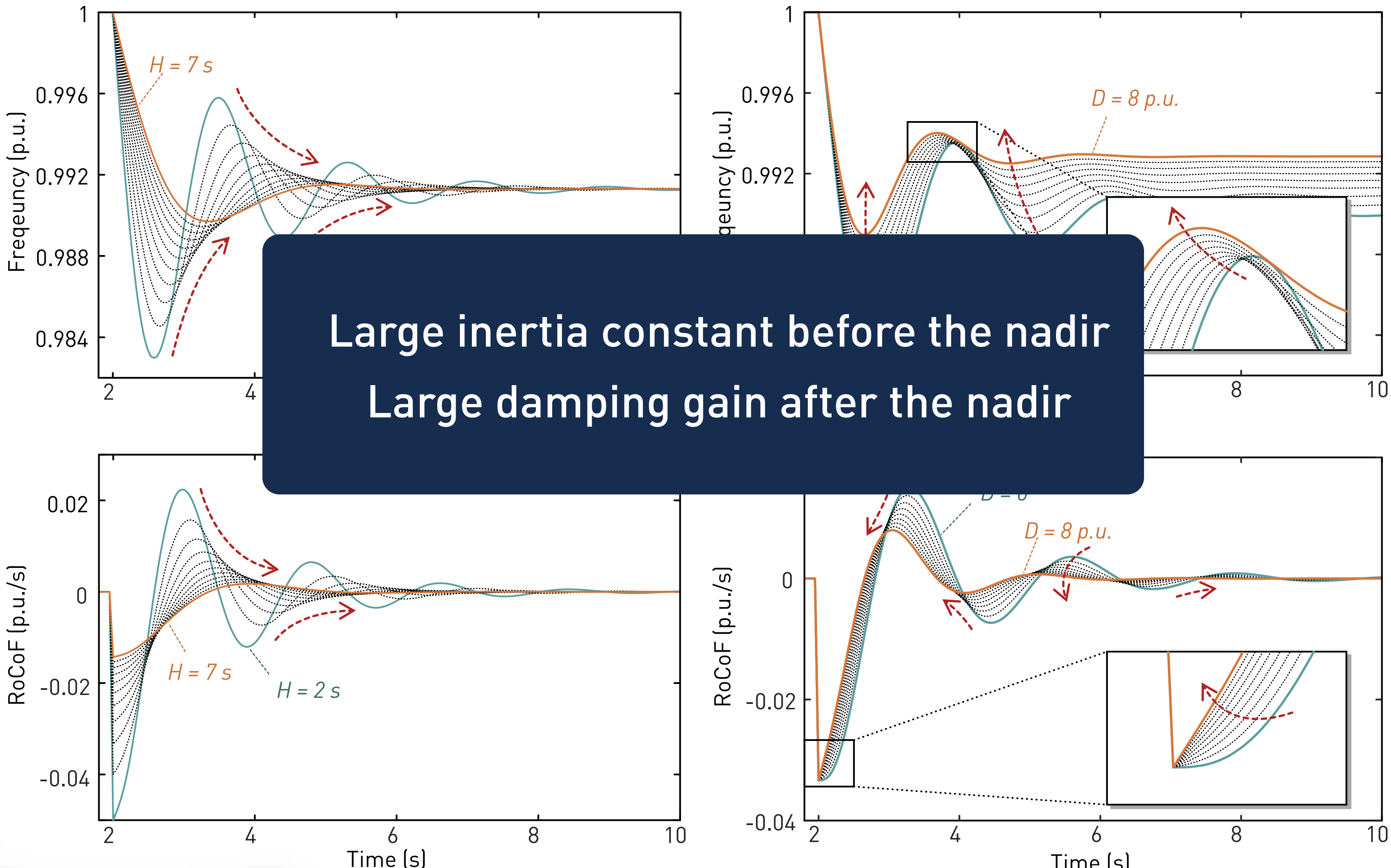
* Required by local system operators, where the regulation code of the Danish power grid is applied.

❖ Frequency quality improvement

- Optimally utilize power reserve ("energy storage") of PV system
- Adaptively adjust inertia constant and damping gain

Flexible Frequency Support from PV Systems

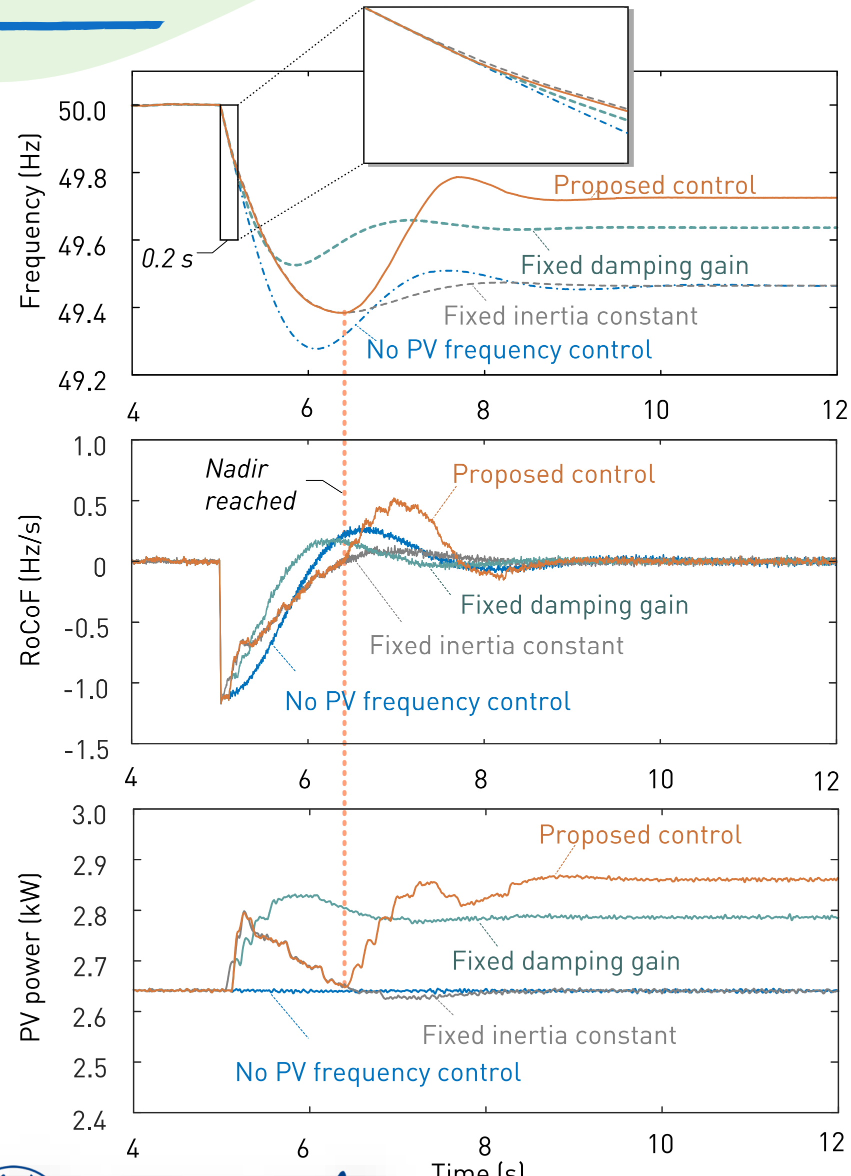
Coordination for inertia emulation and frequency damping

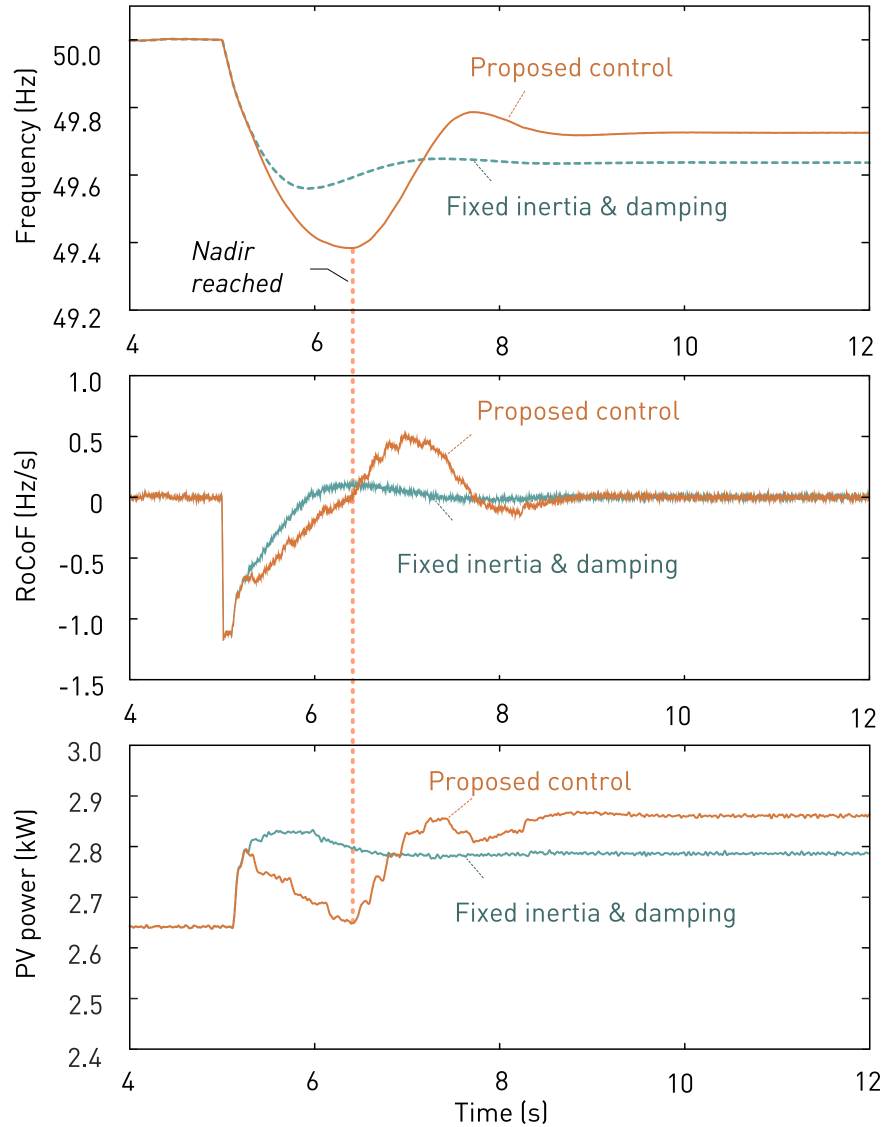


Large inertia constant before the nadir

Large damping gain after the nadir

Simulation Results





Simulation Results

Proposed Control:

- Performs well in reducing RoCoF and instantaneous frequency deviation
- Optimally utilizes the power reserve to reduce the steady-state frequency deviation.

TABLE V
FREQUENCY QUALITY INDICES WITH DIFFERENT FREQUENCY CONTROL STRATEGIES OF PV SYSTEMS.*

Control method	Nadir	|RoCoF|	Recovery frequency
No PV control	49.28 Hz	1.10 Hz/s	49.46 Hz
Fixed inertia constant	49.38 Hz	**0.95 Hz/s**	49.46 Hz
Fixed damping gain	**49.53 Hz**	1.05 Hz/s	49.64 Hz
Fixed inertia & damping	**49.56 Hz**	1.00 Hz/s	49.64 Hz
Proposed control	49.38 Hz	1.00 Hz/s	49.72 Hz

* The indices in bold are those better than the proposed.

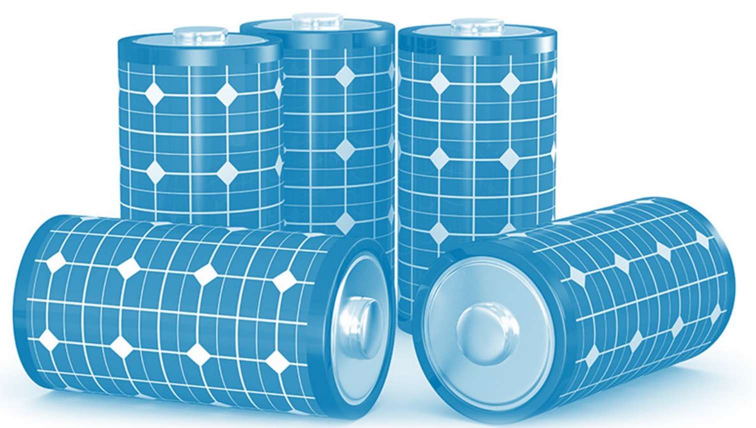
Summary and Outlook

- **PV is still booming → Challenging the power grid**

  PV is still one major renewable energy, and its installations are still increasing. Catering for a higher penetration degree of PV systems may challenge the grid itself. More stringent requirements have been released to enable grid-friendly integration of PV systems.

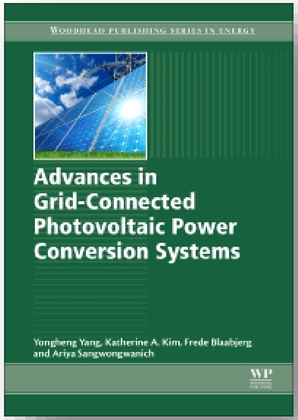
- **Grid-friendly strategies are necessary → Advanced control**

  "Virtual energy storage control", e.g., Power limiting control, Power reserve control, is, cost-effective solutions to frequency stabilities to a large extent. Advanced control of PV systems will further enable the manageability.



References – Books

Based On



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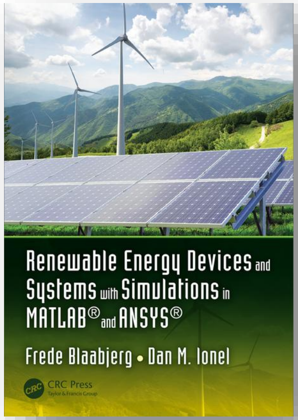

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