Control of Photovoltaic Systems

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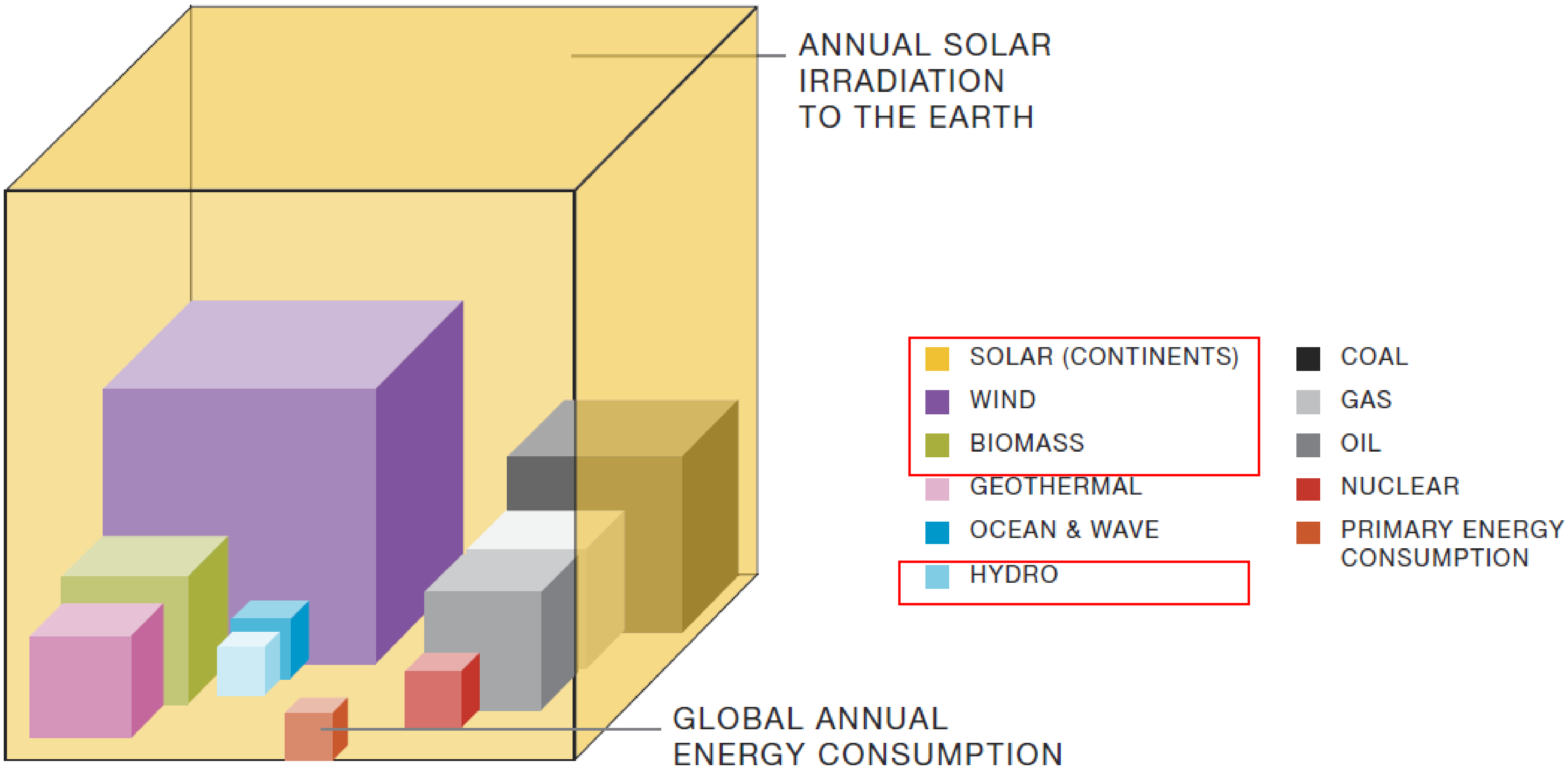
Outline

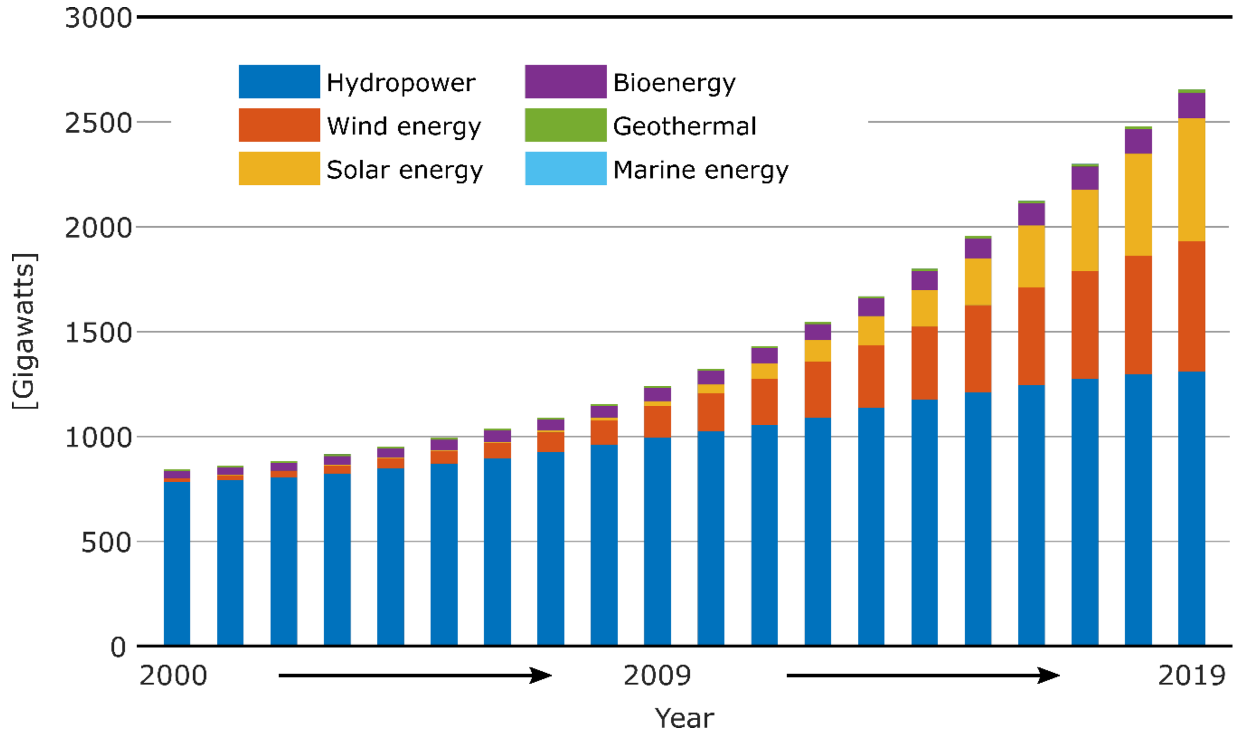
Solar PV energy

Energy resource

Solar energy – High potential to supply the energy demand



State of the Art – Renewable Evolution



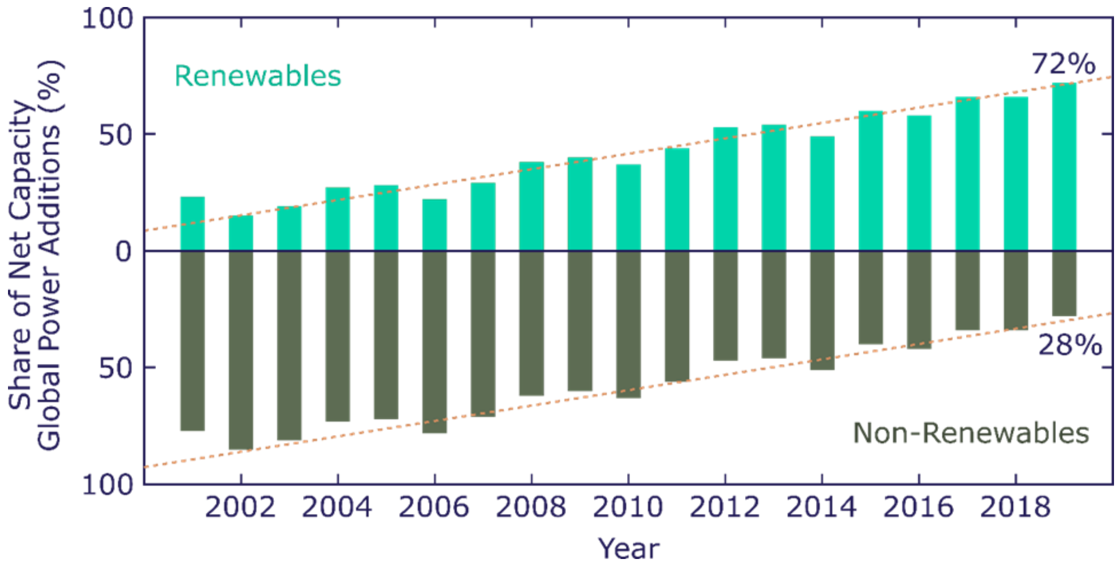
Global Renewable Energy Annual Changes in Gigawatt (2000-2019)

(more than **2500** 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 2020", http://www.irena.org/publications, March 2020)

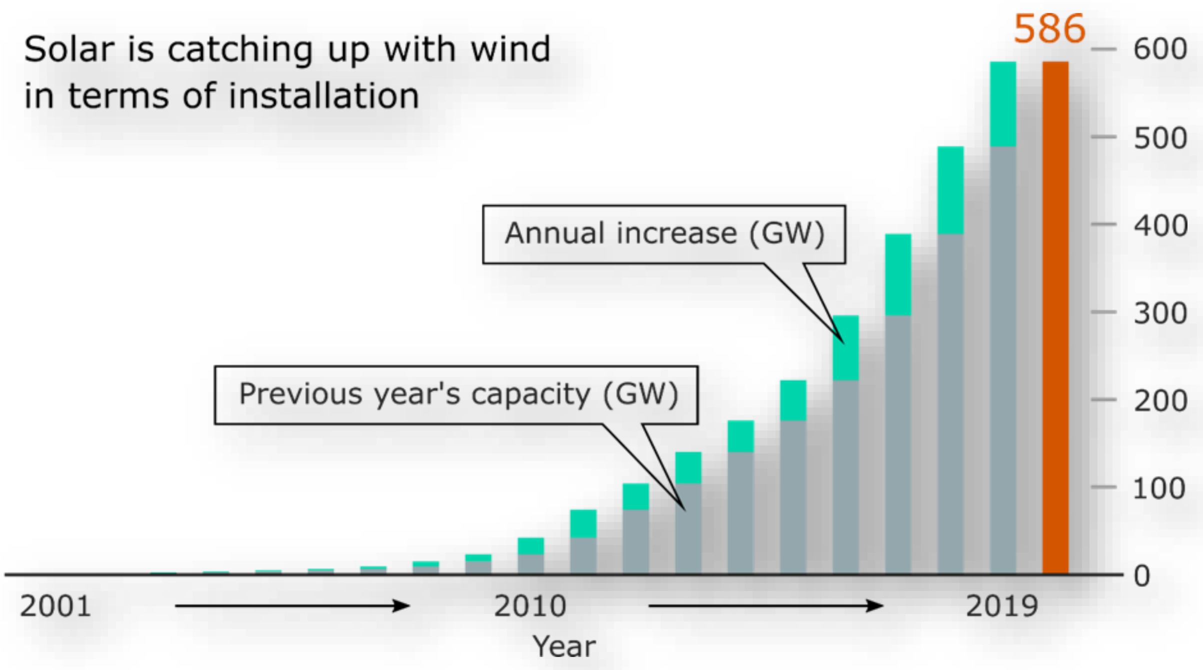
State of the Art – New Total Annual Additions



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/2020/Mar/IRENA_RE_Capacity_Highlights_2020.pdf?la=en&hash=B6BDF8C3306D271327729B9F9C9AF5F1274FE30B, March 2020)

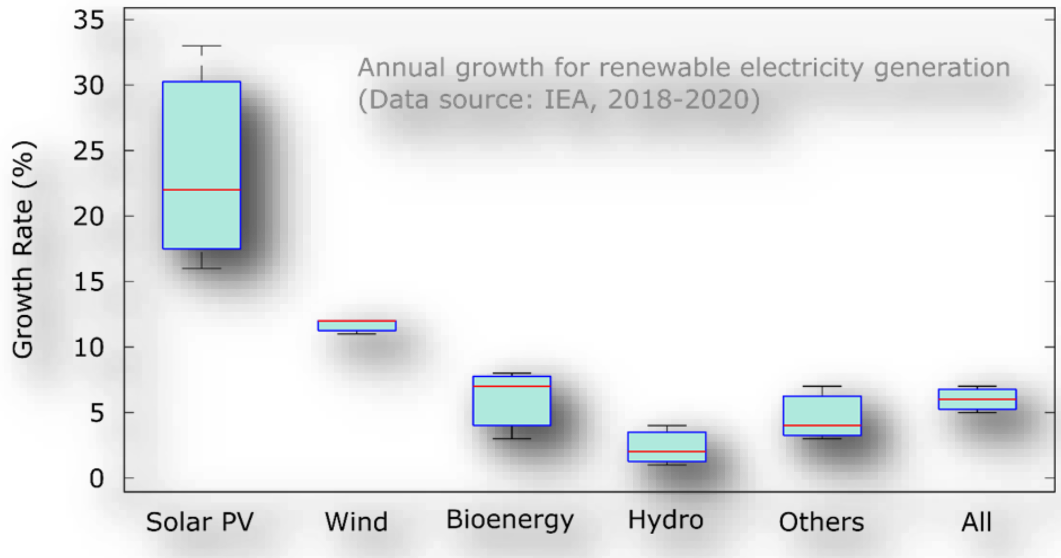
State of the Art Development – PV Power



Global installed solar PV capacity (until 2019): **586** GW, 2019: **97** GW

- More significant total capacity (29 % non-hydro renewables).
- Fastest growth rate (22 % between 2018-2020, 33% in 2018).

State of the Art Development – PV Power



Global installed solar PV capacity (until 2019): **586** GW, 2019: **97** GW

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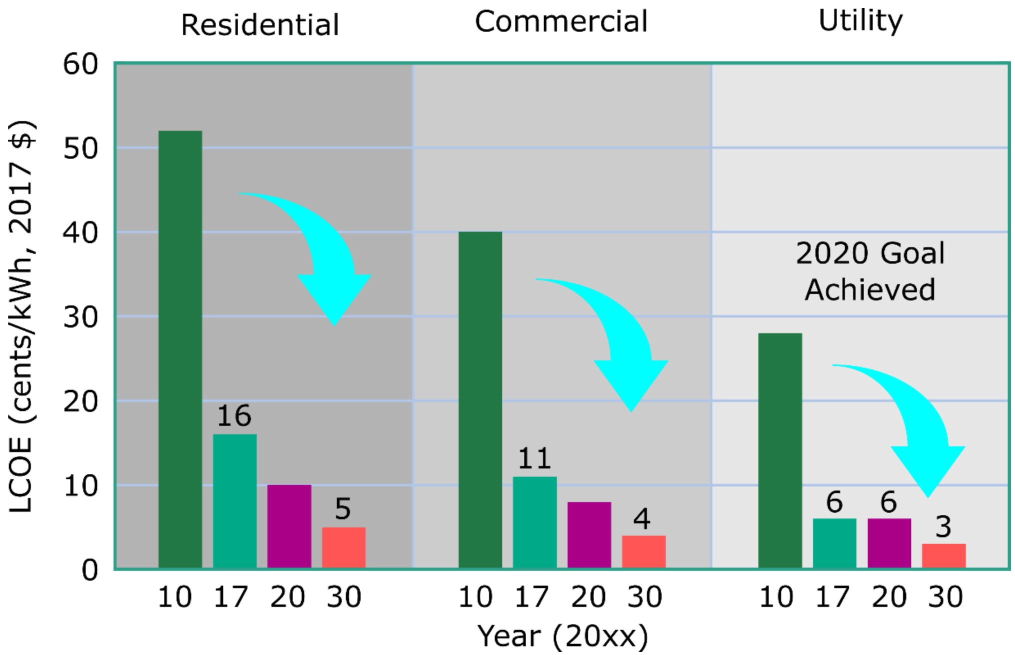
Future Target

Increasing competitiveness by lowering **Cost of Energy**

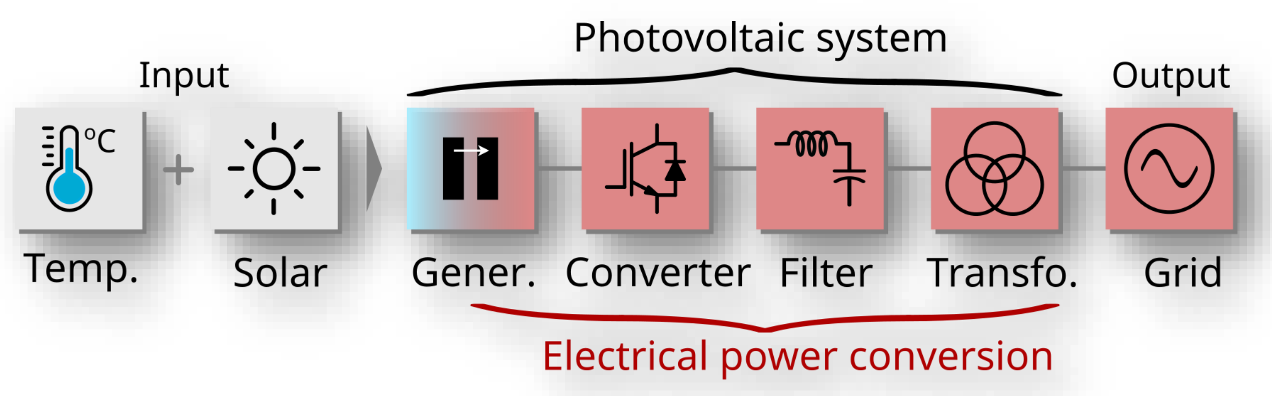


In 2017, DOE's Solar Energy Technologies Office (SETO) announced that the industry had achieved the 2020 cost goal for utility-scale solar of 6¢ per kilowatt hour (kWh).

*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.

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 freq. and voltage

Example

Residential application

Example

Utility application

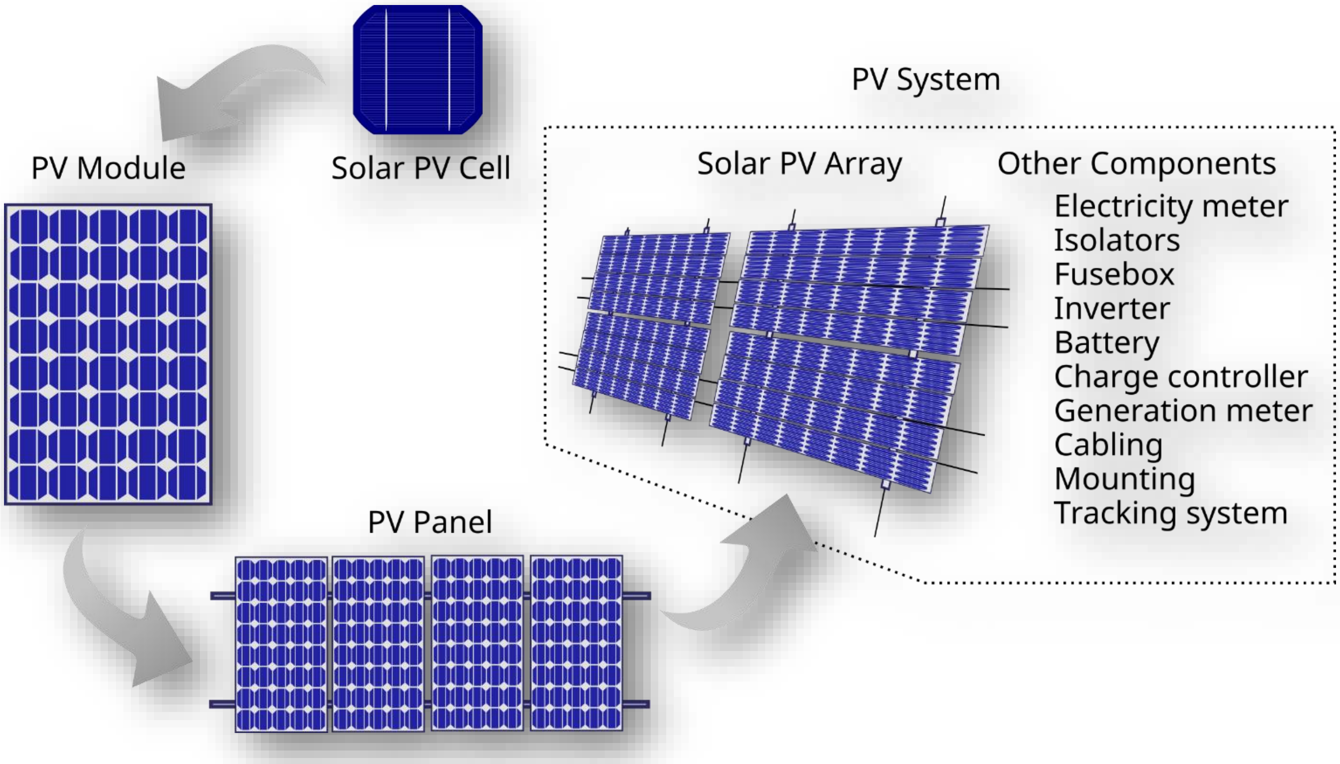
Outline

Basic PV modeling

PV cell-module-panel-array

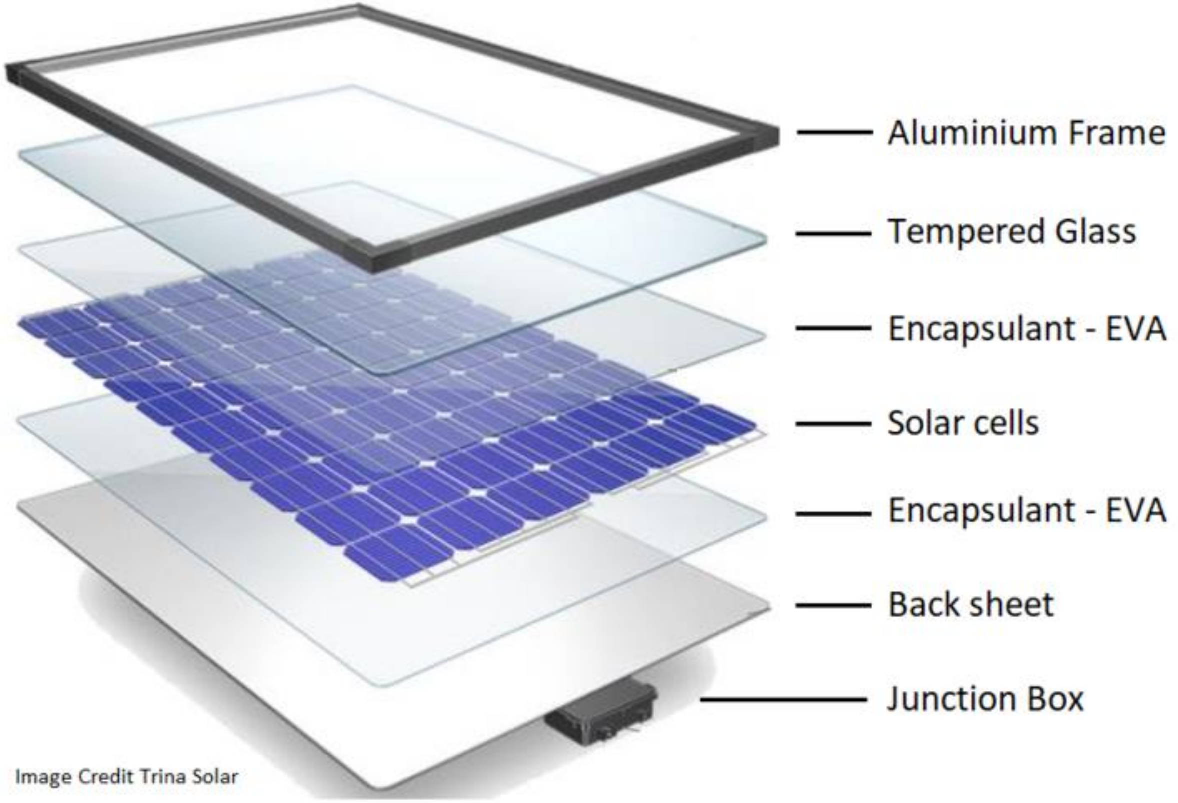
Many PV Modules are used to form panels, and then arrays

- Series-connected solar cells (as PV module)
- Series-connection of PV modules for higher voltage
- Parallel-connection of PV modules for higher current



https://en.wikipedia.org/wiki/Solar_cell#/media/File:From_a_solar_cell_to_a_PV_system.svg

PV module structure



https://blog.ibc-solar.com/2018/09/new-module-technologies-lhs-half-cut-mbb/

PV cell technology

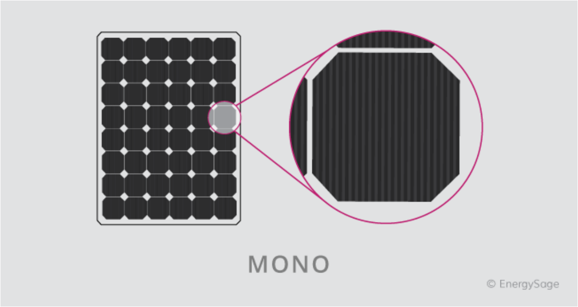
Major type of solar panels

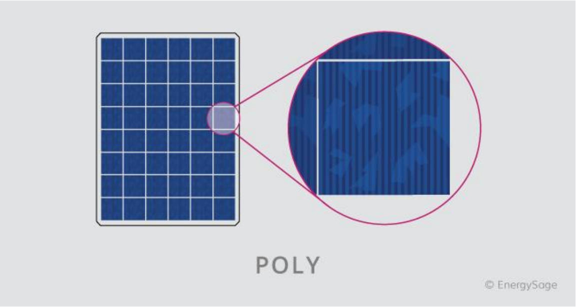
https://www.solarmarket.com.au/residential-solar/different-types-of-panels/

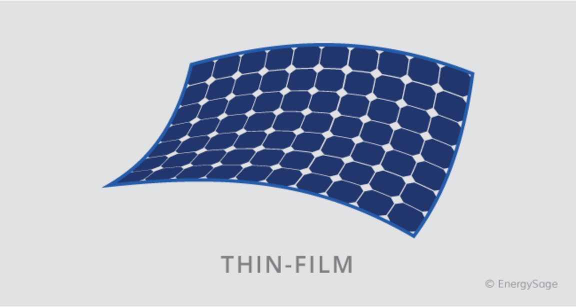
PV cell technology

Major type of solar panels

Solar panel type	Advantages	Disadvantages
Monocrystalline	• High efficiency/performance • Aesthetics	• Higher costs
Polycrystalline	• Low cost	• Lower efficiency/performance
Thin-film	• Portable and flexible • Lightweight • Aesthetics	• Lowest efficiency/performance



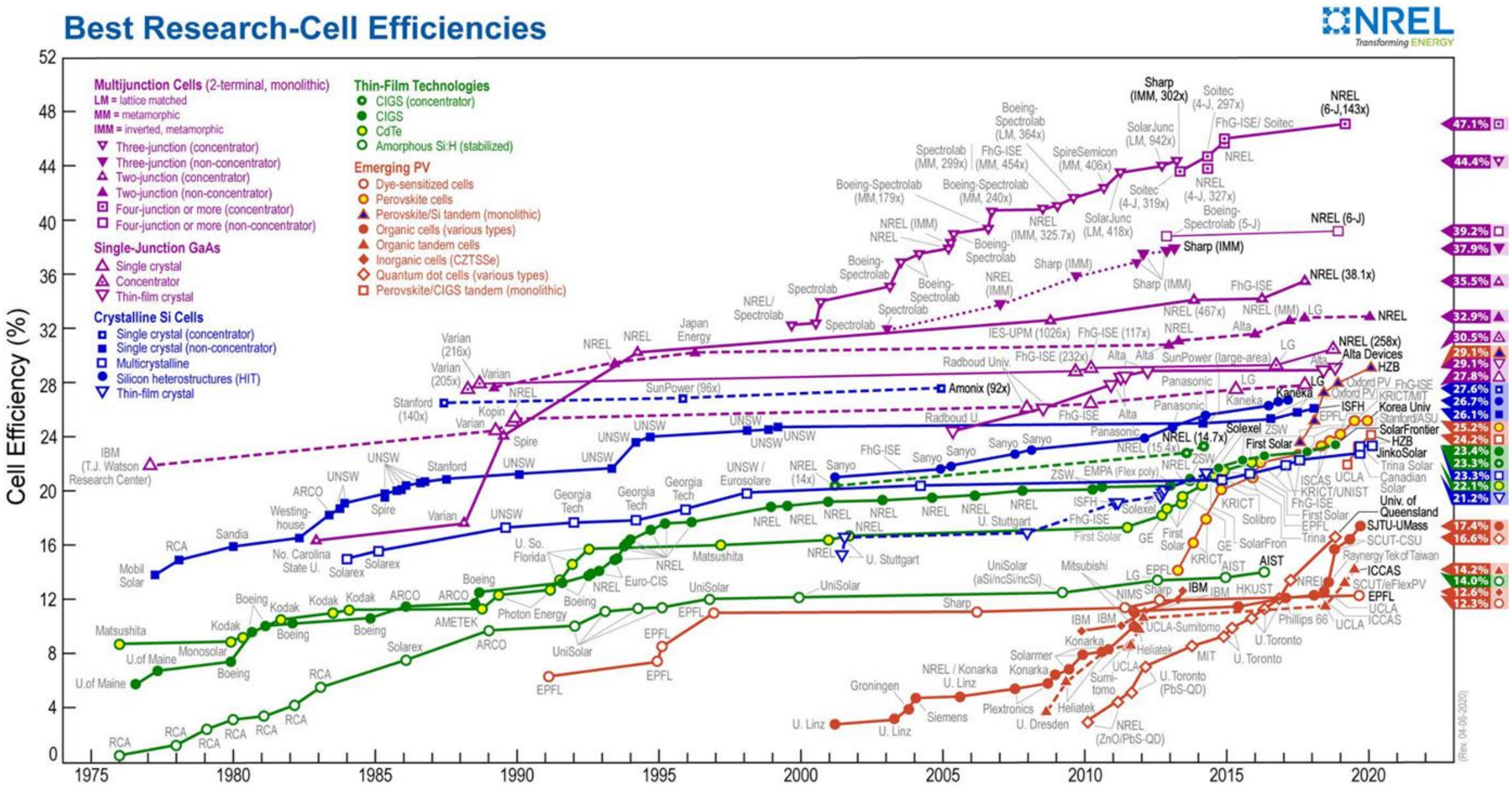




https://www.energysage.com/solar/101/types-solar-panels/

State of the Art – PV Cell Technologies

Race of efficiency



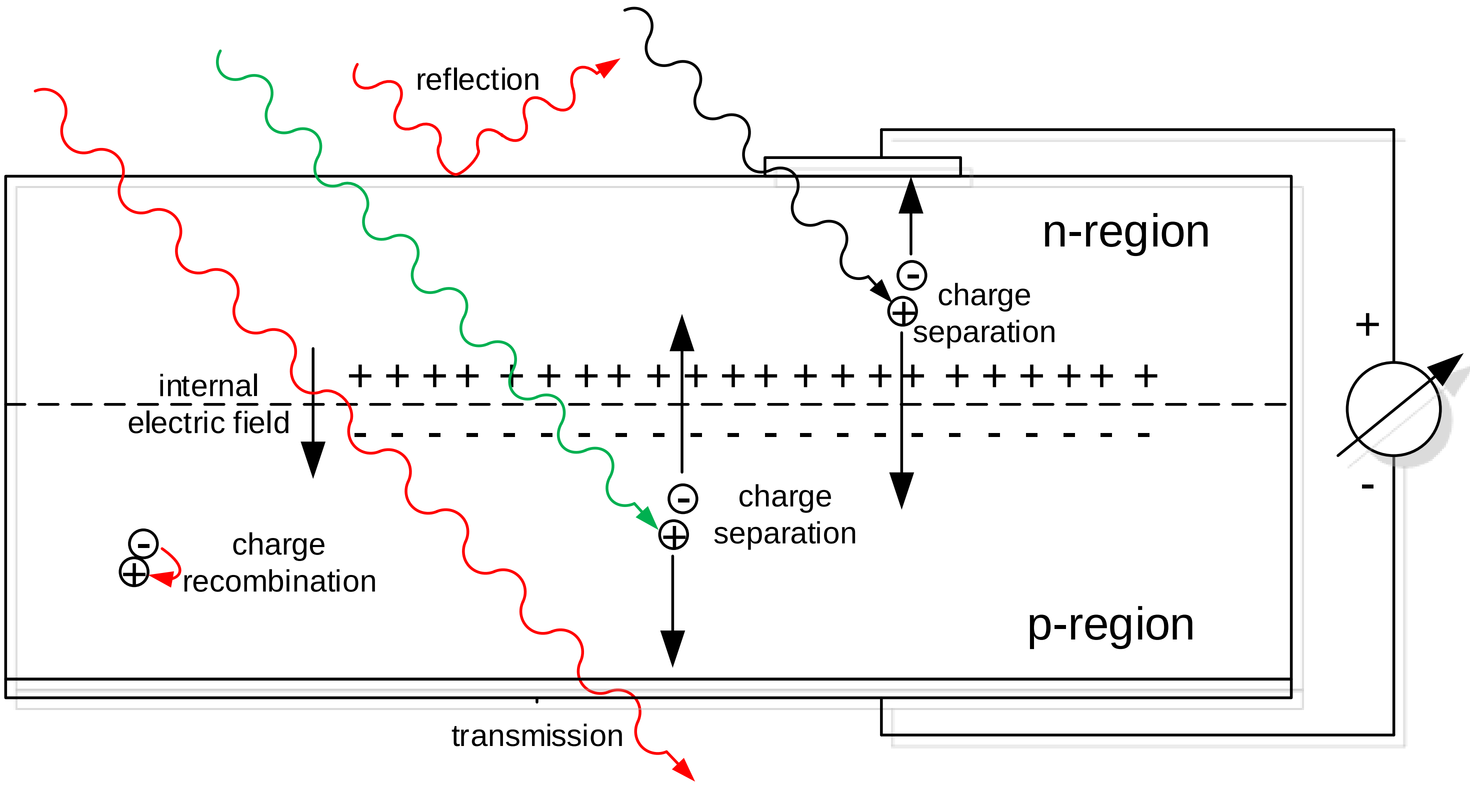
Top 10 most efficient PV panels (2021)

No.	Manufacurer	Model	Power	Efficiency
1	SunPower	Maxeon 3	400 W	22.6 %
2	LG	Neon R	380 W	22.0 %
3	REC	Alpha	380 W	21.7 %
4	FuturaSun	FU M Zebra	360 W	21.3 %
5	Panasonic	EverVolt	370 W	21.2 %
6	Trina Solar	Vertex S	405 W	21.1 %
7	Jinko Solar	Tiger Pro 6Rl3	390 W	20.7 %
8	Q cells	Q.Peak DUO G9	360 W	20.6 %
9	Winaico	WST-375MG	375 W	20.6 %
10	Longi Solar	Hi-Mo 4	375 W	20.6 %

https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels

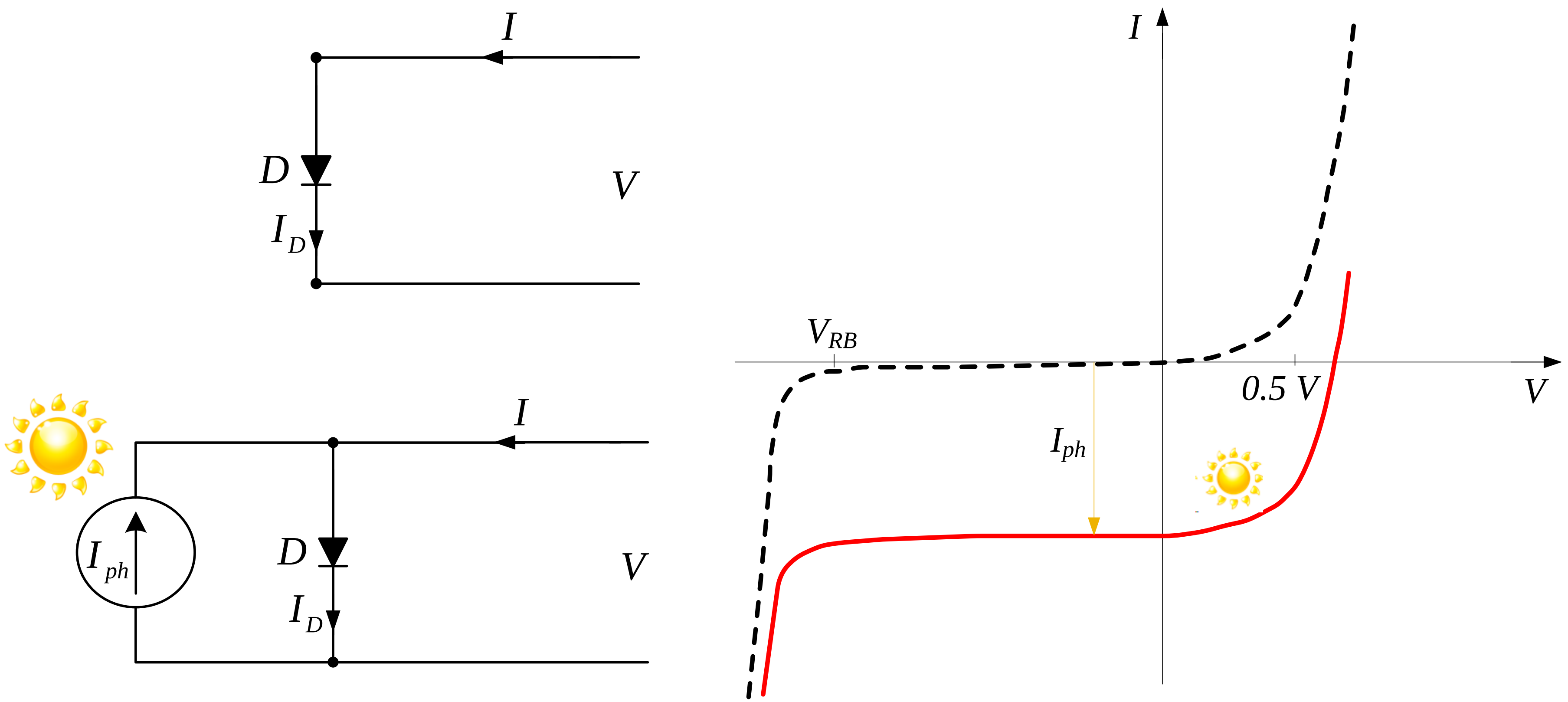
Solar cell operating principle

Photovoltaic effect



PV cell models

Ideal model of a PV cell – most PV cells can be modelled as a P-N junction



PV cell models

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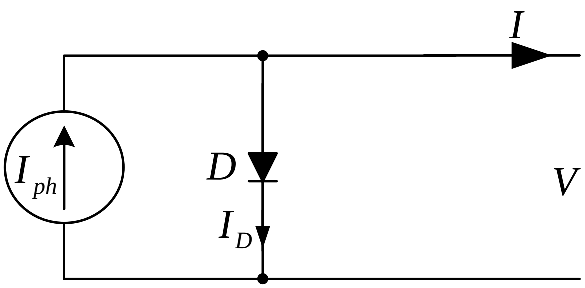
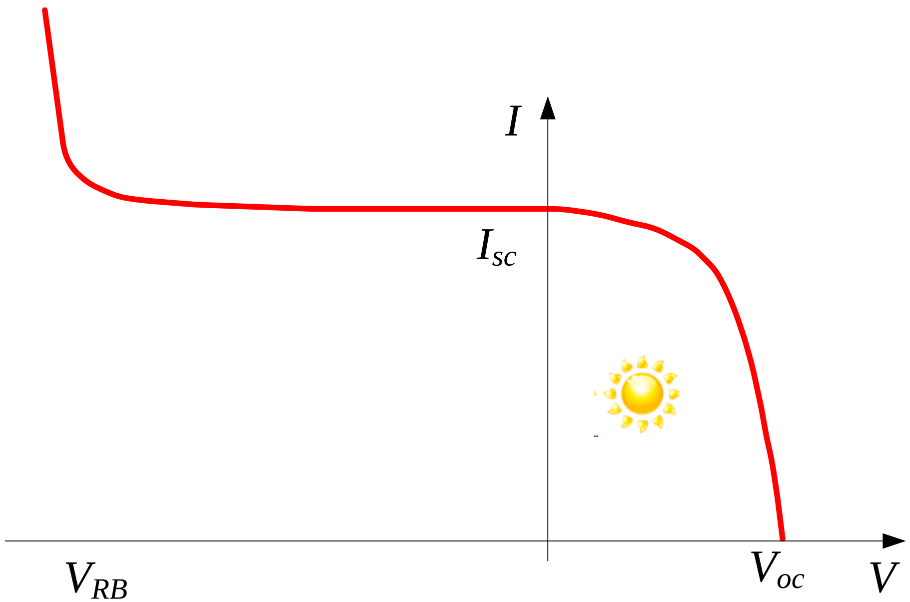




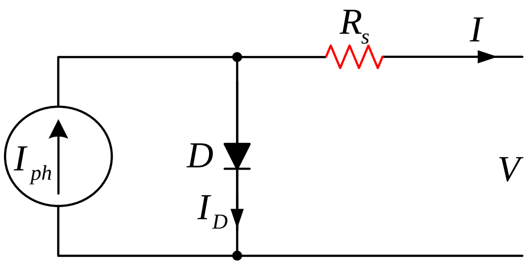
$$I = I_{ph} - I_0\left(e^{\frac{V}{V_t}} - 1\right)$$

$$V_t = \frac{kT}{q}$$

- I_{ph} - photo-generated current
- I_0 - dark saturation current
- V_t - cell thermal voltage
- k - Boltzmann's constant
- T - Temperature (˚K)
- q - Charge of an electron

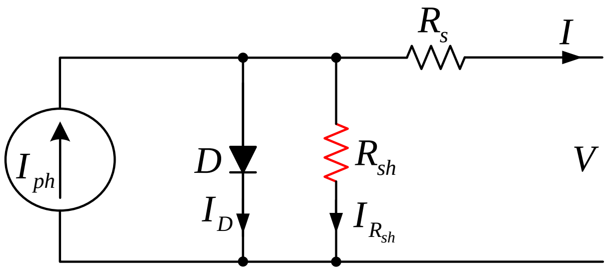
PV cell models are based on the Shockley diode equation

PV cell models



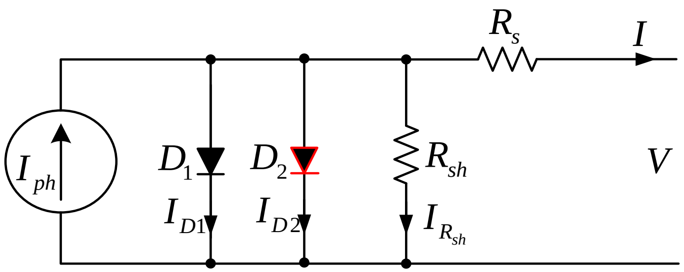
Four-parameter model

- \+ Simplicity
- \+ Analytic solutions for parameters
- \- Limited accuracy



Five-parameter model

- \+ Better accuracy
- \- Increased complexity
- \- No analytic solutions for model parameters



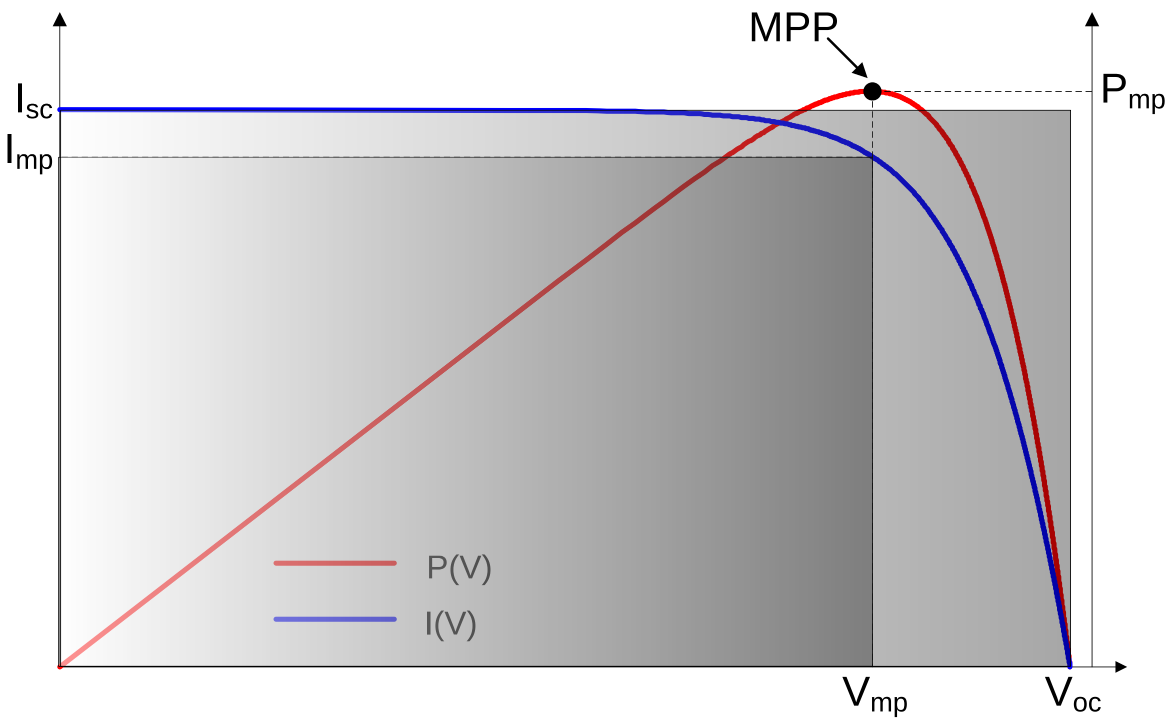
Five, six or seven-parameter model

- \+ Better accuracy, especially at low irradiations
- \- Increased complexity
- \- No analytic solutions for model parameters

Electrical characteristic – P-V curve

Standard Test Condition (STC)

- Irradiance level of **1000 W/m²**
- Spectral irradiance distribution corresponding to Air Mass **(AM) 1.5**
- Junction temperature **25 C**



$$I = I_{ph} - I_0\left(e^{\frac{V+IR_s}{V_t}} - 1\right)$$

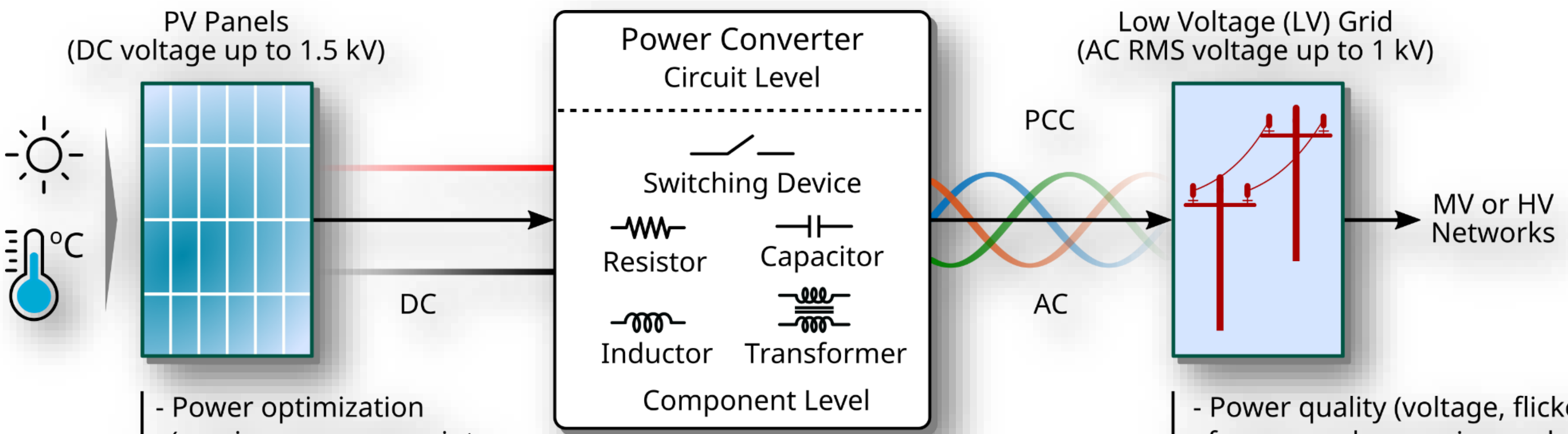
$$FF[\%] = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}100$$

Outline

Power Converters for PV

Demands on PV Systems

Power converter – key enabling technology for PV integration



- Power optimization (maximum power point tracking - MPPT)
- DC voltage/current control
- Monitoring and diagnosis

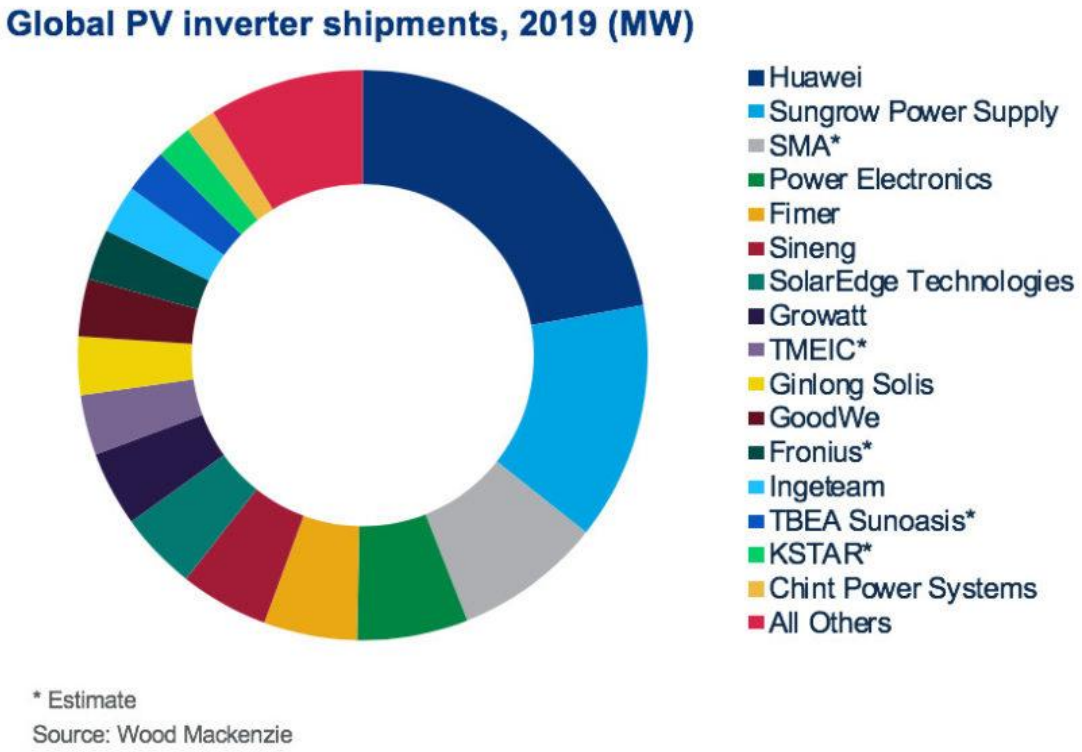
- Converter controllability
- Conversion efficiency
- Reliability
- Thermal management
- Energy management
- Islanding detection/protection
- Response to grid recovery
- Monitoring and safety
- Communication

- Power quality (voltage, flicker, frequency, harmonics, and power factor)
- Power flow controllability

Supportive Schemes for MV/HV

- Frequency-Watt control
- Voltage-VAr control
- Fault ride-through
- Grid-forming
- Inertia provision

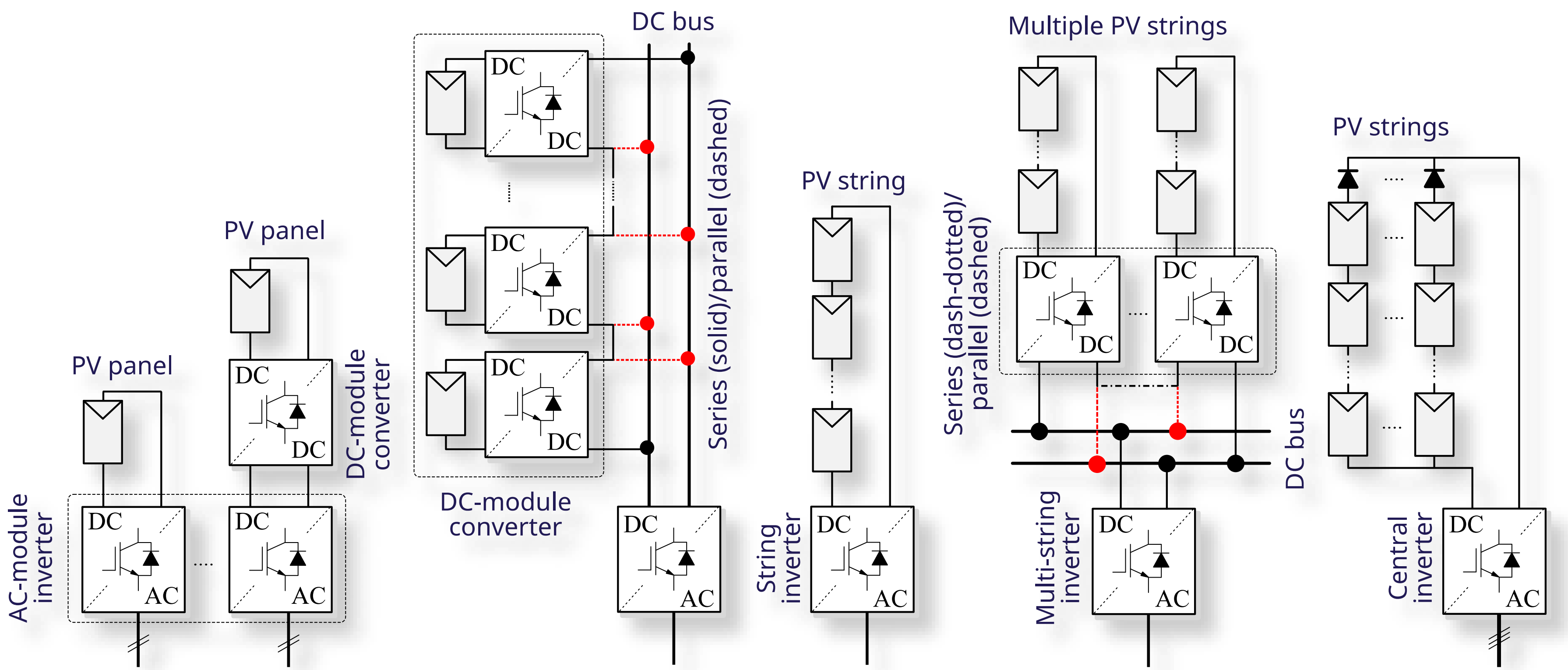
Top global Photovoltaic inverter supplier



Global Market Share of Top PV Inverter Suppliers (2012-2015)

https://www.pv-magazine.com/2020/04/29/huawei-sungrow-and-sma-dominate-global-inverter-market/

PV inverter system configurations



Module Converter	DC Grid	String/Multistring Converter	Central Inverter

- Single-phase
- Hundreds watts
- Small systems

- DC grid → AC grid
- Single-/three-phase
- Several kilowatts
- Small systems / resisdential

- Single-/three-phase
- 1~30 kW applications
- Residential/commercial

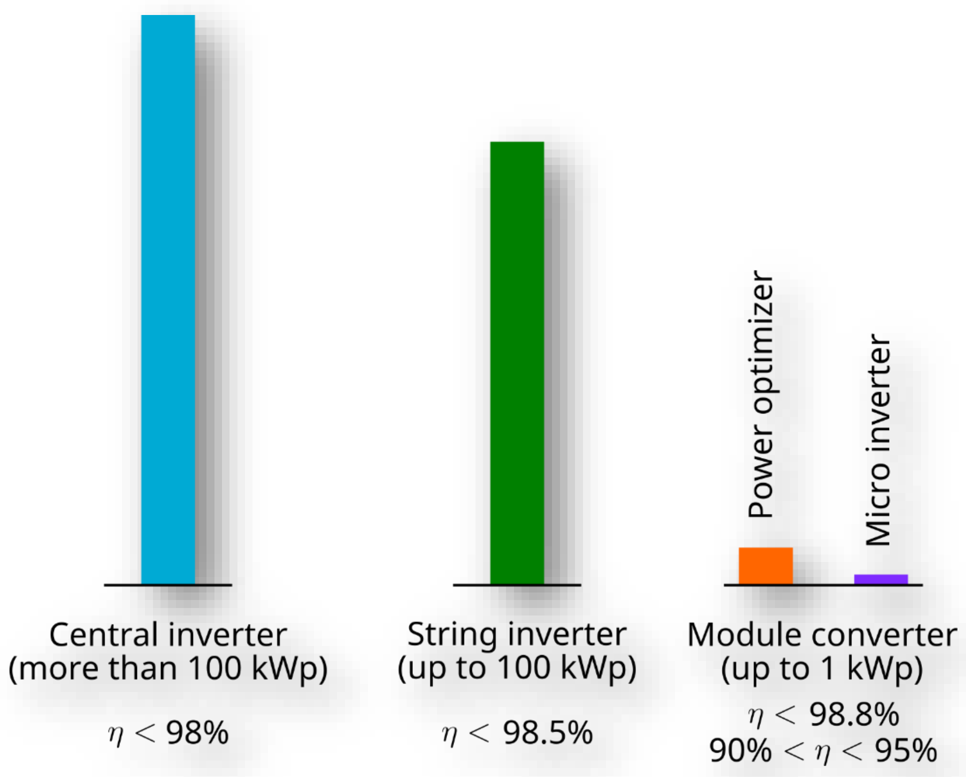
- Three-phase
- 30~ kW
- Commercial / utility-scale

Chapter 03 in *Renewable energy devices and systems with simulations in MATLAB and ANSYS*, Editors: F. Blaabjerg and D.M. Ionel, CRC Press LLC, 2017

Market size of different PV configuration

Center and String Inverters are dominating the market

(market share in respect to the central inverter – the base value)



Examples

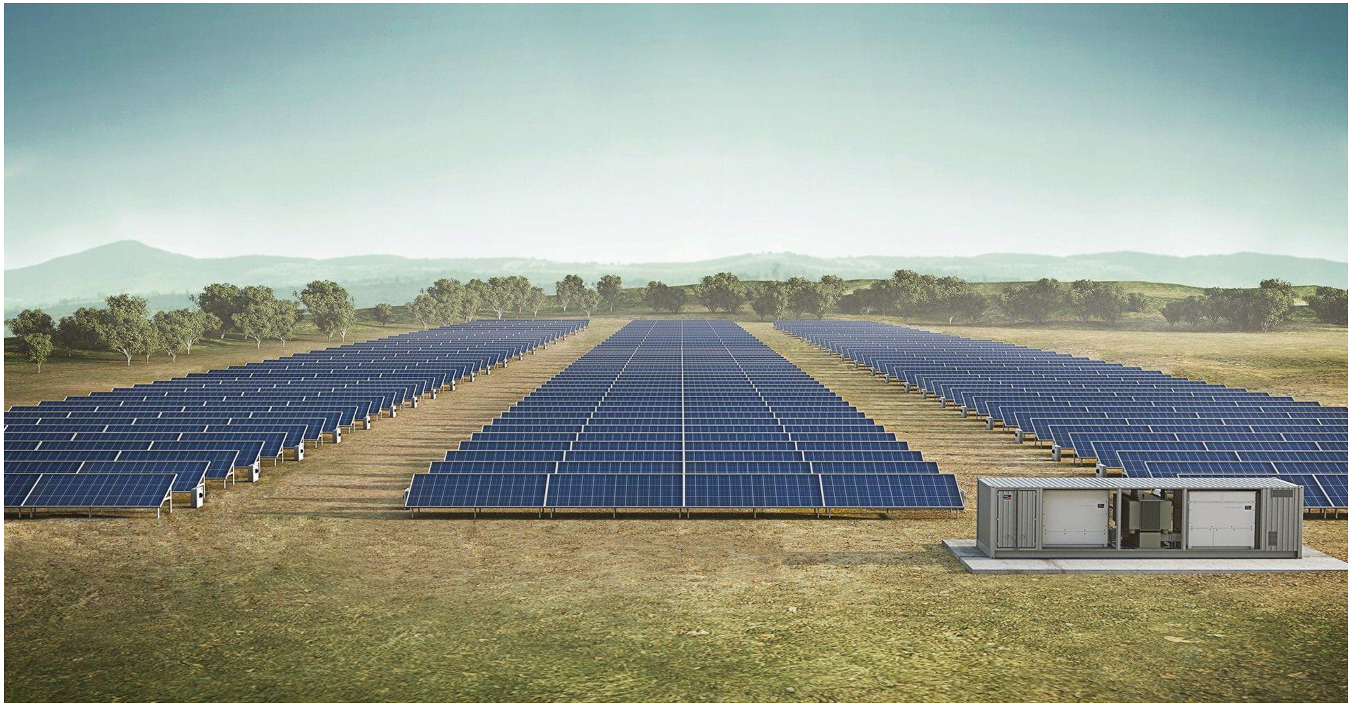
Central inverter solution

ABB MW Solution

Sungrow Solution

Examples

Central inverter solution



Examples

String inverter solution

Rooftop-installed PV systems: (a) PV arrays with a total rating of 60 kW installed on the roof of Aalborghus High School in Denmark and (b) power electronic converters with the schematic are installed within the building and are connected to the AC grid.

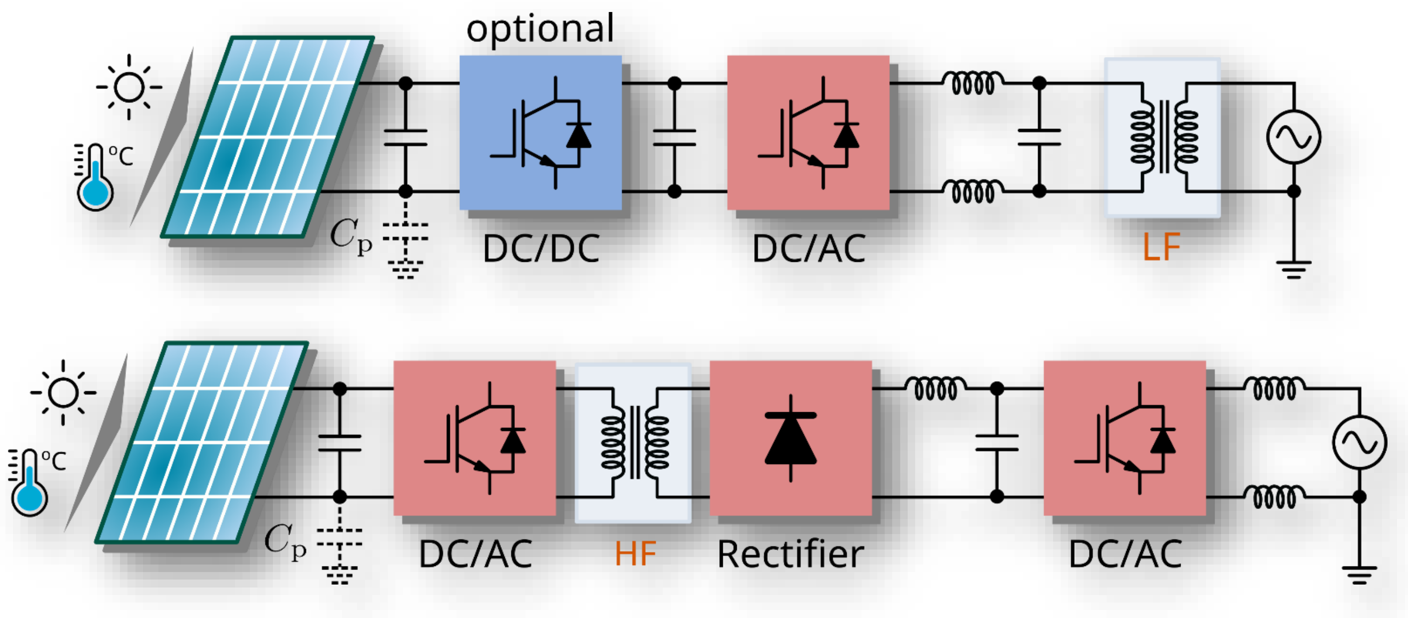
Examples

Microinverter solution

String inverter configurations

Transformer-based grid-connection

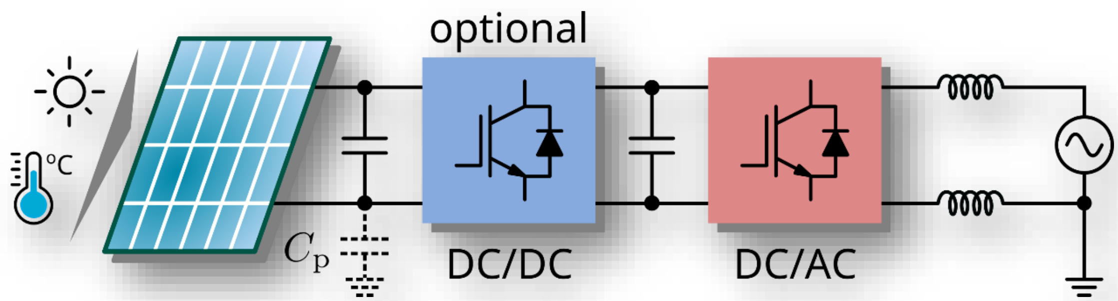
→ Galvanic isolation
→ Bulky



String inverter configurations

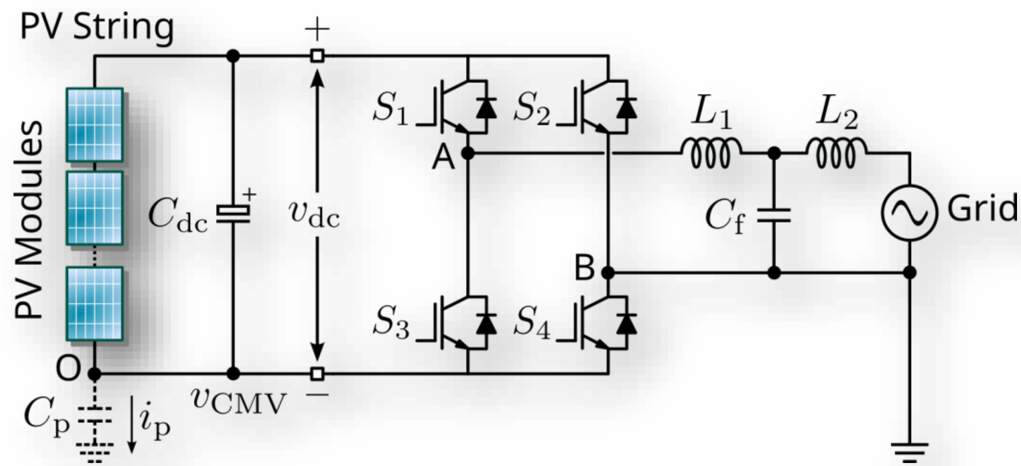
Transformerless grid-connection

→ Higher efficiency
→ Smaller volume

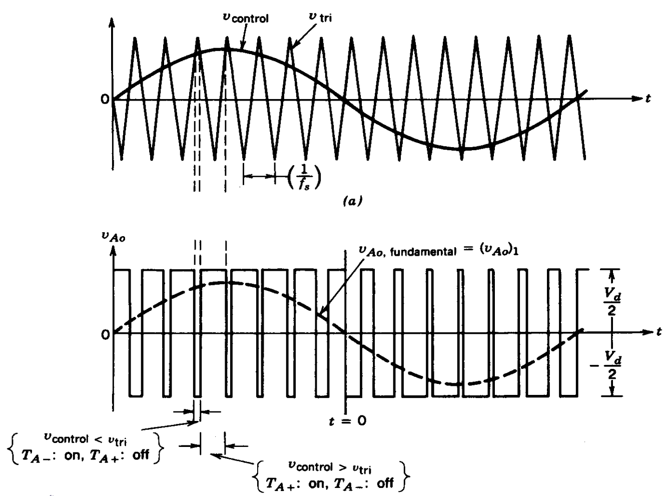


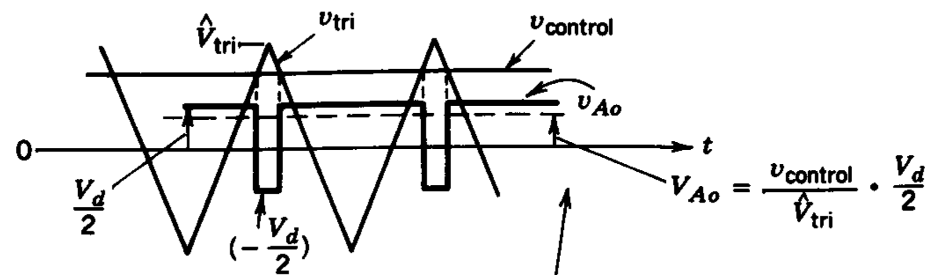
String inverter topologies

Full-Bridge inverter



Basic Pulse-width modulation





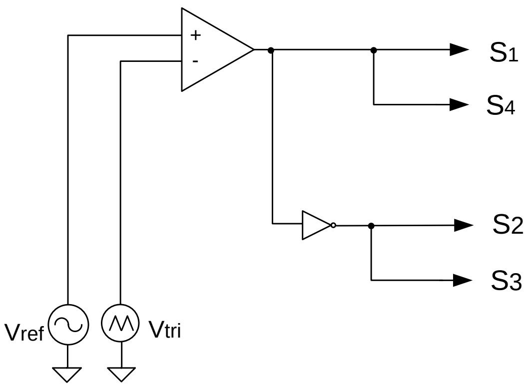
$$V_{Ao} = \bar{v}_{Ao} = \frac{v_{control}}{V_{tri}} \frac{V_d}{2} \quad ; \quad v_{control} \le \hat{V}_{tri}; \; m_a = \frac{v_{control}}{V_{tri}}$$

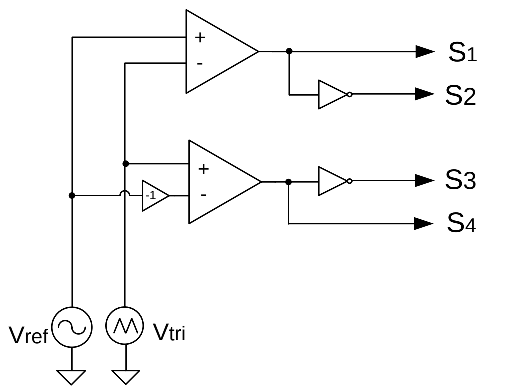
Pulse-width modulation techniques

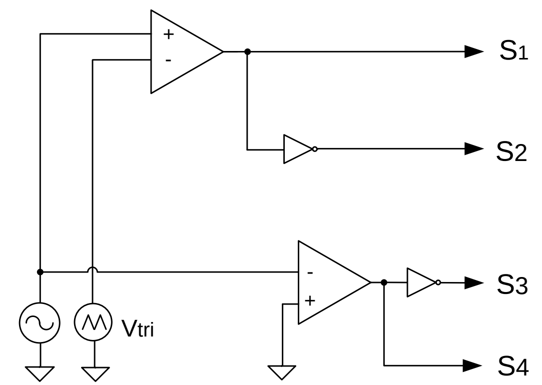
Bipolar PWM
S1 + S4 and S2 + S3 are switched complementary at high frequency

Unipolar PWM
Leg A and B are switched with high frequency with mirrored sinusoidal ref.

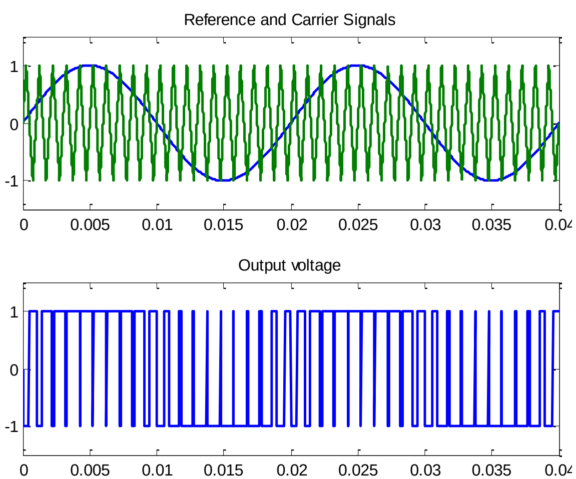
Hybrid PWM
Leg A is switched with high frequency and Leg B is switched with grid frequency



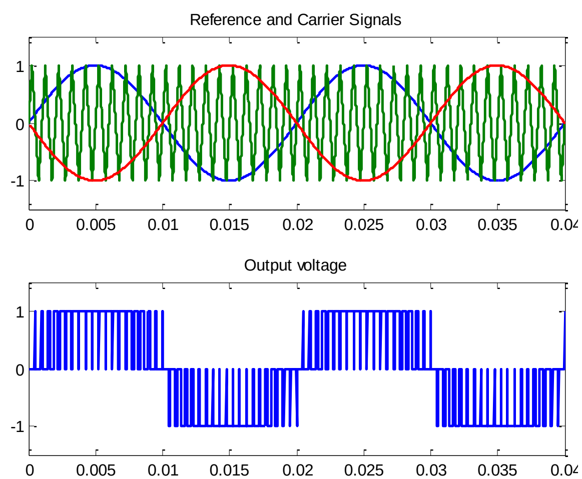




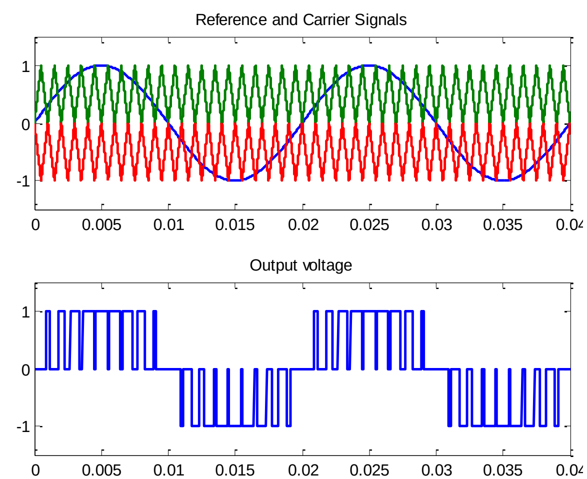
Bipolar PWM



Unipolar PWM



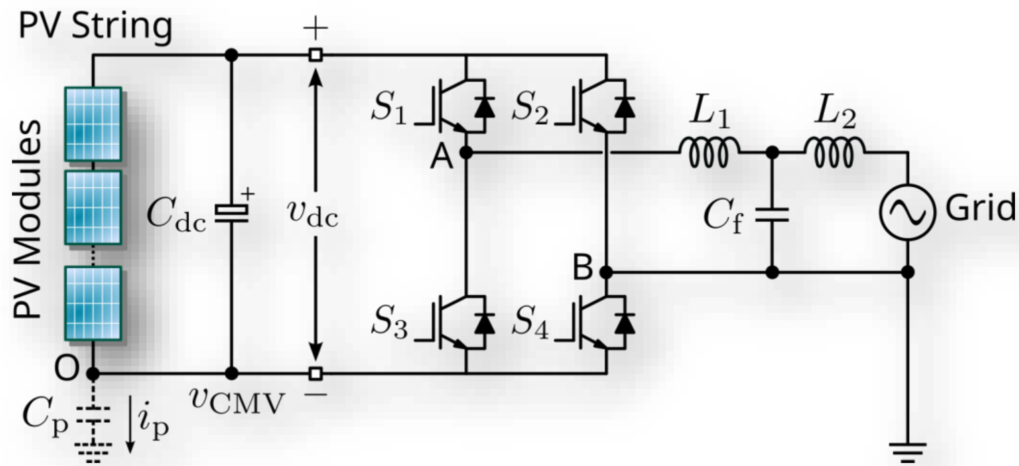
Hybrid PWM



1kHz triangular wave and 50Hz sinusoidal reference

String inverter topologies

Full-Bridge inverter



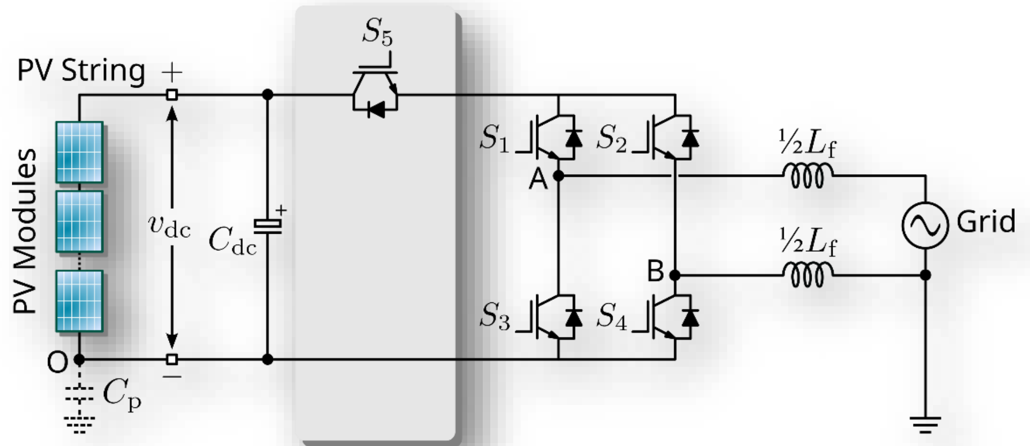
Bipolar Modulation is used:

- ❑ No common mode voltage → free for high frequency → low leakage current
- ❑ Max efficiency 96.5% due to reactive power exchange between the filter and C_P during freewheeling and due to the fact that 2 switched are simultaneously switched every switching
- ❑ This topology is not special suited to transformerless PV inverter due to low efficiency!

Transformerless string PV inverters

H5 Transformerless inverter

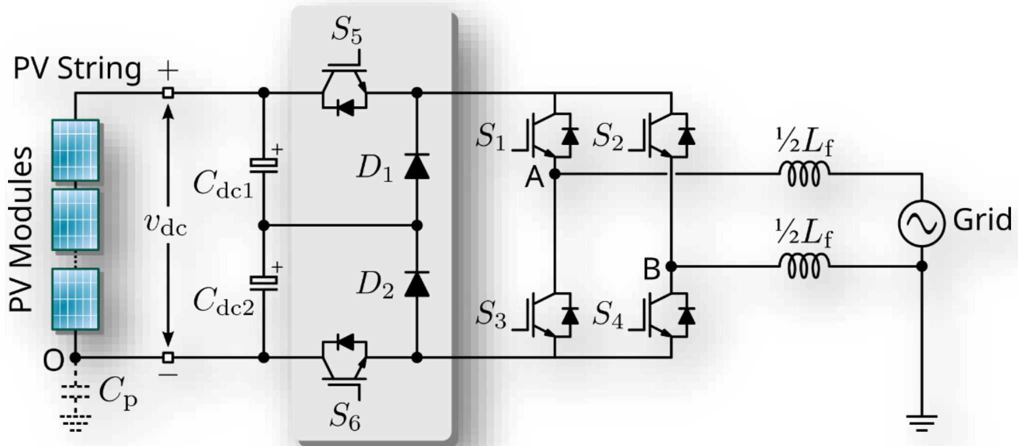
- Efficiency of up to 98%
- Low leakage current and EMI
- Unipolar voltage across the filter, leading to low core losses



Transformerless string PV inverters

H6 Transformerless inverter

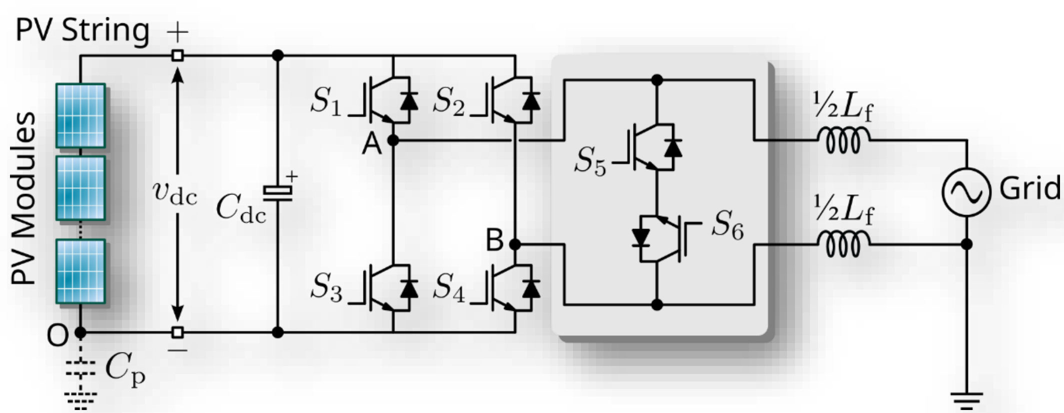
- High efficiency
- Low leakage current and EMI
- DC bypass switches rating: Vdc/2
- Unipolar voltage across the filter



Transformerless string PV inverters

HERIC – highly efficiency and reliability inverter concept

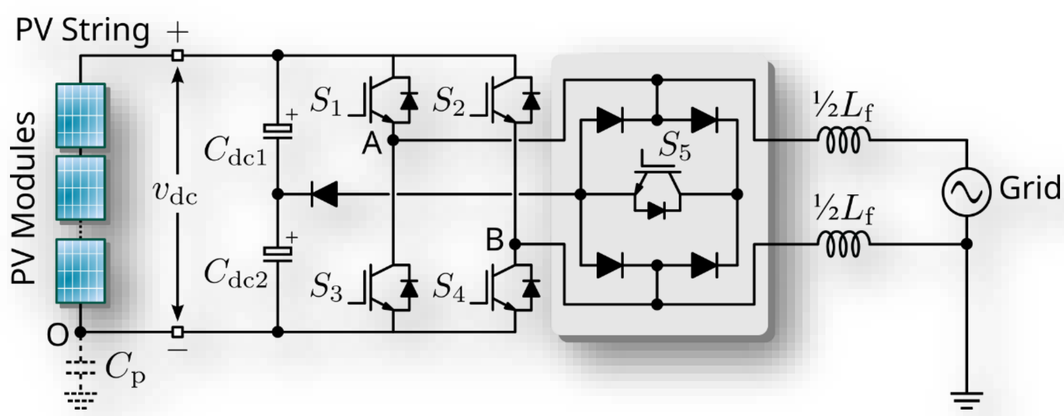
- High efficiency of up to 97%
- Very low leakage current & EMI
- Low core losses



Transformerless string PV inverters

FB-ZVR – full-bridge zero-voltage rectifier inverter

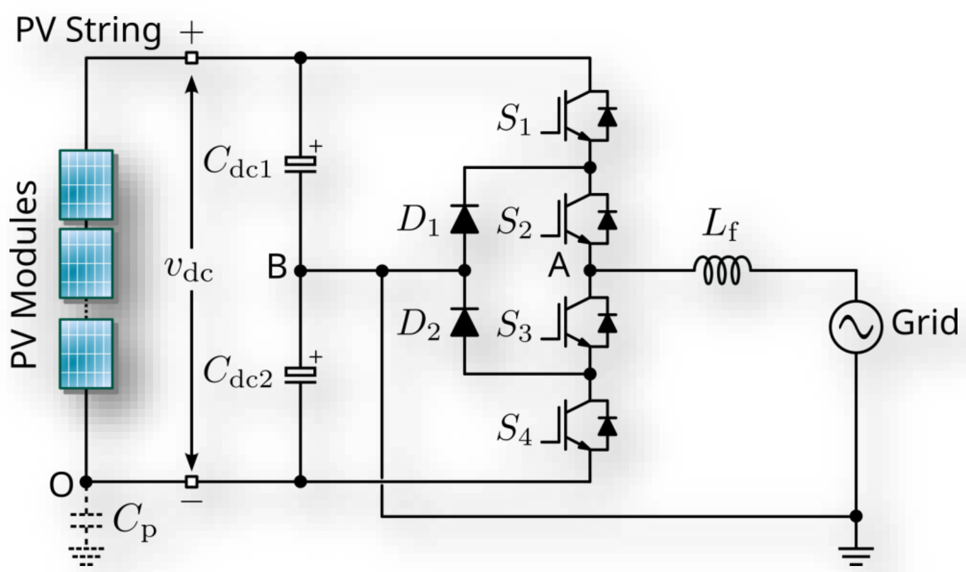
- Efficiency of up to 96%
- Low leakage current and EMI
- Unipolar voltage across the filter, leading to low core losses



Transformerless string PV inverters

Multilevel Inverters for transformerless applications

- Constant voltage-to-ground → Low leakage current, suitable for transformerless PV applications.
- High DC-link voltage (> twice of the grid peak voltage)



Transformerless string PV inverters

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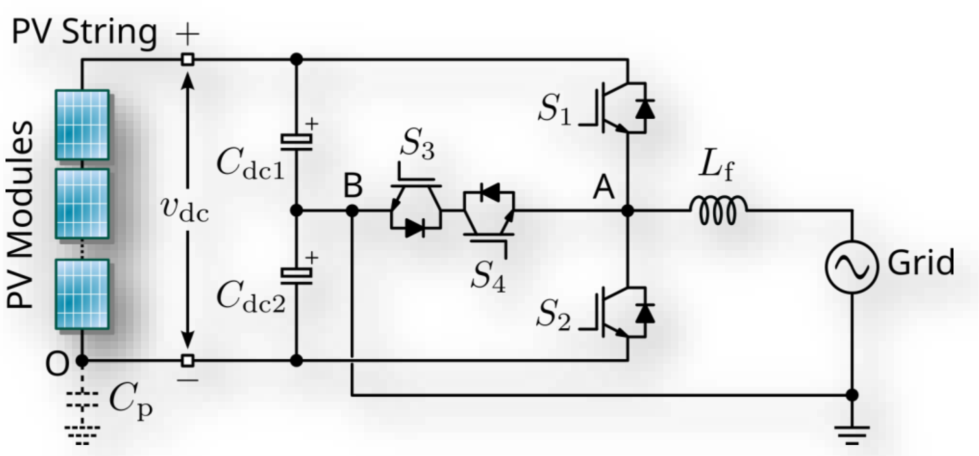
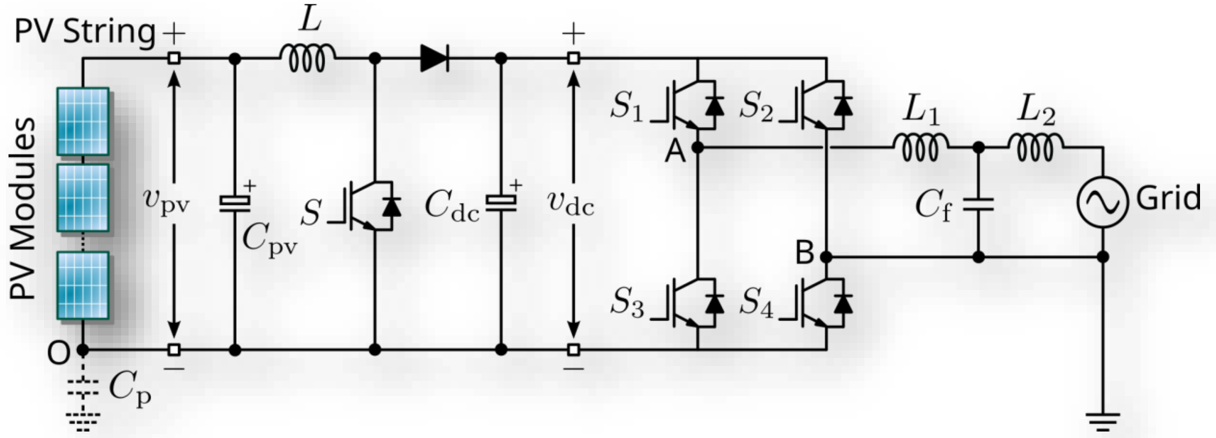


String PV inverters

Other String Inverters – two-stage

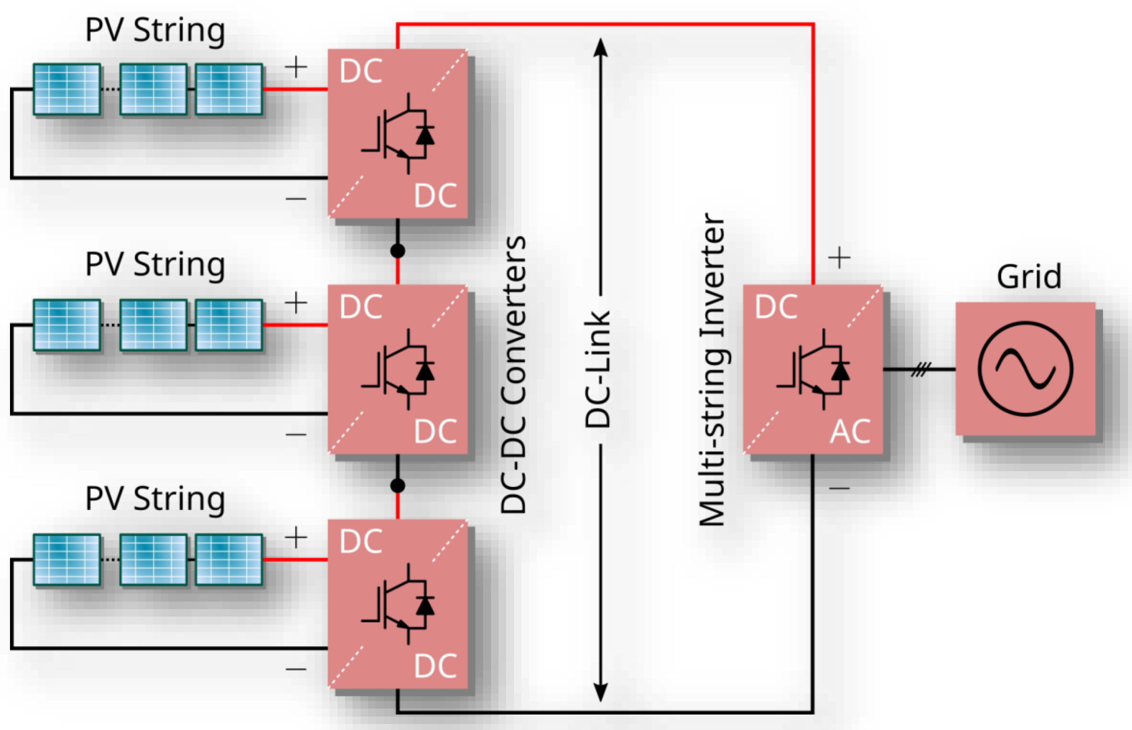
- Single-phase double-stage with a boost converter and a full-bridge inverter
- Half-bridge converter with a parallel-input series-output converter



String PV inverters

Multistring Inverters – to process more power

- Series connection of multiple PV string DC-DC converters
- Parallel connection of multiple PV string DC-DC converters



String PV inverters

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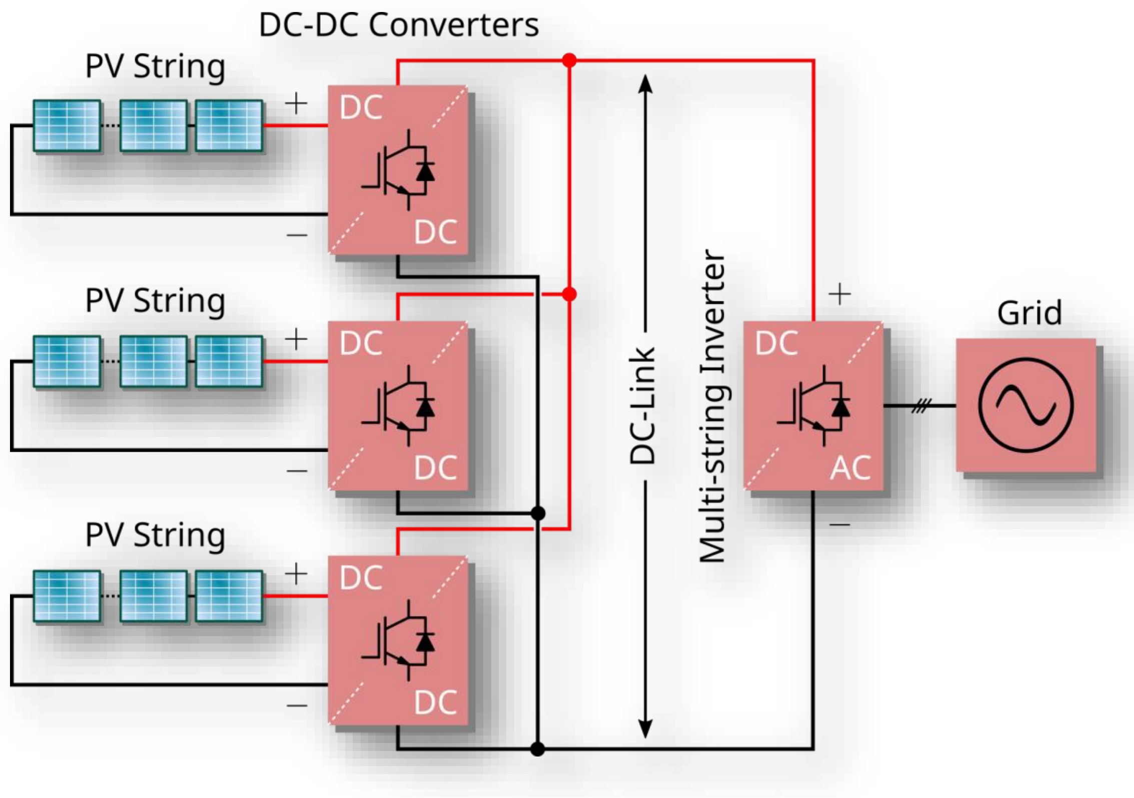
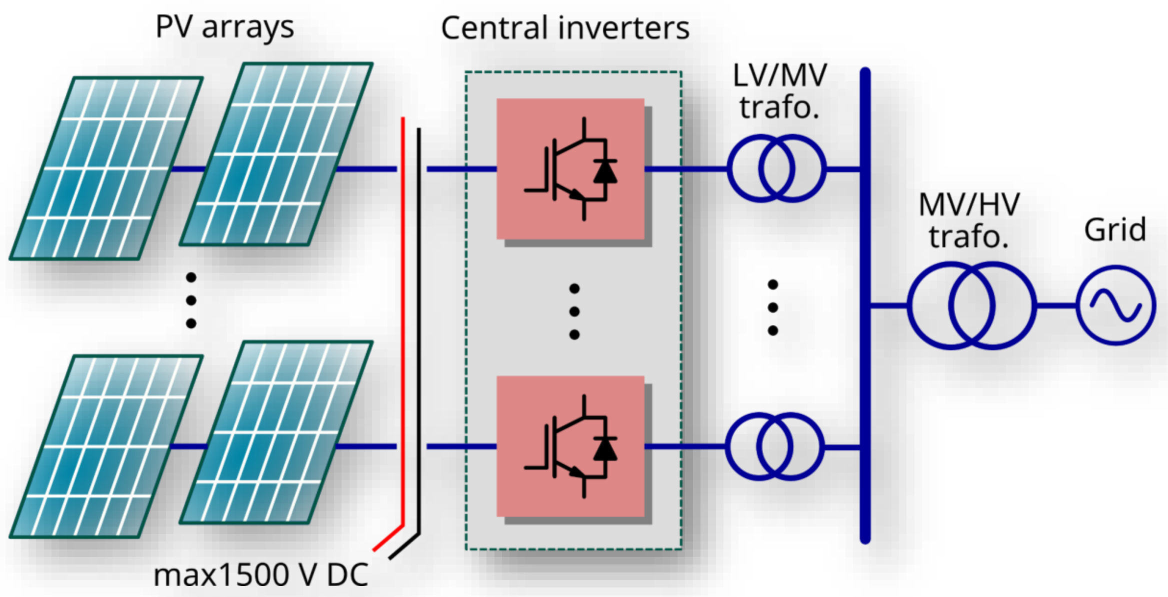


Central inverters

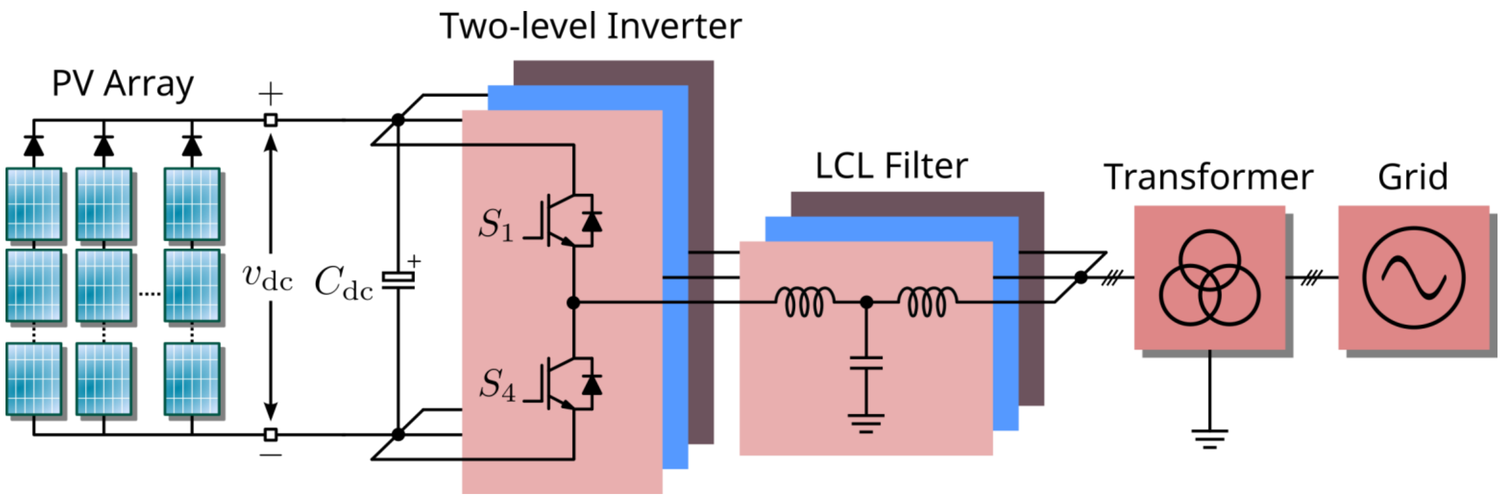
Towards **Even Higher Power Capacity** with central inverters



- Large PV **power plants**, rated over several MWs, adopt many central inverters with the power rating of up to 900 kW.
- DC-DC converters can be optionally used before the central inverters.
- Similar to wind turbine applications → NPC topology might be a promising solution.

Central inverters

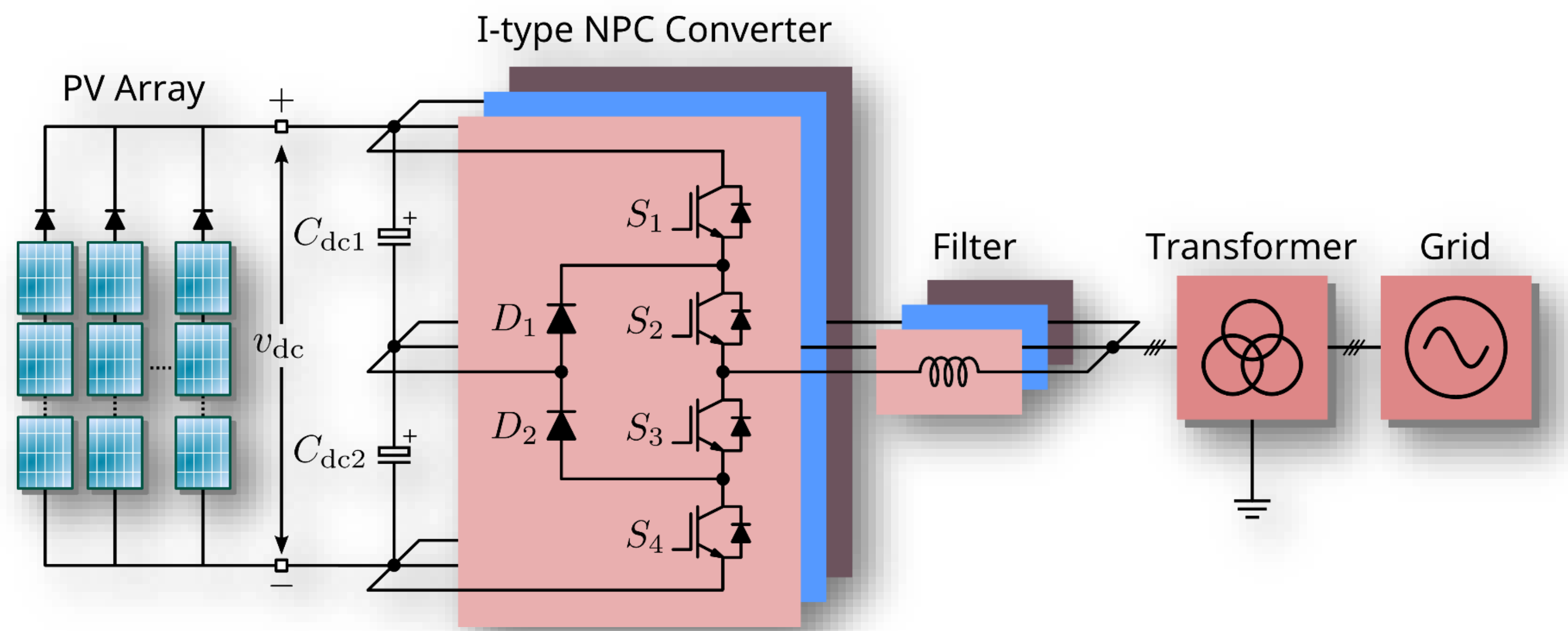
Towards **Even Higher Power Capacity** with central inverters



Three-phase two-level central inverter

Central inverters

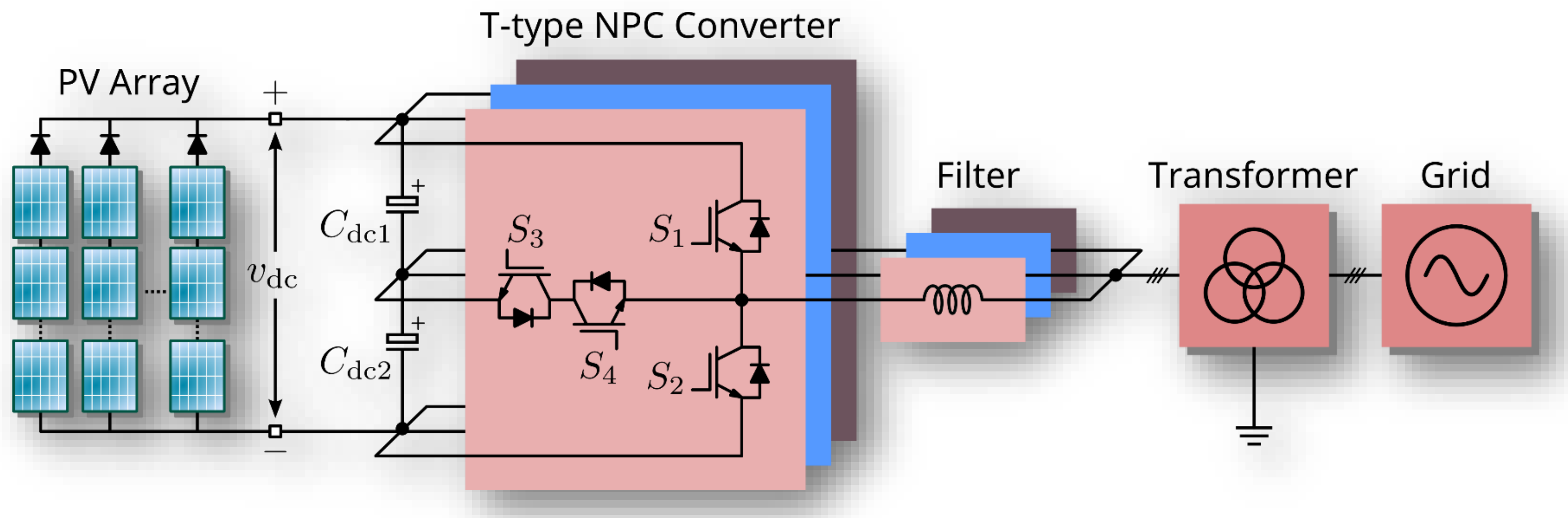
Towards **Even Higher Power Capacity** with central inverters



Three-phase I-type NPC central inverters

Central inverters

Towards **Even Higher Power Capacity** with central inverters

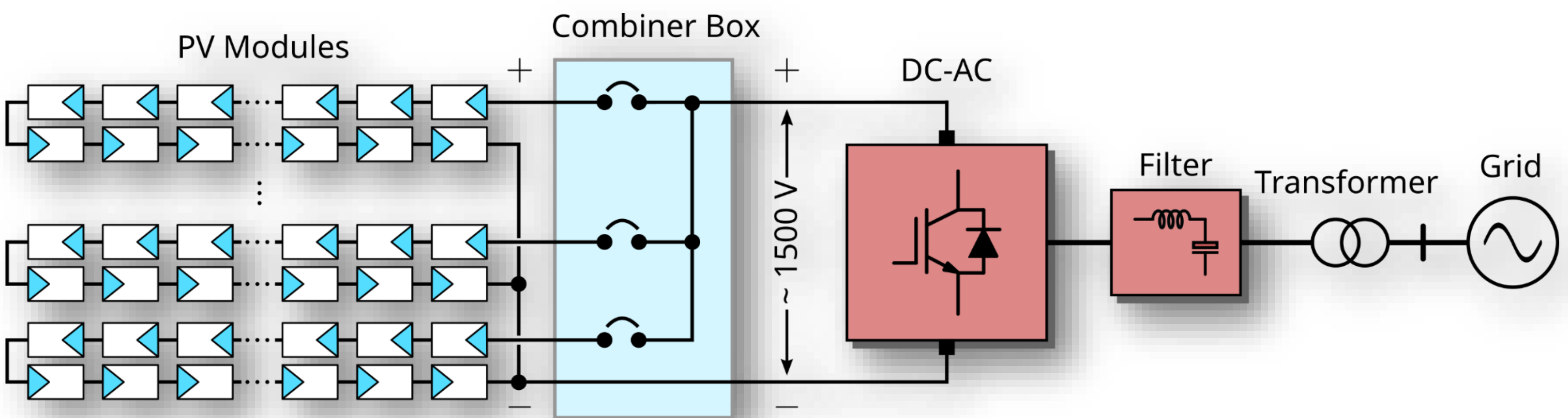


Three-phase T-type NPC central inverters

1500-V DC PV systems

Becoming the **Mainstream Solution** to LV PV systems!

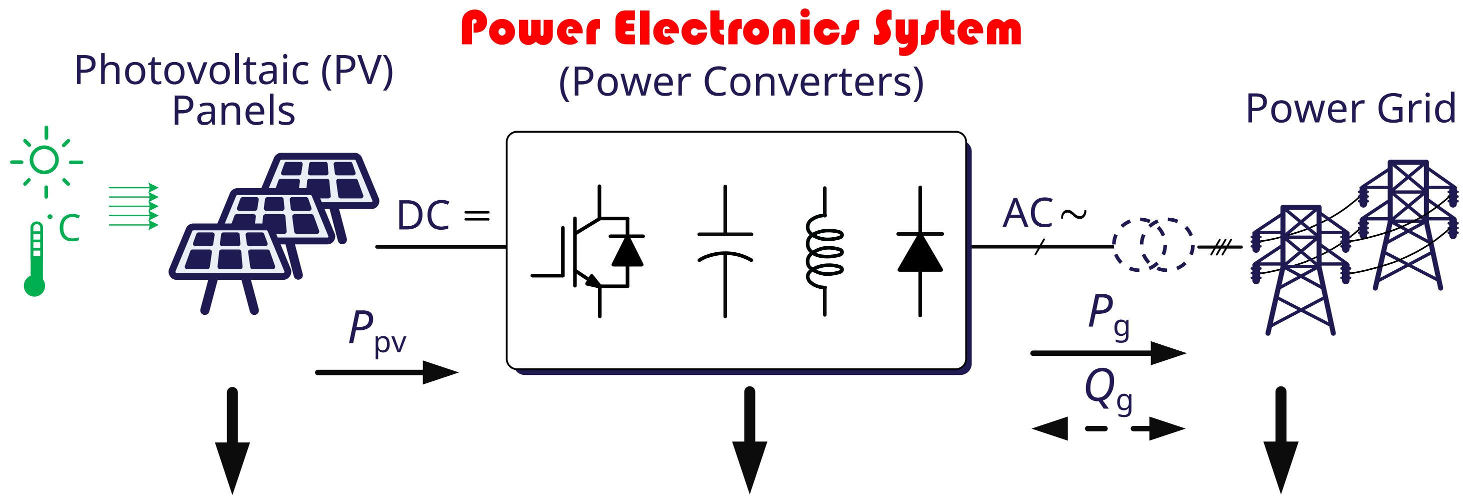
- Decreased requirement of the balance of system (e.g., combiner boxes, DC wiring, and converters) and Less installation efforts
- Contributes to reduced overall system cost and increased efficiency
- More energy production and lower cost of energy
- Electric safety and potential induced degradation
- Converter redesign – higher rating power devices



Outline

Control of PV Inverters

Control requirements for PV systems



- MPPT
- DC voltage/current
- Panel monitoring & diagnosis
- Forecast & prediction (mission profiles)

- High efficiency
- Temperature management
- High reliability
- Monitoring & safety
- Islanding protection
- Communication

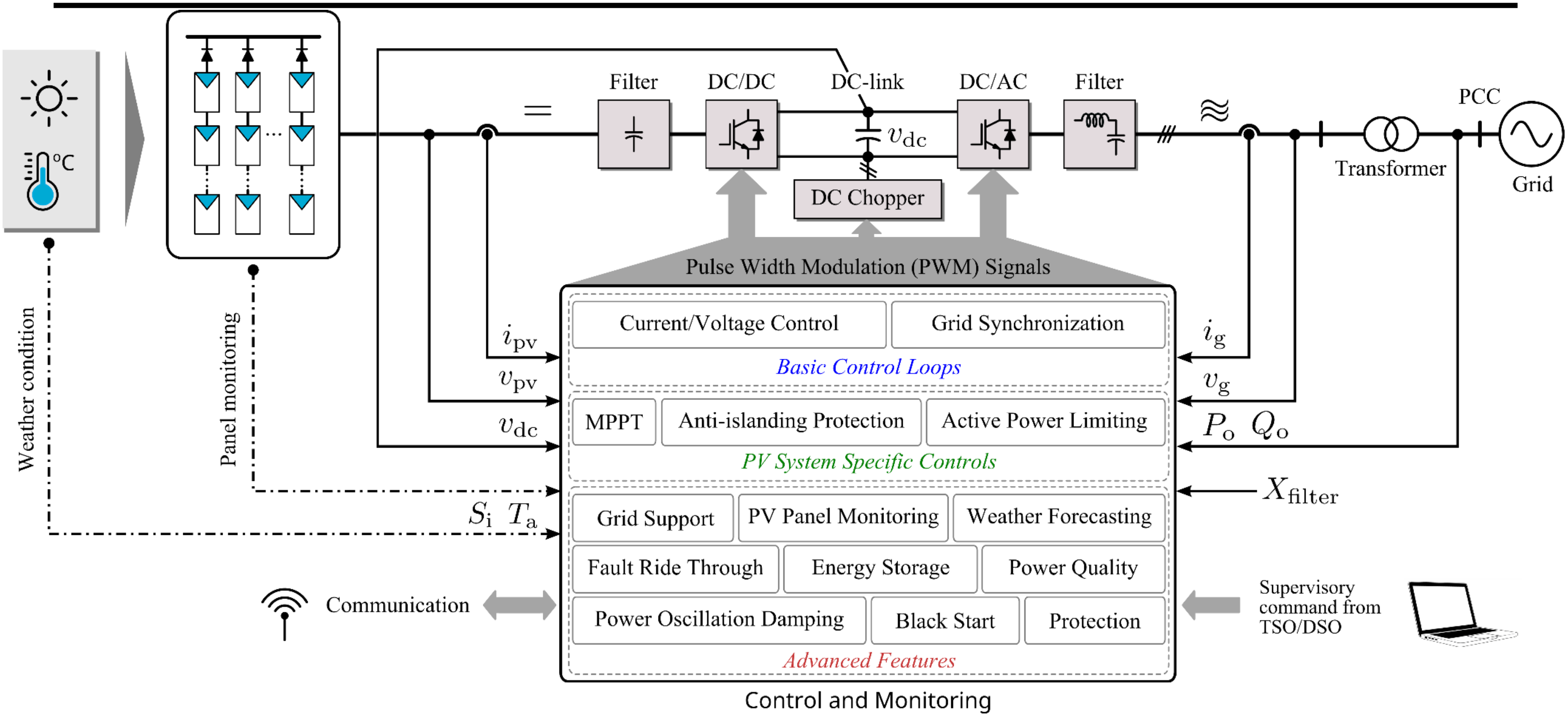
- Power quality (THD)
- Voltage level

In the case of large scale:

- Freq. - Watt control
- Volt - Var control
- Fault ride-through

General Requirements & Specific Requirements

General control structure for PV systems



Basic functions – all grid-tied inverters

- Grid current control
- DC voltage control
- Grid synchronization

PV specific functions – common for PV inverters

- Maximum power point tracking – MPPT
- Anti-Islanding (VDE0126, IEEE1574, etc.)
- Grid monitoring
- Plant monitoring
- Sun tracking (mechanical MPPT)

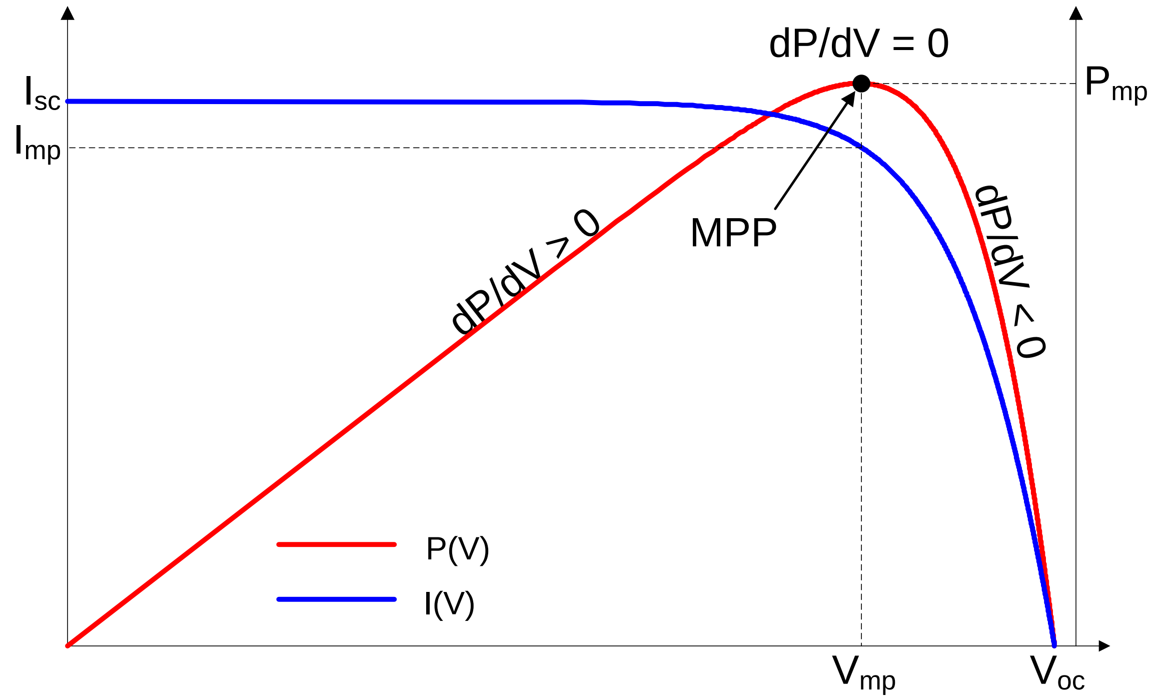
Ancillary support – in effectiveness

- Voltage control
- Fault ride-through
- Power quality
- …

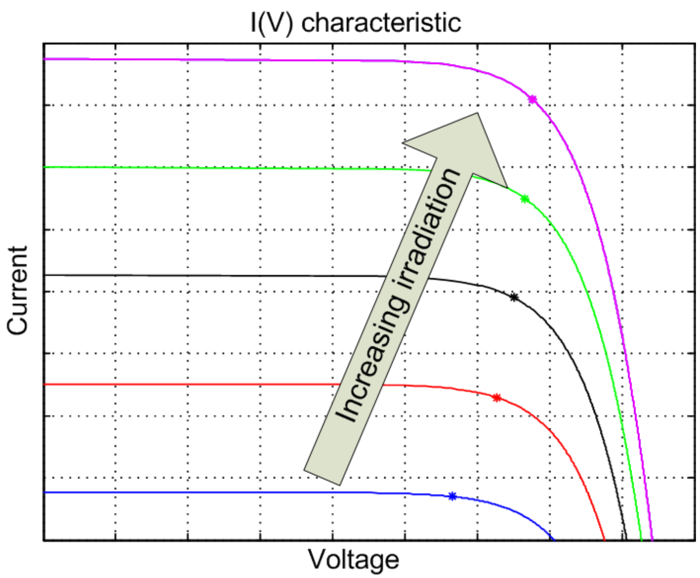
Maximum Power Point Tracking (MPPT)

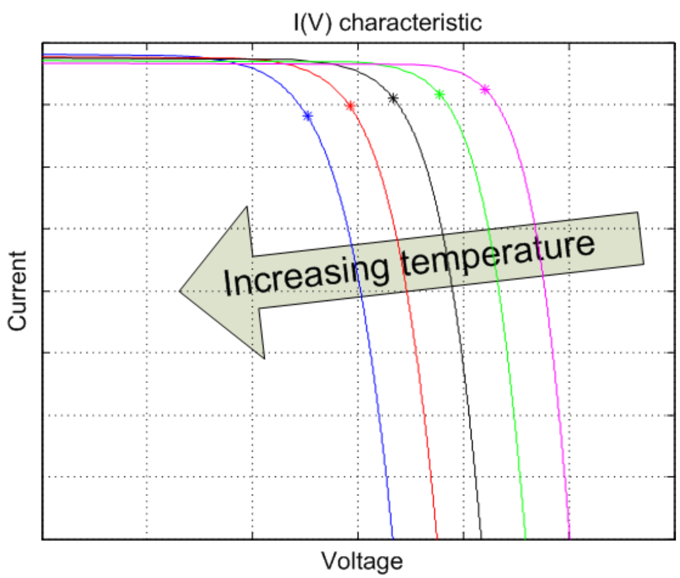
Role of MPPT

- PV array characteristic is non-linear → MPP
- MPP depends on environmental conditions → the operating point needs to be adjusted to follow weather conditions



Maximum Power Point Tracking (MPPT)

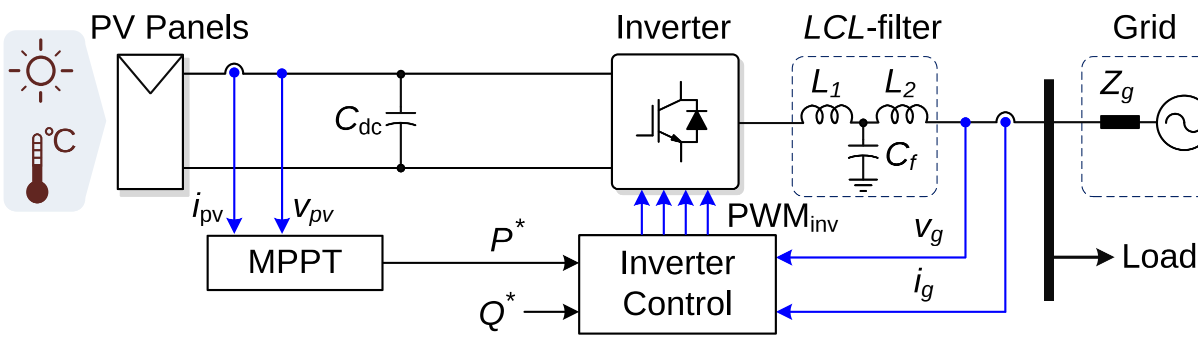




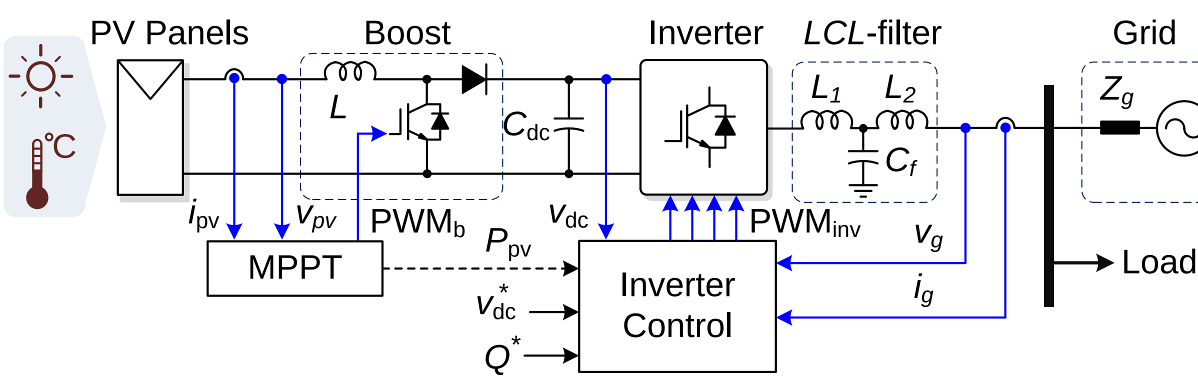
MPPT should keep the operating point at MPP in all conditions

Implementation of MPPT control

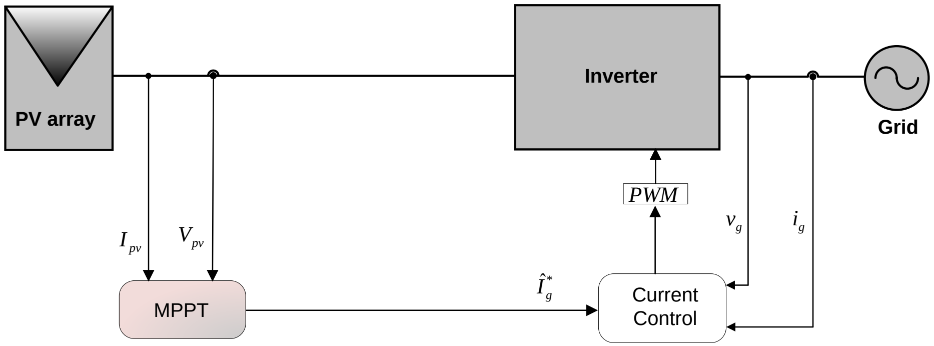
Single-stage system



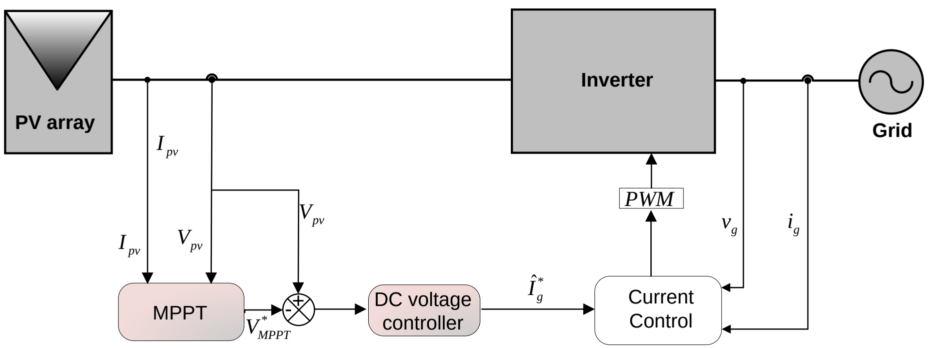
Two-stage system (in the DC-DC converter)



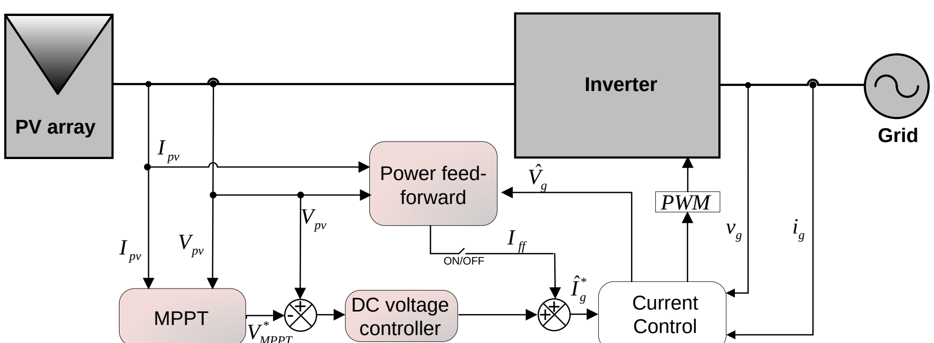
MPPT for single-stage PV inverters



MPPT directly controls the AC current

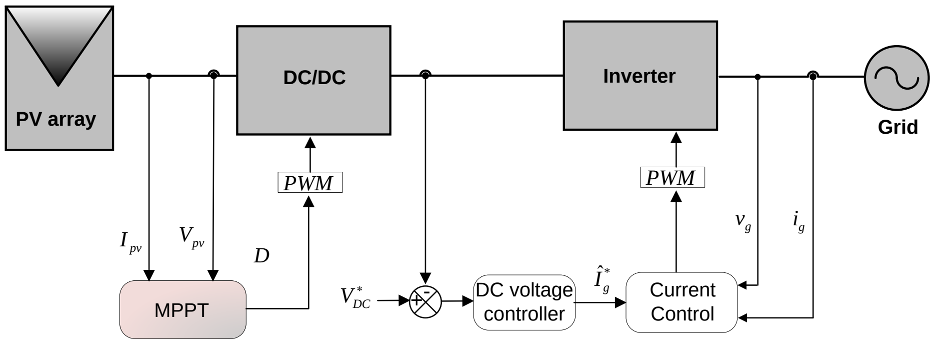


MPPT controls the DC voltage → AC current is controlled through a DC voltage controller

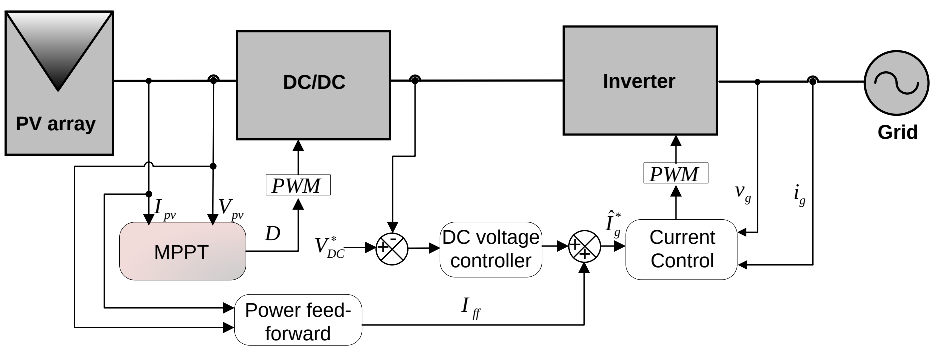


Power feedforward enhances the dynamics of the MPPT

MPPT for two-stage PV inverters



- MPPT controls the boost ratio of the DC/DC converter
- DC link voltage is controlled by Inverter

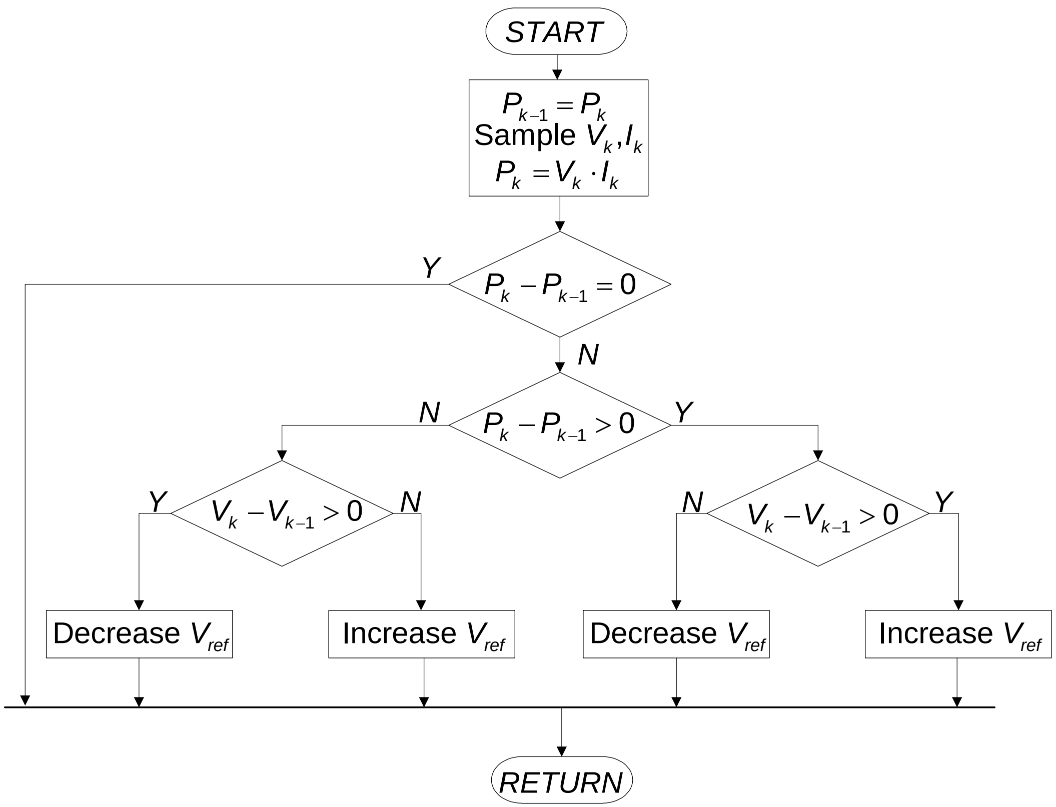


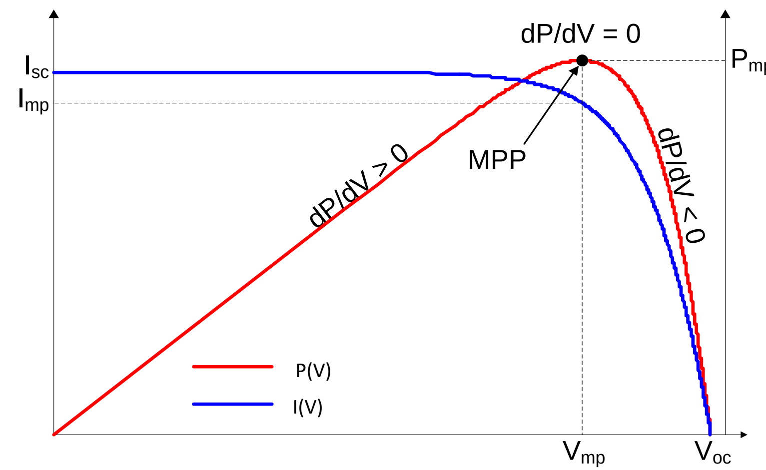
- Power feed-forward can be used

- Regardless of system topology, or output reference, most MPPT today share similar algorithm

MPPT algorithm

Perturb and Observe (P&O) – Most widely used MPPT method





$$\left.\frac{dP}{dV}\right|_{P=P_{mp}} = 0$$

MPPT algorithm

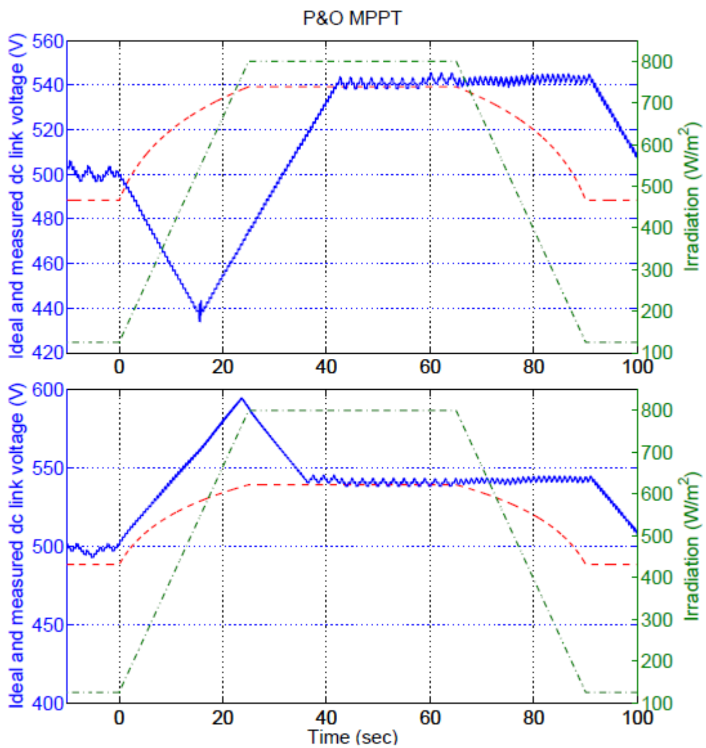
Perturb and Observe (P&O) – Most widely used MPPT method

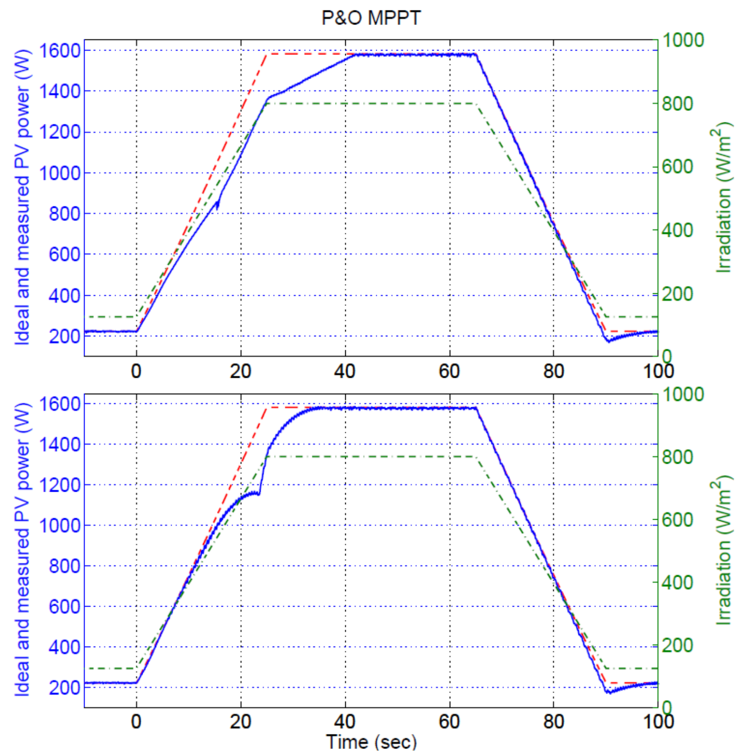
Advantages:

- Simple, low computational demand
- Generic – applicable for most systems

Disadvantages:

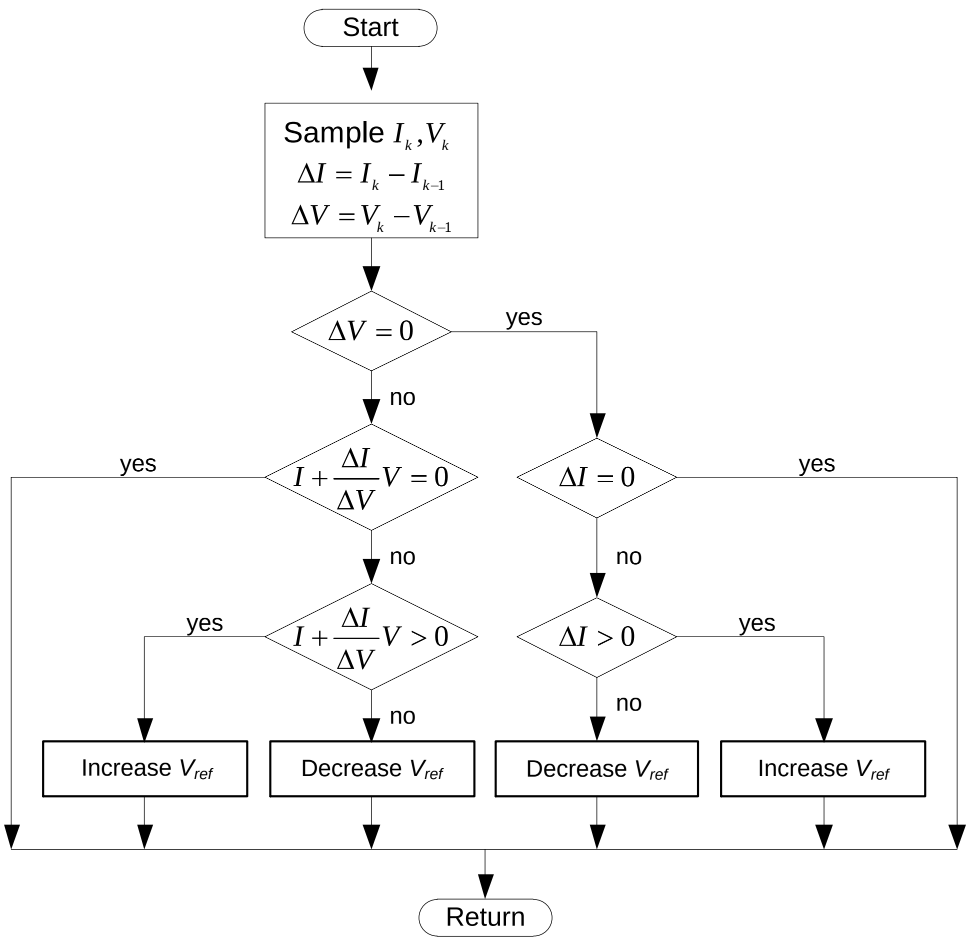
- Trade-off between speed and accuracy
- Can track in wrong way dusing fast changing conditions

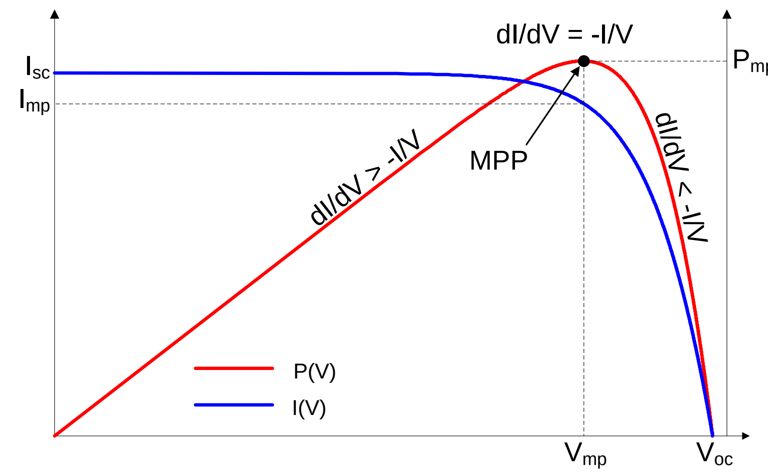




MPPT algorithm

Incremental Conductance (INC) – Monitoring the slope of the P-V curve



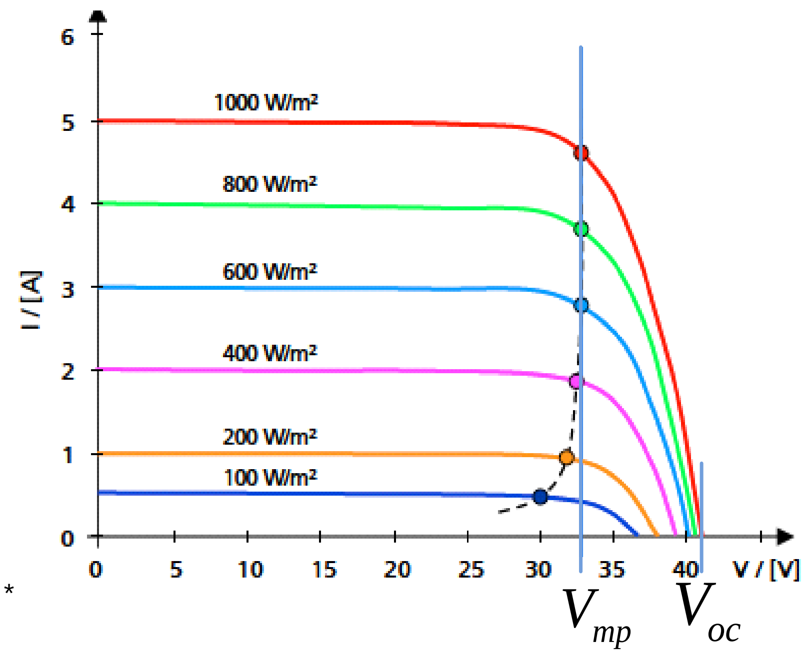


$$\frac{dP}{dV} = \frac{V \cdot dI}{dV} + \frac{I \cdot dV}{dV} = V\frac{dI}{dV} + I$$

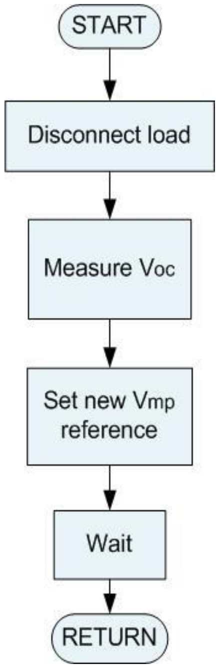
$$\left.\frac{dP}{dV}\right|_{P=P_{mp}} = 0 \Leftrightarrow \left.\frac{dI}{dV}\right|_{\substack{I=I_{mp}\\ V=V_{mp}}} = -\frac{I_{mp}}{V_{mp}}$$

MPPT algorithm

Constant Voltage method (CV) – Approximation of Voc/Vmp ratio



Source: *

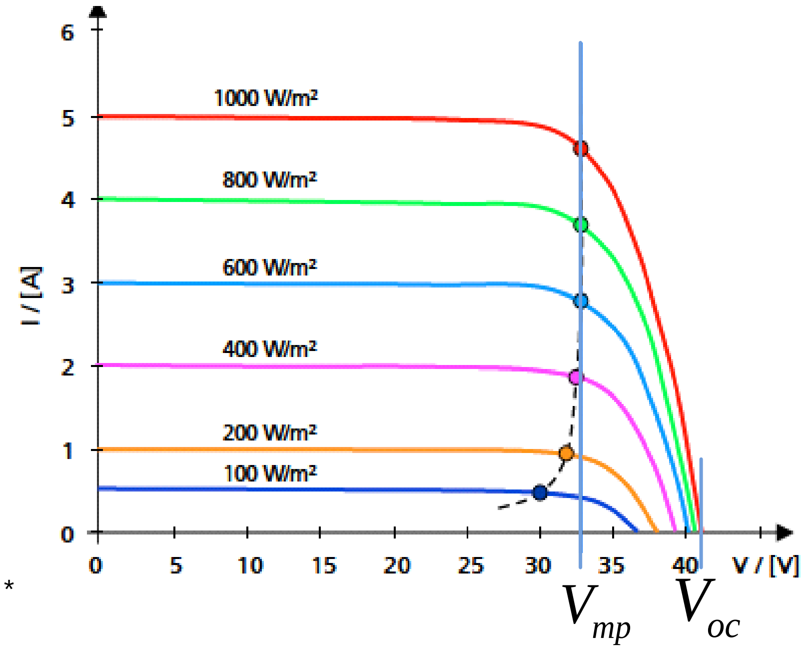


- CV relies on the fact that the voltage changes only a little with irradiation
- For a wide range of irradiations V_{mp} is about 76% of V_{oc} for crystalline modules

* Heribert Schmidt, Bruno Burger, Ulrich Bussemas, Stephan Elies: "HOW FAST DOES AN MPP TRACKER REALLY NEED TO BE?", 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany

MPPT algorithm

Constant Voltage method (CV) – Approximation of Voc/Vmp ratio



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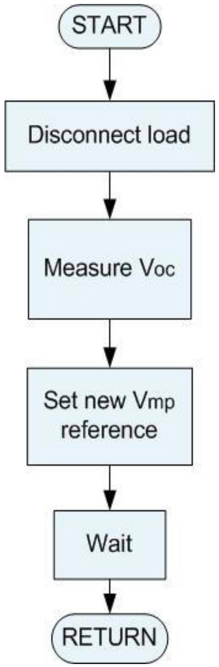


Advantages:

- Simplicity
- No ripple due to perturbation

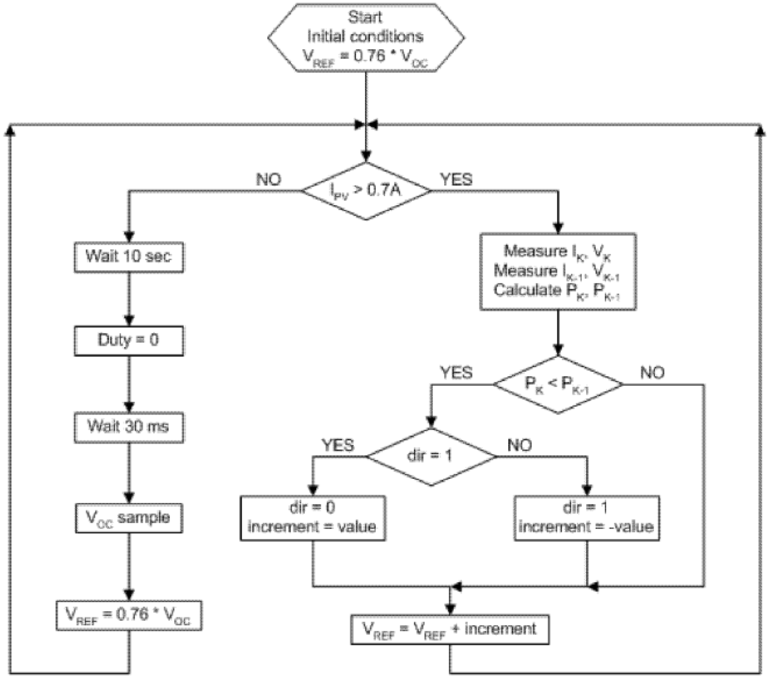
Disadvantages:

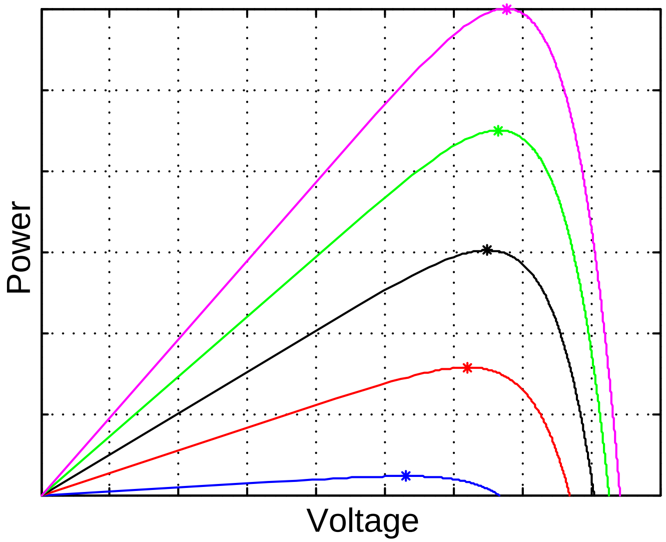
- Energy is wasted during V_{oc} measurement
- V_{mp}/V_{oc} is not always 0.76

* Heribert Schmidt, Bruno Burger, Ulrich Bussemas, Stephan Elies: “HOW FAST DOES AN MPP TRACKER REALLY NEED TO BE?“, 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany

MPPT algorithm

Hybrid method – Combination of Hill-climbing and CV methods





$$\left.\frac{dP}{dV}\right|_{P=P_{mp}} = 0 \Leftrightarrow \left.\frac{dI}{dV}\right|_{\substack{I=I_{mp}\\ V=V_{mp}}} = -\frac{I_{mp}}{V_{mp}}$$

At low irradiation levels:

- The P-V characteristic becomes 'flatter' →the signal-to-noise ratio decreases in hill-climbing methods → efficiency decreases
- The efficiency of CV is not affected

*Cristinel Dorofte, Uffe Borup, Frede Blaabjerg: " A Combined Two-method MPPT Control Scheme For Grid-connected Photovoltaic Systems", EPE 2005, Dresden

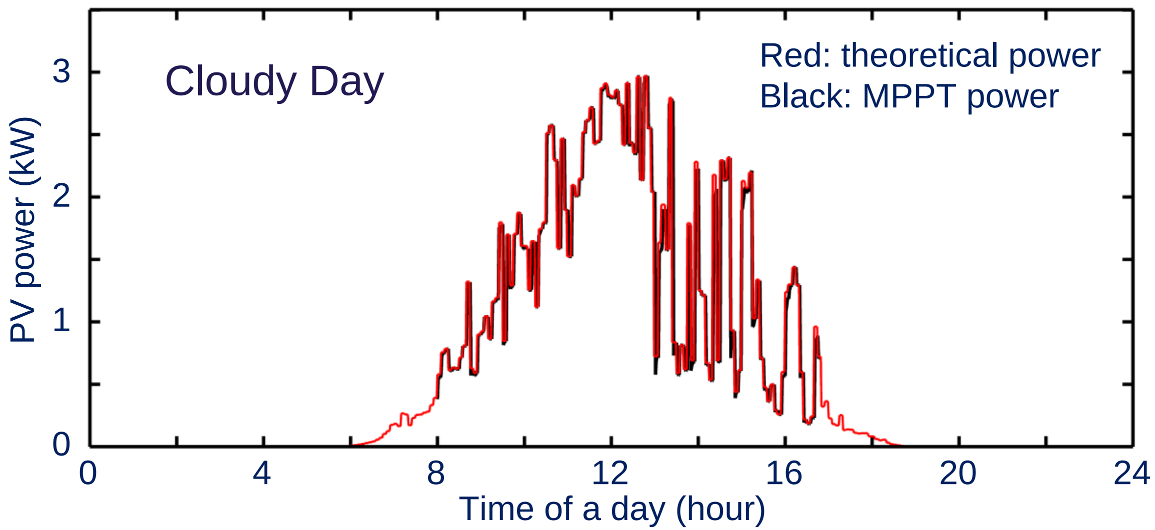
MPPT summary

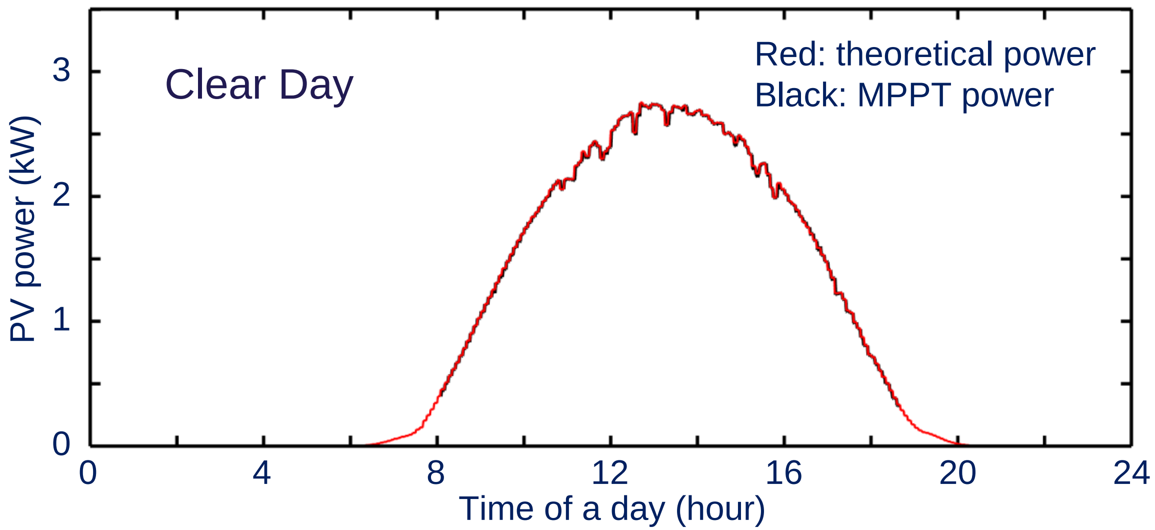
MPPT Methods	Advantages	Disadvantages
Perturb & Observe (P&O) / Incremental Conductance	• Simple • Low computation • Generic	• Tradeoff beteween speed and accuracy • Goes to the wrong way under fast changing conditions
Constant Voltage (CV)	• Much simple • No ripple due to perturbation	• Energy is wasted during Voc measurement • Inaccuracy
Short-Current Pulse (SCP, i.e., constant current)	• Simple • No ripple due to perturbation	• Extra swith needed for short-circuiting • Inaccuracy
Ripple Correlation Control	• Ripple amplitude provides the MPP information • Noneed for perturbation	• Tradeoff between efficiency loss due to MPPT or to the ripple

P&O – the most commonly used MPPT algorithm!

Example of MPPT control

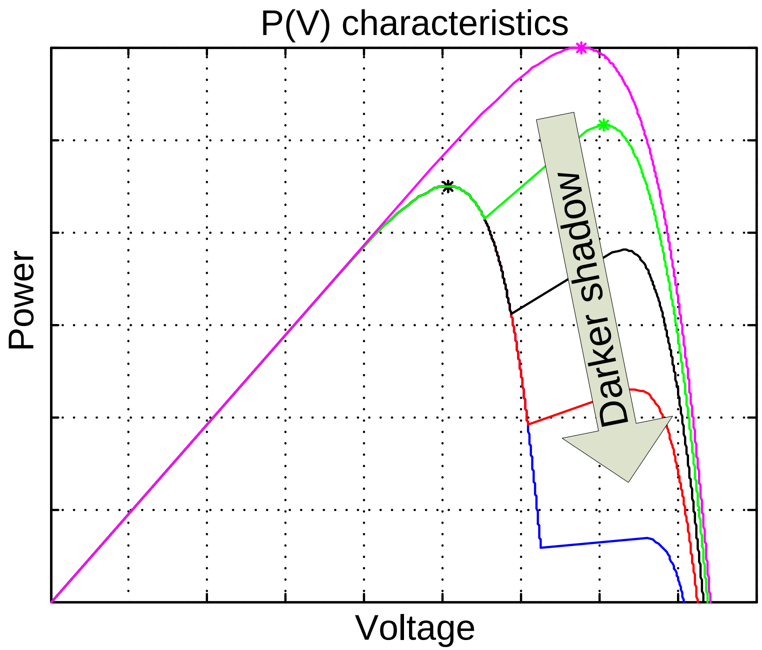
Experiments of P&O on 3-kW PV system

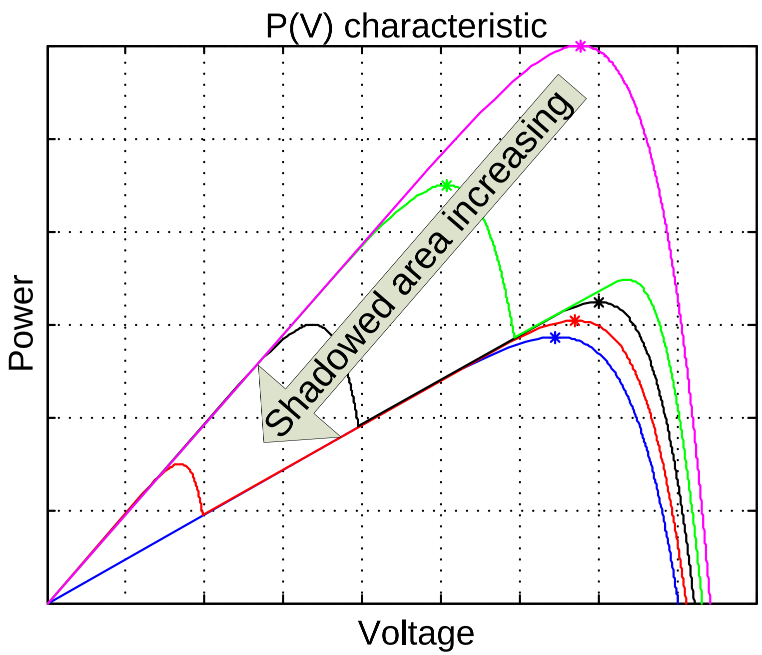




MPPT in partial shading

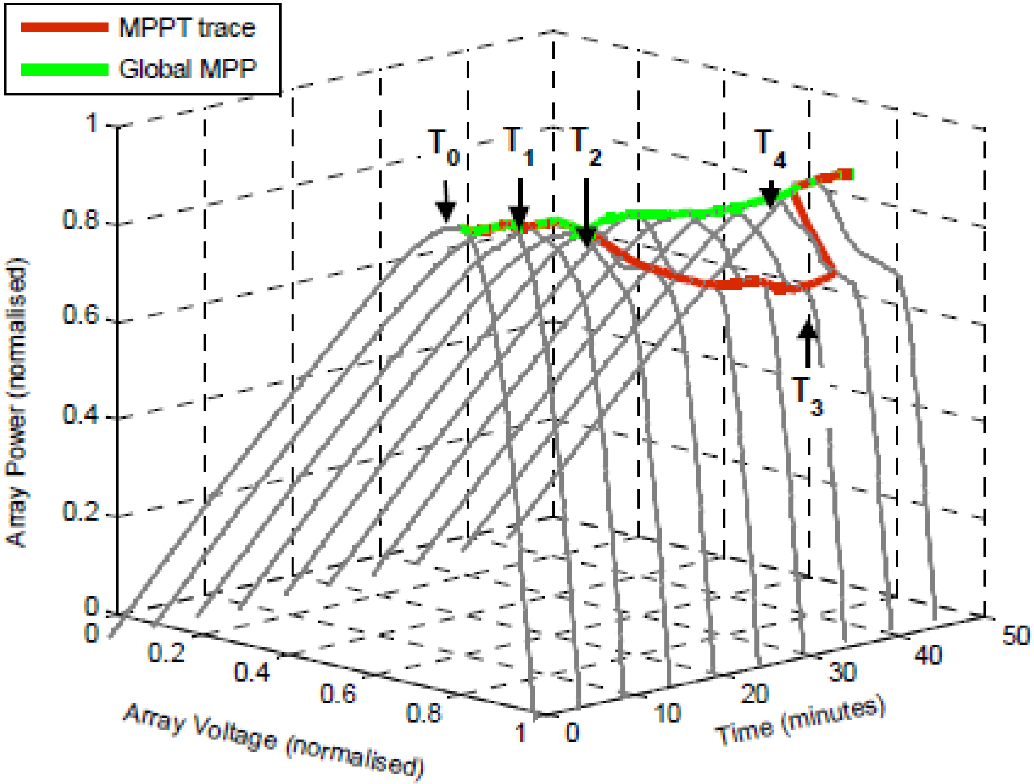
Power-voltage curve under partial shadow – multiple peaks

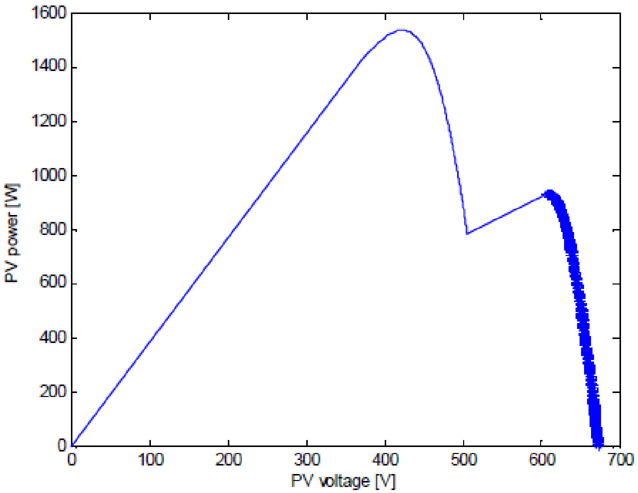




- P-V curve of a PV array affecting 25% of its surface as changing from no shadow to 90% reduction of irradiance
- P-V curve of a PV array as increasing the shadowed area from non-shadowed condition to fully shadowed. Irradiance on shadowed area is reduced to 50% of full irradiance

MPPT in partial shading



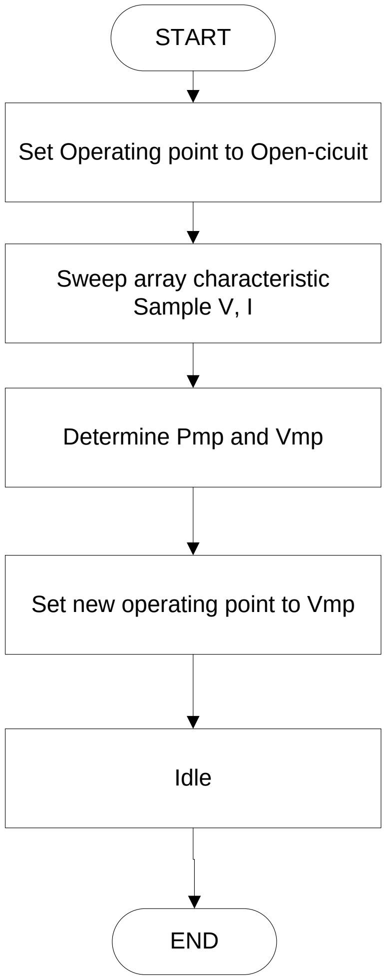


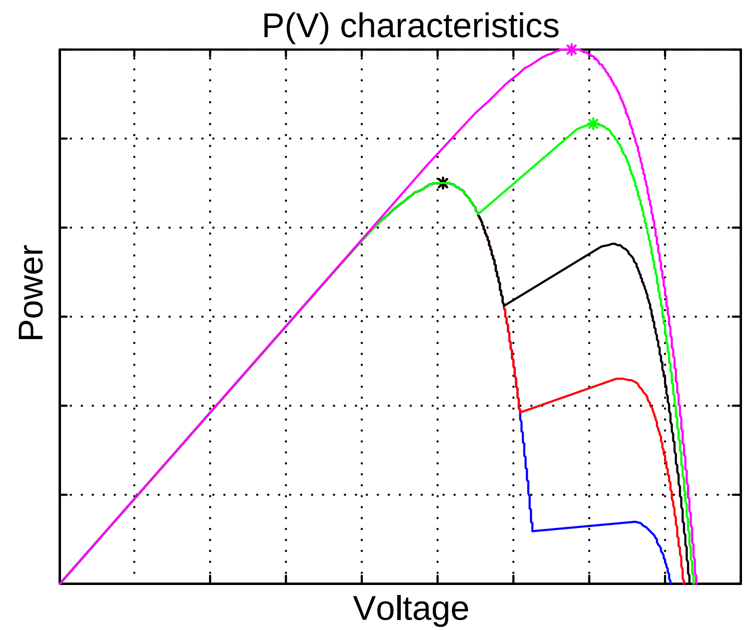
- Hill-climbing MPP trackers stop tracking at finding the first local maxima

*Roland BRUENDLINGER1; Benoît BLETTERIE; Matthias MILDE; Henk OLDENKAMP3: "MAXIMUM POWER POINT TRACKING PERFORMANCE UNDER PARTIALLY SHADED PV ARRAY CONDITIONS", 21st EUPVSEC

MPPT in partial shading

IV curve sweeping





Disadvantage: energy is wasted during the sweep

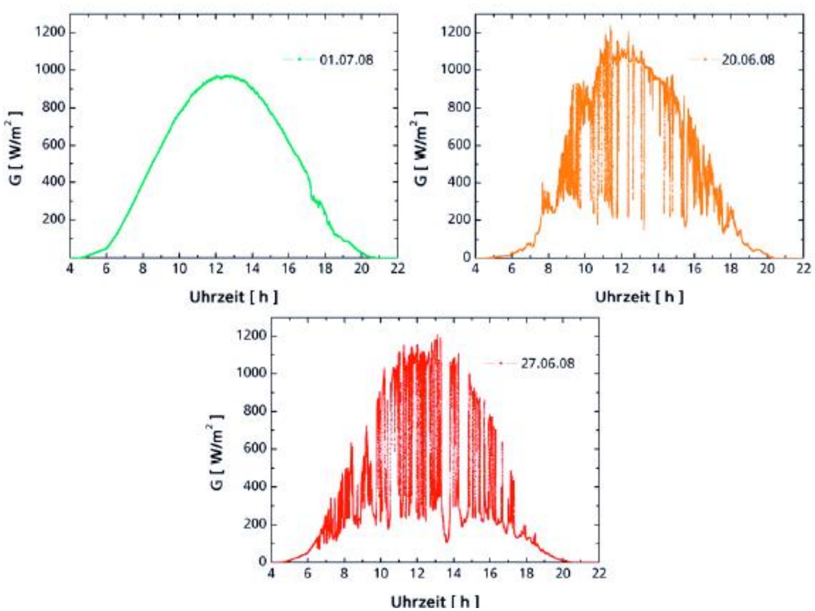
IV curve sweeping is the only generally-accepted method today that can reliably find the MPP in case of partial shadow

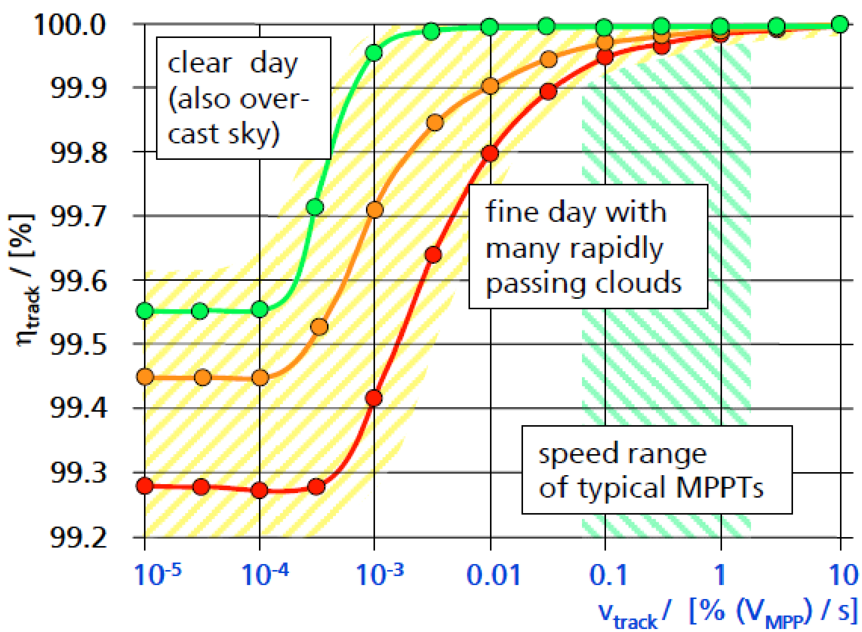
MPPT design consideration

Tracking speed – MPPT should follow environmental changes

- MPPT voltage adjustment speed of ~1% of MPP voltage per second is enough for most conditions

$$\frac{dV_{tracker}}{dt} \cong \frac{V_{MP}}{100} \Big/ s \quad [V/s]$$

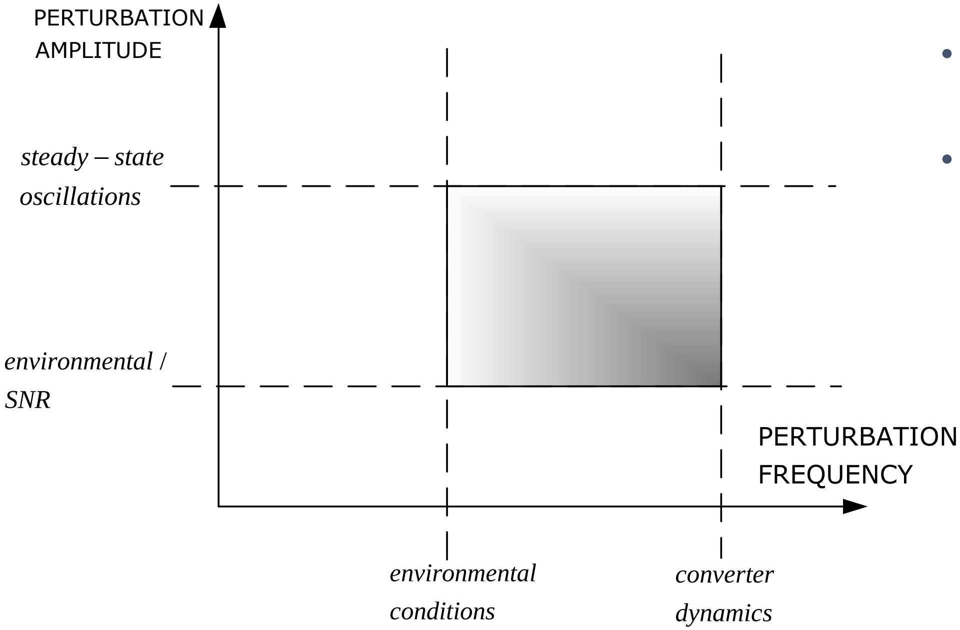




[1] Heribert Schmidt, Bruno Burger, Ulrich Bussemas, Stephan Elies: "How fast does an MPP tracker really need to be?", 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany

MPPT design consideration

Speed and accuracy of hill-climbing MPPT



- In practice, perturbation frequency varies between 0.5-20Hz
- To ensure fast enough response to environmental conditions, voltage adjustment speed:

$$\frac{dV}{dt} \cong \frac{V_{mp}}{100} \Big/ s$$

For example:

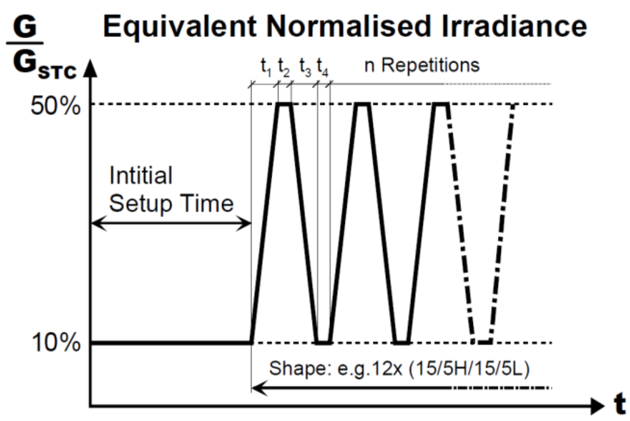
$$\left. \begin{aligned} f_{MPPT} &= 5Hz \\ V_{mp} &= 500V \Rightarrow \frac{dV}{dt} \cong 5V/s \end{aligned} \right\} \Rightarrow dV \cong 1V$$

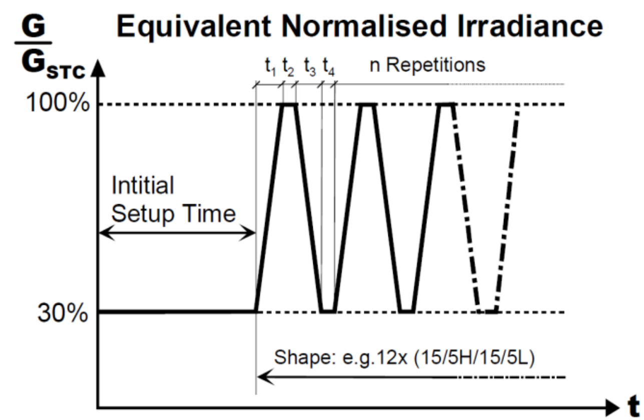
- Sampling period should be long enough for allowing the system to reach steady state before next perturbation – depends on the dynamics of the converter used
- Perturbation frequency should be high enough to follow environmental changes
- Perturbation amplitude should be large enough that effects caused by perturbation are not diminished by system noise
- Perturbation amplitude is limited by steady state oscillations around MPP (steady state efficiency)

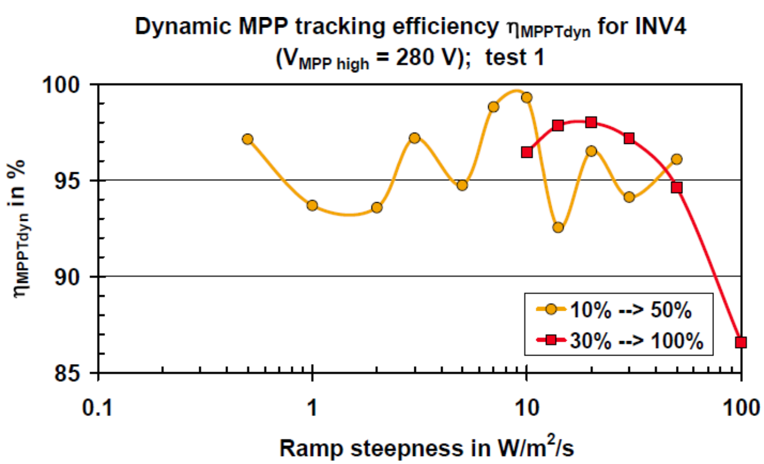
MPPT efficiency

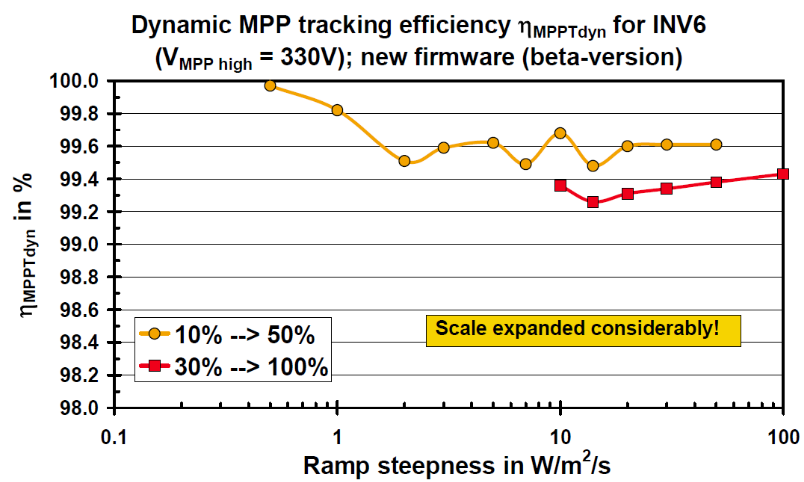
Testing MPPT efficiency (EN50530 standard)

- Dynamic MPPT efficiency can be tested using trapezoidal irradiance profiles





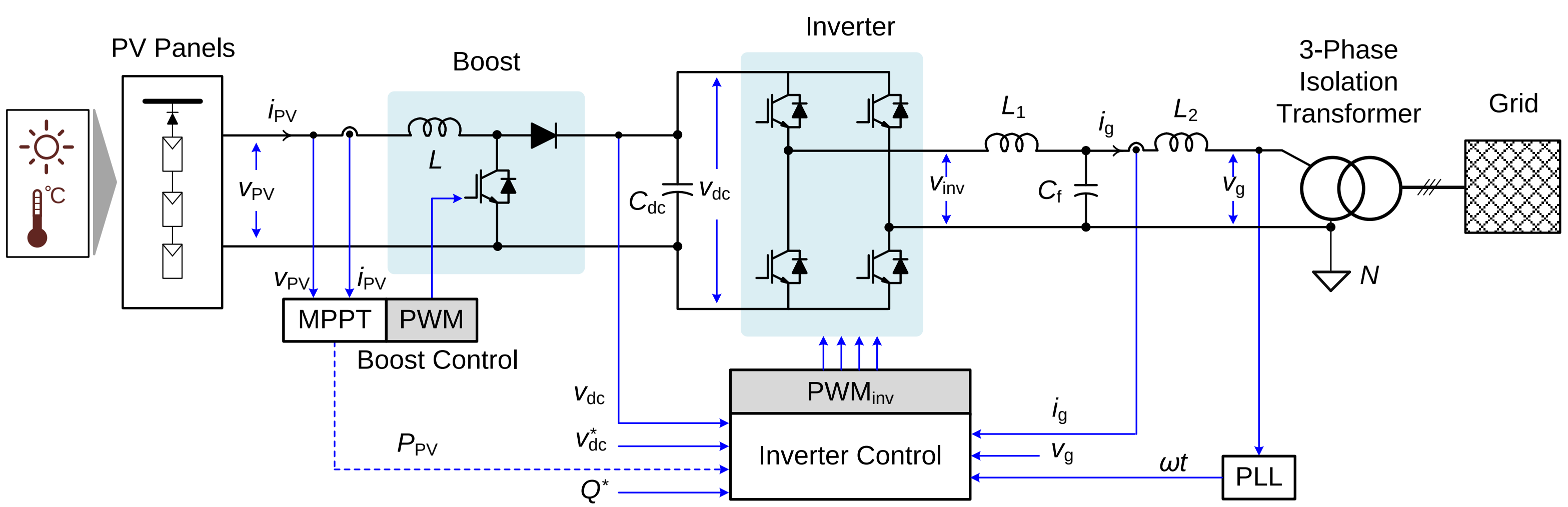




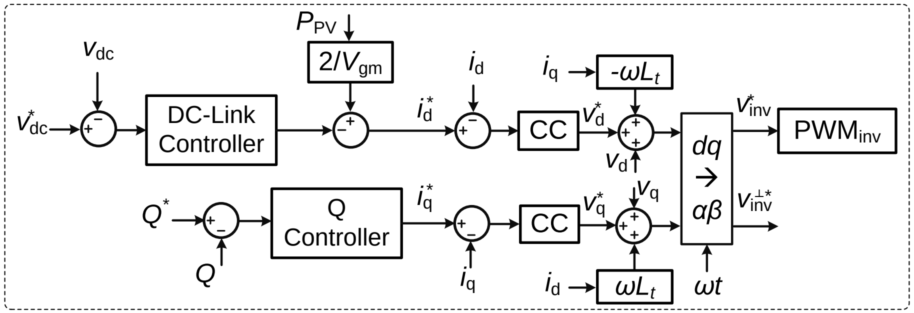
* H. Haeberlin and Ph. Schaerf: "New Procedure for Measuring Dynamic MPP-Tracking Efficiency at Grid-Connected PV Inverters", EUPVSEC 2009, Hamburg

Control of single-phase PV systems

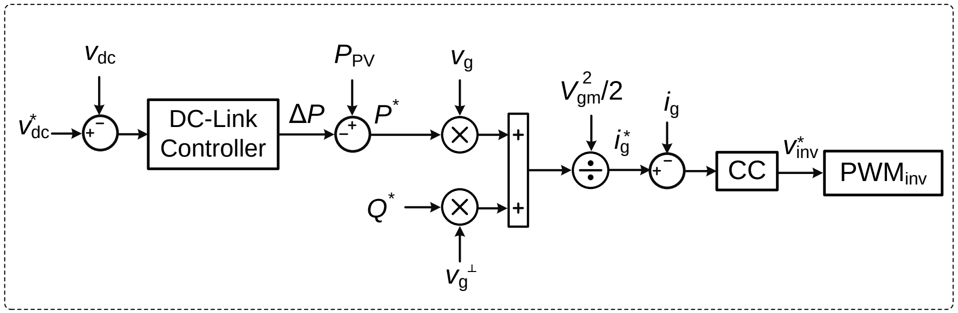
Dual-loop control systems:



System Schematic



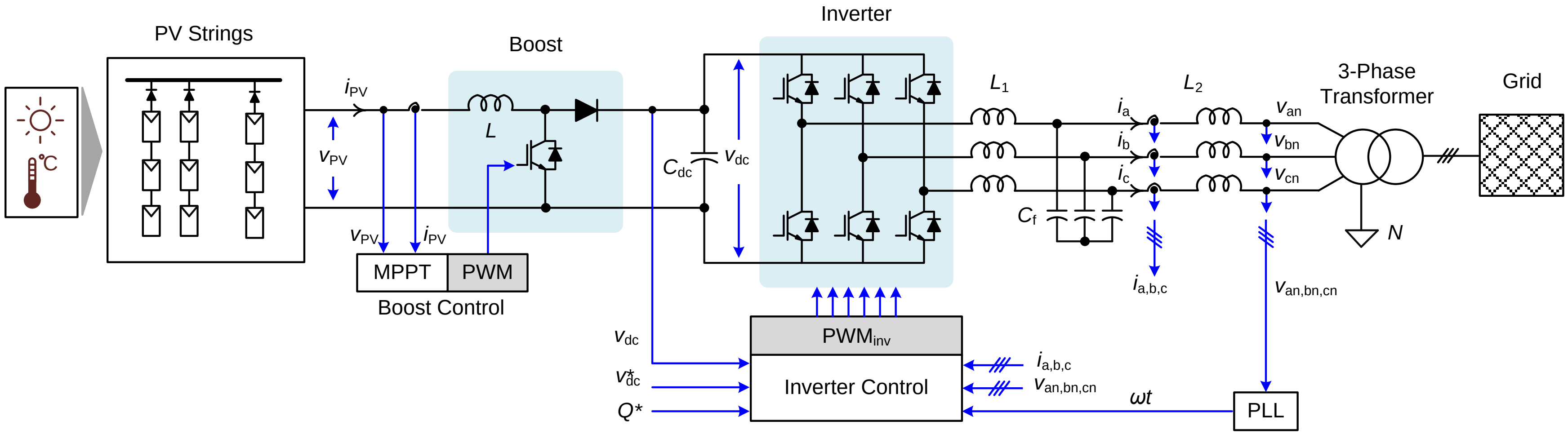
Control in the *dq*-frame



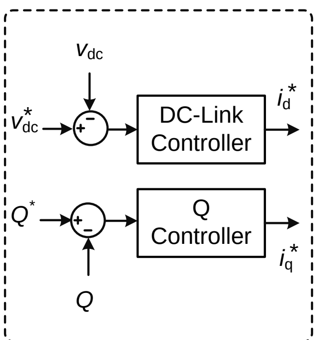
Control in the *αβ*-frame

Control of three-phase PV systems

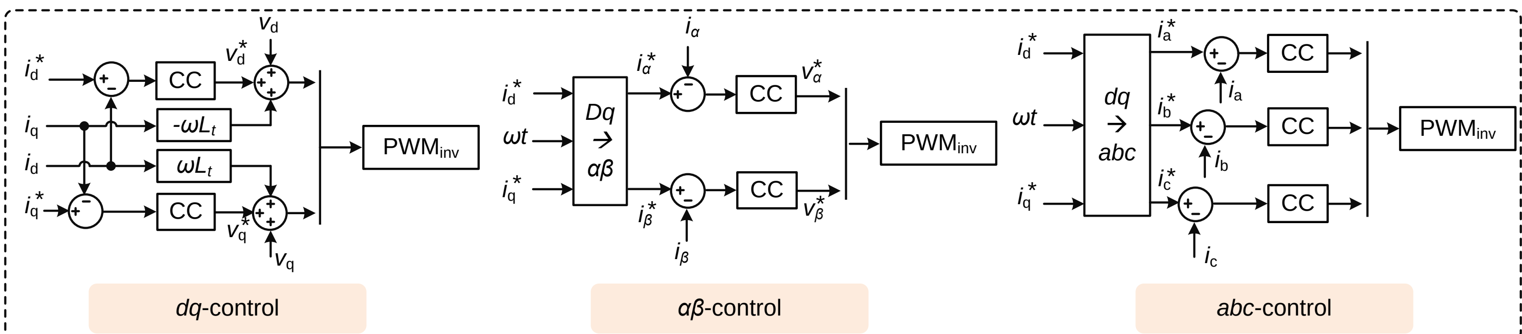
Dual-loop control systems:



System Schematic



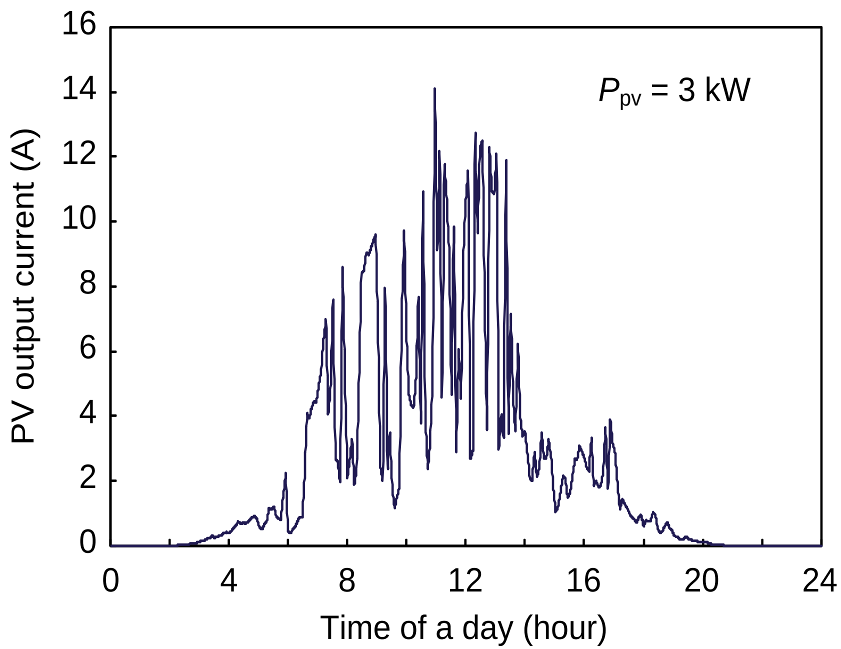
DC-link control



Control in the different reference frames

Current control of PV inverters

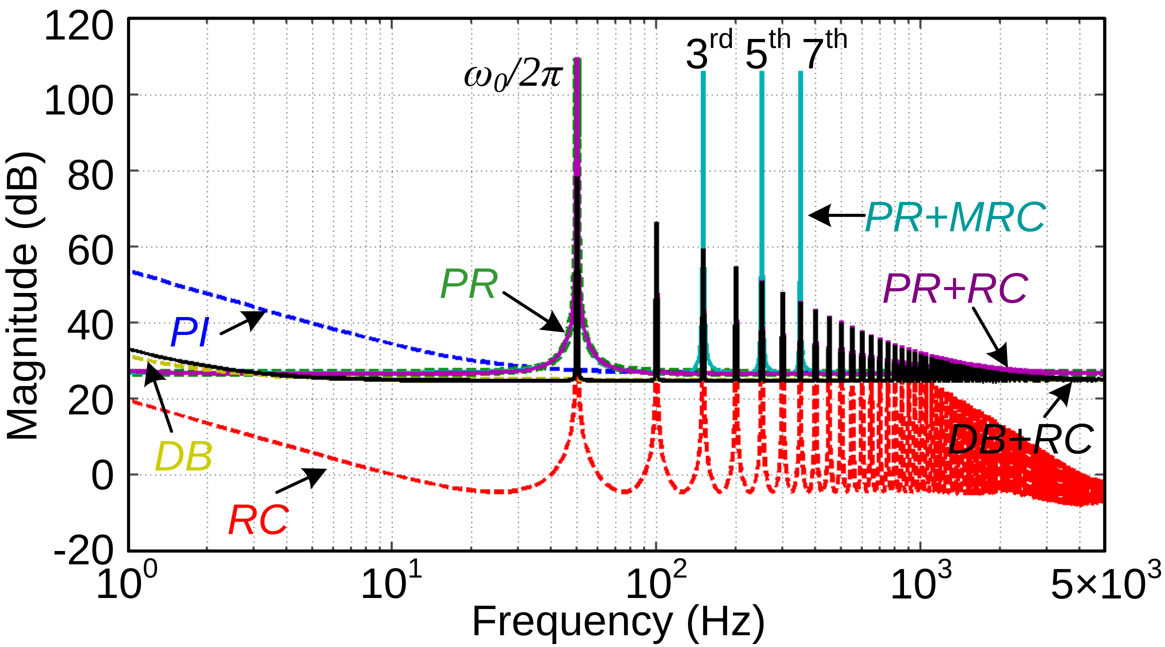
- Outer control loop for proper reference generation;
- Current controller responsible for current shaping.
  - Power quality concern
  - Harmonics from PV inverters
  - Harmonic control in the current controller



PV power weather-dependency

Harmonic control

Harmonic compensation – different current controllers

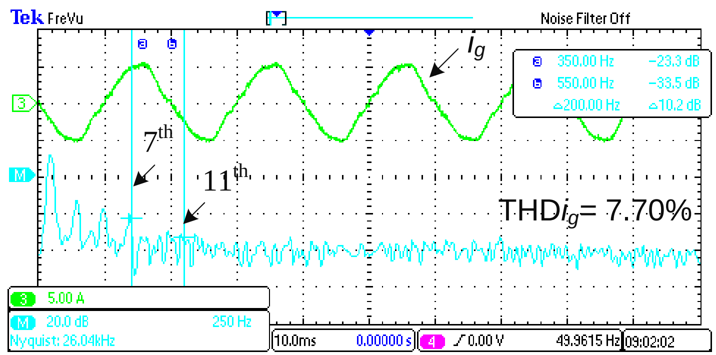


Magnitude responses of different current controllers

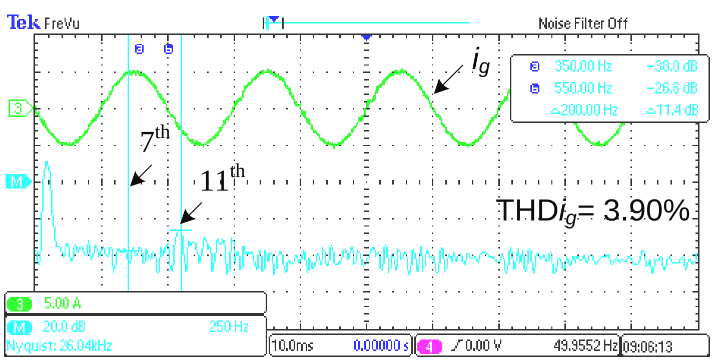
Harmonic control

Experimental results – harmonic compensation from PV inverters

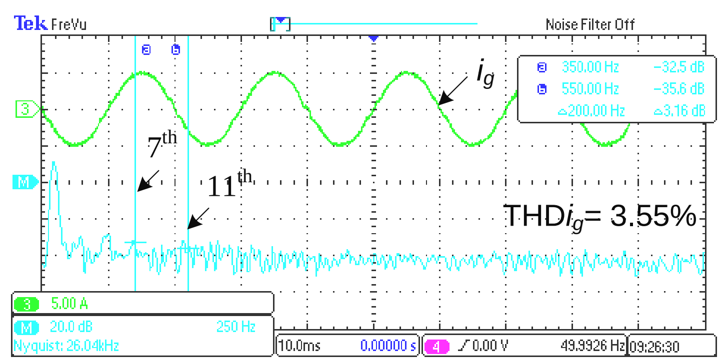
PR w/o HC



PR with MRC



PR with RC

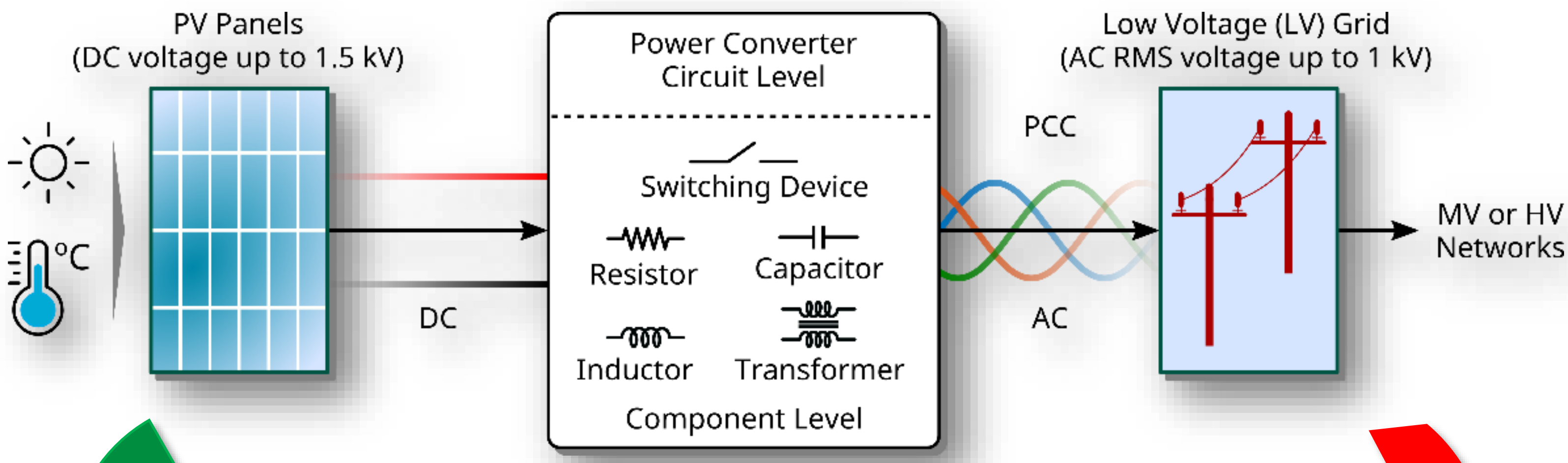


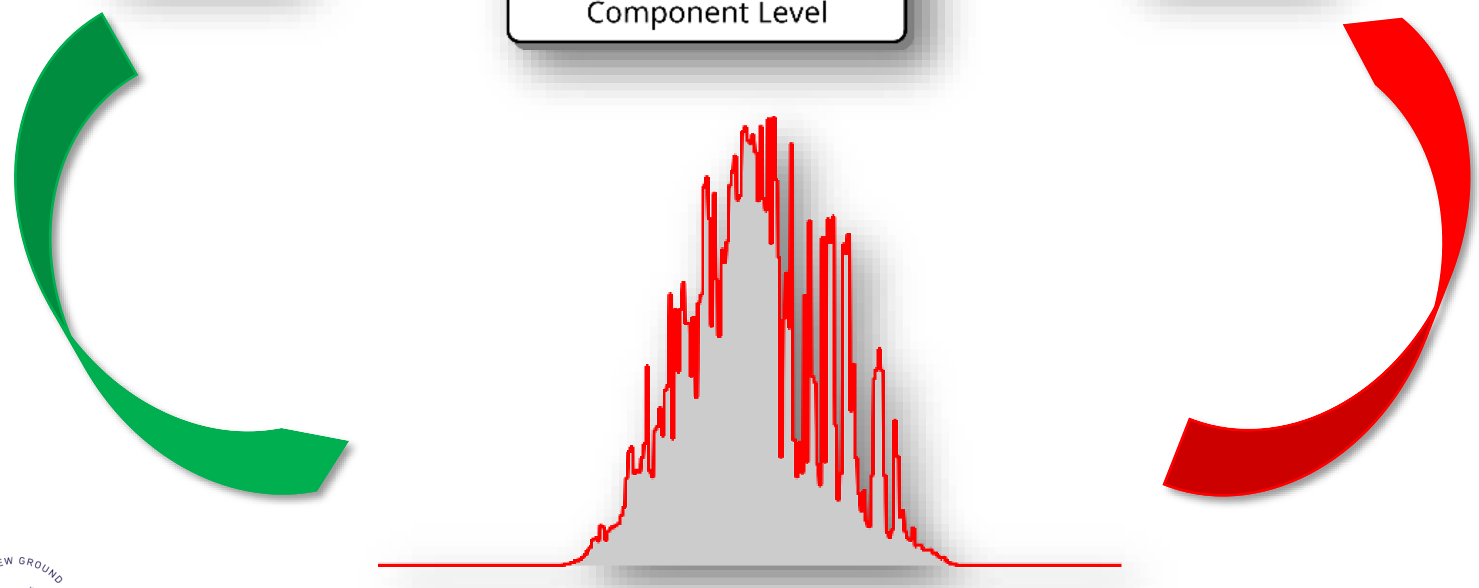
Outline

Advanced power control of PV Inverters

Grid integration challenges

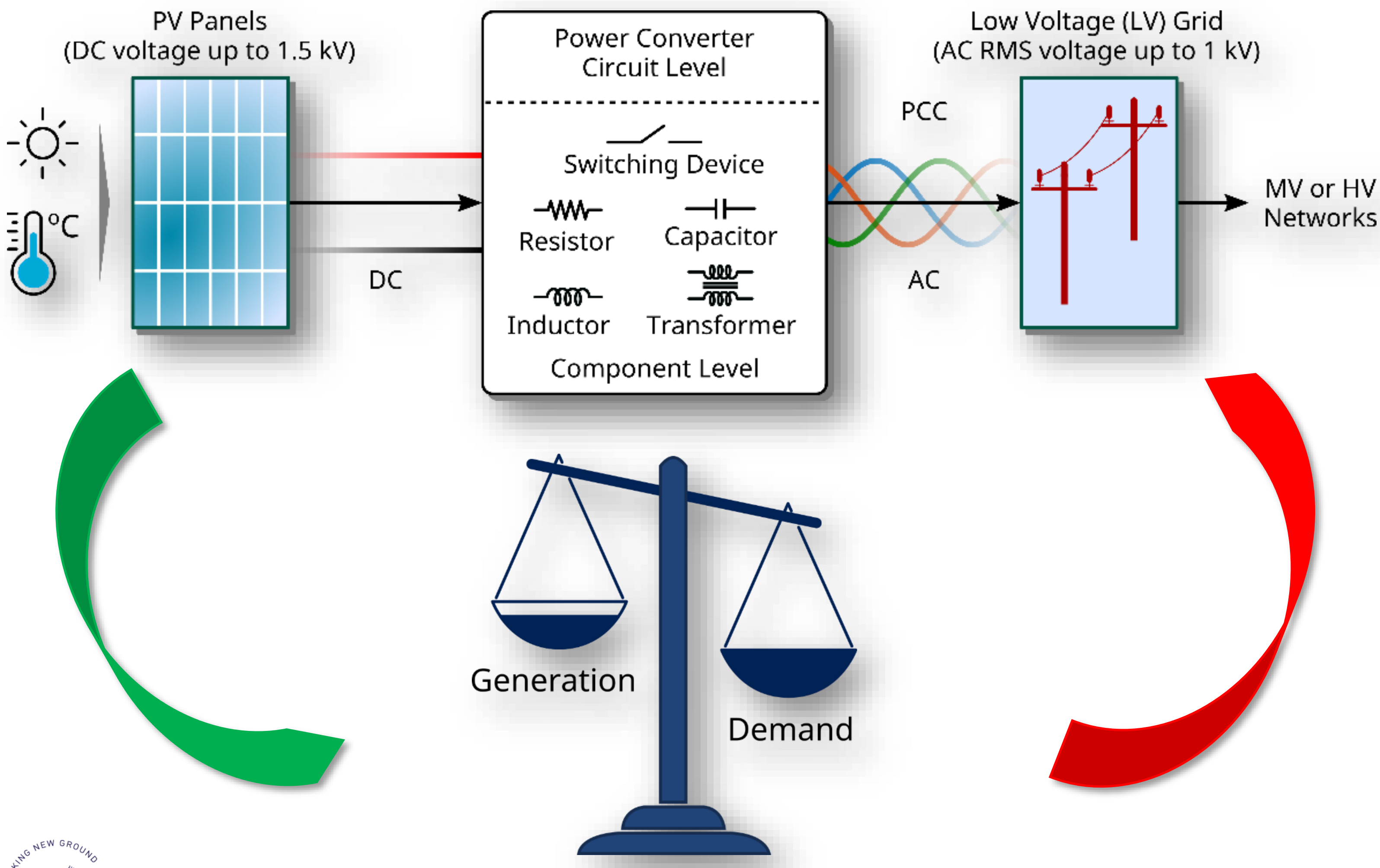
Intermittency of PV power production: Power regulation capability?





Grid integration challenges

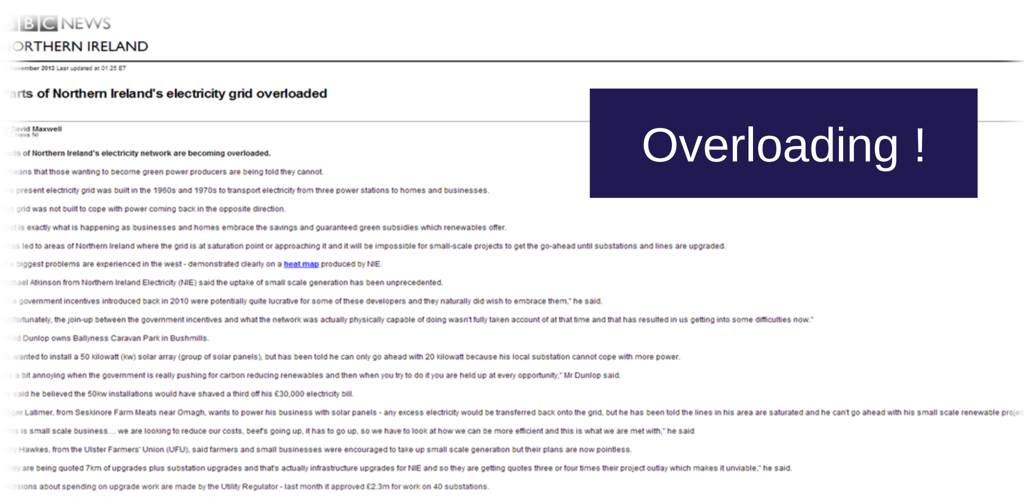
Intermittency of PV power production: Power regulation capability?



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
November 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.

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.

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 project.

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.

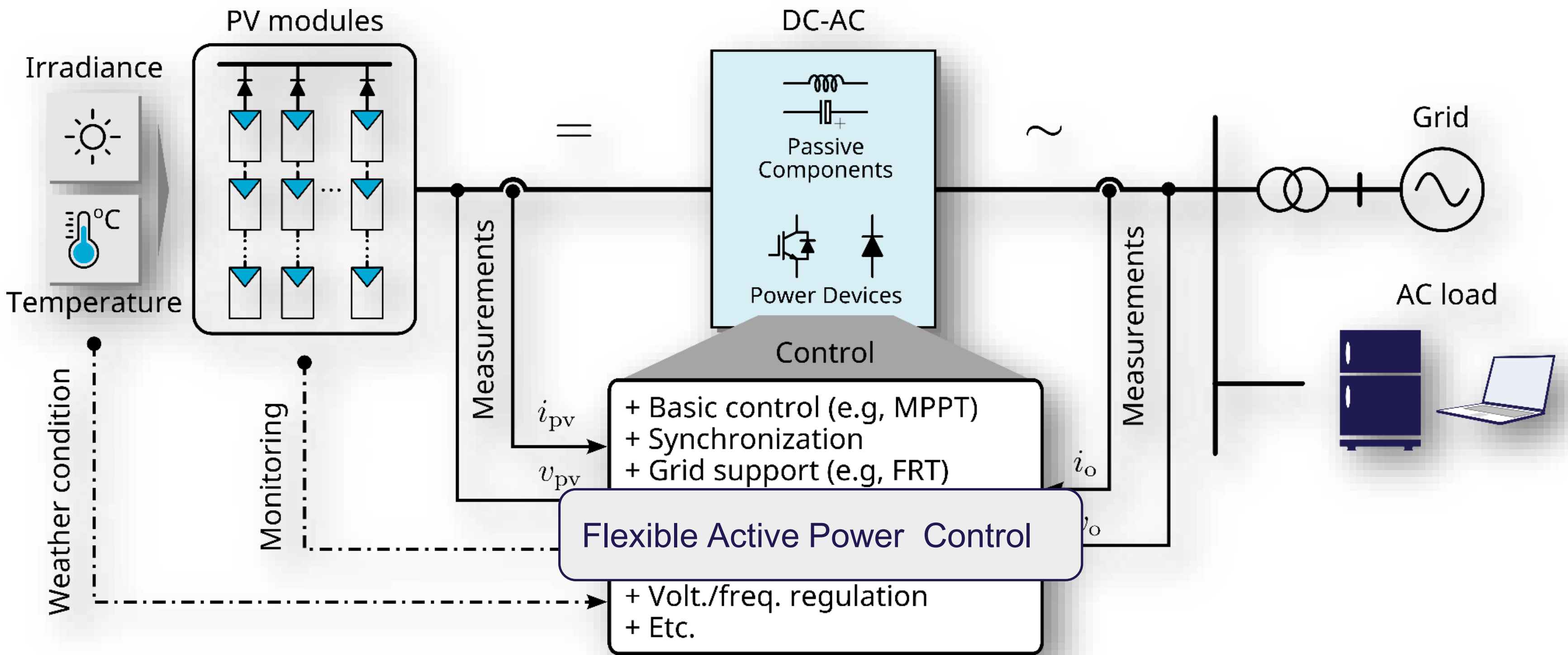
ey are being quoted 7km of upgrades plus substation upgrades and that's actually infrastructure upgrades for NIE and so they are getting quotes three or four times their project outlay which makes it unviable," he said.

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.

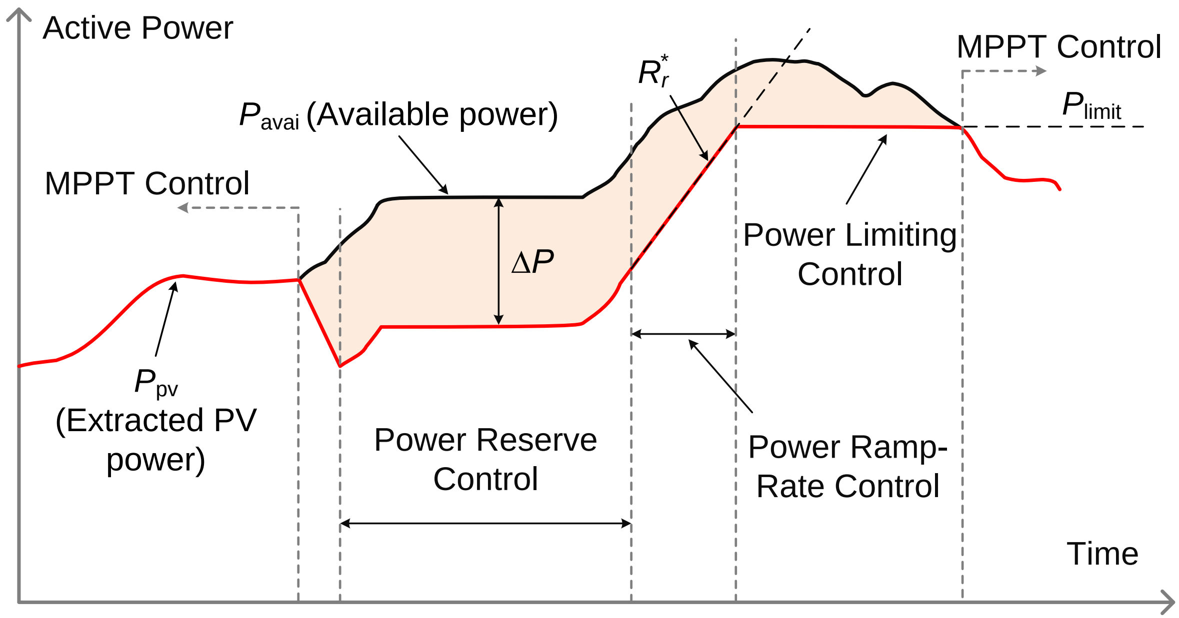
PV inverter control

Advanced control – Flexible active power control



Almost all demands → Controlling PV converters

Overview of active power control

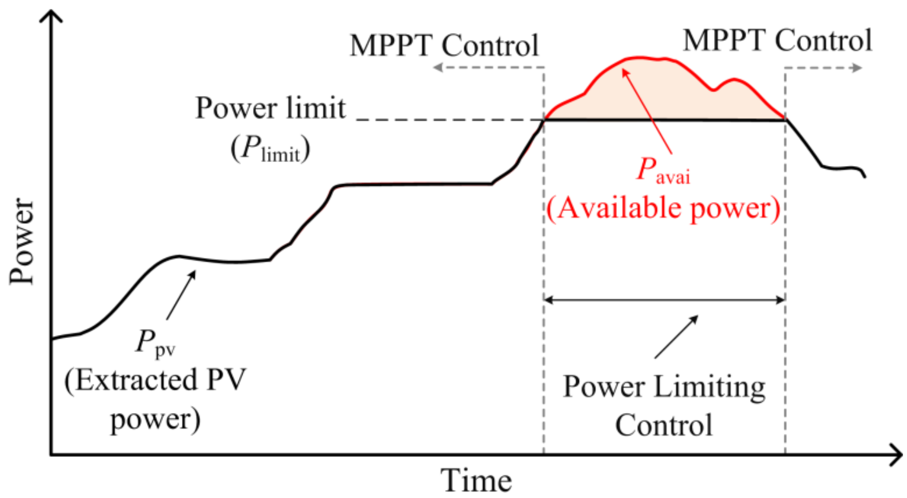


Solution:

- **Power limiting control (PLC)** – Overloading during peak power generation period
- **Power ramp-rate control (PRRC)** – Grid voltage fluctuation
- **Power reserve control (PRC)** – Limited frequency regulation capability

[1] Energinet.dk, **"Technical regulation 3.2.2 for PV power plants with a power output above 11 kW,"** 2015.

Power limiting control strategy

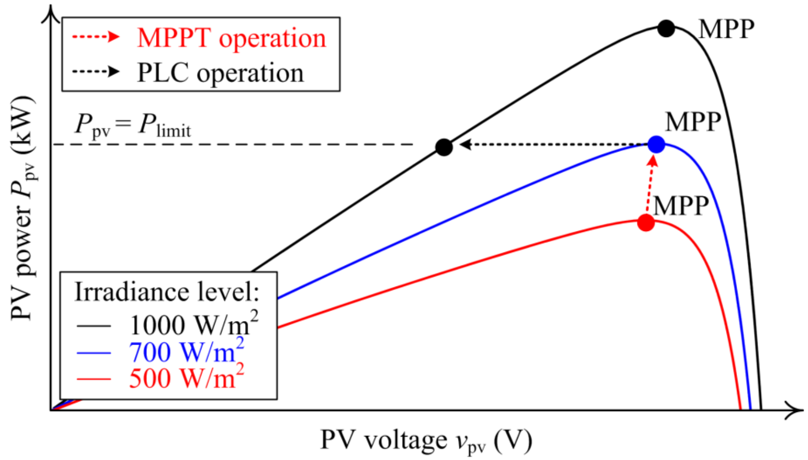


Concept

- Limit maximum extracted PV power P_{pv} to a certain power limit level P_{limit}
- During low solar irradiance ($P_{avai} \leq P_{limit}$) : MPPT operation
- During high solar irradiance ($P_{avai} > P_{limit}$) : Reduce the extracted PV power according to the set-point

Power limiting control strategy (2/3)

Operational principle: Perturbing the operating point along the horizontal line of the power limit level



PV voltage reference:

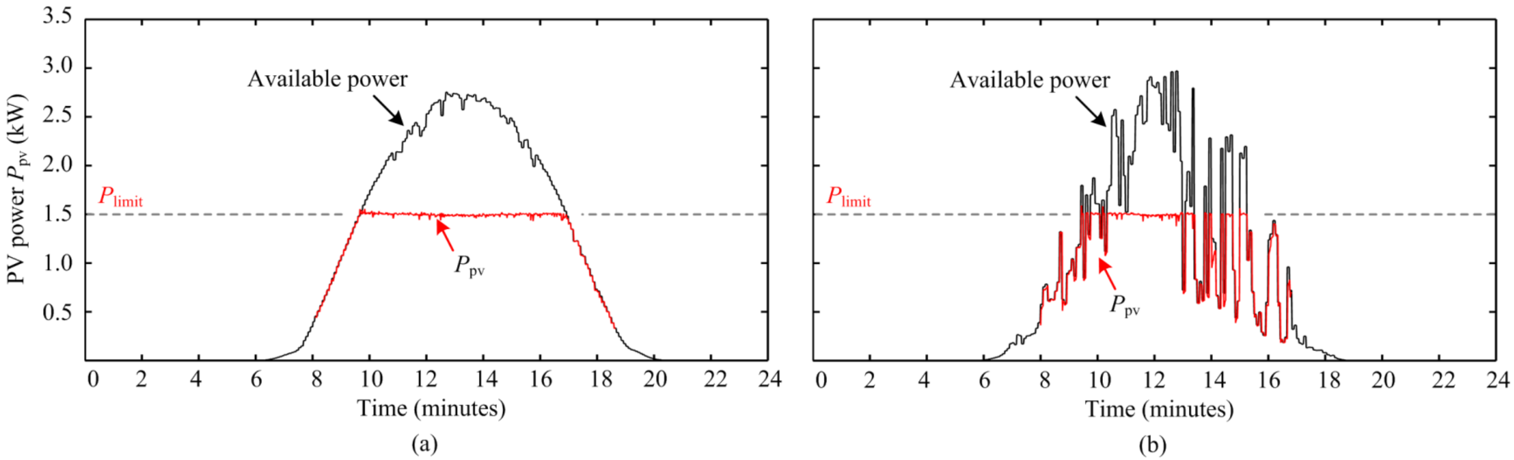
$$v_{pv}^{*} = \begin{cases} v_{MPPT}, & \text{when } P_{pv} \leq P_{limit} \\ v_{pv} - v_{step}, & \text{when } P_{pv} > P_{limit} \end{cases}$$

v_{MPPT}: reference voltage from MPPT algorithm, v_{step}: Perturbation step size

Power limiting control strategy

Example:

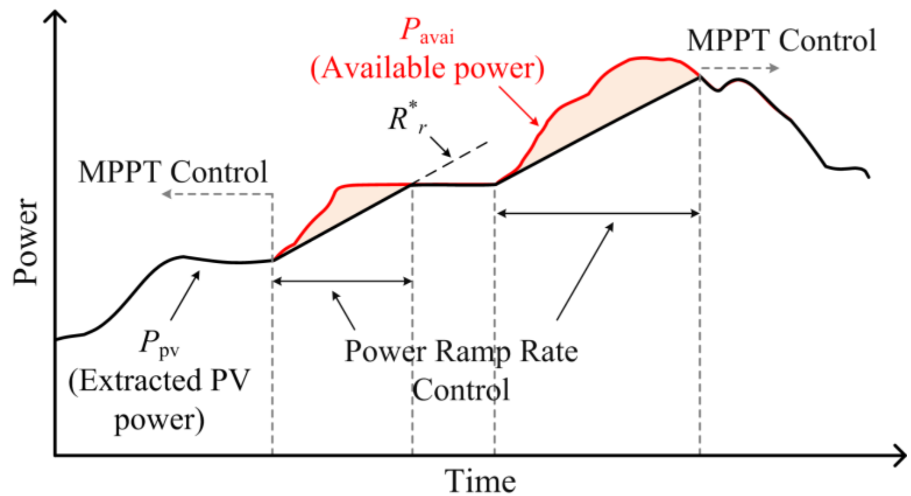
- Power limit level P_{limit} = 1.5 kW (50 %)



Clear day

Cloudy day

Power ramp-rate control strategy



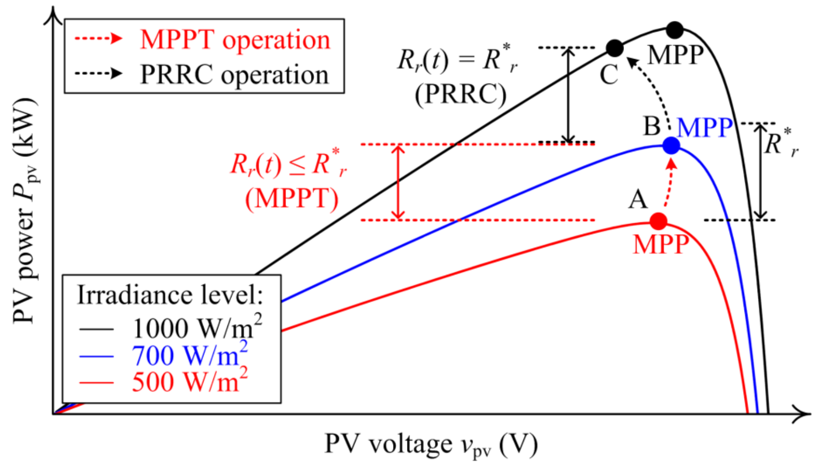
Concept

- Limit PV power change rate $dP_{pv}/dt = R_r(t)$ to a certain limit R^*_r

- During slow changing solar irradiance ($R_r(t) \le R^*_r$) : MPPT operation
- During fast changing solar irradiance ($R_r(t) > R^*_r$) : Reduce the extracted PV power following the ramp rate constraint

Power ramp-rate control strategy

Operational principle: Perturbing the operating point away from the MPP once the power ramp rate exceeds the maximum limit



PV voltage reference:

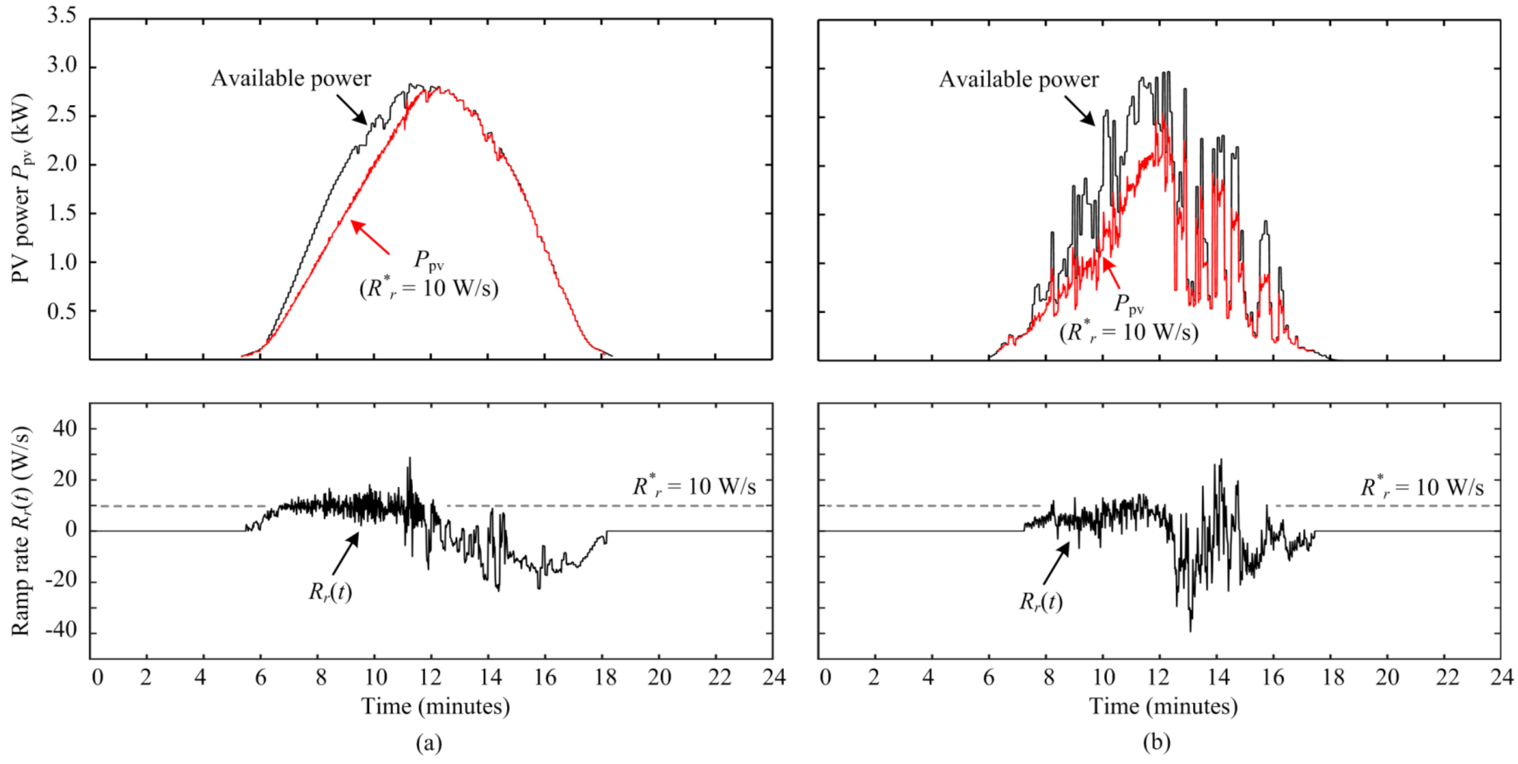
$$v^*_{pv} = \begin{cases} v_{MPPT}, & \text{when } R_r(t) \leq R^*_r \\ v_{pv} - v_{step}, & \text{when } R_r(t) > R^*_r \end{cases}$$

v_{MPPT}: reference voltage from MPPT algorithm, v_{step}: Perturbation step size

Power ramp-rate control strategy

Example:

- Ramp rate limit R^*_r = 10 W/second



Clear day

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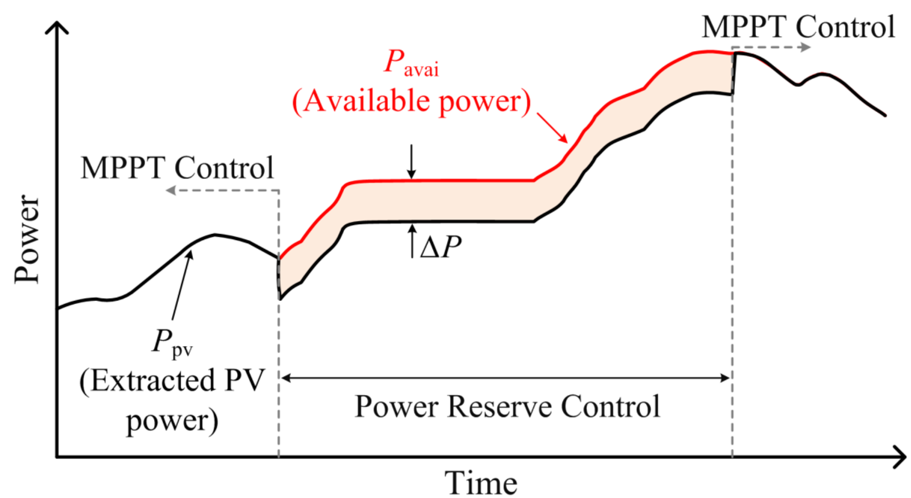
Power reserve control strategy



Concept

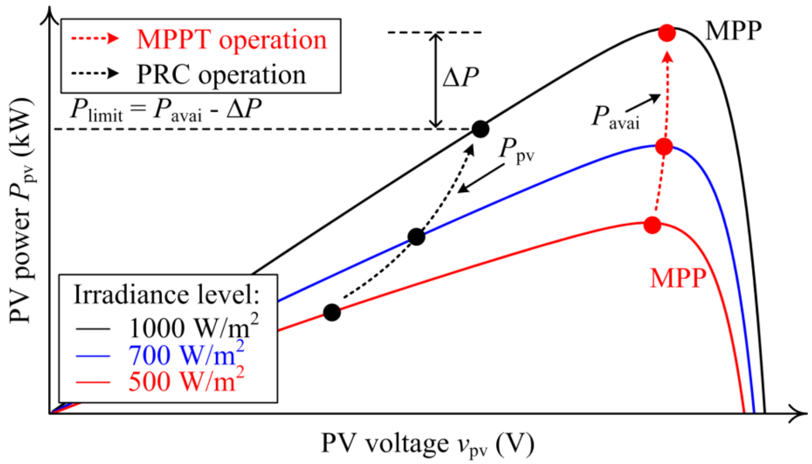
- Regulating the extracted PV power P_{pv} below the available power P_{avai} with the amount of power reserve ΔP

$$P_{pv} = P_{avai} - \Delta P$$

- Special case of power limiting control (e.g., $P_{limit} = P_{avai} - \Delta P$)
- Need to estimate the available PV power during operation

Power reserve control strategy

Operational principle: Perturbing the operating point away from the MPP with respect to the available power



PV voltage reference:

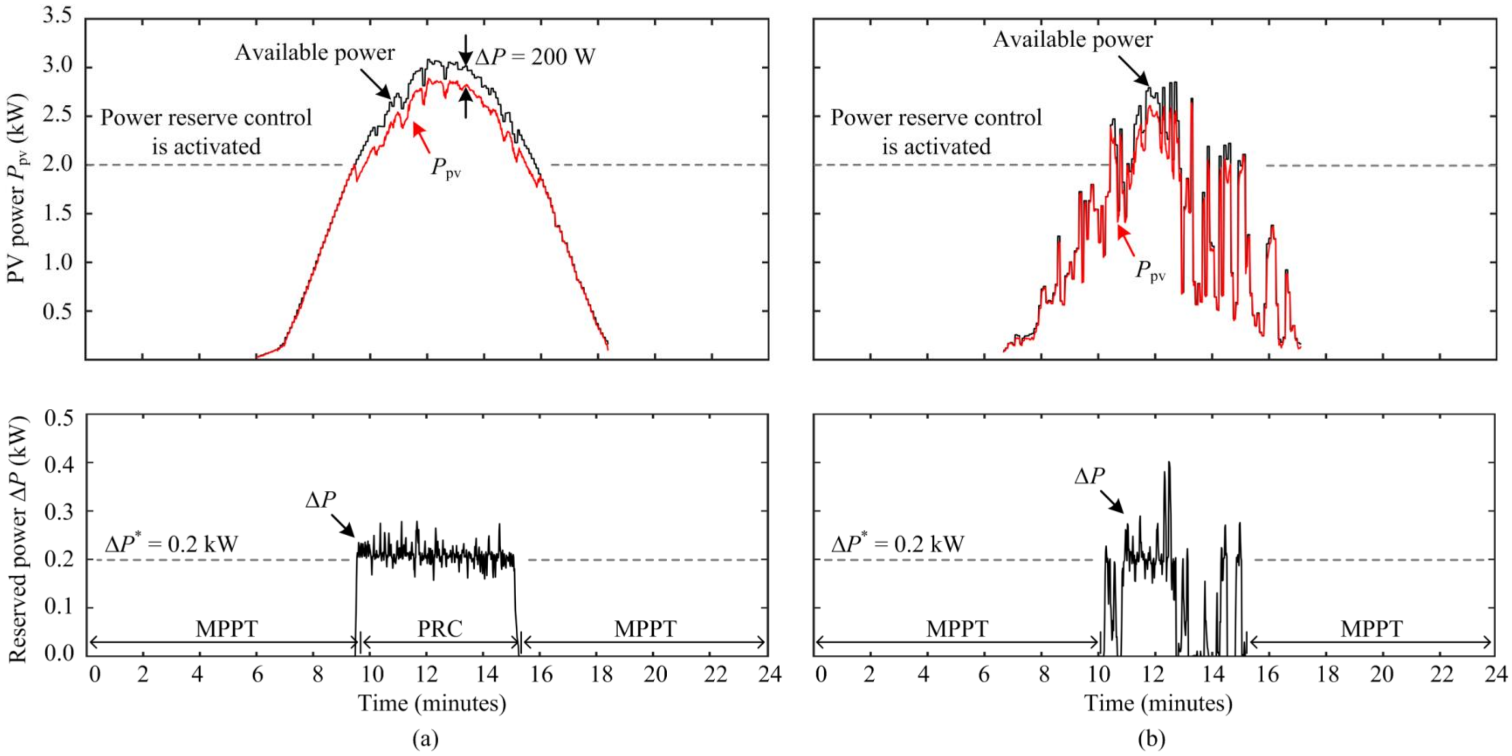
$$v_{pv}^{*} = \begin{cases} v_{MPPT}, & \text{when } P_{pv} \le P_{avai} - \Delta P \\ v_{pv} - v_{step}, & \text{when } P_{pv} > P_{avai} - \Delta P \end{cases}$$

v_{MPPT}: reference voltage from MPPT algorithm, v_{step}: Perturbation step size

Power reserve control strategy

Example:

- Power reserve level ΔP = 200 W (activated when P_{pv} > 2 kW)



Clear day

Cloudy day

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Further reading

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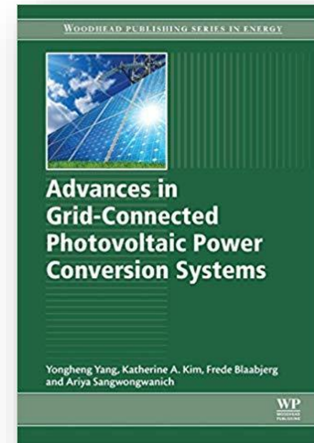
Acknowledgement



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www.et.aau.dk
https://www.et.aau.dk/research-programmes/photovoltaic-systems/

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Thank you for your attention!

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Questions?