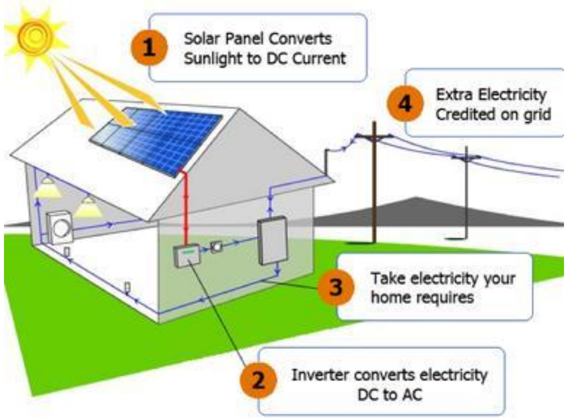
PV power electronic converters

Operation and Characterization

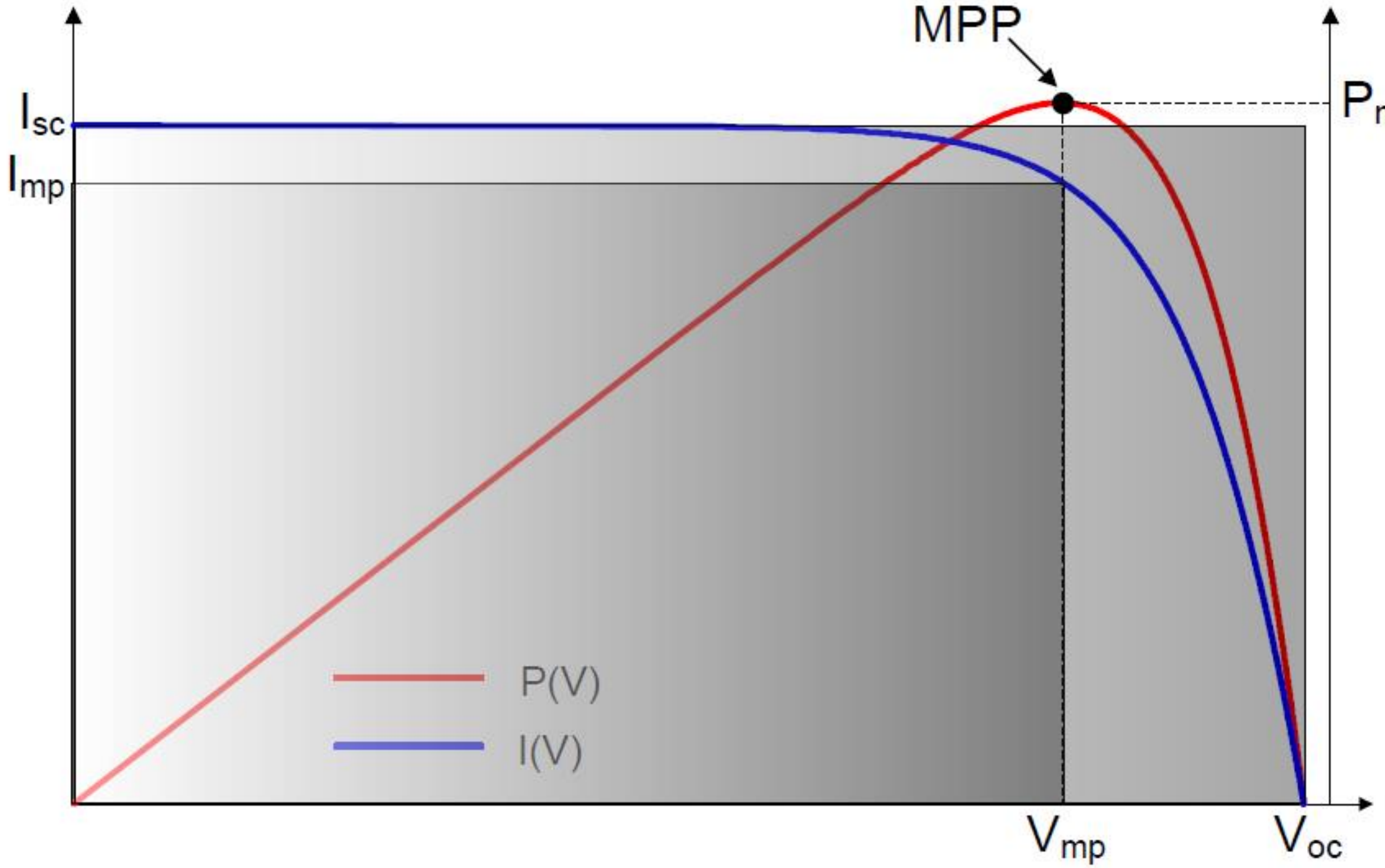
34553: Applied Photovoltaics

What is the role of the PV inverter?

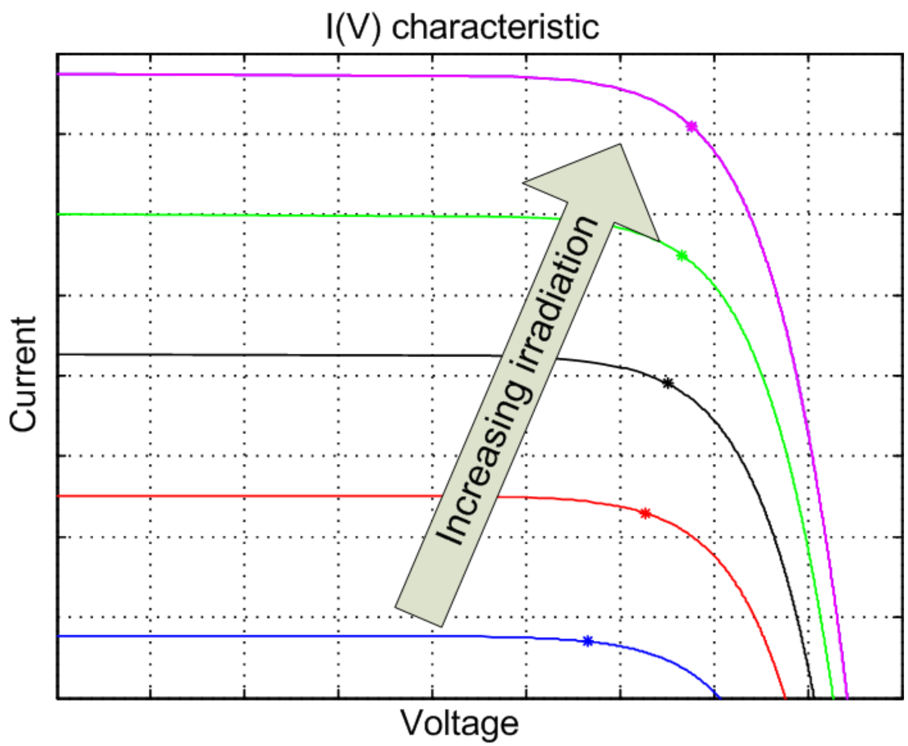
– Extract the **maximum possible power** from the **PV panels** at all times
– **Convert** the **DC** current and voltage from the panels into **AC** current and voltage with **high efficiency**
– **Provide safety functions**
– **Generate** AC current and voltage that is compliant with **the national grid code requirements**
– **Support** the electrical grid
  - **Grid stabilization**
  - **Grid fault ride through**
– **Monitoring** of energy production and system performance

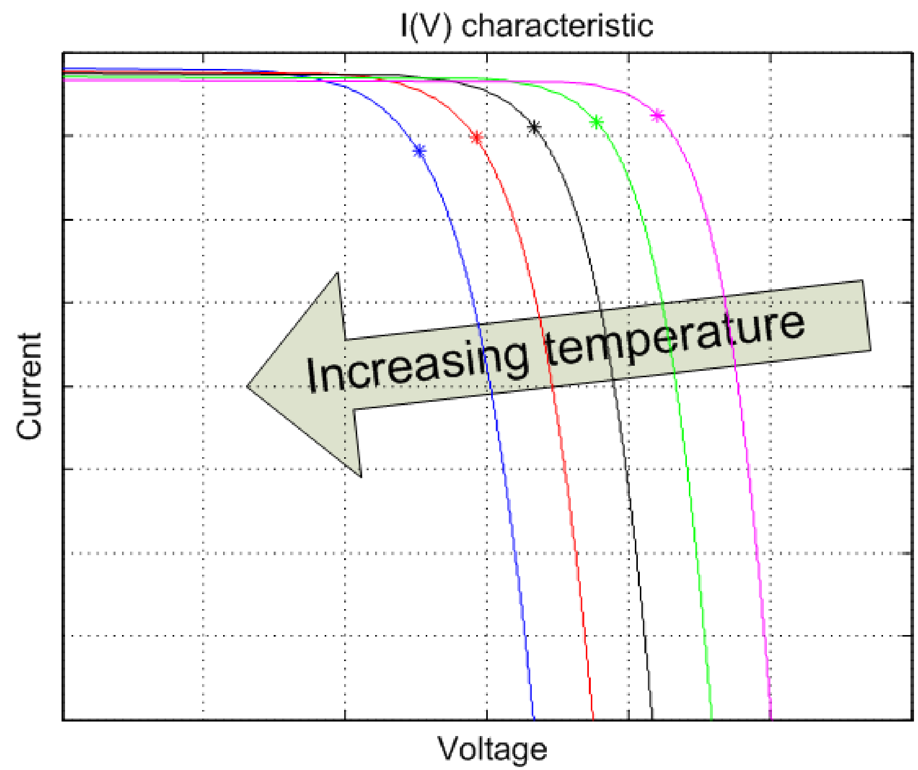


How does the electrical characteristic of a PV panel look?



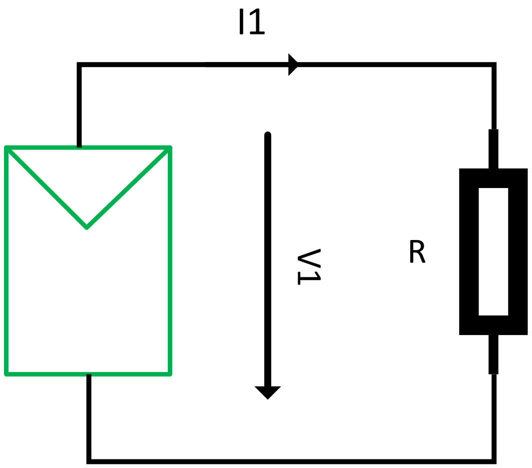
How does the I-V vary with irradiance and temperature?

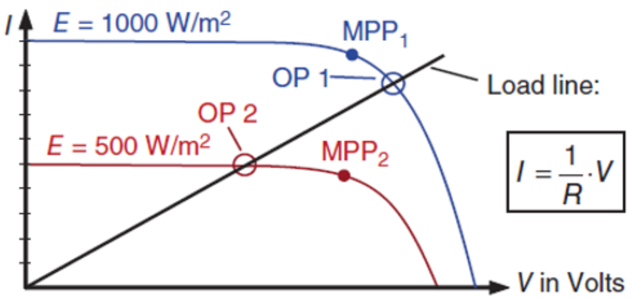




How can we extract power from the panel?

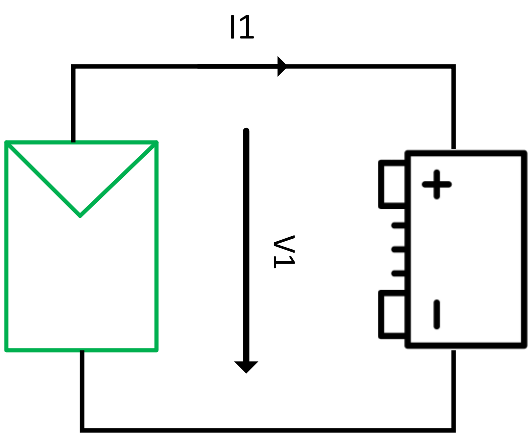
- Using **DC load/consumer**
- **Will this work?**
- **What if we assume** it's compatible with the DC voltage and current of the panel
- What will decide the operation point on the I-V charateristic?
- What happens when the irradiance or temperature changes?

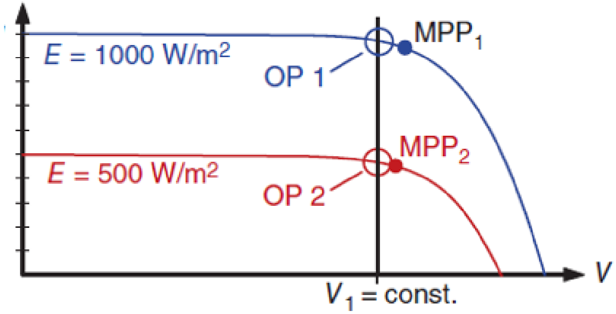




How can we extract power from the panel?

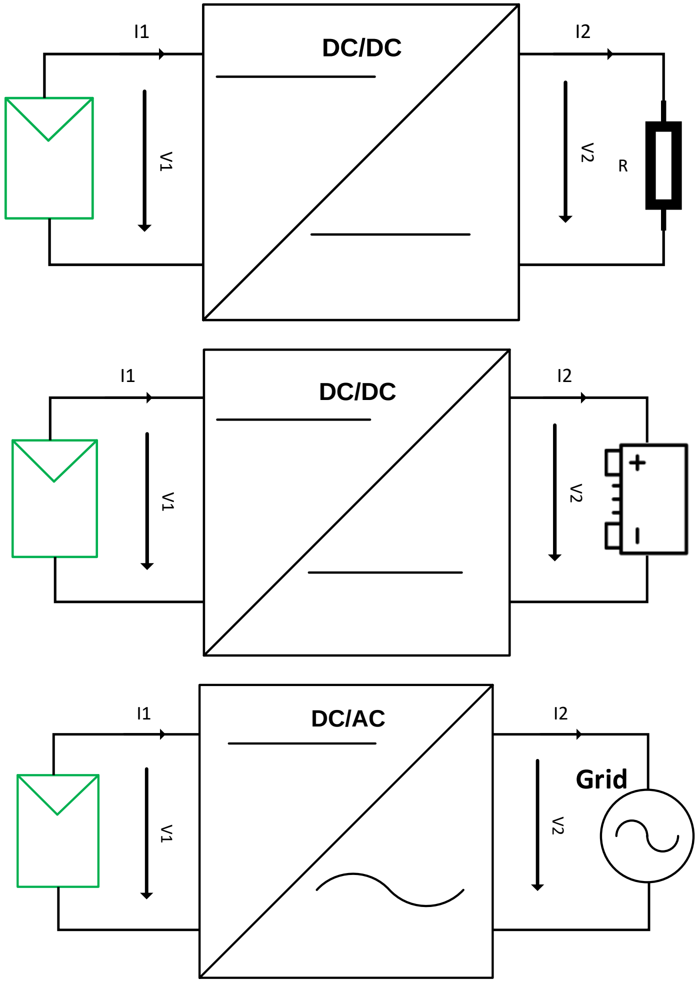
- Using a **battery**
- **Will this work?**
- **What if we assume** the battery has a nominal voltage of 12 V and the STC Vmp of the panel is 14 V
- What happens under high irradiance?
- What happens under low irradiance?
- What happens under high temperature ?





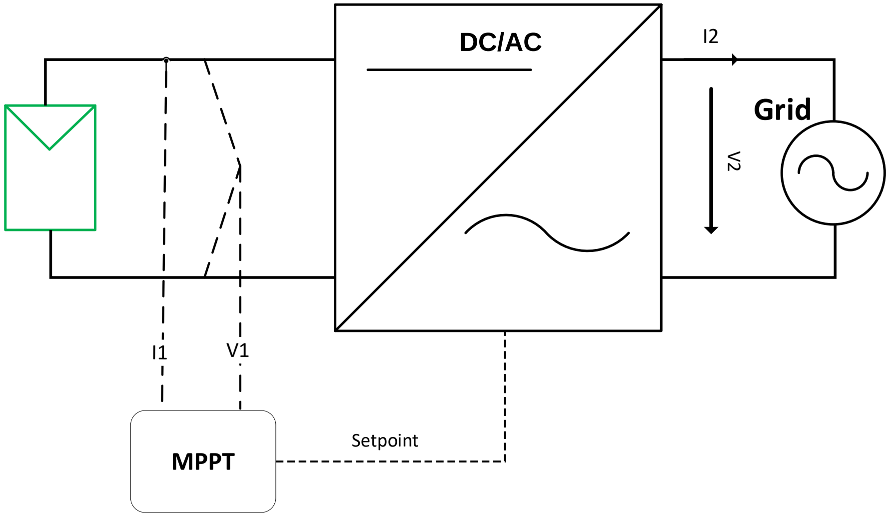
How can we extract power from the panel?

- Using a **power converter**
- How much power can we extract from the panel in each case?
- How can we extract the maximum possible power from the panel?



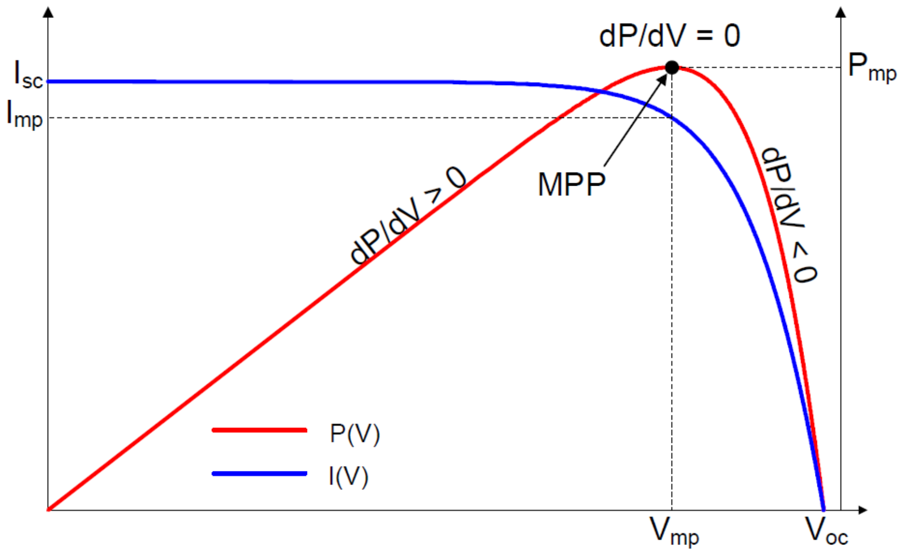
How can we extract the maximum power from the panel?

- Using a **power converter**
- We **monitor** V1, I1, P1=V1*I1 and **control** one of them
- We search for the maximum power continuously using a **MPPT algorithm**

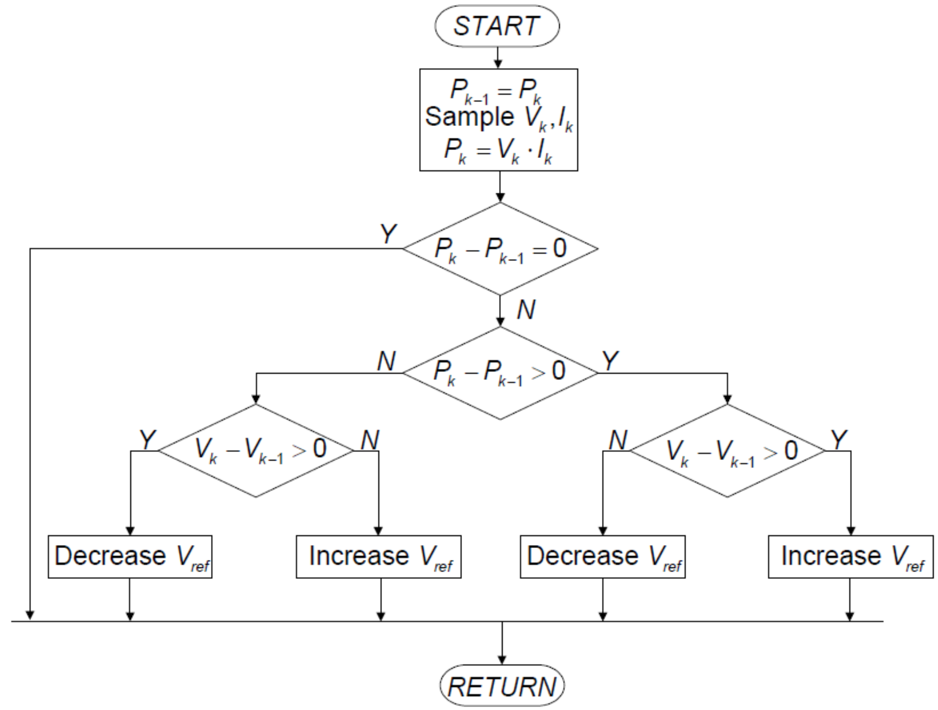


How does an MPPT work?

- **Perturb and Observe MPPT**

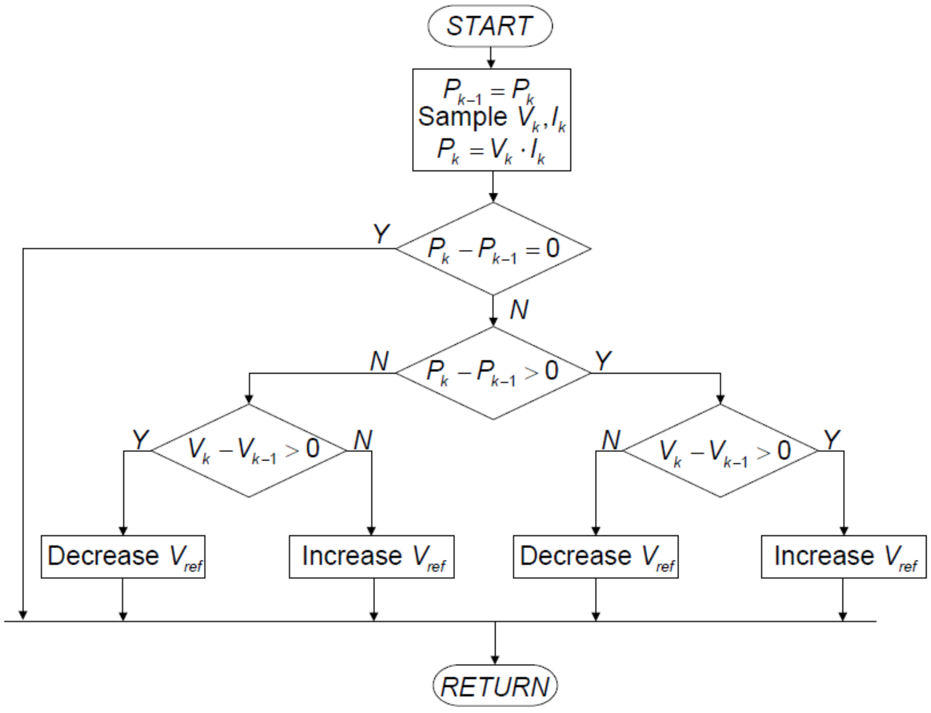


$$\left.\frac{dP}{dV}\right|_{P=P_{mp}} = 0$$



How does an MPPT work?

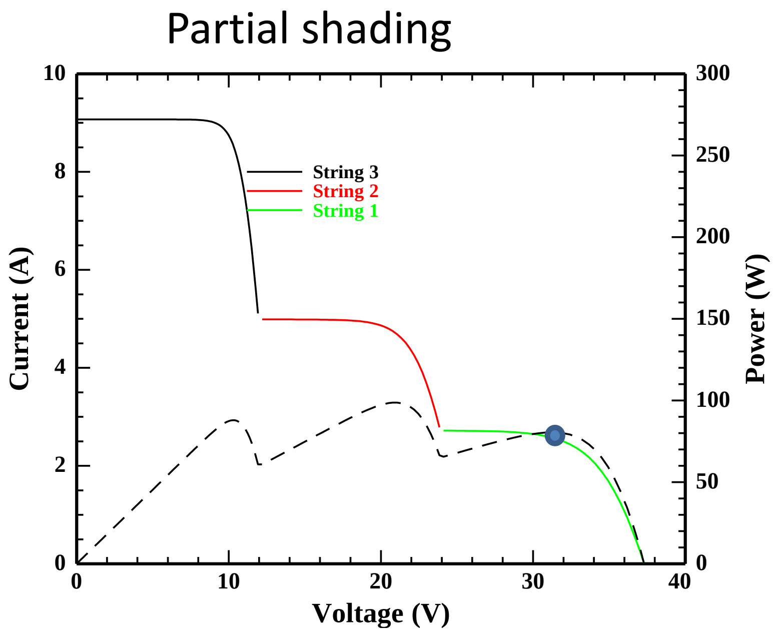
- **Perturb and Observe MPPT**
  - Simple, low computational demand
  - Generic – applicable for most systems
  - Tradeoff between speed and accuracy
  - Can track in wrong way during fast changing conditions
  - **P&O is the most used MPPT algorithm today**

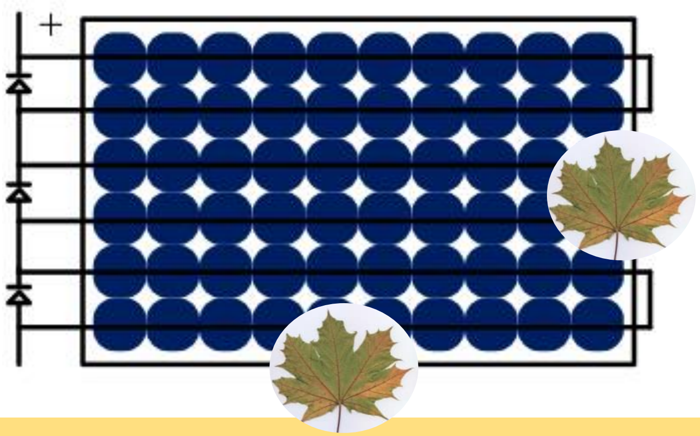


How well does the MPPT work under partial shading?

Partial shading on strings

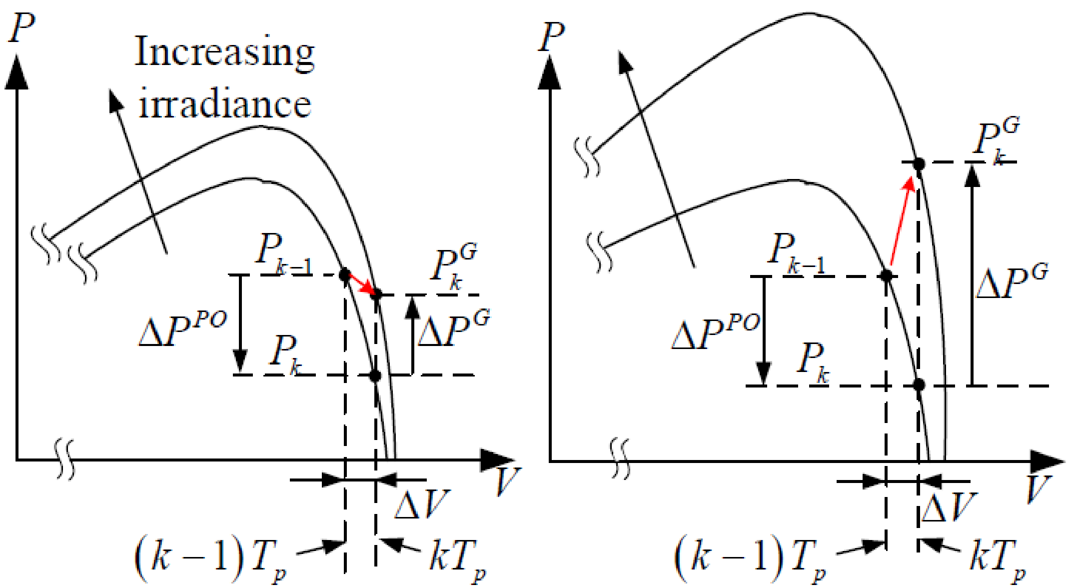
- MPP may not be @full voltage
- Simple algorithms stays around the same **local** maxima
- Frequently full IV sweeps required
- During sweeps PV is not at MPP
- Shade button on some inverters
  - Can be default disabled
  - ”Optitrac”
  - ”Smart trac”





How well does the MPPT work under fast changing irradiance?

- **P&O under fast changing irradiance**



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

kT_p - actual MPPT perturbation period $(k+1)T_p$ - next MPPT perturbation period

inc - MPPTvoltage increment amplitude

P_k - measured power at the k-th MPPT sampling instance P_{k+1} - measured power at the (k+1)-th MPPT sampling instance

dP - change of power in one sampling period caused by the MPPT dP_2 - change of power in one sampling period caused by the irradiance

If the change of power caused by environmental change within one MPPT perturbation period is larger than the change of power caused by the MPPT perturbation, the tracker gets confused

How is the efficiency of the MPPT measured?

- MPPT efficiency defined in EN-50530
- Characterizes how close the operating point is to the MPP

$$\eta_{MPPT,i}\left[\%\right]=\frac{P_{PV\_meas}}{P_{MP\_ideal}}\cdot 100$$

Instantaneous efficiency

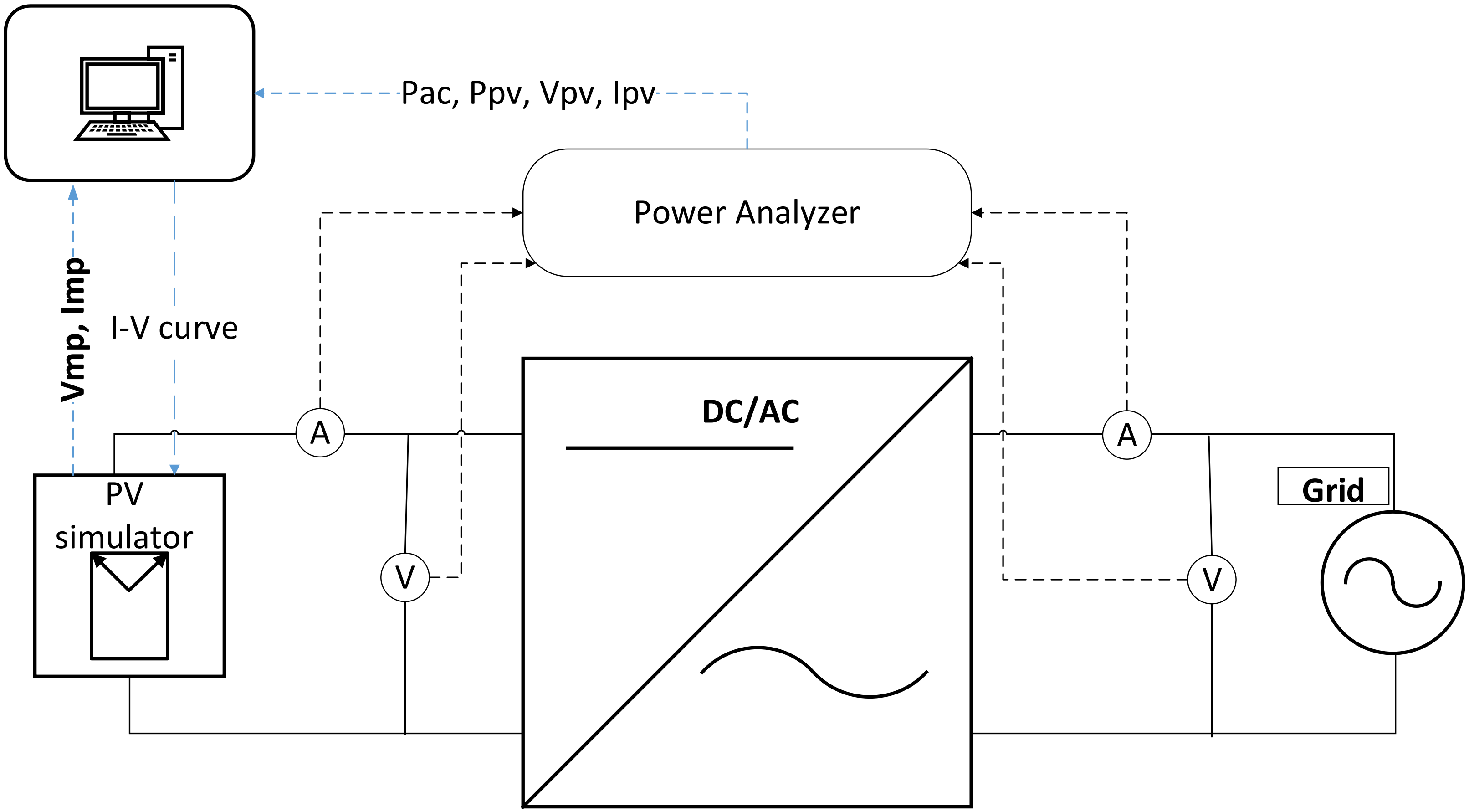
$$\eta_{MPPT,d}\left[\%\right]=\frac{\int_{0}^{T_m} P_{PV\_meas}(t)\,dt}{\int_{0}^{T_m} P_{MP\_ideal}(t)\,dt}\cdot 100$$

Dynamic efficiency

T_m – measurement duration

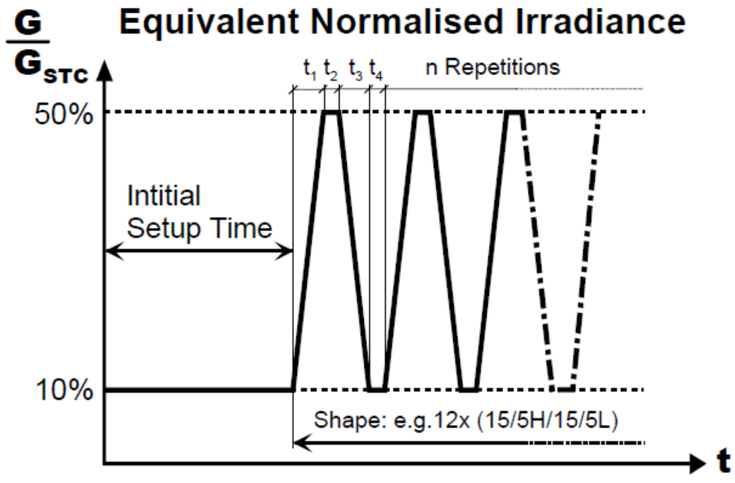
How is the efficiency of the MPPT measured?

- Measuring the MPPT efficiency requires a PV pane/array simulator



How is the efficiency of the MPPT measured?

- Dynamic MPPT efficiency can be tested using trapezoidal irradiance profiles (EN50530 standard)



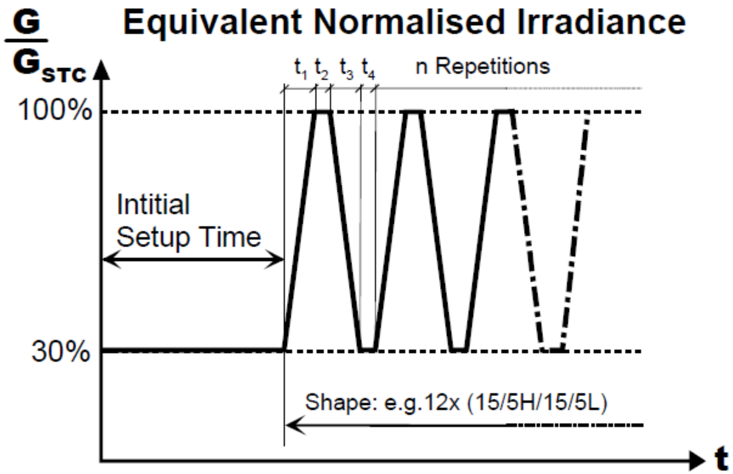
Test with variations between low and medium irradiance

Irradiance Variation 10 % ⇒ 50% of G_{STC}			
Number n	Slope [W/m^2/s]	Mode	Duration [s]
2	0.5	(800 / 10H / 800 / 10L)	3540
2	1	(400 / 10H / 400 / 10L)	1940
3	2	(200 / 10H / 200 / 10L)	1560
4	3	(133 / 10H / 133 / 10L)	1447
6	5	(80 / 10H / 80 / 10L)	1380
8	7	(57 / 10H / 57 / 10L)	1374
10	10	(40 / 10H / 40 / 10L)	1300
10	14	(29 / 10H / 29 / 10L)	1071
10	20	(20 / 10H / 20 / 10L)	900
10	30	(13 / 10H / 13 / 10L)	767
10	50	(8 / 10H / 8 / 10L)	660
Total	Time for Setup + Measurement		15939

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

How is the efficiency of the MPPT measured?

- Dynamic MPPT efficiency can be tested using trapezoidal irradiance profiles (EN50530 standard)



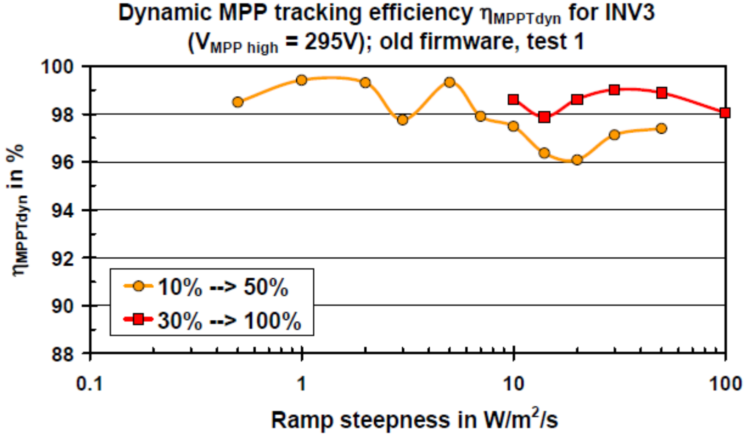
Test with variations between medium and high irradiance

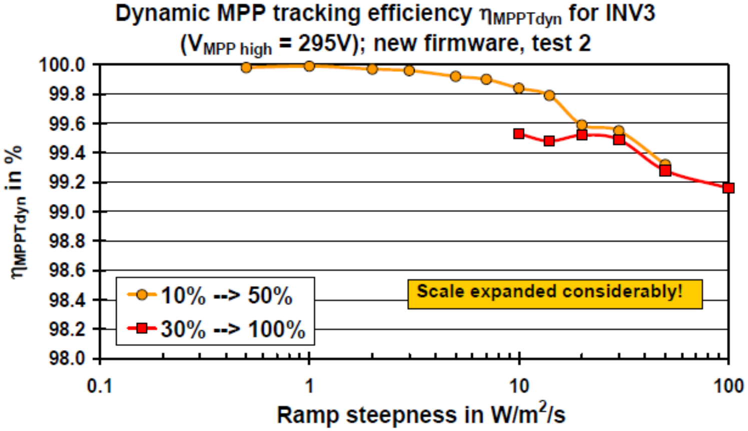
Irradiance Variation 30 % ⇒ 100% of G_{STC}			
Number n	**Slope [W/m²/s]**	**Mode**	**Duration [s]**
10	10	(70 / 10H / 70 / 10L)	1900
10	14	(50 / 10H / 50 / 10L)	1500
10	20	(35 / 10H / 35 / 10L)	1200
10	30	(23 / 10H / 23 / 10L)	967
10	50	(14 / 10H / 14 / 10L)	780
10	100	(7 / 10H / 7 / 10L)	640
Total	Time for Setup + Measurement		6987

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

How is the efficiency of the MPPT measured?

- The MPP tracking algorithm used by the manufacturer is decisive for the dynamic tracking behavior
- It can very between different inverter manufacturers and different inverter firmware versions





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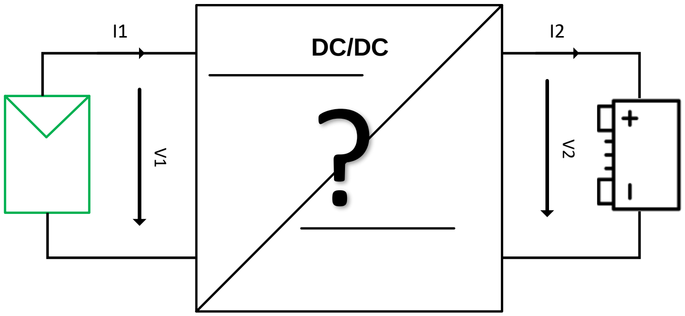
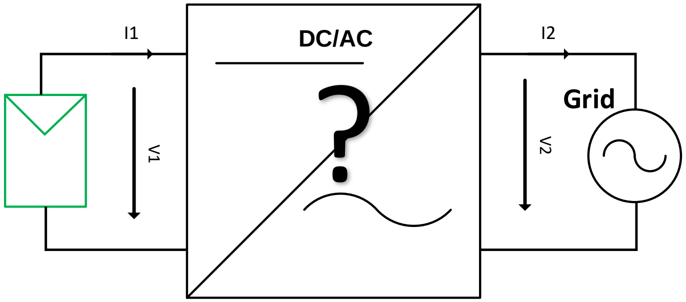
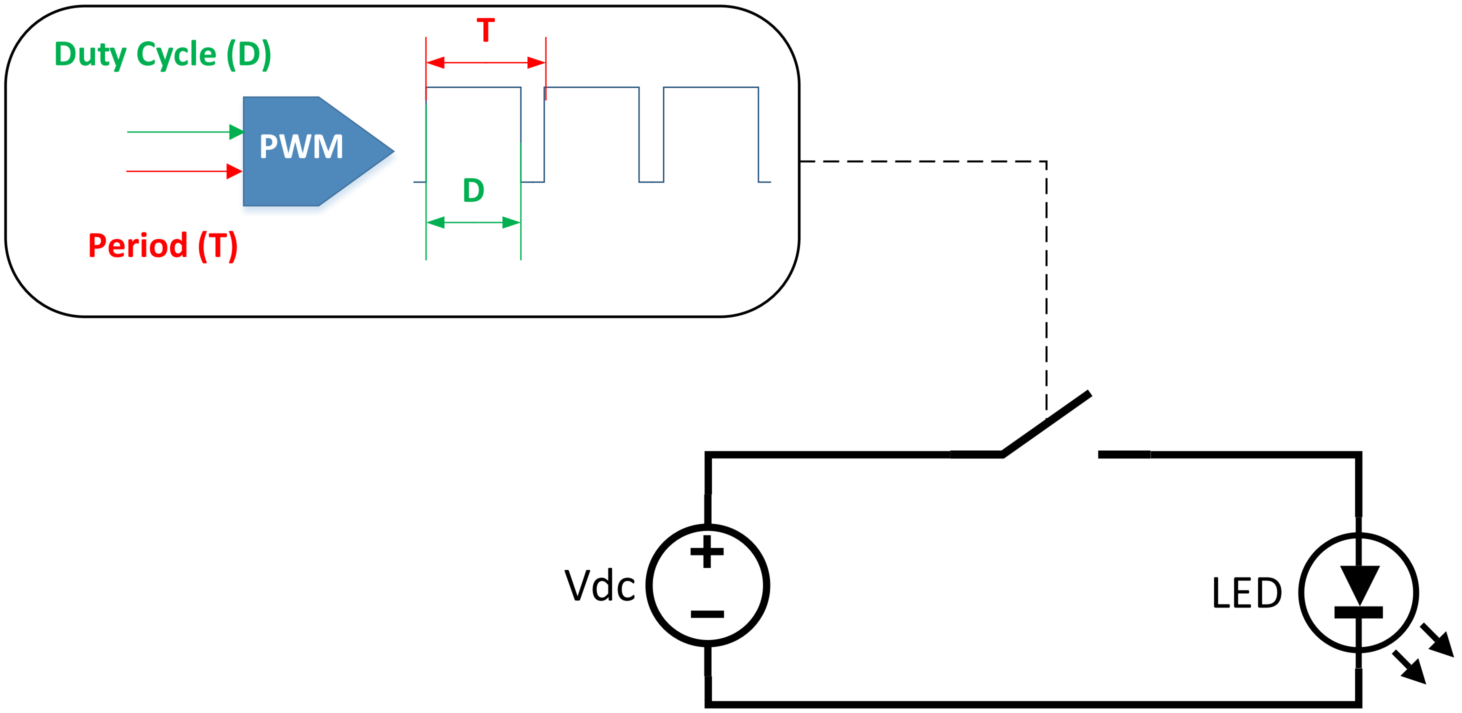
How do power converters work?





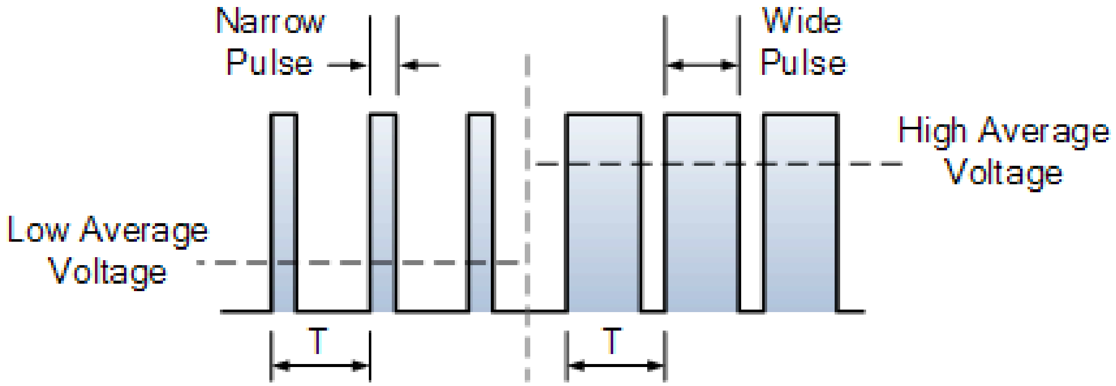
How do power converters work?

- Let's look at the simplest power converter possible
- How does the led's intensity vary with the duty cycle?



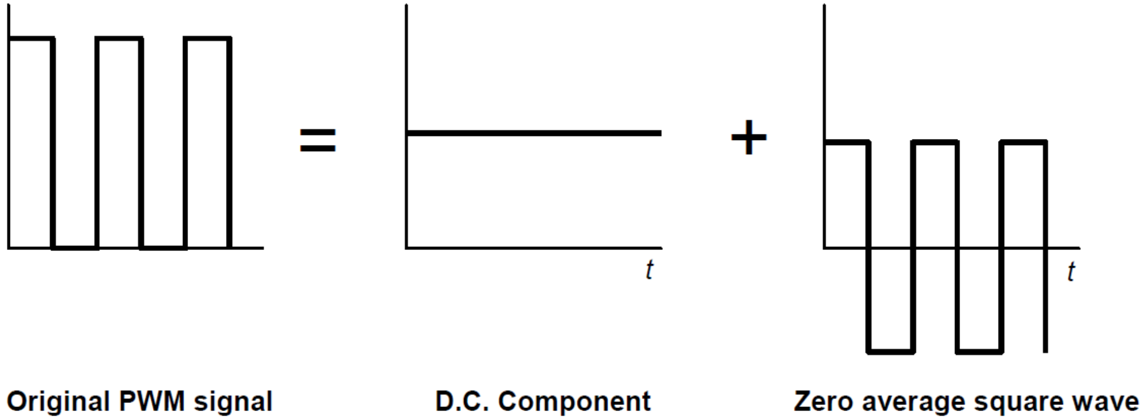
How does PWM work?

- Let’s look at the simplest power converter possible
- How led’s intensity vary with the duty cycle?
- We see the **average intensity** of the led which depends on the **average load voltage**



How does PWM work?

- The **average of a periodic signal** represents the **DC component** of that signal
- A PWM signal is the composed of **DC component (A0)** and an infinite number of harmonics
- **What is the value of the DC component A0?**

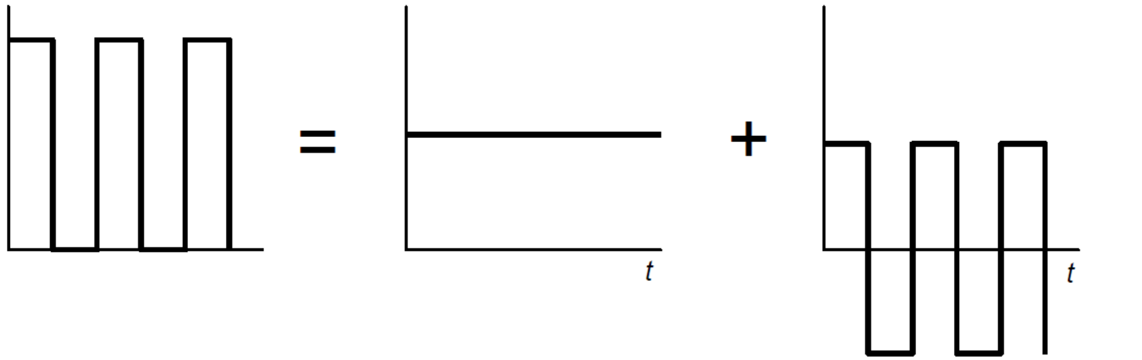


$$f(t) = A_0 + \sum_{n=1}^{\infty}\left[A_n \cos\left(\frac{2n\pi t}{T}\right) + B_n \sin\left(\frac{2n\pi t}{T}\right)\right]$$

$$A_0 = \frac{1}{2T}\int_{-T}^{T} f(t)\,dt$$

How does PWM work?

- **What is the value of the DC component A0?**
- DC Component = duty cycle x period



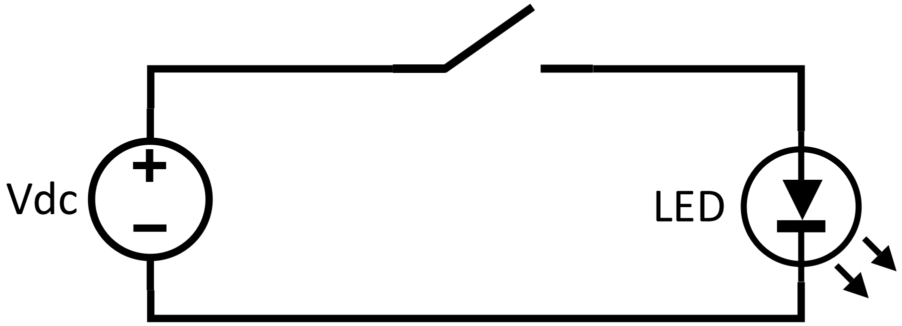
Original PWM signal D.C. Component Zero average square wave

$$f(t) = A_0 + \sum_{n=1}^{\infty}\left[A_n \cos\left(\frac{2n\pi t}{T}\right) + B_n \sin\left(\frac{2n\pi t}{T}\right)\right]$$

$$A_0 = \frac{1}{2T}\int_{-T}^{T} f(t)dt$$

How do power converters work?

- In practice most electric devices cannot work with pulsing power
- They need a continuous and stable power supply
- We need to store energy temporarily as the switch is disconnected
- **What can we use?**



Temporary energy storage devices

Inductors:

- Current introduces a magnetic field, characterized by the magnetic Flux:

$$\Phi = LI$$

L: Inductance (Coil property)

From Faradays law:

$$V = \frac{d\Phi}{dt} = L\frac{dI}{dt}$$

Energy stored:

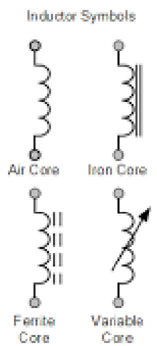
$$E = \int VIdt = L\int_0^I I\,dI = \frac{LI^2}{2}$$

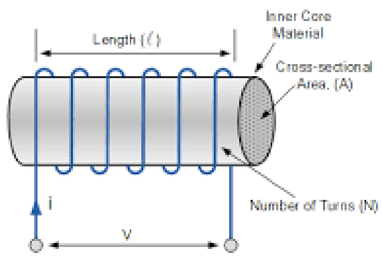
Reactance:

$$\mathrm{X} = \omega L$$

Losses:

- Parasitic resistance
- Magnetic hysteresis
- Skin effect





Capacitors:

- Storage of charges in a dielectric:

$$Q = CV$$

$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

Q: charge

C: capacitance

Energy stored:

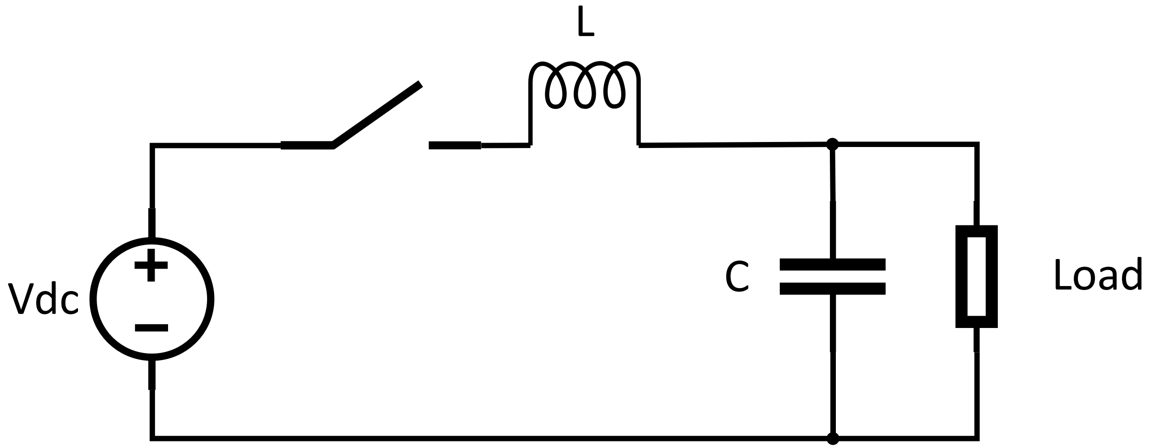
$$E = \int VIdt = C\int_0^V V\,dV = \frac{CV^2}{2}$$

Reactance:

$$\mathrm{X} = \frac{1}{\omega C}$$

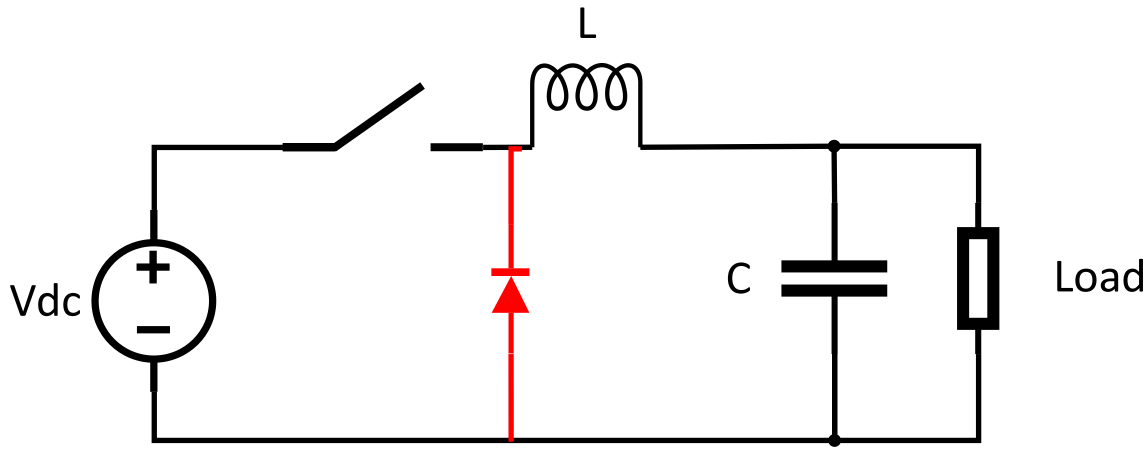
How do power converters work?

- Inductors stabilize the current
- Capacitors stabilize the voltage
- **Will this work?**



How do power converters work?

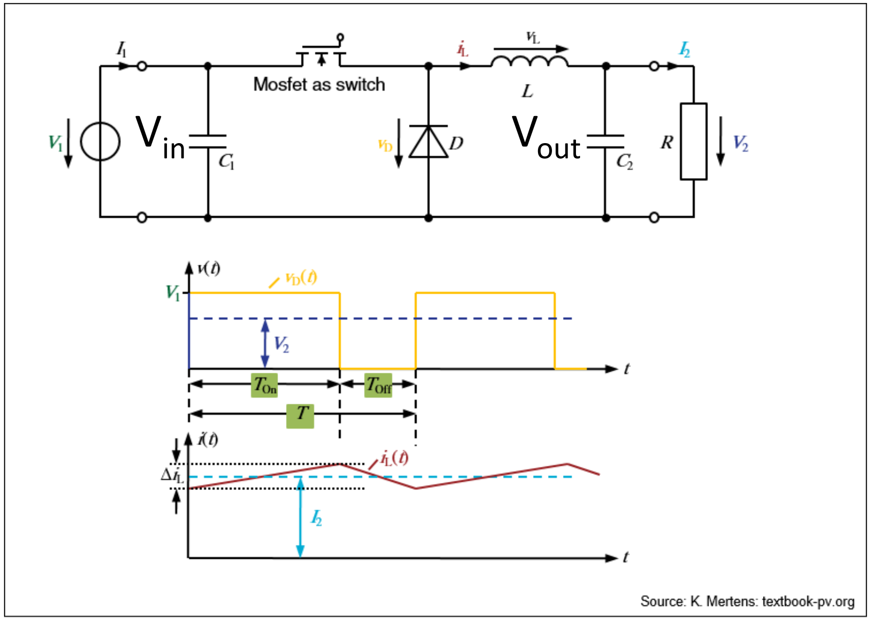
- Current in a capacitor cannot change suddenly
- Voltage in a capacitor cannot cange suddenly



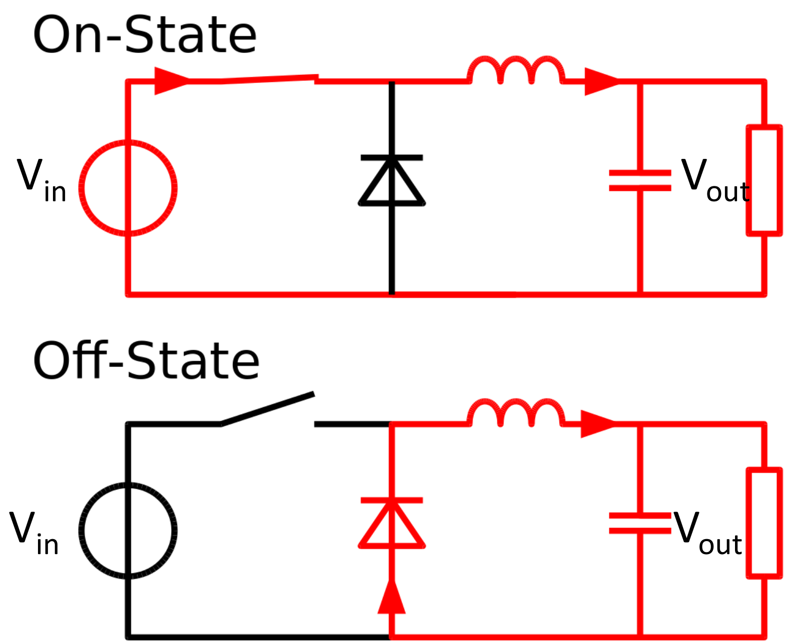
The Buck converter

- The buck converter lowers the input voltage

$$V_{out} = \text{duty cycle x } V_{in}$$



Source: K. Mertens: textbook-pv.org

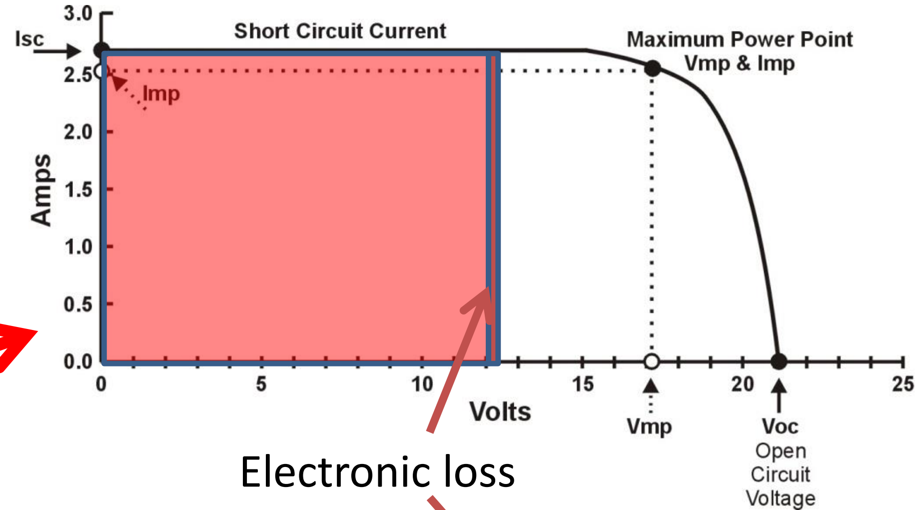


Application of the Buck converter

Example as Charge regulator for 12 V battery sys.

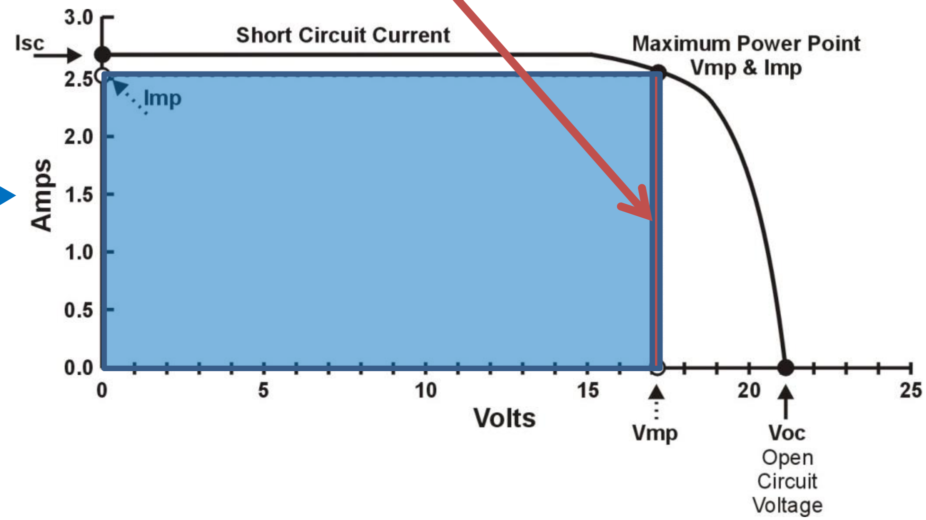
- Vpv~18V
- Vbat ~12 V
- Loss ~33 %

Energy harvest without conversion
Connecting the battery to the panel



Electronic loss

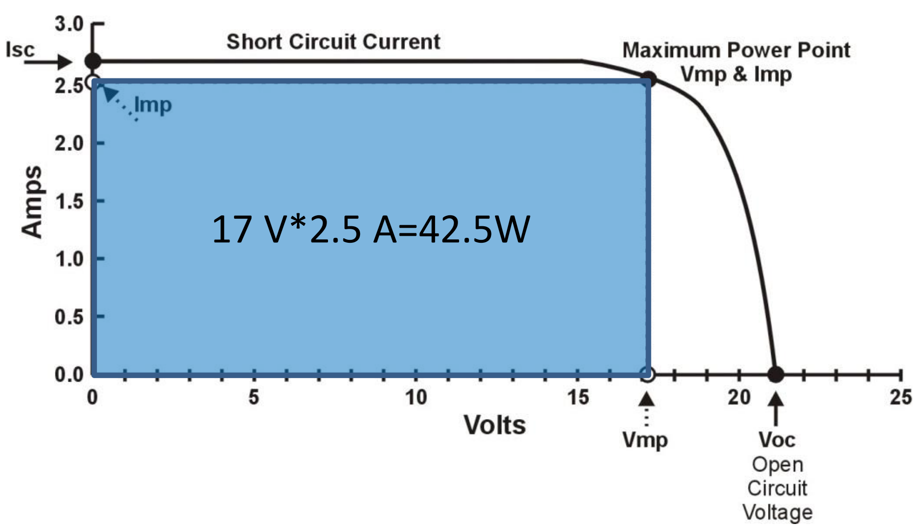
Energy harvest with a Buck converter



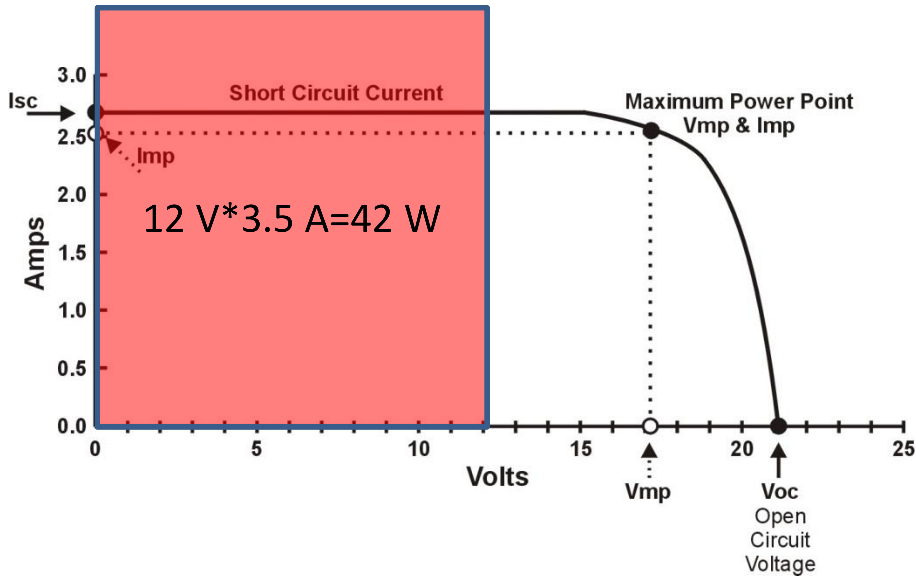
Electronic Conversion

DC-DC Converter

Harvested Energy (Pin)



Converted Energy (Pout)



Conversion efficiency:

$$\eta = \frac{P_{out}}{P_{in}}$$

Other DC-DC power converters

- Boost (Increases the voltage)
- Buck (Decrease the voltage)
- Buck Boost (Both)

Properties

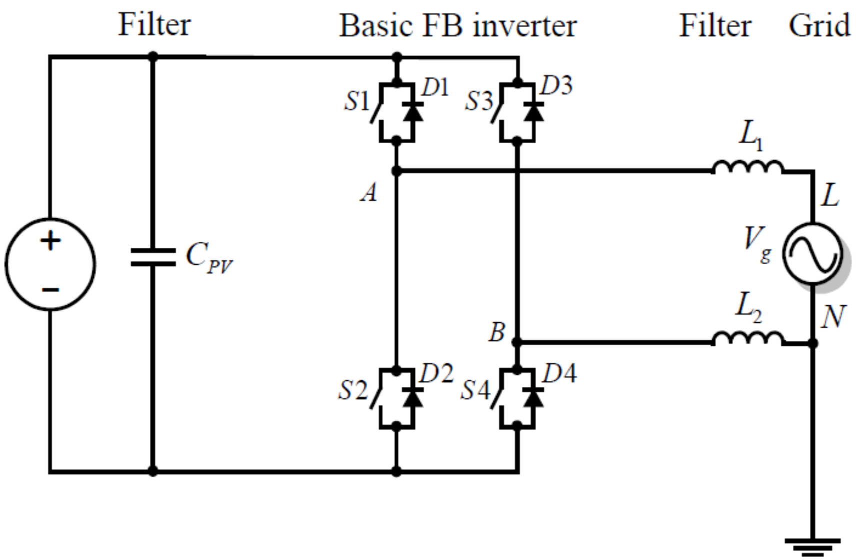
- Generally Conversion ratio is a function of Duty cycle
- Finite operating range
- Voltage change
  ~ factor 1-5 voltage change
- Energy is almost conserved

$$P_1 = V_1 I_1 = \eta V_2 I_2 = \eta P_2$$

- Efficiency typical over 90 %
  - Within most of the operating range
- Switching creates HF noise (Ripples)

How do PV inverter work?

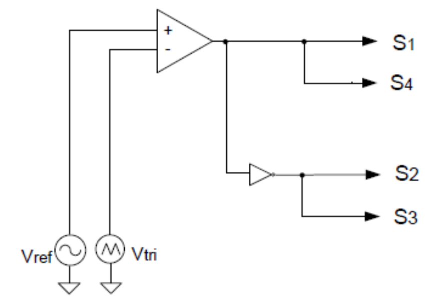
- There are many topologies of PV inverters
- The most basic the **full-bridge inverter**
- Uses 4 switches in a H configuration
- Uses an **L** or **LC filter** for suppressing current and voltage harmonics

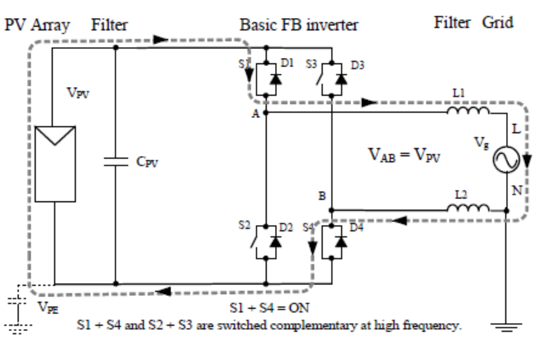


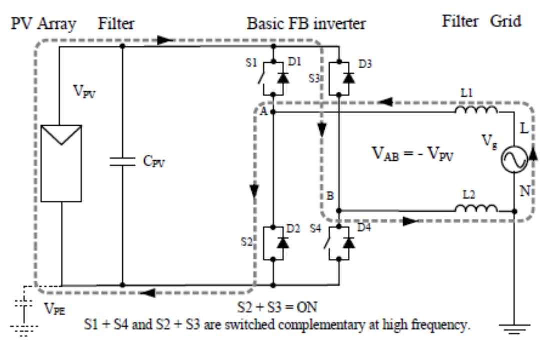
How do PV inverter work?

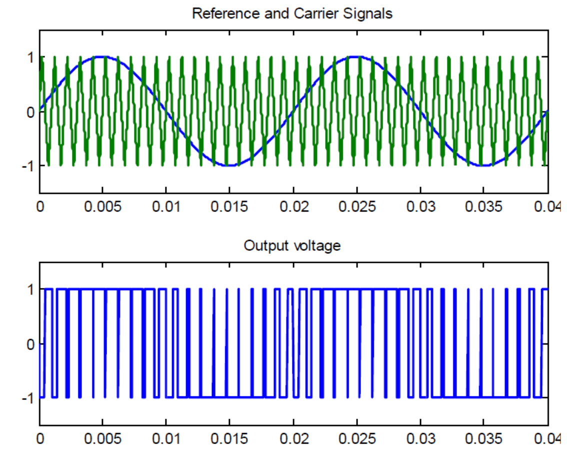
- The switches are controlled to generate a **sinusoidal voltage at the output** with a 50 Hz period
- There are several **switch control schemes** the most simple is bipolar switching
- S1 + S4 and S2 + S3 are switched complementary at high frequency (PWM)

Bipolar PWM



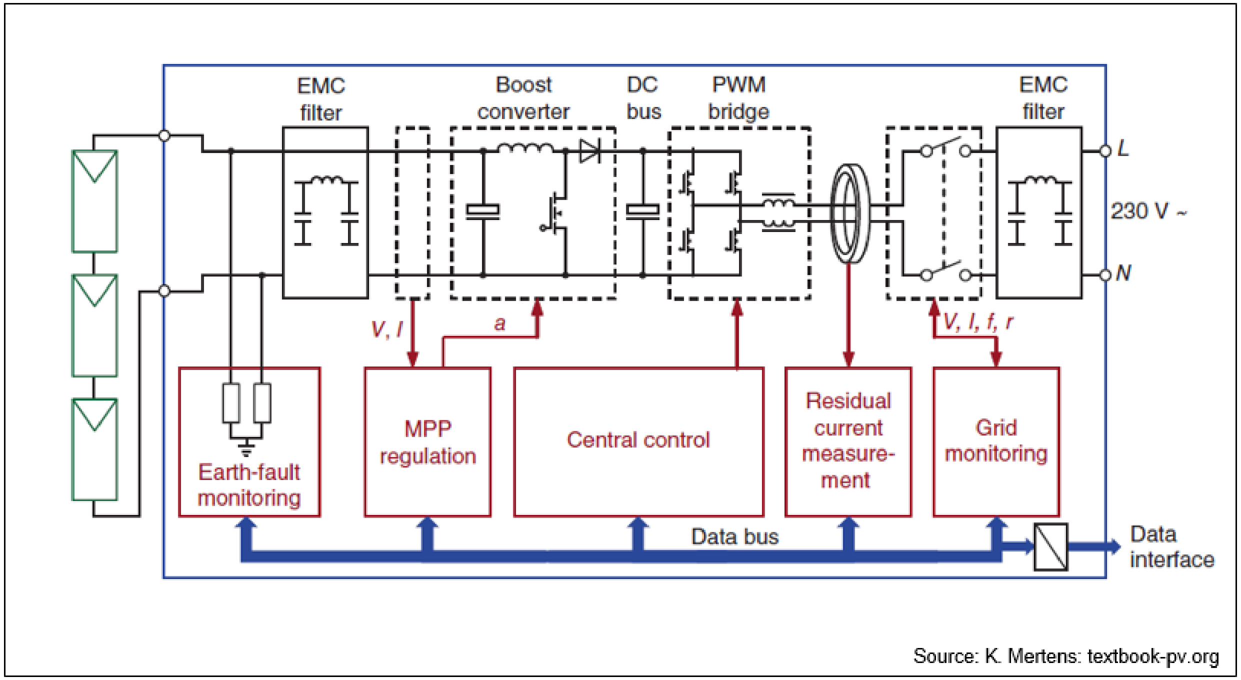






How do PV inverter work?

- A PV inverter has multiple hardware and software subsystems
- Grid monitoring and synchronization
- Current and voltage control
- Maximum power tracking
- Residual current detection
- Earth fault detection
- Data logging and communication

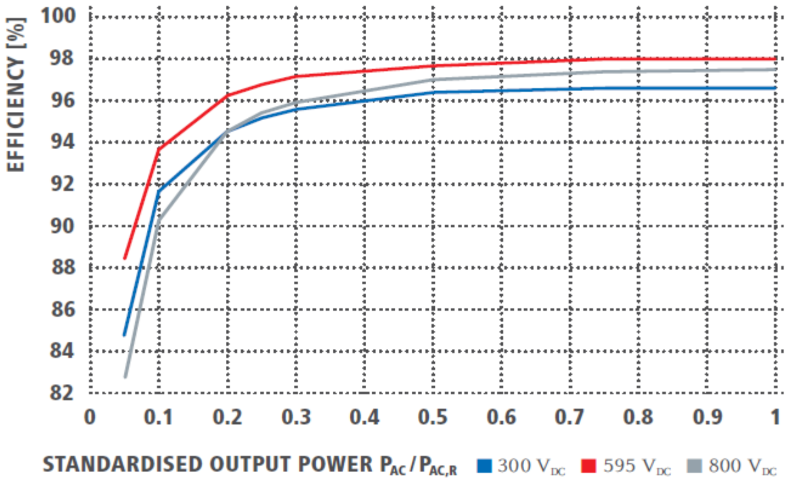


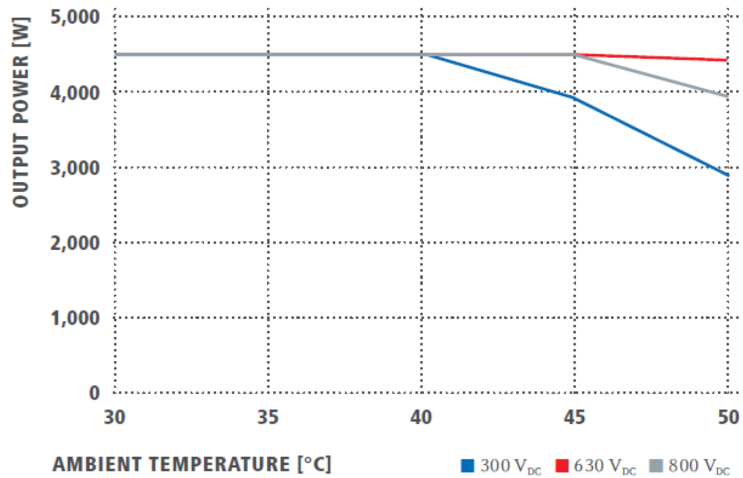
What losses occur in power converters?

- Inductor, capacitor and wire losses
- Switch conduction losses
- Swich turn-on turn-off losses
- Body diode losses
- Control circuit power consumption
- Some of the losses are voltage, current, switching frequency and/or temperature dependent

What is the power conversion efficiency of PV inverters?

- It varies primarily with the load/power, input voltage and operation temperature





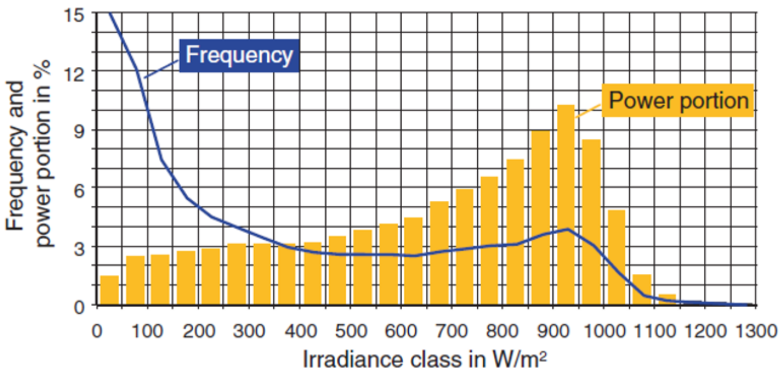
- The inverter's datasheet will specify the peak efficiency, the CEC or EU weighted efficiency and the MPPT efficiency

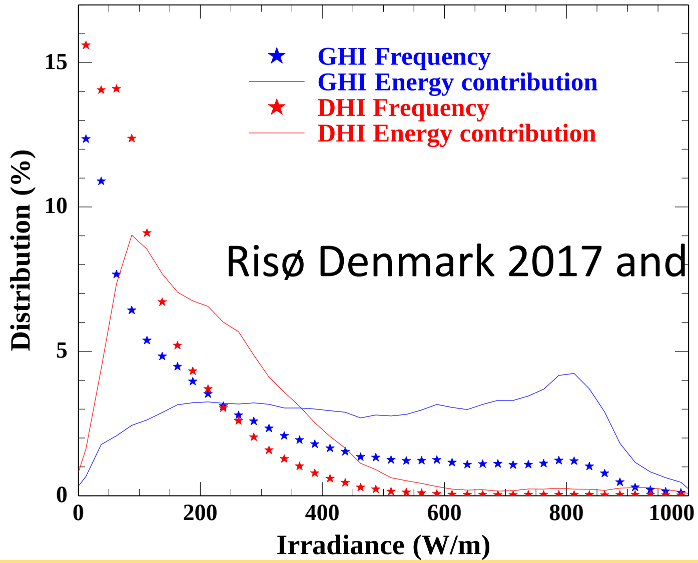
EFFICIENCY	SYMO 3.0-3-S	SYMO 3.7-3-S	SYMO 4.5-3-S	SYMO 3.0-3-M	SYMO 3.7-3-M	SYMO 4.5-3-M
Max. efficiency	98.0 %					
European efficiency (ηEU)	96.2 %	96.7 %	97.0 %	96.5 %	96.9 %	97.2 %
MPP adaptation efficiency	> 99.9 %					

What are weighted efficiencies and why are they used?

Freiburg Germany

- Solar irradiation changes over the day
- Inverter may only operate in its peak efficiency range for a very small part of the day or not at all
- Weighted efficiencies offer an indication of how an inverter might perform throughout the day and at different locations
- Weighted efficiencies measure inverter performance across the range of the inverter's capacity





Risø Denmark 2017 and 2018

What are weighted efficiencies and why are they used?

- The "European Efficiency" is an averaged operating efficiency over a yearly power distribution corresponding to middle-Europe climate.

- **Euro Efficiency** = $0.03 \times \eta_{5\%} + 0.06 \times \eta_{10\%} + 0.13 \times \eta_{20\%} + 0.1 \times \eta_{30\%} + 0.48 \times \eta_{50\%} + 0.2 \times \eta_{100\%}$

- This was proposed by the Joint Research Center (JRC/Ispra), based on the Ispra climate (Italy), and is now referenced on almost any inverter datasheet.

- The value of this weighted efficiency is obtained by assigning a percentage of time the inverter resides in a given operating range.

- "CEC Efficiency" was proposed by the California Energy Commission (CEC) for the climates of higher insolations like US south-west regions, which is now specified for some inverters used in the US.
- **CEC Efficiency** = $0.04 \times \eta_{10\%} + 0.05 \times \eta_{20\%} + 0.12 \times \eta_{30\%} + 0.21 \times \eta_{50\%} + 0.53 \times \eta_{75\%} + 0.05 \times \eta_{100\%}$

*J. Newmiller, et al, "Sandia Inverter Performance Test Protocol efficiency weighting alternatives," 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, CO, 2014, pp. 0897-0900, doi: 10.1109/PVSC.2014.6925058.

What is the total efficiency of a PV inverter?

- **Tracking efficiency**:

$$\eta_{tracking} = \frac{P_{in,DC}}{P_{mp}}$$

- **Conversion efficiency**:

$$\eta_{Conversion} = \frac{P_{out,DC\ or\ AC}}{P_{in,DC}}$$

- **Total efficiency**:

$$\eta_{Total} = \frac{P_{out,DC\ or\ AC}}{P_{mp}} = \eta_{Conversion} * \eta_{tracking}$$