TSTE26 Powergrid and technology for renewable production

Lecture 2
Photo Voltaic – solar generator systems

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Outline

- PV Cell Modeling 2
- Shading
- Module configuration
- DC/DC conversion
- MPPT
- Grid connection

Solar module configuration

Understanding array configurations
- PV-cell characteristics
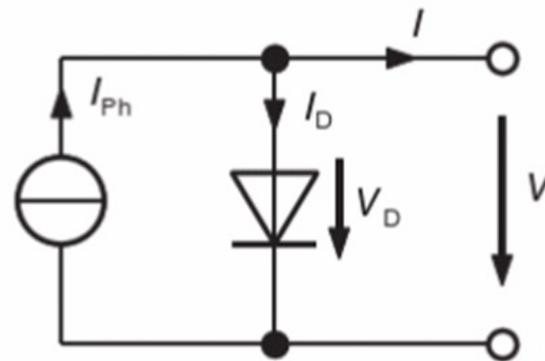- Parallel, series connection
- Bypass diodes
- Shading

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The PV-cell
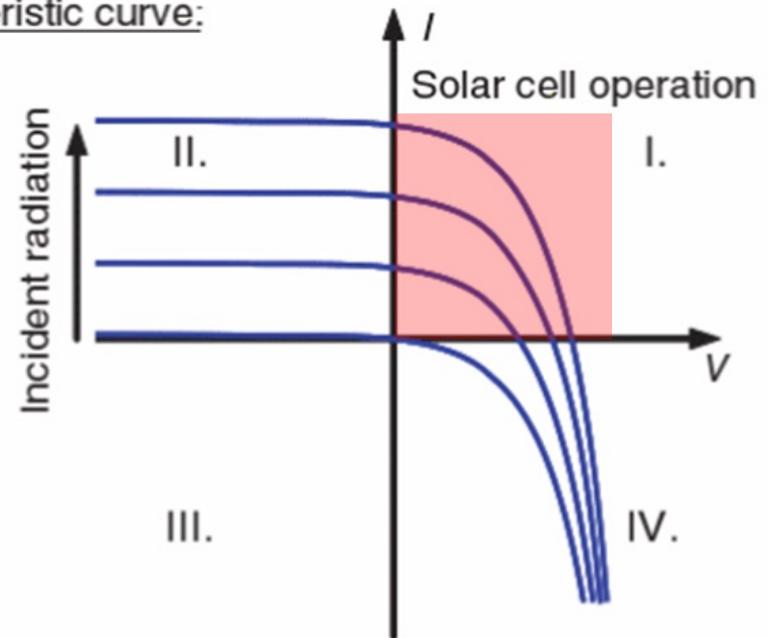
Solar-cell defined with generator references
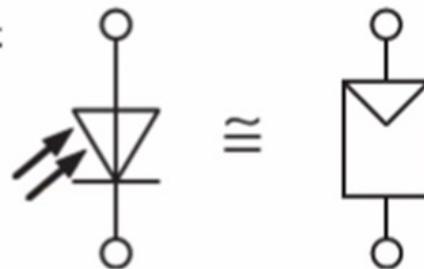Current direction out of the cell
Only 1st quadrant used
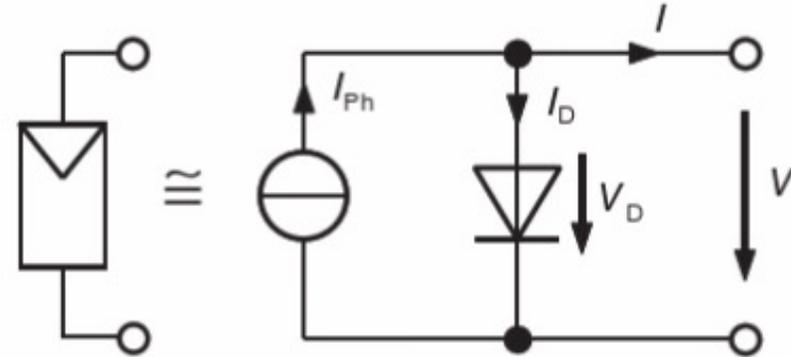
Generator reference-arrow system:

Characteristic curve:

Solar cell symbol:

IV-characteristics

Maximum Power Point

I_{SC}

I_{MPP}

$P_{MPP} = V_{MPP} \cdot I_{MPP}$

V_{MPP} V_{OC} V

I_{Ph} I_D V_D V
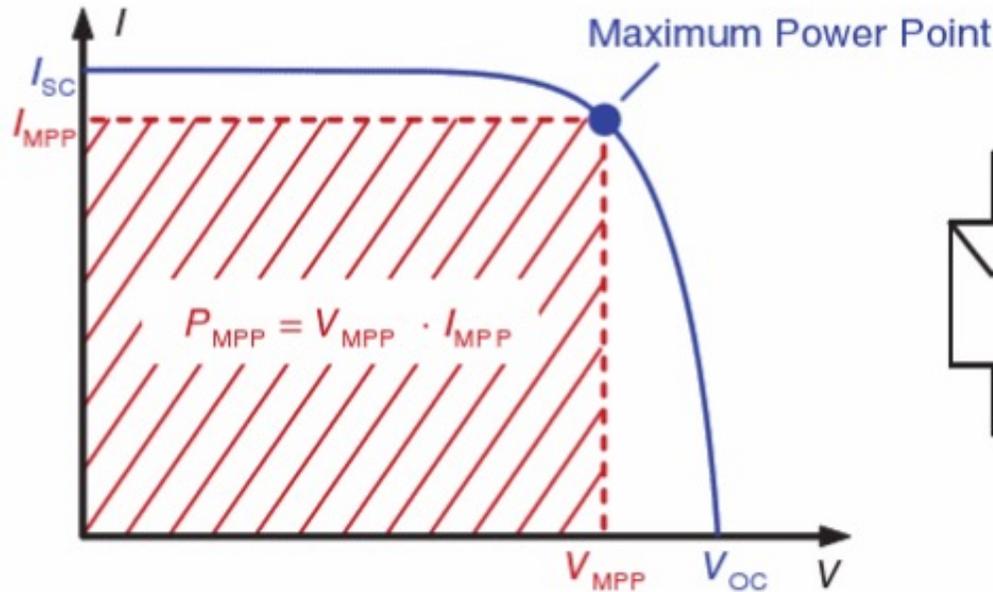
Shockley diode equation

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot \left(e^{\frac{V}{m \cdot V_T}} - 1 \right)$$

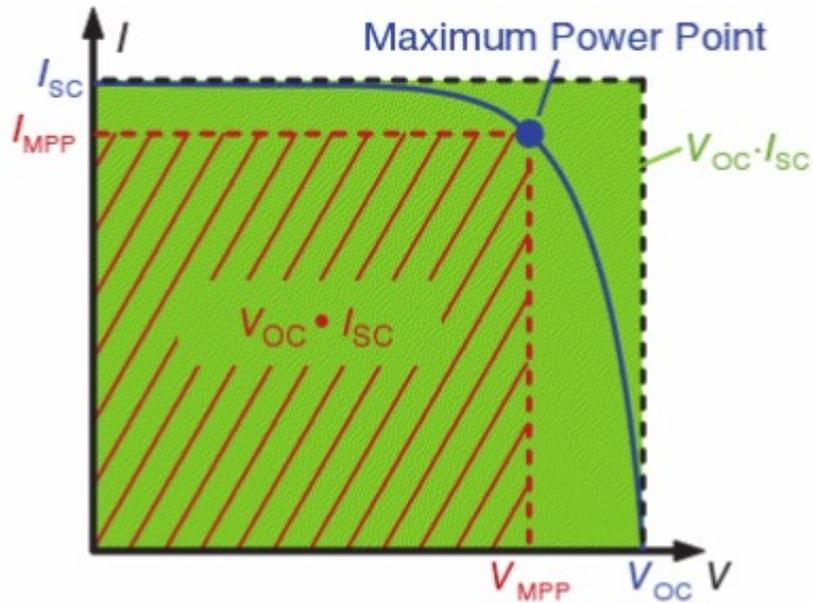$$V_T = \frac{kT}{q} = 25.9 \text{ mV (thermal voltage)}$$

m ideality factor (1<m<2)

Short circuit current

$$I_{SC} = I(V=0) = I_{Ph} - I_S \cdot \left(e^0 - 1 \right) = I_{Ph}$$

Open circuit voltage

$$V_{OC} = V(I=0) = m \cdot V_T \cdot \ln\left(\frac{I_{SC}}{I_S} + 1 \right)$$
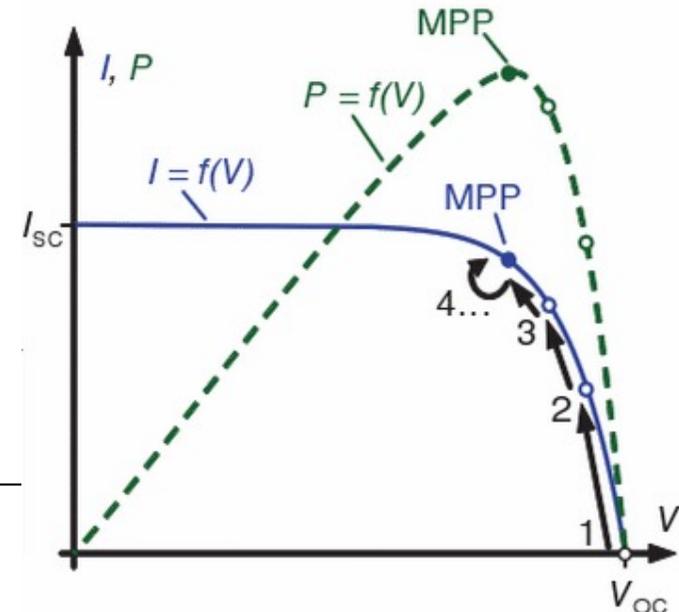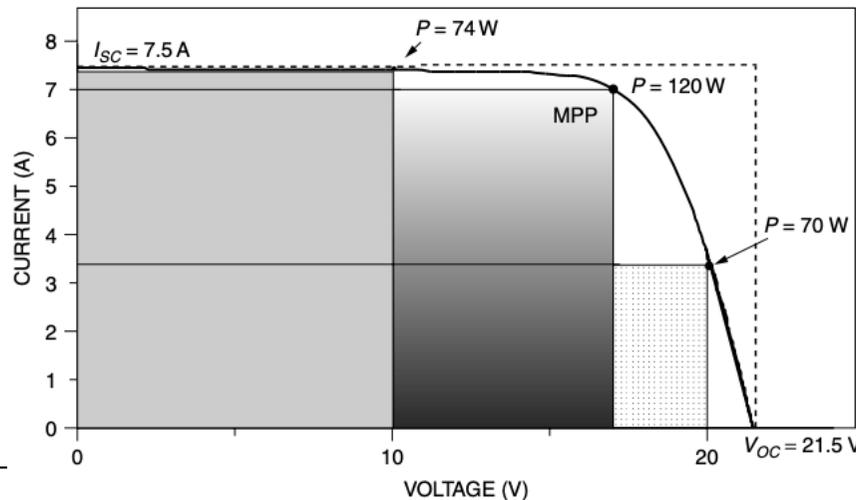
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Maximum Power Point

- Fill Factor

$$FF = \frac{V_{\mathrm{MPP}} \cdot I_{\mathrm{MPP}}}{V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}} = \frac{P_{\mathrm{MPP}}}{V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}}$$

- Efficiency

$$\eta = \frac{P_{\mathrm{MPP}}}{P_{\mathrm{Opt}}} = \frac{P_{\mathrm{MPP}}}{E \cdot A} = \frac{FF \cdot V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}}{E \cdot A}$$
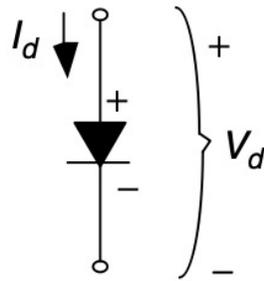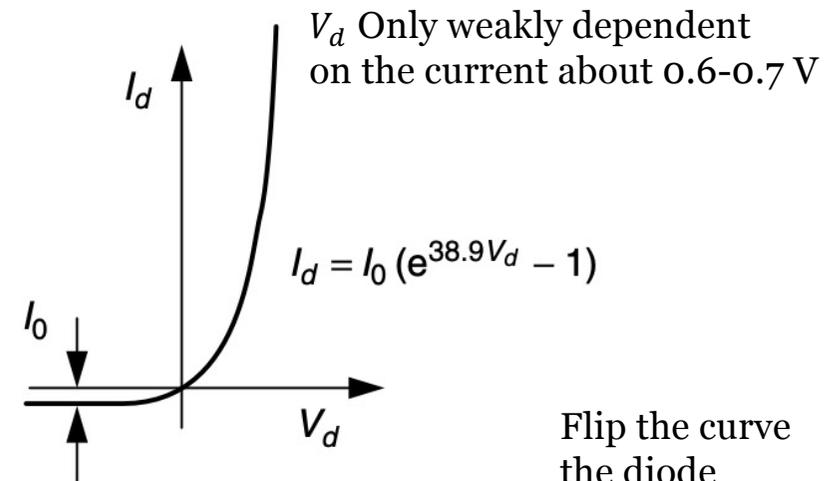

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Step 1 – Diode equationen

- Characteristics for Diode: Shockley Equation $I_d = I_0\left(e^{\frac{k}{qT}V_d} - 1\right)$
  - k – Boltzmann's konstant $(1.381 \cdot 10^{-23}\,\mathrm{J/K})$
  - q – Elementary charge $(1.602 \cdot 10^{-19}\,\mathrm{C})$
  - I_0 – Reverse saturation current $(\sim 10^{-12}\ \mathrm{A}/cm^2)$
  - 25°C conditions, $\dfrac{k}{qT} = 38.9 = \dfrac{1}{25.7 \cdot 10^{-3}} = \dfrac{1}{V_T}$

I_d

p

n

V_d

I_d

+

V_d

−

I_d

I_0

V_d

$I_d = I_0\,(e^{38.9 V_d} - 1)$

V_d Only weakly dependent on the current about 0.6-0.7 V
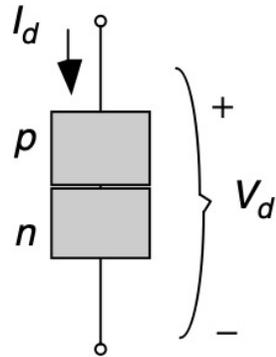
(a) p–n junction diode

(b) Symbol for real diode

(c) Diode characteristic curve
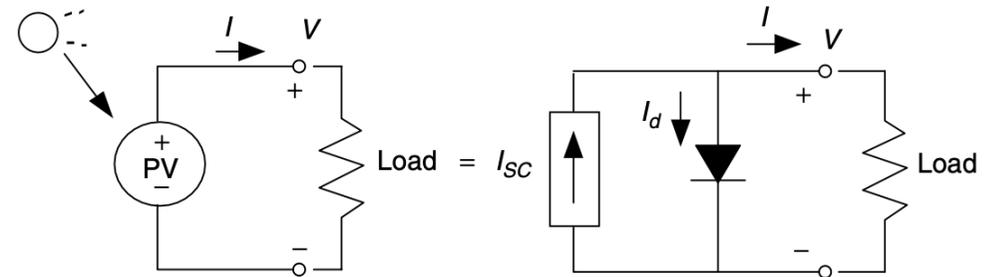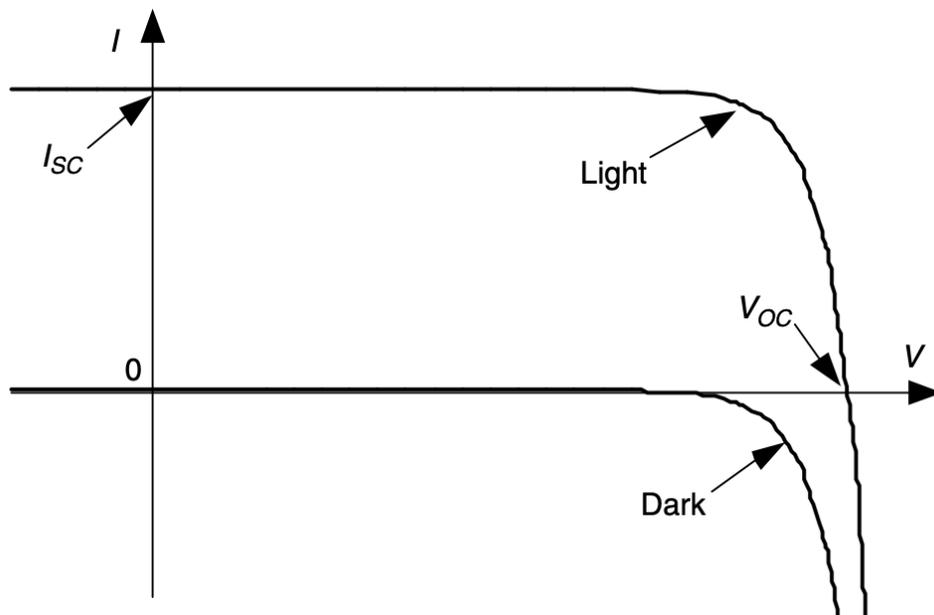
Flip the curve the diode "steals" current $-I_d$

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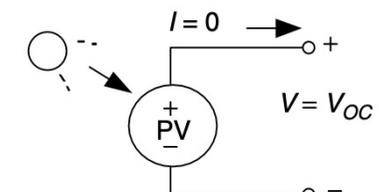
Step 2a: Current source + Diode equation

Current I_{SC} is determined by irradiation and the diode steals current

$$I = I_{SC} - I_d$$

$$I = I_{SC} - I_0 \left(e^{\frac{k}{qT} V_d} - 1 \right)$$
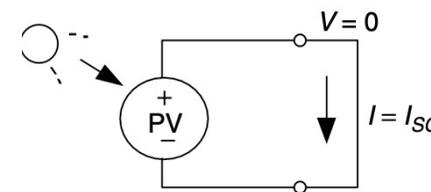
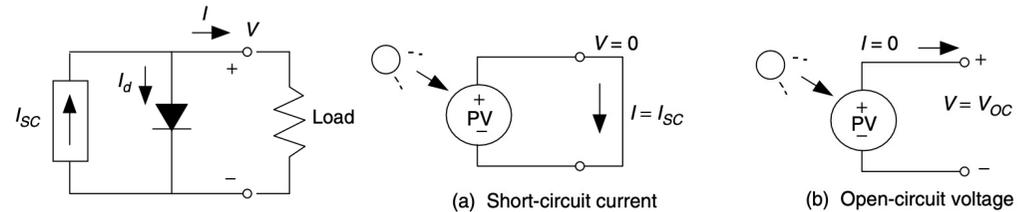(a) Short-circuit current

(b) Open-circuit voltage

No Power delivery at the extreme points.
-Vill veta vad vi får ut mellan extremerna

Step 2b: Current source + Diode equation

Current I_{SC} is determined by irradiation

$$I = I_{SC} - I_d$$
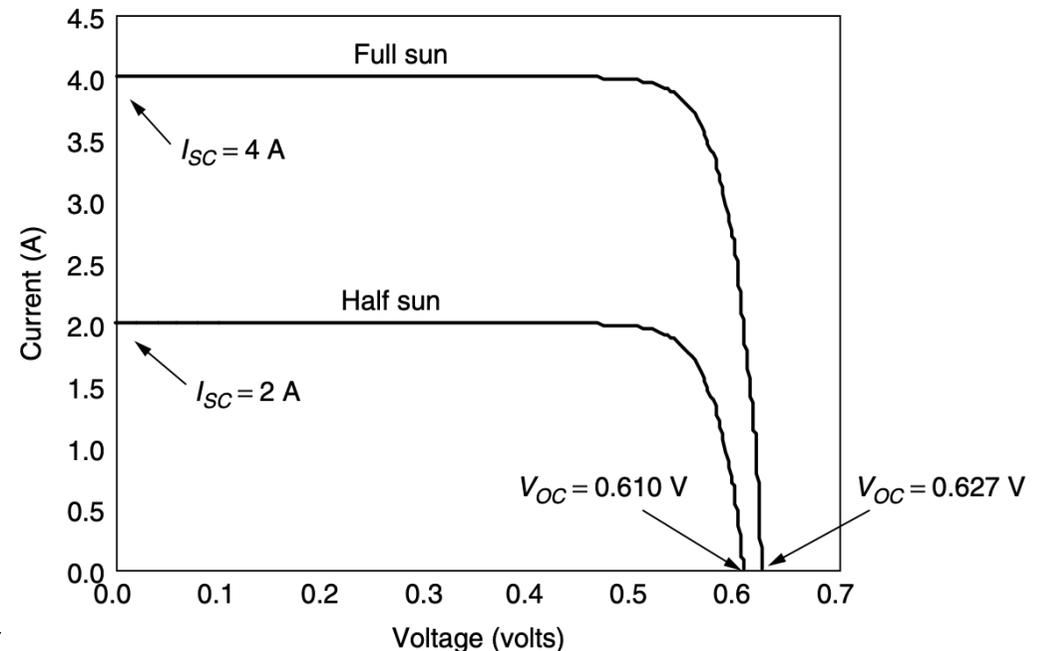
$$I = I_{SC} - I_0 \left(e^{\frac{k}{qT} V_d} - 1 \right)$$

(a) Short-circuit current

(b) Open-circuit voltage

Solve for $V_{OC}, I = 0$

$$V_{OC} = \frac{kT}{q} \ln \left(\frac{I_{SC}}{I_0} + 1 \right)$$

at 25° we get

$$I = I_{SC} - I_0 (e^{38.9\, V_d} - 1)$$

$$V_{OC} = 0.0257 \ln \left(\frac{I_{SC}}{I_0} + 1 \right)$$

Step 3: More complete cell description

- Need two elements more
  - Shaded cell $I_{SC} = 0$
    - Diode blocks
    - Current goes through R_P
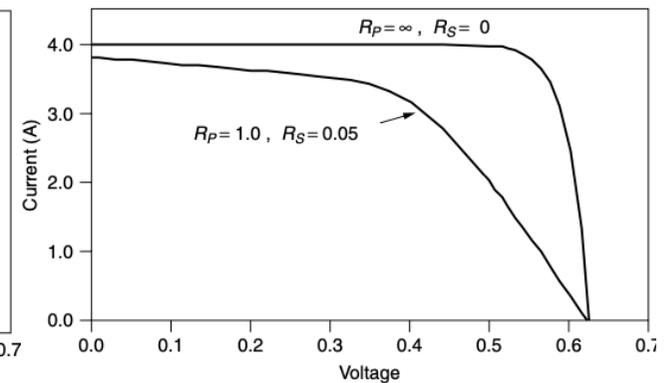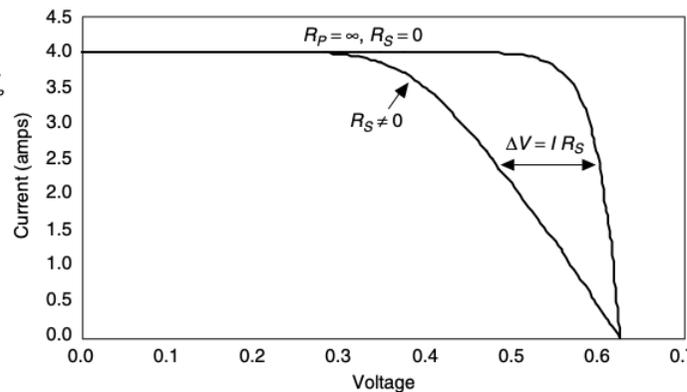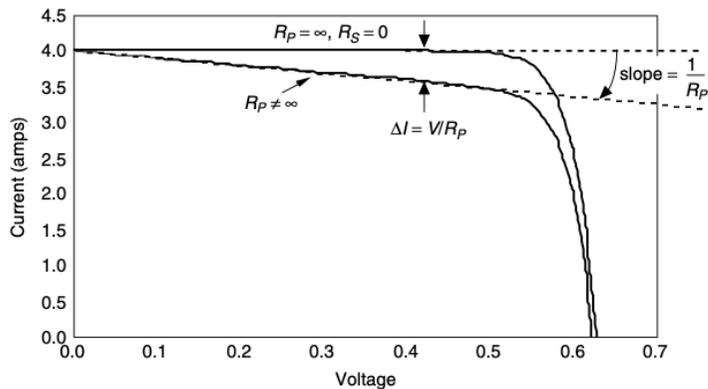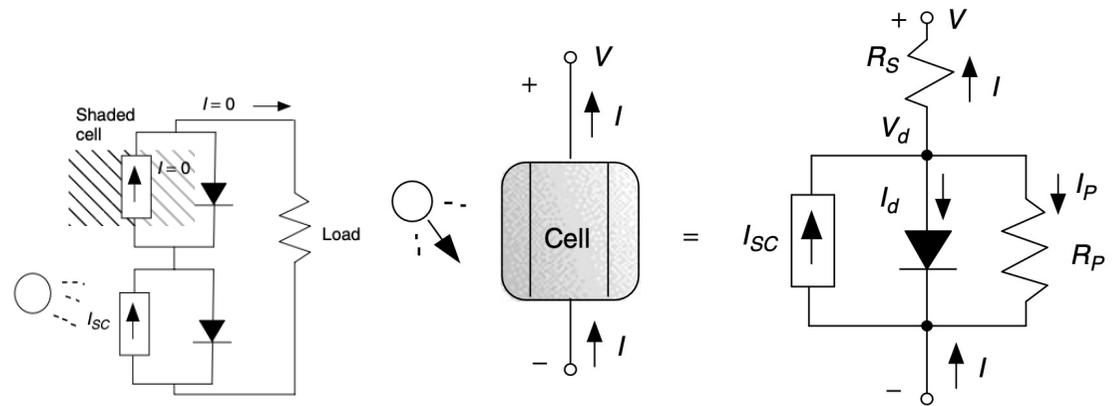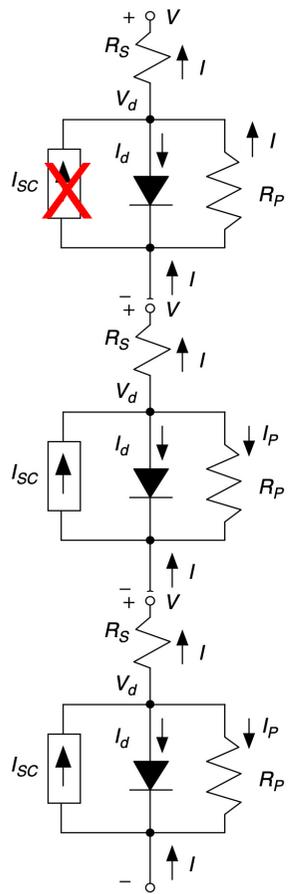 - Resistive series loss R_S

Illustration of the effecta.
More reasonable: $R_p \approx 6$, $R_S \approx 0.005$

An Example of shaded panels, a street light pole

Shading – One shaded cell

- Voltage from one module with a shaded cell
  - n-1 cells are active

- Rewritten to expression in normal voltage V

- Voltage loss in the module

- R_P is much greater than R_S

$$V_{SH} = V_{n-1} - I(R_P + R_S)$$

$$V_{SH} = \left(\frac{n-1}{n}\right) V - I(R_P + R_S)$$
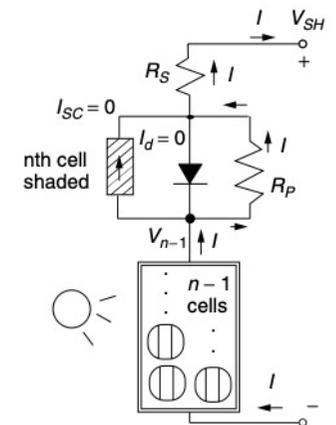
$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I(R_P + R_S)$$
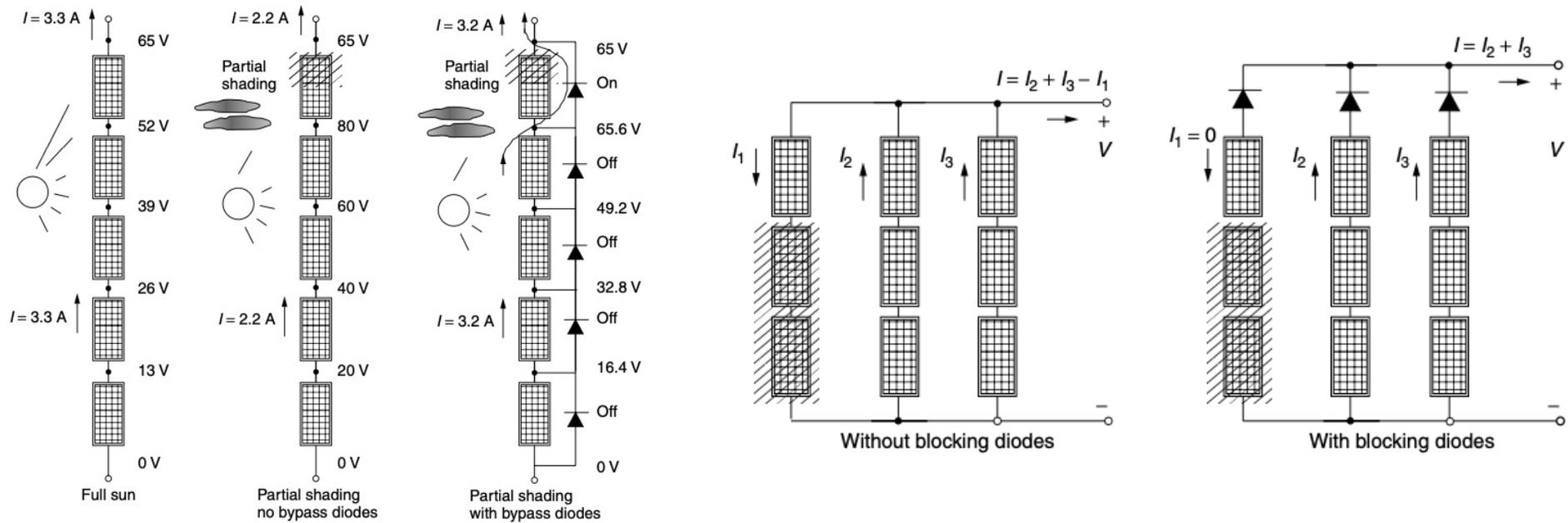
$$\Delta V = \frac{V}{n} + I(R_P + R_S)$$

$$\Delta V \cong \frac{V}{n} + I R_P$$
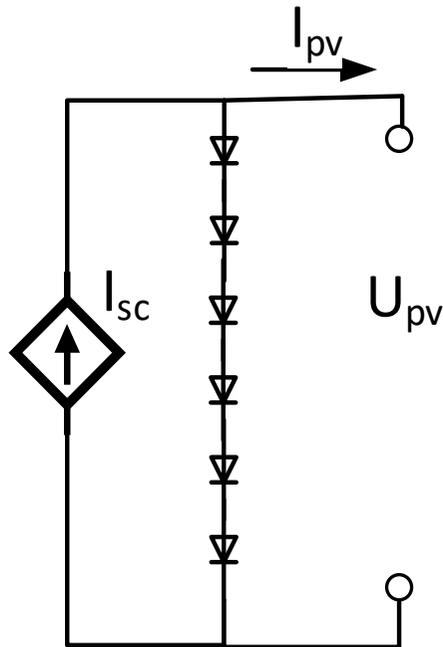
Tool to counteract the shading losses
Bypass diodes

PV-module modelling

PV-module with N cells with equal solar radiation defined by

$$I_{pv} = I_{sc} - I_s \left(e^{\frac{V_{pv}}{N \cdot m \cdot V_T}} - 1 \right)$$

I_{pv}

I_{sc}

U_{pv}

Open circuit conditions: $\begin{cases} I_{pv} = 0 \\ V_{pv} = V_{oc} \end{cases}$

I_s: a diode parameter, typically μA, can be calculated as

$$I_s = \frac{I_{sc}}{e^{\frac{V_{oc}}{N \cdot m \cdot V_T}} - 1}$$
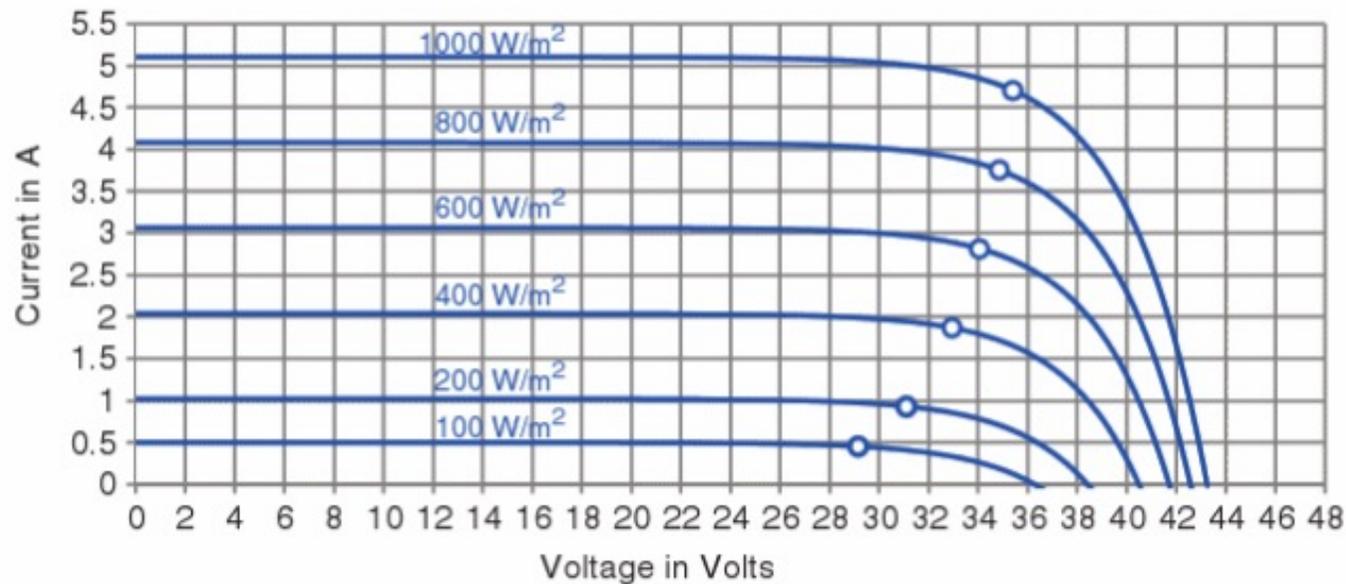
IV-characteristics vs Irradiance

Figure 6.13 Characteristic curve of the SW-165 module at various irradiances and constant module temperature of 25 °C (Spectrum: AM 1.5)

Solar World SW-165 W,
1.6x0.8 m, Monocrystalline, 72 cells
V_{mp} = 35.3 V, I_{mp} = 4.68 A,
V_{oc} = 43.2 V, I_{sc} = 5.1 A

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Paralleling PV-cells

$$V = V_1 = V_2 = V_3$$

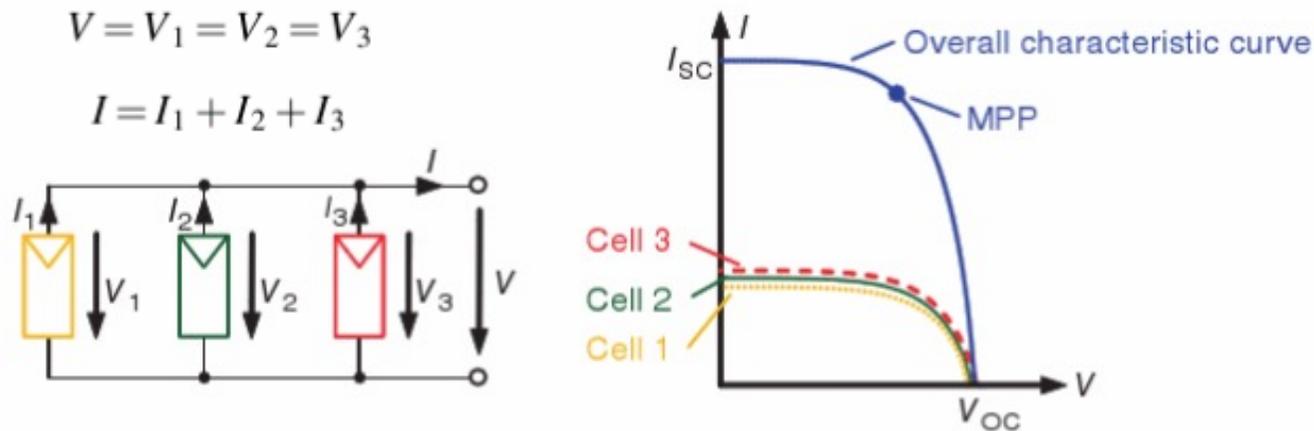$$I = I_1 + I_2 + I_3$$

Figure 6.2 Parallel connection of solar cells: The voltage is the same in all cells while the currents add up
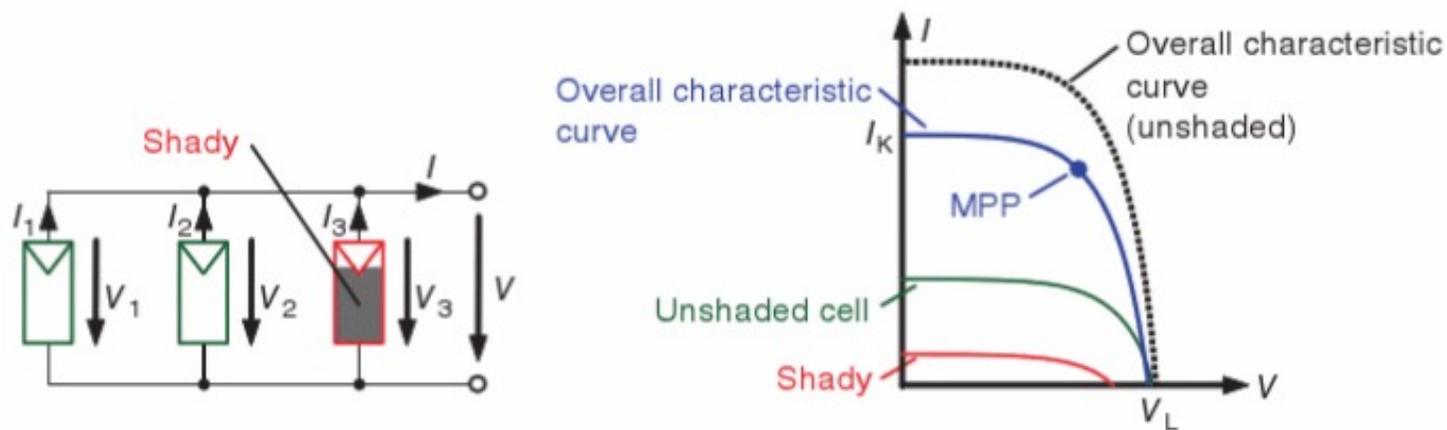

Figure 6.3 Shading one of the three cells: The current of the overall characteristic curve decays by the same amount as the current of Shady
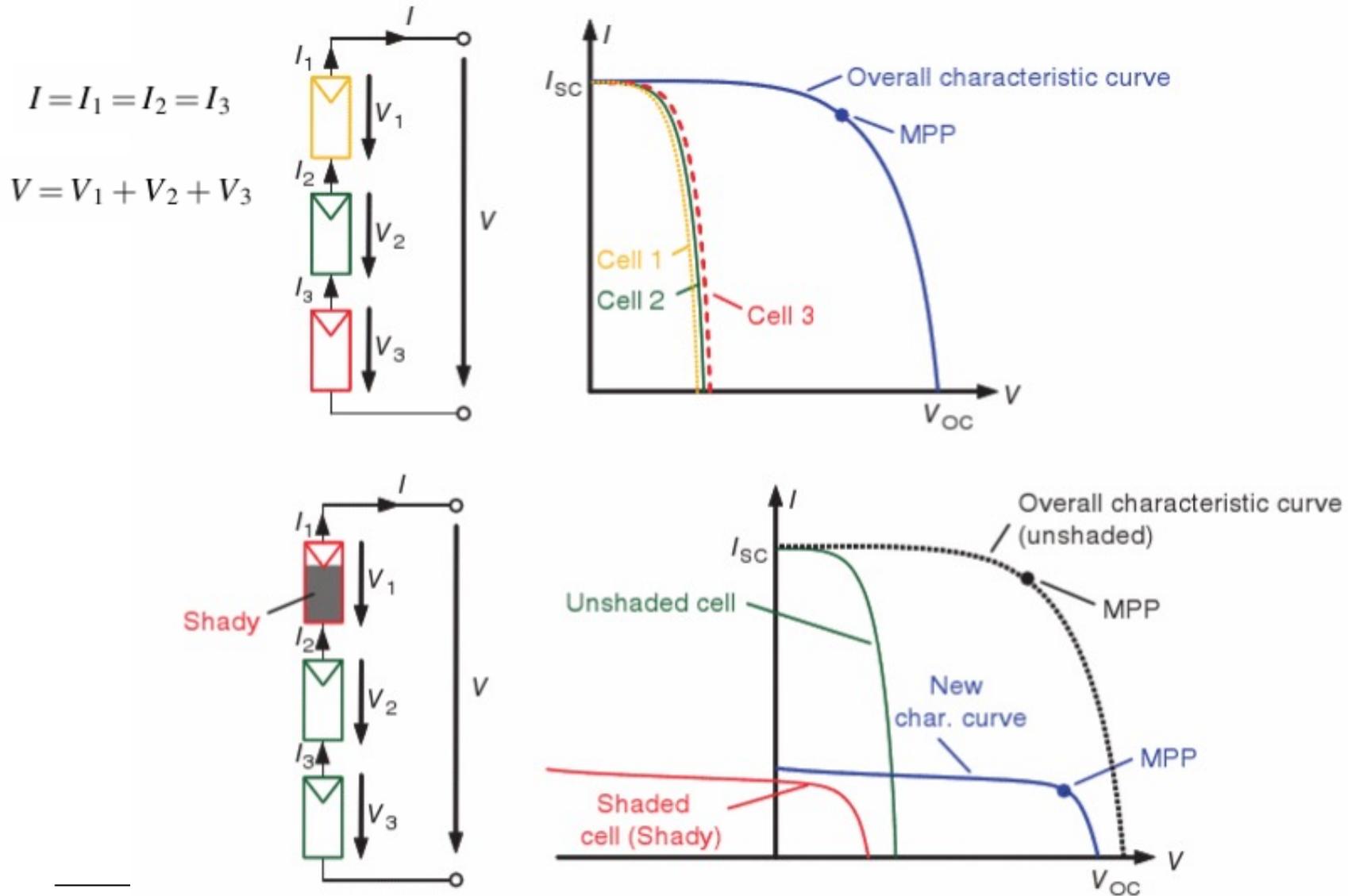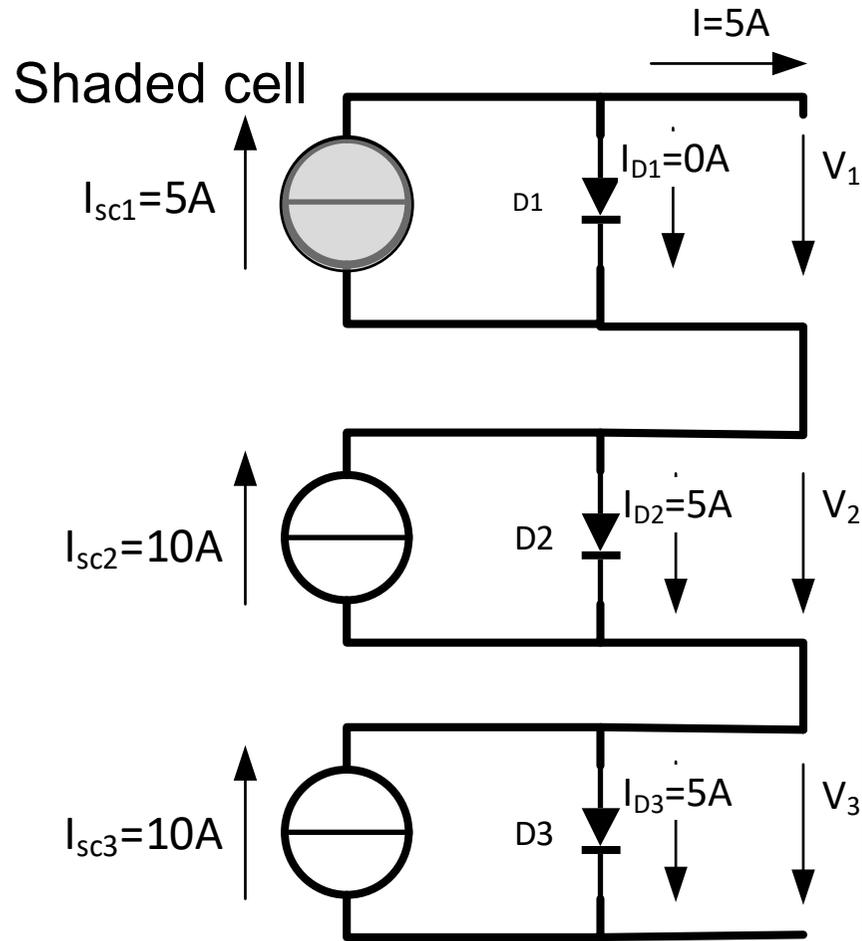
Series connection

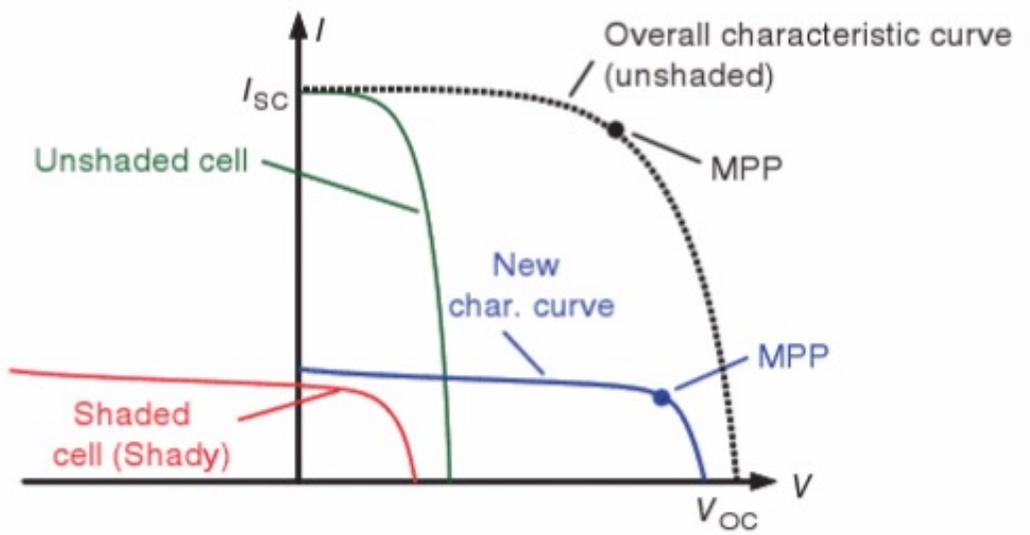$$I = I_1 = I_2 = I_3$$

$$V = V_1 + V_2 + V_3$$

Figure 6.5 Partial shading of a cell with series connection: As Shady acts as the bottleneck, the overall current sinks strongly

Series connection. Shading

Shaded cell

$I = 5A$

$I_{sc1} = 5A$

$I_{D1} = 0A$ V_1

D1

$I_{sc2} = 10A$

$I_{D2} = 5A$ V_2

D2

$I_{sc3} = 10A$

$I_{D3} = 5A$ V_3

D3

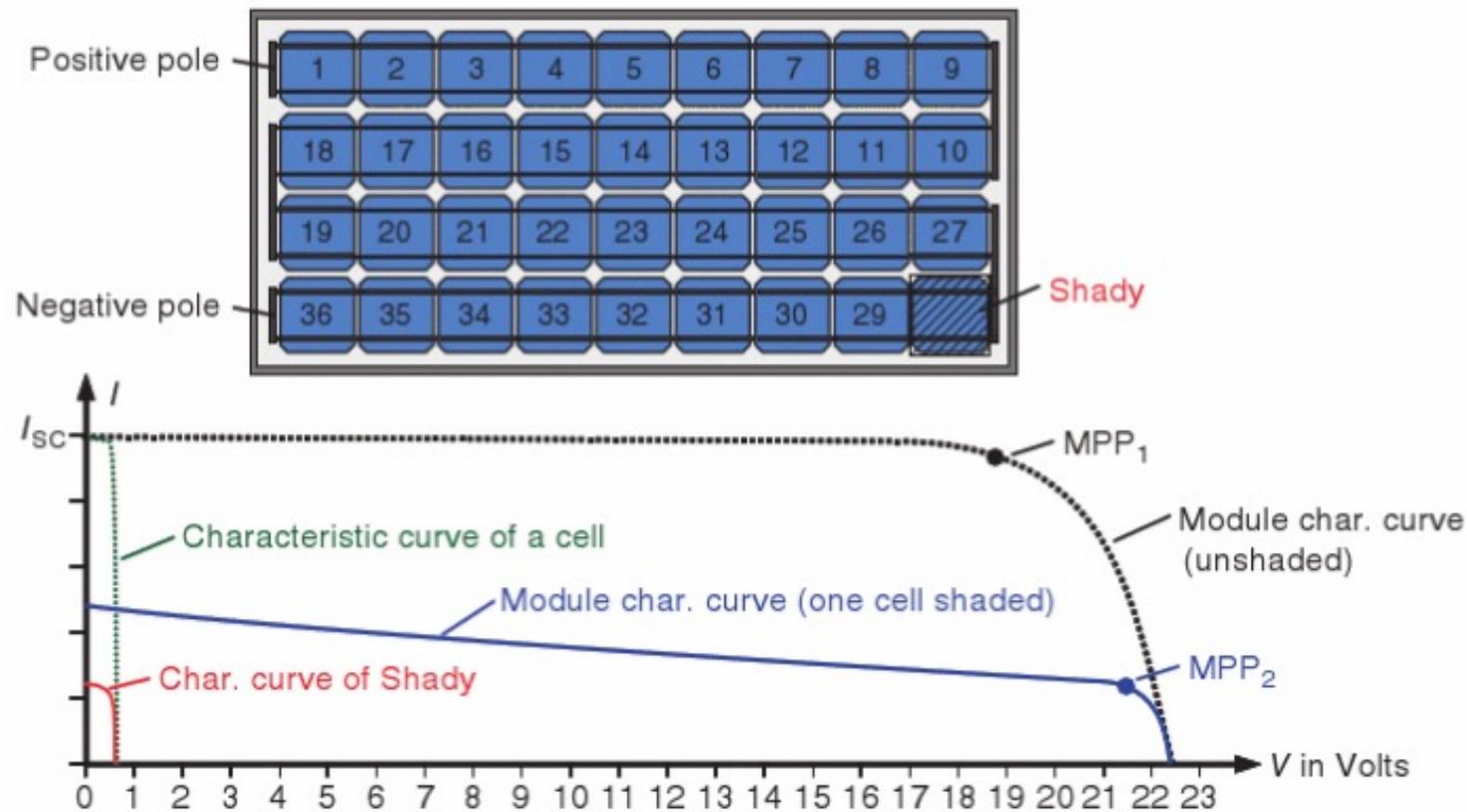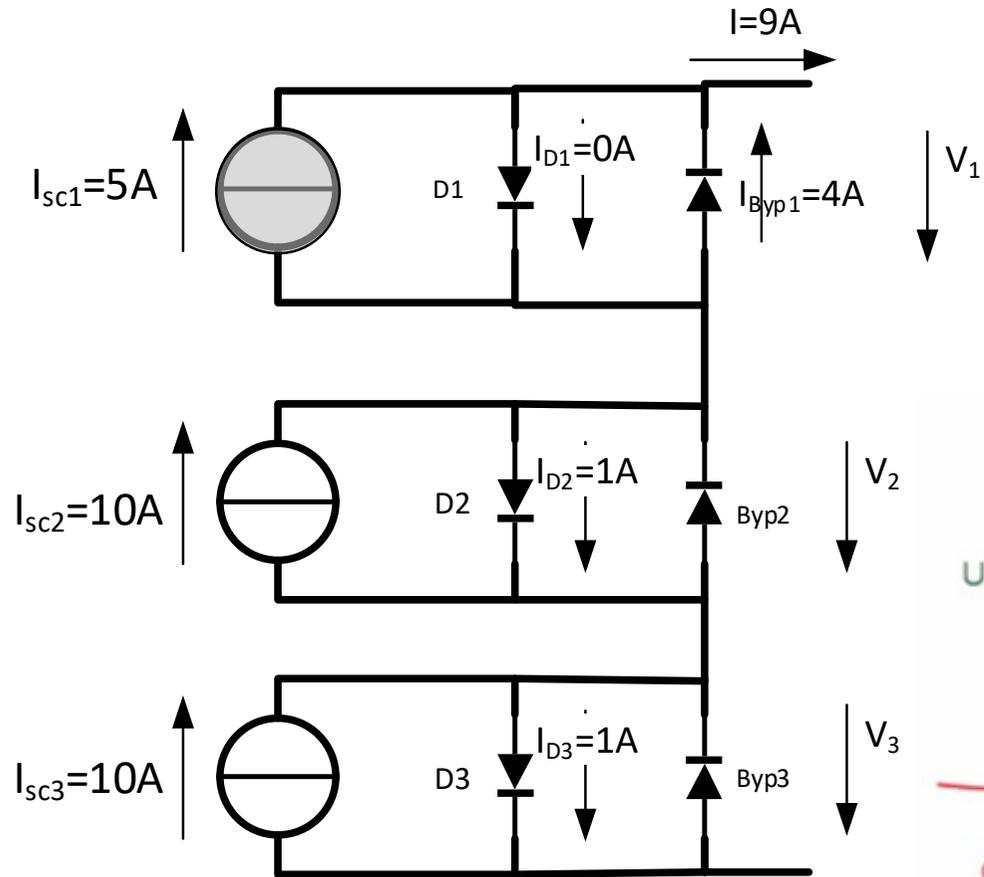The shaded cell
is limiting current

Solar module shading

Figure 6.6 Solar module with 36 cells: The module power sinks drastically in the case of shading of a single cell

The bypass diode

$I = 9A$

$I_{sc1} = 5A$
D1
$I_{D1} = 0A$
$I_{Byp1} = 4A$
V_1

$I_{sc2} = 10A$
D2
$I_{D2} = 1A$
Byp2
V_2

$I_{sc3} = 10A$
D3
$I_{D3} = 1A$
Byp3
V_3

Bypass diode of shaded cell carries the current deficit

Overall characteristic curve (unshaded)

I_{SC}

Unshaded cell

MPP

New char. curve

MPP

Shaded cell (Shady)

V_{OC}
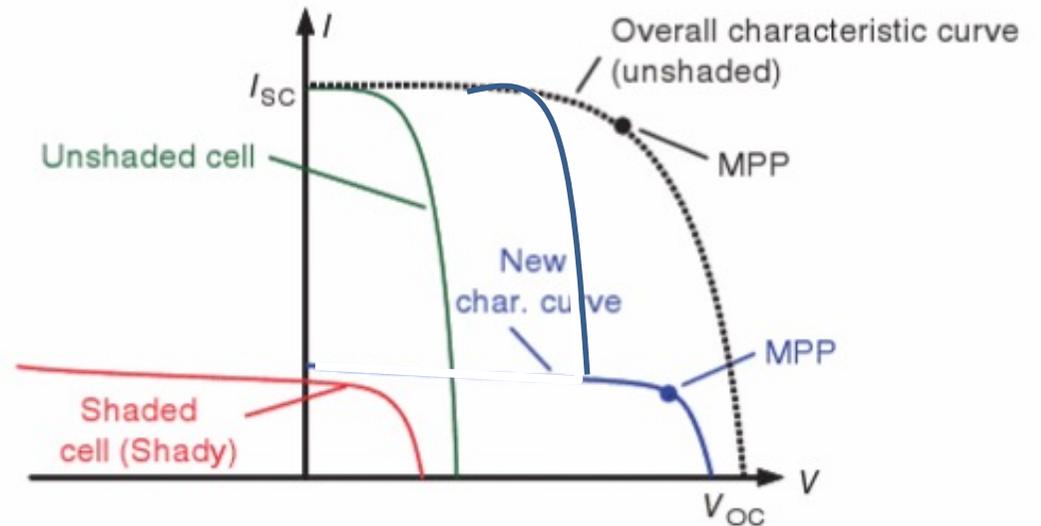
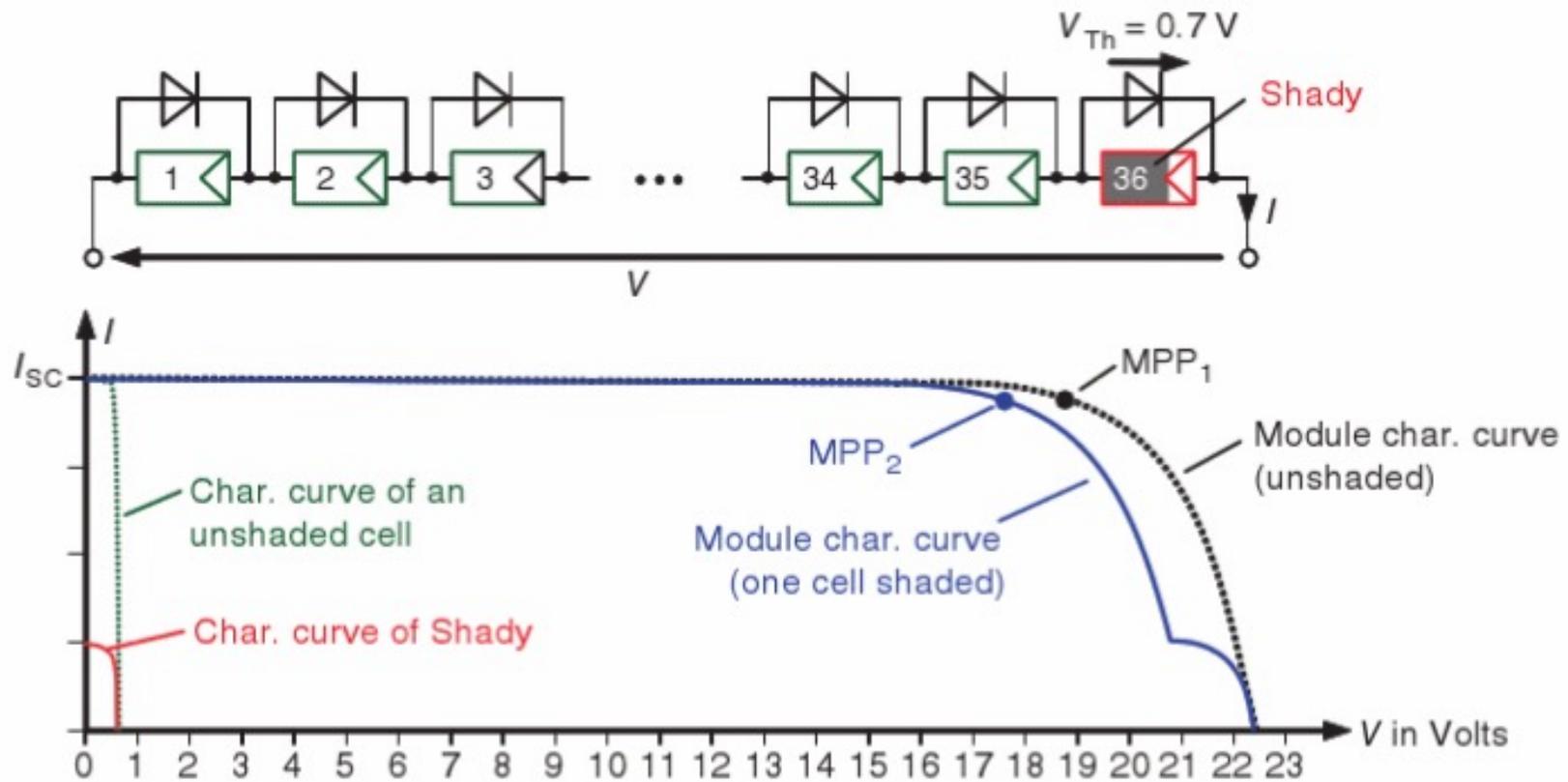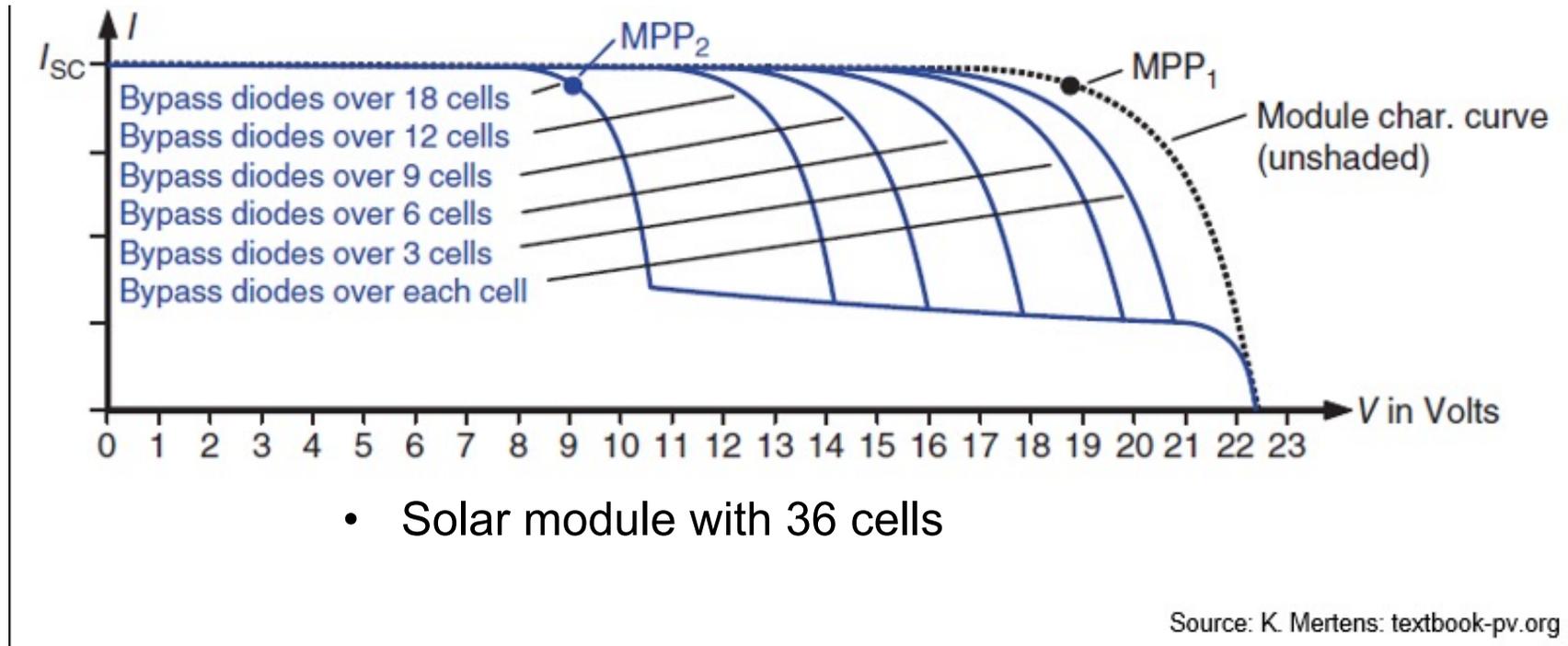# Bypass diodes, ideal case

Figure 6.7 Solar module with 36 cells and bypass diode over each cell: The power loss is a minimum in the case of shading of any cell

Practical case of bypass diodes

- Solar module with 36 cells

Source: K. Mertens: textbook-pv.org
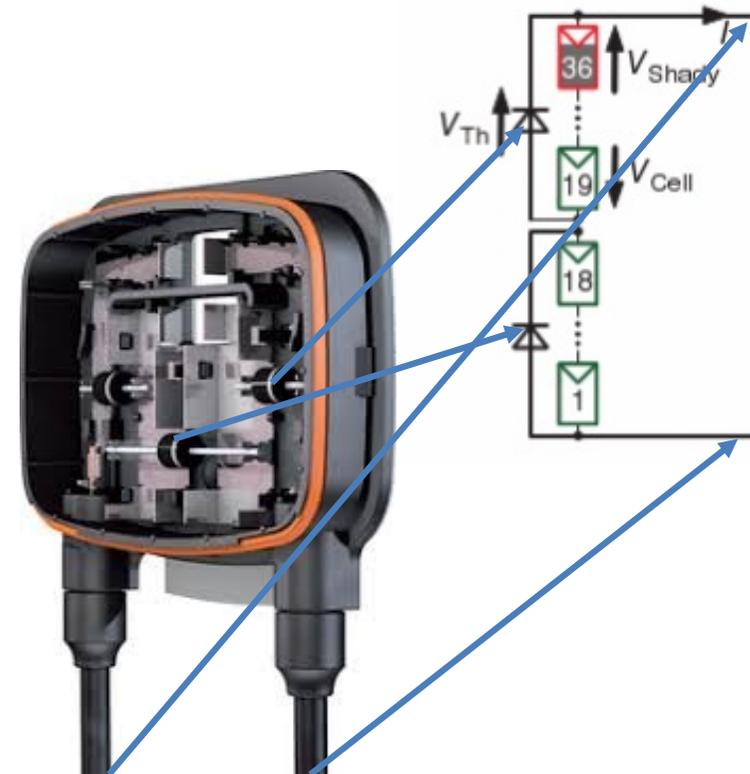
Module design is typically using 1-3 bypass diodes
- Voltage loss from bypass diodes of shaded cells
- Not practical to accommodate many diodes in a module housing.

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The junction box

Back side of the module
External connections
Bypass diodes

V_{Th} V_{Shady} V_{Cell}
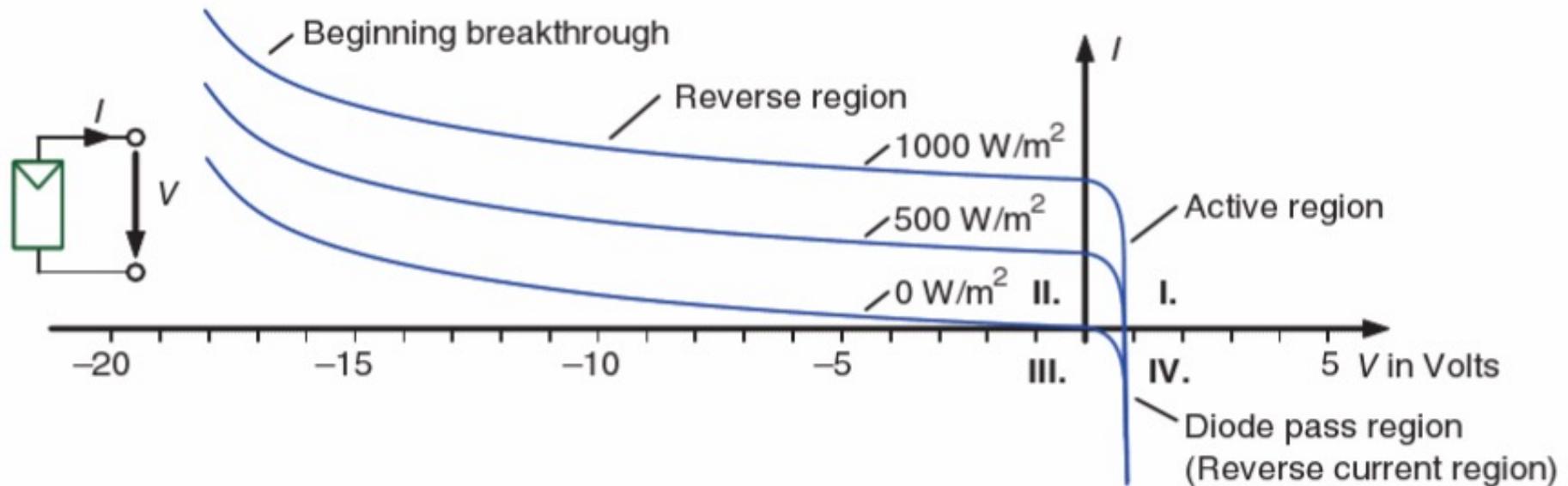
PV-cell characteristics

Figure 6.1 Solar cell characteristic curves in all quadrants in the generator reference-arrow system

Beginning breakthrough at high negative voltages

Critical hot spot

Module with 36 cells, shaded cell without bypass diode

- Loaded by **reverse voltage** from other 35 cells
- Beginning break-through at high reverse voltage
- Risk of overheating
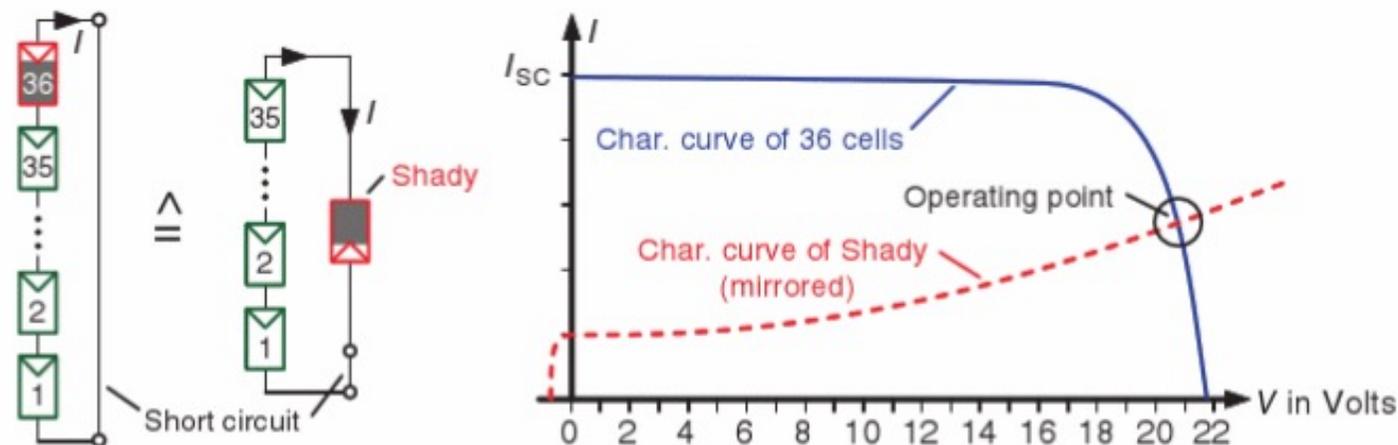- Worse case under short circuit

Figure 6.9 Solar module with 36 cells without bypass diodes: Shady acts as a load that is massively heated by the remaining 35 cells

Hot spots reduced with bypass diode

Bypass diode across 18 cells groups
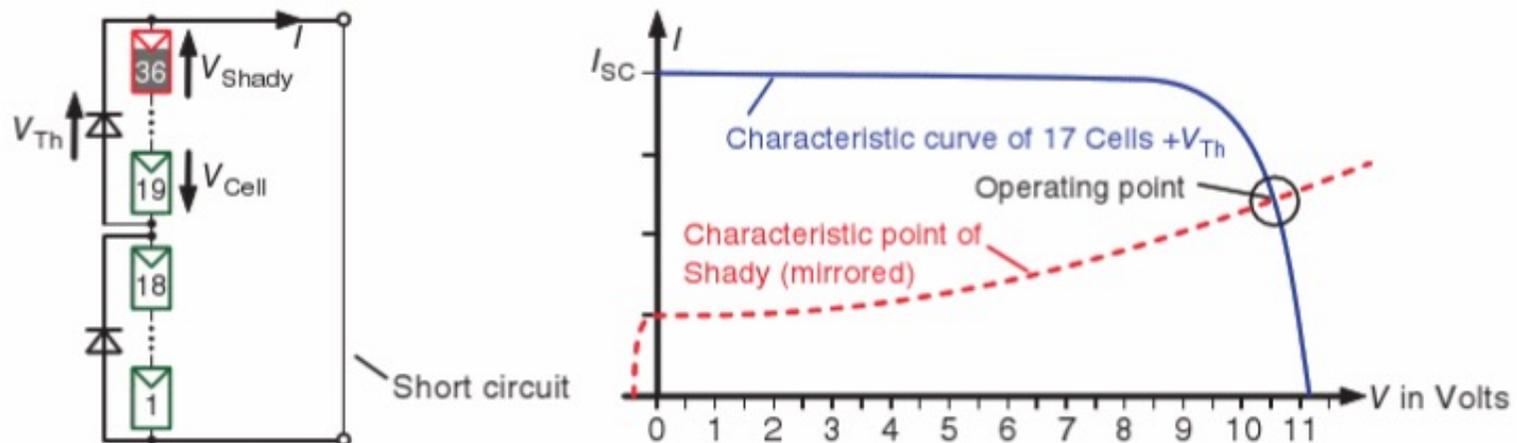Hot spot in shaded cell reduced to 50%

Figure 6.10 Solar module with 36 cells and two bypass diodes: The voltage at Shady clearly sinks compared with Figure 6.9 so that the heating is reduced

$$V_{Shady} = (z-1) \cdot V_{Cell} + V_{Th}$$

Where z is the number of cells under a bypass diode.

Configuration summary

- **Paralleling** principally better to combine many cells (current sources) since current is added. Very low cell voltage (0.6V) gives high current, and **high cabling losses** when paralleling
- **Series connection** efficient to achieve high voltage at low current. **The predominant solution**!
- Shading becomes a **bottleneck** for current reducing output power of also unshaded cells.
- Shaded cells, can be overloaded by unshaded cells. **Hotspot**.
- **Bypass diodes** used to mitigate consequences of shading for series connection.
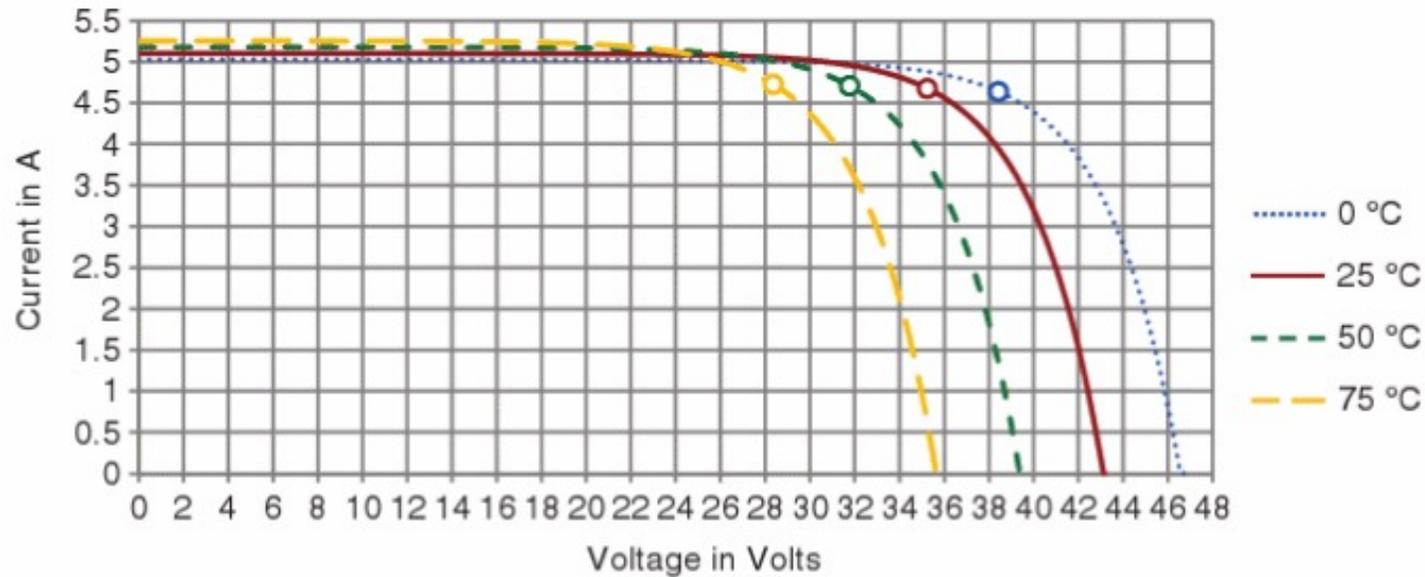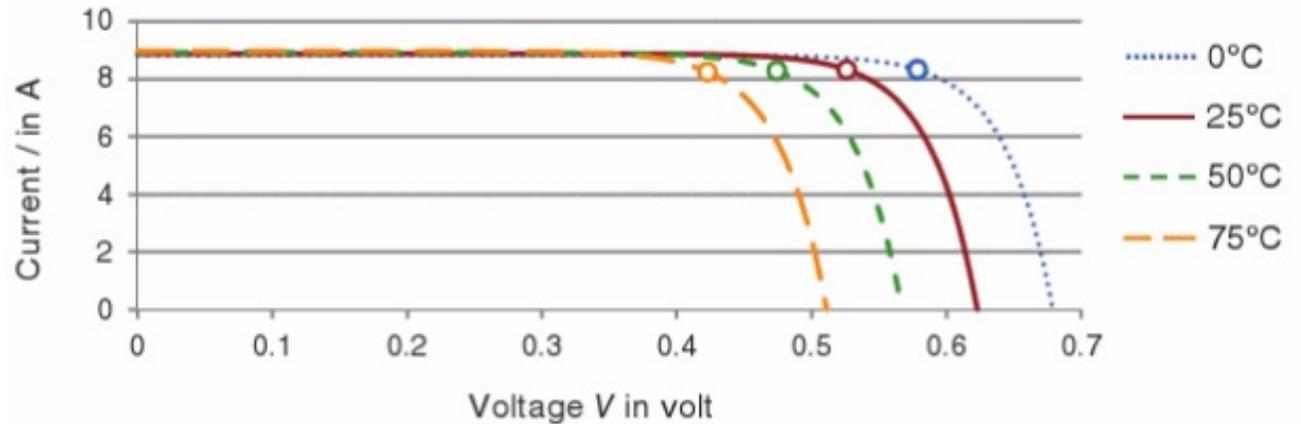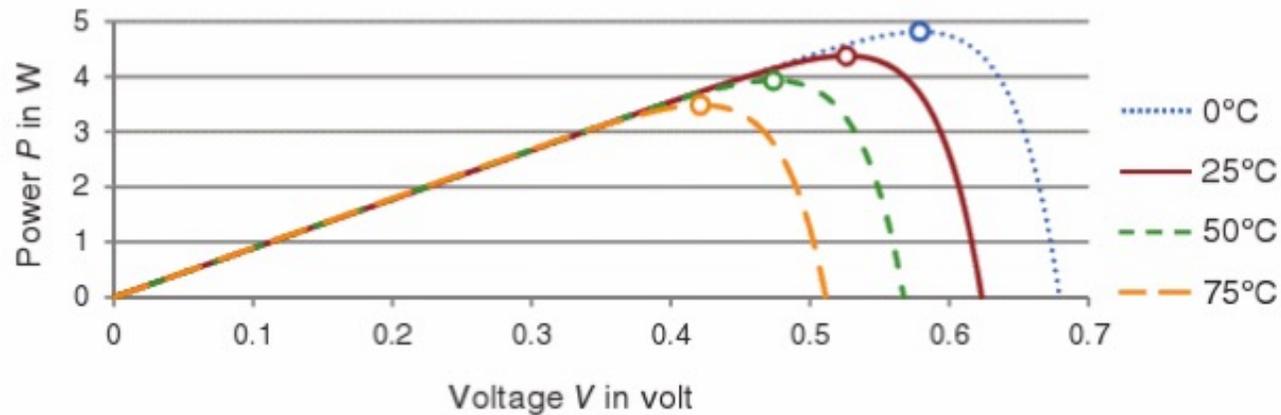
Temperature dependency

Figure 6.14 Characteristic curve of the SW-165 module from Solarworld at various module temperatures (Irradiance: 1000 W/m^2, spectrum: AM 1.5)

Temperature dependency

$$\frac{\Delta V_{OC}}{\Delta \vartheta} = -2.3\,\text{mV/K}$$

$$TC(P_{MPP}) = \frac{\Delta P_{MPP}}{\Delta \vartheta \cdot P_{MPP}} =$$
$$= -0.4 \ldots 0.5\,\%/K$$

Monocrystalline 156x156mm Bosch solar cell M 3BB

Typical Si-Solar cell

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Cell operating temperature

Nominal Operating Cell Temperature, NOCT

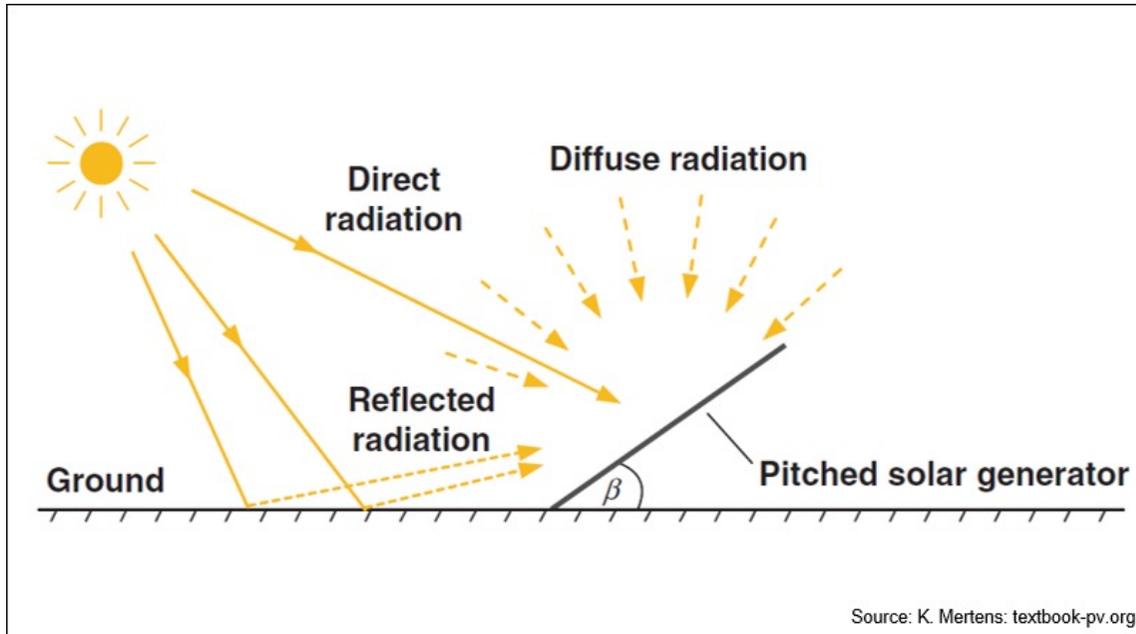$$\boldsymbol{NOCT = \vartheta_{cell} \ @ \ E = 800 \ ^W/_{m^2} \, , \vartheta_A = 20°C}$$

- Irradiance: $E = E_{NOCT} = 800 \ ^W/_{m^2}$
- Ambient temperature: $\vartheta_A = 20°C$
- Wind speed: $1 \ ^m/_s$

$$\vartheta_{cell} = \vartheta_A + (NOCT - 20)\frac{E}{E_{NOCT}}$$

$$\frac{\vartheta_{cell} - \vartheta_A}{NOCT - 20} = \frac{E}{E_{NOCT}}$$

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Standard Test Conditions (STC)

Source: K. Mertens: textbook-pv.org

$$E_{\mathrm{G}} = E_{\mathrm{Direct}} + E_{\mathrm{Diffuse}}$$

- $E_G = E_{STC} = E_{Direct}(AM1.5) + E_{Diffuse} = 1000\,^W/_{m^2}$
- $Module\ temp, \vartheta_{cell} = 25°C$
- $AM = 1.5$

PV module

320 W at STC
1.6 m^2
5kW = 15.6 modules
Total 25 m^2

Elektriska egenskaper(STC 1000W/m², 25°C, AM1.5)

Modell	PPAM-Onyxium
Max. Effekt [Pmax]	320 Wp
Öppenkretsspänning [Voc]	40,67 V
Spänning vid maxeffekt [Vmpp]	32,25 V
Kortslutningsström [Isc]	10,49 A
Ström vid maxeffekt [Impp]	9,92 A
Modulens effekttolerans	0/+3%
Verkningsgrad panel modul	19,76%

Fysiska egenskaper

Celltyp	Monokristalin
Celldimensioner	156x156mm
Celler/Dioder per modul	60
Ram	Anodiserad Aluminum
Max spänning system	1000 V
Modulvikt	19,5 kg
Moduldimensioner	1640 x 990 x 40mm
Testade vädertemperaturer	-40°C to +85°C
Max belastning	550 kg/m² framsida(snö) 245 kg/m² bak & framsida (vind)

Termiska egenskaper

NOCT	46 °C
Spänning temperaturkoefficient	-0.24%/K
Temperatur koefficient ström	+0.032%/K
Temperatur koefficient effekt	-0,40%/K
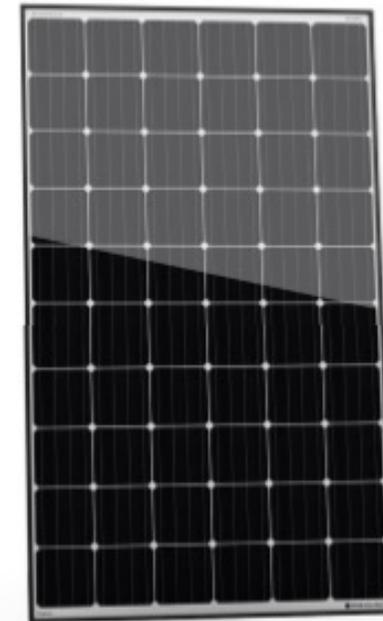
Example 6.1 Actual module power on a summer's day

The 200 W *Bosch c-Si M48-200* solar module has a NOCT temperature of 48.6 °C. What module power can be expected on a nice summer's day ($E = 1000$ W/m², $\vartheta_A = 30$ °C)? The actual cell temperature is:

$$\vartheta_{cell} = \vartheta_A + (NOCT - 20)\frac{E}{E_{NOCT}} = 30 + (48{,}6 - 20)\frac{1000}{800} = 65{,}75°C$$

With the temperature coefficient $TC(P_{MPP})$ we obtain as actual power: $TC(P_{MPP}) = -0.47 \%/K$

$$P = P_{STC} \cdot [1 + TC(P_{MPP}) \cdot (\vartheta_{Cell} - 25 °C)] = 200 \text{ W} \cdot (1 - 0.47\%/K \cdot 40.75 \text{ K}) = 161.7 \text{ W}$$

The **200 W module** thus **generates only** a power of **161.7 W**.

Reduced temperature impact
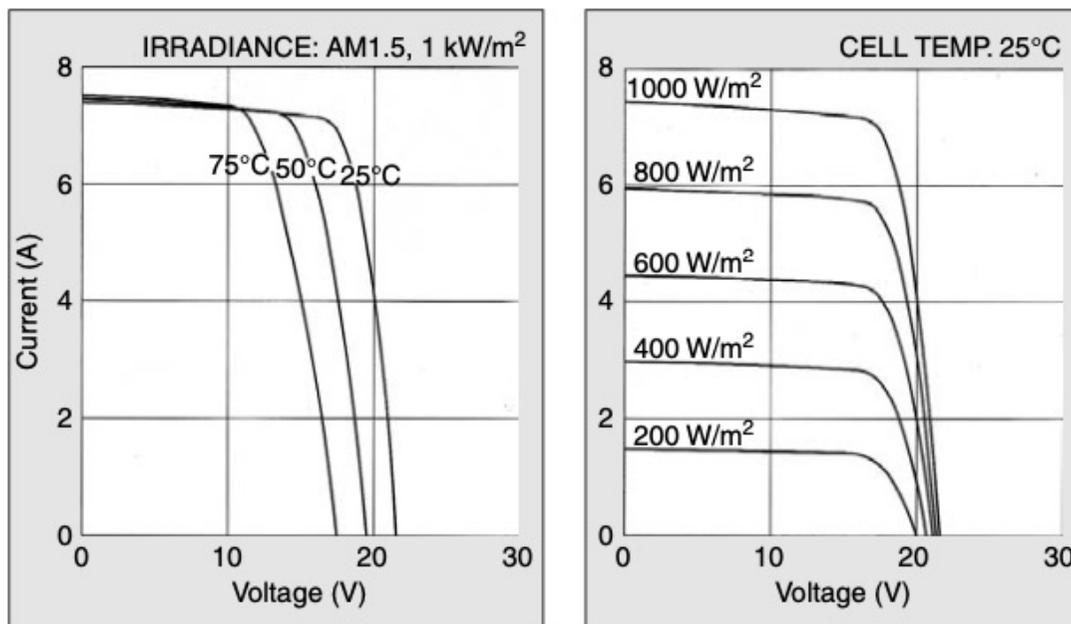
Figure 8.36 Current-voltage characteristic curves under various cell temperatures and irradiance levels for the Kyocera KC120-1 PV module.

- Cooling increases power, efficiency and lifetime.

- Swedish SolHybrid combines
  - Solar cell
  - Solar heating
  - Geothermal heating
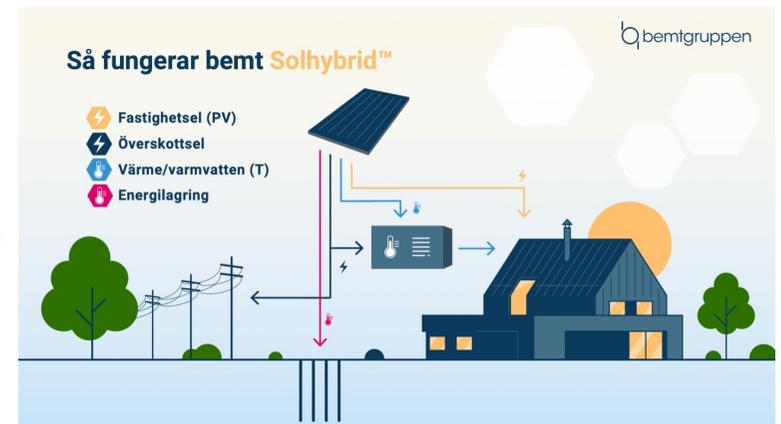
Grid connection

- DC/DC conversion
- Maximum power point tracking
- Grid inverter
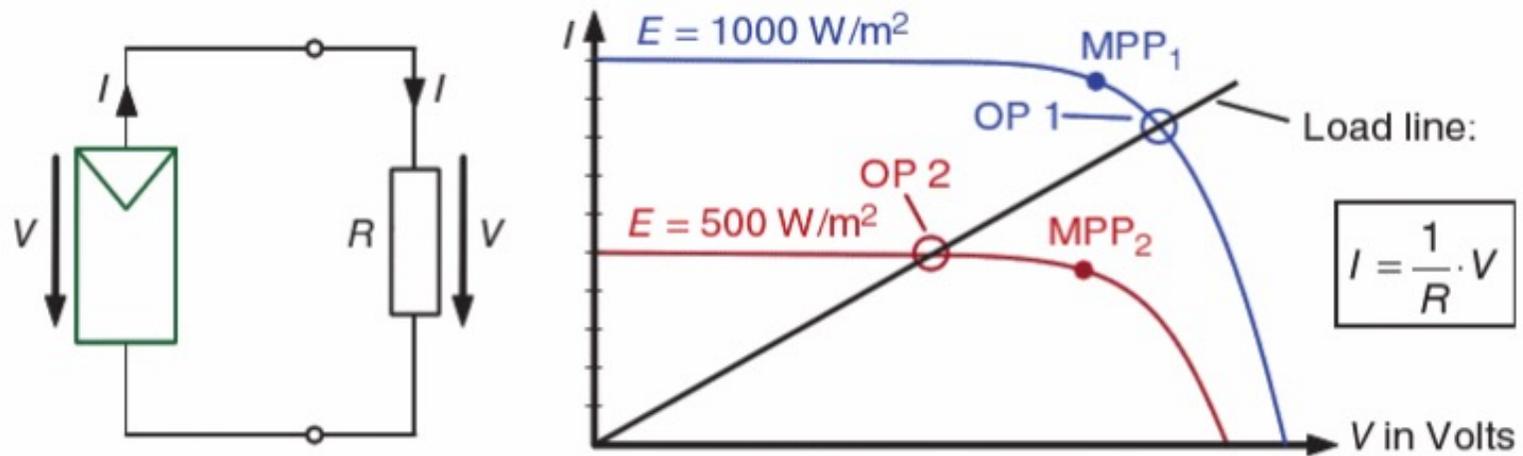
Solar modules and resistive load

Figure 7.1 Operation of an ohmic load at a solar module: In the case of half the Sun's irradiance $(E = 500\,\text{W/m}^2)$, the operating point (OP 2) is far away from MPP$_2$

Solar modules and DC/DC conv
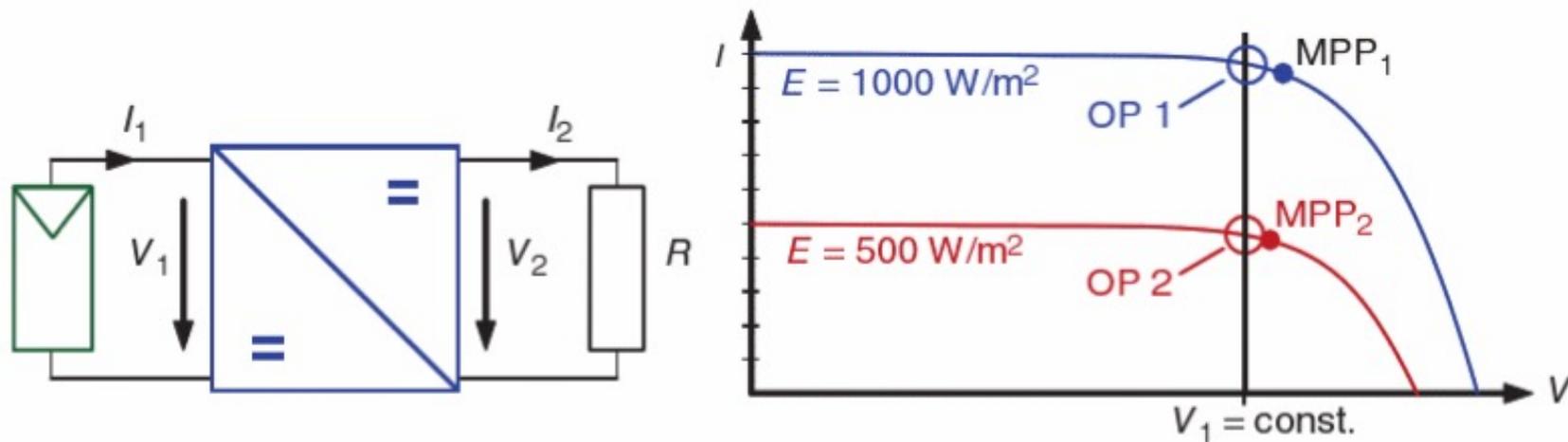
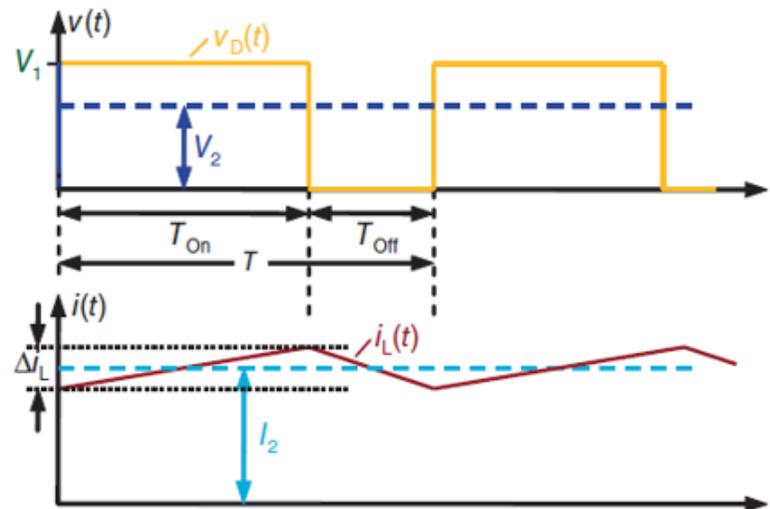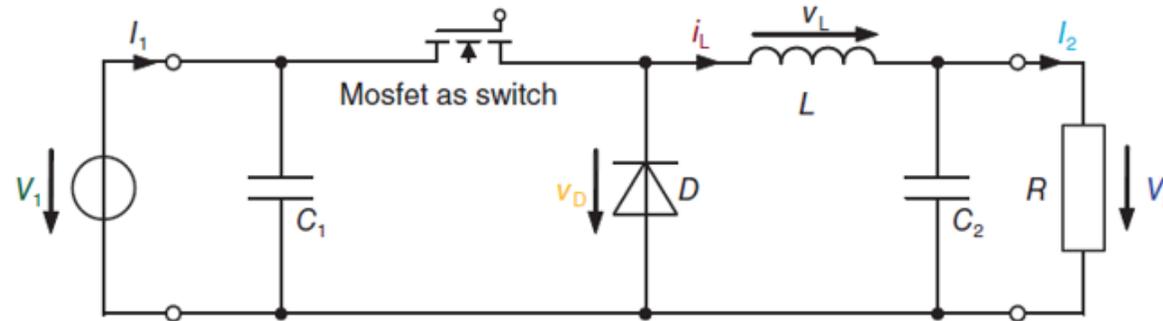**Figure 7.2** Application of a DC/DC converter: The voltage at the solar generator can be selected independently of that at the load; for example, it can be left constant

DC/DC step-down(buck) converter

$$\frac{V_2}{V_1} = \frac{T_{on}}{T} = D, 0 < D(Duty\ cycle) < 1$$

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DC/DC step-down(buck) converter
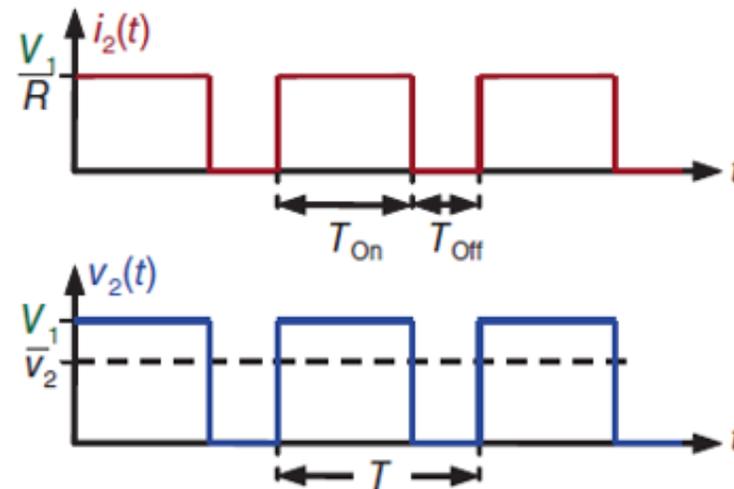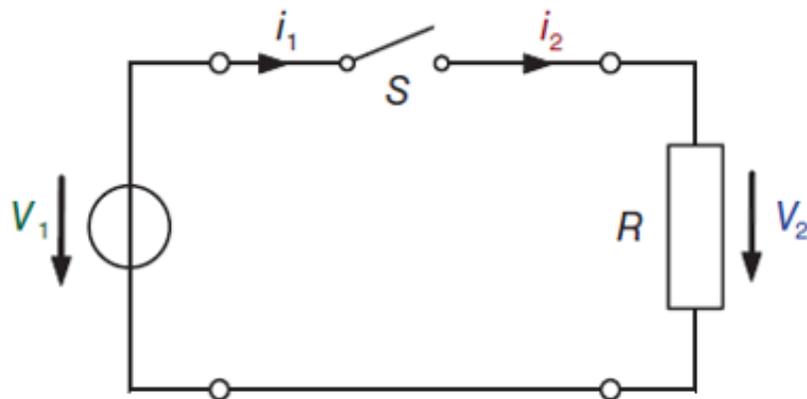
$$\frac{V_2}{V_1} = \frac{T_{on}}{T} = D$$

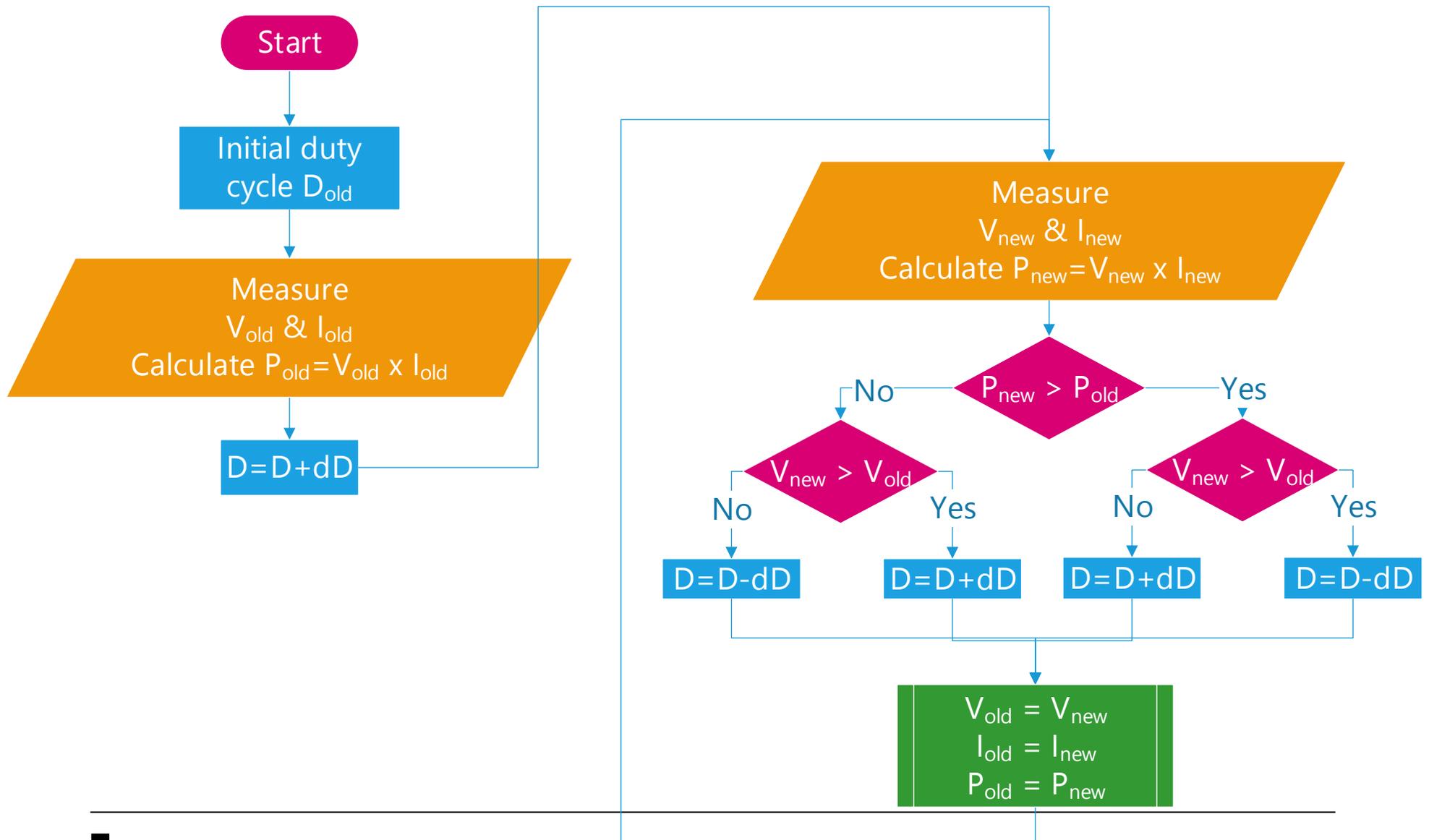Source: K. Mertens: textbook-pv.org

DC/DC step-up(boost) converter

$$\frac{V_2}{V_1} = \frac{T}{T_{off}} = \frac{1}{1-D}$$

Source: K. Mertens: textbook-pv.org

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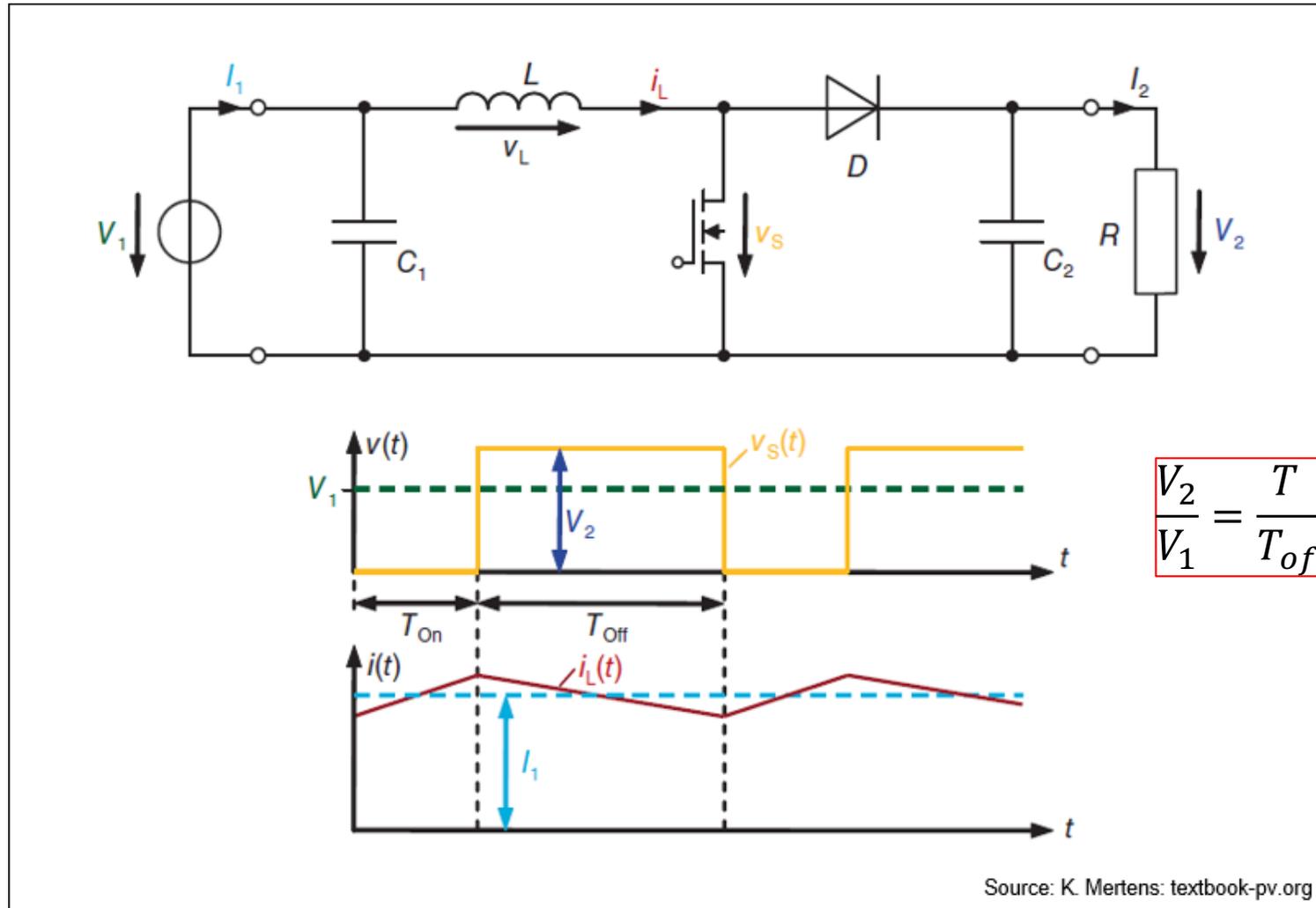
MPPT, Maximum Power Point Tracking

- DC/DC converter to allow different pv- and load voltage
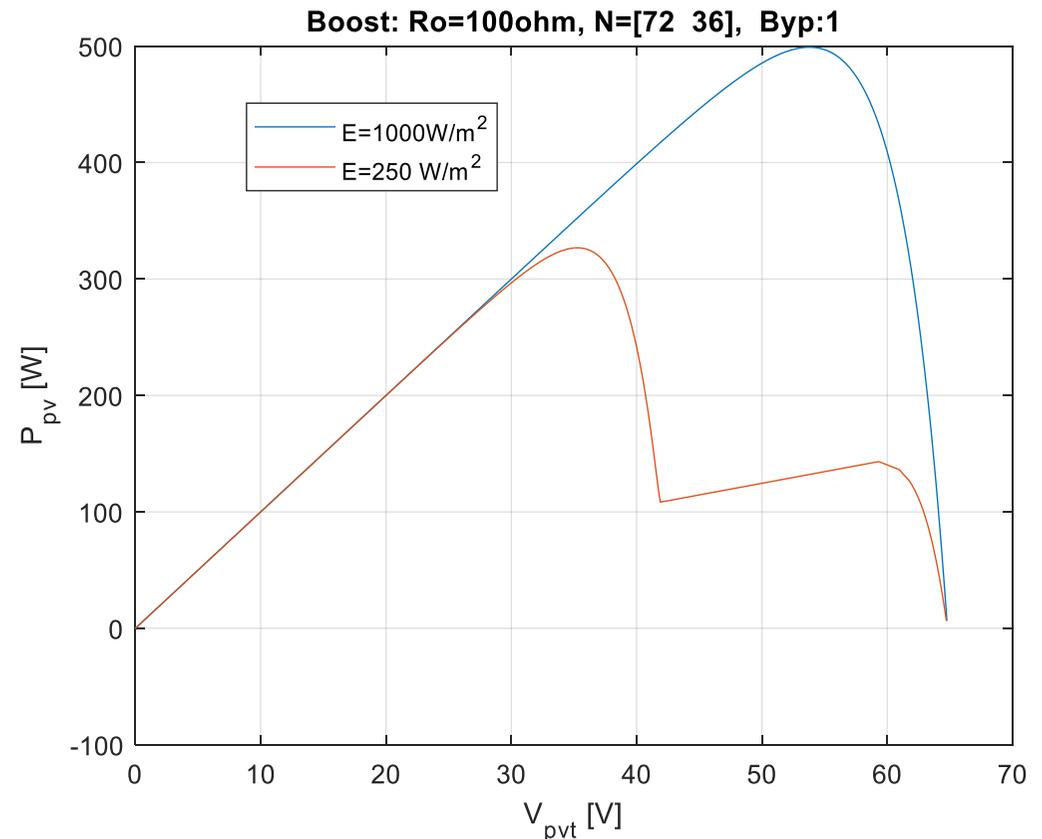- PV-voltage is optimized to reach MPP
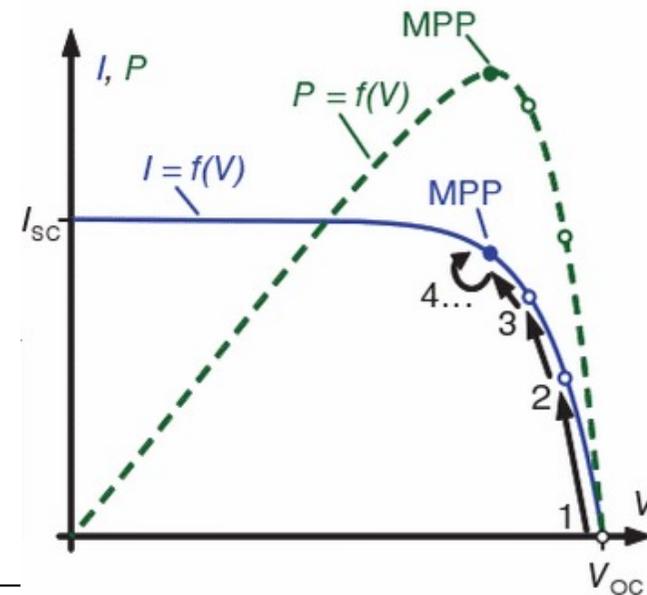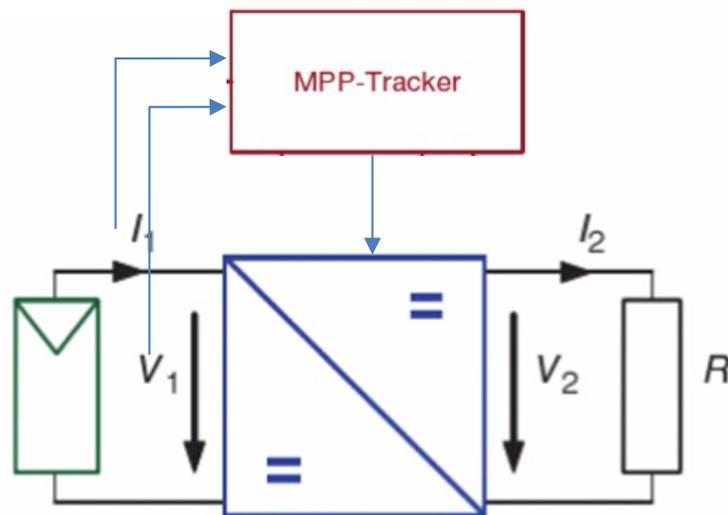
MPPT Perturb & Observe (PandO)

MPPT for partial shading

- Partial shading may give multiple local MPPs
- PandO might not find the MPP
- Global scan over larger range required

Boost: Ro=100ohm, N=[72 36], Byp:1
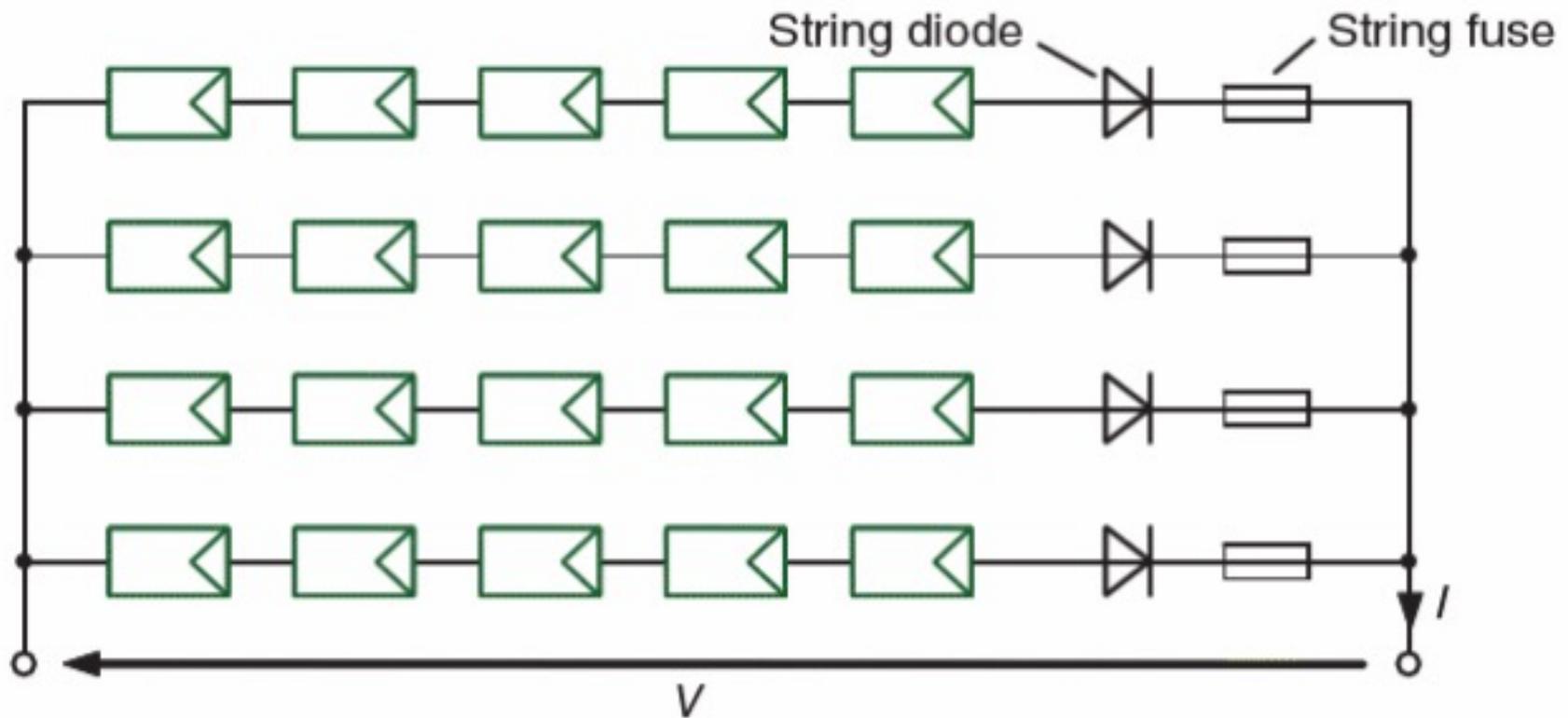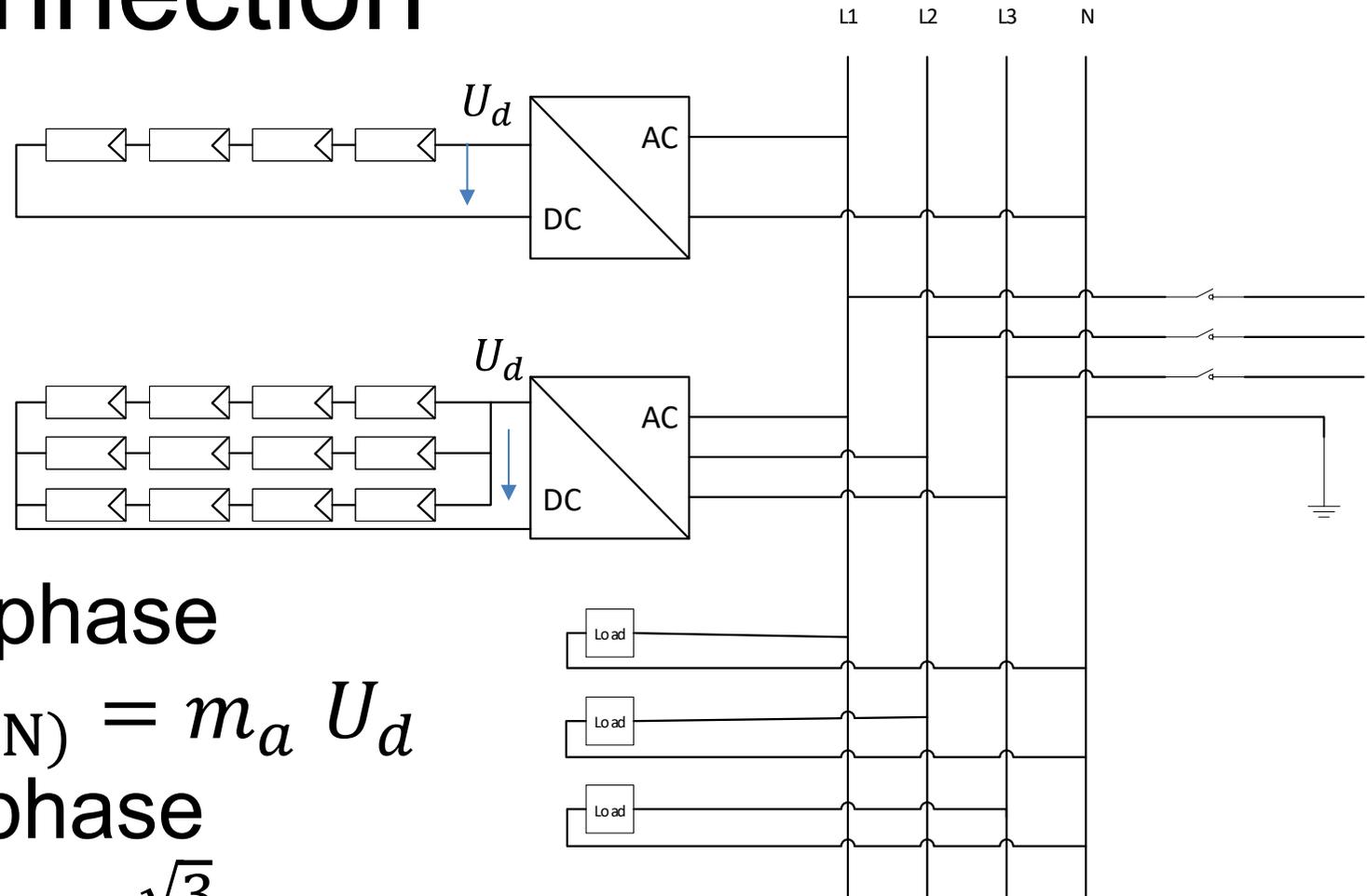
Parallel strings for high power

Figure 6.17 Structure of a solar generator with several strings

Grid connection

- Single phase
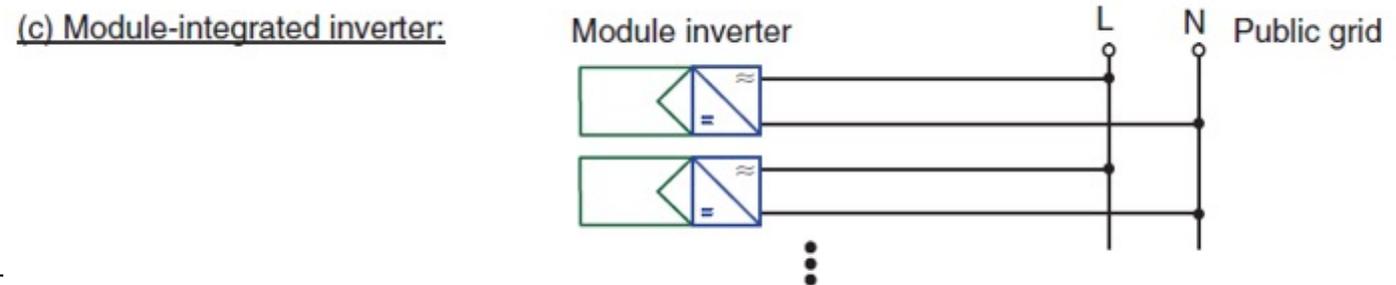$$\widehat{U}_{ac(\text{L1}-\text{N})} = m_a \, U_d$$
- Three phase
$$\widehat{U}_{ac(\text{L}-\text{L})} = \frac{\sqrt{3}}{2} m_a \, U_d$$

$$m_a < 1$$

Grid inverter configurations

(a) Central inverter:

String 1   Generator connection box   Central inverter

String 2

Public grid — L, N

(b) String inverter:

String inverter   L   N   Public grid

String 1

String 2

(c) Module-integrated inverter:

Module inverter   L   N   Public grid

Source: K. Mertens: textbook-pv.org
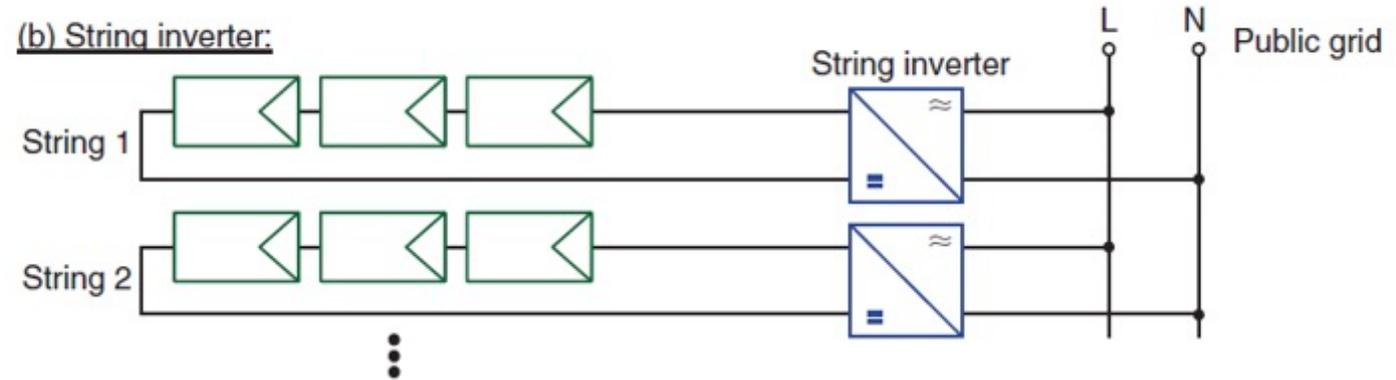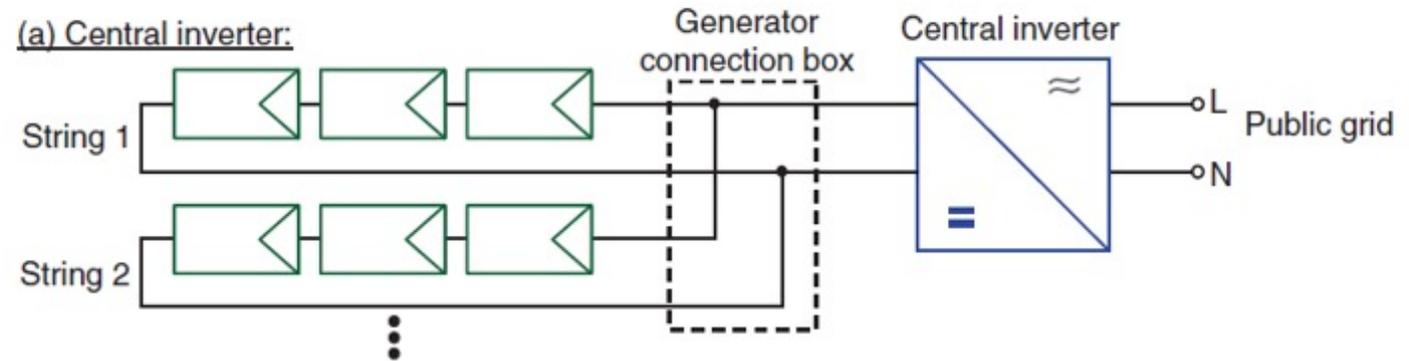
Grid inverter tasks

- Converting direct current to alternating current

- DC voltage at similar amplitude as the ac-voltage

- - else, DC/DC boost converter required

- MPP tracking
- Fixed ac-side voltage amplitude
- Variable dc-side voltage

- Synchronizing infeed to the grid voltage
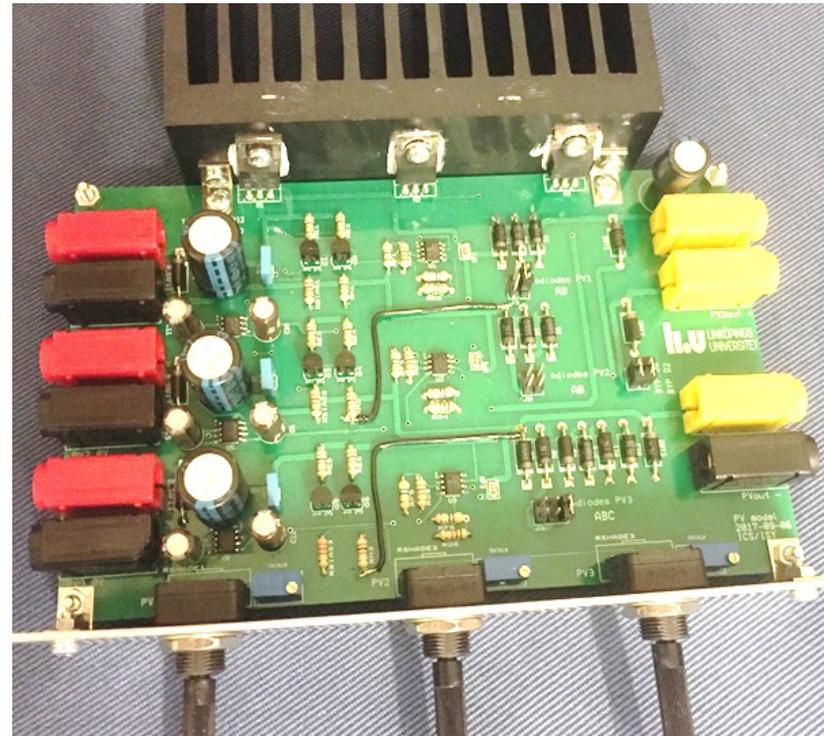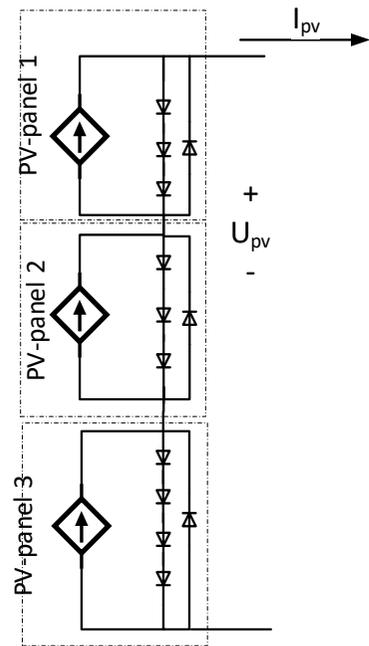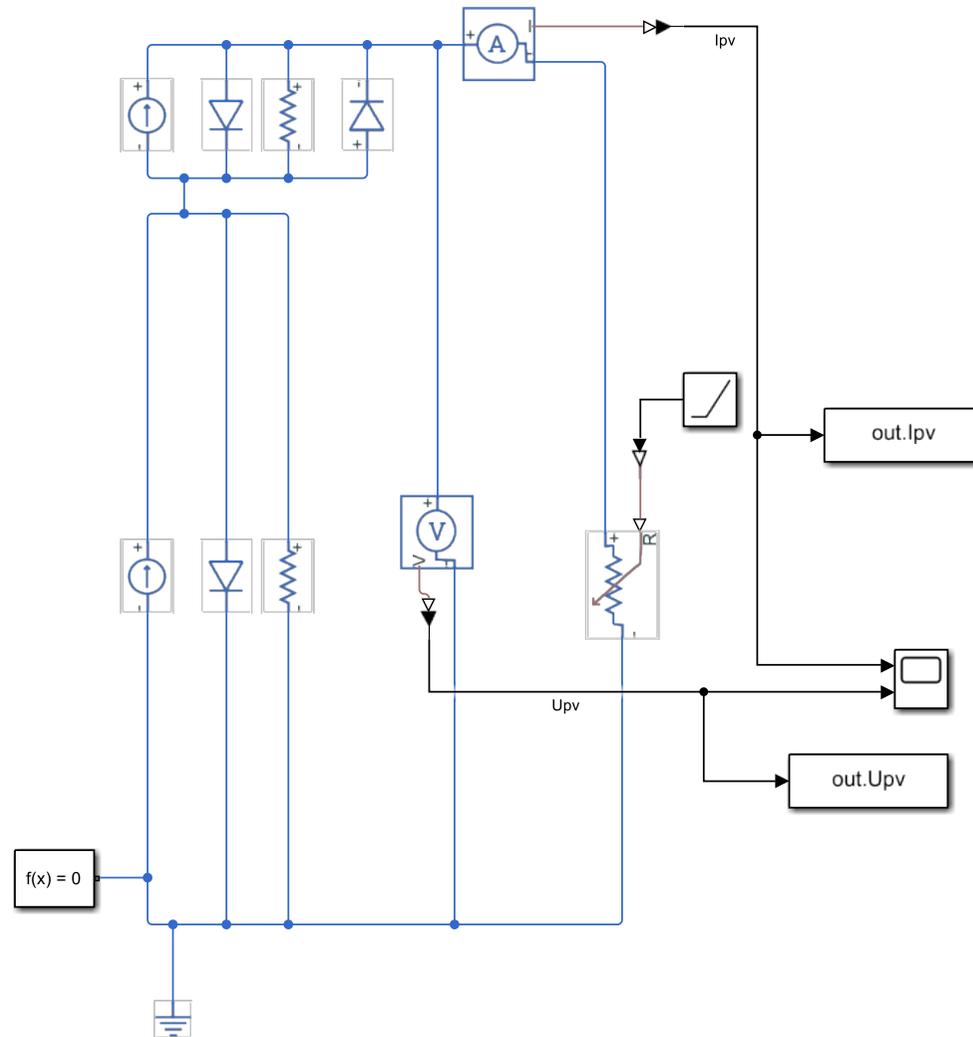
- Detecting stand-alone operation

Typical small PV-system

Source: K. Mertens: textbook-pv.org
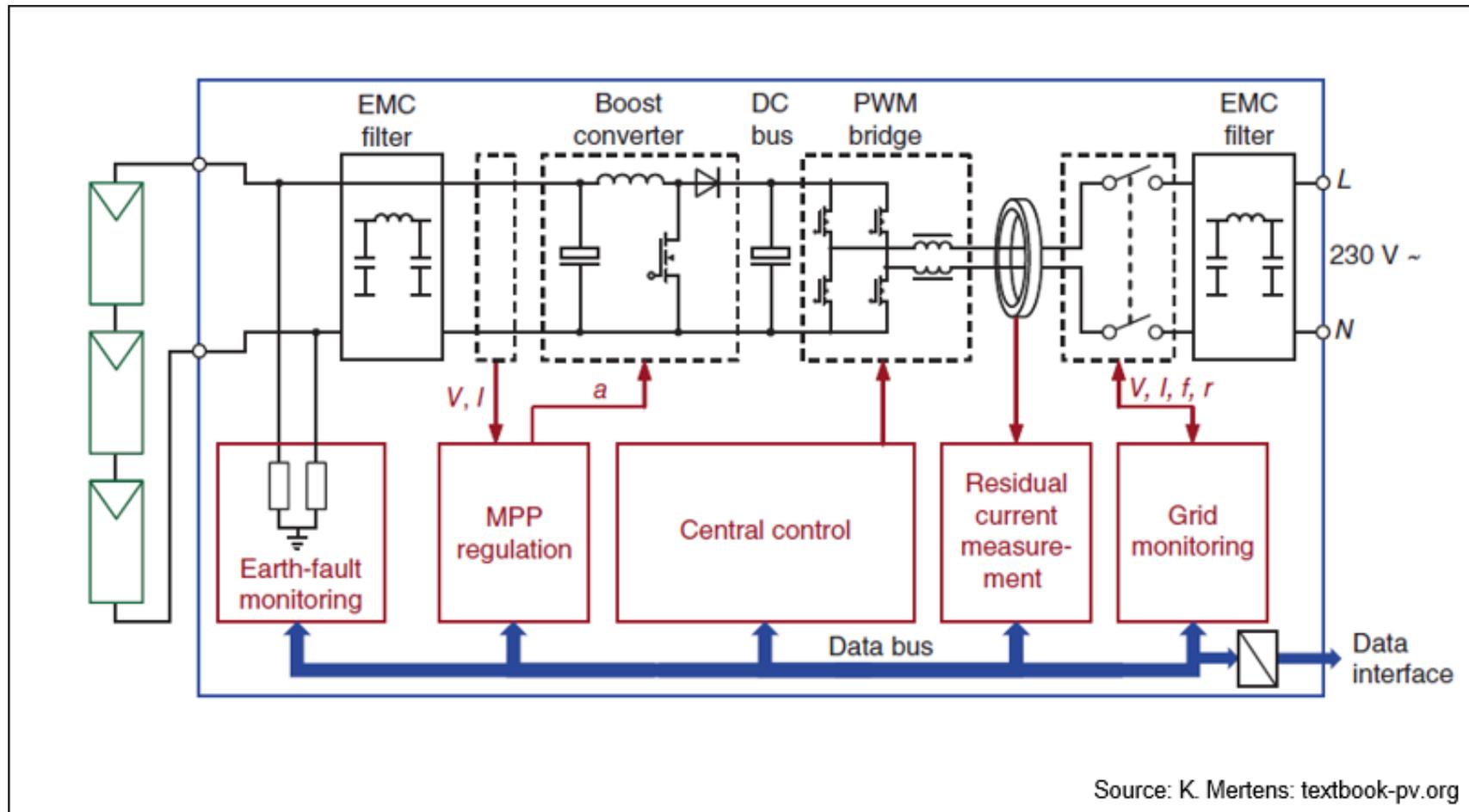
Lab1 introduction

- PV-module emulator
- Partial shading
- DC/DC Boost MPPT converter

PV-emulator

Partial shading

DC/DC Boost MPPT
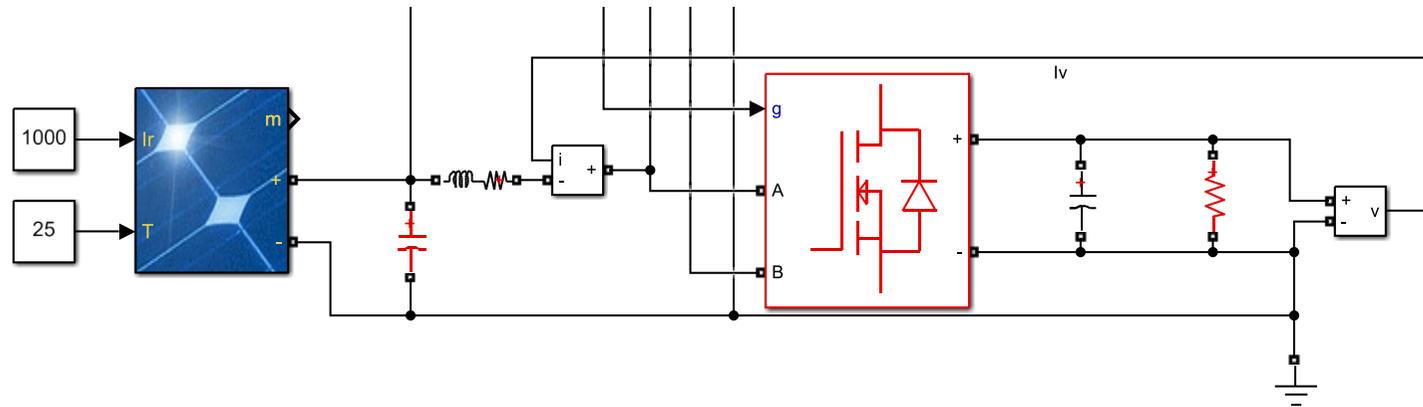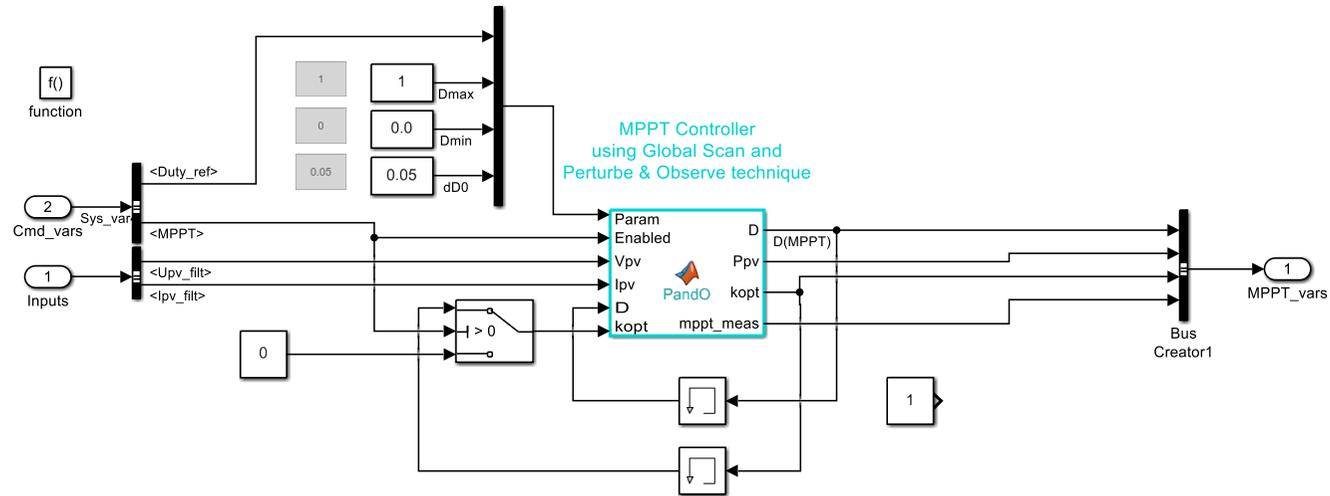
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