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Aspects on designing switched-mode power electronic converter for photovoltaic application

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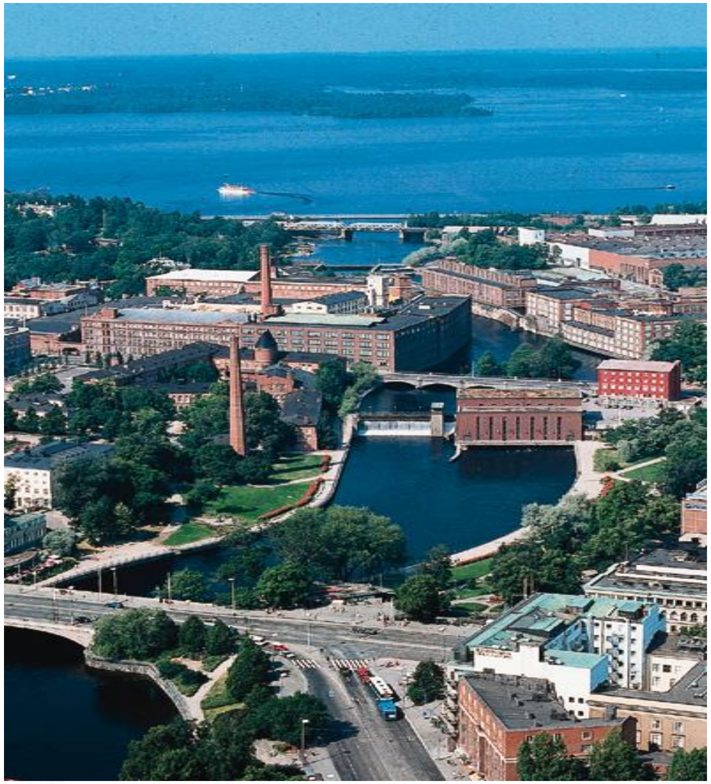

TAMPERE UNIVERSITY OF TECHNOLOGY

- Established in 1965
- 7900 students and 1600 employees, including 1700 international students + employees from 80 countries

- Research combines natural sciences, fields of engineering and business to strengthen export industry of Finland
- Key research areas

✓ Digital operating environment
✓ Energy- and eco-efficiency
✓ Health technology
✓ Light-based technologies

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Target of the training

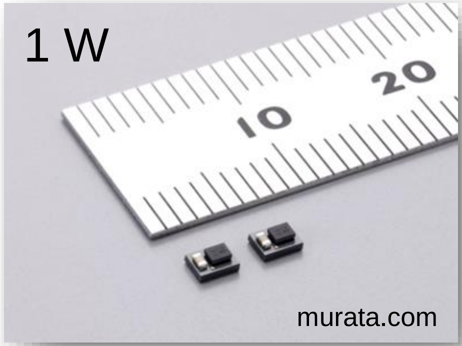
- The objective of the training is to give the basic knowledge on switched-mode converters used in photovoltaic applications.
- The attendees are able to solve the voltage/current stresses for selecting the power-stage components suitable for given application.
- The attendees get the knowledge of basic control and modulation methods of the converters. The attendees are able to understand, what kind of control methods are required in photovoltaic applications.
- The attendees create the simulation model by Matlab Simulink as well as the laboratory prototype of the power converter. In addition, their report the results and critically analyze the results.

Agenda: Day 1

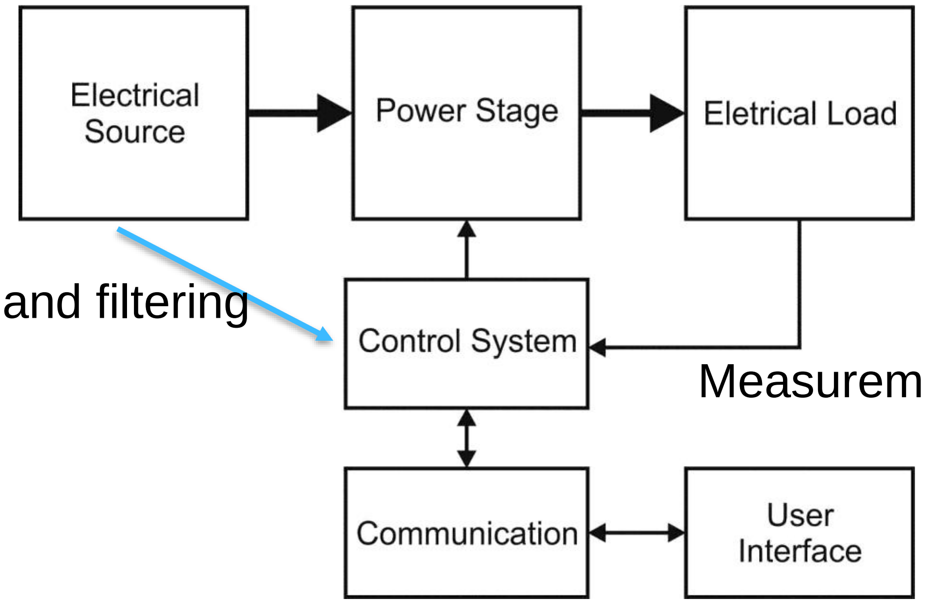
Time	Topic
8.30-9.45	Introduction: Solar power as power electronic point of view
9.45-10	Coffee break
10-12	Operation principle of buck and boost converters - hardware design - steady-state and transient equations
12-13	Lunch
13-14	Calculation exercises
14-15	Pulse width modulation (PWM) for buck and boost converters
15-15.15	Coffee break
15.15-17	Simulation exercise: Buck and boost converter in Matlab Simulink by using SimPowerSystems Toolbox and/or by using mathematical equations Analyze - The required size of passive components and the switching frequency of MOSFET - PWM with constant duty cycle, effect of varying duty cycle to the output voltage - How to report the simulation results (report template) including high quality figures - The effect of simplifications to the results (e.g. internal resistance of the components) - The effect of linear/non-linear operation, the continuous and discontinuous conduction modes - Effect of simulation time step to the results (max step size, variable/constant step)

Power Electronic Converters

- Power electronic converters vary in size, power rating and application
- Power levels start from mW range and go up to MW range



Power Electronic Converters



- The actual power converter requires more than just semiconductor switches to operate

Electrical Loads

- Electrical loads such as electrical motors require AC with different frequency and amplitude or DC with different amplitude
- Most consumer electronics work with DC and have very strict requirements on the regulation of DC voltage amplitude (< 5%)

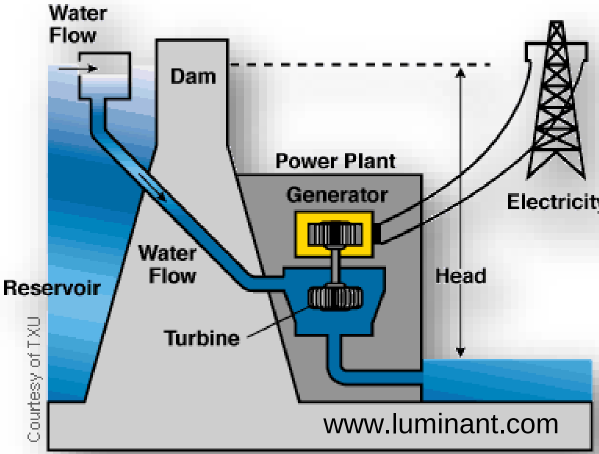
abb.fi

smartphoneexperts.com

extravaganzi.com

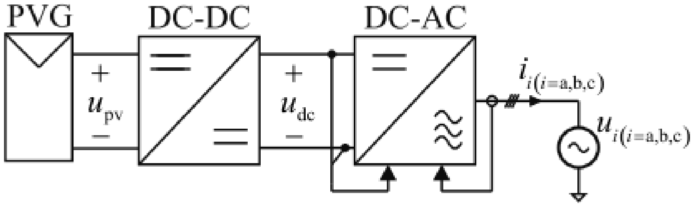
Conventional Power Generation

- Mechanical or potential energy is transformed into electrical energy by using a synchronous generator
- Frequency of the grid is determined by the synchronous generators
- No power electronics is needed in conventional power generation

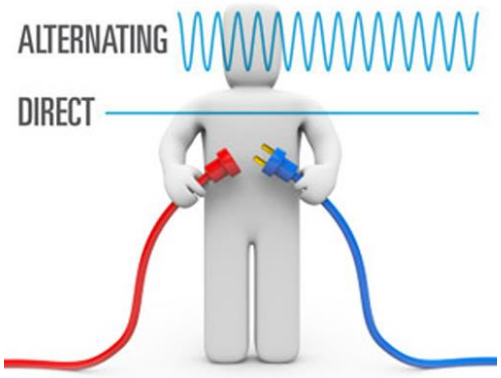


Renewable Power Generation

- Power electronics is needed to interface renewable sources with the grid
- Photovoltaic power plants produce DC current -> needs to convert to DC with correct amplitude by a DC/DC converter or AC by an inverter



topazsolar.com



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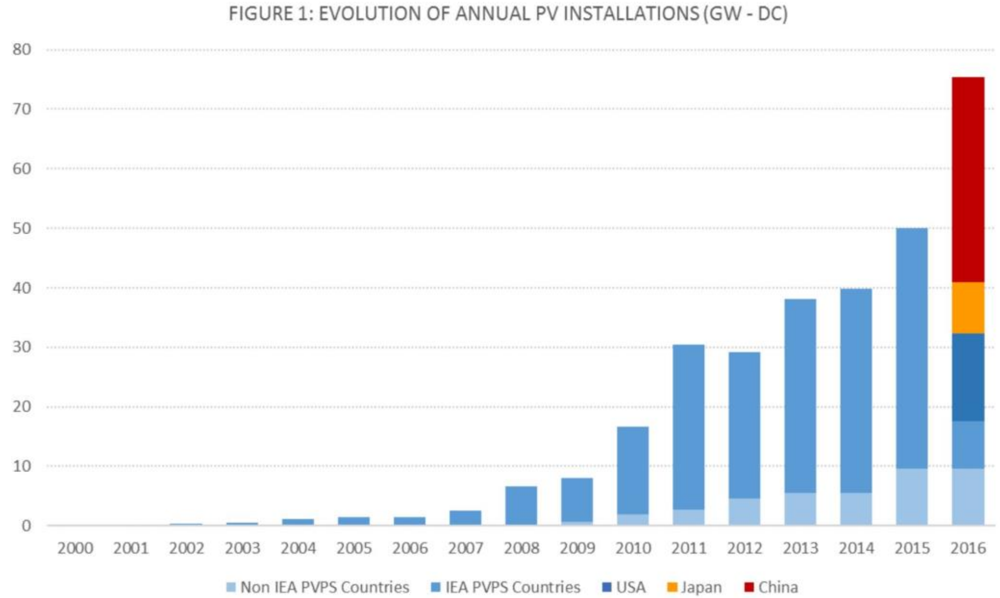
Solar power as power electronic point of view

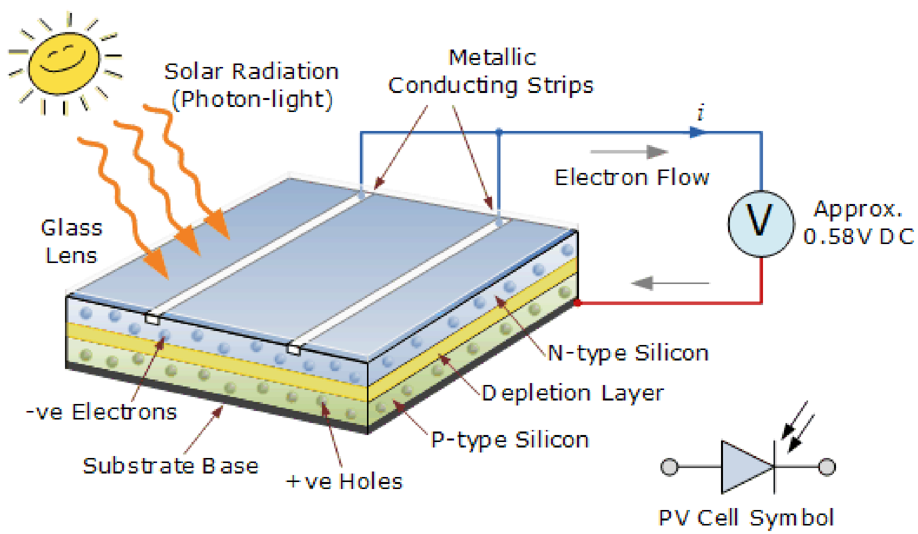
- Solar energy can be used to heat water using solar thermal collector or it can be converted directly into electricity by using photovoltaic generator
- The amount of installed PV capacity has increased rapidly during the last decade. The total amount of installed photovoltaic capacity was 303 GW in the end of 2016. The capacity was increased 75 GW compared to previous year.
- As the amount of installed PV capacity is expected to increase in the future, it becomes increasingly important to design the PV converters to be reliable, cheap and efficient



https://www.greentechmedia.com/articles/read/iea-global-installed-pv-capacity-leaps-to-303-gw#gs.=A_EF6M

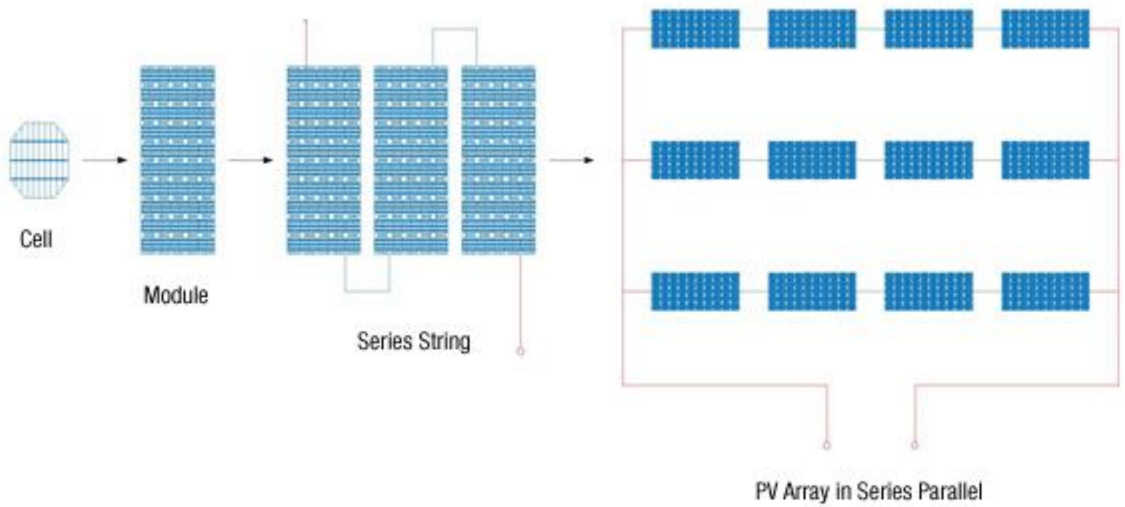
Properties of a photovoltaic generator

- The photovoltaic generator consists of photovoltaic cells
- The single photovoltaic cell is basically a p-n junction that converts the sunlight into electrical current by photovoltaic effect
- Commonly used materials in commercial PV cells are monocrystalline and polycrystalline silicon. In this case, the voltage across the terminals of a single PV cell is < 1 V. Therefore, cells are connected in series to form a PV panel.
- The maximum voltage is approximately 40 V in 250W PV panel.



Properties of a photovoltaic generator

- The amount of maximum current can be increased by increasing the cell area by connecting cells in parallel.
- The series connection of PV panels is called string and combination of series and parallel connected cells is called PV array.
- Photovoltaic generator is a general name for a system consisting of several PV panels

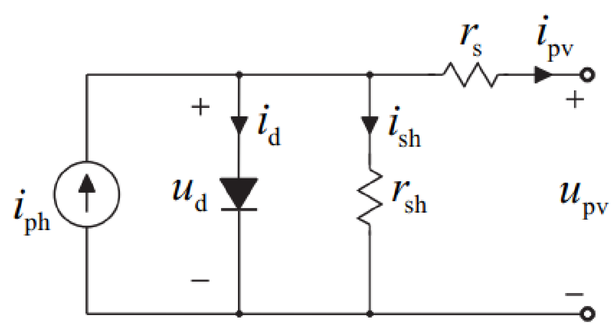


Properties of a photovoltaic generator

- Electrical properties of a PV panel can be modeled by equivalent circuit based on one-diode model, where I_{pv} is the photocurrent generated by the incident light, R_s is the equivalent series resistance of the PV panel and R_{sh} is the equivalent parallel resistance.
- The current produced by PV panel can be expressed mathematically using one-diode model as, where I_0 is the saturation diode current, N_s is the number of series connected cells, α is the diode ideality factor, k is the Boltzmann constant, T is the temperature of the p-n junction and q is the electron charge

$$I = I_{pv} - I_0 \left[\exp\left(\frac{u_{pv} + R_s I_{pv}}{N_s \alpha kT / q} \right) - 1 \right] - \frac{u_{pv} + R_s I_{pv}}{R_{sh}}$$

- Even if more complex models has been presented, one-diode model offers good compromise between accuracy and complexity



Picture: PhD Jukka Viinamäki

Properties of a photovoltaic generator

- When I_{pv} is zero, PV panel operates in open-circuit condition (OC).
- When the voltage U_{pv} is zero, PV panel operates in short-circuit (SC) condition.
- The output power of the PV model is zero in both of these cases.

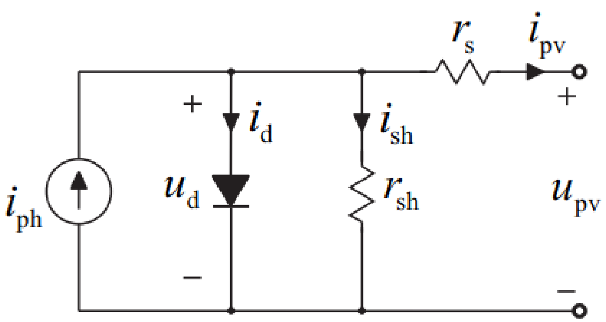
$$I_{SC} = I_{SC,STC} \frac{G}{G_{STC}}$$

$$V_{OC} = \ln\left(\frac{GI_{SC,STC}}{G_{STC} I_0} + 1\right)\left(\frac{N_s \alpha kT}{q}\right)$$

$I_{SC,STC}$ = the short-circuit current in standard conditions (STC)

G = solar irradiance on the surface of the panel

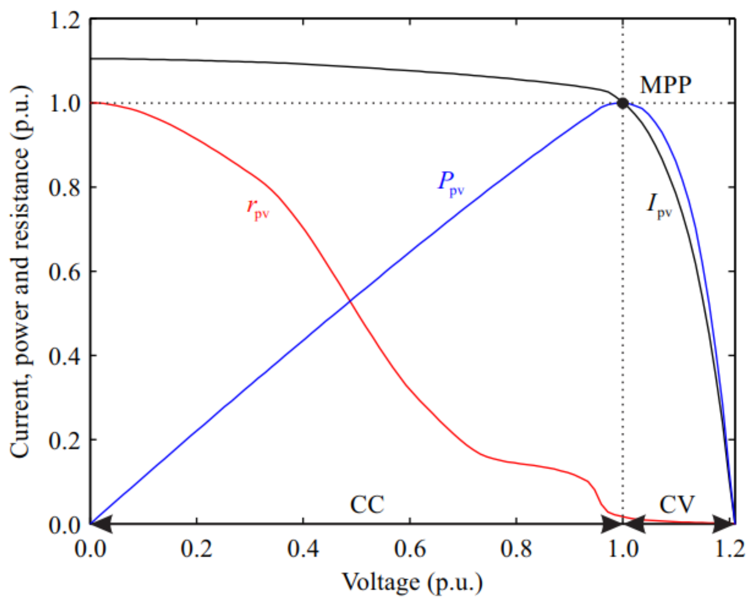
G_{STC} = solar irradiance in STC



Picture: PhD Jukka Viinamäki

Properties of a photovoltaic generator

- The output power is maximized at a certain operating point called maximum power point (MPP) located between these conditions. The dependency on output current, output power and dynamic resistance on voltage of typical PV panel is shown in Fig. below
- As the current is almost constant in the area between short-circuit (SC) and MPP, it is called constant current (CC) region. Correspondingly, the area between MPP and open-circuit (OC) is called constant voltage (CV) region.



Picture: PhD Jukka Viinamäki

Properties of a photovoltaic generator

The dynamic resistance represents the low-frequency value of the PV panel output impedance and it can be defined as

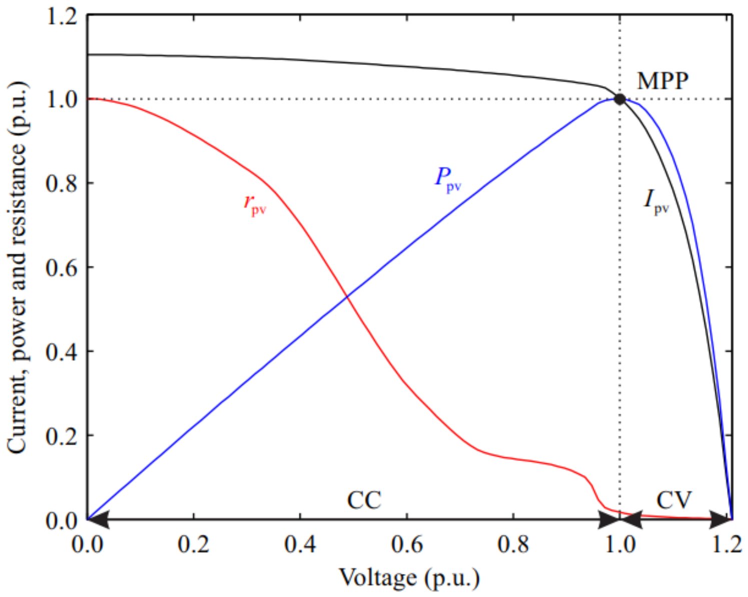
$$r_{pv} = -\frac{\Delta U}{\Delta I_{pv}}$$

where the minus sign indicates that the current flowing out from the PVG.

The dynamic resistance is nonlinear and dependent on the operating point. At the MPP, static and dynamic resistances are equal, i.e.

$$r_{pv} = \frac{U_{MPP}}{I_{MPP}} = R_{pv}$$

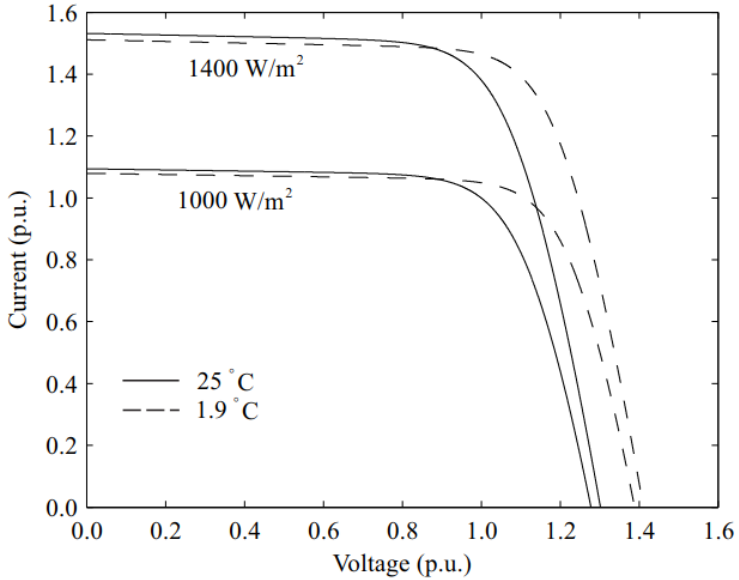
In CC region, dynamic resistance is higher than static resistance, whereas in CV region, dynamic resistance is lower than static resistance.



Picture: PhD Jukka Viinamäki

Properties of a photovoltaic generator

- The current-voltage (IV) curve of a PV panel is shown for two different irradiance and ambient temperature levels. The current produced by the PV panel is linearly dependent on irradiance level and inversely proportional to temperature. However, the effect of irradiance is much stronger compared to the effect of temperature level.
- The voltage across the PV panel terminals is inversely proportional to temperature and it is also slightly affected by the irradiance level. The highest output power is obtained at low temperature and high irradiance level.

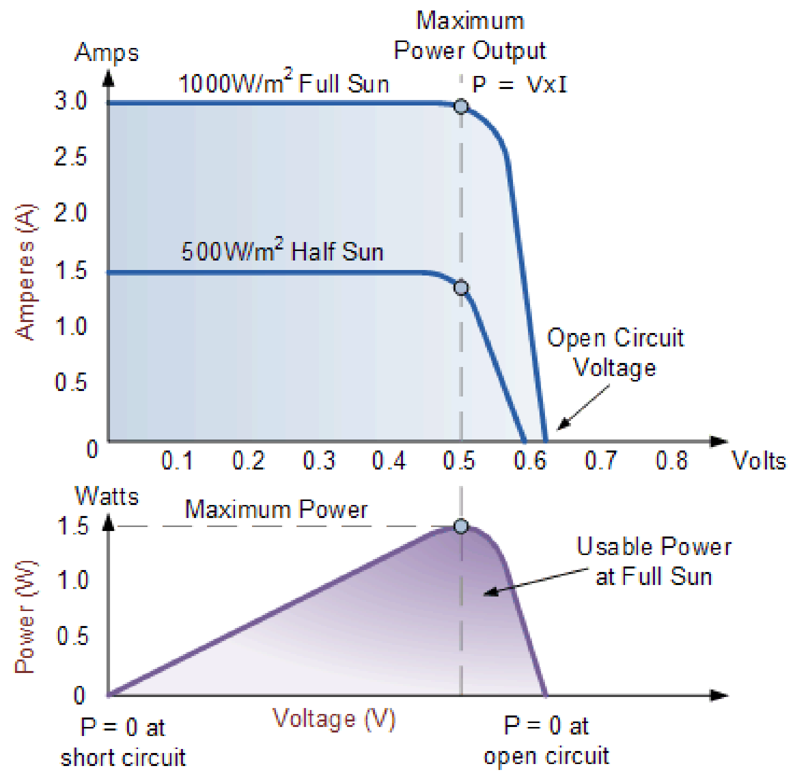


Picture: PhD Jukka Viinamäki

Properties of a photovoltaic generator

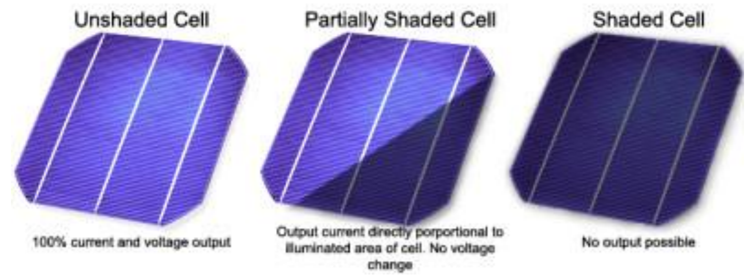
- Manufacturers of PV panels provide values of OC voltage, SC current, MPP voltage and MPP current in the datasheet of the panel. These values are measured in standard test conditions (STC) i.e. when the irradiance is 1000W/m^2, and the ambient temperature is 25°C.

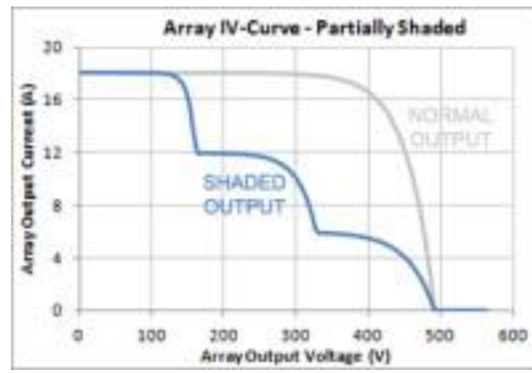
- However, both the ambient temperature and the irradiance are varying for real due to e.g. the passing clouds. In addition, the irradiance can be reflected from the clouds yielding as high irradiance as 1400W/m^2 at the surface of the PV panel. This phenomena is known as cloud enhancement. The maximum value of produced current and power together with the maximum voltage must be taken into account in the design of the interfacing converter.

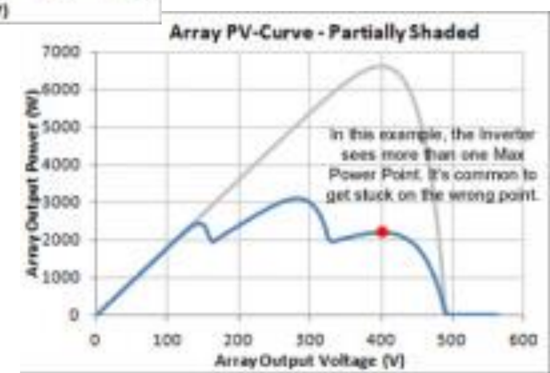


Properties of a photovoltaic generator

- When part of a PV module is shaded, the shaded cells will not be able to produce as much current as the unshaded cells. Since all cells are connected in series, the same amount of current must flow through every cell.
- The unshaded cells will force the shaded cells to pass more current than their new short circuit current. The only way the shaded cells can operate at a current higher than their short circuit current is to operate in a region of negative voltage that is to cause a net voltage loss to the system.
- The shaded cells will dissipate power as heat and cause “hot spots”. And the shaded cells with drag down the overall IV curve of the group of cells.

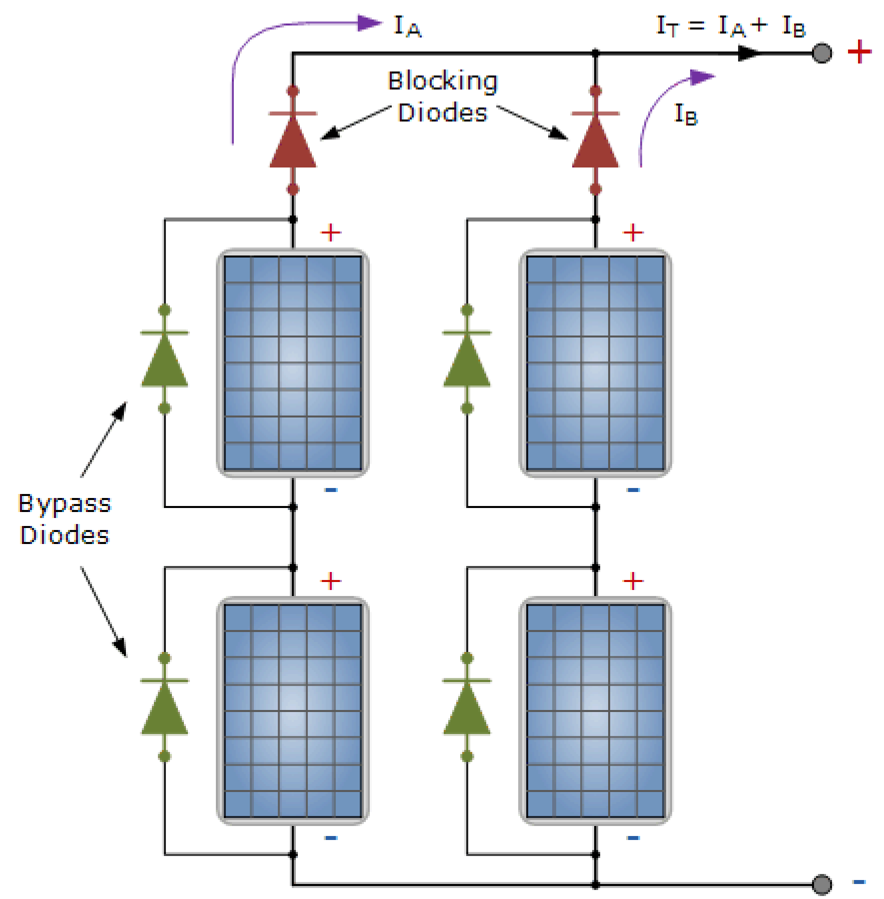






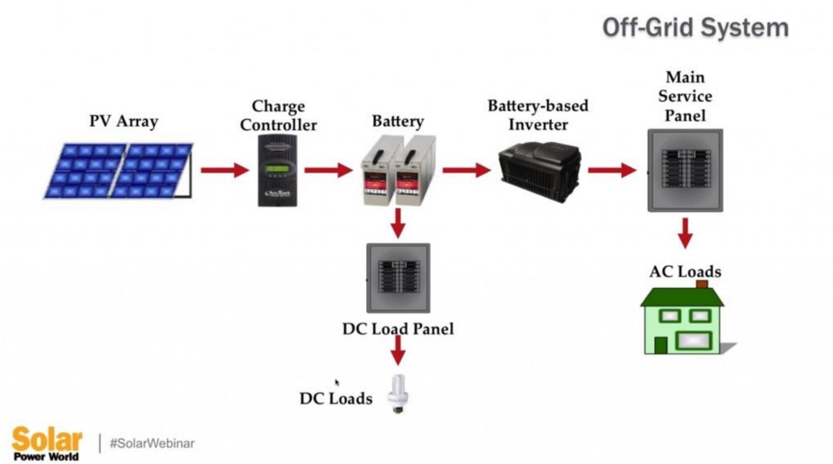
Properties of a photovoltaic generator

- One way to minimize the effect shading has on a single module in a series string, is to use bypass diodes in the junction box.
- Antiparallel-connected bypass diodes allow current to pass around shaded cells and thereby reduce the voltage losses through the module.
- When a module becomes shaded its bypass diode becomes “forward biased” and begins to conduct current through itself. All the current greater than the shaded cell’s new short circuit current is “bypassed” through the diode, thus reducing drastically the amount of local heating at the shaded area.
- Typically, the size of the cell group is around 20 cells yielding 3 bypass diodes in 190 W panel.

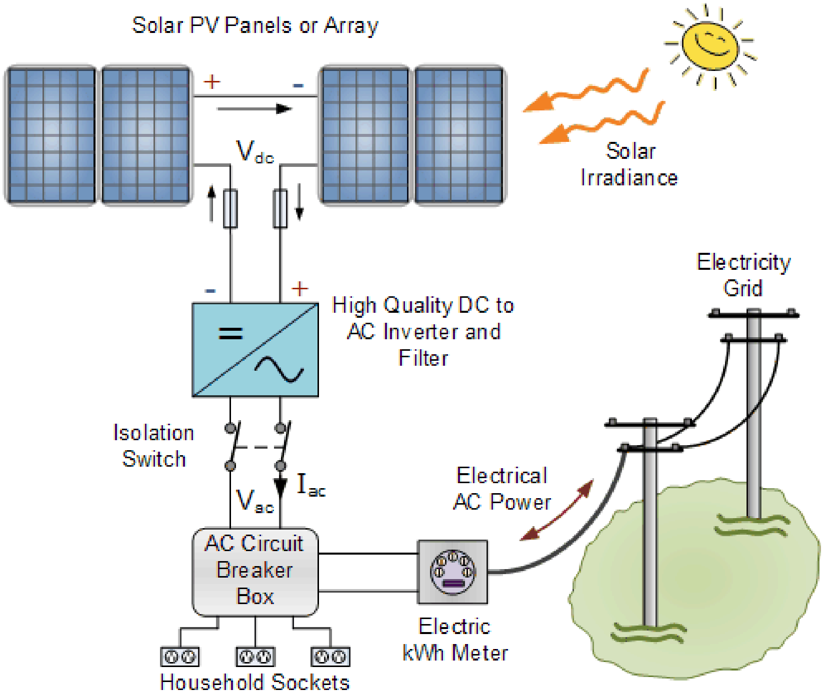


PV power plant concepts

1. PV panel supplying DC loads
   and/or battery

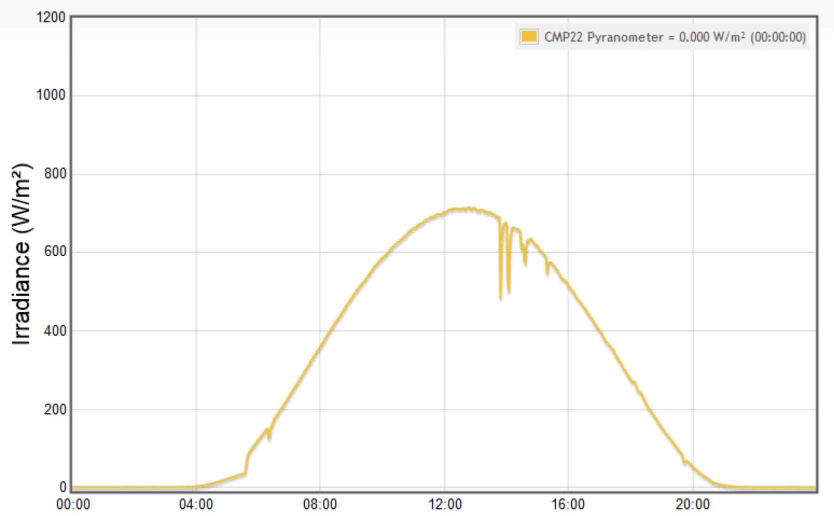


2. Grid-connected PV power plant concepts

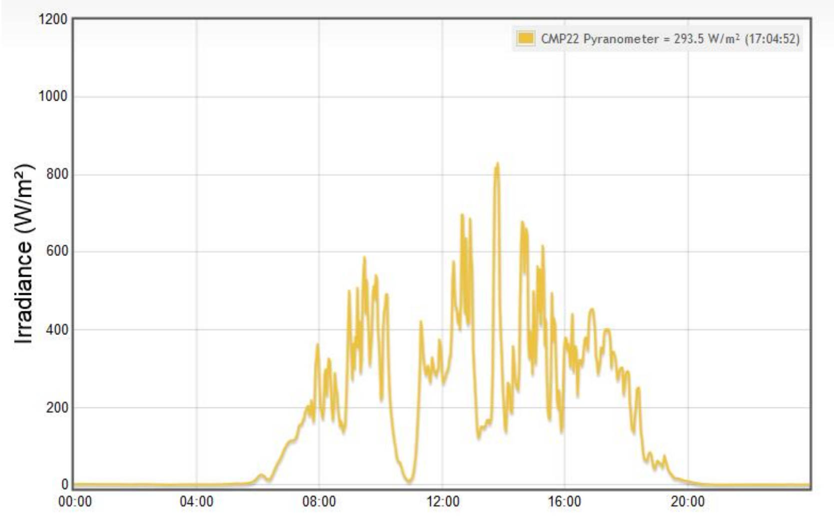


Battery storages

- Energy output from renewables is not constant (clouds, shading by buildings etc)
- The amount of available energy may be hard to predict
- Excess energy can be stored in batteries using power electronic converters
- Constant power output of a renewable energy source can be achieved



Irradiance at TUT in 5.8.2014.



Irradiance at TUT in 3.9.2014.

PV power plant concepts

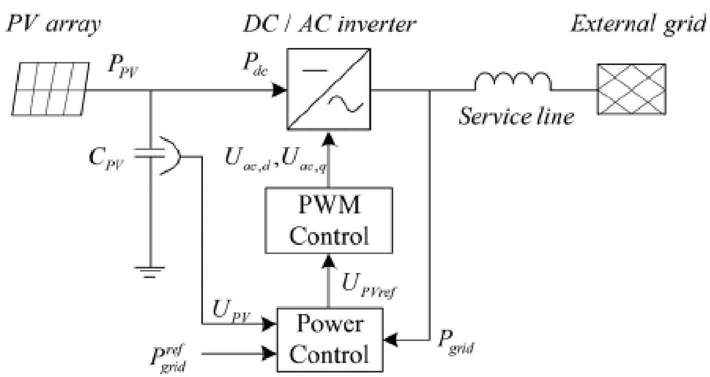
2. Grid-connected PV power plant concepts

a) Single-stage PV inverter

PV panel + DC/AC inverter
Simple structure

Used in large-scale PV power plants

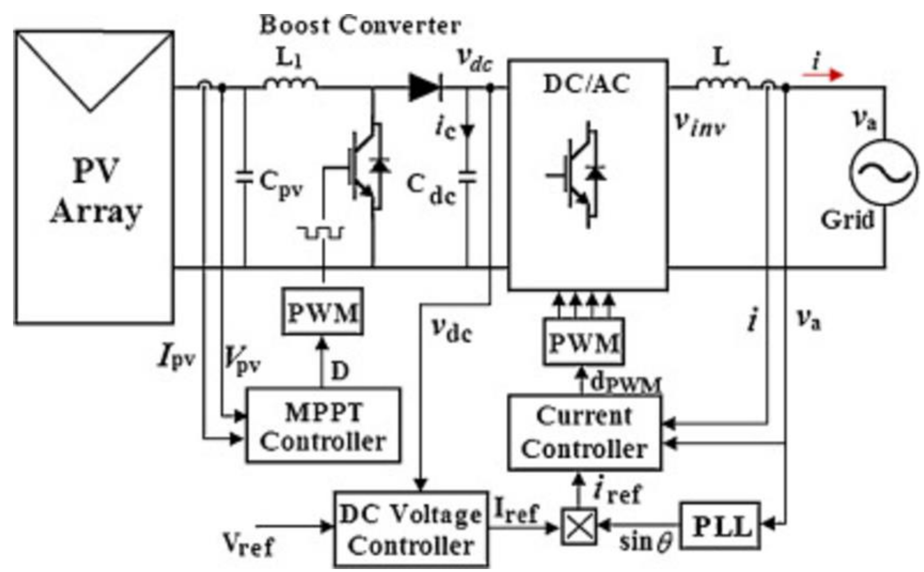
$$V_{pv} > \hat{V}_{grid}$$



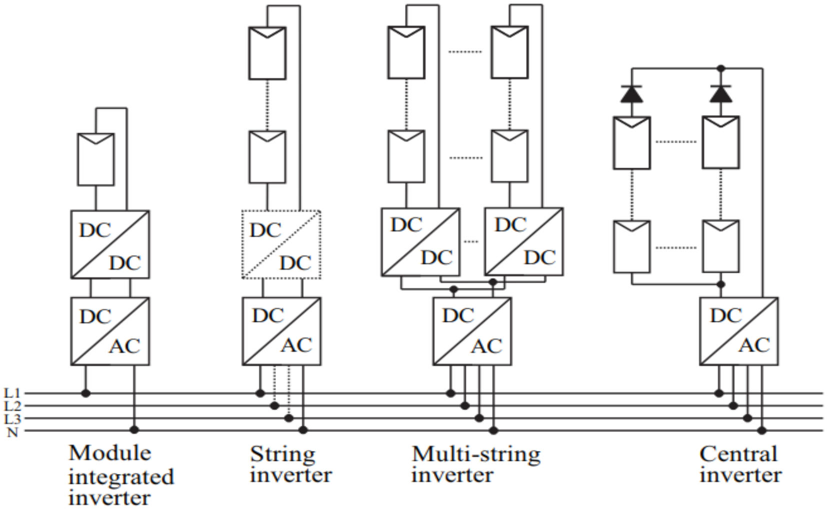
b) Two-stage PV inverter

Voltage-boosting DC/DC converter between PV panel and inverter

Also galvanic isolation can be integrated in the DC/DC converter (high frequency transformer)



PV power plant concepts



2. Grid-connected PV power plant concepts

b) **Two-stage PV inverter**

- ✓ module-integrated-inverter concept

  -> able to locate the MPP of each PV panel, lower power converter efficiency and higher price per kW

- ✓ String inverter

  -> the converter efficiency is higher and price per kW lower, used in domestic and other small to medium scale PV power plants

- ✓ Multistring concept

  -> individual DC/DC converters, used in medium to large-scale PV power plants

- ✓ Central inverter

  -> Unable to locate more than single MPP for the whole PV array yielding low MPPT efficiency

Picture: PhD Jukka Viinamäki

Design considerations of DC-DC converter in PV applications

1. The DC/DC converter increases the input voltage range of the PV inverter
2. The DC/DC converter increases MPP range
3. The DC/DC converter limits the output power of the PV converter referred to as a constant power generation

- The power electronic devices are selected based on the standard test conditions (STC) power of the PVG. It must be checked, that the maximum input current of the PV converter is high enough and the input voltage range is suitable for the PVG.
- The relation between the STC power of the PVG and the nominal power of the converter can be described by the sizing ratio SR

$$SR = \frac{P_{conv,nom}}{P_{pv,STC}} \qquad I_{in,\max} = \frac{P_{pv,STC}SR}{V_{in,\min}}$$

- The optimal value of the sizing ratio depends on the location of the PV plant, governmental incentives, converter power efficiency curve, converter protection scheme, costs of the PV panels and converters, cloud shading conditions etc.
- The optimum value of the sizing ratio is in the range of 0,6-1,5, typically 0,7

Design considerations of DC-DC converter in PV applications

- The PV converter is not usually designed for a specific PVG, the converter manufacturers aim to design the converter as generally applicable as possible. Therefore, the input current of the converter is usually calculated by dividing the nominal power of the converter by the minimum input voltage

$$I_{in,\max} = \frac{P_{nom}}{V_{in,\min}}$$

-> the nominal power can be handled over the whole input voltage range

-> however, as the source is PVG, the power is maximized at higher than the minimum voltage, yielding oversized components and uneven temperature distribution if PV converter has wide input voltage range.

$$SR = \frac{P_{conv,nom}}{P_{pv,STC}} \quad \Rightarrow \quad I_{in,\max} = \frac{P_{pv,STC} SR}{V_{in,\min}}$$

Reading material

The lecture notes are constructed based on the applicable topics in the books

- Teuvo Suntio, Tuomas Messo and Joonas Puukko, “Power Electronic Converters: Dynamics and Control in Conventional and Renewable Energy Applications”, Wiley VCH, 720 pages, ISBN: 978-3-527-34022-4

- R. Shaffer, ”Fundamentals of Power Electronics with MATLAB”, pp. 183-195
- D. Hart, ”Power Electronics”, Chapter 1,pp. 1-11
- R. W. Erickson, ”Fundamentals of power electronics”, Chapter 1, pp. 1-10
- A. Ioinovici, “Power electronics and energy conversion systems”, pp. 81-85 (Chapters 1.4.1 and 1.4.2) and Chapter 1.3, pp. 28-56
- Trzynadlowski, Andrzej M., "Introduction to Modern Power Electronics"
- Mohan, Undeland, Robbins, "Power Electronics: Converters, Applications, and Design"
- Irwin David (ed.), "Power Electronics and Motor Drives“

- PhD thesis by Jukka Viinamäki and by Jyri Kivimäki