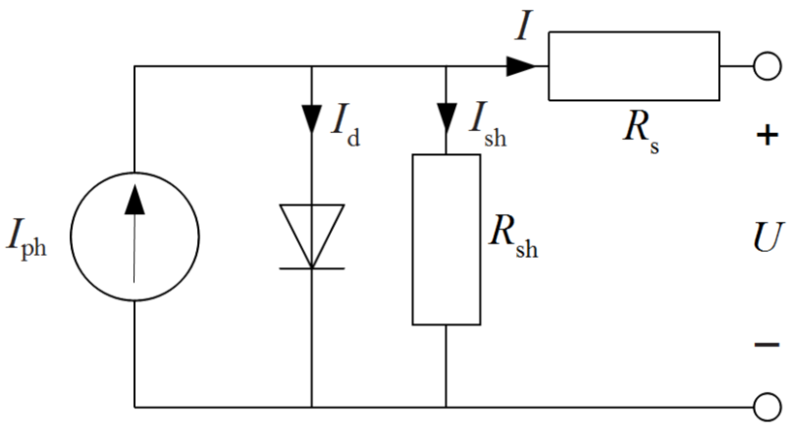
DEE-53117 Solar Power Systems
Practical work

Operation of PV power generators

Content of the practical work

- Effects of ideality factor, parasitic resistances, temperature and irradiance on the operation of PV modules
- Operation of series-connected PV modules under partial shading conditions and the effect of bypass diodes
- Operation of basic MPPT algorithm (perturb and observe) under varying operating conditions
- Thermal behaviour of PV modules

Modelling of a PV cell



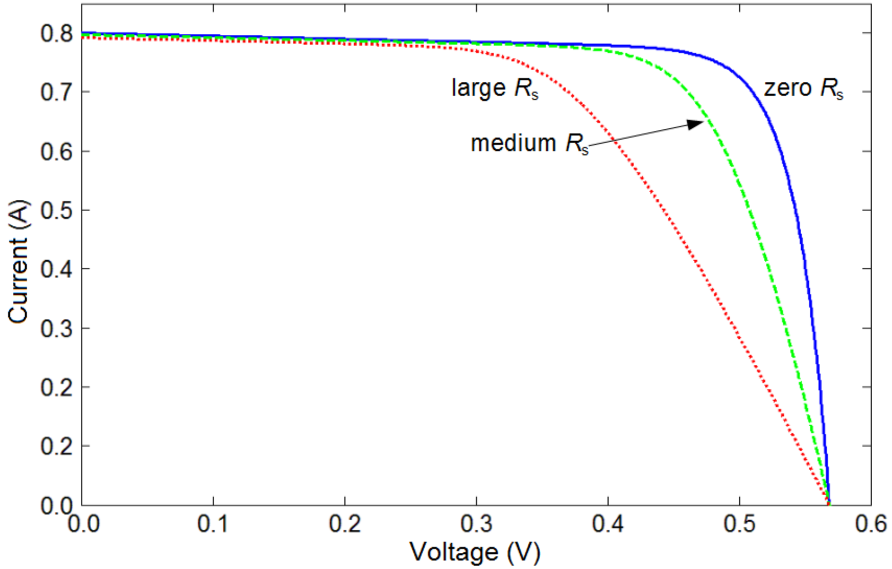
Equivalent circuit of a PV cell based on the one-diode model.

- The current–voltage characteristic of a PV cell:

$$I = I_{ph} - I_o\left(e^{\frac{U+R_sI}{AkT/q}} - 1\right) - \frac{U + R_sI}{R_{sh}} = I_{ph} - I_d - I_{sh}$$

Parasitic resistances

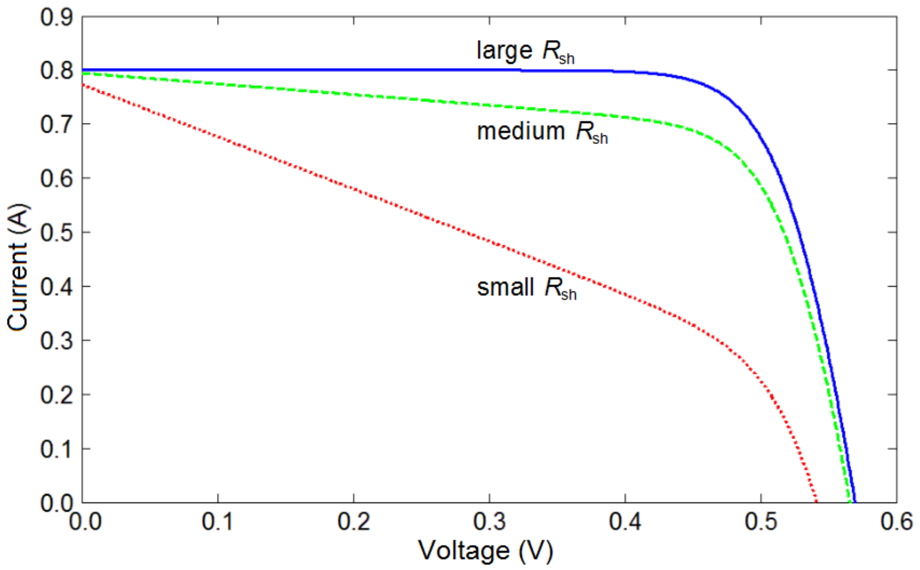
- Series resistance R_s is mainly due to the bulk resistance of a semiconductor material, the metallic contacts and interconnections, the contact resistance between the metallic contacts and the semiconductor and charge carrier transport through the top diffused layer.



The effect of the series resistance on the I–U curve of a PV cell.

Parasitic resistances

- Shunt resistance R_{sh} is mainly due to p-n junction non-idealities and impurities near the junction, which cause partial shorting, especially near the edges of a PV cell.



The effect of the shunt resistance on the I–U curve of a PV cell.

Effect of temperature

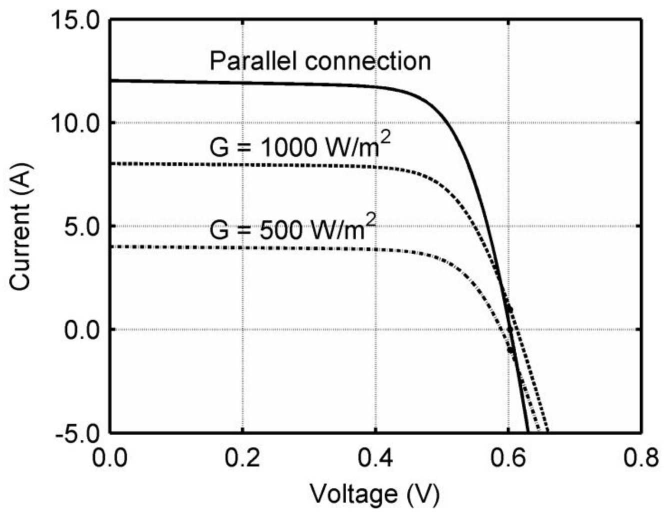
- Open-circuit (OC) voltage decreases as the temperature increases.
- Short-circuit (SC) current increases with the temperature because the band gap energy decreases and photons with less energy are allowed to create electron-hole pairs.
- However, the effect of the temperature on the SC current is small.
- The power output of a silicon PV cell decreases as the temperature increases.

Effect of irradiance

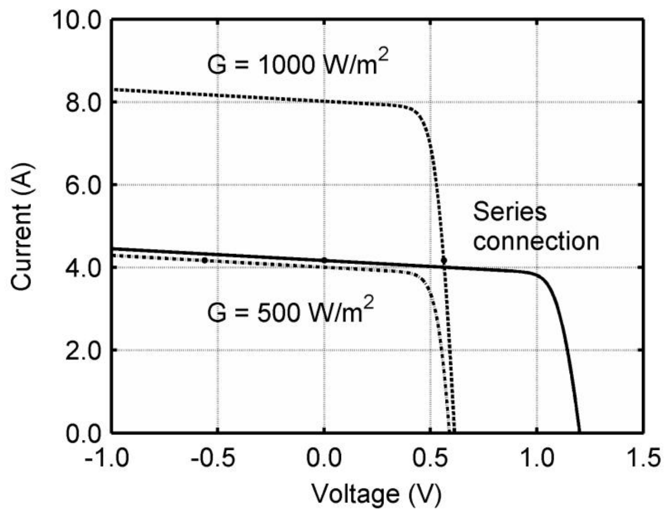
- As the irradiance increases the photon flux increases, in the same portion, and generates a proportionately higher current.
- Thus, the SC current of a PV cell is approximately directly proportional to the irradiance.
- The OC voltage depends on the SC current and, therefore, slightly increases with the irradiance.

Interconnections of PV cells

- PV cells are usually not used individually due to the low voltage and power levels.
- They are connected in parallel to increase the current or in series to increase the voltage.



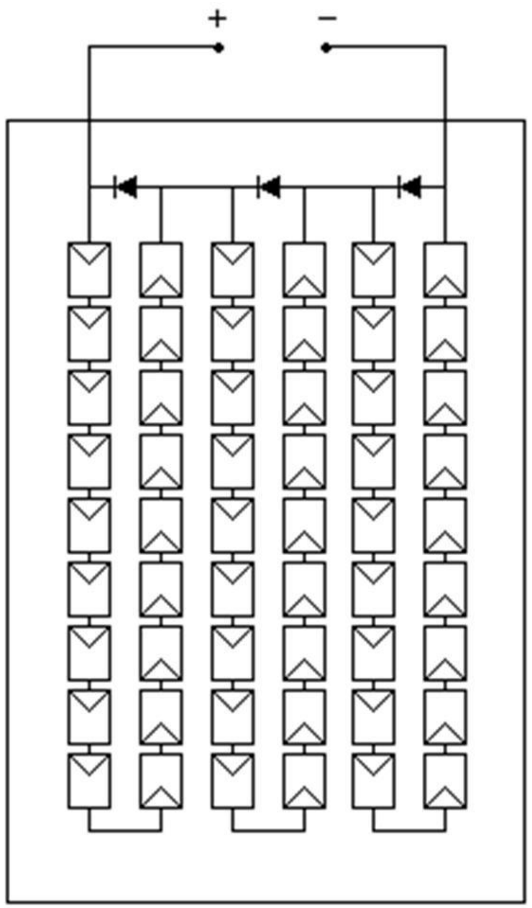
I–U characteristics of two parallel-connected PV cells operating under non-uniform conditions.



I–U characteristics of two series-connected PV cells operating under non-uniform conditions.

Bypass diodes

- If a series connection of PV cells is partially shaded, the cell that receives the lowest irradiance level limits the total current of the series connection.
    - The shaded cell can dissipate part or all of the power produced by the other cells and can be damaged. This is known as the hot-spot heating.
- In order to protect PV cells from damaging due to hot-spots, manufacturers have connected bypass diodes in antiparallel with the cells.

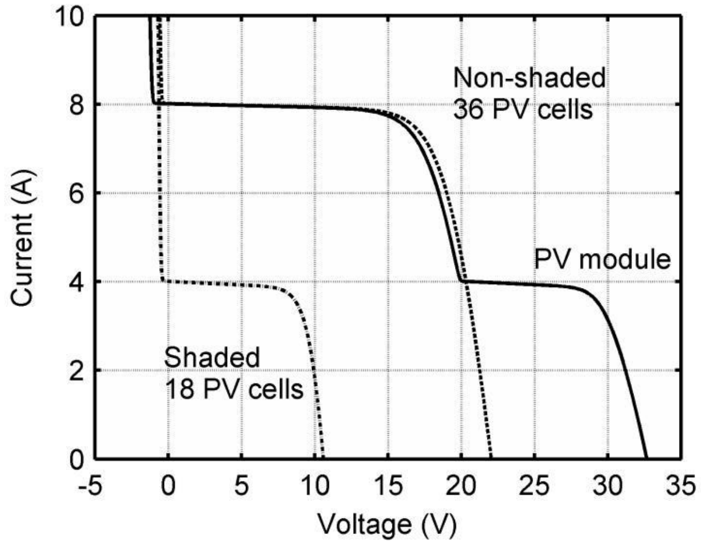


Typical structure of a PV module composed of 54 PV cells and 3 bypass diodes.

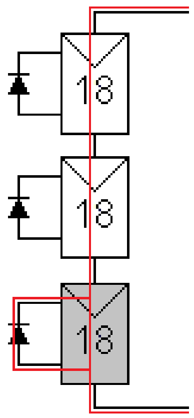
Tampere University

Effect of bypass diodes

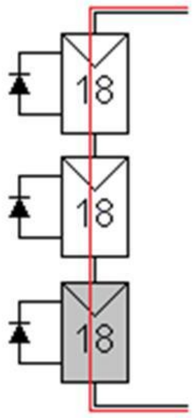
- Bypass diodes have a significant effect on the electrical characteristics of PV modules under non-uniform conditions.



I–U characteristics of a PV module composed of 54 PV cells with 18 cells shaded and 36 cells non-shaded. The effect of a bypass diode can be seen at voltages below 20 V.



Path of the current below 20 V.



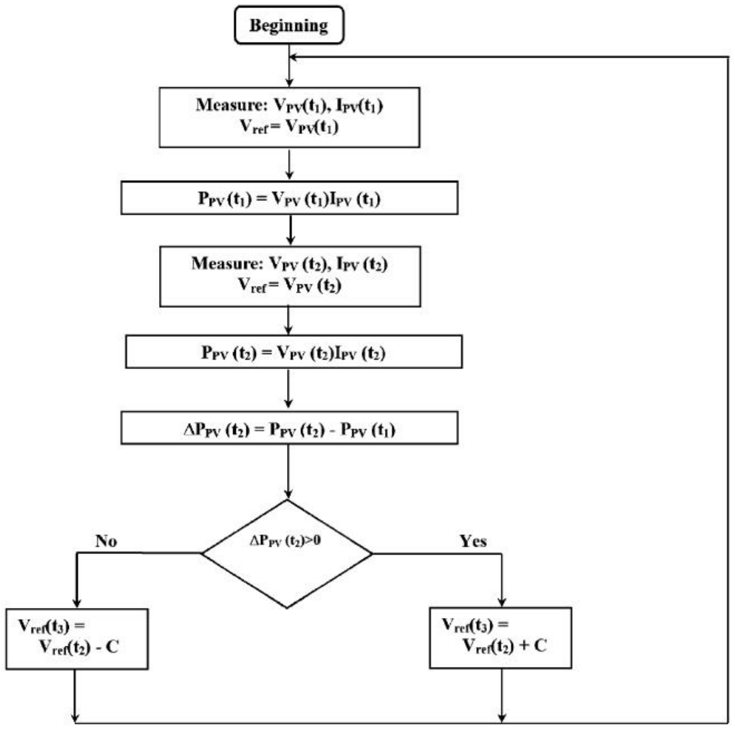
Path of the current above 20 V.

Maximum power point tracking (MPPT)

- The maximum power of PV modules varies greatly with operating conditions.
- Maximum power point tracking is relatively easy in the case of uniform conditions.
- In the case of partial shading, certain difficulties like multiple maximum power points can occur and simple MPPT techniques can easily be trapped at a local MPP. This can substantially reduce the energy yield of a PV generator.
- The most commonly used MPPT algorithms are Perturb and Observe (PO) and Incremental Conductance (IC).

Perturb and Observe algorithm

- Based on the perturbation of the operating voltage (or current) of the PV generator.
- By increasing or decreasing the voltage of the PV generator and observing changes in the power it is possible to find a local maximum power point.
- This is done periodically.
  - Once the maximum power point has been reached the operating point oscillates around it.

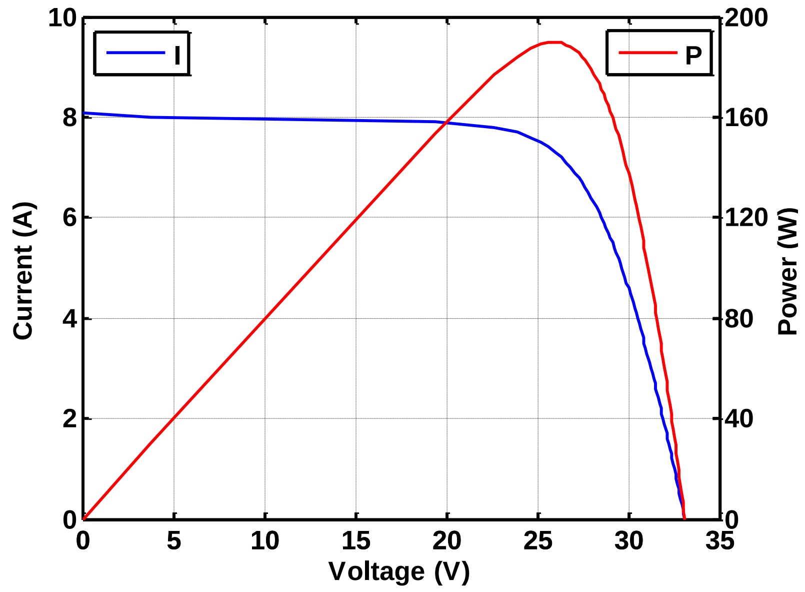


One implementation of the Perturb and Observe MPPT algorithm.

TUT solar PV power station research plant

TUT solar PV power station research plant

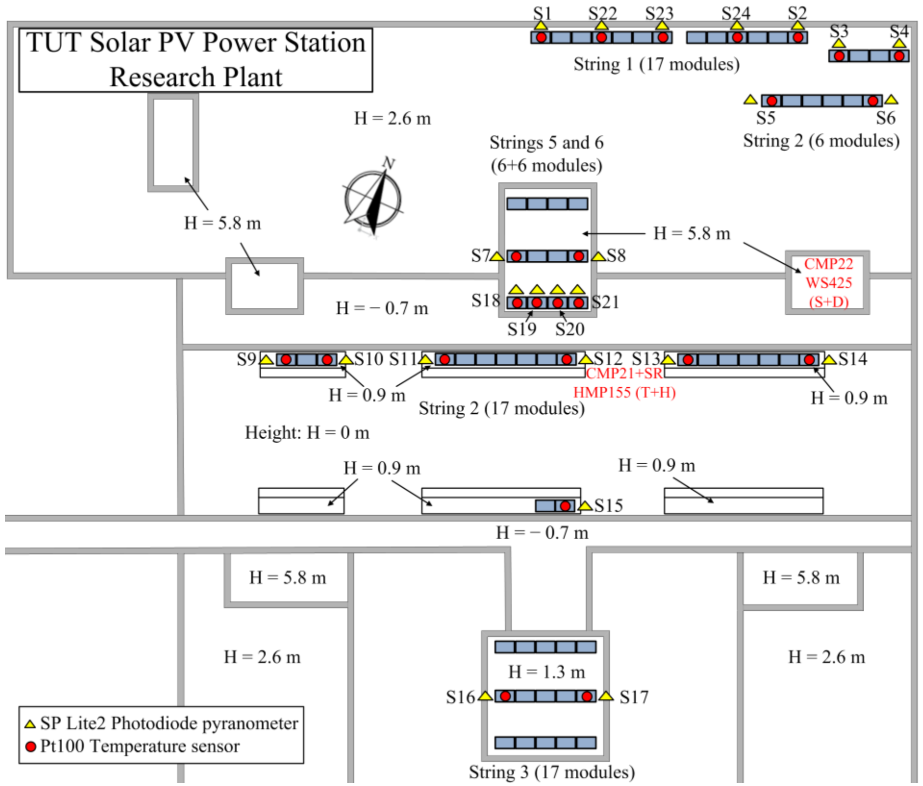
- 69 NAPS NP190GKg PV modules
- Total peak power: 13.1 kWp
- Technology: polycrystalline silicon PV cells
- Electrical performance of NAPS NP190GKg PV module in STC:
  - I_{SC} = 8.02 A
  - U_{OC} = 33.1 V
  - P_{MPP} = 190 W
  - I_{MPP} = 7.33 A
  - U_{MPP} = 25.9 V



The I–U and P–U curves of NAPS NP190GKg PV module under STC.

TUT solar PV power station research plant

- Climatic measuring system
  - Weather station
  - Mesh of irradiance and module temperature sensors
  - Automatic data acquisition system and database storage
- Electrical measuring system
  - I–U curve tracers based on controllable switches (IGBTs)



Layout scheme of the TUT solar PV power station research plant.

TUT solar PV power station research plant

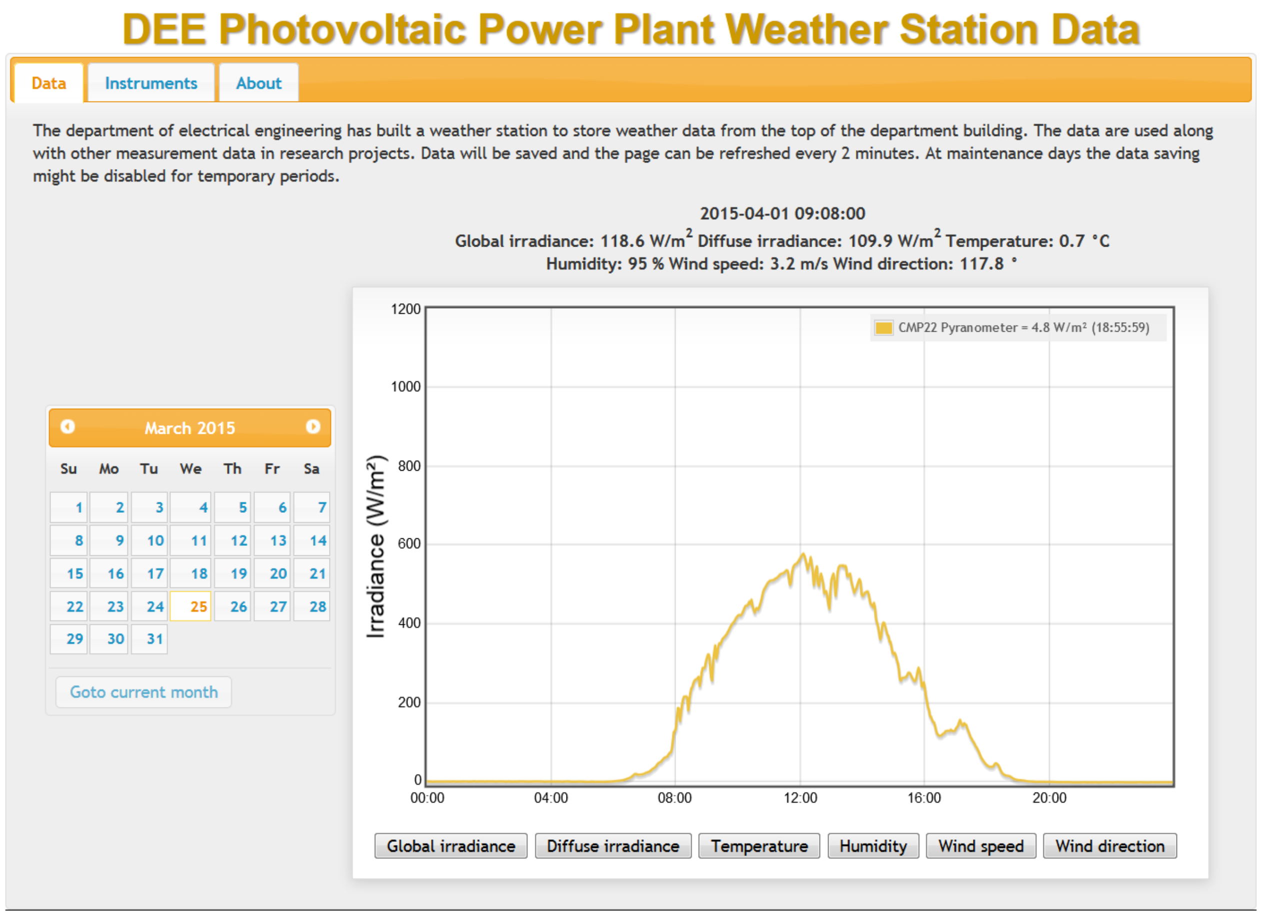
Kipp & Zonen CMP22 Pyranometer: *global solar radiation on the horizontal plane*

Kipp & Zonen CMP21 Pyranometer + Shadow ring: *diffuse solar radiation on the horizontal plane*

Vaisala WS425 S+D sensor: *wind speed and direction*

Vaisala HMP155 T+H sensor: *ambient temperature and humidity*

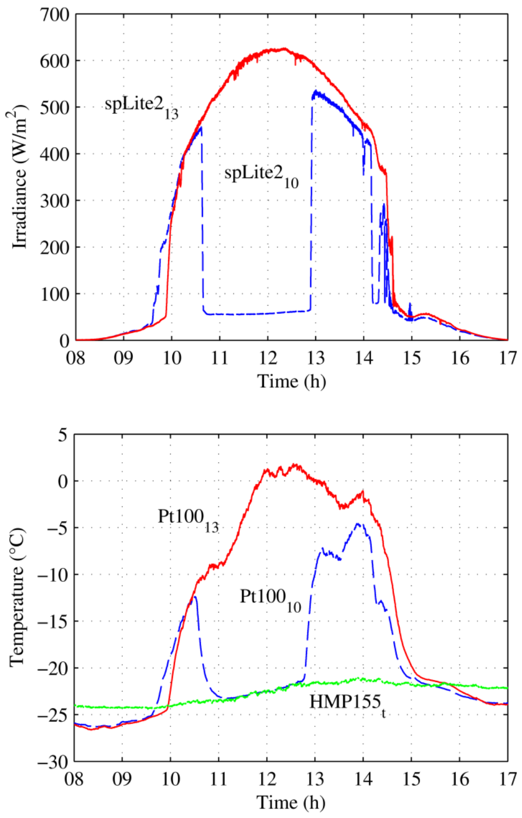
TUT solar PV power station research plant



Website: http://www.tut.fi/solar/

Thermal behaviour of PV modules

- Temperature response of PV modules depends on:
  - Climatic and environmental conditions
    - Solar radiation
    - Wind speed
    - Ambient temperature
    - Roof /ground temperature
  - Absorptivity of the modules
  - Heat capacitance of the modules
  - Mounting configuration of the modules

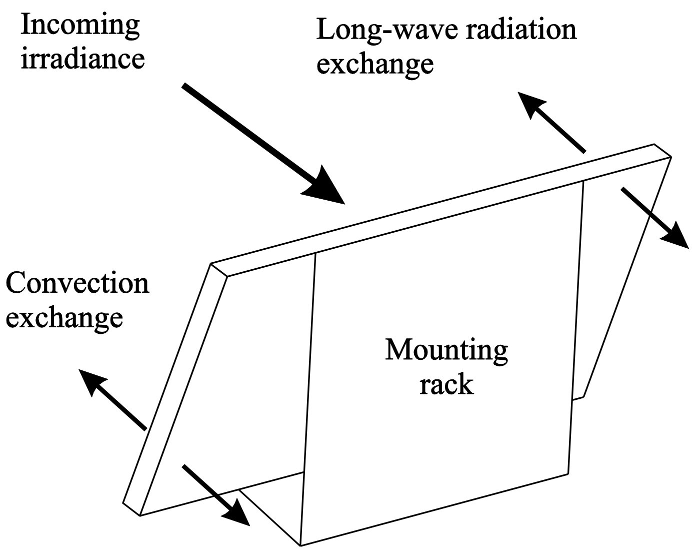


Irradiances received by two PV modules, corresponding module temperatures and ambient temperature.

Thermal behaviour of PV modules

- Dynamic thermal model of a PV module: total energy balance on the PV module leads to:

$$q_{\mathrm{in}} - P_{\mathrm{out}} - q_{\mathrm{conv}} - q_{\mathrm{lw-rad}} - C_{\mathrm{mod}} \frac{\mathrm{d}T_{\mathrm{mod}}}{\mathrm{d}t} = 0$$

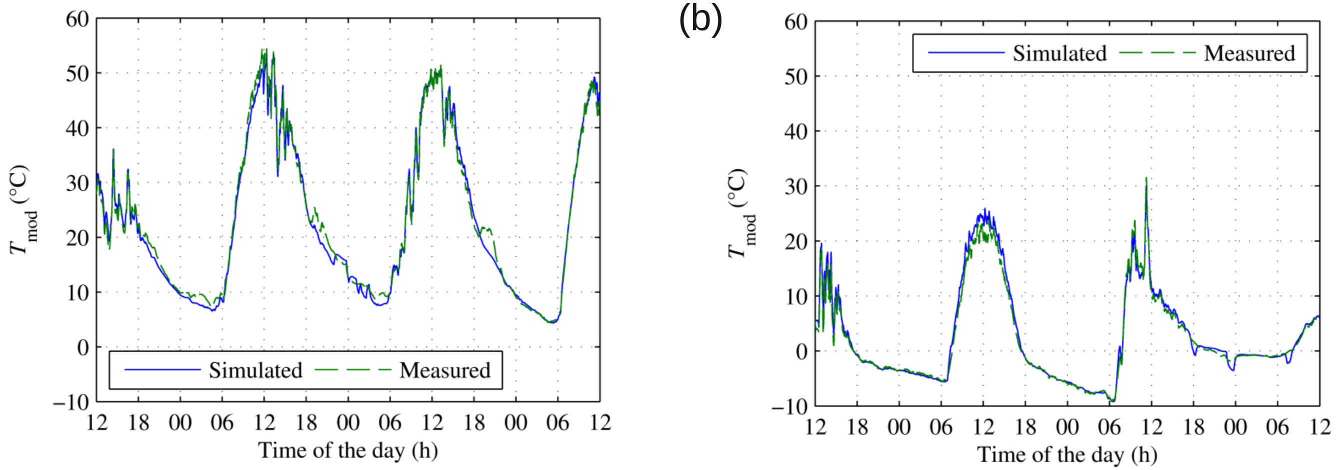


Mounting configuration of a PV module with its mounting rack.
The heat transfer processes are indicated with arrows.

Thermal behaviour of PV modules

- Accuracy of the dynamic thermal model

(a) (b)



Simulated and measured module temperatures of a PV module during 3 days in winter (a) and summer (b).

- Importance of controlling the operating temperature:
  - Important effect in the electrical performance of PV modules
  - Detection of failure or degradation of PV modules

Structure of the practical work

- Mandatory parts:
  1. Operation of PV modules
  2. Operation of series-connected PV modules under partial shading
  3. Operation of Perturb and Observe MPPT algorithm
  - A total of 6 points can be achieved from the mandatory parts.
  - A minimum of 3 points is required for acceptable performance.
  - You can revise the mandatory parts of your report once. The maximum score which can be achieved by revising the report is 3 points.
- Optional parts:
  - Thermal behavior of PV modules
  - Simulation of the operation of series-connected PV modules with real measurements
  - Up to 4 extra points can be achieved.
  - You cannot revise the optional parts after you have returned the report.

Instructions for the practical work

- Simulations will be done using the Matlab and Simulink.
- Download the files used in the practical work from POP.
- Reports will be scored based on
  - the analyses of the results
  - independence while doing the practical work
- The report can be written in English or in Finnish.
- The report should be returned in PDF format to markku.jarvela@tuni.fi.
- Dead-line is two weeks after the practical work session.
- Obey the dead-line, **late submissions will be rejected.**