PHOTOVOLTAIC SYSTEMS

OBJECTIVE

Record the characteristics of a photovoltaic module (solar cell) as a function of the luminosity

EXPERIMENT PROCEDURE

- **Measuring the *I-U* characteristics of a photovoltaic module (solar cell) at various illumination levels.**
- **Comparing the measured characteristics with a calculation in accordance with the single-diode model.**
- **Determining the relationship between the no-load voltage and the short-circuit current for various illumination levels.**

SUMMARY

A photovoltaic system converts light energy from sunlight to electrical energy. To do this, solar cells are used which are comprised of, for example, suitably doped silicon and consequently correspond to an up-scaled photodiode. Light absorbed by the solar cell releases charge carriers from their crystal bonds which result in a photoelectric current flowing opposite the forward direction of the p-n junction. It is the diode current of the solar cell that limits current output to an external load. When at the so-called no-load or idle voltage U_{OC}, this current reaches a zero value because the photoelectric current and the diode current precisely offset each other and only becomes negative when a voltage is applied that is above the no-load voltage. When a positive current range is reached, the solar cell can be operated as a generator that outputs electrical power to an external load. In the experiment, the voltage-current characteristics of this generator are measured as a function of the illumination level and described with a set of simple parameters.

REQUIRED APPARATUS

Quantity	Description	Number
1	SEK Solar Energy (230 V, 50/60 Hz)	**1017732 or**
	SEK Solar Energy (115 V, 50/60 Hz)	**1017731**
1	DC Power Supply 0 – 20 V, 0 – 5 A (230 V, 50/60 Hz)	**1003312 or**
	DC Power Supply 0 – 20 V, 0 – 5 A (115 V, 50/60 Hz)	**1003311**

BASIC PRINCIPLES

The term photovoltaic is a combination of the Greek work phos (light) and the Italian name Volta. This is in honour of *Allessandro Volta*, who, among other things, invented the first functional electrochemical battery. A photovoltaic system converts limitlessly available and free light energy from sunlight into electrical energy without causing any CO_2 emissions. To do this solar cells are needed, which in most cases are made of suitably doped silicon and thus corresponds to a scaled-up photodiode. Prior to reaching the external contacts of the solar cell, first the light absorbed by the solar cell releases charge carriers from their crystal bonds (internal photoeffect), due to the electrical field achieved through suitable dosing of the p-n junction the electrons drift to the n-doped side and the holes drift to the p-doped side (Fig. 1). This is how a photoelectric current arising flows in the reverse direction to the forward direction of the p-n junction, which can output the electrical power to an external load.

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The photoelectric current I_{Ph} is proportional to the illumination level Φ:

(1) $$I_{Ph} = \text{const} \cdot \Phi$$

It is superpositioned by the diode current in the forward or conducting direction:

(2) $$I_D = I_S \cdot \left(\exp\left(\frac{U}{U_T} \right) - 1 \right)$$

I_S: Saturation current, U_T: Temperature voltage

and grows ever stronger the more voltage U between the contacts exceeds the diffusion voltage U_D. Thus the current I output available for external loads is limited by the diode current:

(3) $$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot \left(\exp\left(\frac{U}{U_T} \right) - 1 \right)$$

It reaches the value zero for so-called no-load or idle voltage U_{OC} because the photo-electric current and the diode current mutually offset each other and only becomes negative if a voltage $U > U_{OC}$ is applied.
In the range of positive currents the solar cell can be operated as a generator to output electrical energy to an external load. Eq. (3) expresses the *I-U* characteristic of this generator. Since in actual practice the photo-electric current I_{Ph} is considerably higher than the saturation current I_S, we can derive from (3) the following relationship for the idle voltage:

(4) $$U_{OC} = U_T \cdot \ln\left(\frac{I_{Ph}}{I_S} \right).$$

If the terminals of solar cell are short-circuited, the cell supplies the short-circuit current I_{SC}, which corresponds to the photo-electric current since $U = 0$ according to Equation (3). Consequently, we obtain:

(5) $$U_{OC} = U_T \cdot \ln\left(\frac{I_{SC}}{I_S} \right) \text{ where } I_{SC} = I_{Ph}$$

Eq. 2 describes the diode response within the framework of the so-called standard model. Here the saturation current I_S happens to be a material variable, which depends on the geometrical and electrical data of the solar cell. For the temperature voltage U_T, the following holds true:

(6) $$U_T = \frac{m \cdot k \cdot T}{e}$$

$m = 1 \ldots 2$: Ideal factor
k: Boltzmann's constant, e: Elementary charge,
T: Temperature in Kelvin

In a more precise examination of the characteristic, leakage currents at the edges of the solar cells and point-like short-circuits of the p-n junction would be taken into consideration, which can be modelled using a parallel resistance R_P. Eq. 3 then becomes

(7) $$I = I_{Ph} - I_S \cdot \left(\exp\left(\frac{U}{U_T} \right) - 1 \right) - \frac{U}{R_P}$$

So in order to achieve effectively utilisable voltages in the range between 20 and 50 V, in practice we see a significant number of solar cells connected in series. Such a series connection configuration comprised of 18 solar cells is illuminated in the experiment using a halogen lamp of variable luminosity and the current-voltage characteristics of the module are recorded at varying luminosities.

EVALUATION

The family of current-voltage characteristics from the photovoltaic module (Fig. 2) can be described using Equation 7, if regardless of the luminosity the same set of parameters i.e. I_S, U_T and R_P is inserted and the photo-electric current I_{PH} is selected as a function of the luminosity. Of course the temperature voltage is the 18 times the value estimated in Eq. 6 because the module consists of 18 solar cells connected in series. A parallel circuit comprised of an ideal power source, a series connection of 18 semi-conductor diodes and an ohmic resistor, see Fig. 3 is provided as an equivalent circuit diagram for the photovoltaic module. The power source supplies a luminosity-dependent current in the reverse direction.

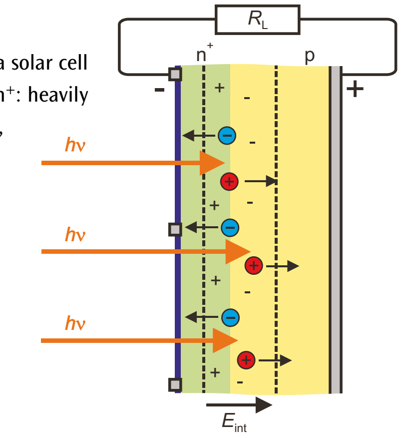

Fig. 1: Schematic depiction of a solar cell as a semi-conductor element, n^+: heavily n-doped area, p: p-doped area,
⊕: mobile hole produced by light absorption,
⊖: free electron produced by light absorption,
+ : stationary positive charge,
- : stationary negative charge,
E_{int}: electrical field imposed by the space-charge differential,
R_L-load resistance

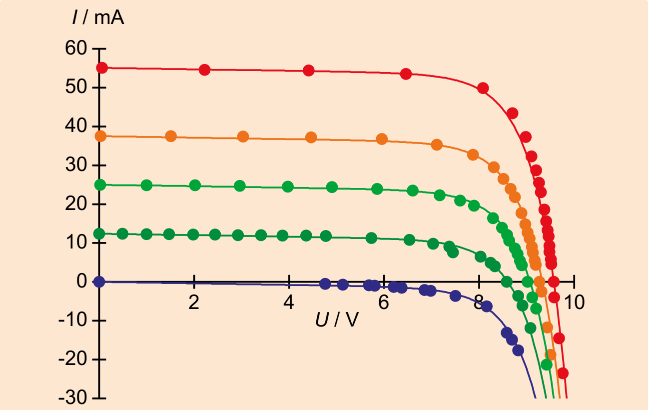

Fig. 2: Current-voltage family of characteristics of a photovoltaic module for five different luminosities

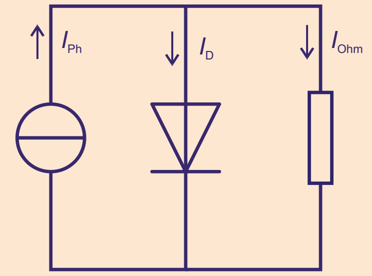

Fig. 3: Equivalent circuit diagram for the photovoltaic module