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Sensor System for Long-term Recording of Photovoltaic (PV) IV-curves

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Introduction

The purpose of this paper is to present a recording system for long-term investigation of PV panel dynamics under partial shading conditions. The system is intended to be a low-cost system deployable for stand-alone field use and long-term data recording at PV-plants. Passing clouds will affect the energy production due to lower irradiation and the resulting induced imbalance in current/voltage characteristics [1]

Figure1. Arduino platform; ATMega2560 board and Memoire SD/RTC-shield [2].

Hardware platform

The solar irradiation and the resulting IV-curve of an attached PV-panel are measured and stored in one-second intervals. The recording unit is based on the low cost Arduino platform [2].

The system consists of 3 main parts: CPU unit with ADC, communication etc. (Arduino ATMega2560), SD storage shield with Real-time-clock, custom designed analog interface/sweep unit and electronic load unit, based on power MOSFETs, as well as Hall-effect based current sensor with low internal resistance in the current path ($100\mu\Omega$). The use of a Hall-effect based current sensor (Allegro ACS758LBC) eliminates the need for a series resistor in the current path and allows for future extension to large currents up to and above 50A [3].

The analog power stage must comply to the power level of the PV-source to be monitored, but as the sweep time is kept short, the average power dissipation will be significantly lower than in continuous operation at the maximum power point of the source. The device presented here primarily addresses the measurement around the maximum power point of a panel, therefore no special attempt is made to measure the true short circuit current I_{SC}, which can be a difficult task in itself due to the on-resistance of transistors. See figure 2.
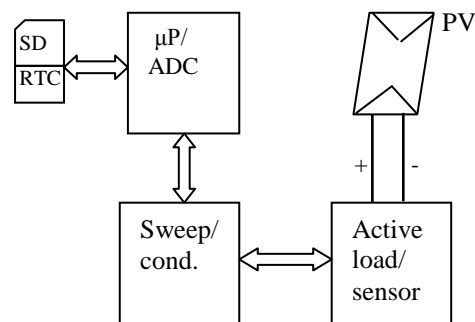

Figure 2. Basic components of the recording unit.

The recording unit is initially powered by battery, but an extended version, harvesting energy from the solar panel under test, is under development.

Due to the price and size of large heat sinks the load handling demand of the sweep unit is an important design parameter, in order to keep the overall cost of the unit to a minimum. The average power dissipation depends on the IV-curve of the panel/string to be monitored and the sweep profile (fast/slow). The needed cooling capacity will therefore depend on the sweep profile.

In order to estimate the power dissipation and thus the needed cooling requirements, a system model has been implemented,

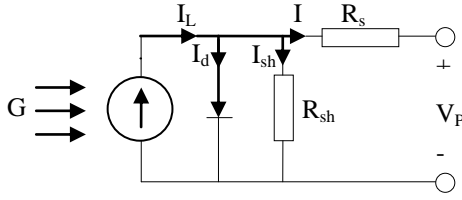based on the classical one-diode model of a solar cell [4] shown in figure 3.

Figure 3. One-diode model of a PV-cell [4].

The one-diode model IV-characteristics of a solar cell are given by Eq. 1.

$$I = I_L - I_0 \left(e^{\frac{q(V_P + R_S \cdot I)}{n \cdot k \cdot T}} - 1 \right) - \frac{V_P + R_S \cdot I}{R_{Sh}} \qquad (1)$$

A closed-form exact solution of Eq. 1 for the unknown current I is not available, so numerical methods should be applied [4]. A Newton-Raphson method has been applied in this study, following the approach outlined in [4]. Knowledge of the open circuit voltage V_{OC}, the temperature dependency and the saturation current is mandatory to complete the model.

$$I_L(T) = I_L(T_{ref}) + \alpha(T - T_{ref}) \qquad (2)$$

$$I_L(T_{ref}) = I_{SC}(T_{ref}) \frac{G}{G_{ref}} \qquad (3)$$

$$I_0(T_{ref}) = \frac{I_{SC}(T_{ref})}{\left(e^{\frac{q \cdot V_{OC}(T_{ref})}{n \cdot k \cdot T}} - 1 \right)} \qquad (4)$$

$$V_{OC}(T) = V_{OC}(T_{ref}) + \beta(T - T_{ref}) \qquad (5)$$

where G is the irradiation level, k the Boltzman's constant, q the electron charge, α and β the temperature coefficients for the voltage and current, respectively. *n* is the ideality factor of the junction (between 1 and 2)**.** For an estimation of R_{sh} and R_s see [4]. The subscript ref refers to the Standard Test Conditions (STC) T_{ref}=25°C; G_{ref}=1000W/m^2 [5]. The short-circuit current I_{SC} and the open circuit voltage V_{OC} at T_{ref} are panel parameters stated by the manufacturer.

Regulation vs. power dissipation

Examples of active loads are known from literature and the regulation schemes used can be classified as either direct or current/voltage controlled [6,7]. Both constant voltage and constant current implies the use of a regulator/control

function, as shown in figure 4 and in [6], where a direct drive on the gate terminal without feedback loop simplifies the circuitry. This study will compare the direct drive and the voltage feedback schemes.

Loads for PV-systems are typically dimensioned for continuous power, meaning that even modest power levels will require extensive cooling effort. But if the IV-curves of a panel can be measured fast, the average power requirement can be reduced, thus enabling a smaller and cheaper unit. The power dissipation as well as the required sampling rate will depend on the scheme chosen.
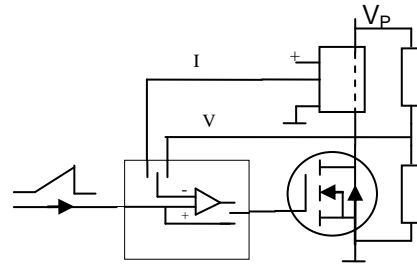

Figure 4. MOSFET/Hall-sensor based load circuit with selectable voltage, current or direct drive.

The active element chosen in this study is a HEXFET Power MOSFET of type IRF530 [8]. The threshold voltage V_{th} of a FET is in the range of a few volts and the panel voltage V_p around the MPP is typically 30-40V, so the FET will be operating mainly in the active/saturated region, where the drain current I_{Drain} is essentially independent of the drain-source voltage V_{DS} [7,9]. Thus I_{Drain} is essentially a function of the applied gate-source voltage $V_{GS.}$
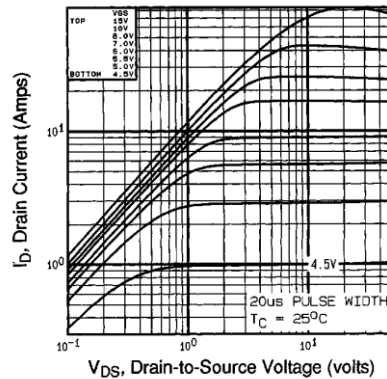

Figure 5. Output characteristics for the IRF530 MOSFET [8].

The following conditions apply:

$$V_{panel} = V_{DS}$$

$$V_{DS} \gg V_{th}$$

For operation in the active/saturated region I_{Drain} can be approximated by Eq. (6) [9].

$$I_D = \frac{K_n}{2}(V_{GS} - V_{th})^2 \qquad (6)$$

where Kn is a device specific constant related to the internal FET geometry.

For operation in the ohmic region I_D can be expressed by Eq. (7).

$$I_D = k[2(V_{GS} - V_{th})V_{DS} - \frac{1}{2}V_{DS}{}^2] \qquad (7)$$

The instantaneous power P_{load} dissipated in the FET in the active region is, for $V_{GS} > V_{th}$.

$$P_{load} = V_{DS} \cdot \frac{K_n}{2}(V_{GS} - V_{th})^2 \qquad (8)$$

By combining the mapped IV-relationship, based on Eq. (1-5), with Eq. (6-8) the instantaneous power P_{load} can be calculated.

The average power P_{av} dissipated in the load can be calculated from the simulated IV-relationship (Eq. 1-5), the applied drive voltage and the transfer characteristic of the MOSFET.

$$P_{av} = \frac{1}{T_{sample}} \int_0^{t_{sweep}} P_{load}(t)\, dt \qquad (9)$$

Simulation results

Different schemes have been simulated for a number of linear sweep rates and solar irradiation. The simulations are based on data for a commercial PV-panel (Sunpower SPR-225, W_{peak}=225W, V_{OC}= 0.674V, I_{SC}=5.87A [9]). See figure 6.
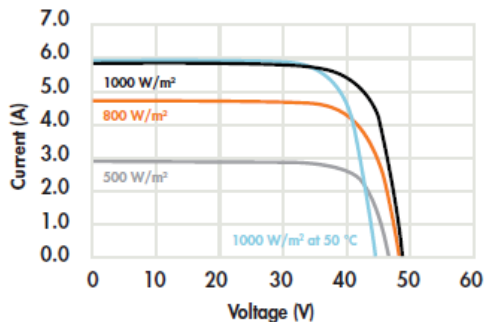

Figure 6. IV-curves for a Sunpower SPR-225 panel [10]

Direct linear ramp drive

The result of using Eq. (8) to simulate the power dissipation in the FET, during 4 different direct linear ramp input signals on the FET gate, is illustrated in figure 7. Ramp rates are 10-15-20-25 V/s. The irradiation level is 1000W/m^2.
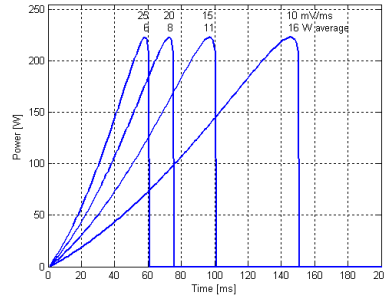

Figure 7. Power dissipation vs. time for 10-25 mV/ms sweep rates.

The power dissipation generated by varying illumination and fixed sweep rate is shown in figure 8.
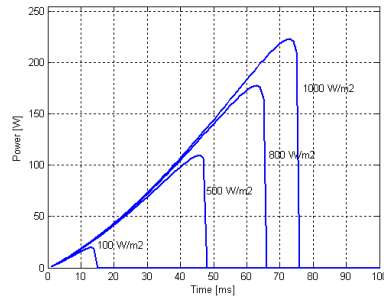

Figure 8. Power dissipation for a selected sweep-rate (20 mV/ms) as function of irradiation level (100-80-50-10% of STC).

Voltage mode, linear ramp

Applying a voltage feedback loop ensures that the panel voltage will track the input ramp voltage. The simulated power dissipation generated by 4 linear input ramps is shown in figure 9.
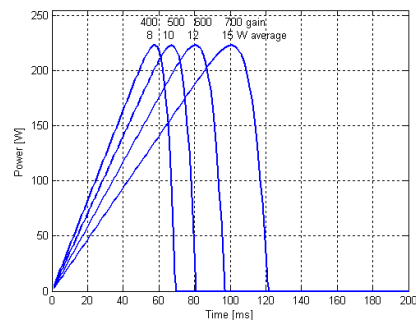

Figure 9. Power dissipation as function of time for 4 sweeps when linear voltage feedback is applied.

The simulated power dissipation generated by varying the irradiation level at a fixed input ramp is shown in figure 10.
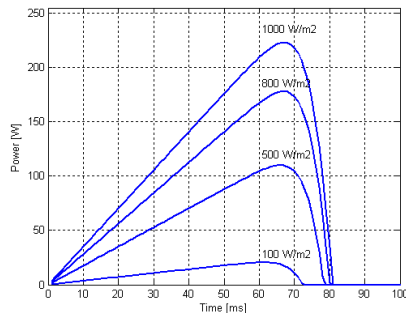
Figure 10. Power dissipation for a voltage feedback system at a fixed linear sweep-rate as function of irradiation level (100-80-50-10% of STC).

By comparing figures 8 and 10 it can be observed that the voltage based regulation scheme has an advantage over the direct drive scheme regarding required sampling speed. Both schemes give comparable power dissipation as function of sweep time, but a considerable difference in the time available for recording the IV-values can be observed. A system with a direct drive mode will generate power curves, whose time duration will depend significantly on the irradiation level. As low cost microprocessor platforms have limited sample rates in general it is recommendable that scanning systems for PV-panels are not based on the direct drive scheme.

Initial test results

A prototype of the recording unit has been tested on a solar panel simulator with a peak power of 80W. An example of the power calculated from the logged IV-data per scan for 1 hour of continuous recording (3600 datasets) is shown in figure 11. The current and voltage values are sampled syncroneously, within 200 uS.

Conclusion and outlook

A stand-alone low-cost microprocessor platform including data storage has been designed for long-term recording of PV IV-characteristics. By default, the scan period is one second. During each scan 200 IV-values are measured and stored on an SD-card. Approx. 6 months of recordings can be stored on a 32 GB card. The implementation of a short scanning time lowers the demand for handling high power levels in the load circuitry, due to low average power dissipation.
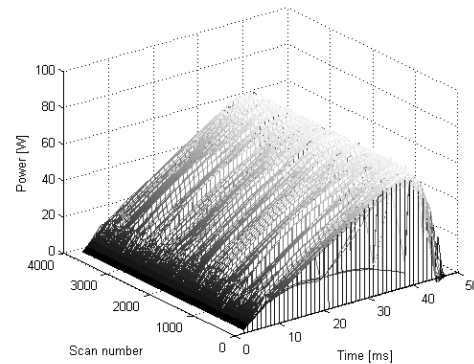

Figure 11. Calculated power dissipation for a direct drive scheme with a slew rate of 15 mV/ms, based on 3600 recorded scans over 1 hour on a solar panel simulator. A few bad scans, due to noise, are visible.

The real-time-clock functionality allows time stamps to be recorded as well as synchronous measurements done by several units. Future work will include wireless synchronization, supply via energy harvesting and PV-string scanning up to 15 kW.

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