

# Basic Linear-Mode Solar-Cell Simulators

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**Abstract** - The paper describes basic types of linear-mode power systems for simulating voltage/current characteristics of solar cells modules. Starting from a current source with a chain of diodes arranged in parallel (being the most simple equivalent circuit diagram of a solar power module) a very basic solar module simulator using a bipolar power transistor and based on the “amplified diode” concept is developed. Furthermore, this principle is modified utilizing a linear-mode series regulator in order to reduce the dissipated power at no-load condition. The paper includes a detailed description of the different operating principles, gives dimensioning guidelines and presents also measurement results taken from laboratory prototype systems.

## I. INTRODUCTION

The importance of photovoltaic (PV) energy generation has been increased rapidly in recent years. Almost all PV applications are characterized by a power electronic converter in order to (i) adopt the DC output voltage of the solar power module to the particular load, (ii) to perform DC-to-AC (sine-wave) conversion, and (iii) to achieve galvanic isolation. A specific task of any PV converter, however, is the maximum power point tracking (MPPT), i.e., to maximize the PV module’s power generation by adjusting the converter’s DC input voltage. Hence, in addition to the converter’s pure conversion efficiency (which is defined as a weighted average value  $\eta_{\text{EURO}}$  of measurements at different load ratings), state-of-the-art PV systems are tested/specified also concerning their MPPT efficiency  $\eta_{\text{MPPT}}$  representing the quantity which ratio of the energy theoretically provided by the solar-cells can be utilized by the converter system [1]. Due to the fact that  $\eta_{\text{EURO}}$  and  $\eta_{\text{MPPT}}$  of modern PV converters usually are very high, compliance tests will require very precise equipment. Besides according power meters, especially an accurate solar-module simulator is required. Usually such a testing system consist of a programmable linear or switch-mode power supply [1, 2] directed by a numeric controller which implements the aimed  $V/I$ -characteristic of the solar module to be simulated in connection with high resolution voltage/current measurement unit.

For a number of applications (e.g., pre-compliance testing, converter development, demonstration or education purposes etc.) the mentioned precise an expensive testing equipment is not required, at least not in an early design state. Furthermore, frequently partial shading effects have to be analyzed if several solar modules are operated in a combined arrangement (e.g., in a series connected string) at different operating/irradiation conditions. This is of specific importance in case

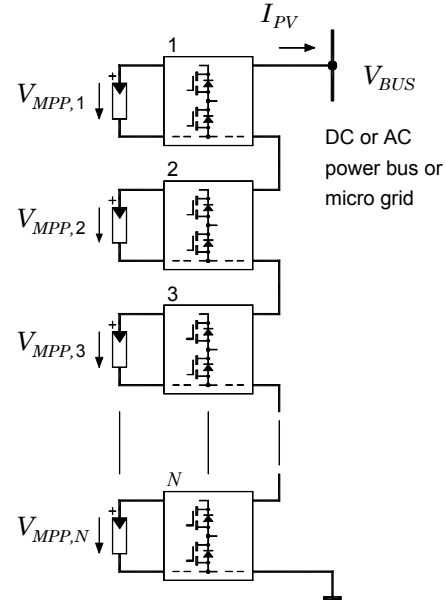


Fig. 1. Distributed solar converter based on a series arrangement of  $N$  low-voltage switching cells operated at different power levels.

of cascaded (“multi-cell”) inverter topologies (Fig.1) based on low-voltage MOSFETs resulting in a very high efficiency system as proposed in [3, 4]. Here the question arises how and under which constraints  $N$  converter cells can be operated such that each of the solar modules is working under individual MPP conditions. A further control difficulty will arise if the converter cell is integrated into the solar module’s terminal box (distributed converter concept) without any possibility to exchange information between the individual cells on contrary to multi-cell concepts based on a centralized systems control as proposed in [5]. For the design procedure and the test of such distributed solar converters, therefore a simple and cost efficient solar cell simulator shall be developed enabling an easy test of a distributed PV converter system operating at different MPP/irradiation conditions.

## II. SOLAR-MODULE MODELING

As described in PV textbooks, a single solar cell can be regarded as a PN-diode-junction following the  $V/I$ -relation  $I_D = I_S(\exp(V_D/V_T) - 1)$  (Fig.2a, with  $I_S$ ...saturation current,  $V_T$  ... thermal voltage  $V_T = kT/q$ ) leading to the well known basic equation

$$I = I_{PH} - I_D = I_{PH} - I_S(\exp(V/V_T) - 1) \quad (1)$$

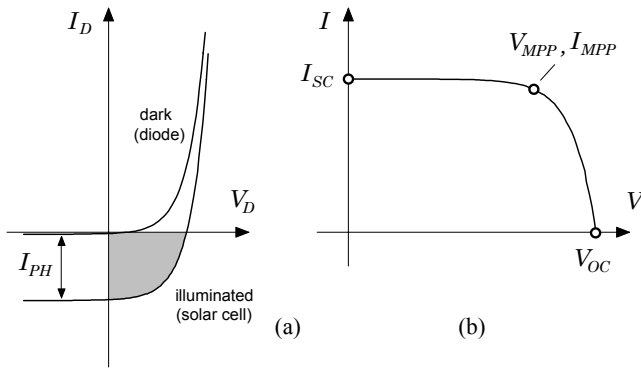


Fig. 2. Basic behavior of a PN-junction with and without illumination (a) and typical  $V/I$ -characteristic of a solar cell (b).

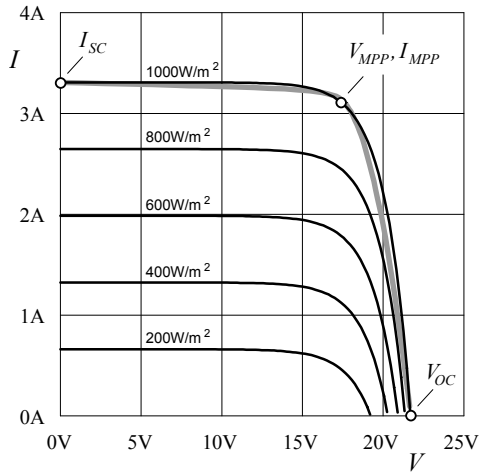


Fig. 3.  $V/I$ -characteristic of a Kyocera KC50T solar module (shaded data-sheet curve) as compared to the simple "three-point model" of Eq.(2).

considering the "active" operating quadrant (indicated in Fig.2a) of the solar cell (Fig.2b). Equation (1) is also valid for whole solar modules consisting of  $n$  cells connected in series if  $V_T$  is adopted accordingly ( $V_T \rightarrow nV_T$ ) provided that partial shading of cells is avoided.  $I_{PH}$  represents the photoelectric generated current being directly proportional to the irradiation level and which appears also as short circuit current of the module ( $I_{SC} = I_{PH}$  for  $V = 0$ ).

In general,  $I_S$  and also  $nV_T$  are not known directly, however, the data sheet of a solar module at least specifies short circuit current  $I_{SC}$ , open circuit voltage  $V_{OC}$  and MPP data set  $V_{MPP} / I_{MPP}$  at standard testing conditions (STC, i.e., irradiation level 1000W/m<sup>2</sup>, 25°C). Using these three data points, (1) can be rewritten to

$$I = I_{SC} - I_{SC} \left[ 1 - \frac{I_{MPP}}{I_{SC}} \right]^{\frac{V-V_{OC}}{V_{MPP}-V_{OC}}} \quad (2)$$

which fully describes the solar module according to the simple PN-diode model. The evaluation of (2) for a, e.g., 54W-Kyocera KC50T module for which the following values

$$V_{OC} = 21.7V \quad I_{SC} = 3.31A \quad V_{MPP} = 17.4V \quad I_{MPP} = 3.11A$$

are specified, shows a quite feasible coincidence (Fig.3) with the  $V/I$ -characteristic given in the module's datasheet.

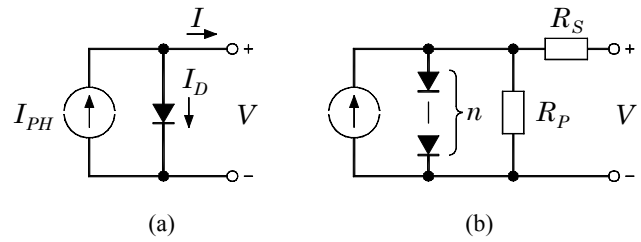


Fig. 4. (a): Basic equivalent circuit diagram of a solar cell; (b): circuit valid for a uniformly irradiated solar power module of  $n$  cells with improved curve fitting.

### Equivalent Circuit Diagrams

The term  $I = I_{PH} - I_D$  in (1) directly suggests the most basic equivalent circuit diagram for solar cells consisting of a current source  $I_{PH}$  (representing the PV current generation) arranged in parallel to a diode providing the exponential dependency (Fig.4a). For a total PV module,  $n$  diodes have to be considered in a string (equal irradiation and temperature conditions of each cell of the module assumed). This basic circuit can be improved by series/parallel resistors (Fig.4b) which model the  $V/I$ -characteristic's slope in the vicinity of  $V_{OC}$  (resistor  $R_S$ ) and  $I_{SC}$  (resistor  $R_P$ ).

**Remark:** A closer examination of Fig.3 indicates that the actual  $V/I$ -curve shows a somewhat sharper bending which could be modeled by adding a second exponential term into (1). The assignment of the parameters of the such a two-diode-model [6], however, is not possible just based on four datasheet values as performed for deriving (2) but will require numerical curve fitting techniques.

### III. SHUNT-MODE SIMULATION OF PV MODULES

Starting from Fig.4a a very basic simulation of a PV module can be simply realized by using a laboratory power supply (PS) whose current limitation  $I_{LIM}$  is adjusted to the value  $I_{SC}$  and which is "terminated" by a chain of power diodes (Fig.5a). Different irradiation conditions, therefore, can be simulated by adjusting the current control of the PS. The number of diodes  $n$  has to be increased such that  $V_{OC}$  of the solar module to be modeled is achieved and the PS's open circuit voltage  $V_0$  is chosen to  $V_0 > V_{OC}$  in order to guarantee current mode control. In Fig.5b a Pspice simulation of such a circuit is given and shows good coincidence with the datasheet values of KC50T. It has been found that 600V diodes give a better approximation than low-voltage devices. Due to the more ohmic behavior of the 600V-diodes,  $R_S$  can be omitted, whereas  $R_P = 200\Omega$  gives good approximation in the region of small output voltages.

Figure 5c clarifies the power relationships. According to the shunt regulator principle, the circuit shows zero efficiency for no-load operation  $V = V_{OC}$ ,  $P_{OUT} = 0$ . In this case the maximum PS output power  $P_{PS}$  totally is dissipated in the diode chain ( $P_{LOSS} = P_{PS}$ ). On the other hand in the vicinity of MPP good efficiency rates (defined as  $\eta = P_{OUT}/P_{PS}$ ) of  $\eta \approx 0.8 \dots 0.9$  appear. A serious drawback of the circuit, however, is that for all diodes power devices have to be used which

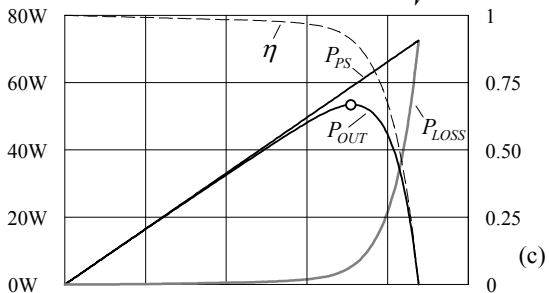
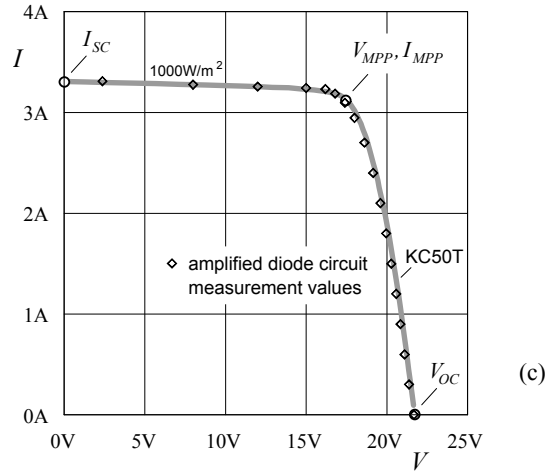
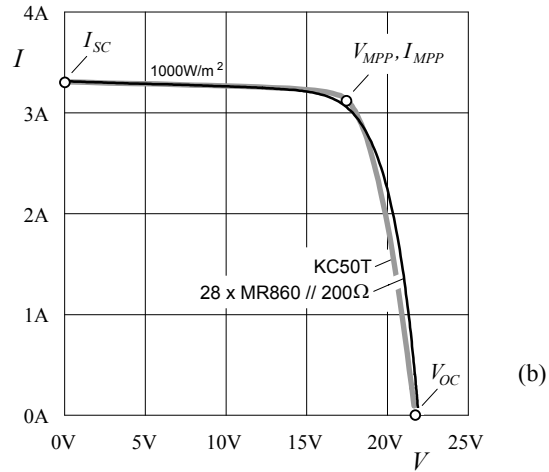
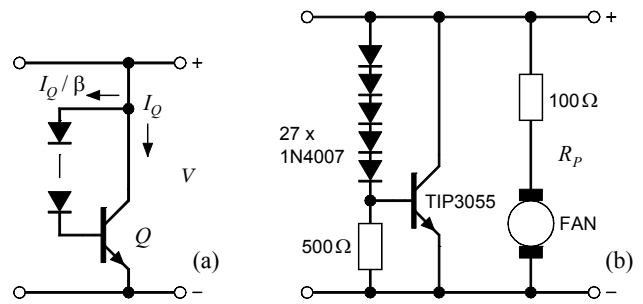
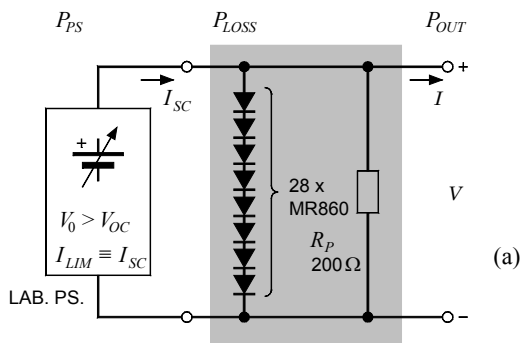


Fig. 5. (a): Circuit diagram of a basic shunt-mode solar module simulator; (b):  $I/V$ -characteristic of the circuit in comparison to the datasheet values of a KC50T-module; (c): power relations and efficiency.

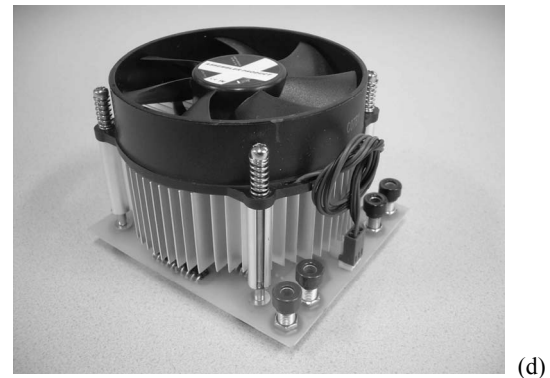


Fig. 6. (a): Principle of an amplified diode solar module simulator; (b): realized circuit; (c): measured  $I/V$ -characteristic in comparison to the datasheet values of a KC50T-module; (d): realized laboratory prototype.

have to be mounted on a proper cooler. In the case at hand each of the 28 diodes may dissipate  $3.31\text{A} \cdot 21.7\text{V} / 28 \approx 2.6\text{W}$ , requiring, e.g., TO-220 devices which results in a high mounting effort. Furthermore, the thermal impedance of the cooler should be quite good, otherwise the chip temperature distinctly increases leading to an unwanted reduction of  $V_{OC}$  due to the temperature coefficient of the forward voltage ( $\approx 2\text{mV/K}$ ).

#### Amplified Diode PV Simulator

To ease the realization of the circuit and avoid the temperature effects mentioned before, a novel simulator topology is introduced. As shown in Fig.6a this circuit uses a diode chain connected from collector to base of a bipolar power transistor  $Q$ . With this, the main power losses now appear in the power transistor due to the fact that the diode current is reduced, by the current gain  $\beta$  of the power transistor. Hence, for this “amplified diode” simulator standard (i.e., non-power) diodes

will be sufficient. Nevertheless, the diode self heating largely is reduced such that only the single power transistor (which does not contribute substantially to the  $I/V$ -characteristic of the total circuit) has to be mounted on the cooler. **Remark:** The basic loss relations of Fig.5c (shunt regulator principle) are still valid for the amplified diode concept.

The actual circuit (Fig.6b) consists of a  $27 \times 1\text{N}4007$  diodes feeding a TIP3055 transistor. All components are located on a  $10 \times 10\text{cm}^2$  PCB (Fig.6d) with  $Q$  mounted horizontally with overhead collector tab such that a standard low-cost CPU cooler can be applied. As a result of a prior Pspice simulation a  $500\Omega$  resistor is added between base and emitter to improve curve fitting. The parallel resistor ( $R_p = 200\Omega$ ) of Fig.5a here

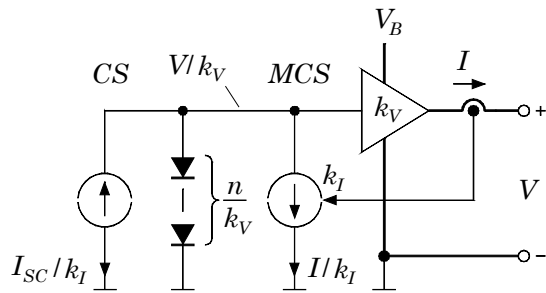


Fig. 7. Basic principle of a series-mode solar module simulator.

is realized by a series connection of a  $100\Omega$  resistor with the fan motor whose equivalent resistance has been found also to approximately  $100\Omega$ . This avoids any auxiliary power supply and leads further to some kind of load dependent cooling characteristic. The measurement results taken from the laboratory prototype show an excellent coincidence with the actual solar power module (Fig.6c).

#### IV. SERIES-MODE SIMULATION OF SOLAR MODULES

The shunt-mode simulation described in the previous section shows (i) very high losses in case on no-load operation (e.g.,  $3.31\text{A}\cdot 21.7\text{V}\approx 72\text{W}$  for circuits Fig.5a and Fig.6a) and (ii) requires power supplies with precisely adjustable output current control. To avoid these disadvantages, therefore a series-mode solar simulator has been designed. Also this concept starts from the basic equivalent circuit diagram of Fig.4. As opposed to the shunt-mode simulator where the current source represents the full module output current  $I_{SC}$ , here this current source (CS in Fig.7) is dimensioned for currents in the mA region, i.e., a fraction  $k_I$  of the module's output current (e.g.  $k_I = 0.001 \equiv 1\text{mA/A}$ ). CS again feeds a chain of diodes, now, however, small-signal diodes will be sufficient (e.g., 1N4148). The voltage across the diodes acts as a control signal for a linear-mode power amplifier of

voltage gain  $k_V$  which generates the output voltage  $V$  of the simulator. The amplifier output current  $I$  is measured and fed back to a mirror current sink (Fig.7, MCS) which is arranged in parallel to the diodes and shows a current gain of  $k_I$ . Consequently, the solar module again is modeled by a current source/diode combination, however, in this case on a very small power level.

According to Fig.8a the MCS is implemented as an active current mirror [7] formed by a current measurement shunt  $R_{SH}$ , an operational amplifier (OPA)  $O_1$  with feed-back path  $k_I \cdot R_{SH}$  and a small-signal NPN transistor  $Q_1$ . Due to its single-quadrant operation, the linear-mode power amplifier can be realized using only a single NPN power transistor  $Q_2$  in emitter-follower configuration driven by OPA  $O_2$ . In the final prototype (Fig.8b) the module's short circuit current is programmed by the PNP-transistor current source feeding the diode chain ( $16 \times 1\text{N}4148$ ) to  $(5.6\text{V}-0.6\text{V})/1.5\text{k}\Omega = 3.33\text{mA}$  leading to  $I_{SC} = 3.33\text{A}$  as a consequence of the 1:1000 current mirror ( $k_I = 1\text{mA/A}$ , defined by the resistor ratio  $0.1\Omega/100\Omega$ ). For the power transistor a Darlington-type (TIP142) is used which can be driven directly by  $O_2$  due to its high current gain. In order to protect  $Q_2$  in case of short circuit, a current limiter (BC547B) is added to its base-emitter path. As power supply  $V_B$  no more laboratory equipment is necessary, a simple industrial SMPS will be adequate. It has to be considered, however, that the selected OPA LM358 (although allowing ground-referenced current measurement as needed for  $O_1$ ) shows a noticeable positive supply voltage margin ( $\approx 3\text{V}$ ). This effect is further enhanced by the base-emitter voltage of  $Q_2$  ( $\approx 1.2\text{V}$  due to the Darlington principle). Consequently, a supply voltage of  $V_B \approx 26\text{V}$  is required to achieve the aimed  $V_{OC} = 21.7\text{V}$ . The application of a true rail-to-rail OPA in connection with a compound Darlington transistor opens a possibility for reducing this voltage "headroom" which worsens the efficiency of the circuit. Alternatively, also a separate (increased) power supply for the OPA would be feasible as known, e.g., from audio power

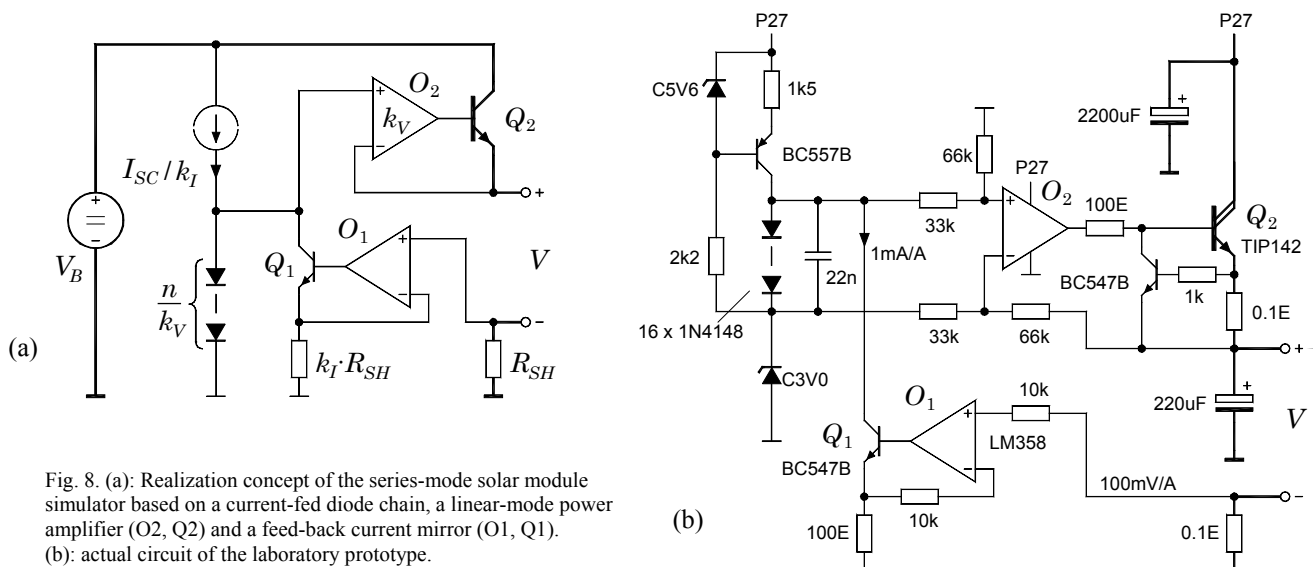


Fig. 8. (a): Realization concept of the series-mode solar module simulator based on a current-fed diode chain, a linear-mode power amplifier (O2, Q2) and a feed-back current mirror (O1, Q1). (b): actual circuit of the laboratory prototype.

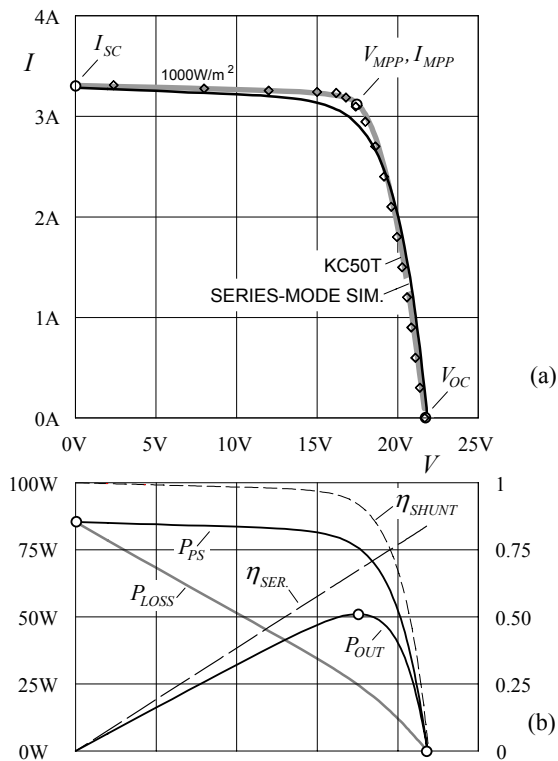


Fig. 9. (a):  $V/I$ -characteristic of the series-mode simulator in comparison to the datasheet values of a KC50T-module; marked: measured values of the amplified-diode shunt simulator; (b): power relations and efficiency.

amplifiers, complicating, however, the SMPS design. The driving stage  $O_2$  is configured as a differential amplifier in order to suppress the 3V “base voltage” of the diode chain provided by the zener diode C3V0 and which is required to guarantee sufficient collector-emitter voltage for  $Q_1$ . The voltage gain of the power amplifier is set to  $k_V = 2$  by the resistor pairs 33k $\Omega$ / 66k $\Omega$ . With this, 16 pcs. of 1N4148 have been found adequate for achieving  $V_{OC} = 21.7\text{V}$ . Finally, it should be mentioned that the 22nF capacitor across the diodes and, especially, the 220 $\mu\text{F}$  electrolytic capacitor at the output are necessary to prevent parasitic ringing.

The measurement values taken from the series-mode laboratory prototype simulator (realized similar as shown in Fig.6d for the amplified diode concept) unfortunately match the real KC50T module in an only suboptimal manner (Fig.9a). On contrary to  $I_{SC}$  and  $V_{OC}$  (which are fixed by the dimensioning) a noticeable deviation exists near the MPP region. Obviously this is a drawback of modeling a solar cell by a small-signal diode like 1N4148 at low current rates. Furthermore, also the efficiency behavior of the series-mode simulator is somewhat disappointing. As indicated in Fig.9b good efficiency rates appear in the “no-load region”  $V \approx V_{OC}$  (for all series-mode regulators  $\eta$  increases proportional to the output voltage  $\eta_{SER} = V/V_B$ ). However, already near MPP the efficiency of the shunt-mode simulator significantly exceeds the series-mode circuit. **Remark:** For common PV modules  $V_{MPP} \approx 0.75V_{OC}$  is valid typically. Assuming about 20% voltage headroom (i.e.,  $V_B = 1.2V_{OC}$ ) gives an efficiency of

only  $0.75/1.2=62\%$  at MPP in comparison to approximately 85% for the shunt-mode simulator. For improving  $\eta_{SER}$  at lower ratings of  $V$ , it would be thinkable to pre-regulate  $V_B$  to lower the voltage drop across  $Q_2$  as is known from advanced linear power amplifiers [8]. Due to the high effort, this solution shall not be pursued here, however.

## V. CONCLUSION

Different types of simple linear-mode circuits for simulating the  $V/I$ -characteristic of solar modules for PV converter testing have been analyzed. The most basic simulator topology is a plain series arrangement of power diodes fed by a laboratory power supply in current-mode control (shunt-type regulator). Numerical simulations show good curve fitting, but the circuit has the drawback of a high mounting/cooling effort and also a “distortion” due to diode self-heating. To avoid the mentioned disadvantages, the diode chain is replaced by a single bipolar power transistor with a non-power diode string connected from collector to base (“amplified diode”-principle). This new low-cost solution is characterized by (i) only a single power element which has to be mounted on the heat sink, (ii) low thermal sensitivity and (iii) good curve fitting. The main drawback are high power losses in case of no-load operation due to the shunt-mode regulator principle. Hence, additionally also a series-mode simulation circuit has been developed which avoids high no-load losses and, furthermore, requires only a plain SMPS instead of a current-controlled power supply. The proposed shunt-mode simulator, however, shows a better efficiency in the MPP region (being generally of importance for PV converter testing) and gives, furthermore, also an improved curve fitting quality in comparison to the series-mode simulator.

## REFERENCES

- [1] M. Valentini, A. Raducu, D. Sera, and R. Teodorescu, “PV inverter test setup for European efficiency, static and dynamic MPPT efficiency evaluation,” 11<sup>th</sup> International Conference on Optimization of Electric and Electronic Equipment OPTIM’08, pp. 433-438, May 2008.
- [2] H. Haerberlin, and L. Borgna, “A new approach for semi-automated measurement of PV inverters, especially MPP tracking efficiency, using a linear PV array simulator with high stability,” 19<sup>th</sup> European Photovoltaic Solar Energy Conference, Paris, France, June 2004.
- [3] H. Ertl, J. W. Kolar, and F. Zach, “A novel multicell DC-AC converter for applications in renewable energy systems,” *IEEE Transactions on Industrial Electronics*, vol. IE-45, no. 5, pp. 1048-1057, Oct. 2002.
- [4] G. R. Walker, and P. C. Sernia, “Cascaded DC-DC converter connection of photovoltaic modules,” *IEEE Transactions on Power Electronics*, vol. PE-19, no. 4, pp. 1130-1139, July 2004.
- [5] O. Alonso, P. Sanchis, E. Gubia, and L. Marroyo, “Cascaded H-bridge multilevel converter for grid connected photovoltaic generators with independent maximum power point tracking of each solar array,” 34<sup>th</sup> IEEE Power Electronics Specialist Conference PESC’03, vol. 2, pp. 731-735, June 2003.
- [6] V. Quaschnig, “Simulation der Abschattungsverluste bei solarelektrischen Systemen,” *Doctoral thesis at the TU Berlin, Germany*, ISBN 3-89574-191-4, 1996 (in german).
- [7] U. Titzte, Ch. Schenk and E. Gamm, *Electronic Circuits: Handbook for Design and Application*. Berlin-Heidelberg, Germany: Springer, 2008.
- [8] G. Gong, H. Ertl, and J. W. Kolar, “Novel tracking power supply for linear power amplifiers,” *IEEE Transactions on Industrial Electronics*, vol. IE-55, no. 2, pp. 684-698, Feb. 2008.