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 (sinewave) 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 η_{EURO} of measurements at different load ratings), state-of-the art PV systems are tested/specified also concerning their MPPT efficiency η_{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 η_{EURO} and η_{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 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.

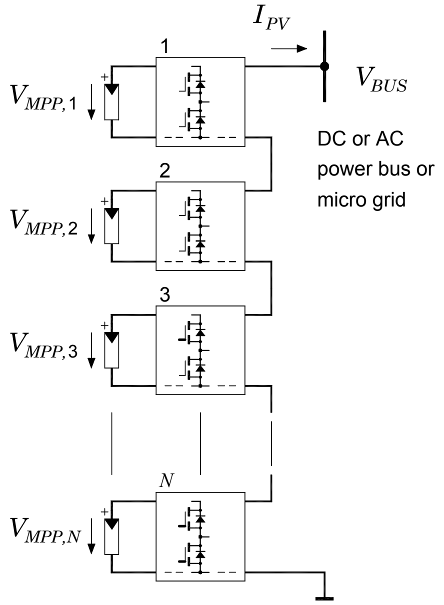


Fig. 1. Distributed solar converter based on a series arrangement of *N* low-voltage switching cells operated at different power levels.

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

$$\boxed{I = I_{PH} - I_D = I_{PH} - I_S\left(\exp(V/V_T) - 1\right)} \tag{1}$$

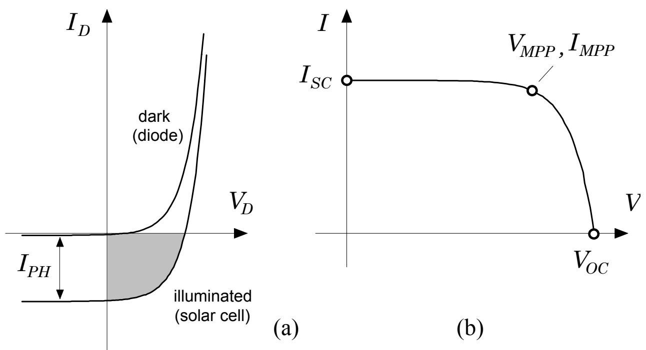


Fig. 2. Basic behavior of a PN-junction with and without illumination (a) and typical *V/I*-characteristic of a solar cell (b).

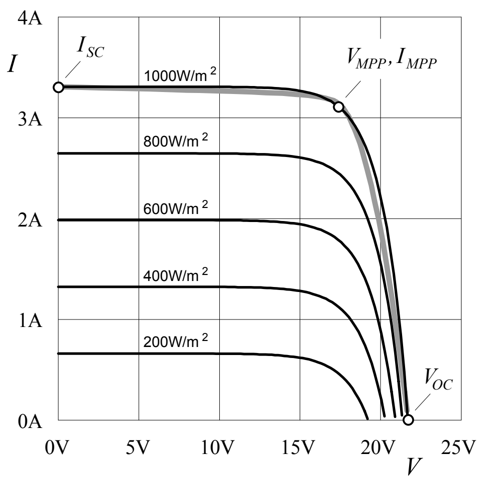


Fig. 3. *V/I*-characteristic of a Kyocera KC50T solar module (shaded datasheet curve) as compared to the simple "three-point model" of Eq.(2).

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^2, 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

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

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

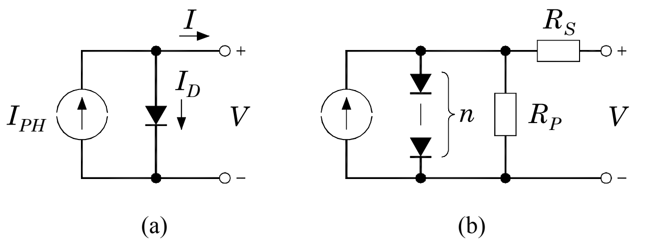


Fig. 4. (a): Basic equivalent circuit diagram of a solar cell; (b): circuit valid for a uniformly irradiated solar power module of n cells with improved curve fitting.

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 =200Ω 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...0.9 appear. A serious drawback of the circuit, however, is that for all diodes power devices have to be used which

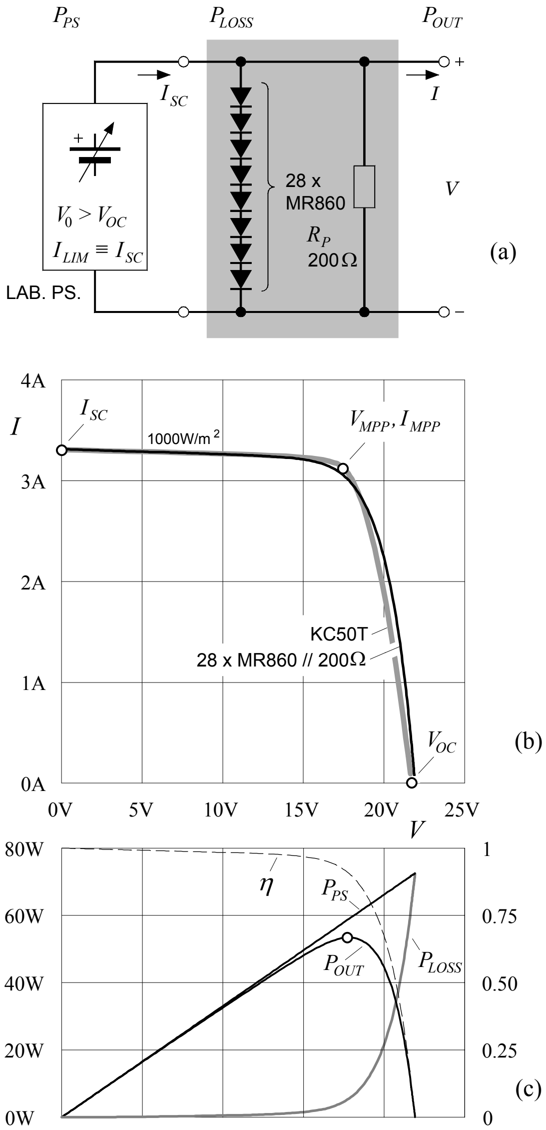


Fig. 5. (a): Circuit diagram of a basic shunt-mode solar module simulator; (b): V/I-characteristic of the circuit in comparison to the datasheet values of a KC50T-module; (c): power relations and efficiency.

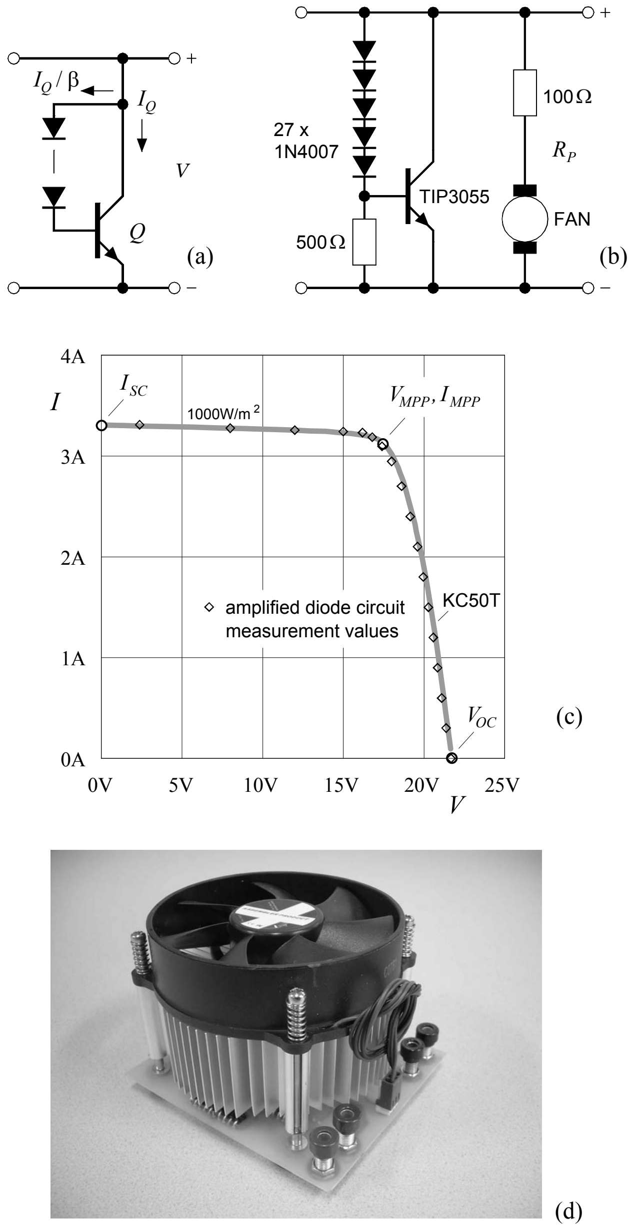


Fig. 6. (a): Principle of an amplified diode solar module simulator; (b): realized circuit; (c): measured V/I-characteristic in comparison to the datasheet values of a KC50T-module; (c): realized laboratory prototype.

have to be mounted on a proper cooler. In the case at hand each of the 28 diodes may dissipate 3.31A·21.7V/28 ≈ 2.6W, 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 (≈2mV/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, by the current gain β 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 V/I-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 27x1N4007 diodes feeding a TIP3055 transistor. All components are located an a 10x10cm^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 500Ω resistor is added between base and emitter to improve curve fitting. The parallel resistor (R_P = 200Ω) of Fig.5a here

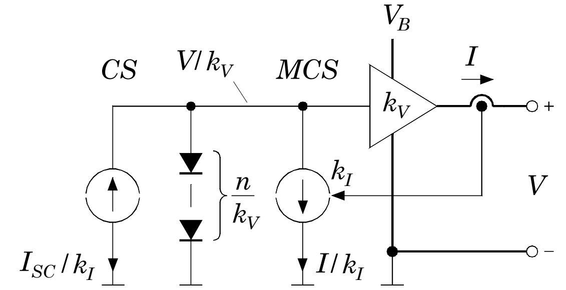


Fig. 7. Basic principle of a series-mode solar module simulator.

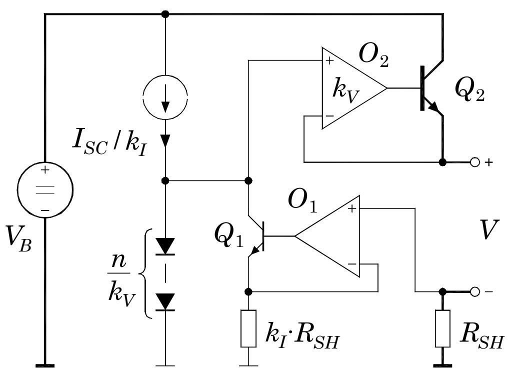
is realized by a series connection of a 100Ω resistor with the fan motor whose equivalent resistance has been found also to approximately 100Ω. This avoids any auxiliary power supply and leads further to some kind of load dependent cooling characteristic. The measurement results taken from the laboratory 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., 3.31A·21.7V≈72W 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. $k_I = 0.001 \equiv$ 1mA/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 (16x 1N4148) to (5.6V–0.6V)/1.5kΩ = 3.33mA leading to I_{SC} = 3.33A as a consequence of the 1:1000 current mirror (k_I = 1mA/A, defined by the resistor ratio 0.1Ω/100Ω). 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 (≈3V). This effect is further enhanced by the base-emitter voltage of Q_2 (≈1.2V due to the Darlington principle). Consequently, a supply voltage of $V_B \approx$ 26V is required to achieve the aimed V_{OC} = 21.7V. 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

(a)



(b)

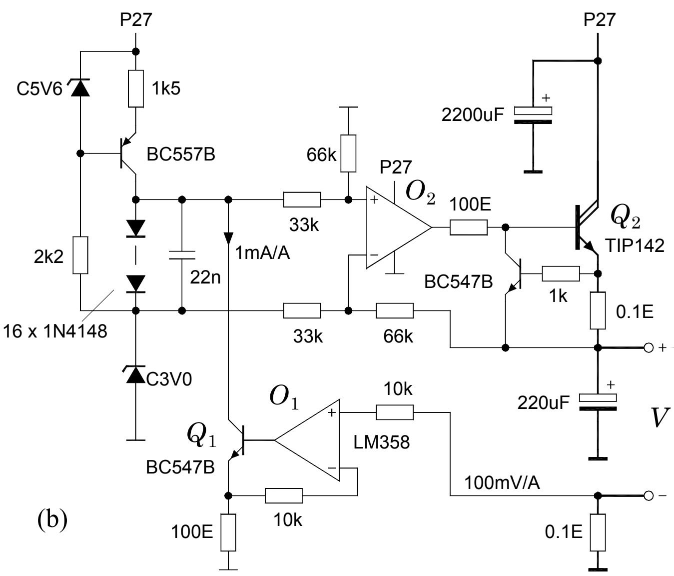


Fig. 8. (a): Realization concept of the series-mode solar module simulator based on a current-fed diode chain, a linear-mode power amplifier (O2, Q2) and a feed-back current mirror (O1, Q1).
(b): actual circuit of the laboratory prototype.

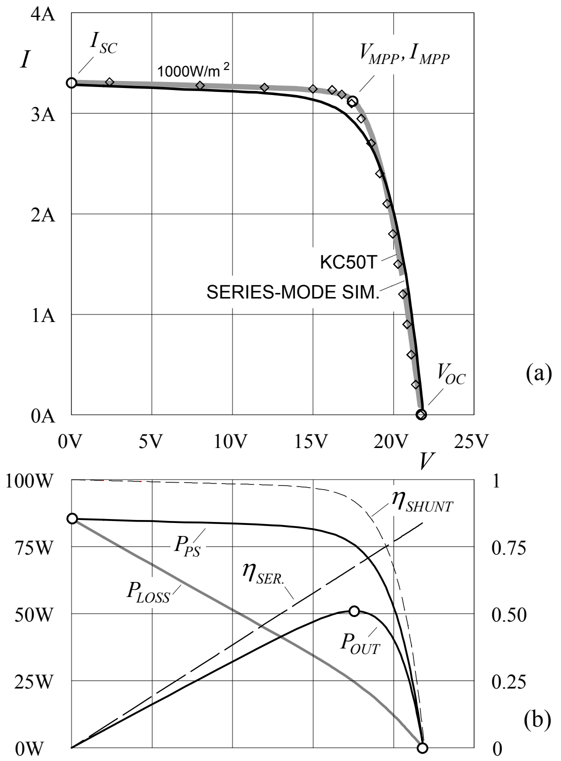


Fig. 9. (a): V/I-characteristic of the series-mode simulator in comparison to the datasheet values of a KC50T-module; marked: measured values of the amplified-diode shunt simulator; (b): power relations and efficiency.

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 33kΩ/ 66kΩ. With this, 16 pcs. of 1N4148 have been found adequate for achieving V_{OC} = 21.7V. Finally, it should be mentioned that the 22nF capacitor across the diodes and, especially, the 220µF 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 noticable 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 η 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 $V_{MPP} \approx 0.75 V_{OC}$ is valid typically. Assuming about 20% voltage headroom (i.e., $V_B = 1.2 V_{OC}$) gives an efficiency of only 0.75/1.2=62% at MPP in comparison to approximately 85% for the shunt-mode simulator. For improving η_{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.

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