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Analysis of the Analogous Models for Photovoltaic Cells by Using of Comparison Models with the Real Modules

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***Abstract*— Standard models used for modeling of photovoltaic cells give partially satisfactory results, which are mostly depending on the physical-mathematical model and of the technology of the photovoltaic cells used. This paper presents the comparison of the characteristic curves obtained by simplified diode model in addition to 1- diode model with the characteristic curves generated by using the parameter of the real photovoltaic modules of three different manufactures. We show the differences in the quality factor according to the model used and give a reference to the limits of the current models.**

Keywords—Modeling, Photovoltaic cells, Simulation component;

I. INTRODUCTION

The analogous model of the current photovoltaic technologies, in particular the silicon-based mono-crystalline as well as polycrystalline solar cells are investigated in regard of their exactness and compared with the real photovoltaic (PV) cells. In diverse publications the topographic influence as well as the inverter-feedback on the PV cells were presented, which up to now were not taken into consideration in the current diode models [1, 2, 3, 4]. In order to test the so called diode models on a real system, technical PV cells data of the manufacturer must be once checked. In order to check the manufacturer's data of the PV cells special precision stamped measuring instruments are to be used. Furthermore simulation applications can be used to draw a comparison between the own developed model and a real PV cell. In this publication simulation application for a test of the simplified diode model as well as 1-diode model are presented. By creating the PV characteristic curves it is possible to get values about the nominal power, open-circuit voltage and short circuit current of the module which are calculated under the so called standard test conditions (STC). By STC one understands the performance of the PV module with an irradiation of 1000 W / m² at module level with a certain spectrum of the light. Furthermore the temperature may amount only 25°C. By the STC standardization of all measuring data, also different modules can be compared with each other by using of different irradiation and temperature conditions and relations.

II. MEASUREMENT PRINCIPLES AND REQUIREMENTS

For the measurement of the current and voltage characteristic curves a module is loaded with a defined electric load and therefore the voltage and the electrical current are measured as a value pair, transfer analogy on the y and x axis, defining the I/U PV model. During the measurement, the environmental parameters play an essential role. The condition of the environment is to be documented indispensably during the measurement, because it is difficult to catch a few moments in the year (at least in central Europe) having optimum measurement conditions. An alternative exists by using of the so called solar spectral simulators. In order to make a projection from the environmental conditions on the STC terms, the irradiation for the most PV instruments, should amount to at least 700 W/m². Due to the respective measuring technology, environmental temperature, irradiation angle and spectral responsivity of the sensor, the measurements of the irradiation strength can become different. Even the determination of the exact PV module temperature is connected with bigger problems since the relevant temperature is not measurable within the solar cell. The simplest, still reliable method is the use of an exact external temperature sensor, which is appropriated to the back side of the PV module. In this work we will firstly present how to compare the PV diode models with the real PV cells of a certain manufacturer device by using the simulations application. In further work we will explain the development of the real test device for the measurement of the specific PV data required by the model of the PV cells.

A. Characteristic curves of three real PV modules

The modeling of the characteristic curve of PV-modules with the help of analogous models is a usual and proven method. To simulate the PV modules, the simulation application "PV-Teach" was used [5]. PV-Teach are a simulation tool which presents the possibilities of the single analogous models. The program allows the import of the real module identity lines and after it a next approximation by means of different analogous models to be able to compare their approximation goodness directly. First of all technical data of real PV modules is read in, in order to construct the characteristic curves. Then, comparison of the real module with one of the PV analog models as e.g. simplistic model, one-diode model, two-diode model or the model of the effectual characteristic curve can be carried out. In addition, an optimization of the parameters takes place. In this work the so called simplified diode model and one-diode model will be presented and compared by using the PV-Teach. In order to test the PV models, characteristic curves of 3 different real PV cells are used. The used PV cells are: SW 165 Wp by Solarworld, Sunrise SRM 185 dp by Solartec and ATF 43 solar cell by Antec. The 3 modules have following main technical characteristics:

TABLE I. TECHNICAL DATA OF SOLARWORLD SW 165 WP

Solarworld SW 165 Wp	
Nominal power	165 Wp
Nominal voltage	35,4 V
Nominal current	4,70 A
Open-circuit voltage	43,3 V
Short-circuit current	5,10 A
Cell type	polycrystalline

By using of PV Teach following characteristic curve is characterized for Solarworld SW 165 Wp module:

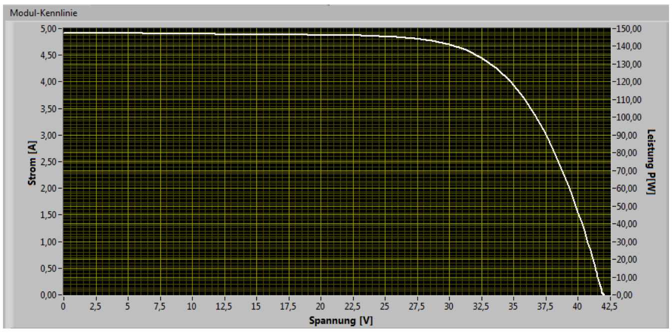

Fig. 1 Simulated characteristic curve Solarworld SW 165

TABLE II. TECHNICAL DATA OF SUNRISE SRM-185

Solartech Sunrise SRM-185	
Nominal power	185 Wp
Nominal voltage	36,3 V
Nominal current	5,10 A
Open-circuit voltage	44,2 V
Short-circuit current	5,51 A
Cell type	monocrystalline

By using of PV Teach following characteristic curve is characterized for Solartech Sunrise SRM-185 module:

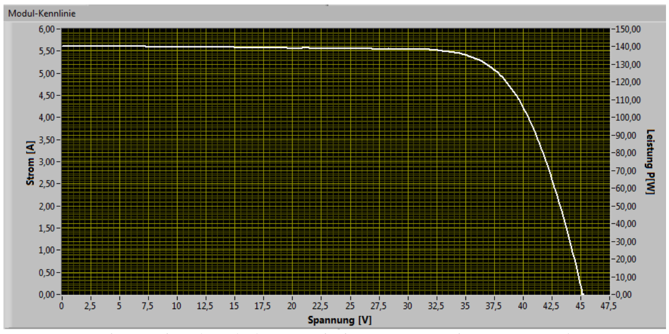

Fig. 2 Simulated characteristic curve Sunrise SRM-185

TABLE III. TECHNICAL DATA OF MODUL ATF 43

Anatec Thin Layer Modul ATF 43	
Nominal power	43 Wp
Nominal voltage	53 V
Nominal current	0,81 A
Open-circuit voltage	81 V
Short-circuit current	1,07 A
Cell type	Cds/CdTE

By using of PV Teach following characteristic curve is characterized for Anatec Thin Layer Modul ATF 43 module:

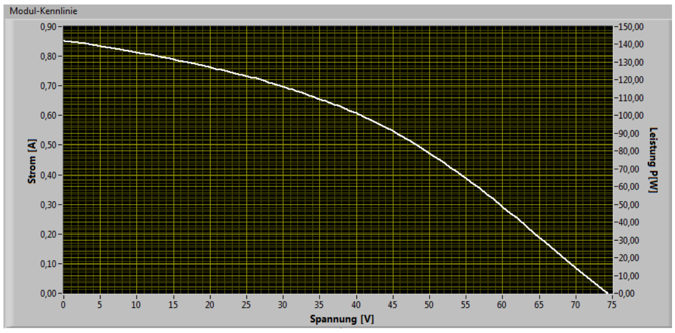

Fig. 3 Simulated characteristic curve ATF 43

Physical simulation models describe the PV module mathematically or physically and offer a relation to the real component. An unirradiated PV module is nothing else than one large-area diode. Hence, this electric structural element can be described by the diode equation according to Shockley. In addition, a numerical simulation model is described with the help of the model of the actual characteristic curve. With the empiric simulation model no relation to the real component exists. Despite of it, the model can deliver actual characteristic curve with very good results.

B. *Simplified Diode-Model vs. Simulation model by using PV Teach*

The unlit solar cell is nothing else than one solid-state diode. It behaves physically in the similar way. By irradiation of the solar cell, so called photoelectric current occurs. The photoelectric current is referred to as I_{Ph}. With an equivalent circuit diagram from an ideal current generator and a diode, these relations can be exposed.

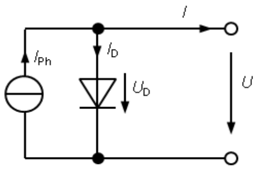

Fig.4 Simplified diode model

The equation for the characteristic curve is given with:

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot \left(e^{\frac{U}{m \cdot U_T}} - 1\right) \tag{1}$$

In order to reproduce better a real solar cell characteristic curves, one more factor, so called ideality factor m is introduced in the exponent. In order to define the holistic solar cell characteristic curves, short-circuit current I_K and open-circuit voltage U_L need to be defined. Based on the simplified diode-model these are defined as follows:

$$I_K = I\,(U = 0) = I_{Ph} - I_S \cdot (e^0 - 1) = I_{Ph} \tag{2}$$

$$U_L = U\,(I = 0) = m \cdot U_T \cdot ln\left(\frac{I_K}{I_S} + 1\right) \tag{3}$$

$$U_L = m \cdot U_T \cdot ln\left(\frac{I_K}{I_S}\right) \textit{for very small currents.} \tag{4}$$

By using the simulations software PV-Teach the measured characteristic curves for PV modules SW 165 Wp by Solarworld, Sunrise SRM 185 dp by Solartec and ATF 43 solar cell by Antec will be simulated with the simplified diode-model. Following starting values for real module characteristics are used (Table IV):

TABLE IV. REAL MODULE CHARACTERISTICS

	Solarworld SW 165 Wp	Solartech Sunrise SRM-185	Anatec Thin Layer Modul ATF 43
Photoelectric current	4,97 A	5,61 A	0,99 A
Saturation current	2,113 µA	1,287 nA	17,53 µA
Diode factor	2,87 V	2,04 V	7,05 V

The simulated characteristic curves compared with the original measured curves are presented in following:

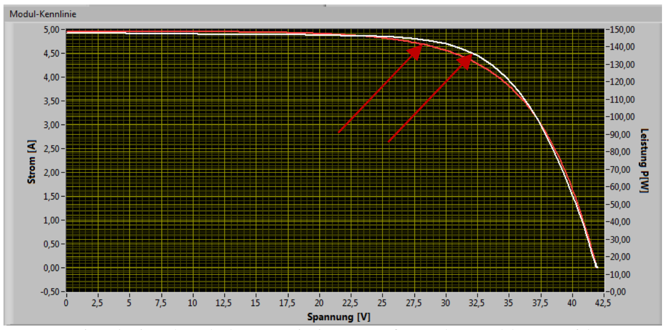

Fig. 5 Simulated characteristic curve for Solarworld SW 165

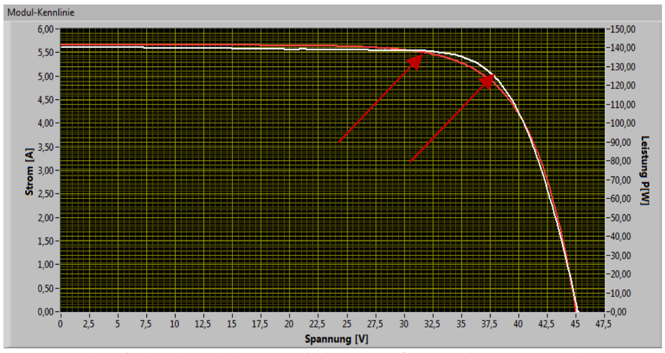

Fig. 6 Simulated characteristic curve for Sunrise SRM-185

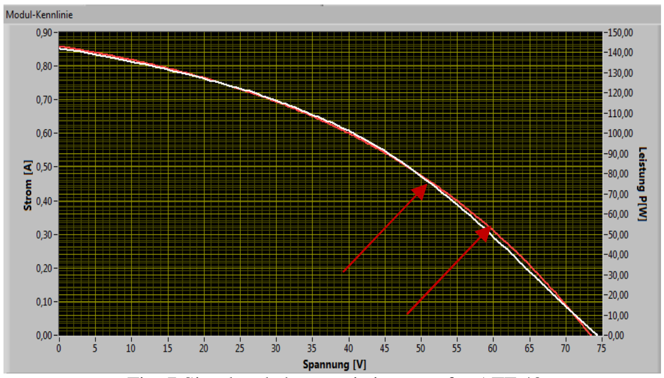

Fig. 7 Simulated characteristic curve for ATF 43

The parameters m and I_S are varied as long, until the curve course of the simulated characteristic curve shows a very good correspondence with the curve course of the real cell. Indeed, it is obvious that even after optimization of the parameters still a clear divergence between measured characteristic curve and the simulated characteristic curve exists. The achieved goodness (quality factor) amounts for the polycrystalline PV module of Solarworld to G = 98.33, for the mono-crystalline module Solartec the achieved goodness is G = 98.39, and at least the goodness for the thin layer-module ATF 43 amounts to G = 98.62. The divergence or the inaccuracy occurs because the simplified diode-model is only an idealized model for presentation of the diode characteristics [7].

C. One Diode-Model vs. Simulation model by using PV Teach

For exact consideration of the electrical losses in the solar cell, it is inevitable to connect the ideal diode with farther components which describe the deviations from the reality.

One possible analogous model of a real solar cell is shown with the so-called one-diode model.

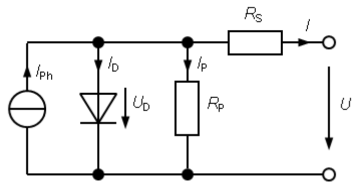

Fig.8 One-diode model

Compared with the simplified diode model, the one-diode model includes standard serial resistance R_S which describes the ohm losses in the front contacts of the solar cell and in the metal semiconductor and parallel resistance R_P which describes the leakage currents. I_D is the saturation current which exists because of the minority bearers available in the barrier layer. The equitation which describes the one-diode model is given with:

$$I = I_{Ph} - I_S \cdot \left(e^{\frac{U + I \cdot R_S}{m \cdot U_T}} - 1 \right) - \frac{U + I \cdot R_S}{R_P} \quad (5)$$

The parameters in one-diode model must be optimized in that way, that the model shows the almost identical electric behavior as the real PV cell. Theoretically it concerns a more dimensional non-linear optimization problem and for it the Levenberg Marquardt algorithm for the optimization can be used. The parameters are varied by the algorithm, as long until the difference of the real and simulated characteristic curve has reached the smallest value. To solve the characteristic curve equation a numerical procedure must be used like the Newtonian iterative method, because the one-diode model owns no explicit solution [7]. This means that the following condition $f(I,U) = 0$ must be defined. The iteration is described with

$$I_{i+1} = I_i - \frac{f(I,U)}{\frac{\partial f(I,U)}{\partial I}} \quad (6)$$

The iteration is carried out until $|I_i - I_{i+1}| < \sigma$. Thereby I_i is calculated current in the iteration step I, I_{i+1} is calculated current in the iteration step i+1 and σ is lower barrier of the terminating condition of iteration. For the function $f(I,U)$ applies:

$$f(I,U) = I_{Ph} - I_S \cdot e^{\frac{U}{m \cdot U_T}} \cdot e^{\frac{I \cdot R_S}{m \cdot U_T}} + I_S - \frac{U}{R_P} - \frac{I \cdot R_S}{R_P} - I = 0 \quad (7)$$

And for the derivation applies:

$$\frac{\partial f(I,U)}{\partial I} = -\frac{I_S \cdot R_S}{m \cdot U_T} \cdot e^{\frac{U + R_S}{m \cdot U_T}} - \frac{R_S}{R_P} - 1 \quad (8)$$

The influence of standard serial resistance R_S on the solar characteristic curve is presented in the following Fig.9:

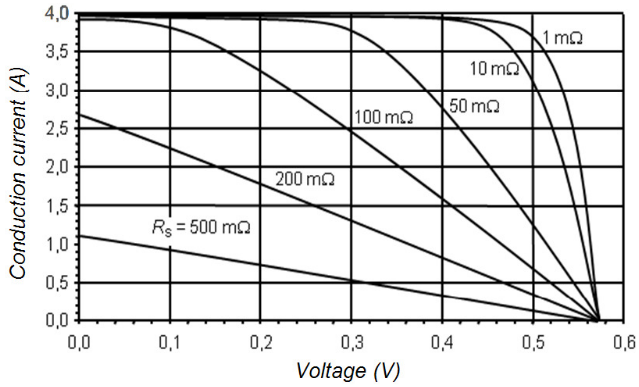

Fig.9 Influence of the standard serial resistance R_S

If the value of R_S rises, the curve flattens and the fill factor - the ratio of a photovoltaic cell's actual power to its maximal power if both current and voltage are at their maxima, gets much smaller. Influence of resistance R_P on the solar characteristic curve is given:

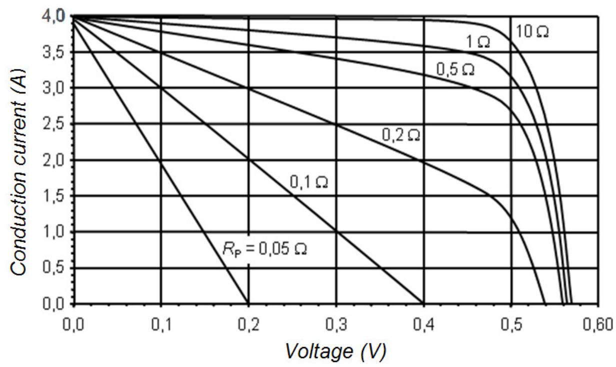

Fig.10 Influence of the parallel resistance R_S

By the falling value of the parallel resistance R_P the situation behaves similarly. The rising parallel current I_P lets the diode voltage descend and influences even the open-circuit voltage. In the following the measured characteristic curves are simulated with the simulation program PV-Teach by using the one diode model. Following starting values are used (Table V):

TABLE V. REAL MODULE CHARACTERISTICS

	Solarworld SW 165 Wp	Solartech Sunrise SRM-185	Anatec Thin Layer Modul ATF 43
Photoelectric current	4,97 A	5,61 A	0,99 A
Saturation current	2,113 µA	1,287 nA	17,53 µA
Series resistance	0,55 Ω	0,53 Ω	34,70 Ω
Parallel resistance	270,25 Ω	702,21 Ω	213,84 Ω
Diode factor	2,87 V	2,04 V	7,05 V

The simulated characteristic curves by using the one diode-model compared with the original measured curves are presented in following:

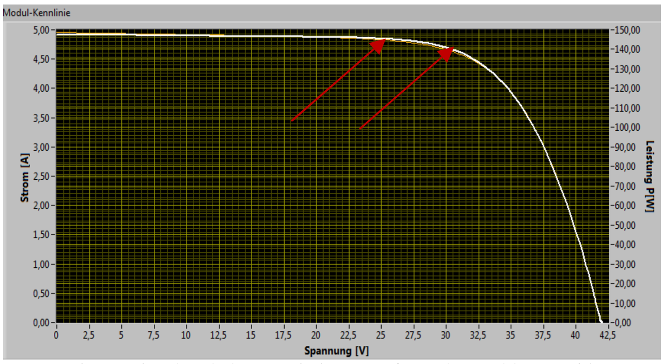

Fig.11 Simulated characteristic curve for Solarworld SW 165

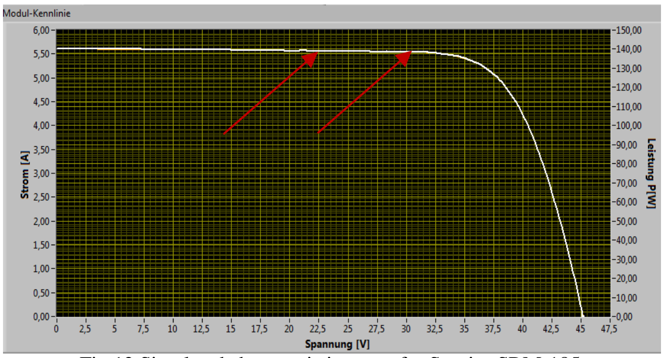

Fig.12 Simulated characteristic curve for Sunrise SRM-185

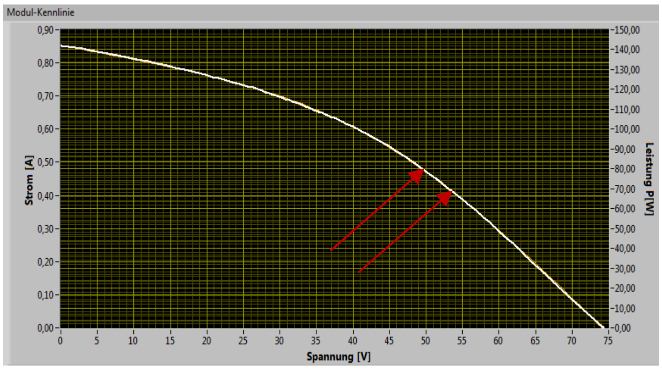

Fig.13 Simulated characteristic curve for ATF 43

By using of the one-diode model a better approximation goodness of the simulated characteristic curves compared with the simplified diode-model is recognizable. Here a very high goodness is achieved. For the polycrystalline module of Solarworld the goodness amounts to G = 99.57, for the mono-crystalline module of Solartech the goodness amounts to G = 99.86 and for the thin layer module of Antec ATF 43 the goodness amounts to G = 99.56. With the extent of the simplified diode-model with the resistances R_S and R_P the losses are described in the solar cell and with it, the real behavior of the cell is more exactly expressed. Even if the existing analog models offer a good simulation results, many important aspects, which have impact on the function of the PV cell are not included in the models and try to be compensated with the ideality factor *m*. So the influence of the topography on the PV cells in the diode models or the influence of the inverter feed-back creating harmonic components influencing the behavior of the PV cells are still not included in the diode models [5,6]. Therefore more precise and more universal models of PV cells need to be presented.

III. Conclusion

All simulation models with equivalent circuit diagrams try to reproduce the physical processes in the solar cell as good as possible. The notion of the modeling of the characteristic curves with equivalent circuit diagrams lies in the calculability of adaptation problems between photovoltaic-solar generators and consumer loads. Hence, certain requirements for the simulation method based on calculation are given and those can be an explicit calculation of the current-voltage characteristic curve equitation or the explicit calculation of the characteristic curve equation parameters from the characteristic value. The simulation results presented in this work are of statically nature which is not including further parameters which are influencing the characteristic curves of solar cells. Also, the diode models are useful only for specific PV technologies. For more exact models and more universal models of PV cells, other analogues models need to be developed.

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