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

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*Abstract*— **This paper is based on the research project between Rheinischen Fachhochschule in Köln - University of Applied Sciences, Germany, and the University of Niš, Serbia in regard of modeling of photovoltaic cells of different technologies. Standard models used for modeling of photovoltaic cells give partially satisfactory results, which are mostly depending on the physical-mathematical model and on the technology of the photovoltaic cells used. In this work we compare simulation results based on simplified diode model and one-diode model with the characteristics of three different real photovoltaic modules of different cell type based on different cell technology. We show the dependency of accuracy of the physical models by the choice of ideality factor and reverse saturation current, which at least often led to calculation of different efficiency factors of PV cells. Thus, the calculated data given by manufacturer can distinguish significantly in regard of cell efficiency compared with the measured data. By varying of ideality factor and reverse saturation current, the curve course of the simulated characteristic curve can be adjusted to show a very good correspondence with the curve course of the real cell. Furthermore, we show the differences in the quality factor according to the model used and give a reference in conclusion to the limits of the current based on different cell technology.**

***Keywords — Modeling, Photovoltaic cells, Simulation component.***

## I. INTRODUCTION

Within the scope of the common research project between the Rheinischen Fachhochschule in Köln - University of Applied Sciences, Germany as well as the University of Niš, Serbia 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 previous 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 and show the dependency of the physical-mathematical models on the variable parameters depending on the cell type, as well as on saturation current and ideality factor, technical PV cells data of the manufacturer must be once investigated. In order to estimate the manufacturer's data of the PV cells special precision stamped measuring instruments are to be used to validate the basic manufacturer's data about the used PV cells. Furthermore simulation applications, which allow the variation of the saturation current and ideality factor, 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 one-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 different irradiation and temperature conditions and relations. In this paper we use symbols according to IEC 60617-2:1996 and EN 60617-2:1997. Symbols used in Figure 4 and 8 for diodes are symbol 05-03-01 out from the EN-60617-range and for ideal current source symbol 02-16-01 out from the EN-60617-range.

## 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 inevitably during the measurement, because it is difficult to catch a few moments in the year (at least in central Europe) when optimum measurement conditions exist. 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 because the relevant temperature is not measurable in 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 [5, 6, 7]. To simulate the PV modules, the simulation application "PV-Teach" was used [8]. PV-Teach is simulation tool which presents the possibilities to use the single analogous models by varying of diverse parameters. The program allows also the import of the real module characteristics and generation of the real curves according to data sheet of the manufacturer. Also it allows simulation by using of analogous models. First of all technical data of real PV modules is read in, in order to construct the characteristic curves. Then, comparison of the real PV module with one of the PV analogues 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 saturation current and ideality factor parameters takes place. In this work the so called simplified diode model and one-diode model will be presented and compared 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 three 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 measured (real) characteristic curve is characterized for Solarworld SW 165 Wp module:

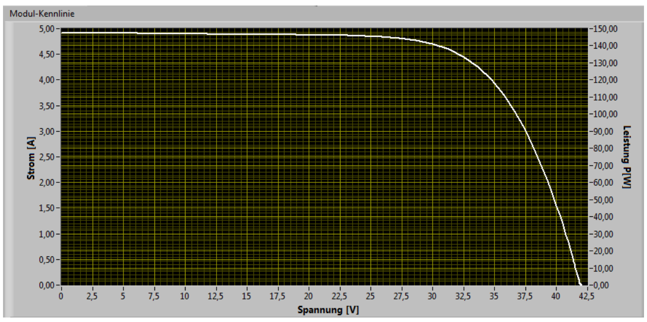


Fig. 1. Measured characteristic curve Solarworld SW 165

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:

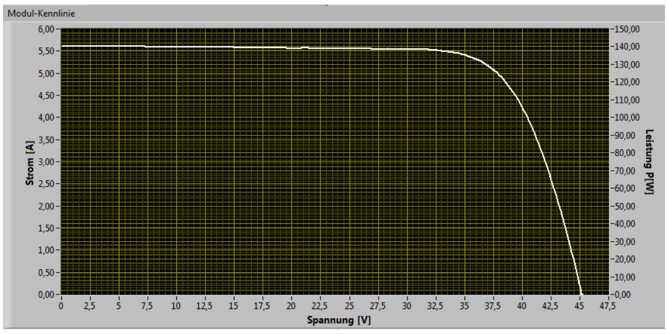


Fig. 2. Measured characteristic curve Sunrise SRM-185

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

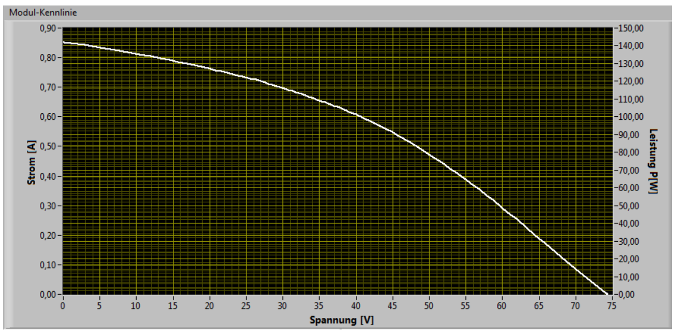


Fig. 3. Measured characteristic curve ATF 43

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 [5, 6]. 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.

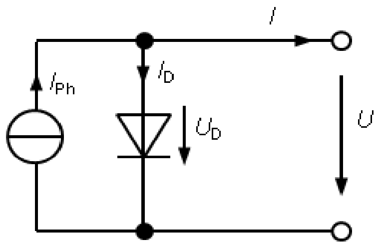


Fig. 4. Simplified diode model

The equation for the characteristic curve is given with:

$$I = I_{Ph} - I_D = I_{Ph} - I_s \cdot (e^{\frac{U}{m \cdot U_T}} - 1) \qquad (1)$$

$I_S$ is so-called reverse saturation current according to the Shockley-Equation. It depends on diffusion voltage (junction built-in voltage), the length of the diffusion of electrons and holes, density of donator atoms, Richardson-Coefficient and the surface of PN-transition area. The $Is$ is in the case of germanium based diodes $Is \approx 100\text{nA}$ and for silicon diodes $I_S \approx 10\text{pA}$ [5, 6, 7]. In order to reproduce better a real solar cell characteristic curves, one more factor, so called ideality factor $m$ (also known as emission coefficient) is introduced in the exponent. Ideality factor $m$ has value between 1 and 2 and it represents the measure of the divergence of the characteristic curve compared with the ideal diode character [7, 9]. 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:

$$I_K = I(U = 0) = I_{Ph} - I_s \cdot (e^0 - 1) = I_{Ph} \qquad (2)$$

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

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

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 compared with simulated 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 (red line) compared with the original measured curves (white line) given by manufacturer are presented in the following figures:

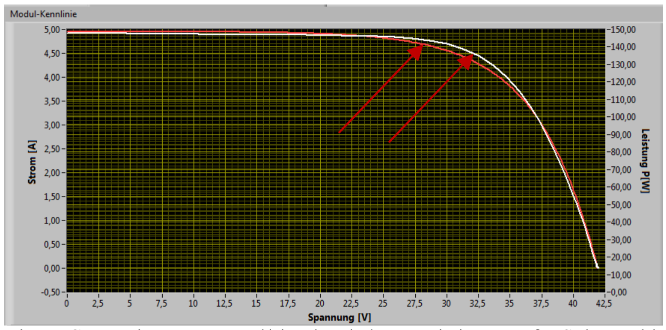


Fig. 5. Comparison: measured/simulated characteristic curve for Solarworld SW 165

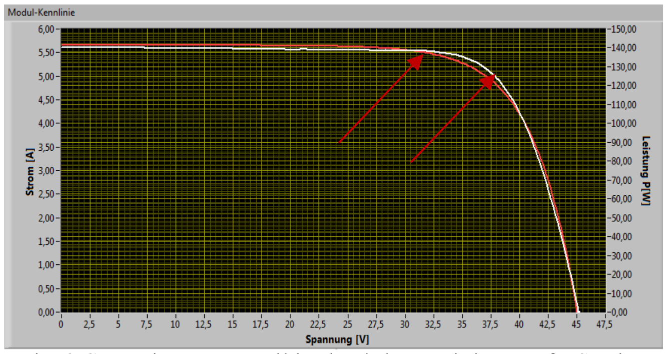


Fig. 6. Comparison: measured/simulated characteristic curve for Sunrise SRM-185

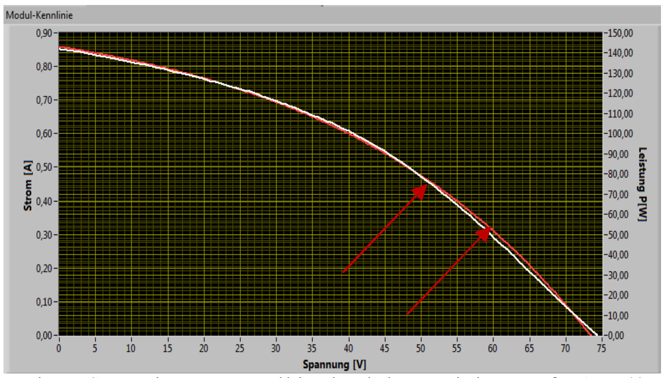


Fig. 7. Comparison: measured/simulated characteristic curve for ATF 43

The already mentioned parameters $m$ and $I_S$ are varied 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. It means that depending on the choice of the parameters, different efficiency data of the PV cell can arise. 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 [10].

*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.

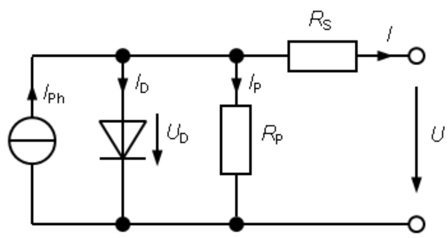


Fig.8. One-diode model of the solar cell

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 equation which describes the one-diode model is given with:

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

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 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 [10]. 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:

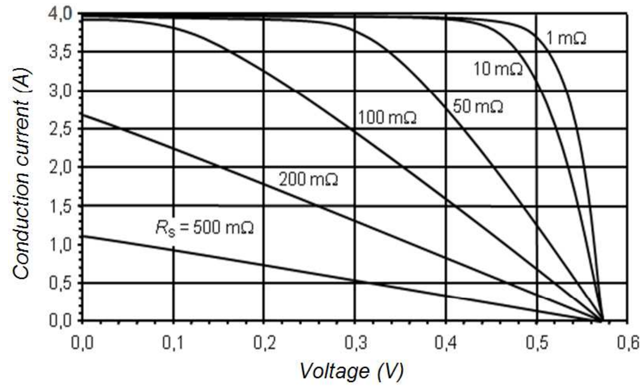


Fig.9. Influence of the standard serial resistance $R_S$

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:

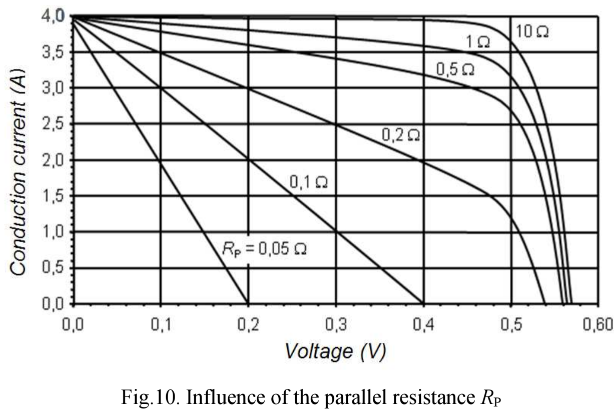


Fig.10. Influence of the parallel resistance $R_P$

By the falling of the 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 compared with simulated for one-diode models. 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 (Figs. 11, 12 and 13):

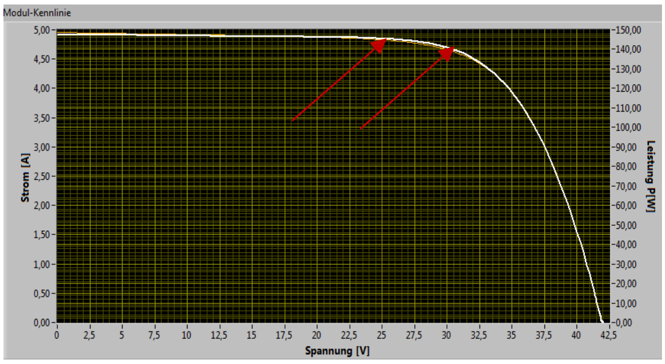


Fig.11. Comparison: measured/simulated characteristic curve for Solarworld SW 165

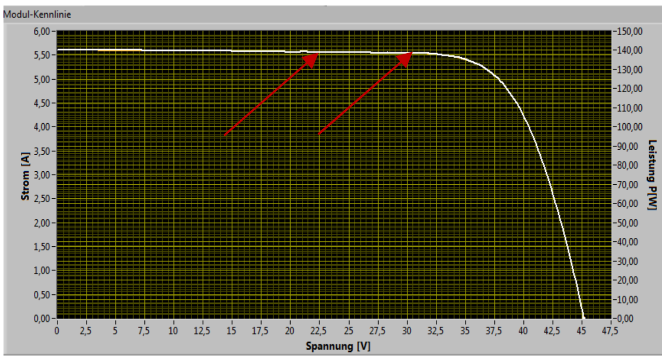


Fig.12. Comparison: measured/simulated characteristic curve for Sunrise SRM-185

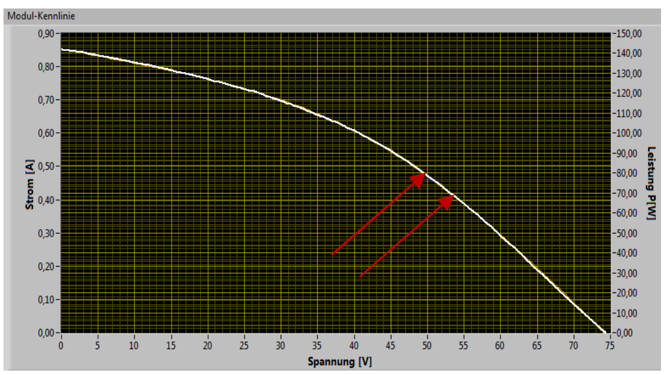


Fig.13. Comparison: measured/simulated characteristic curve for ATF 43

By using of the one-diode model a better approximation goodness of the simulated characteristic curves compared with the simplified diode-model is recognizable because the impact of the parameters saturation current and ideality factor is lower. 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 extend 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 analogues models offer 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 [8, 11]. 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 equation or the explicit calculation of the characteristic curve equation parameters from the characteristic value. The simulation results presented in this work show the dependency of the simulation of the right choice of the saturation current and ideality factor of the cells, as well as the choice of the PV cell model. Also the models are of statically nature which is not including further parameters which are influencing the characteristic curves of solar cells. The diode models are further useful only for specific PV technologies as for instance silicon based amorphous silicon or CdTe technology. For more exact models and more universal models of PV cells, other more universal analogues models need to be developed.

## REFERENCES

[1] M. Andrejević Stošović, D. Lukač, V. Litovski, “Quantification of Power Quality Issues at the PV Panel-ConverterInterface”, INDEL Conference, Banja Luka, Bosnia-Herzegovina, pp. 256-262, November 2012.

[2] M. Andrejević Stošović, D. Lukač, V. Litovski, “A view to the modelling and simulation of the PV system - Converter interface”, TECHNOPORT Renewable Energy Research Conference 2012, Trondheim, Norway, April 2012.

[3] D. Lukač, M. Andrejević-Stošović, V. Litovski, S. Vukomirović, “Technology and Light Source as Challenge for proper Modeling of PV Cells”, XI International Scientific – Professional Symposium INFOTEH, Sarajevo, Bosnia and Herzegovina, pp. 173-176, March 2012.

[4] K. Mertens, “Photovoltaik- Lehrbuch zu Grundlagen, Technologie und Praxis”, PV-Teach, Avaliable <http://www.lehrbuch-photovoltaik.de/software/pv-teach.zip>, 28.12.12, 12:06h.

[5] K. Mertens, “Photovoltaik”, 2nd Edition, Fachbuchverlag Leipzig, pp.64-74, 2013.

[6] J. Siegl, “Schaltungstechnik”,4th Edition, Springer Verlag Heidelberg, pp. 128-129, 2011.

[7] M. Krystek, “Berechung der Messusicherheit”, Betuh Verlag GmBH, Berlin, pp.44-46, 2012.

[8] D. Lukač, M. Andrejević-Stošović, V. Litovski, “Operating Points and Topographic Dependence of the Thin Layer-Photovoltaic Cells as Relevant Characteristics for Modeling of the PV Cells”, Proceedings of the 4th Small Systems Simulation Symposium, Niš, pp. 20-23, 2012.

[9] M. Hofmann, “Time-distraught photoemission spectroscopy in Au-GaAs Schottky contacts”, Thesis, Faculty of Physics and Astronomy, Bavarian Julius-Maximilians University, pp.34-35, 2011.

[10] D. Lukač, H. Kücük, “Validation of the Photovoltaic (PV) - cell models for PV cells of the different cell technologies”, Theis, pp. 1-93, Rheinische Fachhochschule Köln, 2011.

[11] M. Andrejević Stošović, D. Lukač, V. Litovski, “Modeling and circuit simulation of photovoltaic cells – an overview”, 7th Int. Symp. Nikola Tesla, Belgrade, Serbia, pp. 83-92, November 2011, Invited paper.