Manual for PV-Teach 3.0

1.   Installation

The program PV-Teach runs under the software *LabVIEW*. If you have already installed *LabVIEW* 2013 or higher (development environment or runtime-engine), please only download the file "*PVTeach_Installer_without_Runtime*" *and execute the file* "setup.exe".

In all other cases please download the file "*PV-Teach_Installer_Complete*". After the execution of the file "setup.exe" all necessary components as well as the program *PV-Teach* will be installed on your PC.

In order to easily find the program a starting symbol will be created on your desktop.

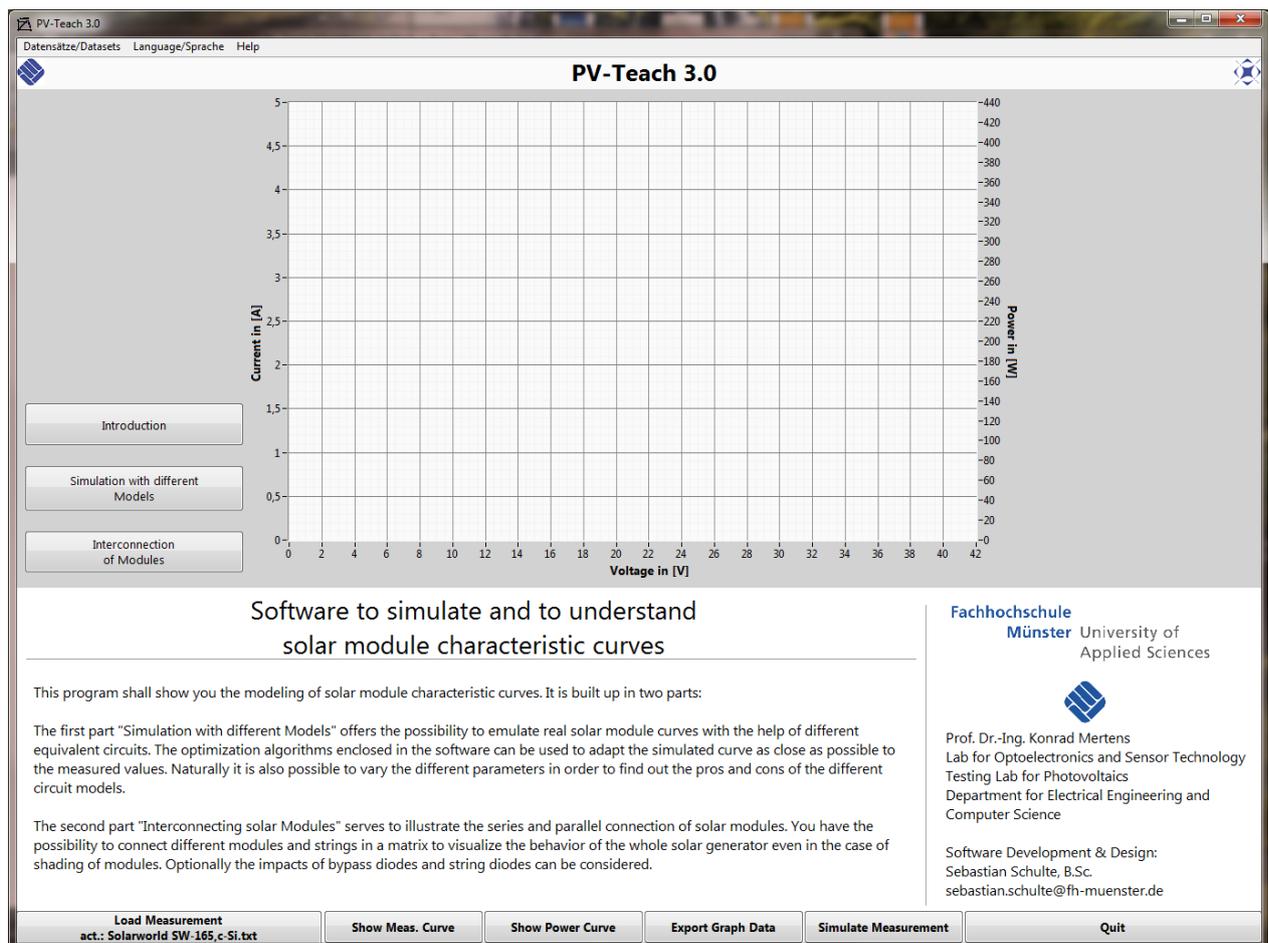After starting the program the following surface should appear:

Figure 1: Screenshot of the PV-Teach Start Window

2.   Motivation and Aim of this Program

The **modeling of characteristic curves** or solar cells and solar modules with the aid of equivalent circuits is a common and approved method. For this its knowledge of transfer plays an **important role in teaching**. However, often the teaching is reduced to looking at the characteristic equations and to enumerate the pros and cons of the different equivalent circuits.

Therefore, it is of great help to have a **simulation tool**, which **shows** the **possibilities of** the **different models**. E.g. it is desirable to import real measured module curves and to show the **approximation qualities** of the different models in order to compare them directly.

Another important subject in practice and teaching of photovoltaics are the **consequences of mismatching and partial shading** on the yield of solar plants. Also here a simulation tool is of great help as the resulting total power can only roughly be estimated. Moreover the resulting power curve is of special interest to predict the behavior of the MPP-tracker of the inverter.

These demands are met by the freeware program PV-Teach which was developed at the Münster University of Applied Sciences in Germany. It facilitates the **simulation of module characteristic curves** with different equivalent circuit models. For this measured curves of solar modules can be imported. The course of the curve then can be approximated as exact as possible. Moreover *PV-Teach* offert the possibility to **simulate strings** which comprise of different module types. Theses strings again can be connected in parallel to show the ***I/V-curve of a whole PV plant***. Here also the **impact of bypass and string diodes** on the total power can be shown.

2.   Short Manual

3.1   Program Part „Simulation with different Models"

In this part of the program you can simulate the solar module curves with different equivalent circuit models (see Figure 2).

- To see the different equivalent circuits move the mouse over the regions on the right hand side of the white rectangle "Chosen Circuit Diagram".

- Load a measured module curve with the button "Load Measurement"; e.g. the module *Solarworld SW-165*.

- By pressing the upper red-white cross below the block "Simplified Model" the curve of the "Simplified Equivalent Circuit Model" is shown.

- By pressing the lowermost red-white cross ("Optimal Fitting") below the block "Simplified Model" the parameters are changed in such a way that the measured and the simulated curve agree as good as possible

- Try the whole also with the other equivalent circuit models. The more parameters the separate models offer the better approximation qualities will result in general.

- Vary tentative the respective parameter by hand and look at the result. Do you achieve a better approximation quality than the program?

- Hint: The Two-Diode Model offers three different methods to automatically optimize the parameters. In case of the two Leven-Marquard optimizing algorithms bad starting values can lead to a very long calculation or even a crash of the program.

- Figure 2 shows how different the "Simplified Model" and the "One-Diode Model" can approximate the measured curve. In the first case (bright green curve) the approximations quality ("Accuracy") only reaches 93.33 %; in the second case (dark green curve) however already 99.57 %.
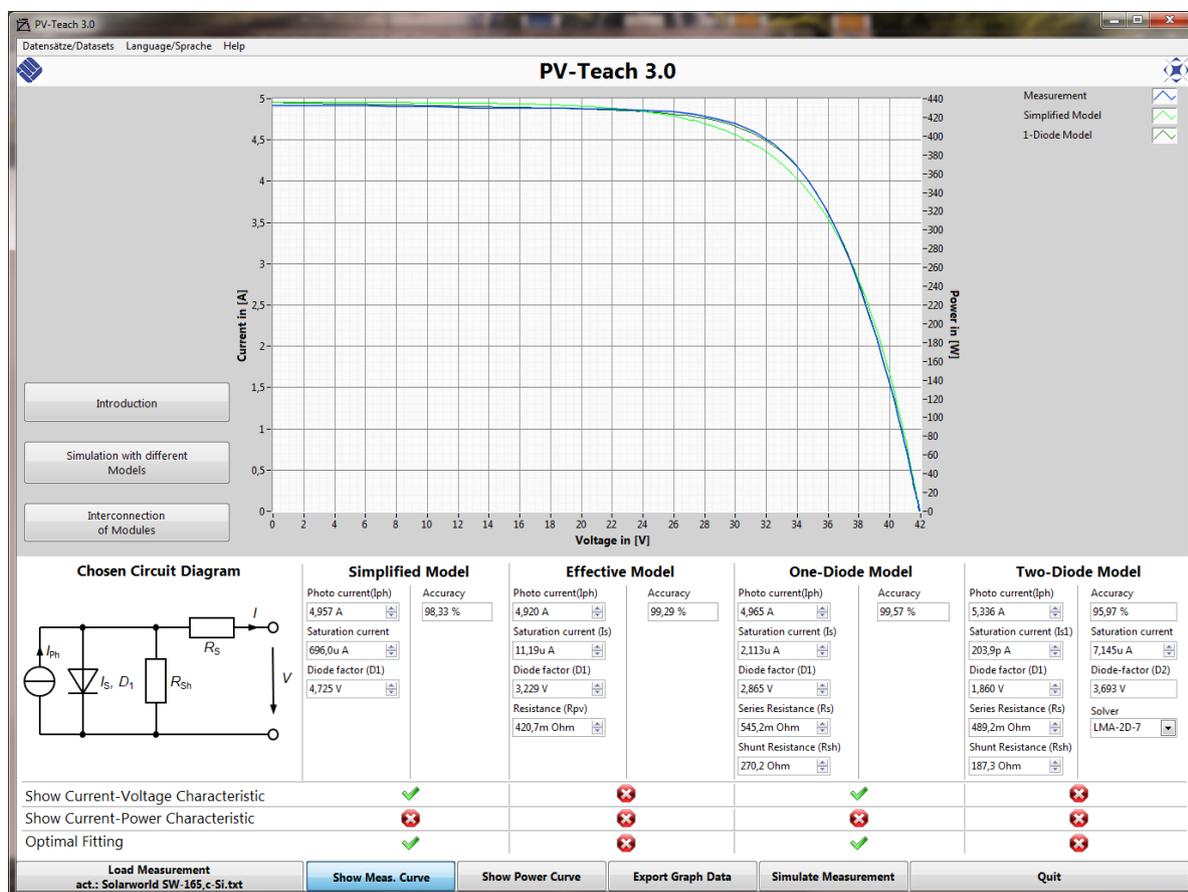

Figure 2: Screenshot of program part "Simulation with different Models"

3.2   Program Part "Interconnetion of Modules"

In this program part you can interconnect different solar modules and display the resulting total curves of the solar generator (see Figure 3).

a) Simulation with existing measurement files

- Load the measured module curve with the button "Load Measurement"; e.g. the module *Solarworld SW-165*.

- By pressing the button "Insert Measurement-Module" you transfer the data in module type A. The *I/V*-curve of module type A is thereupon shown.

- By varying the module number of module type A you can determine how many modules of this type can be connected in series. Moreover you can define the degree of module shading with the slider "Shading-Level".

- By default one bypass diode per module is assumed. This bypass diode can be activated or deactivated. If the module contains several bypass diodes, again it can be defined how many of these are concerned in case of shading.

- Tip: The autoscaling of the diagram axes can be deactivated. With a right mouse click on the corresponding axis you find the switch-off possibility. Möchten Sie die Skalierung von Hand einstellen, machen Sie bitte einen Doppelklick auf die höchste Zahl der Achsenskalierung und geben den gewünschten Wert ein.

- Additionally to module type A you can define two further module types B and C. For this load a new measurement curve and transfer the data to the module type.

- Now the defined module types A, B and C can be arbitrarily interconnected. To do this click below "Total Circuit Configuration" on the red crosses. You can only connect module types that have been defined before.

- By clicking on the area right hand to the text "String Diode" you can insert string diodes in the desired strings.
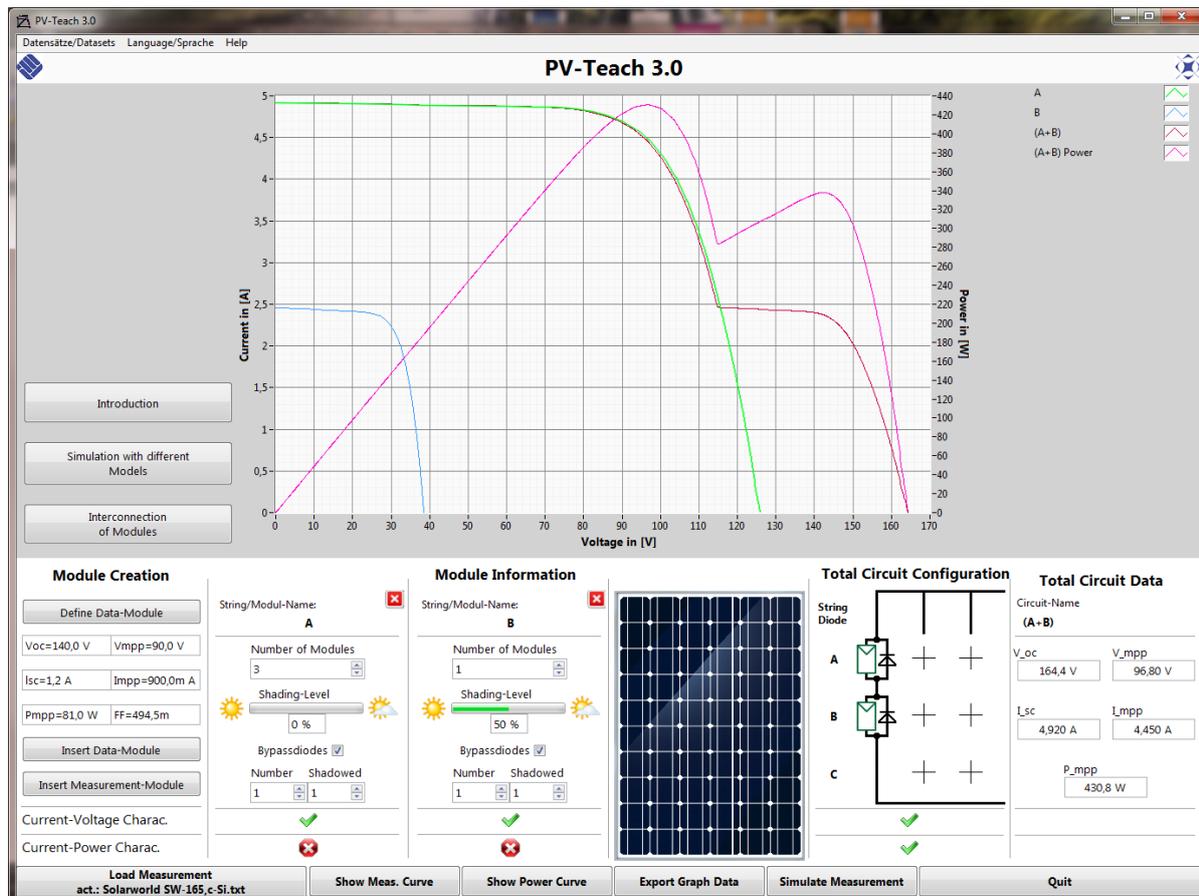
Figure 3: Screenshot of the Program Part "**Interconnection of Modules**"

Example: Partly shaded String

As an example we want to simulate a partly shaded string in the following. We assume a string consisting of 4 modules of the type *Solarworld SW-165*, of which one is irradiated due to shading only with half sunshine (500 W/sqm). The procedure is as follows:

1. Execution of the first tree points of the list above. For module type A 3 modules shall be chosen.

2. Insertion of an additional **module type B**. For this module you can adjust the "**Shading- Level**" to **50 %** (see Figure 3).

3. **Series connection** of module type A and B in the "Total Circuit Configuration".

4. Presenting the **total I/V curve** by clicking on the red-white cross under the "Total Circuit Configuration".

5. Display also the *P/V* **power curve** of the total circuit. Clearly visible are the two MPP-points.

6. Now vary the **shading-level** of module type B. Clearly visible the right **MPP-point** moves.

7. To see the result **deactivate** the **bypass diode** of module type B. The curves are changed totally because module B now always determines the maximum string current. The MPP power is drastically reduced.

8. Now it is possible to connect another **unshaded string** in parallel to the first string. For this the data of the measured module is inserted into module type C. Set the number of modules for type C to "4" and connect this string in parallel to the already existing string.

9. Now again it can be regarded how the **on- and off-switching of** the **bypass diode** of module type B affects the **total power curve**. Again vary the shading-level to observe the changes of the MPP.

b) Simulation with specifications from module data sheets

Beside the possibility to use measured curves of solar modules you can also use the specifications of module data sheets for the simulation.

For this instead of pressing the button "Insert Measurement-Module" you press "**Insert Data-Module**". A popup window will open where you can type in the data (open circuit voltage, short circuit current, MPP voltage and MPP current) (see Figure 4a). By pressing the button "**Define Module**" the popup window is closed and the data are transferred to the main window. Afterwards the generated curve can be used for module types A, B or C by pressing the button "**Insert Data-Module**".
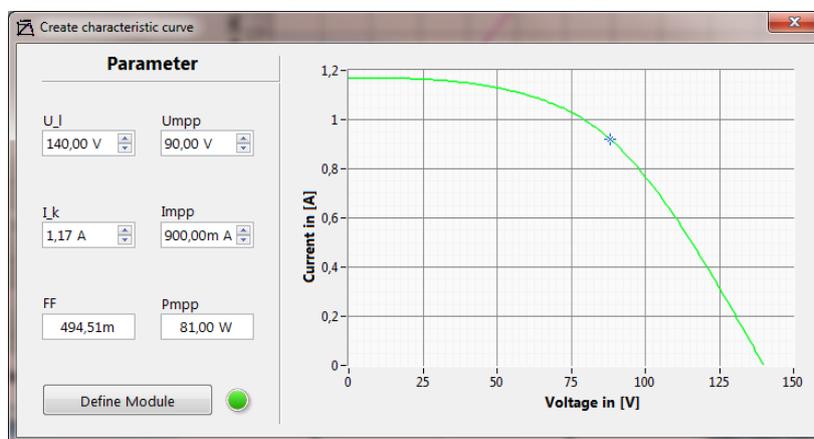

Figure 4a: Successful definition of a module curve out of data sheet data

In case of non-physical of non-suitable data values the generation of a module curve is not possible. This is shown by the red dot besides the button "Define Module" in Figure 4b. In this case the parameters have to be changed until an "allowed" curve is generated and the dot has changed from red to green (see Figure 4b).
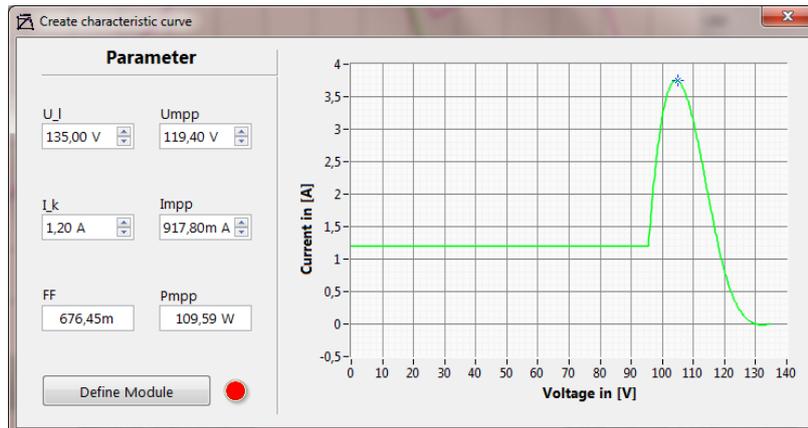
Figure 4b: Non-successful definition of a module curve out of data sheet data

In order not to type in the data of the modules again and again it is possible, to generate a "simulated measurement file" out of the data sheet specifications. For this you press the button "Simulate Measurement". A similar window to that of Figure 4a will open, however now with the possibility to store a file which contains the module curve as an array. First you have to choose the path, then type in the file name and press the button "OK". Afterwards you press the button "Save Module" to really store the generated file. This again can be loaded as a measurement file and be used as described under Section *a) Simulation with existing measuring files*.

3.3   Configuration Files

If you have simulated a special solar generator you may want to store all the settings in a configuration file. This can be done by the menu item "Configuration File" in the upper left corner of the program screen. You can store the current configuration in a new file (e.g. "project_1.PVCFG"). After a new start of the program always the configuration file "standard.PVCFG" will be loaded. Afterwards you can load your desired configuration file.

We wish you joy and new insights in photovoltaics with PV-Teach!
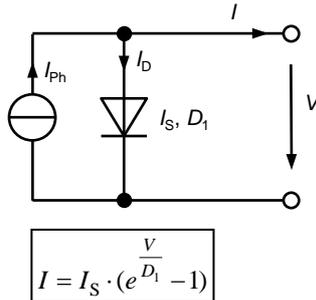
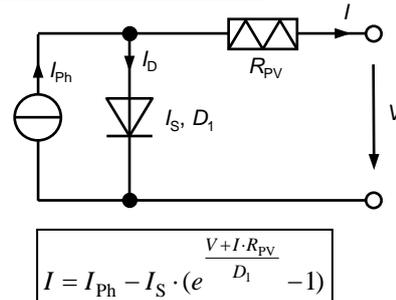## 4.   Good-to-know knowledge to the technical background

4.1   Equivalent Circuit Models of Solar Modules

Here the common equivalent circuit models for solar cells and solar modules shall be shortly described and explained.
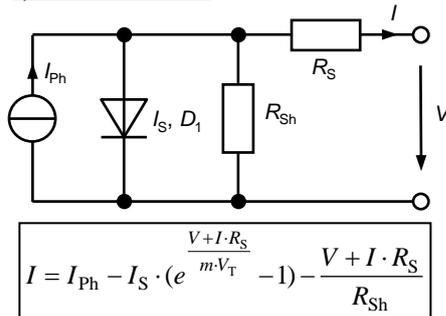

i) Simplified Model:

$$I = I_S \cdot (e^{\frac{V}{D_1}} - 1)$$

iii) Model of effective Curve:

$$I = I_{Ph} - I_S \cdot (e^{\frac{V + I \cdot R_{PV}}{D_1}} - 1)$$

ii) One-Diode-Model:

$$I = I_{Ph} - I_S \cdot (e^{\frac{V + I \cdot R_S}{m \cdot V_T}} - 1) - \frac{V + I \cdot R_S}{R_{Sh}}$$

iv) Two-Diode-Model:

$$I = I_{Ph} - I_{S1} \cdot (e^{\frac{V + I \cdot R_S}{D_1}} - 1) - I_{S2} \cdot (e^{\frac{V + I \cdot R_S}{D_2}} - 1) - \frac{V + I \cdot R_S}{R_{Sh}}$$
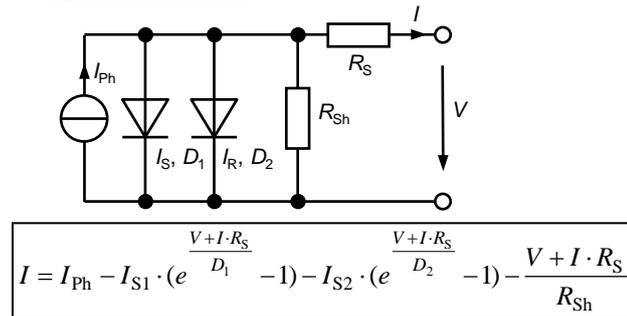
Figure 5: Comparison of different models

i) Simplified Model:

In case of the simplified model only three parameters are available for the approximation of the simulated curve to the measured curve: photo current I_{Ph}, saturation current I_S and diode factor D_1. The diode factor here was defined as the product of ideality factor m, thermal voltage V_T and number of solar cells per module N:

$$D_1 = m \cdot V_T \cdot N \tag{1}$$

ii) Model of the Effective Characteristic Curve:

In this model an additional series resistance R_{PV} is used. For better approximation to real measured curves also negative values for its "resistance" are allowed [Wag06].

iii) One-Diode-Model:

The One-Diode-Model is the most common model as it mostly shows good approximation qualities. This is achieved besides the series resistance R_S with the additional shunt resistance R_{Sh}.

iv) Two-Diode-Model:

The One-Diode-Model does not take into account the recombination current of a solar cell. Thus the Two-Diode-Model uses a second diode which is described by I_{S2} and D_2. D_2 typically amounts the double of diode factor D_1 of the first diode.

4.2   Software Realisation

As the simplified, the One-Diode and the Two-Diode-Model are not solvable analytically an iteration algorithm has to be used. For this the equivalent circuit equation was defined as a Zero problem which is then solved with the **Newton-Raphson-Method** (see e.g. [Pap07]).

Furthermore the automatic approximation of the equivalent model parameters to the measured curve is programming challenge. Here for the Two-Diode-Modell **two methods were implemented**, which can be chosen optionally [Ste11].

The **Principle of Hovinen** uses an **analytical method** [Hov94]. The equations of the equivalent circuit model are rearranged in a way that all the resting parameters can be expressed in dependence o the series resistance R_S. For optimization only the two diode factors D_1 und D_2 are set. Then R_S is varied until an approximation optimum with the measured curve is achieved. Out of the values of D_1, D_2 and R_S finally the other equivalent circuit elements can be calculated.

An alternative is the **Levenberg-Marquardt-Algorithm** [Lou05]. It consists of an **optimizing method** which performs an **iterative fitting** to the measured curve. For this all seven parameters of the equivalent circuit are varied. Critical is the selection of the starting parameters as the method does not converge in any case. A good approach is to first calculate the parameters with the Hovinen method and use them as starting values for the Levenberg-Marquardt iteration.

A concrete example to compare both methods can be found further below.

The program *PV-Teach* was realized under *LabVIEW* 2013. To achieve high performance the calculation-algorithms of Newton-Raphson, Hovinen and Levenberg-Marquardt are implemented in *MathScript*. *MathScript* is a language similar to *MATLAB*, which can be embedded in *LabVIEW*.

4.3   The Methods of Hovinen and Levenberg-Marquardt in a concrete comparison

The method of Hovinen is well suitable for "normal, almost ideal" module curves. An example is shown in Figure 6. The simulated progression virtually lies exactly on the measured curve.

In reality however module curves often look different. The separate cells often show different short circuit currents. This leads to a slightly stepped progression of the current in the lower voltage range. A relative extreme example shows Figure 7.
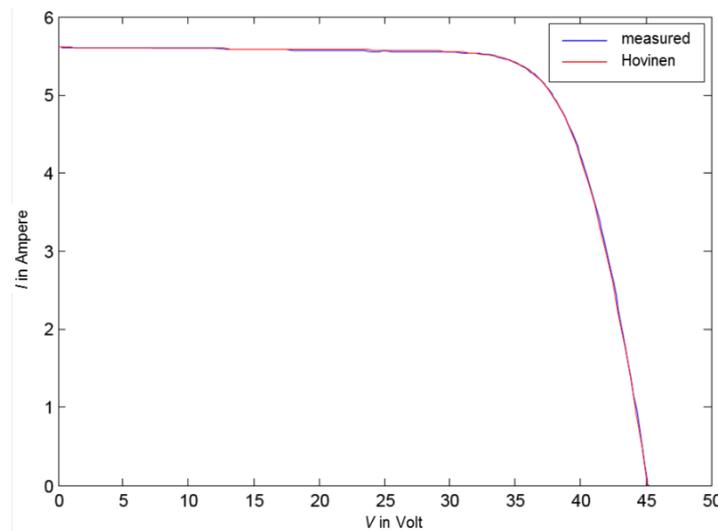
Figure 6: Measured and simulated curve of a "nice module". The Hovinen Method virtually matches the curve exactly.

Both simulation models cannot optimally match the real curve. In case of the **Hovinen Model** the short circuit, the open circuit and the MPP point are hit optimally. However in most of the other ranges the curve runs significantly beside the measured values.

Also the Levenberg-Marquardt-Algorithm (LMA) cannot match the step in the curve. However here the short circuit current is adjusted lower so that in the mid voltage range only a small deviation between measured and simulated curve results. Also the steep decay of the measured curve above the MPP is matched relatively well. This results of the fact, that the algorithm can vary all 7 parameters of the equivalent circuit. In contrast to this in the Hovinen method only the two diode factors can be changed. In case of the approach $D_2 = 2 \times D_1$ even only one parameter is varied.

Which method results as the "best" cannot readily be decided. Base on its analytical calculation the Hovinen model is very robust and quickly shows the optimized solution. The Levenberg-Marquardt algorithm can achieve higher approximation qualities but depends strongly on good starting values and a high number of measurement values. Otherwise no convergence is reached in the iteration.

Moreover the LMA solution in Figure 6 in practice not inevitably offers the more useful result. In this case e.g. a short circuit current clearly too small is calculated which would be a true disadvantage for many applications.
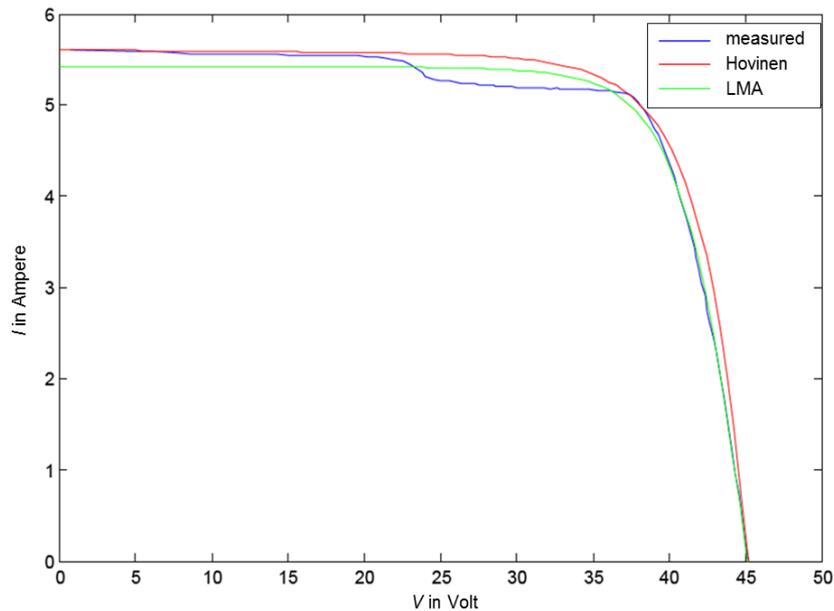
Figure 7: Measured and simulated curve of a „bad module". The two simulation methods show clearly different results. In total the Levenberg-Marquardt algorithm (LMA) achieves a better approximation.

5. Summary

With *PV-Teach* an easy and intuitive simulation tool for solar module curves is available. It interactively shows the possibilities of the different equivalent circuit models. Moreover the different effects of series and shunt connection of solar modules are made clear. Therefore beside the use of the program in teaching it can be helpful for the technician in daily work.

The program *PV-Teach* is available on the website www.textbook-pv.org as a free download.

6.　　Literature

[Hov94]　Hovinen, Anssi: Fitting of the Solar Cell IV-curve to the Two Diode Model. Physica Scripta, Vol. T54, 1994

[Lou05]　Lourakis, Manolis I. A.: A Brief Description of the Levenberg-Marquardt Algorithm Implemented by levmar, Foundation for Research and Technology, Institute of Computer Science, Heraklion, Griechenland, 11. Februar 2005

[Pap07]　Papula, Lothar: Mathematik für Ingenieure und Naturwissenschaftler – Band 1, Vieweg, 2007

[Ste11]　Stegemann, Thomas: Ersatzschaltbildmodellierung von Solarmodulen: Optimierung der FIT-Parameter", Seminararbeit, Fachhochschule Münster, Fachbereich Elektrotechnik und Informatik, 2011

[Wag06]　Wagner, A.: Photovoltaik Engineering – Handbuch, Entwicklung und Anwendung, Springer, 2006

7.　　Version History

PV-Teach 1.0　First simple program version

PV-Teach 2.0　Relaunch of the whole software to attain a handsome outfit and usability

PV-Teach 2.5　Implementation of additional features (simulation of more than one bypass diodes per module etc.)

PV-Teach 3.0　Implementation of additional features:
- Bilingualism German/English
- Generation of measurement files out of data sheet specifications
- Resize Option
- Improved Design
- Resolved minor Bugs
- After Restart from PV-Teach the old configuration is still available
- Actual configuration could be exported and imported