

PV-measurement system for remote laboratory sessions

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Abstract

In recent years the advance of IoT technologies enabled the connection of a wide variety of devices into networks, enabling communication and remote access in an extent that was unseen before. Beside the various applications in consumer electronics, industry 4.0 or interlinking of vehicles the advantages can also be exploited for educational purposes. The possibility of providing remote access to laboratory equipment makes it possible for students to perform some lab practices without physical attendance, thus students in distant locations can be reached and equipment can also be shared among more institutions. This overall increases the range and the effective usage of lab equipment significantly. Also, last two years with COVID-restrictions showed us, how important it is, to be able to provide quality alternatives to the commonly used, attendance-based laboratory work sessions. In this paper we present a fully remote-controlled measurement setup for laboratory practices demonstrating the measurement and the behaviour of PV-cells. The system consists of two main components: a fully remote controllable solar simulator with an I-V curve measurement system and special demo solar module that is capable of simulating different environmental effects and simulating different faults. The functions of this module can also be activated remotely. With this the user is able to perform the measurements and change the measurement conditions remotely during the lab session and can study the behaviour of the PV-device either freely or guided by a tutorial.

Keywords: I-V characteristics, solar simulator, remote access, remote education

INTRODUCTION

To reduce the impact of the COVID-19 pandemic, online formats were introduced in several fields of higher education. The evolution of the Internet of Things (IoT) made it possible to hold not only theoretical lectures, but also practical sessions in the online space. During the online sessions the students - under guidance of an instructor - can handle the same devices and can perform the same tasks as on attendance-based lessons.

To give a deep understanding of the processes, tools and systems in the field of photovoltaics, it is especially important, to develop also practical abilities in addition to the theoretical knowledge. A PV-module for example is a device with a quite complex behavior under operating conditions. Its electric behavior is significantly influenced by the connection configuration of the cells, the cells' temperature dependence, inhomogeneous illumination, and possible inhomogeneous temperature distribution. To describe these phenomena based on a theoretical approach is possible, but much too complicated and the lesson's learned is not proportionate to the effort and mathematical apparatus needed. However, a single laboratory session is already enough

to give the students a good insight into the basic behavioral patterns of a PV-device and the hand-on approach of a practical lab session is most often much more memorable than a theoretic lecture. Thus for a long time we included laboratory practices in our curricula where students can measure solar cells and modules under different environmental conditions, and evaluate them in different configurations and under different operational conditions.

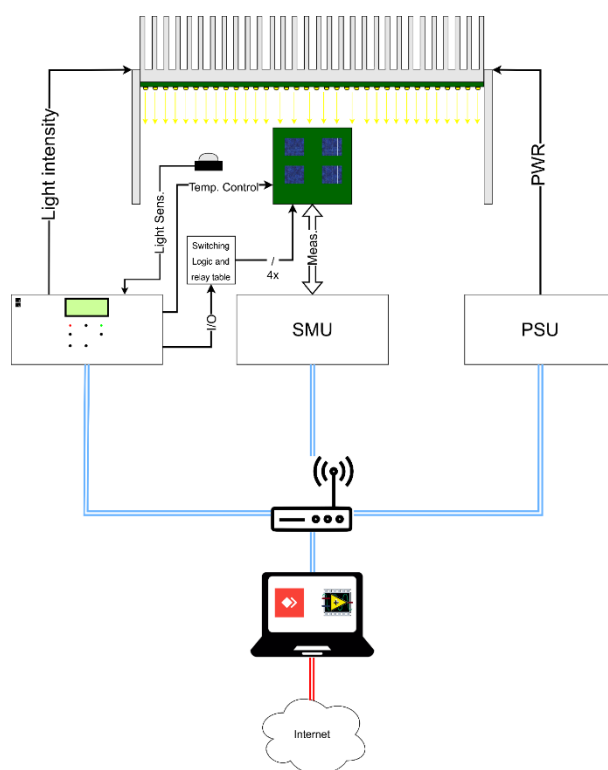
For this evaluation of the module behavior the module's I-V curve is used, since this representation is used in applications in practice and it is able to visualize a wide variety of effects, including the dependence on operational behavior and specific defects. During the attendance-based practical session the students work in smaller groups in the lab where they are measuring the I-V curve of the solar cell or module the guidance of the instructor. Afterwards, they determine the device specific properties for example efficiency, operating point, short circuit current, open circuit voltage from the measurement results. They also explore the effects of inhomogeneous illumination and the module's temperature dependence. The knowledge gained in these lab session helps to develop the necessary professional perspective for the design, measurement, and servicing of multi-module PV systems.

Due COVID-19 restrictions, these practical lessons could not be held in the usual attendance-based form. In order to make the practical knowledge transferable, we have created a complex solar cell measurement system that can be operated remotely (Fig. 1). With this system the students can perform the lab tasks during the online practice from home and can compose the documentation based on the results. The system performs measurement of each I-V curve measurement fully automated, the students only have to set the measurement parameters (representing the different environmental conditions) and start the acquisition of the I-V curve. The main components of the system are an illumination unit and a special PV-module. On the module every cell's temperature can be changed individually. In addition, there is the possibility to change the wiring of the cells within the module, and the users can add an error to a specific cell. This system is not only capable of remote control, but is also faster and thus allows more measurements and the examination of more operational scenarios than the previous manual setup used in the attendance-based lab sessions. With this system each student can perform the lab sessions individually instead of creating smaller groups. If the special demo module is replaced with a DUT (device under test), the system acts as a remote controlled solar simulator and I-V tester, and can be applied for testing different devices.

The system consists of two main components: a fully remote controllable solar simulator with an I-V curve measurement system and a special demo solar module that is capable of simulating different environmental effects and simulating different faults. The functions of this module can also be activated remotely. With this the user is able to perform the measurements and change the measurement conditions remotely during the lab session and can study the behavior of the PV-device either freely or guided by a tutorial.

During the measurements the module is illuminated by the solar simulator. The solar simulator is built up modularly from 110 x 110 mm LED-modules. In the current arrangement a 3 x 3 LED-module arrangement is used, ensuring class A homogeneity and time stability on an area of 20 x 20 cm in a light intensity range from 100 to 2000 W/m². Due to the modular arrangement various solar simulators sizes can be constructed, up to the size of commercial panels.

between the software and the measurement unit takes place over local area network, using standard communication protocol, TCP and using SCPI commands. The system's further part is a power supply for the LED-panels of the solar simulator and a central control unit that controls the light intensity and the power supply, performs the switches of the demo PV-module, sets the cells' temperature. The unit communicates over the local area network with the GUI software and the power supply. The users cannot modify the operational parameters of the power supply in remote access mode over the software, to avoid malfunctions.



The measurement system's components are the following: illumination unit made of LED modules, source meter unit (SMU), high power power supply, personal computer which contains two network cards and a self-developed control unit. As seen on Fig. 1 the main components of the system communicate through local area network which is realized by a router. The personal computer is responsible for controlling the system, this device is connecting at the same time to the mentioned local area network and to the wide area network. The users can connect via internet with AnyDesk to the computer that runs the GUI software made in National Instruments LabVIEW development environment, performs the measurements. On the figure the local area network is marked in blue (double line), the software is

configured to communicate only on this network. The structure and functions of the special module, the structure and tasks of the self-developed control unit, and the operation of the LabVIEW software will be discussed below.

Solar simulator

The special PV-module illuminated by a solar simulator during the measurements. The solar simulator has a modular design, it consists of 9 LED-modules with a size of 110 x 110 mm in a 3 x 3 layout, with a calibrated illuminated area 20 x 20 cm. Thanks to the arrangement of the LEDs, the solar simulator is able to meet the homogeneity criteria of IEC 90604-9 Class A [1] without a special optical solution. Based on our previous work [2] the light homogeneity distribution of an illuminating module is shown in Fig. 2.

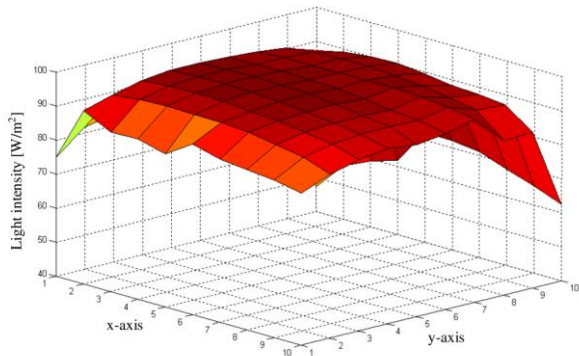


Fig. 2: Light intensity distribution of a single LED-module

The illumination unit can illuminate a 200 x 200 mm area with a light intensity between 100 or 1000 W/m². During the illumination, the system measures the intensity with a sensor module. This device consists of a calibrated PV-cell, with an analogue output signal which is proportional to the light intensity, with a sensitivity of 0,01 V / 100 W/m². Both the special PV-module and the light sensor fit under 200 x 200 mm homogeneously illuminated area of the solar simulator.

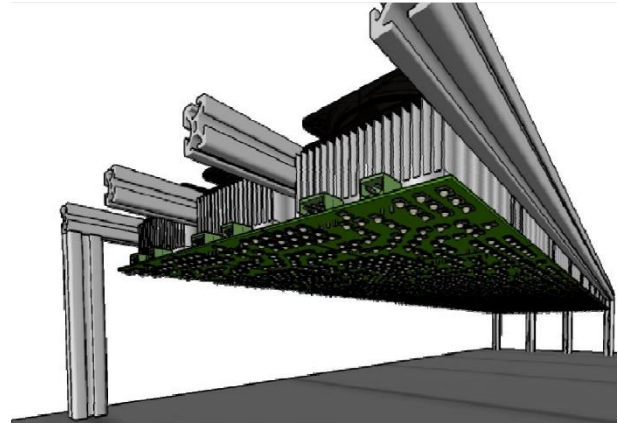


Fig. 3: CAD-drawing of the LED-simulator

Control Unit

This self-developed unit is responsible for several tasks. Previously the control unit of the solar simulator was a current control with an analogue input that received the analogue control voltage from a PC over a D/A converter card. This unit was upgraded to be capable of digital communication and supplemented with additional functions, including the control of the demo module. It controls light intensity by a variable current limiter, that is connected to the 250 V and 2,5 A main power supply. It also contains a power supply that delivers the voltages for the current limiter (symmetric 15 V), the solar simulator's cooling system (12 V), and the digital microcontroller (5 V). The further parts of the control unit are a network module, a microcontroller, and current generators for the PT100 types of temperature sensors. The structure of the control unit is shown in Fig. 4.

One of the main task of the control unit is the communication with the high-power power supply via SCPI commands. The unit enables, disables, and configures the power supply. It also generates the setpoint of the solar simulator. This is an analogue signal which goes to the input of the current limiter. The previous version of the control unit didn't contain a control-loop to sets the light intensity, and it was offline, meaning the user set the intensity with buttons.

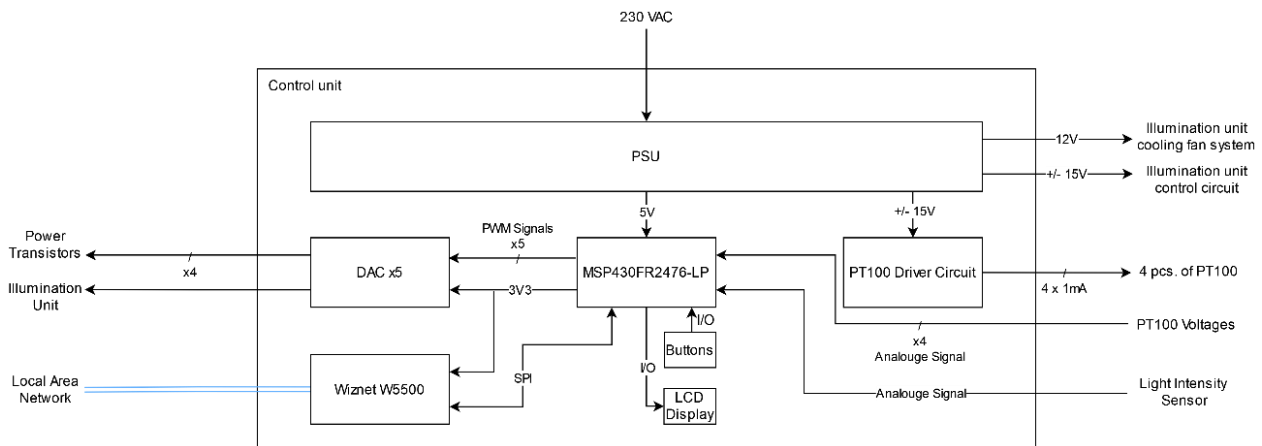


Fig. 4: Control unit architecture

Additional features were added to the control unit. The actual version consists of 5 control loops, one of them is responsible for the light intensity and the other 4 are responsible for the temperature of each cell. The measurement software sends the setpoints of the intensity and the temperatures, the control unit receives it and starts the control. For the control of the light intensity the control unit receives the output signal of the intensity sensor as a feedback. In the unit a PI-type control mechanism is implemented.

An important feature is that the user cannot change the settings of the power supply over the GUI software, to avoid malfunctions. The control unit is also capable to operate in offline mode, meaning that the solar simulator can be operated without GUI software on the main personal computer. In this mode the unit acts as a manual solar simulator.

Special demonstrator PV-module

The special demonstrator module that is used by the students during the remote session consists of 4 solar cells. Due the construction of the module, the connections between these cells can be modified during the remote session, this is how the different module wiring configurations are demonstrated to the students. The PV-module schematic can be seen Fig 5 and the possible cell connection configurations are shown in Fig. 6.

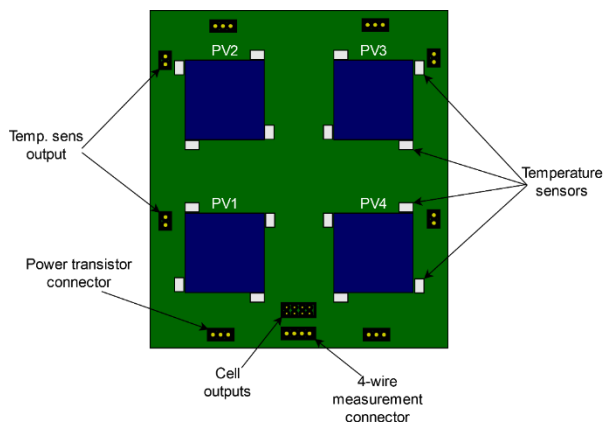


Fig. 5: Layout of the special demo-module

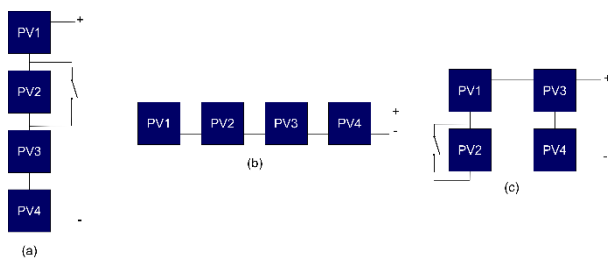


Fig. 6: Possible configuration of the demo module. a) series, b) parallel, c) hybrid (2 strings of 2 cells in parallel)

The anode and cathode of each cell are routed to the connections of the module where the switching logic circuit and relay table are connected to the module. With this switching circuit the user can choose between the connect modes, and can insert a fault to the module via the GUI. This fault is the short circuit of the cell number two. With this function, it is easy to demonstrate the change in the U-I characteristic of the given connection mode in the event of such fault.

As already mentioned, each cell's temperature can be modified. Heating is achieved by high power transistors which have been integrated to bottom side of the PCB, under the cells. The transistors transfer heat through thermal vias to the cells to reach the desired temperature. Four PT100 type temperature sensors are responsible for the temperature feedback for each cell. The location of the thermometers and the module itself have been designed according to design considerations that help to determine the temperature of the component as accurately as possible [3]. The temperature sensors have been placed as close as possible to the cells and there are poured copper surfaces between the cells and the sensors' bottom side to increase the thermal conductivity. The four resistors are connected in such way that their resulting resistance is 100Ω ($T = 0^\circ \text{C}$). Thus, the measurement of the area limited by them, i.e., the average cell temperature, is realized. The temperature sensors and the heating transistors can be contacted over the connectors marked in Figure 5. The location of the transistors in the module is shown in Fig. 7.

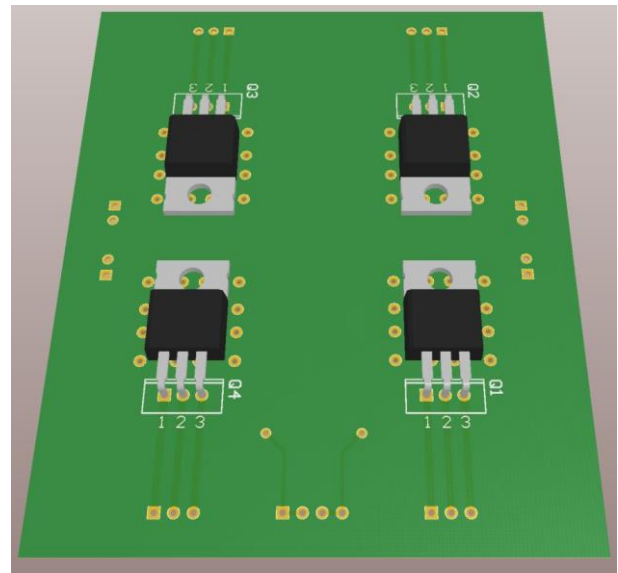


Fig. 7: Transistors for the heating of each cell

MEASUREMENT

The system performs the measurement with a Keithley 2450 source meter unit (SMU) [4] which is marked on Fig. 1. The device performs the measurement in 4-wire measurement mode. For the measurement the voltage

generator mode of the SMU is used that forces different voltage values to the terminals of PV-module and at every value the current will be measured. This device can measure maximum in the range of ± 20 V modules, and a maximum current of 1 A.

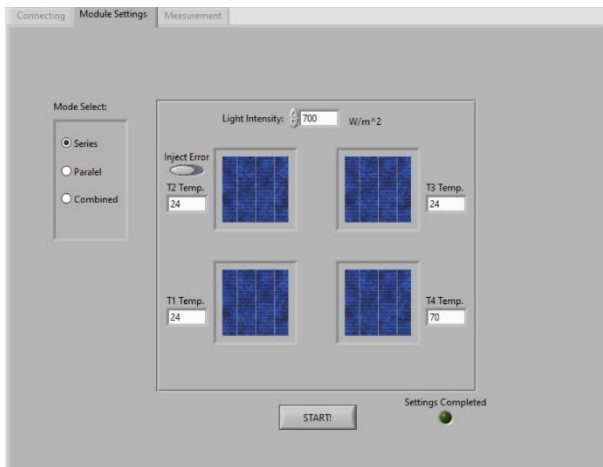


Fig. 8: GUI for setting the measurement parameters

After a measurement is done, its results can be saved before a new one is started. The software saves the result into coma separated values file format. (*.csv) As default the software recommends the actual date as the file name, but the user can modify it. The data saves into the file also contains the cell connecting method, the illumination value, and the temperature values. The GUI for the module settings can be seen in Fig. 8.

Measurement software

The GUI software is responsible for the connection between the user and the measurement system. The software communicates over the local area network with the components of the measurement system. After the start of the application the software tries to connect to the SMU and the control unit. The software can't connect directly to the high-performance power supply, only the control unit is capable of this. The block diagram of the measurement software can be seen in Fig. 9.

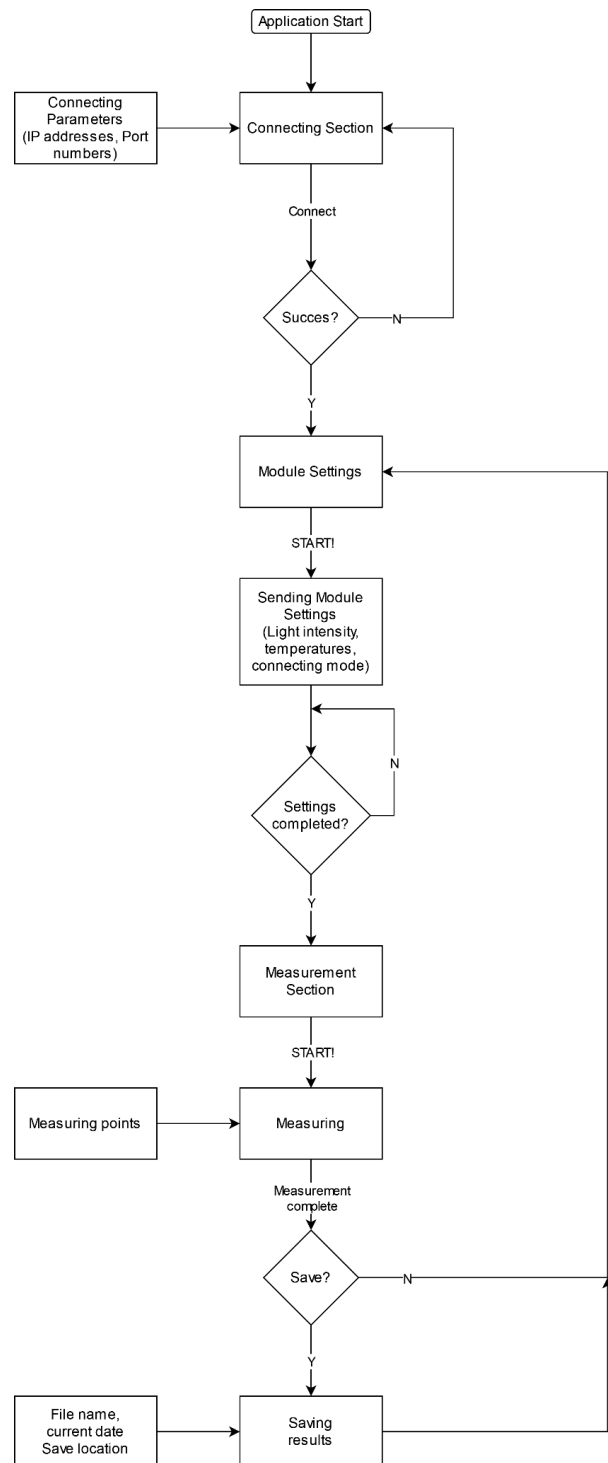


Fig. 9: Block diagram of the measurement software

Measurement results

The I-V curves of the measurement results are displayed in X-Y plots on the screen of the GUI. For comparison reasons it is possible to display more curves in one plot. The user has the possibility to save the I-V curve data after each measurement and use the measurement data for processing and analysis later. Fig. 10 shows some examples for the visualization of measurement data at different module configurations and light intensities.

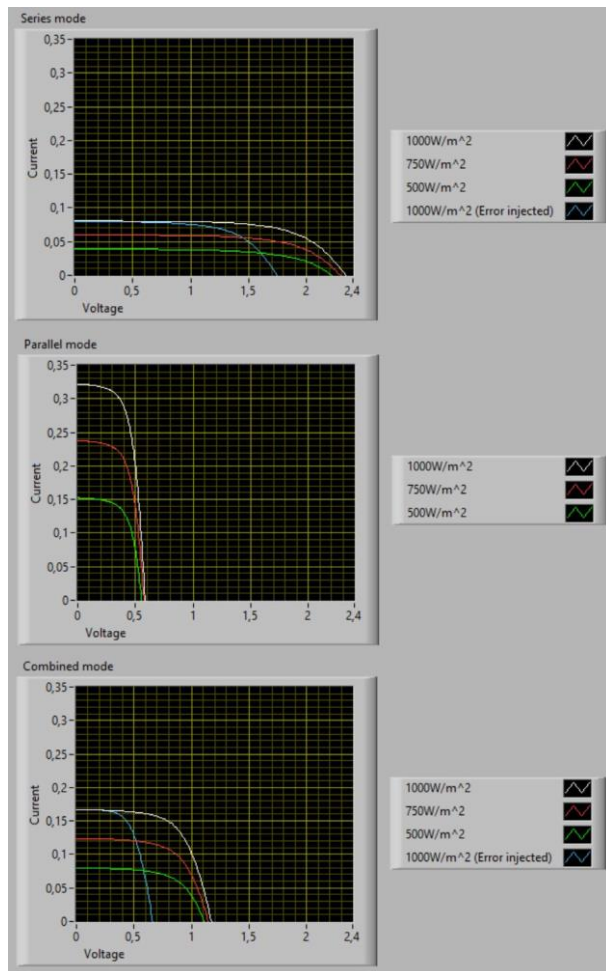


Fig. 10: Displayed results for different configurations of the demo module configurations at different light intensities, with cell failure switched on and of. a) series configuration, b) parallel mode (no cell failure available), c) hybrid mode

CONCLUSIONS

To be able to deliver practical laboratory sessions in times of COVID-19 human contact restrictions a fully remote controllable measurement setup was developed for the demonstrations of the effects of the environmental conditions on the behaviour of PV-devices. With the developed setup the I-V curves of solar cell and small modules can be measured in remote control and fully automatically. The system comprises of a solar simulator and a special demo module. In the demo module the configuration of the wiring of the cells can be change, also faults can be inserted into the circuit over a GUI. In addition, the temperature of each cell can be seat with the help of a heating transistor on the backside of the demo module. This enables students to investigate and evaluate the behaviour of solar cells and modules over a wide range of possible operational conditions remotely. Without the special demo module the system operates as a remote controlled solar simulator.

ACKNOWLEDGEMENTS

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