# Innovative Laboratories for Teaching on Photovoltaic Generation in Higher Education

Alessandro Ciocia [1], Paolo Di Leo[1], Stefania Fichera[1], Gabriele Malgaroli[1], Angela Russo[1], Filippo Spertino[1], Slavka Tzanova[2] and Bolormaa Dalanbayar[3]
[1]Energy Department, Politecnico di Torino
Corso Duca degli Abruzzi 24, Torino 10129, Italy
{alessandro.ciocia, paolo.dileo, gabriele.malgaroli, angela.russo, filippo.spertino}@polito.it
[2]Department of Microelectronics, Technical University of Sofia, 8
Kliment Ohridski blvd., 1000 Sofia,
slavka.tzanova@tu-sofia.bg
[3]Department of Electronics and Communication Engineering, National University of Mongolia
Ikh Surguuliin Gudamj-1 P.O.Box -46a/523, 14201 Ulaanbaatar, Mongolia,
bolormaa@seas.num.edu.mn

*Abstract* –**The production of energy from Photovoltaic technology is becoming more and more relevant. Therefore, it is essential that academic world focuses attention on this topic in order to properly teach and transmit knowledge, skills and abilities. These ones are very useful in work activities. The academic course "Photovoltaic Power Generation" aims to better explain theoretical aspects by practical activities which require the implementation of innovative laboratories for learning. This paper presents the guidelines for replication of laboratory practices (twin labs), already offered to Italian students, in the context of the project EU-MONG.**

*Keywords* –**education; e-learning; innovative teaching; laboratory practices.**

## I. Introduction

The course "Photovoltaic Power Generation" (PPG) provides to the students the knowledge related to the solar resource and the photovoltaic generators, including power electronics. Students obtain the skills to estimate the solar source and calculate the instantaneous and average performance of the main components, and finally the energy productivity of photovoltaic (PV) plants. The competences are the design, in a proper way, of the main components of PV plants and the energy analysis of their operation. In order to reach these goals, the course is planned combining theoretical lectures with practical exercises, and innovative laboratories [1], which enhance the active learning of theoretical knowledge [2].

The PPG course is offered to students of Politecnico di Torino by frontal lectures, and in e-learning to Mongolian students in the framework of the European Project "Euro-Mongolian cooperation for modernization of engineering Education" (EU-MONG) [3][4]. The EU-MONG project aims to modernize and internationalize the higher education in engineering sciences in selected Universities in Mongolia. It is done through innovation of MSc curricula according to the labor market demand and the development in the area.

Virtual mobility, through e-learning provided by ICT, is a key point in the EU-MONG project. In order to provide e-learning courses, EU-MONG uses an Open edX platform. Open edX is the open-source platform software derived by EdX project founded by Harvard and MIT universities [5]. Open edX project permits to freely make platforms for other institutions to share online course. More than 30 e-learning university courses in electrical engineering, communications and energy efficiency are available on the Open edX platform of EU-MONG [6]. Each course is characterized by its number of credits, the title of each theoretical lecture, practical exercise or laboratory test.

The lectures, provided by four European universities/institutions (Technical University of Sofia that is the coordinator, Politecnico di Torino, Technical University of Berlin, National Institute of Solar Energy, INES, from France) and three Mongolian universities, include different kinds of teaching material, such as video lectures, video slides, scripts, exercises and written exams.

The main goals of the laboratory practices are two. First, student will gain practical experience about the operation of photovoltaic generators, electronic devices and components (i.e. transistors and AC/DC converters). Secondly, students will be introduced to practical knowledge of devices used to measure voltage and current. In fact, students enrolled in courses in industrial engineering do not always have competences related to electrical measurements.

Thus, students will learn how to handle three types of measurement instruments, starting from the simplest to the most complex: digital multimeters, oscilloscopes and automatic data acquisition systems. The main difference between these typologies of devices is the number of digits of their display and their sampling rate [7].

## II. INNOVATIVE LABORATORIES

The effectiveness of the course and, in particular, of the laboratories presented in the following subsections has been assessed by questionnaires submitted to the students. The results of the questionnaire for the students' satisfaction demonstrate that, with more than 100 filled questionnaires, the 90 % of the students believe that laboratories and practical exercises are very useful for the understanding of the course's topics.

### *A. Laboratory practice #1: Measurement of the I-V curve of solar cells in dark conditions*

In the first laboratory practice, students will check the performance of solar cells in dark conditions, in case of both Forward Bias (FB) and Reverse Bias (RB). In particular, the activities performed in the laboratory consist of Theoretical Explanations (TE) and Practical Activities (PA). First, a brief introduction to the operating principles of digital multimeters will be provided. A digital multimeter permits to measure several physical quantities using the same device: in the present activity, students will use two identical multimeters (having 4 ½ digits [8]) to measure voltage and current of solar cells. Fig. 1 shows the display of the multimeter, the setup buttons of the device and the positive and negative terminals to measure voltage or current.

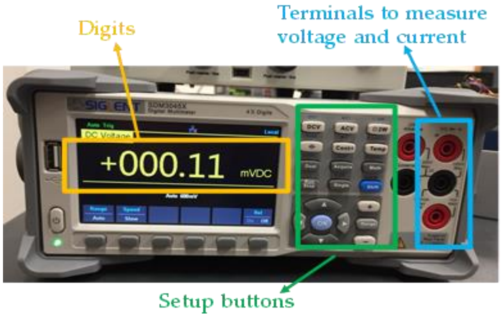



Fig. 1. Digits, setup buttons and terminals of the multimeter

Then, the operating principles of a solar cell will be presented. In particular, the performance of solar cells can be described by an equivalent circuit consisting of a current source, a diode connected in antiparallel and two resistances. The first is a current source that generates by photovoltaic effect; the diode takes into account diffusion in the p-n junction and the recombination of hole-electron pairs; the resistances quantify the leakage current through the lateral surfaces of the solar cell and the voltage drop across the fingers and busbars on the front of the solar cell [9][10].

Solar cells are diodes: however, their performance is affected by the irradiance investing their front surface. In dark conditions, when an external voltage is applied, if the solar cells are forward biased, i.e. a positive voltage is applied, the electric field generated by the p-n junction decreases, making the diffusion across the depletion region easier. As a consequence, the diffusion current increases and a substantial amount of current circulates in the circuit.

On the contrary, if the cells are reverse biased, i.e. a negative voltage is applied, the electric field increases and the diffusion current decreases, leading to a negligible current in the circuit. In the present laboratory practice, the measurement of the current-voltage (*I-V*) curve of shaded solar cells in FB and RB is performed.

After this theoretical description, the measurement circuit and the connections in case of FB cells will be presented and students will trace the *I-V* curve of solar cells in dark condition. In particular, students will increase the voltage of the power supply from zero to the open-circuit voltage of the PV module (1.2 V), with detected currents up to few A. The most important electrical data of the PV module are reported in Table 1.

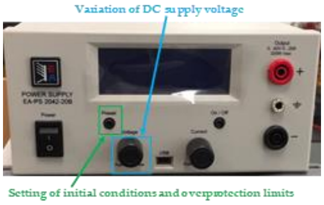
TABLE 1. MAIN ELECTRICAL DATA OF THE PV MODULE UNDER ANALYSIS.

| | | |
|---|---|---|
| Open-circuit voltage | 1.2 | V |
| Short-circuit current | 8.6 | A |
| Rated Power | 8 | W |

As previously mentioned, PV modules are diodes. As a consequence, at low voltages no conduction occurs, while, after a threshold voltage, the current exponentially increases [11]. For this reason, at low voltages, few experimental points can be stored, while students are required to trace a huge number of points after the threshold, i.e. when conduction occurs, in order to better appreciate the shape of the curve, which is similar to the one of diodes. The same procedure will be repeated for reverse biased PV cells. In this case, the current detected in the circuit will be lower than previous measurement performed (tens of milliampere) and the curve is almost linear: thus, students can store fewer experimental points, reaching voltages up to -20 V because measured current will be negligible.

Finally, the uncertainty of the measurements will be calculated by the students starting from the uncertainty of digital multimeters from the datasheet (two contributions depending on the readings and the ranges). Fig. 2 presents the PV module (dimensions: 35 cm x 17 cm) and the power supply used in this laboratory practice. A PowerPoint file for each laboratory session will be provided to the students before the start of the activities.

(a)




(b)

Fig. 2. PV module (a) and power supply (b) used by students

### *B. Laboratory practice #2: Measurement of the I-V curve of irradiated solar cells.*

In the second laboratory practice, students will check the performance of solar cells irradiated by artificial lamps. In this laboratory session, an oscilloscope [12] will be used to trace the *I-V* curve of irradiated solar cells.

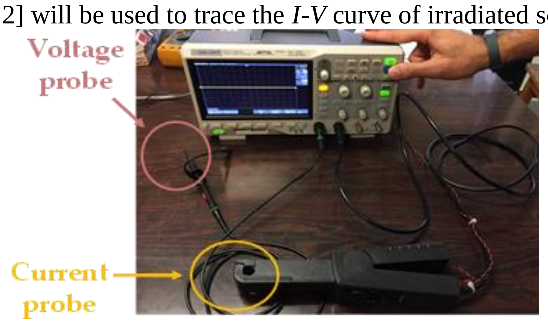
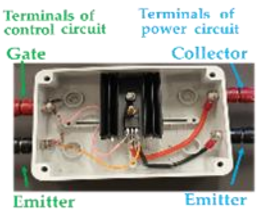



Fig. 3. Oscilloscope and probes for current and voltage signals.

First, the basic notions regarding the operating principle of an oscilloscope and the proper settings for the experience are presented. In particular, the oscilloscope will be connected to current and voltage probes (Fig. 3); a proper trigger will be set on current signal in order to start the measurement. The electrical performance of PV generators can be determined by few methods [13]: in the third part of the laboratory practice, the most common methods to trace the *I-V* curve of a PV module are presented. In the present activity, a PV module charges a capacitor [10], initially discharged, from short-circuit to open-circuit condition. The same module used in the previous laboratory (Fig. 2a) is irradiated by artificial lamps, which provide the irradiance to measure a current up to few amperes. At the beginning of the transient process before the closing of a switch, the PV module works in open-circuit condition: after the closing of switch, PV voltage is the same across the terminals of the capacitor, which is zero because the capacitor is discharged, and the current flowing in the circuit is the maximum current that solar cells can provide (the short-circuit current). Then, for a limited time interval, the voltage linearly increases, while the photo-generated current keeps almost constant. After this interval, capacitor voltage saturates reaching the open-circuit voltage of PV cells and the current decrease to zero (open-circuit condition). At the end of the transient, the capacitor is charged: no current is flowing in the circuit and the voltage across its terminals is the open–circuit voltage of the PV module. At the end of the two laboratory practices, students can represent on the same plot the *I-V* curves of the PV module in dark conditions and artificially irradiated in order to compare the *I-V* curves in different conditions.

### *C. Laboratory practice #3: Measurement of the current-voltage characteristic of a transistor*.

In the third laboratory session, students will trace the output *I-V* curve of a transistor operating as a power switch [14]. The laboratory activities are the following: first, an introduction to the measurement circuit and its connections will be provided. Then, the operating principles and applications of transistors are described. A transistor is a semiconductor permitting to amplify or commutate electric signals or electrical power using a control signal. In the present activity, the characteristic curve of an Insulated Gate Bipolar Transistor (IGBT) will be measured; this device has three terminals: a collector, a gate and an emitter (Fig. 4a).




(a)

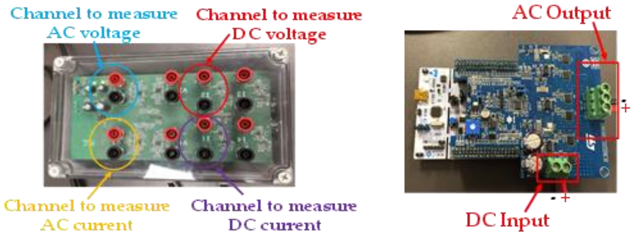
(b)

Fig 4. Terminals of control circuit and power circuit of the IGBT under analysis (a) and measurement circuit (b).

In particular, a voltage applied between the gate and the emitter (the control voltage) permits to control the operation of the transistor: if this voltage is lower than a threshold indicated by the manufacturer (the activation voltage), the transistor will be OFF. On the contrary, if the control voltage is sufficiently high, the transistor will be activated and its operation will be determined by the voltage applied to the collector and the emitter (the power voltage). In the first practical activity of the laboratory, students will apply a constant power voltage (3 V), while the control voltage will assume two values. In particular, it will be equal to 2 V and 10 V: in the first case, the control voltage is lower than the activation voltage of the transistor (8 V): therefore, the transistor will be OFF and a negligible current will be measured for any power voltage applied. In a second stage, the control voltage will be 10 V: in such condition, students will check the active operation of the transistor measuring a current in the circuit in the order of few amperes. Then, the second practical activity will consist of the tracing of the output *I-V* curve of the transistor (Fig. 4b) in operation mode (control voltage higher than the activation one). In this case, the transistor will be activated and students will vary the power voltage from 0 to 3 V, measuring the current circulating in the circuit.

### *D. Laboratory practice #4: Measurement of the performance of a DC/AC converter.*

In the fourth laboratory session, students will use an Automatic Data Acquisition System (ADAS) in order to evaluate the performance of a Pulse Width Modulation (PWM) inverter. The laboratory activities are presented in detail: first, the operating principles and the main components of ADASs will be described. In particular, students will handle the data acquisition board (Fig. 5a), which has eight channels to measure current and voltage signals: in the present activity, two channels are used to acquire DC current/voltage, and two channels permit to acquire AC current/voltage. Then, the measurement circuit of the activity will be described: in this case, students will use proper components on DC and AC side to filter the input/output signals and reduce their distortion. In particular, on DC side, an inductor permits to filter the current, while, on AC side, an inductor and a capacitor permit to filter (low pass) the current and voltage signals, respectively.




(a) (b)

Fig. 5. Data acquisition board (a) adopted to analyze the performance of an inverter (b).

In another step, the operating principles of DC/AC converters will be described. An inverter converts DC quantities into equivalent AC signals. However, the DC/AC conversion leads to losses, which depend on the operation of the inverter. In particular, at full load, the efficiency of the converters increases, leading to lower losses, while at partial load the impact of losses on PWM inverter production increases, corresponding to a lower efficiency. In the following step, students will check the effects of the filters on DC and AC side comparing the signals with and without the filters. Fig. 6 shows the interface of the ADAS with the DC and AC signals.

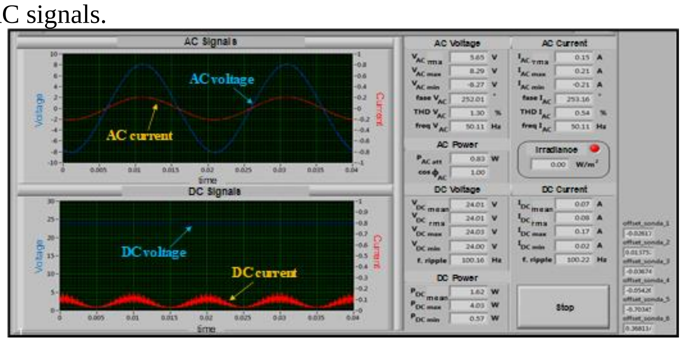



Fig. 6. Interface of the ADAS used by students with an example of DC and AC signals.

Finally, the students will evaluate the total harmonic distortion for both voltage and current signals [14], and the performance of an inverter (Fig. 5b) supplying different loads [15]. In this case, inverters will supply bench resistors: students will progressively reduce the corresponding resistance. Thus, an increase of the efficiency will be measured.

## III. CONCLUSION

The “Photovoltaic Power Generation” is an academic course for electric and energy engineering students of Politecnico di Torino. This course is offered in e-learning to Mongolian students within the European Project EU-MONG. The key element of this educational approach consists of the acquisition of new abilities through a direct and concrete participation and it results in the combination of traditional theoretical lectures, practical exercises and innovative laboratories. These labs are devoted to measure the actual efficiency performance of the PV modules and DC/AC converters, that are the crucial components of the PV systems. The proposed laboratory practices permit to introduce students in the measurements of electrical quantities by handheld and bench multimeters, oscilloscopes and data acquisition systems.


## ACKNOWLEDGMENT

The project "Euro-Mongolian cooperation for modernization of engineering education" 585336-EPP-1-2017-1-BG-EPPKA2-CBHE-JP is co-funded by the European commission, program Erasmus+ Capacity Building in Higher Education. "The European Commission support for the production of this publication does not constitute an endorsement of the contents which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein."


## REFERENCES


[1] J. Zalewski, G. Novak, R. Carlson," An Overview of Teaching Physics for Undergraduates in Engineering Environments,"in Education Sciences, vol. 9 pp. 278, 2019.

[2] S. Hartikainen, H. Rintala, L. Pylväs, P. Nokelainen, "The Concept of Active Learning and the Measurement of Learning Outcomes: A Review of Research in Engineering Higher Education," in Educ. Sciences, vol. 9 pp. 276, 2019.

[3] Euro-Mongolian cooperation for modernization of engineering education (EU MONG). [Online] Available: http://eu-mong.eu/ (accessed on 06 March 2020).

[4] Tzanova, S., Work in Progress: Competence Building in Engineering Education in Mongolia, Proc. of EDUCON 2020, 27-30 April, 2020, pp. 33-36.

[5] Open edX® platform of the EU-MONG project. [Online] Available: http://34.90.160.25/ (accessed on 06 March 2020).

[6] edX project. [Online] Available: https://www.edx.org/about-us (accessed on 06 March 2020).

[7] J. Gao, W. Huang, W. Wei, L. Guo, H. Li, P. Ye, "Trade-off between Sampling Rate and Resolution: A Time-synchronized Based Multi-resolution Structure for Ultra-fast Acquisition," IEEE International Symposium on Circuits and Systems (ISCAS), Florence, Italy, pp. 1-5, 2018.

[8] SDM3045X datasheet [Online] Available: siglentna.com/wp-content/uploads/dlm_uploads/2017/10/SDM3045X_DataSheet_DS06034-E02B.pdf.

[9] M.B.H. Rhouma, A. Gastli, L.B. Brahim, F. Touati, M. Benammar, "A simple method for extracting the parameters of the PV cell single-diode model", in Renewable Energy, vol. 113, pp. 885-894, 2017.

[10] F. Spertino, A. Ciocia, P. Di Leo, S. Fichera, G. Malgaroli, A. Ratclif, "Toward the Complete Self-Sufficiency of an nZEBs Microgrid by Photovoltaic Generators and Heat Pumps: Methods and Applications", IEEE Transactions on Industry Applications, vol. 55, no. 6, pp. 7028-7040, Nov.-Dec. 2019.

[11] J. Ahmad, F. Spertino, A. Ciocia, P. Di Leo, "A maximum power point tracker for module integrated PV systems under rapidly changing irradiance conditions," 2015 International Conf. on Smart Grid and Clean Energy Tech., Offenburg, pp. 7-11, 2015.

[12] SDS1104X-E datasheet. [Online] Available: siglentna.com/product/sds1104x-e-100-mhz/.

[13] A. Ciocia, G. Malgaroli, A. Spedicato, F. Spertino, H. Andrei, V. Boicea, "A. Quality Check during Manufacturing of Custom Photovoltaic Modules with Back-Contact Cells," 54th International Universities Power Engineering Conference (UPEC), Bucharest, Romania, pp. 1-6, 2019.

[14] F. Spertino, G. Chicco, A. Ciocia, G. Malgaroli, A. Mazza, A. Russo, "Harmonic distortion and unbalance analysis in multi-inverter photovoltaic systems," 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi, pp. 1031-1036, 2018.

[15] F. Spertino, G. Graditi, "Power conditioning units in grid-connected photovoltaic systems: A comparison with different technologies and wide range of power ratings," in Solar Energy, vol. 108, pp. 219-229, 2014.