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Innovative Teaching on Photovoltaic Generation

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Abstract – **One of the most important technologies for the renewable energy production is the Photovoltaic (PV) one. In the last decades, the enormous growth in the world of Photovoltaic installation capacity, and future trends, makes the knowledge of this topic fundamental for engineers working in the energy field with this competence, and not only. Thus, for students enrolled in industrial engineering courses, appropriate and innovative teaching methods are necessary. This paper aims to describe the structure of the course "Photovoltaic Power Generation" in which solar resource and the photovoltaic generators, including power electronics, are explained. The topics of traditional theoretical lectures are presented, with the links to practical exercises and laboratories.**

Keywords – **engineering education; higher education; e-learning; innovative teaching; laboratory practice.**

I. Introduction

In Europe there are many different higher educational and training systems. In the past, it was difficult to understand and compare the qualifications from other countries. The titles of the qualifications, despite being the same, could consider different contents. For this reason, in 2004, the development of the European Qualifications Framework (EQF) started in response to requests from the European member states for a common reference for qualifications [1][2]. In this context, the definition of the learning outcomes for knowledge, skills and competences are stated. The acquisition of theoretical knowledge is required to build specific skills, which permit to gain competences in work activities. The term 'competence' means the proven ability to use knowledge, skills and personal, social and/or methodological abilities, in work or study situations and in professional and personal development. According to these definitions, 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 [3], which enhance the active learning of theoretical knowledge [4].

The PPG course is offered to students of Politecnico di Torino by frontal lecturers, and in e-learning to Mongolian students in the framework of the European Project "Euro-Mongolian cooperation for modernization of engineering Education" (EU-MONG) [5]. 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 new 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, because it is well-known in the Mongolian universities. Open edX is the open-source platform software derived by EdX project founded by Harvard and MIT universities [6]. 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 [7]. Each course is characterized by its number of ECTs, 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 from France) and three Mongolian universities, include different kinds of teaching material, such as video lectures, video slides, scripts, exercises and written exams. In this last case, there are several samples of past written tests with the solutions provided by excellent students.

II. Course "Photovoltaic Power Generation"

The course "Photovoltaic Power Generation" is devoted to the photovoltaic power systems starting from their operating principles, in which general aspects of power electronics are included. The course is organized with 40 hours of lectures,

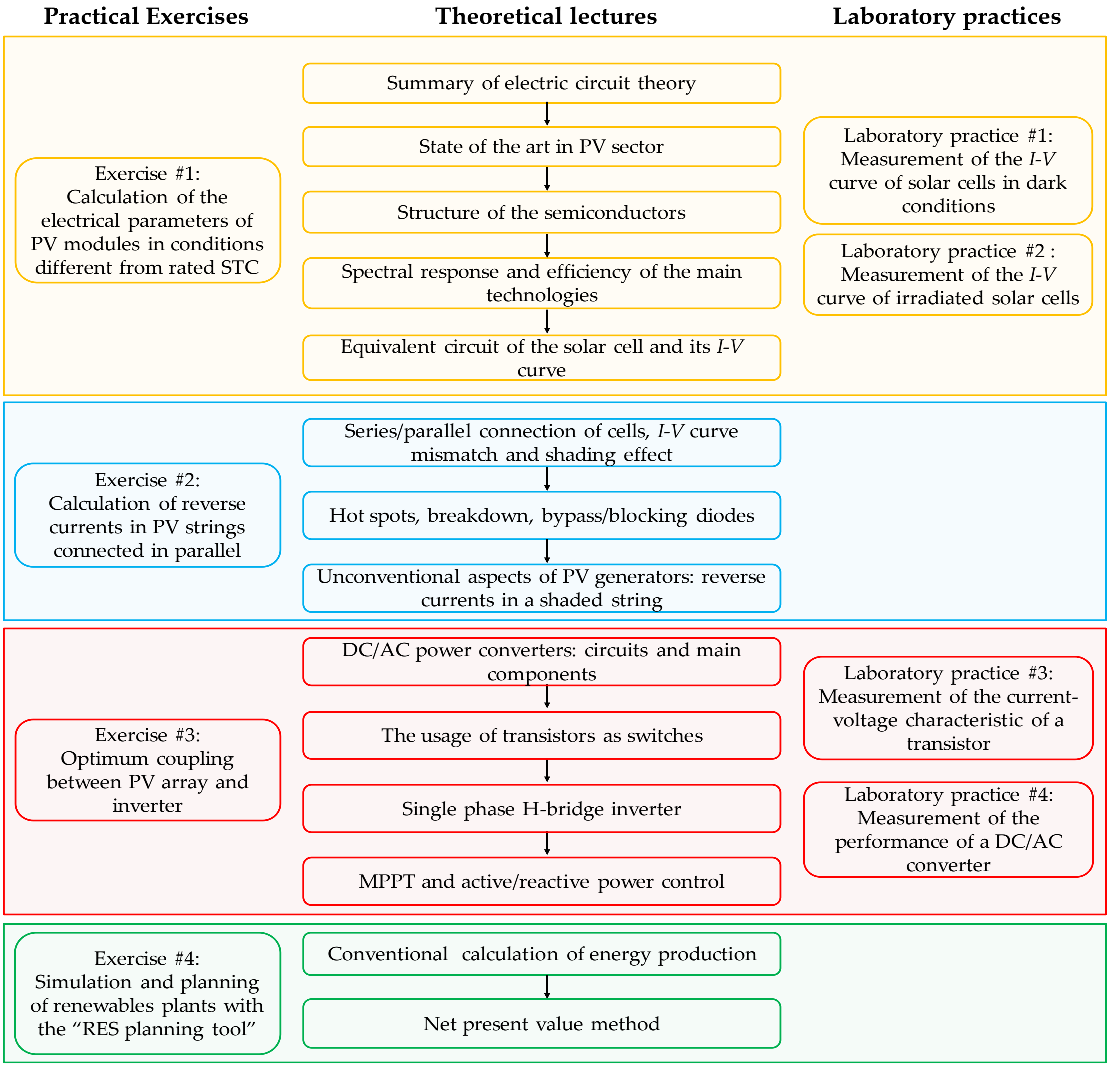

Fig. 1. Organization of the course

14 hours of practical exercises and 6 hours of laboratories. The duration of each lecture is of 1.5 hours. It is offered to students from the different courses in industrial engineering [8].

During the lectures, theoretical notions regarding the description of photovoltaic generation and plants will be provided. In order to permit a correct understanding of the topic, the first lectures are dedicated to basics of electric circuit theory. In fact, in the past years, students showed difficulties to understand the electric aspects of the topics, due to their different background from different courses in industrial engineering.

After the introduction, the state of the art in Photovoltaic (PV) sector is presented; in particular, the advantages/drawbacks and cost of installation; manufacturing process of silicon solar cells. The initial explanation of advantages and drawbacks of PV technologies, with respect to fossil fuels, is fundamental. It allows the students to understand the importance of this technology, and the current widespread over the word. As a result, the students show greater interest, also in the theoretical lectures in the first part of the course.

Lectures continue with the explanation of the structure of the semiconductors: energy band, doping, p-n junction and electric field, losses in the energy conversion. Spectral response and efficiency of the main technologies (crystalline and amorphous silicon, thin films of cadmium telluride, copper-indium-diselenide) permit to understand the principle of operation of the photovoltaic generation. As a conclusion of the first theoretical part, the equivalent circuit of the solar cell and the current-voltage characteristic curve (in short, *I-V* curve) at variable levels of irradiance and temperature are presented.

The students have acquired the skill to perform the first and second laboratories in this course: the measurement of the I-V curve of solar cells in dark conditions using digital multimeters, and the measurement of the I-V curve of solar cells irradiated by artificial lamps using digital oscilloscope. Moreover, students can perform the first practical exercise regarding the calculation of the electrical parameters of PV modules at different irradiance and temperatures starting from data in the datasheet of the manufacturers. Thanks to these calculations, students better understand the correlation between electrical parameters and environmental variables. Moreover, the reading of the datasheets allows students to get familiar with this kind of technical documents, and to understand which parameters are useful for carrying out the calculations.

Theoretical lectures continue with the explanation of series/parallel connection of cells, I-V curve mismatch and shading effect, hot spots and breakdown; bypass and blocking diodes. Unconventional aspects of PV generators with respect to the traditional voltage sources are described in detail. The option to use the blocking diodes in case of reverse current in a shaded string, and the designer choice in case of shadowing between the concentrated one and the equally distributed one are presented. These concepts are used in the second practical exercise, consisting of the calculation of reverse currents in PV strings connected in parallel.

In the second part of the course, the teacher describes DC-AC power converters. Lecture starts with the description of the circuits and details about the main components. Regarding, the transistors used as power switches, the students learn their principle of operation, and the usage of the single-phase H-bridge converter with PWM (Pulse Width Modulation) control for grid connection. Regarding the software, the operations of the Maximum Power Point Tracking (MPPT), and active/reactive power control are explained. In this way, the students can perform the third and fourth laboratory practice, in which they measure the output characteristics of a transistor operating as a switch using digital multimeters, and they measure the efficiency and power quality for a single-phase inverter using an automatic data acquisition system.

In the last part of the course, the students learn theory about the coupling of PV array and the DC-AC power converters, the constraints of power/voltage/current and the grid interface protections. Thus, a practical exercise is dedicated to the optimum coupling between PV array and inverter. They calculate the maximum voltages and currents from the PV generators, and they will compare them with the limits required by the electronic converters for correct operation and safety. The installed power and the configuration of PV models (the number of series connected modules and the number of strings) will be changed to satisfy the power, voltage and current constrains.

Finally, students are introduced to the conventional calculation of energy production, i.e., the evaluation of solar radiation, and loss sources in the productivity. In addition, students receive an overview on the economic analysis by the Net Present Value (NPV) method. Thanks to this knowledge, the students are ready for the last practical exercise, consisting of the simulation and planning of photovoltaic plants, wind turbines and storage systems with a spreadsheet usable in both real and virtual classrooms.. Figure 1 shows the organization of the course, with the division between theoretical lectures, laboratory practices and practical exercises.

A. A first approach to measurement instrumentation

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 [9].

Generally, a measurement instrument converts an analog (continuous) signal into a digital (discrete) one. The display digits refer to the level of resolution of the acquisition instrument, i.e. the level of detail that the instrument is able to quantify during the acquisition of physical quantities. On the contrary, the sampling rate indicates the number of experimental points acquired by the instrument in the time unit. However, resolution decreases when acquisition speed increases: as a consequence, it is hard to achieve high number of digits with high sampling rate. For this reason, an optimal compromise between the level of resolution and the measurement speed needs to be selected according to the experimental context.

In case of simple troubleshooting, preventive maintenance work, a high measurement resolution is not required. In such applications, handheld digital multimeters represent an optimal solution, providing a low number of bits (typically, ranging between 12 and 16) with sampling rates up to several tens of thousands samples per second to calculate root mean square values. In the proposed laboratory practice, handheld digital multimeters have an accuracy of ≈0.05% for voltage and ≈1% for current. On the contrary, bench multimeters provide a higher number of bits, ranging between 18 and 24, corresponding to much lower uncertainty down to some parts per millions. These devices are high-performance instruments, mainly used for high precision applications such as in metrology labs. In the proposed lab, bench multimeters used by students are characterized by 4½ digits and sampling rate up to 500 kSa/s. The accuracy is ≈0.02% for voltage and ≈0.1% for current.

Oscilloscopes are instruments that display and analyze the waveform of electric signals. In particular, these devices permit to draw a graph of the instantaneous voltage and current signals as functions of time. Oscilloscopes are connected to electric devices by means of voltage and current probes, which permit to select the desired attenuation ratio of the signals. Moreover, the acquisition can be manual or automatic, using a trigger on voltage or current signal and high performance oscilloscopes can reach sampling rates up to 1 GHz. On the contrary, their resolution is lower than digital multimeters because, in general, they are characterized by 8 bits. Typically, oscilloscopes are used for testing malfunctioning electronic equipment, measuring time between events, looking at signal shapes and measuring the amplitude and frequency of a signal. In the proposed lab, oscilloscopes used by students are characterized by 8 bits and sampling rate up to 1 GSa/s (with analog bandwidth of 100 MHz).

Finally, Automatic Data Acquisition Systems (ADASs) are electronic devices that permit to automatically read, store, and transmit measurements from sensors to a computer. Generally, ADASs consist of the following components:

- Transducers and sensors.
- Conditioners or circuits permit to shift the transducer signal to the range of the input voltage of an Analogue to Digital Converter, which is ± 5 V.
- ADCs convert an analogue signal into a digital one using a multiplexer for acquiring up to differential channels.
- Digital multimeters, oscilloscopes or computer monitors display the results of the acquisition.
- Computers with dedicated software and memory units process the results of the measurements.

These devices permit to reach an optimal compromise between high levels of resolution and high sampling rates. In fact, ADASs can display results with a resolution up to 16 bits and millions of recordings per second can be acquired. In the proposed laboratory practice, ADAS used by students are characterized by 12 bits and sampling rate up to 250 kSa/s.

B. Feedback from the students

At the end of all the courses at Politecnico di Torino , students are asked to fill in an anonymous questionnaire concerning the quality of the course. The questionnaire is an increasingly used course evaluation method [10][11], and it is a not mandatory. Students answer questions related to the teacher's ability to teach, the organization of the course, the infrastructure, and their degree of interest and satisfaction. They can choose one of four levels of appreciation: from "one" corresponding to the lowest level, up to level "four" which is the highest. Thus, the satisfaction rate is calculated as the number of high (level "three") and very high ratings (level "four") with respect to the total ratings. Regarding the "Photovoltaic Power Generation" course, the students show appreciation for the course and the use of supplementary teaching activities. In the last three academic years, the students of the courses in Italian and English languages have been from 100 to 200, and more than 60 % of the students of each course completed the questionnaire. In all the courses, offered in Italian or English languages, the satisfaction rate is always about 80% for the general appreciation of the courses. Regarding the appreciation of exercises and laboratory practices, the satisfaction rate is close to 90%, demonstrating the importance of the integration of this teaching methods with the traditional theoretical lessons.

II. Conclusion

The course "Photovoltaic Power Generation" is offered to students of Politecnico di Torino by frontal lecturers. In the context of the European Project "Euro-Mongolian cooperation for modernization of engineering Education" (EU-MONG), this course is offered to Mongolian students in e-learning. In order to provide high level knowledge, skills and competences related to the photovoltaic generation, the teachers offer traditional theoretical lectures combined with practical exercises and innovative laboratory practices. The practical activities enhance the active learning of theoretical knowledge, according to the well-known "learning by doing" theory. The questionnaires concerning the quality of the course demonstrate that the appreciation of students for the course is high. The satisfaction rate is higher than 80% for the general course, and the satisfaction rate for the laboratory exercises is about 90%.

In case of e-learning, the video lectures are the main tool for teaching. They include the records of theoretical lessons, and the laboratory exercises performed by the teachers. Students can also access to the script of the course, as a complementary source for learning. The practical exercises in the form of spreadsheet files can be solved by the students using free software.

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