

Photovoltaic Microgrid Emulator for Educational Purposes

Manuel Pérez García^{1,2}, Jose Luis Torres Moreno^{1,3}, Serafín Limonchi Valenzuela², Aarón Raúl Poyatos Bakker³ and Ismael Sánchez López³

¹ CIESOL, University of Almería, Almería (Spain)

² Department of Chemistry and Physics, University of Almería, Almería (Spain)

³ Department of Engineering, University of Almería, Almería (Spain)

Abstract

Nowadays, the world is involved in a process of change of the paradigm for the exploitation of the primary sources of energy aiming to reach a cleaner and more sustainable scenario for the fulfillment of the power demands of the society. Together to the incorporation to the mains of huge quantities of renewable electricity from wind and solar parks, many industries and dwellings are also currently using private small scale renewable installations for self-consumption and/or local grids balancing. This is due both to the competitive costs of the systems and to environmental consciousness of their users. Photovoltaic systems, including batteries, play a key role in this kind of installations, which, in general terms, must be also considered as part of the emerging smart distributed energy schemes. Engineers and technicians must them be trained in these new specific subjects which require a wider approach to the projects that must be tackled taking into account, instead than before, a multiplicity of possible operation modes for the own and neighbor installations according smart management schemes: fully autonomous, PVgrid tied, hybrid (PVgrid tied+battery)... This work describes an educational resource developed for the UAL engineering studies aiming to ease, throughout a direct and instrumental approach, the learning of the dynamic processes underlying these systems and their operations modes as well as the learning on the different installations elements specifications (PV modules, batteries, charge regulators, grid inverters,...) that constitute them.

Keywords: photovoltaic systems, solar installations, PV microgrid, education

1. Introduction

The high penetration of renewable sources in the energy grids is traditionally associated to the involvement of large public or private companies because the technical and economical requirements of any project needing to interact with the utility mains. However, the present decreasing of costs and the widespread access of the renewable technologies, especially to the photovoltaic one, make numerous individual consumers being interested in the production of their own energy. These prosumers (Gray and Morse, 2017) can be able to tackle the intermittent and unpredictable nature of renewable sources by the use of energy storage (batteries) but, at the same time, they can consciously interact with local grids. This complex and interactive scenario can also include non-conventional loads, as those related to mobility (electric vehicle) as well as some specific requirements of an optimal management of the elements and interconnections that constitute this new energy distribution paradigm (Torres et al., 2018).

In Spain, after a period during which some political decisions and changing regulations conducted to an unsteady development of renewable projects, both for utility plants and, especially, for small scale private facilities (Rosales-Asensio et al., 2019), two Royal Decrees related to photovoltaic energy self-consumption and corresponding administrative, technical and economic conditions for intallations have been recently aproved, in addition to the elimination of the previously imposed so-called “sun tax” (Sánchez Molina, 2019). The new regulations take into account not only individual self-consumption connected to an internal network but collective self-consumption, in such a way that several consumers can be associated promoting new schemes for

self-consumption in residential and industrial communities. Other important issue is the simplification of the procedures for connecting and registering of the installations and for the payment for any surplus energy injected back into the grid. In this way, installations of up to 15 kW, or up to 100 kW for self-consumption without surplus currently have a promising situation and photovoltaic self-consumption Spanish market is being increased at 80% rate (AMPIER, 2019)

In this context, engineers and technicians must them be trained in these new specific subjects which require a wider approach to the projects that must be tackled, instead than before, taking into account a multiplicity of possible operation modes for the own, and neighbor, installations. So, installations must not be considered as fully autonomous or fully PVgrid tied, but the installations are part of complex and interactive environments characterized by a high relevance of the dynamical coupling between user electricity demands and the production and storage systems capabilities. This paper outlines development of the hardware of a solar microgrid emulator at the University of Almería (UAL) created for educational purposes. The renewable source for the microgrid are two 310 Wp photovoltaic modules connected to DC/AC and DC/DC converters and batteries bank, to one load profile generator and to the local grid. An extensive set of measuring and control capabilities have been also implemented to create the following testing scenario: fully autonomous mode, PVgrid tied mode ad hybrid (PVgrid tied+battery) mode. This microgrid emulator laboratory provides experimental learning opportunities for engineering and solar energy undergraduate- and graduate-level students of University of Almería.

In general terms, new learning resources in this context are being developed by universities and other educational agents. Some of the can be found in the literature. Thus, in (Coleman et al., 2017) a testbed is developed at the University of Drexel (US) for teaching purposes, involving undergraduate and graduate level students. This testbed is composed of a 1.6 kW PV system, including storage and power converters, and allows students to develop skills as conversion/loss calculations, the study of the effects of varying weather conditions and the management of batteries SOC constraints. In (Kotsampopoulos et al., 2017), a hardware-in-the-loop (HIL) approach is used to test typical components of a microgrid as inverters and batteries in presence of PV and wind energy, which enable students of the University of a better understanding of their working principle through experimental learning at the National Technical University of Athens (Greece). A similar approach is used in (Patrascu et al., 2016), at the University Politehnica Timisoara (Romania). In (Gaouda et al., 2013), a traditional power system plant is combined with modern monitoring systems, which can be used by students for interfacing the main variable of interest which better describe the complete plant. For this purpose, an Arduino board is used allowing different programing platforms compatibility. In (Zachariadou et al., 2012), a low-cost and small-scale PV testbed is presented as an effective alternative for laboratory sessions of physics and electricity courses. At the core of this testbed, an Arduino board is in charge of reading the signals from the solar panels and controlling their tilt angle by means of a servomotor, as well as and a digital potentiometer as variable load, which allows to simulate different scenario. Among the concepts to be taught is the P-V and the V-I curves. These concepts are also experimentally explained in energy laboratory practical sessions in (Martin and Chebak, 2016), and many works also use Arduino as hardware and software interface (Del Carmen Currás-Francos et al., 2014; Torres et al., 2019). However, in our work, we use industrial equipment and standard protocols for the communications, as will be described in the next section, in which the testbed is presented, before the guidance for practical laboratory lessons are presented in section 3.

2. The testbed

2.1. Photovoltaic Microcgrid Emulator Elements

A schematic view of the general system is represented in the Figure 1. It consists, as advanced, in several elements being the central one an inverter connected to the public grid. The battery cells are connected to the inverter, and, also to the solar panels trough the solar charger controller. AC loads are output connections from the system.

The system can be configured to perform two different operating modes. The first one, referred to as ‘power assist’ mode follows the following rules: (i) the charger/inverter keeps the batteries at is maximum state of charge (SOC) under normal load conditions, by using the public grid. (ii) if a peak of consumption which may exceed the contracted power is demanded, the batteries provided the necessary power to avoid

overconsumptions. (iii) The PV energy is used for both self-consumption and feed-in, depending on the load conditions. The second operating mode is referred to as ‘Energy storage system (ESS)’ and is based on the use of the solar energy and batteries for satisfy the power demand whereas these sources are available. Otherwise, the public grid is used for compensating the demand, whenever the solar energy is not enough and the batteries SOC reaches its lower bound. At the same time, the excess of solar energy is used for charging the batteries and feeding-in. Then, the system can feed the loads in the most expensive electricity hours or letting the utility reuse it when there is a shortage in the renewable sources.

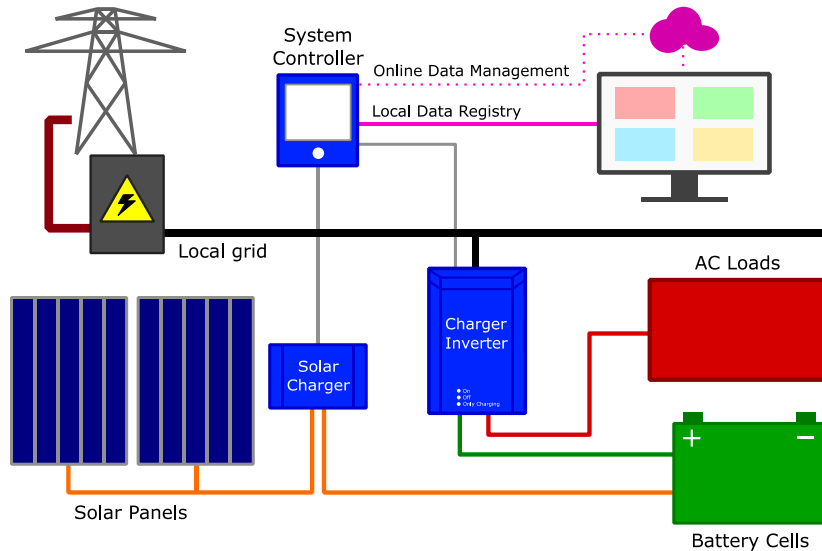


Figure 1. Diagram concerning system behaviour and connections between elements.

The selection of the operating mode can be easily done by configuring the charger/inverter accordingly by means of an USB programmer. In addition, three more scenarios can be simulated. The first one is an island mode operation. This is carried out by disconnecting the testbed from the public grid, by unplugging the AC input or by actuation of an interrupt switch. The second one is achieved by disconnecting the batteries using another interrupt switch, which simulates a PV system without storage. Finally, another interrupt switch allows to disconnect the solar panels, which may be useful for exercises of battery modelling.

The experimental testbed is depicted in Figure 2. The inverter is a Multiplus 800-16, the Solar Charge Controller is an MPPT 100 30 and there is also a battery balancer (all those devices are from Victron Energy). The system is managed from a Color Control GX and there is a monitoring system for external control by the COM'X 510 server (manufactured by Schneider Electric). These elements, along with the mentioned switches and the electrical protection and measurement devices are shown in the right side of the Figure 2-b, and are placed in the box shown in Figure 2-a. As can be seen, two screens allow to communicate directly with the devices, whereas an ethernet cable connects with the local area net. It is also shown the batteries at the bottom, and the cables connecting to the public grid and the solar panels, depicted in Figure 2-b. Finally, the electronic programable load is connected to the testbed AC output in order to replicate any load profile according to the experiments to perform.

In addition to this, the test-bed account for a tailor-made capacitive *I-V* curve tracer (Guerrero Cabezas, 2016). This system allows the determination of the performance both of the individual modules and the string connected to the inverter under different irradiance and temperature situations.

Finally, specifically dedicated channels and sensors are used for the measuring of the meteorological (solar irradiances and ambient temperature) and operation (modules and battery temperatures) variables necessary for the characterization of the systems.



Figure 2. Class material. (a) Batteries and equipment box outer view. (b) Solar panels. (c) Electronic load (d) Box inner view displaying devices setup.

2.2. Communications and measuring capabilities

There are three different ways to manage information from the system controller. One of them consists in periodical uploads to a website database (can be configured to every minute/hour/day/week). The second way to manage it (more practical for experimental purposes) is to read and register all the information locally on a computer with a Modbus TCP/IP connection by our self-made software (it registers and plots useful information such as AC power consumption, solar and battery power in real time) under MATLAB® environment. A third option is to use the COMX-510 energy server as a gateway integrating the system controller, by Modbus communication, and the measurements of each individual AC line obtained from the Powertag sensors, gathered

by a Smart-Link communication module, also manufactured by Schneider Electric. Figure 3 represents the system architecture, regarding to the physical layout (Figure 3-a) and the communications scheme (Figure 3-b). All these communications correspond to power exchanges and, of charge, state of health and temperature of the batteries, voltage and current of each device, etc. In addition, a pyranometer is in charge of providing the level of solar irradiation.

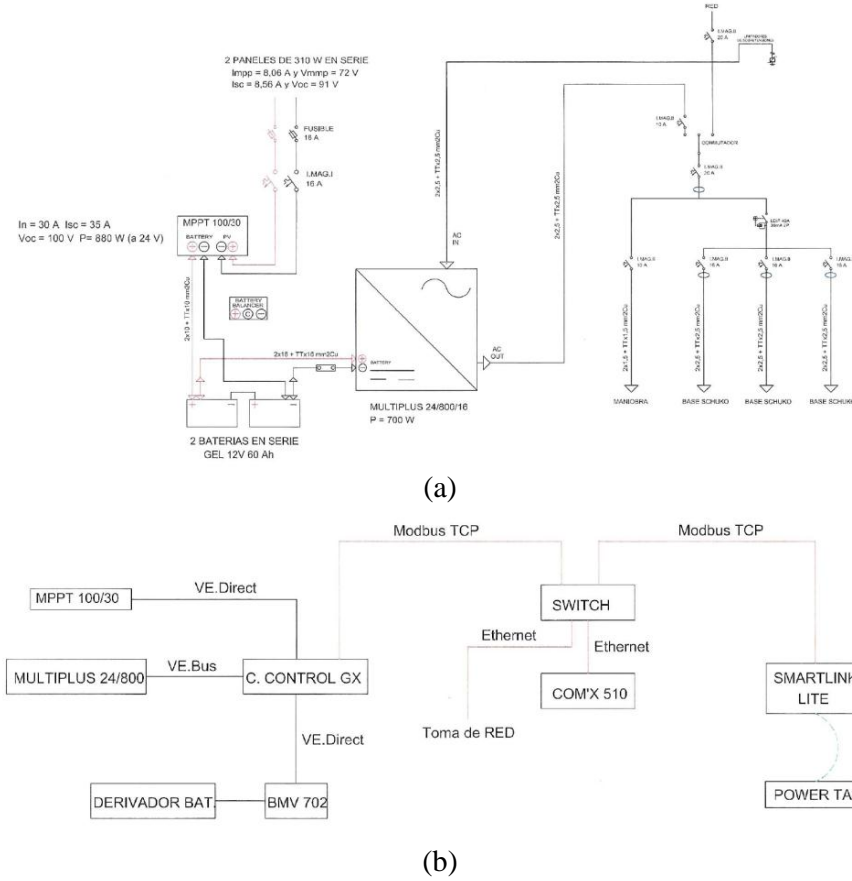


Figure 3. Hardware and communications layout. (a) Devices layout. (b) Communications between the different devices comprising the microgrid.

3. Teaching methodology

In Table 1, some specific practical activities for university bachelor or master's degrees are presented, to achieve all the proposed objectives, namely acquiring the know-how to handle the operation modes of PV systems in microgrids, and management of their information in different situations.

Table 1. Practical classes schedule and description

Title	Description
Characterization and parameterization of system I-V curve	Finding empirical current-voltage dependence model by data acquisition and processing
Analysis of disturbances due to shading	Study of transient, both in systems and coupling to the dynamic load profiles
ESS mode and Power Assist	Explanation about ESS mode behavior, configuration and comparison with Power Assist
Batteries charge and discharge operation	Determination of battery charge and discharge curves by measuring voltage and current through both processes
Practical issues related to operation and control of microgrids	Elaboration and testing of optimal controllers for operation of microgrid and dynamic testing of its operation

Session 1: Characterization and parameterization of system I-V curve

This session deals with the characterization and parametrization of the PV modules of the system, in order to obtain their V-I curve.

Task 1.1: Test under real and STC conditions

Having as reference the existing standards (IEC, 2016), I_{sc} , V_{oc} and P_{max} of the modules can be measured under different real conditions together to solar irradiance impinging the modules and ambient and module temperatures. Manufacturer nominal specifications of the modules, including thermal coefficients, allow to estimate the modules STC specifications and the concordance between measured and nominal parameters. In Figure 4-a, the nominal specifications of the modules are depicted (curves extracted from Exiom Solution Poly 310 Wp 72 cells specifications forms). Figures 4-b and 4-c show module theoretical performance according standard model used in PVsyst software.

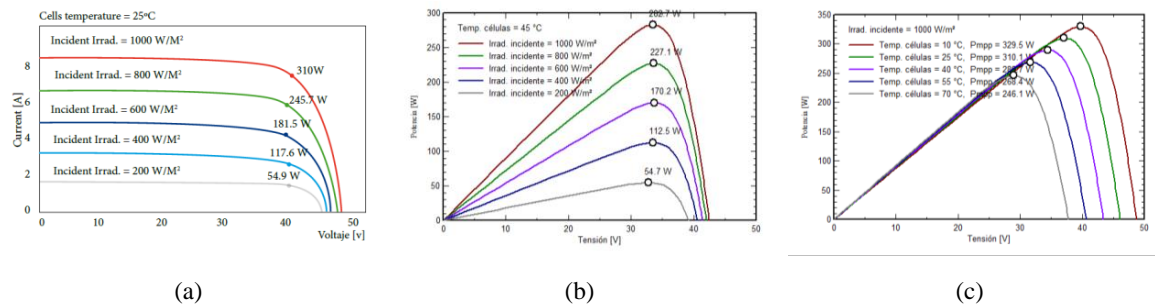


Figure 4. Curves for the characterization of the photovoltaic modules. (a) Performace curves by manufacturer (module Exiom Solution Poly 310 Wp 72 cells). (b) Influence of variations of the irradiance on the P-V curve (according PVsyst) (c) Influence of variations of the temperature, for a stable solar irradiance, on the P-V curve (according PVsyst).

Task 1.2.: Mathematical modelling:

The students are provided of references including mathematical models of photovoltaic module, as the used in, in order to estimate the power generation as a function of measurable variables (Ayop and Tan, 2017; Ibrahim and Anani, 2017) as well as the module basic parameters, namely, module reverse saturation current (I_o), photogenerated current (I_L), series resistance (R_s), shunt resistance (R_{sh}) and ideality constant (α) (Pranith and Bhatti, 2015)

Session 2: Analysis of disturbances due to shading

This session deals with the study of the transitory effects of the power generated by the solar panels under dynamic loads and partial shaded conditions (PSC).

Task 2.1: Data acquisition: The students, with a background in industrial communications, are encouraged to read the system data by means of Modbus TCP/IP protocol, accessing to the registers providing information regarding to variables as voltage, current or power of the elements of interest.

Task 2.2: Calibration and installation of the pyranometer: The students must perform measurements of the solar irradiance, in W/m^2 . For this purpose, they count with signal amplifiers and conditioners and an USB-DAQ board. The data obtained are then combined with those obtained in task 1.1.

Task 2.3: Comparison and interpretation of the registered data: The data obtained in task 2.1 are compared with respect to the data that the system publishes to the manufacturer cloud, which are considered as ground truth. Once the data are validated, the following graphs must be represented and analyzed: (Bhukya and Kota, 2019)

- V-I and P from both the solar panels and loads versus time.
- Battery state of charge (SOC) versus time.
- Irradiance versus time.

By considering the dynamic loads and solar irradiance, the effects of the PSC can be easily identified.

Session 3: ESS mode and Power Assist

This session deals with the setup and analysis of the different operating modes of the microgrid, which correspond with the typical configurations in real world conditions.

Task 3.1: Configuration of the operating mode: The students are provided with the inverter datasheet and the USB programmer so they can configure the operation mode and the parameters related to the power thresholds, the depth of discharge, etc.

Task 3.2: Testing the Power Assist mode: This test consists in establishing a combination of the demand and the generation of PV modules which allows to check the different operation status of the batteries.

Task 3.3: Testing the ESS mode: This test is similar to the one of task 3.2 with the difference that the microgrid must be configured now in ESS mode. The students are encouraged to verify that the configuration parameters correspond with the measure data.

Session 4: Batteries charge and discharge operation

This session covers the study of the batteries under a cycle of discharging followed by a cycle of charging.

Task 4.1: Configuration of the discharging load:

There exist two options of configuration of the loads. The first one is to directly connect the electronic load at the batteries, working in DC-mode. The second one is to connect the electronic load to an AC output of the inverter, which is the preferable solution for two reasons: (i) safety: when the electronic load is plugged into one of the AC sockets of the testbed, the protection devices prevent from any eventual fail. (ii) communications: since the power from the batteries is managed by the inverter, all the related information is registered by the system controller. For this purpose, the electronic load must be programmed by using a script with a customized load profile.

Task 4.2: Discharging and charging experiments:

With the electronic load programmed, the following step consists in conducting the experiment and register the main variables. As an example of experiment, in Figure 5 is shown the evolution of the battery voltage, current and state of charge during a cycle of discharging followed by a charging cycle. Concretely, it can be seen in Figure 5-a that the batteries remain at floating state until the electronic load starts to demand a power equivalent to 10 A at nominal batteries voltage. This demand is introduced as a train of pulses in order to let the batteries to periodically stabilize after a given period of consumption. The corresponding state of charge is depicted in Figure 5-b. The charging cycle corresponds with the positive value of the current.

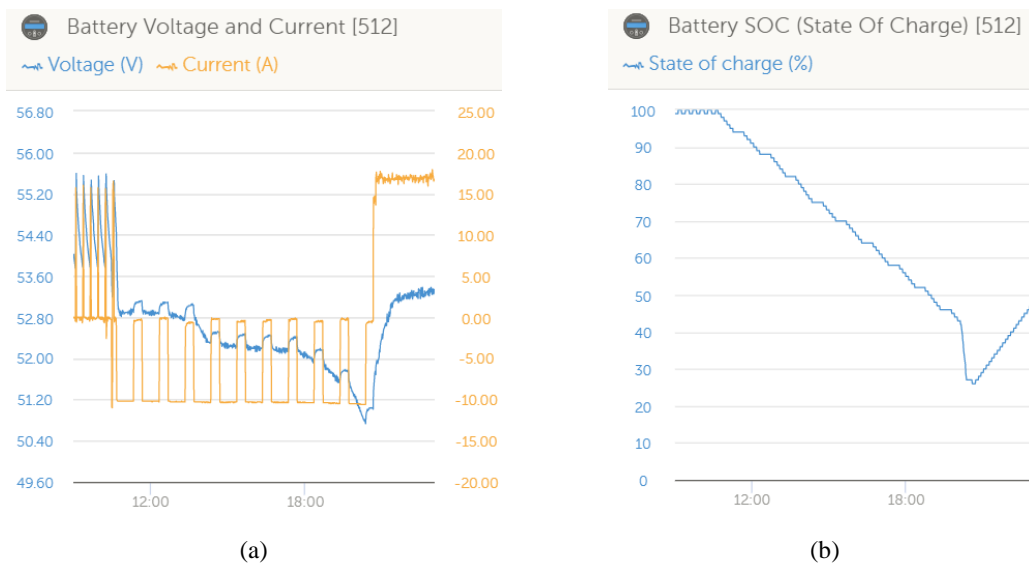


Figure 5. Batteries discharge and charge. (a) Voltage and current of the batteries. (b) State of charge.

Task 4.3: Mathematical modelling:

By using the methods proposed in (Gazzarri et al., 2014), the students are encouraged to build a mathematical model of the batteries taking into account the data registered in task 4.2.

Session 5: Practical issues related to operation and control of microgrids

This session leads with the operation of the microgrid with a load profile equivalent to the real consumption of a laboratory.

Task 5.1: Working with real consumptions:

A register of consumption measurements for a typical working day is given to the students. These data are sent to the electronic load in order to replicate this consumption for a one-day experiment. Then, with the obtained data, the students must discuss about the electricity costs are reduced by the use of batteries and solar panels.

Task 5.2: Microgrid dimensioning:

At this stage, the students count with models of both batteries and solar panels, as well as measurement of the solar irradiance and the consumption data. With all this information, the students are encouraged to evaluate different alternatives of number of solar panels and capacity of batteries in order to increase the self-consumption taking into account also the economic cost of the investment.

4. Results and conclusions

Figure 6 shows a sample of a study of a daily profile in which C_{load} is the actual laboratory energy consumption (or, alternatively, a tailored one according the simulation needs), P_x are the different energy fluxes from PV plant, local grid and storage and SOC is the state of charge of the batteries.

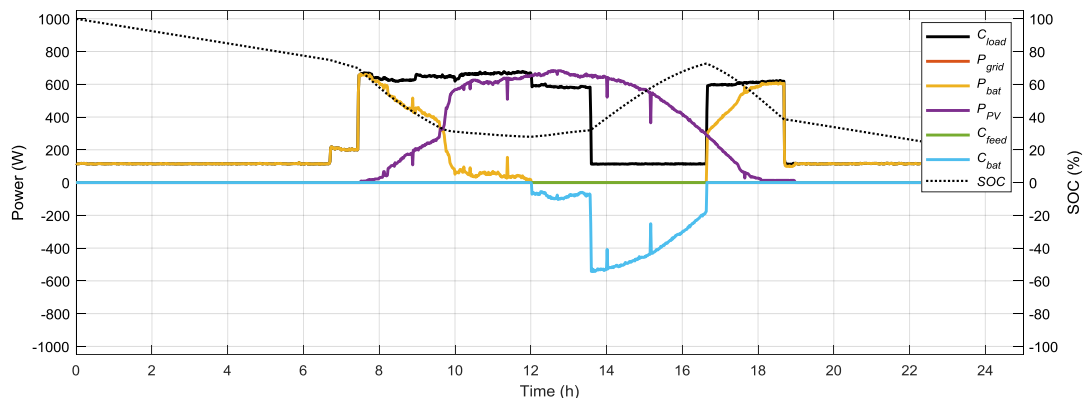


Figure 6. Sample of a dynamic power pattern for a testing day operation.

After test bench set-up at laboratory and preliminary studies, this microgrid emulator laboratory allows experimental learning to engineering and solar energy undergraduate- and graduate-level students of University of Almería. All the components of the presented kit are low cost and easily available in most of the university laboratories and the proposed experiences can be easily related to the actual performance of microgrids.

5. Acknowledgments

To the Secretariat of Innovation and Virtual Teaching of the Vice-Rectorate for Official Studies and Continuing Education of the University of Almería, for the consideration of this work in the 2018-2019 Program of Groups for the Innovation in Teaching.

6. References

- ANPIER, 2019. Asociación Nacional de Productores de Energía Fotovoltaica. Anuario fotovoltaico 2019. (<https://anpier.org/wp-content/uploads/2019/06/anuario245x173-DEF.junio-2019-WEB.pdf>).
- Ayop, R., Tan, C.W., 2017. A comprehensive review on photovoltaic emulator. *Renewable and Sustainable Energy Reviews*, 80, 430-452.
- Bhukya, M.N., Kota, V.R., 2019. A quick and effective MPPT scheme for solar power generation during dynamic weather and partial shaded conditions. *Eng. Sci. Technol. an Int. J.* 22, 869–884.
- Coleman N. S. et al., 2017. Hardware setup of a solar microgrid laboratory, IEEE Power & Energy Society General Meeting, Chicago, IL 1-5.
- Del Carmen Currás-Francos, M., Diz-Bugarín, J., García-Vila, J.R., Orte-Caballero, A., 2014. Cooperative development of an Arduino-compatible building automation system for the practical teaching of electronics. *Rev. Iberoam. Tecnol. del Aprendiz.* 9, 91–97.
- Gaouda A. M., Abd-Rabou A. and Dahir A., 2013. Developing educational smart grid laboratory in Proceedings of 2013 IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE), Bali, 404-409.
- Gazzarri, J., Shrivastava, N., Jackey, R., Borghesani, C., 2014. Battery Pack Modeling, Simulation, and Deployment on a Multicore Real Time Target. *SAE Int. J. Aerosp.* 7, 207–213.
- Gray, M.K.; Morsi, W.G. 2017. On the role of prosumers owning rooftop solar photovoltaic in reducing the impact on transformer's aging due to plug-in electric vehicles charging. *Electr. Power Syst. Res.*, 143, 563–572.
- Guerrero Cabezas, F.J. (2016) Análisis e instalación de un sistema fotovoltaico en el vehículo eléctrico UAL-eCARM. Degree Project University of Almería.
- Ibrahim, H., Anani, N., 2017. Variations of PV module parameters with irradiance and temperature. *Energy Procedia*, 134, 276-285.
- IEC (2016) International Electrotechnical Commission. IEC 61215-1:2016. Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements. (<https://webstore.iec.ch/publication/24312>)
- Kotsampopoulos P. C., Kleftakis V. A. and Hatzirygiou N. D., 2017. Laboratory Education of Modern Power Systems Using PHIL Simulation in IEEE Transactions on Power Systems, vol. 32, no. 5, 3992-4001.
- Martin, S.S., Chebak, A., 2016. Concept of educational renewable energy laboratory integrating wind, solar and biodiesel energies. *Int. J. Hydrogen Energy* 41, 21036–21046.
- Patrascu C., Muntean N., Cornea O. and Hedes A., 2016. Microgrid laboratory for educational and research purposes, IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, 1-6.
- Pranith, S., Bhatti, T. S., 2015. Modeling and parameter extraction methods of PV modules — Review. Published in: 2015 International Conference on Recent Developments in Control, Automation and Power Engineering (RDCAPE)
- Rosales-Asensio, E., de Simón-Martín, M., Borge-Diez, D., Pérez-Hoyos, A., Comenar Santos. A., 2019. An expert judgement approach to determine measures to remove institutional barriers and economic non-market failures that restrict photovoltaic self-consumption deployment in Spain. *Solar Energy* 180, 307-323.
- Sánchez Molina, P., 2019. Spain's new rules for self-consumption come into force. *pv magazine - Photovoltaics Markets and Technology* (<https://www.pv-magazine.com/2019/04/08/spains-new-rules-for-self-consumption-come-into-force/>).
- Torres, P.F., Costa, A. P., Chaar Junior, V.L., Monteiro, W.L., Galhardo, M.A.B., Pinho, J.T., Macêdo, W.N., 2019. A mobile educational tool designed for teaching and dissemination of grid connected photovoltaic

systems. *Comput. Electr. Eng.* 76, 168–182.

Torres-Moreno, J.L.; Gimenez-Fernandez, A.; Perez-Garcia, M.; Rodriguez, F., 2018. Energy Management Strategy for Micro-Grids with PV-Battery Systems and Electric Vehicles. *Energies*, 11, 522.

Zachariadou, K., Yiasemides, K., Trougakos, N., 2012. A low-cost computer-controlled Arduino-based educational laboratory system for teaching the fundamentals of photovoltaic cells. *Eur. J. Phys.* 33, 1599–1610.