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Flexible laboratory for testing electrical devices and emulating microgrids

Laboratorio flexible para probar dispositivos eléctricos y emular microrredes

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Abstract: The analysis of the electrical behavior of microgrids including renewable sources, storage devices, nonlinear loads, and traditional components, has a high importance for researching and educating new professionals in energy systems. This paper presents the design and implementation of a flexible laboratory for testing modern electrical devices and emulating real microgrids. The laboratory design begins with the selection of several devices, followed by the structuring and implementation of a bus to connect the devices. The bus includes circuit breakers, contactors, copper bars, a ground connection, PLCs, and safety terminals. The flexible laboratory is experimentally validated by testing a single-phase converter, charging, and discharging three VRLA batteries, replicating a discharge profile and emulating a real microgrid installed on Isla Fuerte, Colombia. The results are used to evaluate the operation of the devices and to analyze the behavior of a real microgrid, demonstrating the usefulness of the laboratory in education and research contexts.

Keywords: Microgrids emulation, Power converters, Power laboratory, Renewable sources, Research and education, Storage devices.

Resumen: El análisis del comportamiento eléctrico de microrredes que incluyan fuentes renovables, dispositivos de almacenamiento, cargas no lineales y componentes tradicionales, es de suma importancia para investigar y formar nuevos profesionales en sistemas de energía. Este artículo presenta el diseño e implementación de un laboratorio flexible para probar dispositivos eléctricos modernos y emular microrredes reales. El diseño del laboratorio comienza con el diseño de varios dispositivos, seguido de la estructuración e implementación de un bus para conectar los dispositivos. La integración incluye interruptores, contactores, barras de cobre, conexión a tierra, PLC y conectores de seguridad. El laboratorio flexible se valida experimentalmente probando un convertidor monofásico, cargando y descargando tres baterías VRLA, replicando un perfil de descarga y emulando una microrred real instalada en Isla Fuerte, Colombia. Los resultados se utilizan para evaluar la operación de los dispositivos y para analizar el comportamiento de una microrred real, demostrando la utilidad del laboratorio en contextos de educación e investigación.

Palabras clave: Convertidores de potencia, Dispositivos de almacenamiento, Emulación de microrredes, Fuentes renovables, Investigación y educación, Laboratorio de potencia.

1. INTRODUCTION

Traditional power systems have become modern energy systems due the integration of new sources, storage devices, power electronics, and information and communication technologies. Those modern systems require the best scenarios to do research and educate the new professionals required by the industry. For those reasons, the development of laboratories that emulate modern power systems and allow to test converters, batteries, etc. are required.

Micrograms are modern energy systems that are adopted around the world and consequently several researchers have designed and implemented microgrid laboratories to study their behavior [1], [2], [3], [4], [5]. A microgrid educational laboratory is presented in [1], the authors focus on the integration of electric and communication infrastructure, demonstrating the usefulness of microgrid laboratories to teach modern concepts to the electrical engineering students. On the other hand, a diesel generator emulator is presented for teaching frequency analysis in a laboratory-scale microgrid, the authors of [2] emulate the diesel generator using an inverter equipped with voltage and current control loops. The work presented in [2] is an example on how to implement generators in AC or AC/DC microgrids.

In [3], the authors design, model, implement, and operate a microgrid with renewable energy sources, where the focus of the laboratory-scale microgrid is teaching power flow from renewables. Other example of a microgrid laboratory for educational and research purposes is presented in [4]. The authors highlight the advantages of microgrid laboratories to study and understand the behavior of microgrids before to be implemented in definitive projects. Additionally, the work emphasizes the use of emulators allowing to implement different renewable energy sources in a laboratory, but also the use of commercial devices, as inverters, to obtain a sense of real behavior.

In [5], the authors use the concept of hardware-in-the-loop to implement a modern power system and teach students. In that case, the experimental education is used as the strategy to teach about modern power systems. The last works illustrate the importance of implementing laboratory-scale microgrids to teach and research about modern electric systems.

An important concept in modern electric systems is its storage capacity; therefore, a laboratory-scale system that allows teaching and testing storage devices is of high importance. VRLA batteries are widely used as storage systems in multiple applications; therefore, some authors have focused their research on modeling and testing VRLA batteries [6], [7]. One way to assess the VRLA battery performance and teach about those devices is to build a simulation model with several objectives [6]. However, to build the simulation model requires experiments to understand the real behavior of the batteries and to estimate the parameters of the model.

On the other hand, experiments are necessary when a VRLA battery is submitted to specific operating conditions e.g. fast-charging methods [7]. The authors of [7] presented a fast-charging method of VRLA batteries because the fast-charging is required by several applications. The results shown that the fast-charging method is beneficial for the life cycle of VRLA batteries. The last works show that a flexible laboratory with the capacity to carry out experiments and validate detailed models of electric devices as battery cells and packs is necessary.

The main objective of this paper is to present the design and implementation of a flexible laboratory of energy systems to teach and research. Several topologies can be achievable to emulate real word applications as a test bench to operate power converters, a test bench to fully charge and discharge batteries, and microgrids. The successful integration of several devices implies to know their electric characteristics and operation; therefore, knowledge about electric behavior, management software, communication protocols, and safety must be acquired. The main advantage of this platform is that researchers and learners of energy systems can analyze different systems from their real characteristics.

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The rest of the paper is organized as follows: The design of the flexible laboratory is presented in Section II, which includes the description of all devices and elements, and the calculation of the main bus resistances. Section III presents three different applications of the flexible laboratory: testing a full bridge power converter in off load and on load operation, applying a battery discharge profile, and emulating a real word microgrid. Finally, Section IV presents the conclusions of the paper.

2. STRUCTURE AND MAIN ELEMENTS OF THE LABORATORY

2.1. Selection of the elements for the flexible laboratory

The laboratory was designed considering the interoperability of components under multiple conditions, *e.g.* the equipment operation tests and the emulation of electrical systems. To carry out the experiments, a busbar of twelve single-phase circuits was implemented, which allows the connection of sources or loads; each circuit has 4mm banana jacks on its terminals. The control to connect and disconnect the sources or loads to the busbar was centralized in a main board with a three-position selector associated with each circuit: Automatic, Off, and Manual. Also, four PLCs were installed inside the board which can connect or disconnect the sources or loads remotely when the selector is in the automatic position. Also, the busbars, contactors, and 32A protections associated with each circuit were placed in the board.

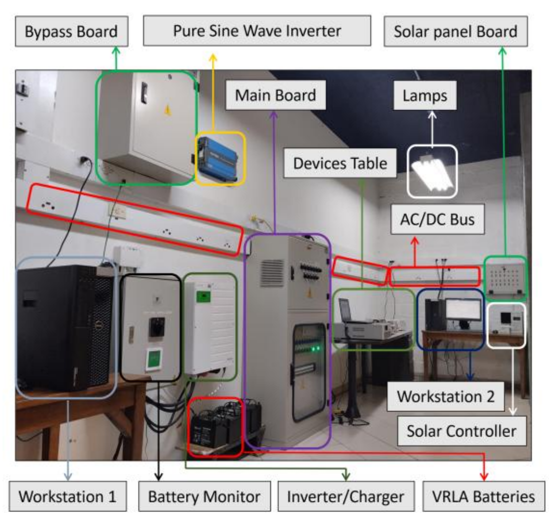
DC power sources were acquired to operate in a wide range of voltages and currents. One solar panel emulator with an operating range up to 600V and 8.5A, two power sources one of 20V and 10A, and other one of 30V and 5A. On the other hand, nine solar panels of 65W each, with 4mm jack bananas per panel allowing series or parallel arrangements as required. Also, a storage system formed by six 12V and 35Ah VRLA batteries was selected.

Regarding the electrical loads, the following components were selected: One 600W programmable DC electronic load, two 47Ω 5A rheostats of 1000W each, one 100W LED reflector, and three lamps each with two 29W T8 LED tubes. For the use of the laboratory lamps as electrical loads during the experiments, one bypass board was installed, which selects the energy source, either from the building's electrical network or from the laboratory’s busbar.

For energy conversion and management, the following equipment was acquired: One Full Bridge Power Module 2.4kVA that can operate as an inverter, Buck/Boost converter or rectifier. One 5.5kW dual three-phase inverter with integrated sensors and controllers. One kit for managing energy from and to the batteries, consisting of an inverter/charger of 5.5kVA. One pure sine wave inverter 1.5 kVA, 120V or 220V. For managing the energy delivered by the solar panels, one solar controller with a capacity of 48V and 45A was acquired, which operates with a ground fault protection device.

The equipment selected for measuring and recording variables in the laboratory are: one digital power meter with a DC and AC measurement range of up to 600V and 30A, expandable values up to 1200V and 60A using a high voltage sensing kit and an ultra-high precision current transformer respectively, two multimeters, one infrared thermometer with a range from -40°C to 550°C, and one oscilloscope.

One microcontroller was chosen to manage the sensor signals and to generate the control signals such as the PWM signals to drive the Full Bridge Power Module. On the other hand, one LC filter was designed for the elimination of high frequency switching signals composed of a 950uH toroidal inductor and a 11uF capacitor built from five 2.2uF polyester capacitors, this filter is located at the output terminals of the Full Bridge Power Module for the inverter operation. Regarding the computing equipment, two desktop workstations were selected. Fig. 1 shows the main components of the flexible lab.



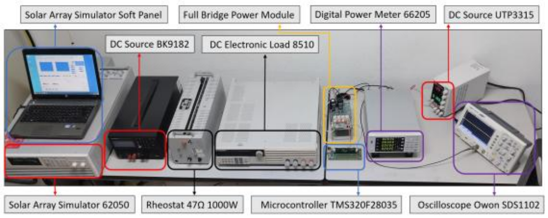


***Fig. 1**. Flexible laboratory with multiples components. **Source:** own elaboration.*

2.2. Estimation of the electrical resistances of the circuits connected to the main bus

The voltmeter-ammeter (drop of potential) method [8] was used to estimate the electrical resistance of each circuit connected to the main bus. Two terminals of the circuit were short-circuited using a 14 AWG wire, then a power source with an output current limited to 10A and voltage to 2V was used. The voltage and current data delivered by the power source were recorded, in addition to the temperature at its terminals using an infrared thermometer.

Fig. 2 shows the scheme to estimate the electrical resistance of circuit 7. At the end of the tests, the total resistance of the circuit in operation was calculated considering the voltage and current values after 60 minutes. The same method was applied to estimate the resistance of the source and short-circuit cables. Then, the electrical resistance of circuit 7 was calculated and divided by the length of the cable obtaining the resistance per unit length 8.114 mΩ/m. With this value, the electrical resistance of all circuits of the main bus were calculated, Table I presents the electrical resistance of each circuit in the main bus.

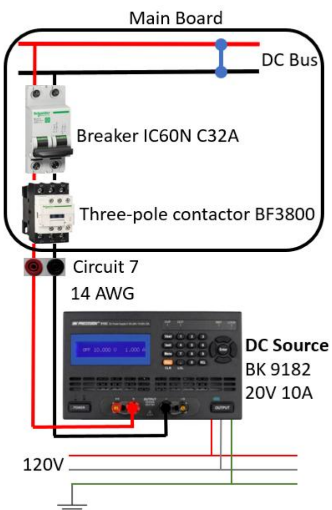


***Fig. 2**. Voltmeter-Ammeter (Drop of potential) test. **Source:** own elaboration.*

***Table 1:** Electrical resistance of each circuit in the main bus*

Circuit	mΩ	*Circuit*	mΩ
1	67.325	**7**	51.719
2	64.793	**8**	54.378
3	62.216	**9**	66.223
4	56.134	**10**	69.776
5	54.051	**11**	76.311
6	51.719	**12**	80.028

***Source:** own elaboration.*

3. APPLICATIONS OF THE FLEXIBLE LABORATORY

Three different applications of the flexible laboratory are presented in this section: testing a full bridge power converter in off load and on load operation, discharging batteries through the application of a common profile, and emulating a real microgrid.

3.1. Experimental testing of a commercial full bridge power converter

A full bridge power module SPM-FB was acquired by the laboratory. The converter consists of four semiconductors that must operate sequentially in pairs UH, VL and VH, UL. For this, a GDC 7A4S1 driver manages the PWM signals received from a controller, either by managing four PWM signals, one for each semiconductor or by addressing only two received signals, one PWM signal and one inverted PWM signal. The second method was selected to operate the converter. To input the PWM signals to the driver, the TMS320F28035 microcontroller was used and programmed from MATLAB. The *Embedded Coder Support Package* for *Texas Instruments* was installed, which allows the use of specialized blocks in Simulink.

To test the full bridge power converter, two experiments were performed, one in no load operation where the frequency and duty cycle were varied. And the other one in load operation, where the power-frequency curve provided by the manufacturer was replicated and compared.

In the first experiment, the solar array simulator was used as the source at 50 V DC, and the output of the bridge was observed with the scope. Fig. 3 shows the set up implemented in the laboratory using the main bus, two DC sources, the full bridge converter, the microcontroller, and the oscilloscope. The constant duty cycle was set to 50% and the behavior of converter output voltage at the UV terminals was observed. Four different switching frequencies were programmed from Simulink; 2, 20, 100, and 180 kHz, see Fig. 4. Only the variation of the frequency is presented here in sake of brevity.

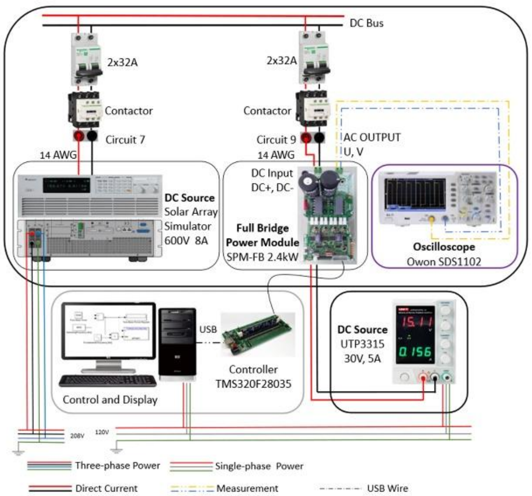


*Fig. 3. Experimental set up to test the power converter in no load operation. **Source:** own elaboration.*

In the second experiment, where the manufacturer power-frequency-curve is replicated and compared, it was necessary to calculate a LC filter to obtain the terminal voltage as a sinusoidal waveform. Also, a resistive load was aggregated to the experimental set up to load the power converter. The filter was calculated for an output DC voltage V_{DC} = 205 V, an output current I_{DC} = 9 A, and a switching frequency f_S= 20kHz. The inductor was designed following (1) and limiting the inductor current ripple to 20%:

$$L = \frac{V_{DC}\,(rms)}{4 \cdot I_L \cdot f_s} = \frac{205\ V}{4 \cdot 1.8 \cdot 20x10^3} = 1.4\ mH \qquad (1)$$

The cut frequency was designed to be one decade lower than the switching frequency $f_C \leq f_S/10$, $f_C \leq 2$ kHz. 1.2 kHz was selected as the cut frequency. Then, the capacitor was estimated to guarantee the cut frequency following (2):

$$C = \left(\frac{1}{2 \cdot \pi \cdot 1.2x10^3}\right)^2 \cdot \frac{1}{1.4\ x10^{-3}} = 12.356\ uF \qquad (2)$$

A capacitor of 12.356 µF was obtained. With the theoretical data of the inductor equal 1.4 mH and the capacitor of 12.356 µF, the practical elements were obtained. Five polyester commercial capacitors of 2.2 µF were parallel connected to obtain a capacitor of 11 µF, and the inductor was constructed using a toroidal yellow core T-157 and an AWG 16 wire, obtaining an inductor of 0.956 mH. Fig. 5 shows the experimental set up including the LC filter and the electric load which is composed by variable resistors.

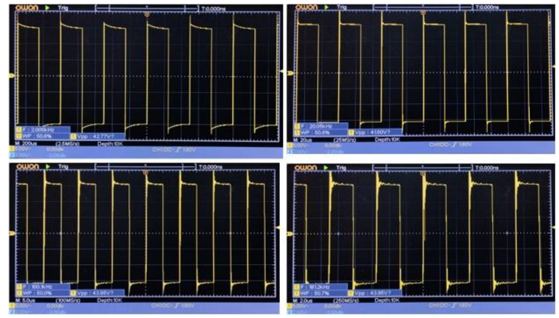


*Fig. 4. Output voltage of the converter in no load operation during the frequency variation. **Source:** own elaboration.*

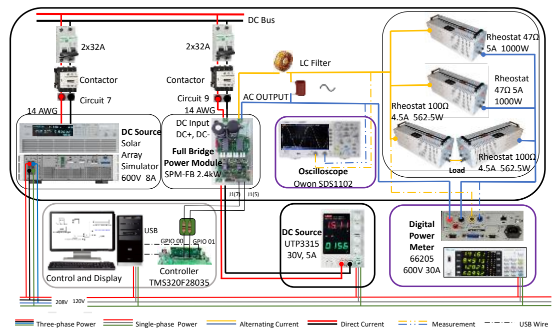


*Fig. 5. Experimental set up to test the power converter in load operation. **Source:** own elaboration.*

Fig. 6 presents the converter output voltage once the filter was connected. A sinusoidal voltage was obtained and applied to the load. When an LC filter is aggregated to the output of the converter and the PWM signal is programmed to produce a fundamental frequency of 60 Hz, the full bridge power module SPM-FB acts as pure sine waveform inverter; therefore, loads are feed from a voltage source free of harmonics.

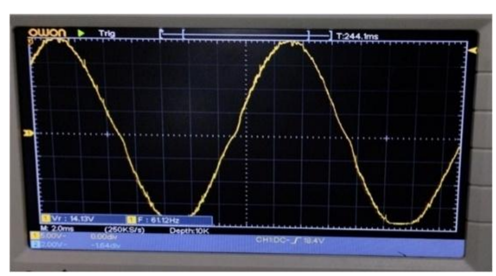


*Fig. 6. Output voltage of the full bridge power module SPM-FB operating as an inverter. **Source:** own elaboration.*

Using the experimental set up of Fig. 5, the converter was loaded, and the switching frequency was varied from 20 kHz to 140 kHz. Fig. 7 shows the time behavior of the real power during the experiment. The power is critically reduced when the switching frequency is increased; however, the converter operates correctly during the whole range. Also, the comparison of the apparent power shows a correspondence of the results obtained by the manufacturer and the results obtained in the flexible laboratory. With the last two experiments, the full bridge power converter was tested.

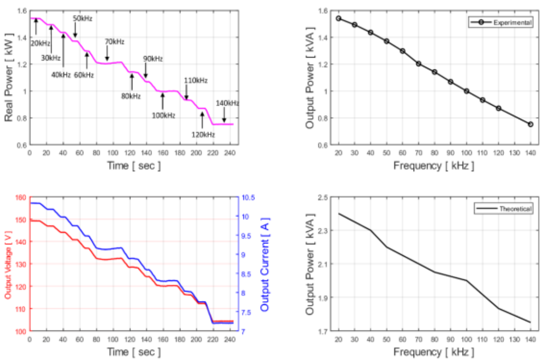


Fig. 7. Power vs switching frequency during on load operation of the full bridge power module. ***Source:*** *own elaboration.*

3.2 Experimental testing of batteries: Discharging VRLA batteries facing a common profile

The second application of the flexible power lab consist of charge and discharge VRLA batteries for testing their operation. Three VRLA batteries of 12V, 35Ah were tested. From the manufacturer, when a battery voltage reaches 10 V, that battery is discharged, and if a battery is under deep discharge < 9.5 V, its life spam will be reduced. First, batteries were visually inspected to recognize their integrity; then, batteries were charged and discharged checking the behavior of the battery variables; voltage, current, and power. Because those curves are almost standard, they are not presented here in sake of brevity. In contrast, a well-known profile was implemented to discharge the batteries and analyze their behavior [9]. Fig. 8 shows the experimental set up implemented to apply the benchmark profile and test the VRLA batteries. The set up is composed by a DC electronic load to draw the current, the digital power meter to record and store the variables, and the battery under test.

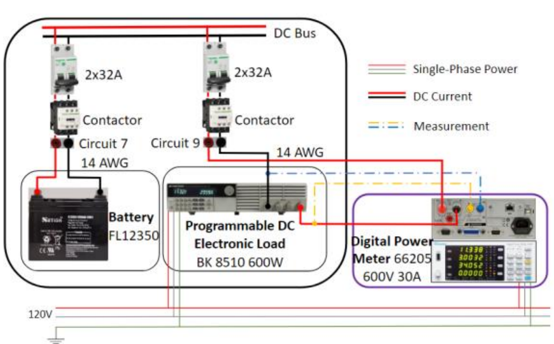


Fig. 8. Experimental set up to discharge the batteries under a benchmark profile test. ***Source:*** *own elaboration.*

Table 2 presents the discharge profile programmed in the DC electronic load. The first two columns include the time and the current demanded by the load $I_{Profile}$. The other two columns present two scaled currents to discharge two VRLA batteries: $I_{Battery1}$ and $I_{Battery2}$. The currents were scaled because in the original profile the values are lower in contrast with the nominal value of the batteries under test, 35 A/h.

Table 2: Discharge profile applied to two VRLA batteries

Time [h]	$I_{Profile}$ [A]	$I_{Battery1}$ [A]	$I_{Battery2}$ [A]
0-1	0.55	1.203	2.406
1-2	0.50	1.094	2.187
2-3	0.25	0.547	1.094
3-4	0.20	0.437	0.857
4-5	1.50	3.281	6.561
5-6	1.85	4.046	8.092
6-7	1.75	3.827	7.655
7-8	0.35	0.765	1.531
8-9	0.20	0.437	0.857

Source: *own elaboration.*

Fig. 9 presents the voltage, current, and power of the batteries during the experiment. For battery 1, the initial voltage started above 12 V, and in the end of the test was close to 11.4 V meaning that more energy was storage. Battery 1 supplied energy during the discharge profile; however, because battery 2 was submitted to a higher current than battery 1, the discharge voltage was reached in the middle of the profile, in that case the profile was not completed. The last experiment highlights the capacity of the flexible laboratory for testing batteries. The batteries were visually inspected, then discharged and charged with a constant current, and finally, they were submitted to a benchmark profile.

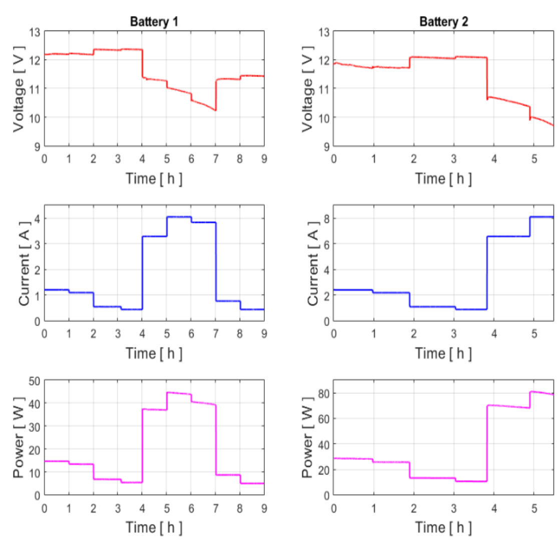


Fig. 9*. Voltage, current, and power of two batteries under a benchmark profile test.* ***Source:*** *own elaboration.*

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3.3 Emulating a real word microgrid: Colombian rural case

The third application of the flexible power lab consist in emulating an existing microgrid in a rural or urban area of Colombia. The microgrid is not connected to the National Interconnected System (NIS). The advantage of emulating those real systems consists of learn about its behavior and propose suitable solutions to their problems. The electric system was selected based on a "Monthly report of telemetry, March 2023" and the "Codification of the political administrative division of Colombia".

The selected area is the small town of Isla Fuerte that belongs to Cartagena city in the province of Bolivar, Colombia. There are a population of 2000 inhabitants which have as main economic activities, fishing, and tourism. Isla Fuerte is located at longitude -76.179141 and a latitude: 9.381067, is impacted by radiation of 4.72 kWh/m^2, an average annual rainfall of 4000 - 5000 mm, and an average annual temperature of 28 °C. Fig. 10 presents average daily solar irradiance curves for 4 months of the year.

The location of the town offers to the inhabitants an amount of solar energy that is harnessed through photovoltaic panels; the rest of the power requirement is supplied with fossil fuels. On the other hand, the energy demand of the population is characterized as monthly maximum power of 190.64 kW, monthly real power of 62498 kWh, and 13 h 34 min of daily average of power service. Fig. 11 presents the average demand curve, which is scaled in a proportion of 1:3000, and the daily average of irradiance curve of July.

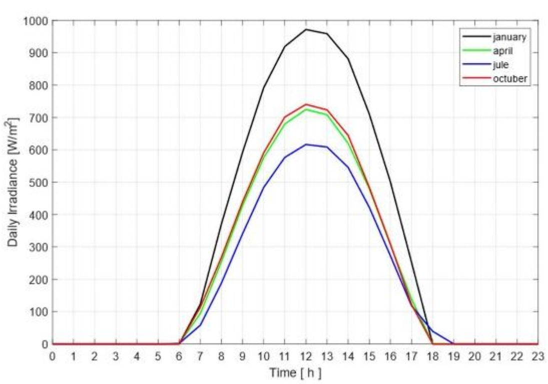

*Fig. 10. Irradiance curves of four months of the year in Isla Fuerte, Colombia. **Source:** own elaboration.*

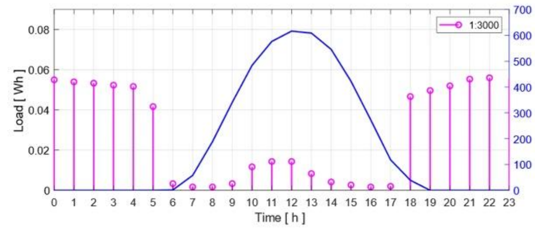

*Fig. 11. Average demand scaled curve of Isla Fuerte and average irradiance curve of July. **Source:** own elaboration.*

The electric system that supplies Isla Fuerte is composed by two caterpillar generators of 400 kW, two transformers of 300 kVA, one solar generator of 175 kWp and 432 batteries with a capacity of 3850 Ah and 2 V. Fig. 12 presents a schematic of the microgrid that operates in Isla Fuerte.

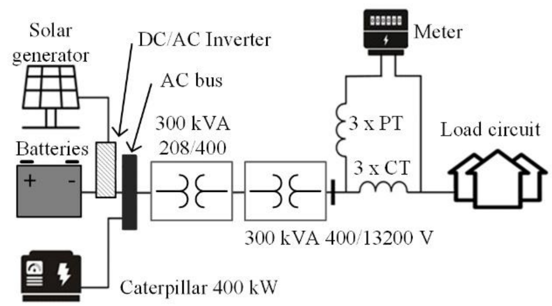

*Fig. 12. Schematic of the microgrid operating in Fuerte Island. **Fuente:** own elaboration.*

The microgrid is emulated in two parts: the power behavior, Fig. 11, and the physical system, Fig. 12. To emulate the power behavior of Isla Fuerte 24 points were chosen, one every hour, a scale of 1:3000 was applied to obtain values in the range [0-55] Wh. Then, the scaled load curve presented in the top of Fig. 11 was divided into two stages:

Stage 1 in the time range of 6:00-18:00 [h], where two operating conditions occur simultaneously, the first condition is the charging of the batteries with the solar panels, and the second condition, where energy is supplied by the diesel generator to the load.

Stage 2 occurs in the time range of 18:00-23.00 [h] and 0:00-5:00 [h], when the batteries provide energy to the load circuit.

The second part of the emulation consist in represent the real microgrid with laboratory devices. The solar generator is emulated by the solar array simulator; the caterpillar generators are emulated with the BK DC source; the batteries are represented with three VRLA batteries connected in series.

The required inverter to connect the solar generator, the batteries, and the caterpillar generators to the transformer is represented with the full bridge power module with the LC filter. The two transformers and the distribution feeder are represented by one step-up transformer 55:220V, the load circuit is emulated using two rheostats of 48Ω, one of 82Ω, three of 100Ω, one of 120Ω, and one of 500Ω. Finally, the meter is represented with a digital power meter and the communication unit was not independently implemented, data were registered using the storage capacity of devices as the solar simulator and the digital power meter. Fig. 13 presents the microgrid that was implemented in the flexible laboratory.

To emulate the demand values, the two stages explained above were imposed with the system implemented in Fig. 13; the rheostats were varied until reach the scaled power demanded by load. For each value of the 24 points, 100 samples per second were storage.

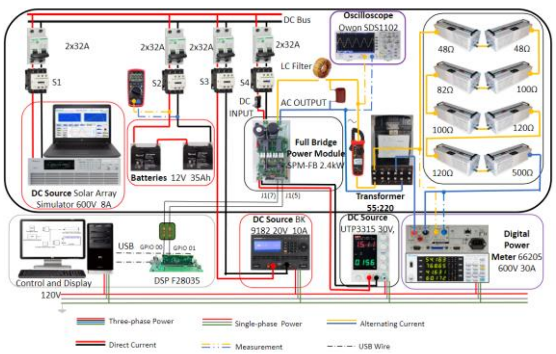

*Fig. 13. Laboratory microgrid emulating the Isla Fuerte real microgrid. **Source:** own elaboration.*

Fig. 14 presents the steady state values of voltage, current, and power in the load during the emulation of the microgrid representing 24 hours. On that figure, there are the measurement and the average values; the measurement are the values registered during the experiment and their corresponding average value.

In the bottom of Fig 14 the comparison with the scaled load in the real microgrid is presented, demonstrating the capacity of the flexible laboratory to emulate real microgrids or small electric systems. Load current and volage, are also presented, offering to students, professors, and researchers the opportunity to visualize and understand systems with more information.

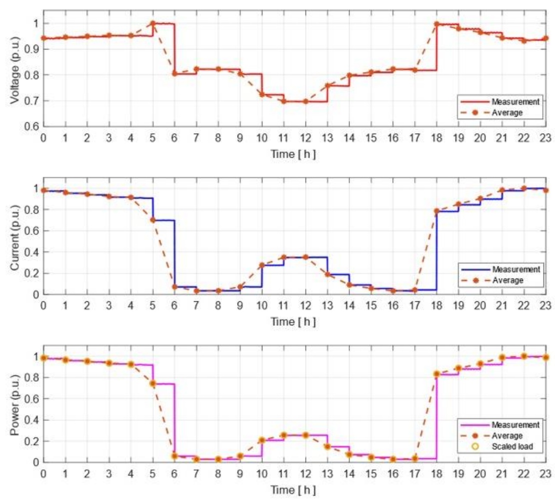

*Fig. 14. Voltage, current and power in the load of the emulated Isla Fuerte microgrid. **Source:** own elaboration.*

4. CONCLUSIONS

The design and implementation of a flexible laboratory for testing modern electrical devices and emulating real microgrids was developed in this paper. The flexibility was validated implementing three different platforms. In the first platform, a new full bridge power converter was tested off-load and full load. During the off-load test the switching frequency was varied from 2 to 180 kHz, and during the full load test, the switching frequency was varied from 20 to 140 kHz. For the full load test, a filter was calculated and connected in the converter output, a capacitor of 11 µF, and an inductor of 0.956 mH. The comparison of the experimental results versus the manufacturer data demonstrated the satisfactory operation of the device. The second platform was implemented to charge and discharge VRLA batteries. A set of batteries was discharged by the DC electronic load, that drawn a benchmark profile. Because the digital power meter several variables were registered, stored, and then analyzed. Finally, an installed real microgrid in Vigia del Fuerte, and its electric behavior were emulated once validating the flexibility of the laboratory.

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70386), which belongs to the research program "Estrategias para el desarrollo de sistemas energéticos sostenibles, confiables, eficientes y accesibles para el futuro de Colombia" (Minciencias code 1150-852-70378, Hermes code 46771).

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