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Design and construction of a didactic standalone photovoltaic plant

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***Abstract*— *This paper proposes the design and construction of a standalone didactic photovoltaic (PV) plant. The system components are available as a didactic kit to the students of the Federal Institute of Education, Science and Technology of Ceará (IFCE), Brazil. Thus, contributing to the teaching-learning process and providing a system to be used in future researches. In addition, the system was designed for supplying electricity to the lighting circuit of the Energy Processing Laboratory, located at IFCE Fortaleza Campus. The PV system developed during the work has an autonomy of 900 Ah and the total installed power of 840 Wp. Using a data capture system, a generation generated by the PV microgeneration was registered in operation up to 647 W.*

***Keywords*— didactics, standalone photovoltaic plant, solar energy.**

I. INTRODUCTION

The generation of electric energy from water resources still occupies the largest share of energy production in Brazil (68.1%) [1], according to data from the Brazilian Energy Research Company (EPE). With the water resource being the main source of electric energy in Brazil, atypical climatic periods of low rainfall lead to a considerable reduction in the hydroelectric water levels.

The water resource is limited and fundamental to the life of living beings. One of the most abundant resources on Earth is the solar resource. The results obtained by the SWERA Project [2] show that in Brazil, since it is an equatorial region, even in the southern states of the country, where the annual average is the lowest, the availability of solar energy is higher than in European countries, such as Germany, Spain and France, where the solar energy source has been widely explored.

An alternative to reduce the consumption of the electricity generated by hydroelectric plants would be to use the photovoltaic (PV) process, converting sunlight into electricity.

Considering that the study of this type of generation is very important for the sustainable development of the country, this work proposes to design and construction of a PV generation plant in a didactic way, with the equipment made available at the Federal Institute of Education, Science and Technology of Ceará (IFCE) Campus Fortaleza-Brazil, and easily accessible to undergraduate and master's students. The system supplies the lighting circuit of the Energy Processing Laboratory (LPE) located at IFCE.

II. LITERATURE REVIEW

A bibliographical review was developed, and it was verified that the use of PV plants as source of electric energy had already been proposed in the twentieth century by [3], where the author designed a solar plant allied to a wind farm. The use of PV energy to conduct desalination units, solving the problem of water shortage in places where there is no access to conventional electricity distribution is proposed by [4]. A PV plant, allied to wind power, for desalination by reverse osmosis of sea water was also proposed by [5]. Therefore, it is noted that the incentive to use this technology does not originate in the 21st century. In the case of hybrid systems with part of the generation using the PV process, the methodology for optimal sizing of stand-alone PV/wind-generator systems using genetic algorithms was suggested by [6].

With the popularity that autonomous PV systems were reaching, new ways to improve the design were investigated, as presented by [7]. The authors present a study and analysis of the sizing curves, revealing that the solar radiation data collected daily are better than the use of average monthly values. In the state of the art, researchers propose and apply algorithms for sizing PV systems. An algorithm for optimized sizing of each component of the system is proposed by [8].

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One way of ensuring high performance was suggested by [9], introducing an advanced pitch converter in DC power conversion to improve efficiency over conventional impulse converters. A system for voltage control of the Pulse Width Modulation (PWM) inverter has also been implemented to maintain the sinusoidal output voltage with low harmonic distortion and variation of the output voltage for different types of load. In addition, the system has a solar tracking system, keeping the PV module better positioned. Due to the low efficiency of solar cells (around 16%), new technologies are emerging to improve the efficiency, as presented by [10]-[11], however, solar tracking is considered by [12] as the most appropriate technology to increase the efficiency of solar cells.

An analysis of the requirements for an autonomous PV system project is made by [13]. The proposed methodology aims mainly to assist in the choice and configuration of the load controller. Many advances in PV electricity generation can be observed [14].

The year 2017 was highlighted by [15] for having a greater number of publications related to renewable energies, showing that the interest for the subject is increasing. With this growing interest, it is necessary to encourage the study of the generation of electric energy from renewable energy sources by educational institutions. A system based on a microgrid wind-PV-battery, in laboratory scale for didactic use, is proposed by [16].

III. MATERIAL AND METHODS

PV off-grid systems, also called isolated or standalone systems, are usually used in locations that do not have access to conventional electrical power. With a wide application area, such as street lighting, power supply for communication systems, electric vehicle charging and aerospace systems, the PV standalone systems have become a low maintenance solution. To ensure greater autonomy in the power supply, these systems have a battery bank that stores the energy to be used at night or with lower solar irradiation. The off-grid system is generally composed of a set of PV modules, load controller, bank of batteries, and, depending on the application, a DC drive for alternating.

The criteria for the design of PV systems generally depend on the average values of solar irradiation and monthly or annual electricity consumption. In the annual average criteria, the PV generator capacity is determined from the generation capacity of the modules, calculated by the average solar irradiation over a year, and the consumption in the same period. While in the criteria of the critical month, also called the criteria of the worst month, the generation capacity of the modules in the month of lower generation must meet the average monthly consumption, guaranteeing the energy supply during the period where the solar irradiance is lower [17]. In a PV off-grid system, where this is the only power source, the critical month method must be used to ensure year-round power supply.

The analysis of the installation site should be one of the first criteria to be evaluated. In this step a geographic analysis of the location where the PV modules will be installed is made. The climatic conditions and buildings or large vegetation in the surroundings must be observed, thus avoiding the appearance of shade during the hours of greater solar irradiation. The installation site is a factor of great relevance in urban PV microgeneration systems, where space is generally limited to the roofs of residences. In this case the space for installation is a determining factor to define the energy potential in that location. In order to provide support for the design of PV systems, the Reference Center for Solar and Wind Energy Sérgio Brito (CRESESB) provides an online platform, called SunData, which is used to calculate the average monthly solar irradiance in any place in the Brazilian territory [18]. The position of the Earth relative to the Sun varies according to the time of day and day of the year. Therefore, the geographical location of a PV plant is directly linked to the energy potential of the plant. To install the PV modules to obtain the best use of this potential annually, the PV modules must be positioned correctly.

Another point to be evaluated is the energy consumption that the PV system must supply. In a system that will supply all the energy consumed in a property, the average consumption verified in the energy bill will serve as the basis for the design of the PV system by the criteria of the annual average, while the highest consumption recorded will serve as the basis for the sizing by the criteria of the critical month. In other situations, in which there has never been an energy bill, or a system will be designed only for a specific circuit, such as lighting, for example, a survey of the loads to be supplied by the system must be done.

The system must be dimensioned to supply the demand for active energy (L) consumed daily. For the design of the autonomy it is necessary to consider the efficiency of the inverter and the bank of batteries, according to Equation 1:

$$L(Wh/dia) = \left(\frac{L_{CC}}{\eta_{bat}}\right) + \left(\frac{L_{CA}}{\eta_{bat}\eta_{inv}}\right) \tag{1}$$

L_{cc} (Wh/day) is the amount of DC energy consumed daily in the critical month; L_{CA} (Wh/dia) is the amount of AC power consumed daily in the same month; η_{bat} (%) is the overall battery efficiency and η_{inv} (%) is the efficiency of the inverter. Suggested values are 85% for inverters and 86% for overall battery efficiency [19]. For [20], the type of battery that will be used is first defined. Then the discharge depth and the voltage of the battery bank are

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defined. Once this is done, we can calculate the capacity of the battery bank for a given autonomy by Equation 2:

$$Capacity\ (Ah) = \frac{Consume(Wh/dia) \times Aut(days)}{\mathrm{V_{BB}}\ (V) \times Prodes\ (pu)} \tag{2}$$

$Aut(days)$ is the set autonomy for the PV system; V_{BB} (V) is the voltage of the battery bank; $Prodes\ (pu)$ is the depth of discharge of the battery at the end of the range (pu). With the necessary capacity to supply the determined autonomy, one can choose the batteries appropriate to the system. It should be emphasized that the battery must be of the stationary type and the disposal must be done in an appropriate way, so that the environmental impacts are minimized. Existing technologies and the environmental impacts caused by them are discussed in [21].

For sizing the inverter, it is necessary to establish the maximum power demand. According to CEPEL and CRESESB, if the power of the inverter is equal to or greater than the installed power, and in loads that demand peak power, electric motors during starting, it is necessary to be aware of this power and its duration to define the surge capacity that the inverter must withstand. The inverter input must be compatible with the battery bank configuration voltage for stand-alone PV systems and the output according to the load requirement.

Another factor that directly influences the PV generation is the shading, since each totally shaded cell stops producing energy. Thus, an analysis of the shading around the PV system is necessary. After calculating shading relative to objects in the surroundings and the total area available for free shading installation or partially shaded during some time of the year, modules that meet the power requirements generated for the available space must be chosen. The peak power (Wp) of the PV generator that guarantees the power supply needed to supply the load is defined by CEPEL and CRESESB (2014) by Equation 3:

$$P_m = \max_{i=1}^{12} \left(\frac{L_i}{HSP_i \times Red_1 \times Red_2} \right) \tag{3}$$

P_m (Wp) is the peak power of the generation; L_i (Wh/dia) is the amount of energy consumed daily in month “i”; HSP_i (h/day) are the hours of full sun in the plane of the PV module in month “i”; Red_1 is the factor reducing the power of the PV modules in relation to their nominal value, including dirt, physical degradation, manufacturing tolerance for less, losses due to temperature. By default, $Red_1 = 0{,}75$; e Red_2 is the power derating factor due to losses in the system by conductors, controller, diodes. By default, $Red_2 = 0{,}9$. The hours of full sun (HSP) correspond to the number of hours at which the solar irradiation should remain at 1 kWh/m². Thus, the number of hours of full sun can be calculated by Equation 4:

$$HSP = \frac{Daily\ solar\ radiation\ (kWh/m^2)}{1\ (kW/m^2)} \tag{4}$$

Knowing the peak power of the generation (P_m) and the unshaded area, we choose the PV modules that best meet the necessary peak power in the free zone, partially or completely, of shading throughout the year. The number of PV modules needed to meet the demand for electric power can be calculated by Equation 5:

$$N°_{\mathrm{mod}} = \frac{P_m}{P_{\mathrm{mod}}} \tag{5}$$

P_{mod} is the peak power (Wp) of the chosen PV module. The ideal orientation for PV modules in fixed systems is to have the surfaces of the PV modules facing the Equator. That is, in facilities in the Southern Hemisphere, the surface of the PV module will be pointed to the geographical North and in installations in the Northern Hemisphere the surface of the PV module will be pointed to the geographical South [22]. For maximum energy generation annually, CEPEL and CRESESB (2014) suggest that the angle of inclination of the PV modules should be equal to the latitude of the installation site of the system. However, in places where the latitude is between -10° and 10°, a slope of at least 10° is used to facilitate the self-cleaning of the modules by rainwater. This minimum slope also makes it difficult to accumulate leaves on the surface of the modules.

The shape of the PV module (vertical or horizontal) can influence its efficiency. In some situations, such as mounting in snow-friendly environments, the horizontal mounting of the modules can reduce by half the effects of shading caused by snow accumulated on the bottom of the module. This reduction in the effects can be explained by the actuation of the bypass diodes contained in the module. In the horizontal assembly the shading affects two cell lines, whereas in the vertical assembly four cell lines are affected [23]. This is not the climatic reality of Brazil, however other elements can be accumulated in these places, such as leaves and dust. In Fig. 1 two installation modes are shown, and the accumulated dirt is represented by the gradual filling in the lower part of the PV modules. As an example of the module shown in Fig. 1, in extreme cases of dirt, a bypass diode is biased directly into the horizontal mount, while two bypass diodes are biased directly into the vertical mount, compromising every PV module.

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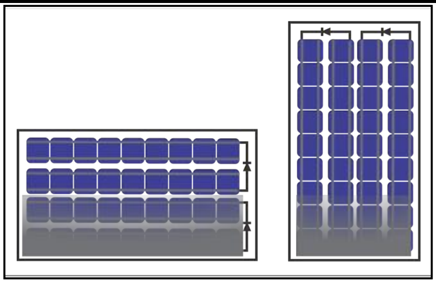

Fig. 1: PV module horizontal (left) and vertical (right)

The load controller must withstand the voltage and current levels provided by the PV system, so it is chosen based on the short-circuit current of the modules. For security reasons, Freitas [24] considers a current 25% greater than the short-circuit in the load controller design. Under these conditions the minimum current supported by the controller can be represented by Equation 6:

$$I_{Cont} \geq 1.25 \times I_{cc} \times Number\ of\ modules\ in\ parallel \quad (6)$$

I_{cc} is the short-circuit current of the PV module.
The input voltage of the load controller must also be observed in the sizing, so you must use modules compatible with the input voltage of the controller.
The correct dimensioning of the conductors, besides guaranteeing safety in the conduction of the generated electricity, reduces the losses caused by the voltage drop and, consequently, increases the efficiency of the system. Freitas [24] suggests the calculation of the section of conductors through Equation 7:

$$S = \frac{2 \times \rho \times l \times I_{max}}{V_n \times \Delta V_{adm}} \quad (7)$$

“S” is the conductor cross-section in mm², ρ is the resistivity of the conductor material (mm²/m); “l” is the length of the conductor (m); I_{max} is the maximum conductor current (A), V_n is the rated voltage of the system (V) e ΔV_{adm} is a dimensionless value between zero and one that corresponds to the percentage of the voltage drop admitted in the stretch.

IV. PROPOSED SYSTEM

The IFCE Campus Fortaleza, where the PV modules are installed, has its approximate geographical location at -3.74431095 Latitude and -38.53687271 Longitude, according to Google (2017). The installation site indicates a lower solar irradiation in the month of April, with monthly average of 4.53 kWh/m² per day. This value will be used for calculation in the sizing by the criterion of the critical month. The PV generation system will be used to supply power to the LPE lighting circuit, where the average daily consumption is shown in Table 1. The average of electric energy spent will serve as the basis for calculating the battery bank that guarantees the autonomy of the system for the expected number of hours.

Table 1: Average daily consumption in LPE

Description	Amount	Unit power
Led lamp	12	18.00 W
Daily use (h)	8.00	
Total Daily Energy (Wh/day)		**1,728**

For the daily energy consumption, we can calculate the capacity of the bank of batteries necessary for the parameters of the Table 2:

Table 2: Parameters for calculating the battery bank

Total consumption (Wh/day)	**1728,00**
Autonomy (days)	1.00
Battery bank voltage (V):	12.00
Depth of discharge at end of range (pu)	0.25

The minimum autonomy for the storage system established by ANEEL REN 493 [25] is two days, however, due to the limitation of the equipment available in the IFCE for this project, the autonomy of only one day was considered. This autonomy can be expanded by acquiring another inverter model and a larger number of batteries, as will be seen later. Considering the efficiency of the inverter (0.85) and battery bank (0.86), the active energy (L) can be calculated:

$$L = \left(\frac{1728,00}{0.85 \times 0.86}\right) = 2,363.89\ Wh/dia$$

And the battery bank's ability for active power:

$$Capacity\ (Ah) = \frac{2363.89 \times 1.00}{12.00 \times 0.25} = 787.96\ Ah$$

Knowing the capacity of the bank of batteries for the determined autonomy, it is possible to arrange the arrangement of batteries in parallel and/or series to meet the calculated autonomy and desired bank voltage. The stationary batteries available at the IFCE have capacity of 150 Ah for each battery and the autonomy of the system is guaranteed by at least six batteries (Fig. 2).

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Fig. 2: Stationary battery bank used

The inverter required to supply the installed power demand must have a power of at least 216 W. The inverter available at the IFCE is manufactured by Hayama and has power of up to 1000 W. The input for this inverter model is 12 V in direct current (DC). The output signal of the inverter is 220 Vac in a modified (square) wave with 60 Hz frequency (Fig. 3). Since the input of the inverter available on the IFCE is 12 V, serial connection to the available batteries could not be made, so all batteries were connected in parallel.

Fig. 3: Hayama Modified Wave Inverter 1000W

For this model of battery, you should not exceed the amount of six batteries in parallel, as indicated for [26], limiting the battery bank to a maximum of six batteries. Therefore, if there is a need to increase the autonomy of the system later, an inverter with an input of at least 24 V must be acquired, allowing the batteries to be connected in series. The waveform of the available inverter output is not sinusoidal, such as the wave pattern supplied by conventional distributors, but is enough for powering the laboratory lighting circuit.

One of the factors that must be considered is where the PV modules are installed. The site should be large enough to accommodate the number of PV modules required for the plant as well as free of shading. One of the alternatives to the installation space problem is addressed by [27], proposing the installation of the modules floating over water.

For this work, a site shading analysis was done to exemplify how this analysis is done, and to provide the best location for installation in case of plant expansion. For this, the shadow projections at the winter solstice, equinox and summer solstice, generated by SketchUp software, are illustrated in Fig. 4.

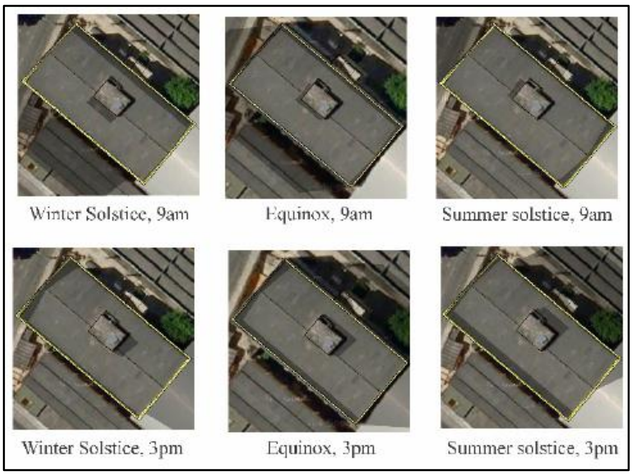

Fig. 4: Projection of the shadow at winter solstice, equinox and summer solstice

In the study of the installation area of the PV modules using the SketchUp software, the projection of the shadow (darkest area) on the roof during the whole year from 9 am to 3 pm is presented in Fig. 5.

Fig. 5: Projection of roof shading throughout the year between 9 am and 3 pm

The interaction of the SketchUp software with Google Earth allows the drawing to be done over the image of the location, captured by satellite, and with the appropriate geographical orientation (north at the top of the figure and south at the bottom). The best place to install the PV modules is on the water tank (rectangle not shaded in the center of the figure) because it is at the highest point of the building and, therefore, does not present shading relative to the buildings in the surroundings.

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After the projection of the shading throughout the year for the hours of greater solar irradiation, the project was exported from SketchUp to software AutoCAD (Fig. 6).

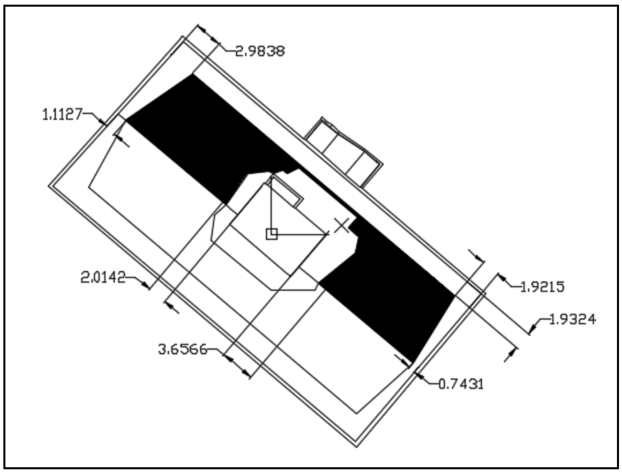

Fig. 6: Drawing in AutoCAD with highlight in the area available for installation without shading between 9 am and 3 pm (dimensions in meters)

In the case of a future expansion of the PV plant, the area for the installation of these new modules should be the part of the sloping roof oriented geographically more to the North. In Fig. 6, this area is highlighted (solid hatching), totaling approximately 216 m².

With a daily average of 4.53 kWh/m² per day at the place of installation, there are 4.53 hours of full sun available daily. The peak power required for the PV generator is then calculated through the parameters of Table 3.

Table 3: Parameters for calculating peak power of the PV generator

Energy consumed daily (Wh/day)	**1,728**
Hours of full sun (h/day)	4.53
Factor of reduction of the power of the modules (%)	0.75
Yield considering losses by conductors, controller, diodes etc.	0.90

$$P_m = \left(\frac{1728{,}00}{4{,}53 \times 0{,}75 \times 0{,}90}\right) = 565{,}12\ Wp$$

The available PV modules are manufactured by Kyocera model KD140SX-UFBS. Considering that these modules are 140 Wp, it is necessary to calculate the number of modules:

$$N°_{mod} = \frac{565{,}12\ Wp}{140\ Wp} = 4{,}04\ PV\ modules$$

Therefore, to meet the daily energy demand, it is necessary to use at least five modules. The six modules fixed on the water tank were used, according to Fig. 7.

Fig. 7: Six PV modules used

Since the input of the available inverter is 12 V, the operating voltages of the load controller and battery bank were also 12 V, making it necessary to arrange all PV modules in parallel. Therefore, the total short-circuit current of the PV array will be:

$$I_{curto-circuito} = 6 \times 8{,}68 = 52{,}08\ A$$

For this PV array, a load controller is required which supports at least 52.08 A at its input. The load controller available from the IFCE for this project is the Schneider Electric C60. This model consists of a relatively simple controller with PWM control. Better results would be obtained with controllers that have MPPT control, as shown by [28]. Some available controller specifications are shown in Table 4.

Table 4: Schneider Electric - C60 Charge Controller Specifications

Supported Rated Current (A)	**60**
Maximum current peak (A)	85
System voltage (Vdc)	12 or 24
Maximum voltage of connected PV array (V)	55
Self consumption current (mA)	15
Ambient operating temperature (°C)	0 to 40

The configurations of this load controller are made through jumpers and potentiometers, as shown in Fig. 8.

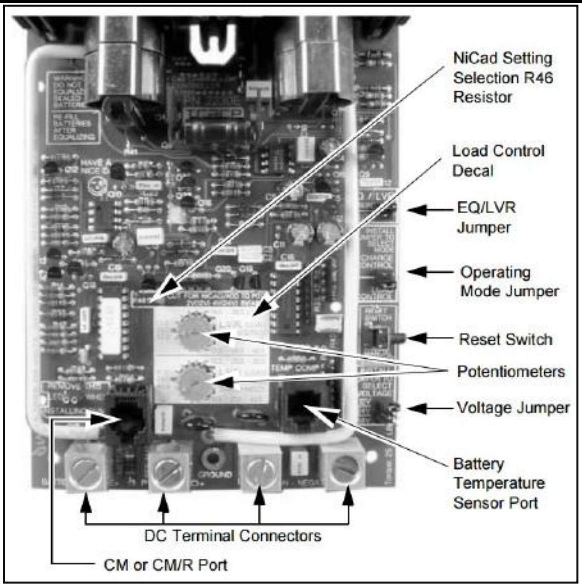

Fig. 8: Configuration Locations and Connections for the C60 Load Controller

The configuration of the jumpers was done as shown in Table 5.

Table 5: Selected load controller settings

Jumper	Selected setting
Operating Mode Jumper	Charge Control
Voltage Jumper	12 V
Automatic/Manual Battery Equalization (EQ) and Low Voltage Reconnect (LVR)	AUTO

The operation mode of the selected controller is the charge control of the battery bank, so the standby operation settings (BULK and FLOAT) have been adjusted according to the values given in the battery manual and the FLOAT is set to 13, 60 V and recharge regime (BULK) at 14.40 V. Due to the availability of the equipment, in this design the load controller supports a short circuit current up to 15% higher than the short circuit current of the PV array, calculated as 52.08 A, different from the 25% suggested by [24].
To facilitate the change of series/parallel configuration between the PV modules for future studies, the connection of the PV modules was made inside the electrical panel through the connection between the terminals (screws) corresponding to each module, organized in a printed circuit board. As the configuration for this project is made by connecting the six PV modules in series, a copper bus was used for connection, as showed in Fig. 9. In the positive pole conductor of each PV module a polarized blocking diode was connected directly as safety measure for the case of shading of the PV module.

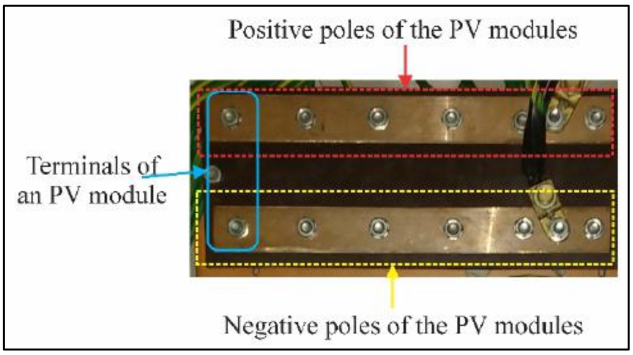

Fig. 9: PV modules connection bus on board developed

A photographic record of the assembled electrical panel, specifying each part, is shown in Fig. 10.

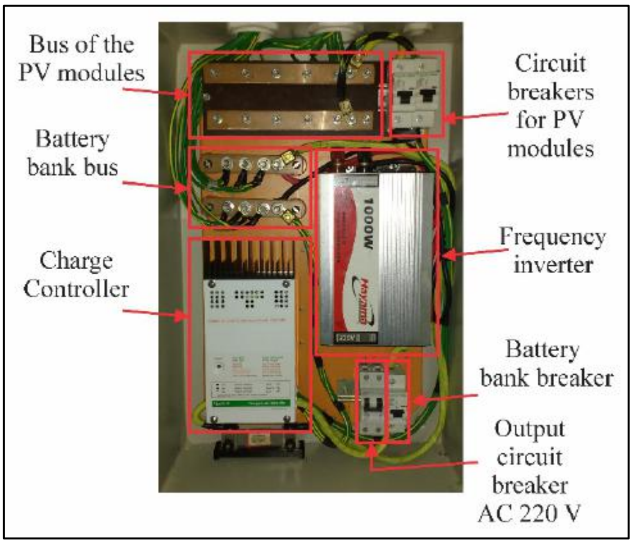

Fig. 10: Electrical panel developed

Because there were no red and black cables available for standardization of the positive and negative poles of the equipment, the conductors used were green and yellow.
Microcontrollers have been applied to the monitoring of power generation systems, as can be seen in the projects proposed in [29]-[31]. For measurement, an IoT embedded system was constructed to measure voltage and current generated by the plant. Arduino Uno R3 measures the analog signals proportional to the voltage and current supplied by the PV modules and an Esp8266 to send the information collected by the internet. A voltage divider was made with resistors to measure the bus voltage of the PV panels and a shunt resistor was added between the bus of the PV modules and the load controller to measure the

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current supplied by the PV modules. The Esp8266 is responsible for connecting to the Internet to capture the time of acquisition and send the data to a server through the MQTT protocol, which stores these in a ".txt" file whenever requested by a web page. In Fig. 11 the schematic of the measuring system is shown. The data acquisition system was in operation for a few days. Fig. 12 shows a chart of the data collected in one day every four seconds from 6 am to 6 pm (sunrire and sunset).

The results of these graphs enable the visibility of the electrical behavior of the system. One can observe, for example, moments in which there is a reduction in the power caused by the passage of clouds.

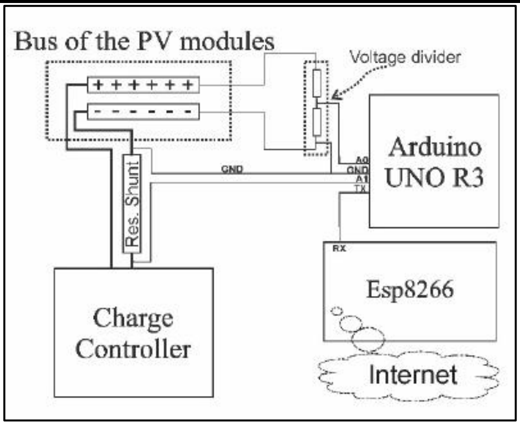

Fig. 11: Schematic of the measurement system

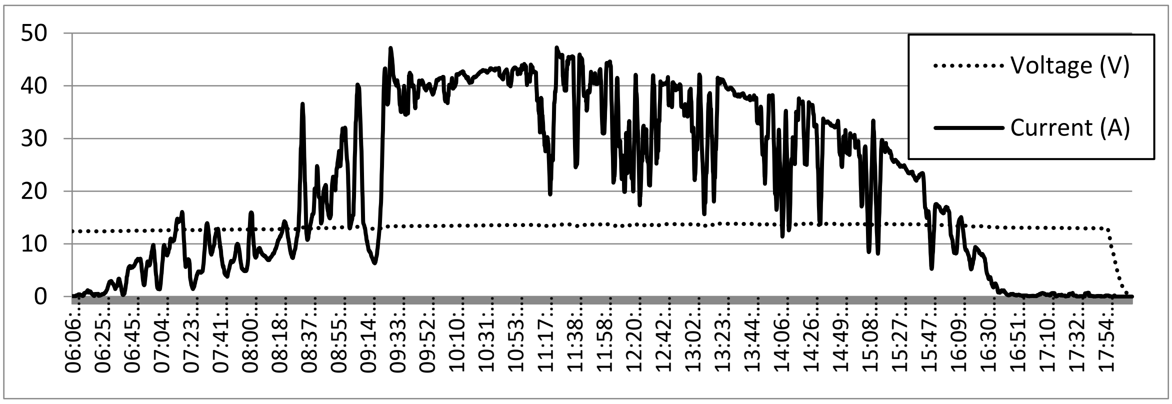

Fig. 12: Voltage graph of PV module bus and current supplied by it

Note that although the current is dramatically reduced by about 4:15 pm, the voltage remains at just over 12 V and decreases until zero at approximately 6 pm. At this moment, the diodes are reverse polarized, not allowing current flow to the PV modules. The power supplied by the modules is shown in Fig. 13.

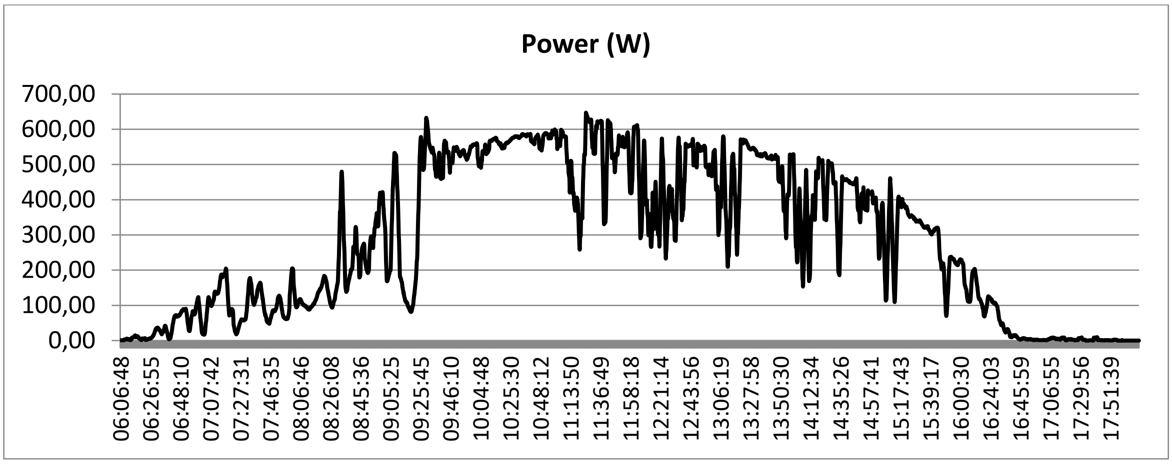

Fig. 13: Graph of the power provided by the PV modules

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The cloud passage is characterized by drops in the power generated by the PV modules, as can be seen in Fig. 13. The highest recorded power was approximately 647 W.

V. CONCLUSION

In this work a standalone didactic PV generation plant was designed and developed. The stages of the project were exposed, presenting factors that influence the generation of the system. Later, the knowledge gathered in this work was applied to design an autonomous PV plant designed to power the lighting circuit of the Energy Processing Laboratory at IFCE, Brazil. By means of a data acquisition system, generated power of up to 647 W was recorded. From the data collected by the acquisition system, the action of the blocking diode and cloud incidence was verified, factors that influence the generation of electricity by the system. An electrical panel has been designed in a way to facilitate access to each PV module separately, providing the different configuration of these PV for future work. This is because in addition to providing energy to the laboratory lighting circuit, the PV plant resulting from this work has the objective of helping students in a didactic way to facilitate the teaching-learning process of PV systems.

For a better analysis of the energy supplied by the PV generator and the behavior of the PV generator over the years, it is necessary to monitor the system for a longer period. Therefore, it is suggested as a theme for future work the development of a system for data acquisition capable of storing an adequate amount of information and transmit it in an accessible way to the user to consult the amount of energy generated among other information that may be relevant to some future study proposed.

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