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Procedure of the design of photovoltaic systems applied to ornamental lighting

X. Serrano-Guerrero[1], C. Ochoa-Malhaber[1], I. Ortega-Romero[1]

[1] Universidad Politécnica Salesiana, Grupo de Investigación en Energías (GIE)
Campus El Vecino – Calle Vieja 12 - 30 y Elia Liut, 010105 Cuenca (Ecuador)
Phone/Fax number: +5937413-5250, e-mail: **jserranog@ups.edu.ec, cochoam2@est.ups.edu.ec, iortegar@est.ups.edu.ec**

Abstract. Photovoltaic systems have the advantage of reducing atmospheric pollution, avoiding CO_2 emissions. Another advantage is the energy savings they produce and that in the long term they can return the investment made. PV systems off grids are applied in remote and rural areas, where there is no electricity distribution network. The use of PV systems off grids can be included in ornamental lighting, as they have low levels of luminous efficiency due to the use of old technologies. Therefore, this study presents a procedure for the design of PV systems applied to ornamental lighting, starting from obtaining adjusted values of solar irradiance, based on estimated solar irradiance data from NASA in the city of Cuenca (Ecuador) and measured data. The critical month (maximum consumption and minimum irradiance) is selected, which corresponds to June with a value of $3,76\ kWh/m^2$. The results indicate that these systems are feasible to be implemented, due to the fact that the total investment cost is around $10.450,00 compared to a 5,2 km grid extension system that costs around $44.512,00. Finally, the responses of the PV systems off grid applied to ornamental lighting are tested in MATLAB/Simulink.

Key words. Solar energy, Photovoltaic (PV) systems off Grids, Boost converter, Ornamental lighting.

1. Introduction

The demand for electrical energy is constantly growing and conventional energy sources have limited reserves that could be depleted in the coming decades [1]. In addition, pollution and climate change impose the need for a rapid energy transition to renewable energies [2], [3].

Solar energy is an inexhaustible resource that has a great potential to be exploited in different ways. One of them is the conversion of solar energy into electrical energy, through a semiconductor electronic device called a photovoltaic cell [3], [4]. Each installed kilowatt (kW) of photovoltaic solar energy avoids the emission of 136 kg of CO_2 per year [5].

In addition to being a clean energy source, photovoltaic solar energy has many applications, including the following: home energy, water pumping, irrigation systems, greenhouse and farm lighting, signaling and communications, transportation, heating, public lighting (streets, monuments, bus stops, etc.) and ornamental lighting. Photovoltaic systems can operate as hybrid systems, grid-connected or off-grid. The latter have a wide application in remote regions for power supply [4].

There are many fields of application of photovoltaic systems in lighting, in [6] the use of a photovoltaic system for lighting in tunnels is presented, using the panels on the outside and carrying the energy to the interior luminaires, they can also be integrated into public lighting with grid connection and storage functions with batteries [7] or in interior lighting such as in offices or classrooms [8].

Public, ornamental, residential and commercial lighting are the four sectors where lighting has the highest energy consumption in Ecuador. In turn, ornamental lighting is susceptible to improvement, because it includes the lighting of parks and gardens, where there is commonly a high consumption due to the low level of luminous efficacy [9]. On the other hand, ornamental lighting systems in the city of Cuenca (Ecuador) use the conventional electrical grid as a power source, which often represents considerable costs when extending the grid to the point of consumption.

There are similar studies where they apply the study of solar photovoltaic panels in lighting, in [10] presents a public lighting system in a remote area of Turkey, where they use a hybrid system (solar wind) with an intelligent fuzzy controller to manage the lighting level and the regulation of the LEDs according to the power delivered by the panels. In addition, the authors suggest that the system is extendable and fully adjustable to any area with low power. On the other hand, in [11] a computer program has been developed to simplify the design process of off-grid photovoltaic systems. Through the developed software, photovoltaic systems with different capacities have been proposed, obtaining the necessary characteristics to determine the number of solar panels, battery bank capacity, inverter capacity and amortization period. In the study presented, similar values were obtained, however, the calculation time was long.

Regarding the design of voltage converters, they present opportunities for improvement, in [12] they use a PI control to provide greater stability, since the response and accuracy of the system are better than those of PD and PID controls. In addition, there are different MPPT optimization algorithms [13] according to the needs of the system, but in [14] a method to extract the maximum power from a solar PV panel using the MPPT algorithm of Perturb & Observe is presented, the authors use a boost converter to obtain the maximum power point (MPP) that helps to raise the system voltage to the maximum operating point. For the case study there was no need for such control since the PV regulator already had the MPPT control in place.

This work presents the design procedure in MATLAB/Simulink of an off grid photovoltaic system applied to ornamental lighting in the city of Cuenca (Ecuador), in order to reduce costs by the implementation of energy converters. In addition, a boost converter is developed to increase the voltage coming from the set of batteries and to feed the LED luminaires.

2. Methodology

It is important to define the type of PV system to be designed, its electrical loads and components, so Fig. 1 shows the steps to follow for such sizing.

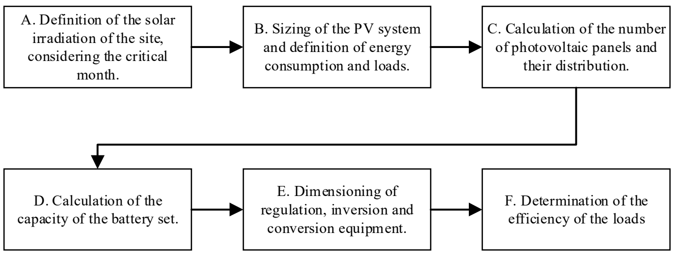

Fig. 1. Procedure for the design of photovoltaic systems applied to lighting.

A. Definition of the solar irradiation of the site, considering the critical month.

It is very common to have irradiance data measured only in the horizontal plane. However, it is not recommended that panels be placed without tilt due to the accumulation of dirt that they will have [1]. There are different databases of solar irradiance at different tilt angles, but these are estimated by satellite. For this reason, in this work we propose to adjust the real data measured in the horizontal plane.

Initially, the actual global irradiance data, measured at the location where the PV system will be implemented, are collected according to [5]. Then, the solar irradiance values according to month and tilt angle are obtained from the NASA database [15], in the section solar irradiance for inclined surfaces oriented towards the Equator.

From the data obtained in [15], a coefficient between the different tilt angles is found. For this purpose, the irradiance of each month is divided into a 15º, 30º and 45º angle for irradiance with an angle of 0º. Then each coefficient is multiplied by the actual value of global irradiance measured in the horizontal plane, according to [5]. Table I presents the adjusted global irradiance data at different tilt angles.

Table I. - Adjusted global irradiance data.

Adjusted global irradiance data $[kWh/m^2]$				
Month	**0° Tilt**	**15° Tilt**	**30° Tilt**	**45° Tilt**
January	5,09	5,25	5,03	4,58
February	4,99	5,02	5,16	5,31
March	4,29	4,23	5,09	4,92
April	4,29	4,11	5,11	5,13
May	4,22	3,92	5,15	5,34
June	3,91	3,76	5,28	5,25
July	3,85	3,92	5,13	5,10
August	4,16	3,93	5,13	5,22
September	4,68	4,57	5,10	5,01
October	4,74	4,76	5,06	4,79
November	5,45	5,60	5,02	4,59
December	5,04	5,25	5,02	4,52

Next, it is necessary to identify the critical month as the one with the lowest solar irradiation in the month of highest energy demand. In this case study, energy consumption is constant throughout the year, so the month with the lowest solar irradiation is the critical month. Then, the slope corresponding to the highest energy collection for that month is selected. In this case study it corresponds to the month of June with a value of $\mathbf{3,76\ kWh/m^2}$ and a 15° tilt.

B. Sizing of the PV system and definition of energy consumption and loads.

For the development of this methodology, three types of loads of different voltage have been considered. In this case study, the PV system is off grid and must supply a load of 500W divided into three parts: a load of 200W at $\mathbf{12\ V_{DC}}$, a load of 200W at $\mathbf{24\ V_{DC}}$ and a load of 100W at $\mathbf{127\ V_{AC}}$. Fig. 2 shows a block diagram with the equipment that make up the PV system.

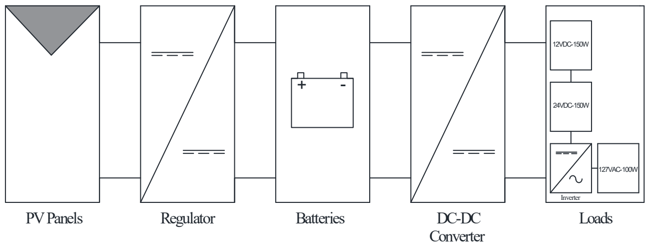

Fig. 2. PV system block diagram.

A PV system is sized according to the energy demanded in a 24-hour period. Table II presents the data for the sizing of the PV system.

Table II. - Photovoltaic system sizing data.

Loads	Voltage [V]	Power [W]	Time of use [h]	Daily energy [kWh/day]	Monthly energy [kWh/month]
LED luminaire in DC	12	200	12	2,4	72
LED luminaire in DC	24	200	12	2,4	72
LED luminaire in AC	127	100	12	1,2	36
Total				**6**	**180**

The PV panels must provide the energy for the loads, but also for the losses of the system elements. This energy can be calculated from Equation 1 [16].

$$E_{T_{PVP}} = \frac{E_{DC,12V}}{n_b} + \frac{E_{DC,24V}}{nb \cdot n_c} + \frac{E_{AC}}{n_b \cdot n_i} \quad (1)$$

Where $E_{T_{PVP}}$ is the total energy of the PV panels [kWh/day], $E_{DC,12V}$ the DC energy [kWh/day] at 12V, $E_{DC,24V}$ the DC energy [kWh/day] at 24V, E_{AC} the AC energy [kWh/day], n_b, n_c and n_i are the performance of the battery, converter and inverter respectively.

Considering an efficiency of 90% of the battery, 90% of the converter and 90% of the inverter, the value of $E_{T_{PVP}}$ is 7,11 kWh/day.

C. Calculation of the number of photovoltaic panels and their distribution.

Initially, the type, brand and model of photovoltaic solar panel is selected. In this case, a 270W polycrystalline photovoltaic solar panel of the POWEST brand, consisting of 60 solar cells in a 10x6 distribution (10 rows and 6 columns), has been considered [17]. Additional characteristics can be seen in Table III.

Table III. - PV Panel Parameters [17].

PV Panel POWEST 270 W	
Parameters	**Value**
Maximum power	270W
Cells per module	60
Open circuit voltage	37,9V
Open circuit current	9,27A
Voltage at maximum power point	30,7V
Current at maximum power point	8,80A

An important value to consider is the global irradiance, which in most cases remains at 1000 W/m^2. The number of panels is calculated through Equation 2 [16].

$$N_T = \frac{E_{T_{PVP}} \cdot 1000}{P_{PV} \cdot G_{dm} \cdot P_R} \quad (2)$$

Where N_T is the total number of PV panels to be used, P_{PV} is the power of the PV panels [W], G_{dm} is the irradiation in [kWh/day] of the critical month and P_R is the coefficient of performance, which in PV systems is 0,8.

$$N_T = 8{,}75 \approx 9\ panels$$

The connection of the panels chosen is series-parallel (3x3), the output voltage is 113,7V, the output current is 27,81A and a total power of 2,43kW.

D. Calculation of the capacity of the battery set.

The nominal voltage of the system is defined by Table IV, the same that is directly related to the installed power, therefore, the nominal voltage for the PV system design is 12V.

Table IV. - PV system nominal voltage ranges from installed power.

Installed power	Nominal voltage
P ≤ 1500W	12V
1500W ≤ P ≤ 5000W	24V
P > 5000W	48V

On the other hand, the value of the maximum capacity of the batteries is the greater value between the daily nominal capacity and the seasonal nominal capacity.

1. Daily rated capacity

For a daily cycle, the maximum daily depth of discharge is recommended between 15 and 30%. It is considered 1 day of autonomy, 12V output and 0,30 depth of discharge and used the Equation 3 [16].

$$B_C = \frac{E_D \cdot D_A}{V_S \cdot DP} \quad (3)$$

Where B_C the battery capacity [Ah], E_D the energy demand [Wh/day], D_A the days of autonomy, V_S the system voltage [V] and DP the depth of discharge.

$$B_C = 1975{,}31\ Ah$$

2. Seasonal rated capacity

It is defined as the number of days that a battery will be discharging without receiving sufficient solar irradiation (they are between 3 and 10 days) with a depth of discharge of approximately 70%. In this case, 3 days of autonomy are considered and Equation 3 is used.

$$B_C = 2539{,}68\ Ah$$

3. Calculation of the number of batteries

The battery to be used is defined, for example, a 12V-200Ah battery. Equation 4 [16] is used as long as the voltage of the set and the battery are equal.

$$N_B = \frac{B_C}{B_E} \quad (4)$$

Where N_B is the number of batteries, B_E is the battery energy [Ah].

$$N_B = 12{,}70 \approx 13$$

The connection of the batteries is in parallel, in this way a total of 12V-2600Ah will be obtained in the output of the batteries.

E. Dimensioning of regulation, inversion and conversion equipment.

1. Dimensioning of the regulator

The short-circuit current coming from the photovoltaic panels and the maximum current consumed by the load are considered, where the higher current is the one that the regulator must withstand. In both cases a safety factor of 1,25 is considered, the expressions of the input and output current are established in Equations 5, 6 and 7 respectively [16].

$$I_{in} = 1{,}25 \cdot I_{PV} \quad (5)$$

Where I_{in} and I_{PV} are the input currents [A] to the regulator and the PV panels respectively.

$$I_{in} = 34{,}76\ A$$

The maximum load current is calculated using Equation 6.

$$IL_{max} = \frac{P_{DC}}{V_B} + \frac{P_{AC}}{127 \cdot \cos\varphi} \quad (6)$$

Where, IL_{max} is the maximum load current [A], V_B the battery voltage [V], P_{DC} the DC power [W] and P_{AC} the AC power [W].

$$IL_{max} = 34{,}32\ A$$

The output current is shown in Equation 7.

$$I_{out} = 1{,}25 \cdot IL_{max} \quad (7)$$

Where I_{out} is the regulator output current [A].

$$I_{out} = 42{,}9\ A$$

2. Dimensioning of the inverter

The expression to determine the power of the inverter is given by Equation 8 [16].

$$P_{inv} = 1{,}25 \cdot P_{AC} \quad (8)$$

Where P_{inv} is the inverter power [W] and P_{AC} is the AC power [W].

$$P_{inv} = 125\ W$$

3. Dimensioning of the boost converter

The boost converter is an electronic circuit that allows converting a DC voltage to a higher DC voltage. The components involved in the converter circuit are sized based on input voltage, output voltage, duty cycle, switching frequency and load power. Equation 9 is used to determine the duty cycle of the converter [18].

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (9)$$

Where D is the duty cycle, V_{in} is the input voltage [V] and V_{out} is the output voltage [V]. The converter has an input voltage of 12V coming from the batteries and a voltage of 24V is expected at the output.

$$D = 0{,}5$$

Load resistance is defined as [18]:

$$R = \frac{(V_{out})^2}{P_{load}} \quad (10)$$

Where R is the resistance [Ω] and P_{load} is the power of the load [W]. Here is considered the load value of 24 V_{DC} which is 200W.

$$R = 2{,}88\ \Omega$$

The average inductor current ($\overline{I_L}$) is defined as [18]:

$$\overline{I_L} = \frac{V_{out}}{(1-D)^2 \cdot R} \quad (11)$$

$$\overline{I_L} = 33{,}33\ A$$

$$L_{min} = \frac{V_{in} \cdot D}{2 \cdot \overline{I_L} \cdot f_s} \quad (12)$$

Where f_s is the switching frequency [kHz] which in this case is 10 kHz.

$$L_{min} = 9\ uH$$

A value greater than the calculated L_{min} is needed, because if this value is taken directly, the current will approach zero [18].

$$L \gg L_{min}$$

$$L = 3 \cdot L_{min} \quad (13)$$

$$L = 27\ uH$$

Equation 14 is used to determine the converter capacitor [18].

$$C = \frac{D}{R \cdot f_s \cdot f_r} \quad (14)$$

Where f_r is the output voltage ripple. For the case study a f_r of 5% is considered.

$$C = 347\ uf$$

F. Determination of the efficiency of the loads.

Currently, LED luminaires have replaced traditional lighting systems almost entirely, occupying 90% of the market, due to their long life, electronic advances, energy efficiency, adaptability in shape and size, high reliability, among others. One of the main aspects to consider for their estimated lifetime is the operating temperature and ambient temperature, this can considerably reduce the lumens and color characteristics [19].

The actual efficiency of current LED light sources is 30% to 40%. On the other hand, 100% efficiency would not be possible in practice, since there are numerous components in an LED bulb in which losses occur in the form of heat and other electrical effects [20].

3. Efficiency, costs and comparison of PV system with conventional systems

A PV system allows the generation of clean and self-sustainable energy. One of the main advantages is that the efficiency of a photovoltaic system and its components is between 90% and 95%, which represents an optimal power quality for the system loads.

Electrical loads use conventional electrical systems as a power source. A conventional electrical system is made up of several electrical elements, which represent considerable investment costs when it is required to extend the electrical network to a load point [16].

In [21] they analyse the costs of extending the network in different remote locations and at different distances. The approximate costs for a distance of 5.2 km are $44.512,00 and for a distance of 10 km it is $85.600,00. This corroborates that extending the power grid to remote locations involves a very significant cost. For this reason, this case study is presented and Table V shows the estimated cost of the off-grid PV system, which presents lower costs compared to a system with grid extension.

Table V. - Estimated PV system off Grid costs.

Estimated PV system off grid costs			
Quantity	**Equipment/Components**	**Unit Price**	**Total Price**
9	270W POWEST Panel - 60 cells	$ 180,32	$ 1.622,88
13	Sealed Battery - Fuli Batery 12V-200Ah	$ 543,20	$ 7.061,60
1	Charge controller - EPEVER Tracer5415AN	$ 364,69	$ 364,69
1	Inverter - Model PST-120-12	$ 206,68	$ 206,68
1	Boost converter 12-24V	$ 200,00	$ 200,00
6	1/0 AWG wire (1 meter)	$ 9,80	$ 58,80
6	6 AWG wire (1 meter)	$ 2,35	$ 14,10
6	18 AWG wire (1 meter)	$ 0,65	$ 3,90
1	Solar panel connectors kit - MC4	$ 15,99	$ 15,99
-	Installation cost	$ 900,54	$ 900,54
Total			**$ 10.449,18**

4. Results

The simulations of the PV system were performed in MATLAB/Simulink. The system is divided into several subsystems: the PV panels, the regulator, the batteries, the boost converter, the single-phase inverter and the loads, as shown in the block diagram in Fig. 3.

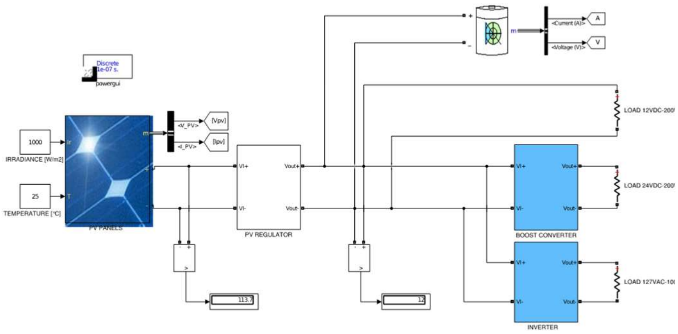

Fig. 3. Photovoltaic system off grid.

Fig. 4 shows the configuration of the boost converter, which has a resistor, an inductor and a capacitor calculated earlier. On the other hand, Fig. 5 shows the output voltage waveform.

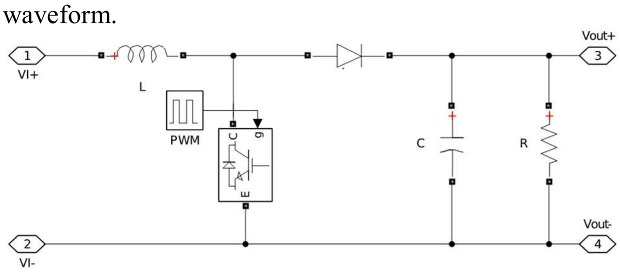

Fig. 4. Boost converter.

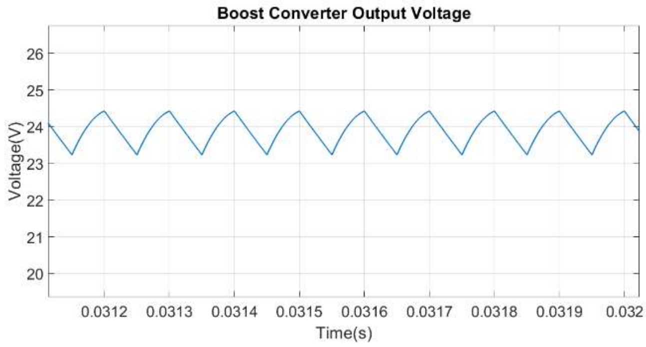

Fig. 5. Boost converter output voltage.

Fig. 6 shows the configuration of a single-phase full-bridge inverter, Fig. 7 shows the inverter output voltage which is approximately 127V.

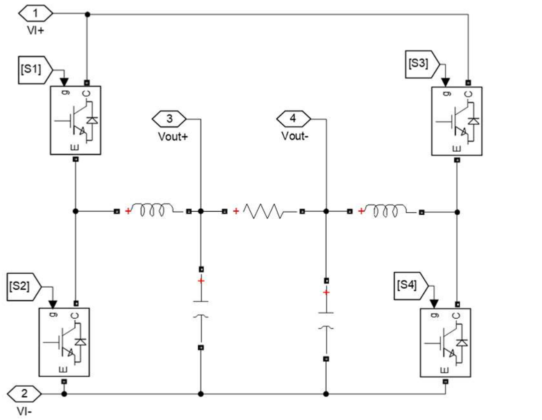

Fig. 6. Full bridge inverter.

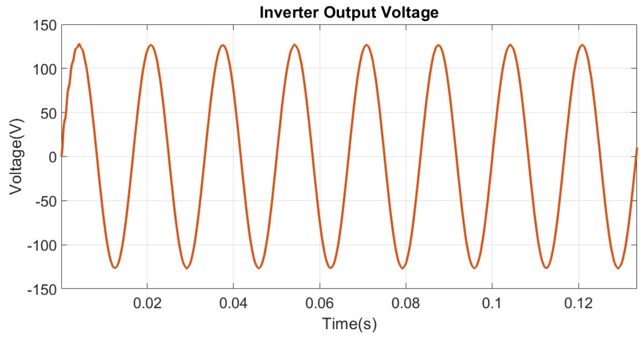

Fig. 7. Inverter output voltage.

The charge and discharge control of the battery bank is performed by the regulator, the simulation of this control is shown in Fig. 8, the output voltage of the batteries is shown in Fig. 9.

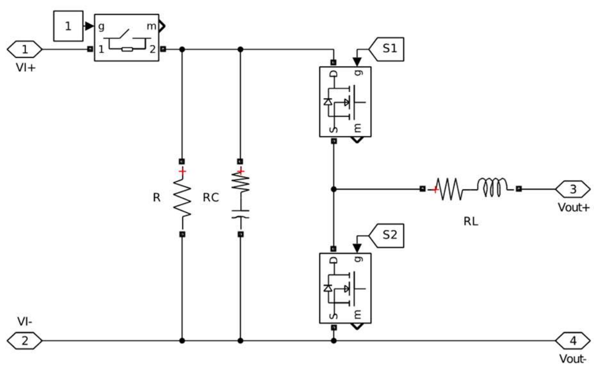

Fig. 8. Battery charge and discharge control.

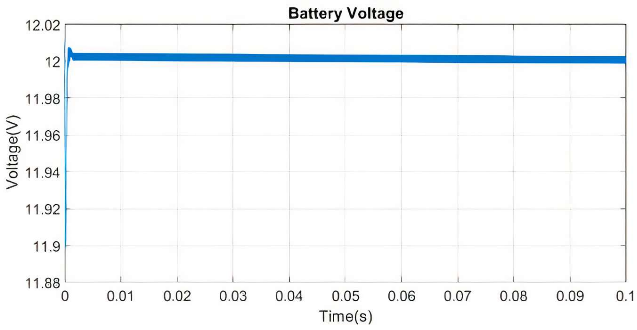

Fig. 9. Battery voltage.

5. Conclusion

The design of photovoltaic systems should be considered in a place with high solar radiation, also if possible connect the array of solar panels in series, to avoid high currents and the use of oversized electrical conductors. A design criterion is to use the values of open circuit voltage and short circuit current to avoid under sizing and future failures. The voltage obtained in the panel is directly proportional to the solar irradiation of the day and this in turn will depend on environmental conditions such as temperature and cloudiness.

The seasonal cycle of a battery is an important aspect to consider, because it is the maximum number of days that a battery can be discharged without receiving sufficient solar irradiation. Batteries are selected based on the days of autonomy, depth of discharge and nominal voltage of the system, which in turn depends on the power of the load.

It is feasible to design a boost converter in case the required output voltage is not so high compared to its input voltage. For example, if a system needs to feed a load of 110 V_{DC} and has an input voltage of 12 V_{DC}, the most advisable is to perform a process of inversion, boost and power rectification. This is due to the complexity that exists when working with high DC voltages and loads.

The impact of photovoltaic systems on the environment is minimal compared to other non-renewable energy sources such as thermal and nuclear power plants. This has greatly benefited the reduction of progressive environmental impacts and the problems they generate. Regarding the economic return of a photovoltaic system, it will be profitable as long as the payback time is less than the useful life of the system components.

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