Abstract — This paper presents a study about an autonomous (off-grid) photovoltaic (PV) system making use of the novel Lithium Iron Phosphate (LiFePO$_4$) as a battery pack for isolated rural houses. More particularly, this thesis studies and tests the behaviour and efficiency of a low-cost isolated PV system for the rural area near Luena in Angola. The proposed system (solar panel, batteries, controller and inverter) has been projected having in mind the required household daily load of 1300Wh and the available irradiation from the sun. The power produced by the panels is directly injected in the battery pack to make the system simpler and cheaper. Thus, PV panels and batteries nominal voltage has been chosen in accordance so the panels operate as closer of the maximum of the $I$-$V$ curve as possible. The power and energy management is done using a Battery Management System (BMS) with resistor passive balancing. The DC-AC conversion is performed by a single-phase pure sine wave off-grid inverter. The system showed an efficiency of 75% measured by a DAQ system with LabVIEW Signal Express which includes the idle powers of the elements.

Keywords - Autonomous/Off-grid PV system, Angola, system efficiency, LiFePO$_4$

I. INTRODUCTION

In the rural areas of developing countries, the access to electricity is still very deficient. This happens once the distances involved are very large and do not justify the investment for supplying small populations. The focus on rural electrification aims to give people better living conditions at low cost, with the certainty that there will be no short or medium term return, but those conditions will make all the difference on the development of that country.

With this motivation the objective is to project and test a final solution that is actually possible to implement immediately, add value and solve these issues, improving the standard of living of people. More particularly, this solution is designed to be installed in the area of Luena in Angola. Previous reports related that Angola is a country with a per-capita consumption below the average in Africa, with its PIB increasing more than 250% after from 2002 to 2011, due to the end of the civil war [1]. It is estimated that in Angola less than 20% of the population has access to energy [2], once the power grid is still very limited supplying only the big cities.

According a survey of system prices made in 2013 by the International Energy Agency Photovoltaic Power Systems (IEA PVPS) European reporting countries\(^1\) showed the system prices in the off-grid sector (<1 kW), irrespective of the type of application, typically ranged from about 2.7 to 20 USD/W [3].

The proposed system is designed with two 225W solar-PV panels with 3000kWh LiFePO$_4$ battery storage to feed an average AC consumer load of 1300Wh/day. The most commonly used batteries for storing applications are lead-acid batteries [4] type but they are being substituted by lithium-ion batteries over time due to several advantages. It is discussed the importance of the first initial charging of the batteries, and also the efficiency of the system (battery pack + BMS + Inverter) was measured experimentally using a Data Acquisition device (DAQ) by Texas Instruments.

II. AUTONOMOUS/OFF-GRID PV SYSTEM COMPONENTS

There are several possible connection configurations for off-grid systems. Fig. 1 shows the basic block diagram of a usual typology with DC and AC loads. Particularly for LiFePO$_4$ batteries presented here, the regulator monitors the voltage of the battery pack on a narrower range than the input DC operating voltage of the inverter, this means that the regulator actuates first than the critical values of the inverter.

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\(^1\) Austria, Denmark, France, Italy, Spain, Sweden and Switzerland

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Off-grid pure sine wave inverters may also actuate as regulators, however this configuration is used mostly for lead acid battery types once the input voltage range levels are made accordingly to its critical voltages ($V_{min\text{, cut-off}}=20\text{V±5\%}$, $V_{max\text{, cut-off}}=30\text{V±5\%}$ for 24V nominal voltage inverters). More particularly, Fig. 2 represents the proposed autonomous PV system block diagram configuration.

![Fig. 2 - Autonomous PV system electric block diagram](image)

The Battery Management System (BMS) is the solar regulator in Fig. 1, used to monitor the battery pack. The straight lines represent a direct connection and the dashed lines the control unit. The BMS actuates on the relays opening and closing the circuit if the batteries go over or under the safe ranges of temperature, voltage and SOC ranges.

**A. Electrical Loads**

In this work, the considered electrical load for a standard house in the countryside of Angola is shown in Table 1. To proceed with the future sizing, Table 1 presents the considered average hours of utilization of each load. The refrigerator has a particular way of working on an on-off regime, which makes it more difficult to know the corresponding utilization time at full load. For this reason, its consumed energy should be always measured once the energy efficiency labels values are far from the real utilization.

<table>
<thead>
<tr>
<th>Device</th>
<th>Nominal Power [W]</th>
<th>Utilization hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>100</td>
<td>4-7</td>
</tr>
<tr>
<td>CRT TV 13&quot;</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Incandescent Lamps</td>
<td>60</td>
<td>5</td>
</tr>
</tbody>
</table>

*Table 1 - Electrical loads for a standard house in Angola*

**B. PV Panels**

**B.1) Tilted Radiation**

To calculate the efficiency of the panels it is necessary to know the incident radiation on the panel’s plane. For the purposes of this work, the diffuse irradiance is not considered once it usually corresponds less than 10% of the total irradiance in clear sky days, calculated using the Liu and Jordan model [5]. Besides, the diffuse component decreases with the tilt angle. Thus, the radiation on the panels’ plane was calculated using beam radiation and the following vectors representation:

$$g_{b\text{, module}} = \frac{g_{b\text{, horiz}}}{\sin \alpha} \cos \theta_i(\beta) = \frac{g_{b\text{, horiz}}}{\cos \theta_i(\beta = 0°)} \cos \theta_i(\beta) \quad (1)$$

where $g_b = g_{b\text{, horiz}}$ is the radiation on the horizontal plane (usually measured), $\alpha$ is the solar angle and the known incidence angle $\theta_i$, which depends on several factors\(^2\), including the tilt angle of the panels, $\beta$ [6].

**B.2) Efficiency**

The efficiency of the panel may be estimated knowing the temperature of the cells. It will produce better results with experimental data using the following expression [7]:

$$\eta(T) = \eta_{STC}[1 + \gamma(T_c - T_{STC})] \quad (2)$$

**C. LiFePO\textsubscript{4} Batteries**

The batteries used in autonomous PV systems must have reduced maintenance, long service time, reduced self-discharge and high energy efficiency, high storage capacity and power density, good performance/price relation, and protection against the occurrence of hazards to the environment and health.

LiFePO4 have the best thermal stability comparing with LiCoO\textsubscript{2}, LiMn\textsubscript{2}O\textsubscript{4}, LiNiXCoXAlYO\textsubscript{2} types, being then appropriate to photovoltaic applications [8].

\(^2\) Besides the tilt angle, it depends on the date, hour and localisation [6]
Regarding the charging/discharging characteristic in Fig. 4, the main conditions that should be verified for LiFePO₄ batteries are [10]:

- The voltage of the cell should not exceed 3.65V when charging and 2.5V when discharging;
- The lifetime of the cells will be drastically reduced if charged outside the range 0°C ~ 40°C and discharged outside the range -20°C ~ 60°C;
- Cell’s lifetime will be reduced if charge/discharged at current rate higher than 30% of the capacity (0.3C);
- The voltage of the cell should not exceed 3.65 V when charge (Fig. 6 a), or a near voltage 3.4V (series string battery pack). When one cell goes under the minimum critical voltage the remaining cells may have a higher voltage (Fig. 6 b).

To estimate the batteries’ state of charge (SOC) it may be used the coulomb counting technique, which simply indicates the remaining capacity of the battery by using electric current integration according to the coulomb counting equation [11]:

$$\text{SOC}_t = \text{SOC}_0 - \int_0^t \eta \times i(t) \, \frac{1}{C_n} \, dt \quad (3)$$

where $\text{SOC}_0$ is the initial SOC, $\eta$ the coulomb efficiency, $C_n$ the battery estimated capacity and $i(t)$ the current. The coulomb counting is usually additionally combined with others sensors such as voltmeters to measure the battery voltage and calibrate the SOC (improve the lack of precision of the current sensors). After all, it is simple and has been used in many BMS’s products on the market which the case of the BMS used in this system – 123BMS™ of 123 electric, Albertronic. The cell usually have slightly different capacities, for this reason the cell with the smallest capacity dictates the capacity of all the battery pack [10].

C.1) Balancing

Other important fact to consider is that new LFP batteries are usually partly charged from factory but due to transport, climate and environment conditions, cells’ SOC is different at the moment of assembling the pack. When assembling the cells in a series string (battery pack) it is absolutely necessary to balance the cells so they have a similar voltage and consequent SOC when charging/discharging. This balancing may be at a low (bottom) or high voltage the so called bottom and top balancing respectively.

In bottom balancing process (Fig. 5), although with different capacities, all the cells have the same reference point at the low end voltage, about 2.5V. If the pack goes under the minimum critical voltage, all the cells get there together.

In top balancing, the reference point is the maximum cell voltage of 3.65 V for individual batteries charge (Fig. 6 a), or a near voltage 3.4V (series string battery pack). When one cell goes under the minimum critical voltage the remaining cells may have a higher voltage (Fig. 6 b).

The balancing process may be done automatically by a so called battery management system which is presented next.

D. Battery Management System (BMS)

The most important feature in any application is to ensure no damaging. A Battery Management System (BMS) is an electronic monitor device which controls the status of individual cells and pack. In order protect and maximize battery pack’s life, cell’s temperature, voltage and current are “read” at a certain rate via several integrated control modules and actuators. To provide a better performance, the SOC and eventually the SOH are estimated and different balancing strategies can be used depending on the system application. They are usually bottom or top balancing seen further in more detail.

E. Autonomous or Off-grid Inverter

For any photovoltaic (PV) system, the off-grid inverter is the essential electronic device that converts low voltage DC electricity from the battery to an independent (from the grid) 100V-120V or 220V-240V AC signal. Pure sine wave inverters have a THD lower than 3% which was confirmed experimentally. They are appropriate for motor loads such as medical equipment, refrigerators, laser printers, etc.

The efficiency of the inverter is given by [6]:

$$\eta_{inv} = \frac{P_{out}}{P_{in}} = \frac{P_{dc}}{P_{ac}} \quad [\%] \quad (4)$$

Fig. 7 shows in advance the typical experimental characteristic of a 1500W pure sine wave off-grid inverter. The curved was plotted with a resistive load with 10 different

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3 Note that “balancing” is the term used for the processo f bringing the SOC levels to similar values. “Balance” refers to the degree by which SOC match each other [10]

4 the inverter was selected and tested after the project in chapter IV
values until the maximum power supply was reached.

Fig. 7 - Typical off-grid inverter characteristic with a pure resistive load

The efficiency ranged from 84-90% between 200-300W with the highest value at 800W (50% of the nominal).

F. Cables

Fig. 8 represents the losses on the DC cables, the voltage the voltage drops and power losses associated to it. The losses on the cables connecting the batteries to the loads are not represented for simplification. The length of these cables is small when compared with the length of the PV cables and might be neglected.

Fig. 8 - Cable losses

where $R$ is the resistance on the cable PV-battery in Ohms, $P_{PV}$ is the power at the panel’s terminals, $P_{injected}$ is the power at the battery’s terminals and $\Delta V$ is the voltage drop on the cables. $R$ is generally calculated according to the manufacturer resistance and length of the cable.

The power produced by the panel $P_{PV}$, knowing the power at the end of the cables terminals $P_{injected}$ and the Joule losses on the cables, is given by:

$$P_{PV} = P_{injected} + 2P_{joule} = P_{injected} + 2\left(\frac{I}{S} \cdot I^2\right)$$

$$= P_{injected} + 2(R \cdot I^2) \text{ [W]}$$

(5)

G. System Efficiency

When the irradiance on the panels is known, the system efficiency approach starts by knowing its elements efficiency: BMS, Battery Pack and Inverter).

Fig. 9 - Off-grid PV system connection diagram

Accordingly to the diagram in Fig. 9 this efficiency may be obtained by:

$$\eta_{system} = \eta_{BMS} \times \eta_{BAT} \times \eta_{inv} \times \eta_{losses} \text{ [%]}$$

(6)

where $\eta_{losses}$ are the losses on the cables.

In case the energy “injected” in the battery pack and the energy consumed by the loads is known, the respective efficiency may be calculated by:

$$\eta_{BMS+BAT+in} = \frac{E_{injected}}{E_{in}} = \frac{E_{consumer}}{E_{injected}} \text{ [%]}$$

(7)

However, as the batteries store energy, this efficiency needs to be estimated during a time period where the batteries start at a certain SOC return to that same SOC point. This may be more accurately done by a battery voltage reference point. In other words, the battery should start the test charged with a voltage $U_o$, discharge during a certain time and charge again until $U_o$. Knowing the energy in and out during this period, the efficiency may be calculated.

III. PROJECT

This chapter aims to project the photovoltaic system for Luena zone in Angola using the maximum daily energy consumption which follows the following steps:

1. Determine the dairy energy consumed by the loads;
2. Calculate the energy production of the PV modules at a given tilt, $\beta$, and azimuth angle, $\gamma$;
3. Project the peak power of the PV modules;
4. Calculation of the batteries parameters;
5. Project of the solar regulator;
6. Project of the autonomous or off-grid inverter.

A. Electrical Loads

To perform the project more accurately, all the loads active and power factor were measured with Fluke 1735 Power Logger and are presented in Table 2. For project purposes only the daily active power is used, the inverter supplies reactive power which is usually 1/3 of its nominal power.

Reminding Table 1, the energy consumption of the refrigerator is not well known being thus measured for a 24h

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5 accordingly to the experiment made in chapter IV
period. The refrigerator has 7 refrigeration levels consuming more energy for higher levels. For a reasonable temperature vs energy use, level 3 is the appropriate one.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>100</td>
<td>127</td>
<td>0.6</td>
</tr>
<tr>
<td>CRT TV 13”</td>
<td>40</td>
<td>41</td>
<td>0.674</td>
</tr>
<tr>
<td>Incandescent Lamps</td>
<td>60</td>
<td>69.6</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2 - Electrical loads experimental power of standard house in Angola

However, once it was not possible to simulate a diary use of the refrigerator, the level 4 was the chosen one to compensate the extra consume caused by the opening of the door on level 3. Fig. 10 shows a zoom (1h) on its 24h load diagram (average active power) at level 4 with no opening of the door.

The refrigerator compressor is on for periods of approximately 4 min at an average power of 127W four times per hour. The power peaks happen when the compressor motor starts which will have to be supported by the inverter.

The total load diagram is the sum of the three previous loads’ consume profile represented in Fig. 11 logged with Fluke 1735.

![Time [h:min] vs Power [W]](image)

**Fig. 10 - KENT 201E refrigerator load diagram (1h)**

The refrigerator switches on and off in regular periods along the day. The lights turn on between 6:00 and 7:00 and from 18:30 to 22:30 according to the working hours in Angola. This power may be achieved with a single lamp or several with less power which is the second more important load of a family’s house. For a regular house entertaining purposes is estimated a 40W TV which is on for 2 hours per day from 20:00 to 22:00 or it can be substituted by a more important electronic device if consuming the same equivalent energy. The maximum power of the system is 250W between 19:00 and 22:00.

Table 3 presents the experimental daily energy consumption and the hours of use for a considered standard house in the rural area of Angola as seen in Table 1. The total daily consume is approximately 1300Wh which should be taken in consideration for the project.

The use of individual loads independently is equivalent to a power of 238W for 5.5 hours.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>100</td>
<td>127</td>
<td>0.6</td>
<td>880</td>
</tr>
<tr>
<td>CRT TV 13”</td>
<td>40</td>
<td>41</td>
<td>0.674</td>
<td>84</td>
</tr>
<tr>
<td>Incand. Lamps</td>
<td>60</td>
<td>69.6</td>
<td>1</td>
<td>348</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>237.6</strong></td>
<td></td>
<td><strong>5.52</strong></td>
<td><strong>1312</strong></td>
</tr>
</tbody>
</table>

Table 3 - Experimental loads energy

B. PV panels production capacity

The PV panels are the only source of energy once in this system. Thus, it is necessary to estimate the necessary power to feeds the loads, $W_\text{d} = 1300$ Wh/day, having in mind the losses that may occur on the cables, regulator and inverter as seen before in expression (6). The respective efficiencies are:

$$\eta_{\text{losses}} = \eta_{\text{cables}} = 1 - P_{\text{cable \ losses}}$$

The losses on the cables may reach 3% on isolated systems ($\eta_{\text{cables}} = 0.97$) [4]. The losses on the regulator or BMS system are considered be less than 2% ($\eta_{\text{BMS}} = 0.98$) for the used BMS. The losses of the inverter are equal to the inverter efficiency which is usually between 80-97% for grid-tied inverters [4]. For off-grid inverters the efficiency does not go much over 90%. In this case it is considered 85% ($\eta_{\text{inv}} = 0.85$) for an operating power of 20% of the nominal inverter power according to Fig. 7. Finally, considering the battery efficiency equal to 1 (currents lower than 10% of the total capacity) and all the applicable losses, the efficiency factor is equal to 81%.

The radiation varies along the year and to project the system is necessary to choose which irradiance to consider. The best procedure is to project the system by the worst case scenario for permanent use houses, which occur in the months of less radiation. This way the feed of the loads all the year is guarantee being the system oversized [4]. The $\tau_d(\beta, \gamma)$ factor makes the equivalent hours of the irradiance at 1000 W/m²...
\( \tau_d(\beta, \gamma) = \frac{\text{Monthly Average Irradiance [Wh/m}^2\text{/day]}}{1000 \text{[W/m}^2\text{]}} \) \hspace{1cm} (9)

The worst month irradiance on the optimal tilted angle occurs on December with 4730 Wh/m\(^2\)/day according to the available energy in Luena area from PVGIS [12] (optimal inclination of 19\(^{\circ}\) with annual irradiation deficit due to shadowing (horizontal) equal to 0\%). Thus \( \tau_d(\beta, \gamma) = 4.73 \text{ h/day} \).

### C. PV array sizing

With this method, the mean energy produced by the PV panels is already considered, consequently it is not necessary to consider the total efficiency of the PV, \( \eta_{PV} \) as used in some methods [13]. The power of the modules is given by:

\[
P_{PV} = \frac{W_d}{\eta_{system} \times \tau_d(\beta, \gamma)} \text{ [Wp]} \hspace{1cm} (10)
\]

The needed power is then equal to 339.3 Wp, for a daily consume, \( W_d = 1300 \text{ Wh/day} \).

However, the off-grid system is expected to have MPPT’s to make the system cheaper and with less stand by consumption. Thus, to choose the power of the panels it is more realistic to use the maximum power on NOCT conditions. The polycrystalline Suntech STP225 - 20/Wd used panels produce 165W on NOCT conditions. The number of PV modules needed to produce the required power is given by equation (11):

\[
N_{PV, modules} = \frac{P_{PV}}{P_{PV, NOCT}} \hspace{1cm} (11)
\]

Two panels produce 330W to be connected in series or parallel regarding the chosen working voltage of the batteries. In this case, the nominal voltage of the batteries is 24V so the panels must be connected in parallel once is \( V_{MP} = 29.6 \text{ V} \).

### D. Batteries

Usually, the nominal operational voltage of the PV system can choose between 12V, 24V or 48V. The working voltage chosen was 24V instead of 12V to decrease the current on the cable and consequently the losses. The daily consume in Ah is given by:

\[
W_{Ah} = \frac{W_d[Wh]}{U_{DC}[V]} \text{ [Ah]} \hspace{1cm} (12)
\]

which result in 54.17 Ah for \( U_{DC} = 24 \text{V} \).

The battery sizing is then [13]:

\[
C_{BAT, tot} = \frac{W_{Ah} \times N_d}{DOD_{max}} \text{ [Ah]} \hspace{1cm} (13)
\]

where \( N_d \) is the number of reserve days (working days with energy from the sun). \( DOD_{max} \) is the maximum deep of discharge of the battery which should be less than 80\% so the batteries can perform more than 2000 cycles. The results gives a 169.28 Ah battery bank with the reserve days equal to 2.5. The number of batteries to perform the capacity needed is calculated as:

\[
N_{BAT} = \frac{C_{BAT, tot}}{C_{BAT}} \hspace{1cm} (14)
\]

where \( C_{BAT} \) is the capacity of a single battery. Choosing a 180Ah the number of batteries needed is just one. The battery capacity is added when the batteries are installed in parallel keeping the voltage and remains the same when they are installed in series, adding to the voltage. In this case to perform the 24V more batteries needed in fact. This number of batteries to perform the 24V system is obtained by:

\[
N_{BAT} = \frac{U_{BAT, tot}}{U_{BAT}} \hspace{1cm} (15)
\]

Each LiFePO\(_4\) battery has a nominal voltage of 3.2V being necessary 8 batteries to perform the 24V voltage. Resuming, to build a battery bank with 24V and 169 Ah, eight batteries with 180Ah and 3.2V are needed.

### E. Autonomous or off-grid inverter

Choosing a slightly larger inverter could allow it to run cooler and can anticipate a future load expansion. These inverters support usually twice its rated power for during periods up to 10 seconds.

To understand what is the peak power of the loads involved it was measured the transitory AC current of the inductive loads. In Fig 13 is represented the starting and the operating current of the Kent refrigerator.

![Fig. 12 - Refrigerator starting current](image)

The peak amplitude of the current is \( I = 9.2 \text{A} \). The peak power is calculated by the expression:

\[
P_{peak, peak} = l_{RMS}U_{RMS} = \frac{l}{\sqrt{2}}U_{RMS} \hspace{1cm} (16)
\]

Making the power peak of the inverter to be more than 1500W. Considering the general fact the inverter may support
twice its nominal power, the minimum inverter necessary power is then 750W.

F. Prototype costs

The system was built considering the project and is specified in more detail in Table 4. The distance from the PV source to the batteries should be as low as possible which may reduce the system costs.

Although the design capacity of the battery is approximately 180Ah according to expression (13), at the time of purchase, the highest capacity battery available at the supplier’s store was 130Ah.

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>Price with VAT</th>
<th>Total</th>
<th>Percentage of Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>225W polycrystalline PV Panels</td>
<td>2</td>
<td>303 €</td>
<td>606 €</td>
<td>20.0 %</td>
</tr>
<tr>
<td>DC Aluminium Cable 4mm2</td>
<td></td>
<td>0.86 €/m</td>
<td>86 €</td>
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</tr>
<tr>
<td>LiFePO4 Batteries 3.2V 130Ah</td>
<td>8</td>
<td>127.48 €</td>
<td>995.84 €</td>
<td>32.9 %</td>
</tr>
<tr>
<td>123BMS + Controllable Relay</td>
<td>1</td>
<td>490.58 €</td>
<td>490.58 €</td>
<td>16.2 %</td>
</tr>
<tr>
<td>BMS Board Cell Module</td>
<td>8</td>
<td>11.06 €</td>
<td>88.48 €</td>
<td>2.9 %</td>
</tr>
<tr>
<td>DC Current Sensor 100A</td>
<td>1</td>
<td>55.62 €</td>
<td>55.62 €</td>
<td>1.8 %</td>
</tr>
<tr>
<td>1500W Off-grid Inverter</td>
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<td>528.9 €</td>
<td>528.9 €</td>
<td>17.5 %</td>
</tr>
<tr>
<td>DC Switch</td>
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<td>101 €</td>
<td>101 €</td>
<td>3.3 %</td>
</tr>
<tr>
<td>Dead Front Fuse Holders</td>
<td>1</td>
<td>6.22 €</td>
<td>6.22 €</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Differential circuit breaker breaker In=25A, ( \Delta I_{\text{min}} = 3 \text{ mA} )</td>
<td>1</td>
<td>68.2 €</td>
<td>68.2 €</td>
<td>2.3 %</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>3026.8 €</td>
<td>100 %</td>
</tr>
</tbody>
</table>

Table 4 - Total system cost

Thus the 130Ah batteries were used for testing, reducing also the system costs that way. To perform better with engine loads, the inverter must support the peak power easily. Also it should be given margin power for future expansion of the system. As such an inverter was chosen with the capacity to double the peak power required by the loads, i.e., an inverter with nominal power of 1500W (peak power 3000W). The total 450Wp system cost corresponds to a price of 6.3 USD/W\(^6\) which is in the range seen in section I.

IV. RESULTS

To analyze the viability of the autonomous system, it is necessary to:

- Determine the amount of energy needs in a daily basis to feed the loads;
- Verify the effective energy available in the battery pack and the reserve days;
- Check the energy supplied daily by the solar energy conversion system (PV panels).

The voltage data logging (storing) was performed by a low-cost NI USB-6008/6009 DAQ\(^\circ\). The electric current logging was done using a LEM LA-25-NP transducer to reduce the losses of the measurement. The logging of the temperature of the cells was performed using a Tiny Tag bound to the PV surface. The logging data consists of: voltage of the panels after the 50m DC cables (the parallel of the panels is done after the 50m to reduce the current in each circuit); output current of the panels; Individual cell’s voltage (8 cells); Battery pack voltage (sum of the 8 cells’ voltage); AC power at the terminals of the load.

A. Experimental Set-up

Fig. 13 shows the major components of the PV experimental arrangement installed according to Fig. 2. The battery pack is installed at the bottom of the experimental bench (bottom in Fig. 13 a) and is connected to a relay in series (number 5 on Fig. 13 b), controlled by the BMS controller (number 6). The relay is connected to the PV panels and the inverter mains circuit (number 4). The BMS uses a current sensor (7) to measure the current going in and out of the battery pack. The PV panel’s circuit is protected by a 25A DC fuse (2) and may be manually switched on/off by a DC switch (3). Also visible Fig. 13 (b) are the DAQ’s that perform data logging of the voltages of the system (1).

B. Initial Charging of the Batteries

Although it was not of the objectives of the work, it was further tested the importance of the initial charge (after leaving the factory) of all cells that constitute a battery pack. Fig. 14 illustrates a partial discharge test comparison between an unbalanced battery pack (Fig. 14 a) and with initial charge balancing (Fig. 14 b) on a constant resistive load of 6Ω (25.5 V/6 Ω = 4.25 A = 0.06C average current). The battery voltage in both figures starts at 26.15V, the cell’s temperature was 15°C and the test was done until the BMS detected a voltage of 2.7V in one cell, opening the load relay.

\(^{6}\) Using a conversion ratio of 1€=1USD
and protecting the “weakest” cell (lowest capacity).

The dissipated energy should be calculated from the dissipated power in a resistor multiplied by the time interval between samples (one minute), $\Delta T_s$, in which the power is considered constant:

$$E = I^2R \times \Delta T_s = V \times I \times \Delta T_s = \frac{V^2}{R} \times \Delta T_s$$  \hspace{1cm} (17)$$

Fig. 14 - Battery pack voltage during discharge on a constant resistive load of 6Ω a) without and b) with initial balancing

Fig. 14 b) shows that with the initial balancing the battery pack voltage is more "flat". Additionally, observing each battery voltage separately the voltage unbalance is visible. The energies spent in each test are shown in Table 5:

<table>
<thead>
<tr>
<th>Unbalanced cells energy [Wh]</th>
<th>Balanced cells energy [Wh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1351</td>
<td>1539</td>
</tr>
</tbody>
</table>

Table 5 - Energy of the discharge tests in Fig. 14 - unbalanced and - balanced cells

The initial charging represented an energy improve of 12%, a clear gain in the discharge time which suggests that the pack should be always charged before use.

C. The Autonomous PV Run – Lisbon, Portugal

The autonomous PV system essays were performed in March 2015 with two polycrystalline 225W panels installed on top of the third floor of North tower building at IST (38°44’15.9’’N and 9°08’17.6’’W). The approximate sun’s trajectory is shown in Fig. 15. The solar maximum angle is 48°at 13:00 [14]. The panels are oriented to the geographical south (7° deviation from south to the west) with an inclination angle of $\beta = 35^\circ$ (optimal angle generally used in Portugal accordingly to [4, 15]).

Due to its location, the PV panels are shaded after between 7:00 and 8:30 and after 14:30, caused the building height (morning) and by the north tower building (located right on the image) which reduces the solar radiation at least 3 hours/day (afternoon) which constitutes a test constraint. This effect is represented by a grey shadow area on the graphs.

Fig. 16 shows in red, the measured solar radiation on a horizontal surface on 14th March 2015 at the IST meteorological station which is installed on the top of the South Tower where the shading effect after 14:30 does not happen. The curve fluctuations represent the passing of clouds. It also shows in black, the radiation incident on the PV tilted plane (35°) calculated accordingly to the expression (1).

To simplify the calculations the direct irradiance on the horizontal plane $G_{b,hori}$ was substituted by the total horizontal irradiance measured at the IST meteorological station once the diffuse radiation represents less than 10% of the total radiation as seen in II.B.1.

The solar power is only injected in the batteries when the irradiance is available and voltage of the panels is higher than the voltage of the batteries. The figure below shows the evolution of the PV (blue) and battery pack voltages (black) during the day.

The PV voltage (blue) is approximately one volt higher than
the battery pack voltage from 8:30 until 14:00, when the sun is hitting the panels. The peaks seen on the graph after 14:00 o’clock represent the opening of the charging relay when the charging is done and one of the cells voltage is above 3.5 V, remaining open for approximately 10 minutes ($V = V_{OC}$). The profile of the loads influences the voltage of the batteries - the variations in the battery’s voltage are caused by the refrigerator.

The refrigerator turns on approximately every 15 minutes causing the batteries voltage to drop in order to provide the higher current to start the refrigerator. After 14:30 the panels inject power no more being the loads feed only by the batteries.

The efficiency of the system is experimentally calculated accordingly with expression (7): the batteries full charged at 14:15 the day before (13th March), the system functioned all day and night for a load of 1270Wh/day. The charging of the battery pack was achieved in about 6 hours at 14:00. This charge state was used as the reference point for the estimation of the efficiency once the system took 23:45h discharge and charge again to the same voltage when the discharging was started. Table 6 resumes the energy of the main components of the system.

<table>
<thead>
<tr>
<th>PV production</th>
<th>Injected in battery</th>
<th>Load consume</th>
<th>Bat. + BMS + Inverter losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1693 Wh</td>
<td>1600 Wh</td>
<td>1270 Wh</td>
<td>331 Wh</td>
</tr>
</tbody>
</table>

Table 6 – Daily energy of the different components

The losses on the DC cables totaled 93 Wh (5% of the production). This values result on a mean daily efficiency of the system (Battery + BMS + Inverter) of 79%, and efficiency of the system (Cables + Battery + BMS + Inverter) of 75% (expression 6) which is an acceptable value compared with the usual 85% used for grid-tied systems (no stand-by consumption) [7]. The system experimental efficiency is further used to estimate the behavior of the system in Angola.

To check the real available energy of the battery pack $W_{bat,Tot}$, with its cells top balanced, a discharge on a 3.3 $\Omega$ resistor was performed in order to obtain an approximately average current of 8A ($26.4 \, V / 3.3 \, \Omega = 8 \, A = 0.06C$) which is a value close to the current that will enter and exit the battery bank while running as a standalone system. Fig. 18 shows the battery’s voltage for the test that proceeded continuously for 17h until one of the cells reached a critical voltage of 2.57V (2nd cell) with a cell temperature of 12°C (BMS monitoring).

![Fig. 17 - PV (blue) and battery pack voltage (black) on 14th March 2015](image)

![Fig. 18 - Discharge at approximate 0.06C current rate or 8A (3.3Ω resistor)](image)

The total energy stored in the battery pack was calculated in approximately 3600Wh accordingly to expression (17) at 80% DOD, which is higher than the nominal theoretical value of 3328 Wh. The minimum pack voltage with top balancing was 21.5V. Note that the axes start at 21V.

Fig. 19 shows the influence of the ambient and the photovoltaic cell’s temperature in the efficiency of the PV panels during its operation. Before analyzing the results it is important to say that the manufacturer indicates a 13.6% efficiency at STC. At the beginning of the day the panels work mainly with diffuse and reflected radiation once the sun rays hit the panels close to 8:30 (shaded area) which makes expression (1) meaningless for this case.

![Fig. 19 - PV module temperature and efficiency on 14th March 2015](image)

When the radiation focuses the panels with a considerable power (600 W/m²) its temperature increases considerably to 25°C being the efficiency 14.7% at 9:00. The increase of the efficiency verified at this time of the day is slightly higher than the efficiency of the manufacturer once the clouds make the diffuse radiation component increase considerably. The diffuse component is summed to the direct component increasing the total incident radiation for a cloudy test conditions study. This indicates that expression (1) does not work properly for more than 10% diffuse radiation conditions. With clear sky after 11:00, the temperature of the cells
increases to 40ºC, consequence of the increase of the radiation and ambient temperature. The fluctuations of the panels’ temperature is caused by the wind cooling effect. The average efficiency for the period between 8:30 and 14:00 is 10.8%.

D. Autonomous PV Run – Luena, Angola

Since it is not possible to make experimental tests in Angola, it is important to compare its radiations with the radiation in Portugal where the system was tested to assess its viability and efficiency. This way, it is possible to make an extrapolation of the energy produced in Angola by correcting the real efficiency of the panels to the average ambient temperature in Angola. This adjust method is further used accordingly to expression (2).

The annual average temperature in Luena is 21.2º opposed to 16.3º in Lisbon (ΔT=5ºC). The efficiency variation with ΔT=5ºC is approximately 0.3% accordingly to expression (2). Consequently, for the energy production estimation in Table 7, it is used a PC efficiency of 10.5% and a system efficiency of 80%, as the system tested in IV.C may be improved by 5% using shorter cables. The PV production is then calculated multiplying the energy available on the PV panel’s area (3.3 m²) by the panel’s efficiency (10.5%), multiplied by the PV production to obtain the energy delivered to the loads. The irradiation values shown are taken from [12] for an optimal inclination angle of 19º.

<table>
<thead>
<tr>
<th>Month</th>
<th>Irradiation [Wh/m²/day]</th>
<th>Energy on PV panels area [Wh/day]</th>
<th>PV production [Wh/day]</th>
<th>Energy delivered to the loads [Wh/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>4890</td>
<td>16137</td>
<td>1694</td>
<td>1356</td>
</tr>
<tr>
<td>Fev</td>
<td>5070</td>
<td>16731</td>
<td>1757</td>
<td>1405</td>
</tr>
<tr>
<td>Mar</td>
<td>5540</td>
<td>18282</td>
<td>1920</td>
<td>1536</td>
</tr>
<tr>
<td>Apr</td>
<td>6290</td>
<td>20757</td>
<td>2180</td>
<td>1744</td>
</tr>
<tr>
<td>May</td>
<td>6980</td>
<td>23034</td>
<td>2419</td>
<td>1935</td>
</tr>
<tr>
<td>Jun</td>
<td>7040</td>
<td>23232</td>
<td>2439</td>
<td>1952</td>
</tr>
<tr>
<td>Jul</td>
<td>7170</td>
<td>23661</td>
<td>2484</td>
<td>1988</td>
</tr>
<tr>
<td>Aug</td>
<td>7330</td>
<td>24189</td>
<td>2540</td>
<td>2032</td>
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<tr>
<td>Sept</td>
<td>6850</td>
<td>22605</td>
<td>2374</td>
<td>1899</td>
</tr>
<tr>
<td>Oct</td>
<td>6150</td>
<td>20295</td>
<td>2131</td>
<td>1705</td>
</tr>
<tr>
<td>Nov</td>
<td>5070</td>
<td>16731</td>
<td>1757</td>
<td>1405</td>
</tr>
<tr>
<td>Dec</td>
<td>4750</td>
<td>15609</td>
<td>1639</td>
<td>1311</td>
</tr>
</tbody>
</table>

Table 7 - Estimated energy available to the loads in Luena, Angola

On an average basis, even with a higher average ambient temperature than in Portugal, and a consequent lower PV efficiency, the higher solar potential in Angola leads to satisfactory energy production results. Analyzing Table 7, we might conclude that only January and December are critical with an energy delivered to the loads close to the 1300Wh daily house consume. Additionally, using the PVGIS tool, the percentage of days with fully discharged batteries is less than 5% for an autonomous PV system in Luena with the following parameters: PV power 450Wp; battery voltage 24V; capacity 130Ah; discharge cut-off limit 35%; daily consumption 1300 Wh; module inclination 19º and orientation north (180º). This enhances that Angola has a high solar potential.

V. CONCLUSION

This paper approached the autonomous energy supply to a typical rural house in Angola. The projected and tested system during the month of March proved to be able to feed the previous specified load with an average consumption of 1300Wh/day.

Although March is not the month of the year with the lowest monthly average irradiation in Portugal the measured system efficiency is considered the same all the year. The efficiency of the PV panels obtained experimentally in Portugal was adjusted to the average temperature in Angola, this way, it was made an extrapolation to the monthly irradiation values in Angola. The results showed a good production energy during almost all the year, except in January and December which revealed critical production values of 1356Wh and 1311Wh, respectively. This values are too close to the daily consumed energy and suggests the addition to the system of a 2nd alternative source of energy (wind generator, diesel generator, etc.). The efficiency may be also improved installing the panels closer to batteries (less than 50m) and another possible solution to improve performance in the critical months is a manual change of the tilt angle of the panels in order to align them with the sun.

The estimation method of solar direct radiation incident on the plane of the panels (G<sub>b_module</sub>) calculated from experimental measurements of radiation in the horizontal plane on site (G<sub>b_horiz</sub>), revealed a deviation of about 2.7% from the experimental value. This value shows that the procedure used for the calculation (section II.B.1) is suitable for clear sky days. However, this method has the limitation of not working properly when the solar angle is close to zero.

With respect to the batteries, the initial charging revealed to be essential to ensure a long life of the batteries and with a balanced pack (close SOC) it is possible to achieve more energy.

On site, the polycrystalline solar panels used showed a daily average efficiency of 10.8% and the total system a 75% efficiency that can be improved by about 5% if the panels are installed at a lower distance 10m of the battery pack.

The control systems are closely related to the performance of the batteries. These systems should consume the lowest power possible, as their use "drains" battery power continuously to supply the installed sensors. This fact will unbalance the batteries faster compared with a system without...
a battery management system. The Deep of Discharge (DOD) must not exceed 80% \((V_{min} > 3.0 \, \text{V})\), since if the system is discharged for an extended period, BMS stand-by consumption, although very small, can cause the cells to be exceed the minimum voltage.

In the future, it is expected to observe a growing investment in these systems by developing countries such as Angola. This work was an approach to autonomous PV isolated systems with the objective of clarify and deepen some aspects in the management and control of LiFePO\(_4\) battery storage. It is expected to open new opportunities for further investigations which may improve with more detail methods of operation of these systems.

VI. BIBLIOGRAPHY


