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Evaluation of the Performance of Lithium-Ion Accumulators for Photovoltaic Energy Storage

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Abstract

In a context of climate change exacerbated by the increasing scarcity of fossil fuels, renewable energies, in particular photovoltaic solar energy, offer a promising alternative. Solar energy is non-polluting, globally available and the most widely distributed resource on Earth. However, the intermittency of this energy source considerably limits its expansion. To solve this problem, storage techniques are being used, in particular, electrochemical storage using lithium-ion batteries. In this article, we will evaluate the performance of lithium-ion batteries when integrated into a photovoltaic grid. To do this, modelling and simulation of a photovoltaic system connected to a lithium-ion battery storage system will be carried out using MATLAB/Simulink software. A diagnostic of the energy consumption of the Kaya Polytechnic University Centre will be carried out, and the data will then be used in the simulator to observe the behaviour of the PV-Lion system. The results obtained indicate that lithium-ion batteries can effectively meet the centre's energy demand. In addition, it was observed that lithium-ion batteries perform better under high energy demand than the other battery technologies studied. Successive storage systems with the same capacity but different battery technologies were compared. It was found that these storage systems can handle a maximum power of 4×10^5 W for lead-acid batteries, 6.5×10^5 W for nickel-cadmium batteries, 8.5×10^5 W for nickel-metal-hydride batteries, and more than 10×10^5 W for lithium-ion technology.

Keywords

Photovoltaic Energy, Energy Storage, Lithium-Ion Accumulator, Modeling, MATLAB/Simulink Simulation

1. Introduction

In a report by the International Energy Agency (IEA), the world final energy consumption in 2021 is estimated at 418 EJ (ExaJoule) compared with 194 EJ in 1973, an increase of 115% in 46 years [1]. In the global energy environment, therefore, we are witnessing a growing trend in energy demand, as well as increasing scarcity and persistent instability in the main areas of production of fossil energy sources. In addition, there are the effects of fossil fuels on climate changed and the continued degradation of the environment [2]. As a result, global energy policies are focusing on renewable energies such as solar photovoltaics (PV). However, the intermittent nature of this energy source is a barrier to its widespread use [3]. Indeed, the production of PV electrical energy depends essentially on meteorological data, which in no way follows consumption needs.

Energy storage is the best possible way of making renewable energies such as solar PV permanent. The techniques used for energy storage are numerous and their performance depends on the field of application [4]. Of these storage techniques, electrochemical accumulators are the most widespread, and lithium-ion technologies are now a mature and credible alternative [5]. Li-ion batteries have excellent energy density, no memory effect and a long service life. This technological prowess will provide new directions and form the basis for development and innovation in the mobile electronics sector, the housing sector and, above all, the automotive sector, where the major firms are throwing themselves into the clean vehicle battle [6].

The aim of this work will be to contribute to making photovoltaic solar energy available at all times through storage in batteries. More specifically, we will examine the behaviour of lithium-ion batteries when integrated into a PV grid, and assess their ability to withstand high power levels.

To do this, we will first use Matlab Simulink to model the photovoltaic module, the Buck-Boost converter, the lithium-ion batteries and other elements of the PV-L system. Finally, we will analyse the performance indices of the system.

Finally, we will analyse system performance indices (PV-Li) such as battery voltage and power response during charging conditions using a simulation with real data, as well as a comparative study of several battery technologies to find the maximum power for each battery technology.

2. Description and Presentation of the Study Site

To account for the performance of lithium-ion batteries in photovoltaic applications, we defined a simplified energy requirement profile based on the consumption patterns of the Kaya Polytechnic University Center (**Figure 1**), located in sector 6 of the commune of KAYA, in the CENTRAL NORTH of BURKINA-FASO. The CENTER is connected to the national electrification network (SONABEL) to meet its electricity demand, but has no other energy source for backup power. This exposes it to frequent disconnections/disconnections from SONABEL's power supply, especially during periods of high demand such as the hot months

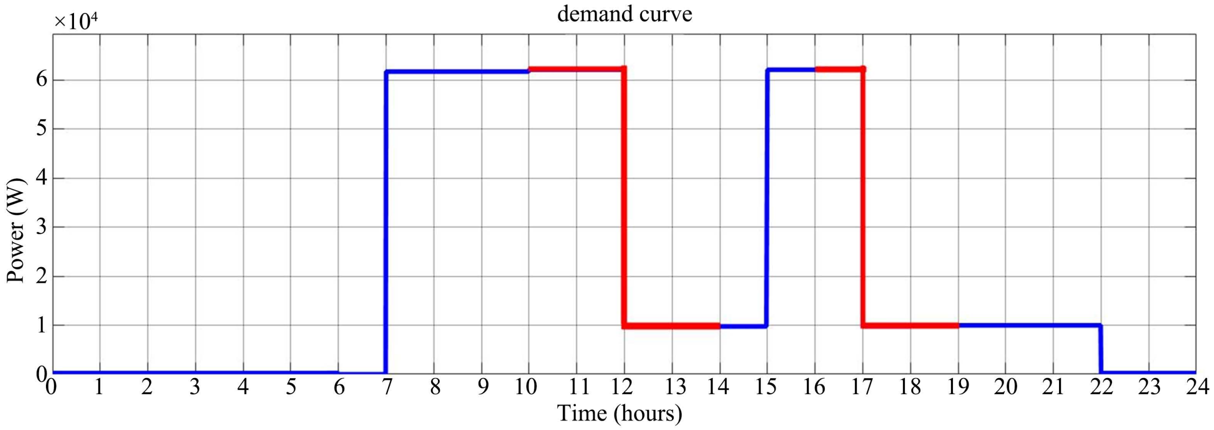

Figure 1. Load curve.

(March, April, May). This all too often leads to malfunctions at all levels, both in the administration and in the classrooms at the CENTRE.

The results of an energy audit carried out on site enabled us to draw up a quantitative and qualitative assessment of the electrical equipment used in the center and their consumption. Analysis of these results enabled us to obtain the CENTRE's hourly load table (**Table 1**), and thus to draw up the load curve (**Figure 1**).

In red, corresponds to the CENTER's power demand during SONABEL's peak periods. SONABEL's peak hours are from 10 am to 2 pm and from 4 pm to 7 pm. During these hours, SONABEL's demand for power is enormous, causing coverage problems.

We therefore propose to hybridise the main power supply (SONABEL) with a PV field, taking into account the need, but also the constraint linked to the surface area available for the installation of a large field at the CENTRE.

3. System Sizing

The PV system is sized for a daily requirement covering not only the peak period, but also taking into account SONABEL load shedding/outages. The sizing of the batteries therefore requires particular attention in order to optimise their service life and, at the same time, reduce the overall cost of the system [7]-[18].

3.1. Sizing the PV System with Storage

- Peak power

$$P_C = \frac{B_j}{E_j \times \eta_{bat} \times \eta_{ins}} \tag{1}$$

where B_j is the daily requirement, E_j is the solar radiation of the worst month, η_{bat} is the battery efficiency and η_{ins} is the plant efficiency.

- Number of modules in series

$$Nm_S = \frac{V_{ins}}{V_m} \tag{2}$$

Table 1. Power requirements at each hour of the day.

CENTRE hourly requirement						
Time of day	00 h - 01 h	01 h - 02 h	02 h - 03 h	03 h - 04 h	04 h - 05 h	05 h - 06 h
Power (W)	225	225	225	225	225	225
Time of day	06 h - 07 h	07 h - 08 h	08 h - 09 h	09 h - 10 h	10 am-11 am	11 am-12 pm
Power (W)	0	61776	61776	110086	107456	62146
Time of day	12 pm-1 pm	1 pm-2 pm	2 pm-3 pm	3 pm-4 pm	4 pm-5 pm	5 pm-6 pm
Power (W)	9762	9762	9762	62146	62146	9762
Time of day	6 pm-7 pm	7 pm-8 pm	8 pm-9 pm	9 pm-10 pm	10 pm-11 pm	11 pm-00 am
Power (W)	9987	9987	9987	9987	225	225

where V_{ins} is the system voltage and V_m is the module voltage.

- Number of parallel modules

$$Nm_P = \frac{P_C}{Nm_S \times P_m} \tag{3}$$

where P_m is the power of a PV module and Nm_s the number of modules in series.

- Number of modules total

$$Nm = Nm_S \times Nm_P \tag{4}$$

- Total system capacity

$$C_{ins} = \frac{B_j \times Aut}{\eta_{bat} \times V_{ins} \times DOD} \tag{5}$$

Aut is the system autonomy and DOD the battery depth of discharge.

- Number of batteries in series

$$Nb_S = \frac{V_{ins}}{V_{bat}} \tag{6}$$

- Number of parallel batteries

$$Nb_P = \frac{C_{ins}}{C_{bat}} \tag{7}$$

- Total number of batteries

$$N_{bat} = Nb_S \times Nb_P \tag{8}$$

Analysis of the CENTRE's energy balance shows that the energy requirement during peak hours is $B_j = 230\ kWh$. Table 2 shows the sizing results.

We've set the DC bus operating voltage to 150 V. This means that the converters used must all have 150 V outputs.

3.2. Sizing Boost Converters

To connect the PV field to the DC bus, we use:

- Four (4) 20 kVA, 96 V - 150 V boost converters. Each converter is connected to 76 panels (4 series 19 parallel), then connected to the DC bus.

Table 2. Results of design calculations.

Sizing a PV system with storage		
Sizing the solar field		
Daily requirement (kWh)	B_j	230
Unfavourable solar radiation (kWh/m²/d)	E_j	5.19
Battery efficiency	η_{bat}	80%
Installation efficiency	η_{ins}	90%
Peak power of the PV array (kWp)	P_c	62
Power of a module (W)	P_m	200
Module voltage (V)	V_m	24
Number of modules in series	Nm_s	4
Number of modules in parallel	Nm_p	77
Total number of modules	Nm_t	308
Sizing the storage system		
Installation voltage (V)	$Wines$	96
Installation autonomy	Aut	1
Depth of discharge	DOD	85%
Installation capacity (Ah)	C_{ins}	3523.28
Battery capacity (Ah)	C_{bat}	200
Battery voltage (V)	V_{bat}	12
Number of batteries in series	Nb_s	8
Number of batteries in parallel	Nb_p	18
Total number of batteries	Nb_t	144

- One (1) 1 kVA, 96 V - 150 V boost converter. This converter is connected to 4 panels in series, then linked to the DC bus.

3.3. Sizing Buck-Boost Converters

Six (6) 11 kVA, 96 V - 150 V buck-boost converters are used to connect the battery pack to the DC bus. Each converter is linked to 24 batteries (8 series, 3 parallel), then connected to the DC bus.

3.4. System Presentation in Matlab/Simulink

Figure 2 is the synoptic diagram of our system.

The system consists of:

- A PV array consisting of Appolo Solar Energy ASEC-200G6M modules. The characteristics of these modules are given in Table 2.
- A lithium-ion battery pack for storage.

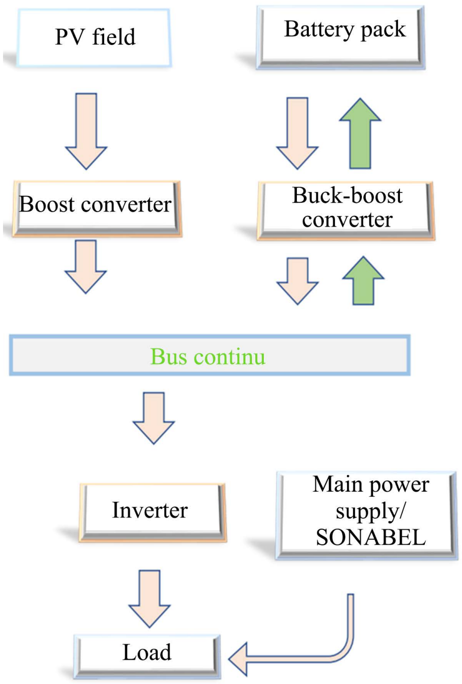

Figure 2. System block diagram.

- A booster or boost converter ensures the transition of energy from the PV field to the DC bus with a rise in voltage. This converter is fitted with MPPT control to track maximum power.
- A bidirectional buck-boost converter links the bus to the battery pack. This converter is controlled by a logic circuit (not) and operates in two stages. When the load is connected to the SONABEL network and the field is active, all the energy coming from the field is stored in the batteries with a drop in voltage (buck operation). When the SONABEL supply is interrupted accidentally or programmed, the battery pack supplies the load with a rise in voltage (boost operation). In fact, we have programmed the system so that during peak hours the Centre operates solely on the basis of the photovoltaic installation.
- Protection boxes and surge protectors are used to protect the system.
- An external control activates the boost or buck function of the batteries. This control takes into account SONABEL's supply and peak times.

4. Simulation Result

4.1. System Response under Load

Figure 3 shows the power transfers between system components over the course of the day.

Figure 4 shows the variations in battery, PV array and load voltages over the course of the day. In this figure, the battery terminal voltage is virtually constant. This means that the batteries are not subject to overcharging or undercharging during the day.

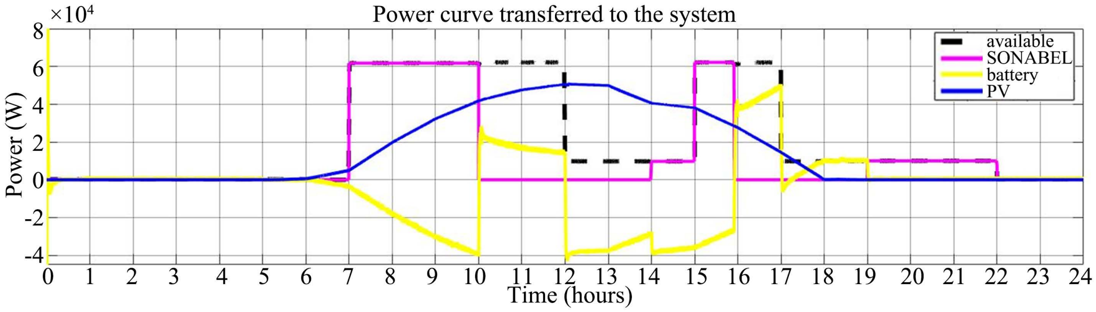

Figure 3. Variation of available power, PV field, battery and SONABEL over the course of the day.

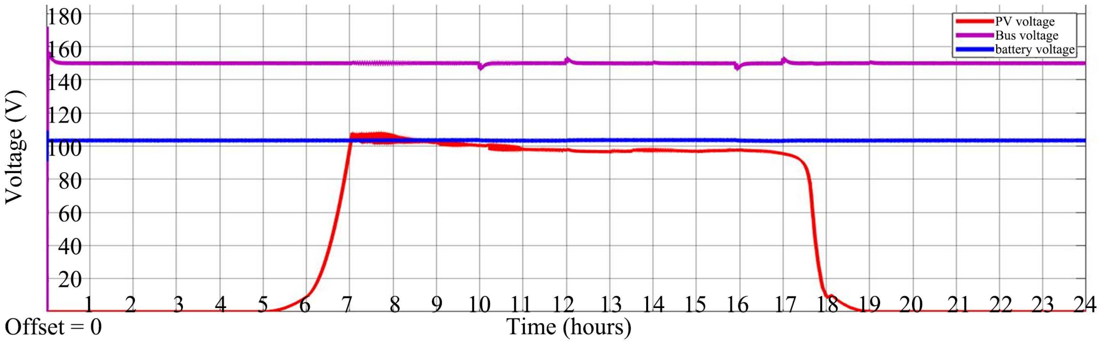

Figure 4. Variation of battery, PV array and load terminal voltages.

4.2. Comparative Study of the Response of Several Battery Technologies

In this section, a comparative study of battery power response for different technologies is presented.

The power demand is gradually increased, and the behavior of the batteries is observed. The technologies studied are: lead-acid (a), Nickel-Cadmium (b), Nickel-Metal-hydride (c), and Lithium-ion (d).

Figure 5 shows the maximum power that can be delivered by the different battery technologies studied.

5. Discussion

The purpose of the power exchanges is to keep the CENTER's loads operational throughout the day. This indicates that the coupling of the main power supply and the backup power supply (PV system with storage) is able to support demand during the daytime hours.

Figure 3 shows:

- From 0:00 to 7:00 and from 22:00 to 23:59, the available power is practically zero. This is because demand in the CENTER is almost negligible (225 W) compared to demand at other times of the day. This power is supplied exclusively by the main power supply. As there is virtually no irradiance, the PV field does not produce, and the batteries are also ordered not to supply power under these conditions (only in the event of load shedding and at peak times).

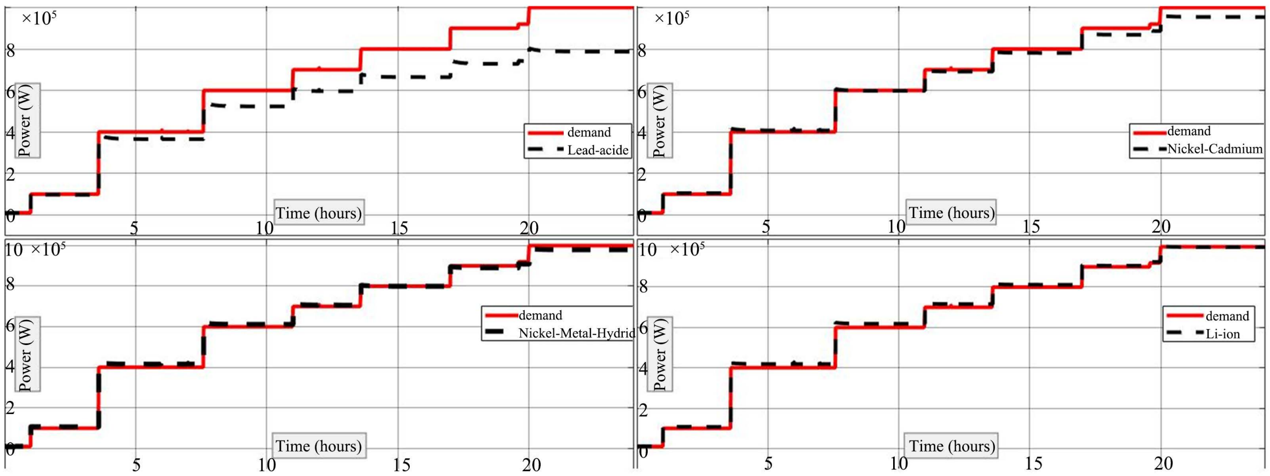

Figure 5. Maximum power curves for different battery technologies.

- From 7:00 am to 10:00 am, the available power and the main supply curve are the same. This means that SONABEL always supplies the power needed for the load. As solar radiation increases, so does the power produced by the PV array. At the same time, the power of the battery bank increases in the negative direction, indicating the load. In this way, the energy produced by the PV field is stored in the batteries.
- From 10:00 a.m. to 2:00 p.m. (peak hours), the PV-battery system supplies the power required for charging, as the main power supply is cut off. We can also see that as irradiance increases, so does the power of the PV array, and conversely the power of the batteries decreases, becoming negative when the power supplied by the PV array exceeds demand (from 12:00 onwards). The intervention of the batteries indicates that the PV field is unable to meet demand, but when the PV field power is high enough, the batteries begin to recharge.
- From 2:00 pm to 4:00 pm we're in peak hours, so the main source resumes supplying energy for load operation. Energy from the PV field is used to charge the batteries.
- From 4:00 pm to 7:00 pm (peak hour), the main power source is cut off, and the PV field and batteries ensure load operation until 6:00 pm. From 18:00 to 19:00, the batteries alone supply the load. For this reason, in this section, battery power is superimposed on available power.
- After 7:00 p.m., the main power supply takes over, providing power for load operation.
- Figure 5 shows that the:
- Acid batteries can handle any demand whose power is less than around 4 × 10^5 W.
- For nickel-cadmium batteries, the maximum power attainable is just under 7 × 10^5 W.
- For nickel-metal-hydride, this power is around 8 × 10^5 W.

- And Lithium-ion batteries reach a maximum power of over 10 × 10^6 W.

We can conclude that lithium-ion batteries offer the best maximum power attainable.

6. Conclusions

At the end of this work, we can say that PV-Li systems are effective for use as a secondary source in addition to SONABEL in large companies or industries that do not have a large plot of land for the installation of a complete PV camp. Indeed, by simulation, such an installation will give the Centre partial autonomy from SONABEL. The installation should cover the Centre's needs during power cuts, and better still, during peak hours when kWh billing is high according to our considerations.

Tests carried out to assess the ability of different battery technologies to withstand high power demands have revealed that lithium-ion models perform best.

However, since the simulation was carried out over a short period of time, it is not possible to assess long-term performance under variable climatic conditions. For this reason, we plan to simulate the system over a very long period (around ten years), taking into account our climatic realities (temperature, radiation) and our loads.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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