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Modelling of an Energy Storage Battery and the Study of its Behavior in Solar application

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Abstract. This paper presents the modelling and simulation of a lithium-ion battery integrated into a photovoltaic (PV) system for energy storage applications. The study begins with an overview of the main types of electrochemical batteries commonly used in renewable energy systems, followed by a comparative analysis based on key parameters such as energy density, efficiency, cost, and lifetime. The lithium-ion battery is selected due to its high energy density, long cycle life, and low self-discharge rate. A mathematical model based on Shepherd's equation is developed and implemented in MATLAB/Simulink to predict the dynamic behavior of the battery during charging and discharging processes. Simulation results demonstrate the model's ability to accurately describe the battery's voltage and state of charge (SOC) under varying solar irradiance conditions. The proposed system effectively maintains a stable DC bus voltage while ensuring reliable energy storage and delivery.

Introduction

1 The global need for energy has continued to climb, owing mostly to global expansion and technological advancements. This enormous energy consumption of fossil fuels has resulted in a climate catastrophe characterized by global warming caused by excessive CO_2 emissions. Therefore, in order to address this climate crisis, it is imperative to shift to renewable energy sources and expand their penetration in our energy mix [1, 2]. As a result, the use of renewable energies is no longer a choice; it has become a necessity.
Among the renewable energy sources, solar energy is becoming more popular across the world since it is a clean, abundant, and renewable energy source. Furthermore, the cost of solar technologies has dropped significantly.
Self-consumption using autonomous photovoltaic solar systems has become a viable approach for accelerating the energy transition, achieving energy independence, reducing CO_2 emissions, and reducing electricity bill.
However, due to the intermittent nature of photovoltaic systems [3], the usage of an energy storage system is required to supply energy demands during the night or in poor weather conditions when solar panel production is small.
There are several types of energy storage systems (ESS), including electrochemical batteries, supercapacitors, and fuel cells. In PV systems, electrochemical batteries, such as lead-acid

and lithium-ion batteries, are the most used in PV systems. Each type has own advantages and disadvantages, but lithium-ion batteries are extensively used due to their advantages of the high energy density, long life cycle, and low self-discharge rate efficiency [4].
This paper is focused on the modelling of a lithium-ion battery, charged by a PV system. Furthermore, this work also includes an analysis of the battery's behavior simulated during charging and discharging as well as an illustration of its state of charge (SOC). This study provides a detailed understanding of the battery's operation. However, before delving into the battery's behavior, this work provides an overview of the battery's characteristics to help in battery selection based on specific requirements.
This paper is organized into five sections. State of the art of batteries is represented in section 2, the developed model of a Lithium-ion battery is represented in section 3. The simulation results are discussed in section 4. And finally, a recapitulation of the results obtained is introduced as a conclusion in section 5.

2 State of art of batteries

2.1 History of batteries

Energy storage has been of great interest for a long time and continues to be. The first electrochemical battery is invented with Alessandro Volta in 1800 [5], and from this time, batteries continue to be the subject of ongoing research and developments aimed to improve their capacity, life cycle, efficiency, safety and other aspects. Fig. 1 represents the evolution of the electrochemical battery technology over time.

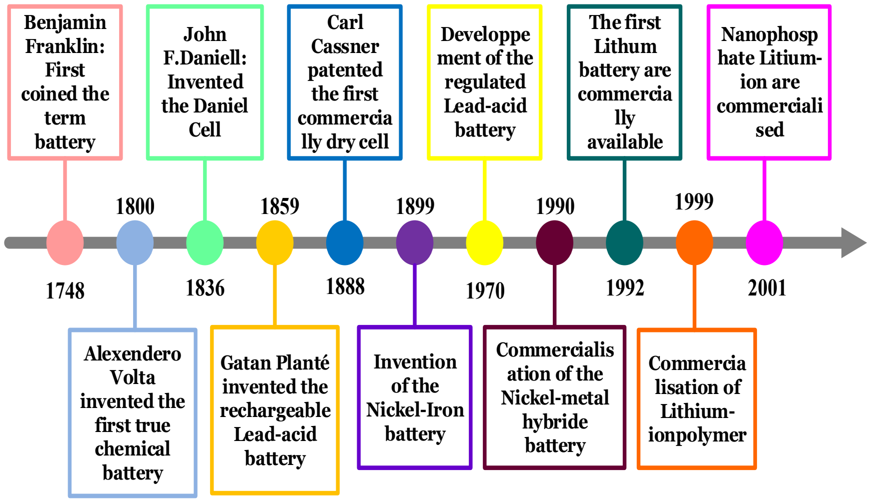

Fig. 1. History of electrochemical battery technology.

This interest given to the batteries is due to many points. In fact, the battery has the advantage of responding to high electricity demand, especially in peak hours or a lack of supply and maintaining the balance between supply and demand. In addition, it can be possible to reduce the cost of setting up power plants (the microgrids).

2.2 Characteristics of an electrochemical battery

Batteries are crucial components in a renewable energy system. The research and developments conducted around the batteries led to the appearance of many types of batteries with various characteristics which make the choice of one very difficult.
According to [6-8], the most used commercial batteries in renewable energy systems include lead-acid, Lithium-ion, Nickel-Cadmium and Sodium sulfur batteries and this for many reasons: First, Lithium-ion (Li-ion) offers a high energy density in comparison with the other rechargeable batteries. Second, the lead-acid batteries are distinguished by their low cost and reliability. Then, Nickel-Cadmium batteries are known as robust batteries with a long-life cycle.

2.3 Comparison of the technical characteristics of the batteries

To make the choice of a battery more straightforward, and to choose the most suitable for an application, it's crucial to study the most important characteristics of the batteries mentioned before and analyze them. In this study we will focus on these characteristics:
Energy density: it's the amount of energy stored in each volume. It quantifies the battery's capacity to hold energy.
Life cycle: It refers to the number of charge-discharge cycles. It indicates how many times a battery can be charged and discharged while maintaining a useful level of performance.
Cost Analysis: This analysis helps determine the overall cost-effectiveness of battery technology and its affordability for a given application.
Efficiency: It represents the ratio between the energy released from the battery and the total of energy stored on it.
Operating temperature: It represents the range of temperatures in which the battery can work effectively and maintain its high performance.
Table 1 illustrates a comparison of the considered batteries characteristics [9].

Table 1. Comparison study of batteries technical characteristics.

	Energy Density (Wh/kg)	Life Cycle (Cycles)	Cost Analysis ($/kWh)	Efficiency (%)	Operating Temperature
Lithium-ion	75 – 250	1000 – 3500	600 – 2500	75 – 95	-30 to 60
Lead-acid	30 – 50	500 – 1000	200 – 400	70 – 90	-5 to 40
Nickel-Cadmium	50 – 75	2000 – 2500	800 – 1500	60 – 65	-40 to 50
Sodium sulfur	100 – 240	2000 – 2500	200 – 600	71 – 90	325

To integrate a battery in a renewable energy system, many other characteristics must be considered. Hence, in our study, it's important to take into consideration the effects and consequences of a battery's production, use and disposal on the environment. It's also crucial to consider the robustness and durability.

Table 2 provides a clear and concise comparison of the advantages and drawbacks of the different batteries.

Table 2. Batteries comparison: advantages and drawbacks.

	Advantages	Drawbacks
Lithium-ion	High energy density Long life cycle	Relatively expansive Safety concerns
Lead-acid	Cost-effective Recyclable	Heavy Shorter life cycle
Nickel-Cadmium	Robust and durable Long life cycle	Contains toxic materials
Sodium sulfur	High energy density Durability	Requires high operating temperatures

According to this comparison, it can be noted that the Lithium-ion battery has several benefits including lower volume, weight, temperature sensitivity, maintenance and longer lifetime and high energy density. For these reasons, the Lithium-ion battery has gained popularity in larger scale applications such as renewable energy systems and electric vehicles in addition to the electronic devices

3 Model of the lithium-ion battery

In the literature, there are many studies that explore different types of battery models which consider the behaviors and characteristics of batteries and vary in terms of accuracy and complexity.
According to this research, these models can be classified into three major groups: electrochemical model, mathematical models and equivalent circuit models [6-8].
Mathematical and electrochemical models are very important as their implementation is easy and understandable. They can also provide quick results with rapid response. On the other hand, they still approximate methods which lead to less accurate predictions.
For the electrical models, they are known by their simplicity and their efficiency. Also, they can be applied to a variety of batteries without significant modifications. However, this type of modelling may not be suitable for some applications which require more details.
In our case and in order to predict the performance of the battery, we consider a mathematical model based on Shepherd's model [9] as shown in Fig. 2, in which a battery cell model is composed of an open circuit voltage and an internal resistance R .

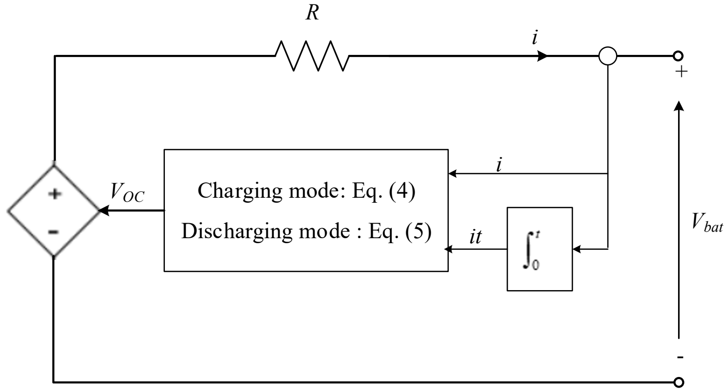

Fig. 2. Shepherd model of the battery.

The Open Circuit Voltage is given by the equation (1):

$$V_{OC} = V_0 - K\frac{Q}{Q-it}.i \qquad (1)$$

Where:

V_0 : The constant battery voltage (V)

K : The polarization resistance coefficient (Ω)

Q : The maximum capacity (Ah)

i : The battery current at the time *t* (A)

it : The discharging capacity

The voltage battery is given by equation (2)

$$V_{bat} = V_0 - K\frac{Q}{Q-it}.i - R.i \qquad (2)$$

According to equation (2), the shepherd's model doesn't consider the charging and the discharging modes. That's why much research take the Shepherd model and introduce modifications by adding equations of the charging and the discharging modes [10]. The battery output voltage equations in discharging and charging modes are given by (3) and (4):

- Charging mode:

$$V_{bat,charge} = V_0 - K\frac{Q}{Q-0,1.it}.i - K\frac{Q}{Q-it}.it - R.i + A.e^{-B.it} \qquad (3)$$

- Discharging mode:

$$V_{bat,discharge} = V_0 - K\frac{Q}{Q-.it}.i - K\frac{Q}{Q-it}.it - R.i + A.e^{-B.it} \qquad (4)$$

Where:

A is the exponential Voltage (V) and B is the exponential Capacity $\left(A.h^{-1}\right)$.

Moreover, in the case of energy storage systems, especially the batteries, it's crucial to analyze and manage the energy consumption of the system through battery information like SOC (State of Charge), to avoid overcharging and over-discharging of the battery. SOC can be calculated using equation (5):

$$SOC = SOC_0 - \frac{it}{Q} \qquad (5)$$

Where:

SOC_0 : The initial SOC of the battery

4. Simulation results and discussion

To study the behavior of the battery, we consider the PV-Battery system shown in Fig. 3 to illustrate the charging and discharging modes and to analyze the efficiency of the developed battery model with the variation of the Solar PV irradiance.

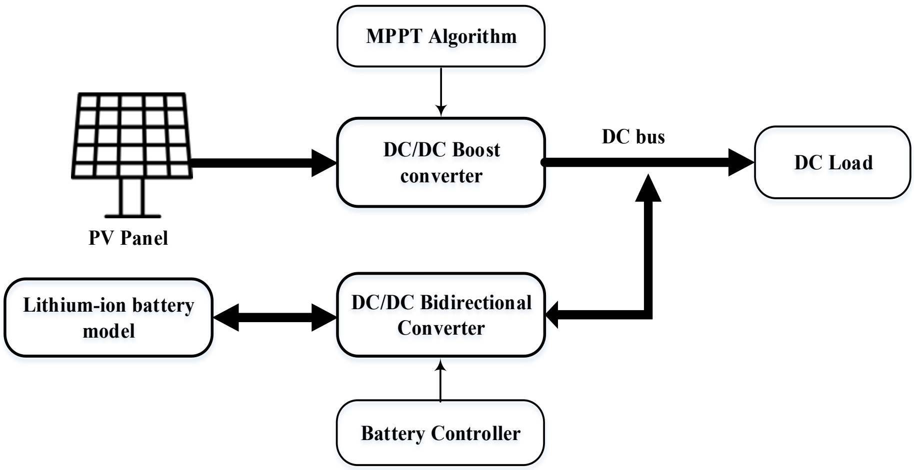

Fig. 3. Topology of the proposed PV-Battery System.

As seen in Fig. 3, the proposed PV-Battery system consists of a PV Panel, with a maximum power of 150 W, connected to a DC/DC boost converter and the developed model of the battery connected to a DC/DC bidirectional converter. The bidirectional converter control strategy involves maintaining DC bus voltage at a constant value equal to 60V and control the charge and discharge of the battery. Table 3 represents the different parameters of the battery.
To simulate the efficiency of the battery in terms of charging and discharging modes, a variable PV Panel irradiance according to the profile illustrated in Fig. 4 is considered.

Table 3. The used battery parameters.

Parameter	Symbol	Value
The constant battery voltage (V)	V_0	26.0246
The polarization resistance coefficient (Ω)	K	0.0059935
The internal resistance (Ω)	R	0.008
The maximum capacity (Ah)	Q	31
Exponential Voltage (V)	A	2.0154
Exponential Capacity (Ah^{-1})	B	2.0354

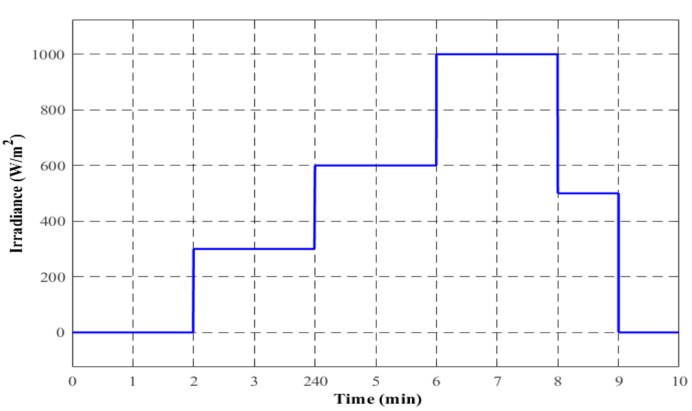

Fig. 4. Irradiance profile as function of time.

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According to the irradiance profile, the SOC of the battery is illustrated in Fig. 5 with an initial battery SOC value of 50%.
The variation of the irradiance impacts the charging and discharging modes. When the irradiance is low, it leads to battery discharge to supply the load. When the irradiance is at its maximum value, the battery switches to the charging mode and the SOC increase.
Fig. 6 represents the DC bus voltage. It can be noted that the DC bus follows the imposed voltage which is equal to 60V.

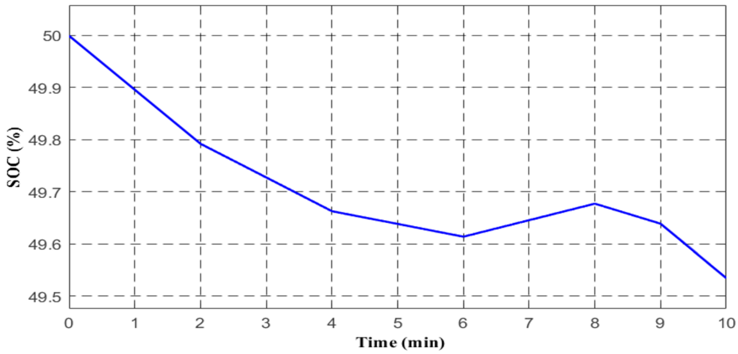

Fig. 5. Battery SOC variation.

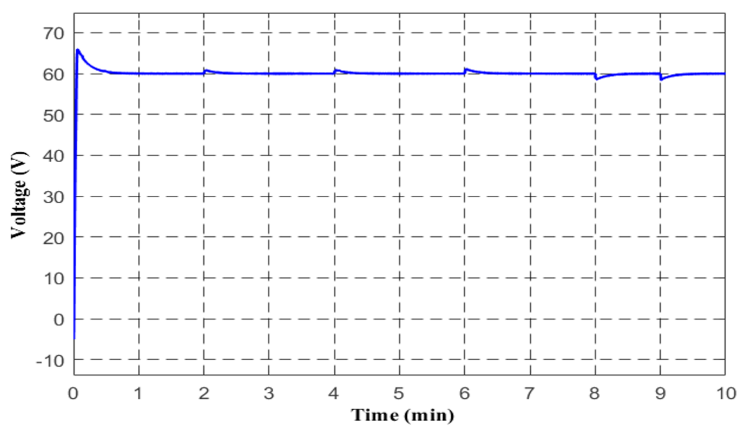

Fig. 6. DC bus voltage.

5. Conclusion

In this paper, the Shepherd Lithium-ion model is proposed and implemented on Matlab/Simulink. The main objective is to analyze the performance and behavior of this model in solar applications. A PV-Battery system that operates under varying irradiance conditions is considered. The simulation results show that the chosen battery model operates efficiently. It can be charged using solar energy when there is an abundance of solar energy and can supply power to the load when solar energy is scarce. Furthermore, the proposed system can maintain a stable DC bus voltage. Consequently, the simple described model serves as a valuable tool for studying hybrid PV-Battery systems.

References

1. T-Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari, N. Prabaharan, A comprehensive study of renewable energy sources: Classifications, challenges and suggestions, Energies Strategy Review, vol. 43, September 2022.
2. C. H. Chou, S. L. Ngo, P. P. Tran, Renewable Energy Integration for Sustainable Economic Growth: Insights and Challenges via Bibliometric Analysis, Sustainability, 2023.
3. M. Abdul Basit, S. Dilshad, R. Badar, Limitations, challenges, and solution approaches in grid-connected renewable energy systems, International Journal of Energy Research, 2020.
4. Z. Liu, Z. Li, J. Zhang, L. Su, & H. Ge, Accurate and efficient estimation of lithium-ion battery state of charge with alternate adaptive extended Kalman filter and ampere-hour counting methods. Energies, vol. 12, n°4, 757, 2019
5. C. H. Holger, S. Michael, K. Daniel, and J. Andreas, Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids, Energies, 2017.
6. A. Dekka, R. Ghaffari, B. Venkatesh, B. Wu, A Survey on Energy Storage Technologies in Power Systems*,* IEEE Electrical Power and Energy Conference (EPEC), 2015.
7. A. Dekka, R. Ghaffari, B. Venkatesh, B. Wu, Comparison of Lithium-Ion Battery Models for Simulating Storage Systems, in Distributed Power Generation, Inventions, 2019.
8. A. K. Abraham, C. Thierry, M. Maarten, J. Tawfik, A. B. Henok, V. M. Joeri and B. Maitane, Techno-economic analysis of lithium-ion and lead-acid batteries in stationary energy storage application, Proc. Int. Conf. on Nuclear Physics (Munich) Journal of Energy Storage, 2021.
9. C. M. Shepherd, Design of Primary and Secondary Cells—Part 2. An equation describing battery discharge, Journal of The Electrochemical Society 1965, vol 112, pages 657 – 664.
10. O. Tremblay, L. A. Dessaint, Experimental Validation of a Battery Dynamic Model for EV Applications. World Electrical Vehicle Journal, 2009, vol 3, pages 289 – 298.