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Suitability Analysis of Different Batteries with Off-Grid Photovoltaic System

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Abstract

The main objective of power generation and distribution companies is to ensure uninterrupted supply at reasonably low cost, minimum losses and high quality. Considering rural areas, where off-grid power systems using renewable resources are becoming more popular are generally equipped with storage elements like batteries. Hence energy storage and battery management system are a vital area of research nowadays. The study presents modelling of an off-grid solar PV model and testing it with different batteries (Lithium Ion (Li Ion), Nickel Cadmium (Ni Cd), Lead acid (Pb acid)) developed in Simulink on MATLAB 2017. Various aspects such as life cycle, energy density, SOC (State of Charge) and DOD (Depth of Discharge) are considered to study the technical performance of each battery. Comparisons among the three batteries have also been made considering environmental impact and safety measures. Pb acid and Ni Cd batteries pose as an environmental threat due to their toxic nature. This leads to an increase in usage of Li-ion batteries which are reasonably harmless and recyclable. The ultimate goal of the study is to choose the most economic and efficient battery with off-grid photovoltaic system as "the greenest power is the power you don't have to produce". From the comparisons performed in this paper, it is seen that Li ion batteries have superior overall performance when compared to Ni Cd and Pb acid batteries.

Keywords: *Performance comparison, battery life prediction, State of Charge (SOC), Depth of Discharge (DOD), result via discrete solver selection*

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INTRODUCTION

Globalization, industrialization and growth in population have led to immense increase in energy demands, in today's era. To meet this ever-increasing demand of energy, various steps have been taken and several methods have been adopted for cleaner, cheaper and safer energy alternatives, such as wind energy, solar energy, tidal energy and so on. Out of all these alternatives, the solar photovoltaic (PV) energy got the most attention due to its multiple advantages over other sources. The major advantage of availability of sunlight that can be converted to electricity made PV systems a topic of interest among the researchers all over the globe. Hence a drastic expansion in the field of PV systems is expected in near future.

The purpose of this study is to demonstrate as to how to manage the battery energy storage of an off-grid PV system. Many photovoltaic systems tend to fail prematurely due to the use of poor quality batteries of inappropriate type. Hence this study has been undertaken in which power specifications were examined for PV system batteries. Battery parameters like charging and discharging characteristics, current and voltage characteristics of batteries including Lithium Ion (Li Ion), Nickel Cadmium (Ni Cd) and Lead Acid (Pb acid) were studied.

There are multiple problems that might arise in stand-alone PV systems. Among them, battery failure is a major concern throughout the PV industry, even if there is a low fraction of starting costs, a battery can be the most expensive component in the overall life-cycle cost of stand-alone PV systems.

On increasing battery size, there is an increase in cycle life for a particular load. However, this is not essentially the case for small PV systems, as increasing the battery size may result in lower rates of charging/discharging and shallower daily DOD also increases the recovery time from low battery SOC.

The battery energy storage system has been explained in several research papers [1–8]. Divya *et al*. discussed the present status of the battery energy storage technology and methods of assessing their economic viability and impact on power system operation [1]. Poullikkas provided an overview of the various types of batteries used for large-scale electricity storage [2]. Yao *et al*. developed an electrical prototype of lithium ion battery in MATLAB/Simulink [9]. The model has been explained in detail and the battery model for lithium-ferro-phosphate battery has been presented. The fundamentals and working of the lead acid battery are provided in various other papers [10–13]. Schiffer *et al*. predicted the life time of a lead acid battery under harsh working conditions [11]. The paper presented a model that allowed comparison among effects of different operating conditions, different system sizing and different battery technologies on battery lifetime. Sauer *et al*. discussed different approaches for lifetime prediction for electrochemical energy storage devices with respect to their general concepts [12]. Finally, nickel-cadmium battery is discussed by Noréus and Henault *et al.* [14, 15]. Henault *et al*. presented a nickel-cadmium (NiCd) battery powered electric vehicles (BEVs) [15]. As batteries are considered the most important part of a PV System, any fault occurring within the system demonstrates itself as an noticeable problem, whether the battery is faulty or not. The concepts of photovoltaic system are made clear by several other researchers [16–20]; of which, Dunlop *et al.* and Cherif *et al.* presented a standalone model of photovoltaic system with its design and size considerations [16, 17]. Manimekalai *et al*. gave an idea about the selection, ratings and maintenance of batteries for PV applications [19].

BATTERY DETAILS

Pb acid battery invented by French physicist Gaston Planté in 1859 is the oldest type of rechargeable battery. This low cost and easily available battery is providing most attractive solutions for use in motor vehicles and off grid renewable systems. Pb acid batteries are physically and chemically less robust.

Ni Cd batteries, discovered by Waldemar Jungner of Swedenin 1899, are made in a wide range of sizes. They have good life cycle and performance at low temperatures. They have an ability to deliver full rated capacity at higher discharge rates.

Li ion batteries were discovered in 1970s at Binghamton University. They are one of the most popular types of rechargeable batteries for portable electronics with high energy density. Li ion batteries are becoming a common replacement for Pb acid batteries due to battery charge/discharge efficiency and better cycle durability.

The basic reactions involved with these batteries are shown in Table 1.

Table 1: *Chemical Reactions.*

Pb acid	$\rightarrow Pb(s)+PbO_2(s)+2H_2SO_4 2PbSO_4(s) +2H_2O$
Ni Cd	$2NiO(OH)+Cd+2H_2O \rightarrow 2Ni(OH)_2+Cd(OH)_2$
Li Ion	$\rightarrow LIC_6 + CoO_2C_6+LiCoO_2$

SYSTEM MODELLING

In the present study, MATLAB 2017 is used to model an off-grid PV system and then test it with various types of rechargeable batteries in the direct current (DC) battery block element. This provides an in-depth comparison between Pb acid, Ni Cd and Li ion batteries for the present system model. Figure 1 shows the block diagram of the system model consisting of a PV array connecting to a Maximum Point Tracker (MPPT) charge controller. The DC power output from the charge controller is fed to the inverter for supplying the AC load and also to the batteries to store excess electricity.

System Simulink Model

In Figure 2, the modeling of an off-grid PV system with battery backup in MATLAB Simulink environment is done in three stages. The first stage deals with the design of a PV system block using 64 solar cells. The second stage involves designing of a boost converter which provides a fixed output DC voltage. The third stage incorporates the DC battery element with charging and discharging circuits.

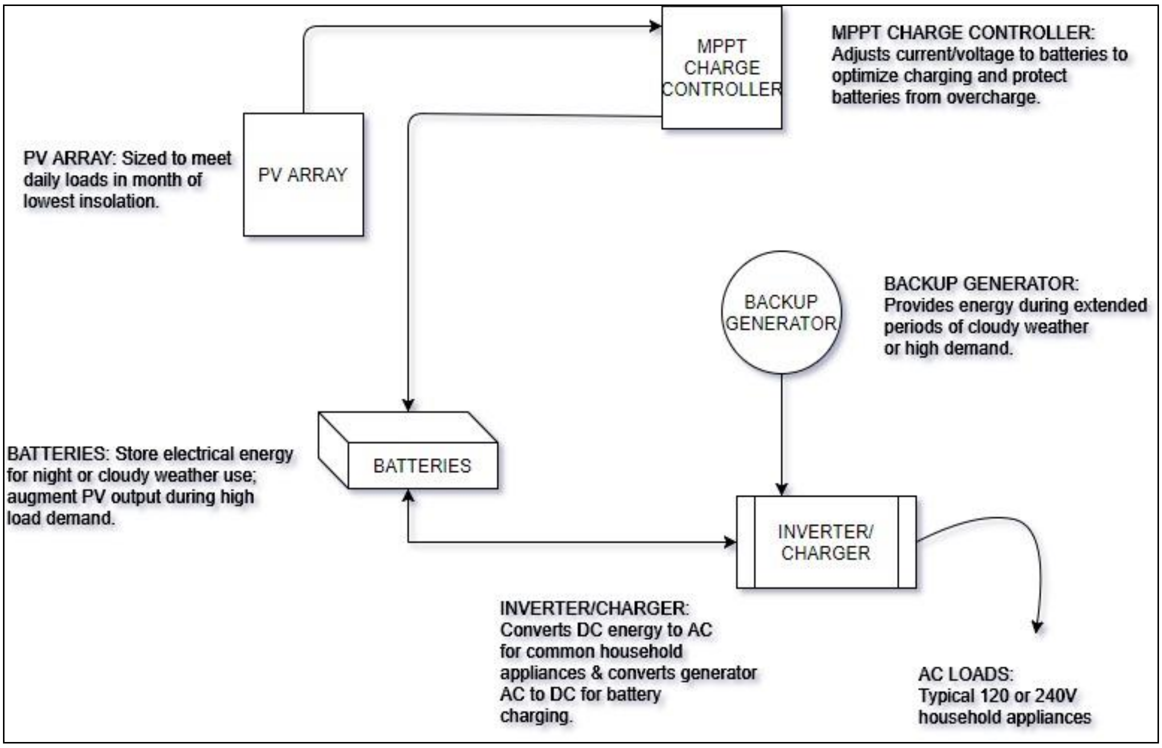


***Fig. 1:** Block Diagram of Main Circuit.*

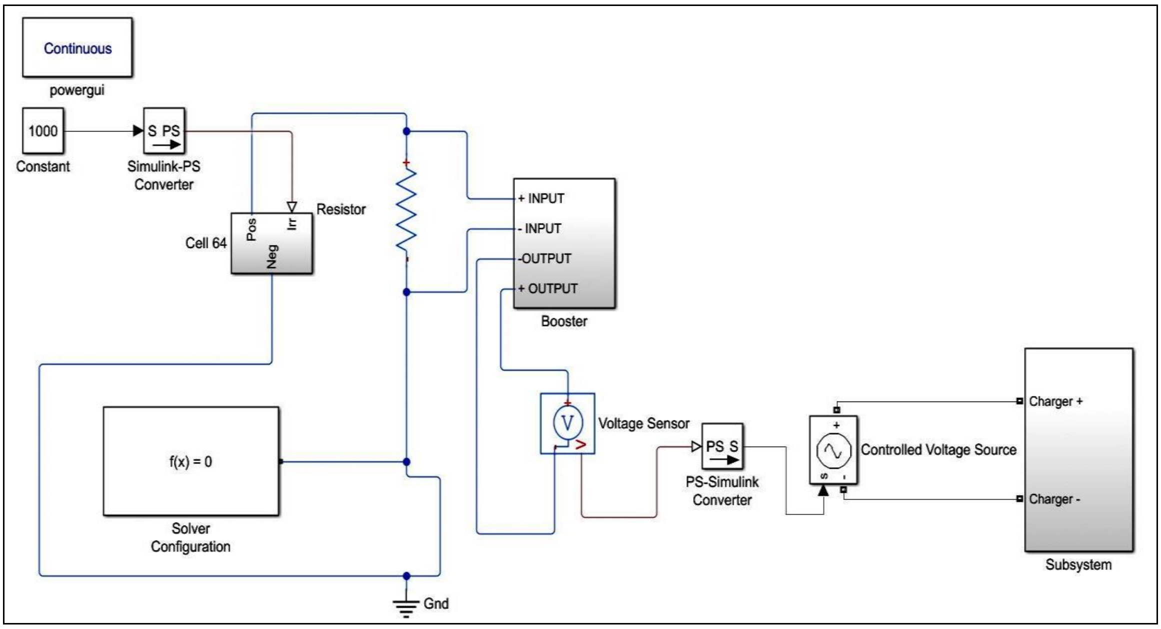


***Fig. 2:** Simulink Model.*

PV System Design

Figure 3 represents a series combination of solar cell elements connected such that a 64 PV cell system is constructed in Simulink. The PV cell is provided irradiance of 1000 W/m^2 at 25°C by a constant block. Further, the PV system generates a voltage difference of 38.4 V which is applied across the boost converter. 3.875 A of current flows from the PV cell to the boost converter, thus supplying 148.8 W of power to it. Table 2 shows the solar cell parameters used in the simulation.

***Table 2:** Solar Cell Details.*

Parameter	Detail
Short Circuit current (A)	7.34
Open Circuit Voltage (V)	0.6
Quality Factor	1.5

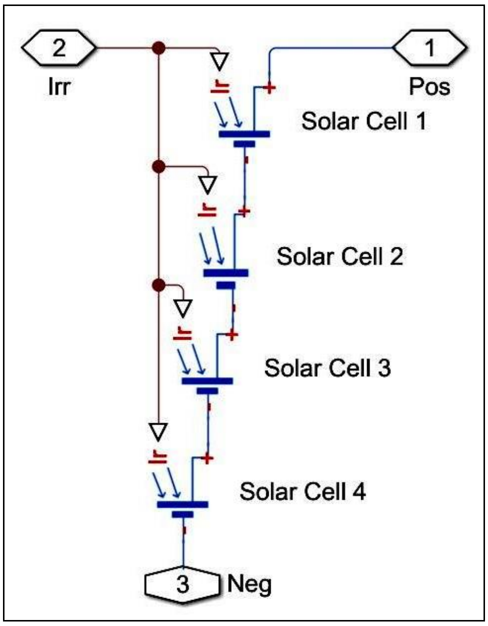


Fig. 3: *Solar Cell Panel.*

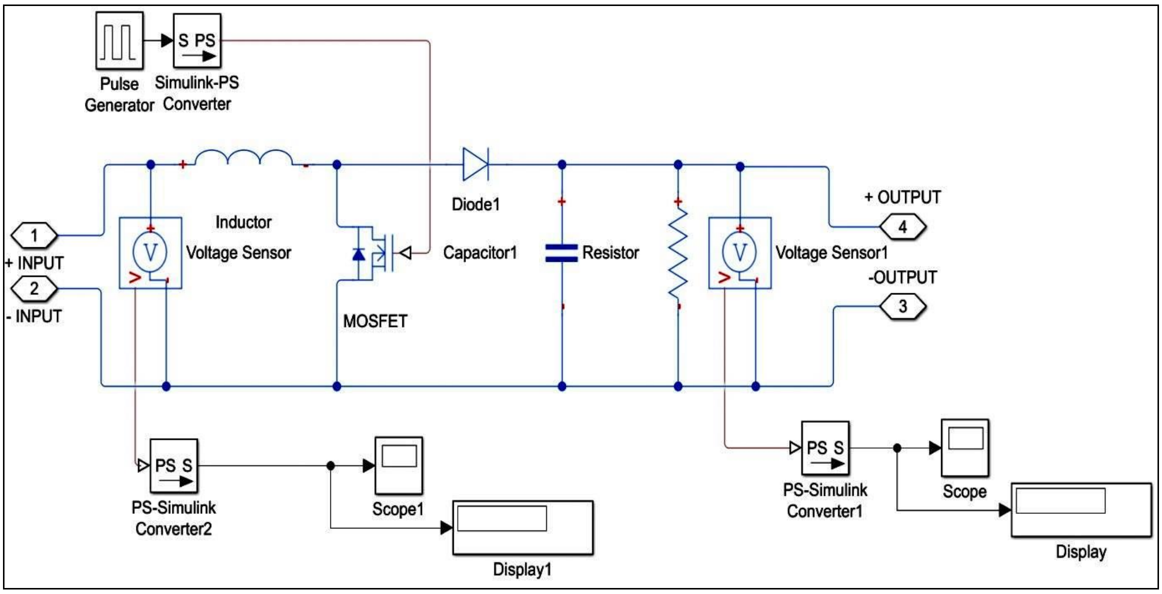


Fig. 4: *Booster Circuit Model.*

Converter Design

Figure 4 represents a booster circuit model developed on MATLAB simulink. The boost converter fulfills mainly two purposes: The first one is to increase the received voltage of 38.4 to 118 V and second is to stabilize the output voltage with the help of filtering techniques. A pulse generator of frequency 5000 Hz is attached to the controlled switch to vary the duty cycle of the boost converter which in turn provides controlled output voltage. The duty cycle of the boost converter is set to 68% to obtain the required output voltage from it. Table 3 shows the values of the circuit components connected in the boost converter.

Table 3: *Boost Converter Details.*

Parameter	Detail
Resistance (Ω)	100
Inductance (H)	1×10^{-3}
Capacitance (F)	33×10^{-6}

Battery Design

Battery circuit model developed on MATLAB simulink is shown in Figure 5. The output voltage of booster is applied across the DC battery block, which starts charging the batteries. This voltage is also supplied to the load. In the absence of irradiance, the load voltage is supplied by discharging of the batteries in the off-grid PV system. Table 4 shows the battery parameters considered for the study.

RESULTS AND DISCUSSION

Three different battery parameters State of Charge (SOC), voltage and current are plotted against time for all the three batteries. Following results were obtained after simulation of the three batteries separately.

Table 4: *Battery Details.*

Parameter	Detail
Nominal Voltage (V)	100
Rated capacity (Ah)	1.5
Initial SOC (%)	50

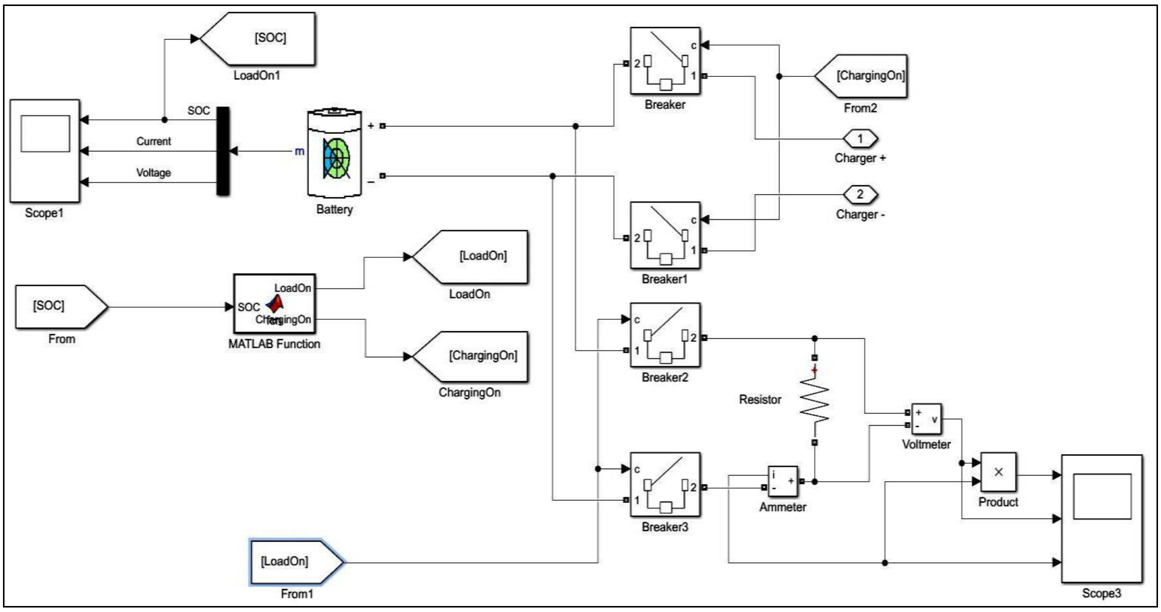


Fig. 5: *Battery Circuit Model.*

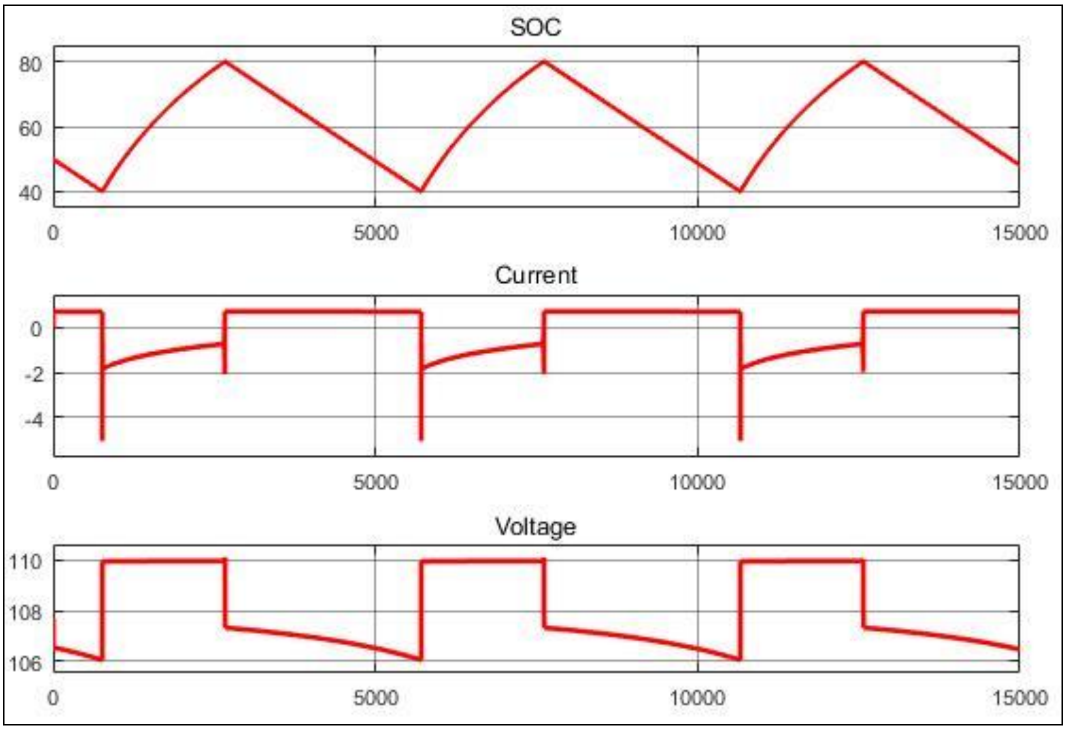


Fig. 6: *Lithium Ion Battery Characteristics.*

Battery Characteristics (SOC, Current and Voltage with Respect to Time)

Figure 6 shows the variation of state of charge, current and voltage with respect to time for a Li ion battery. The battery is provided with a 50% initial state of charge. As the SOC drops below 40%, battery begins to charge. It charges till it achieves at least 80% SOC then it again begins to discharge. The protection circuit is built into each pack, which limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge.

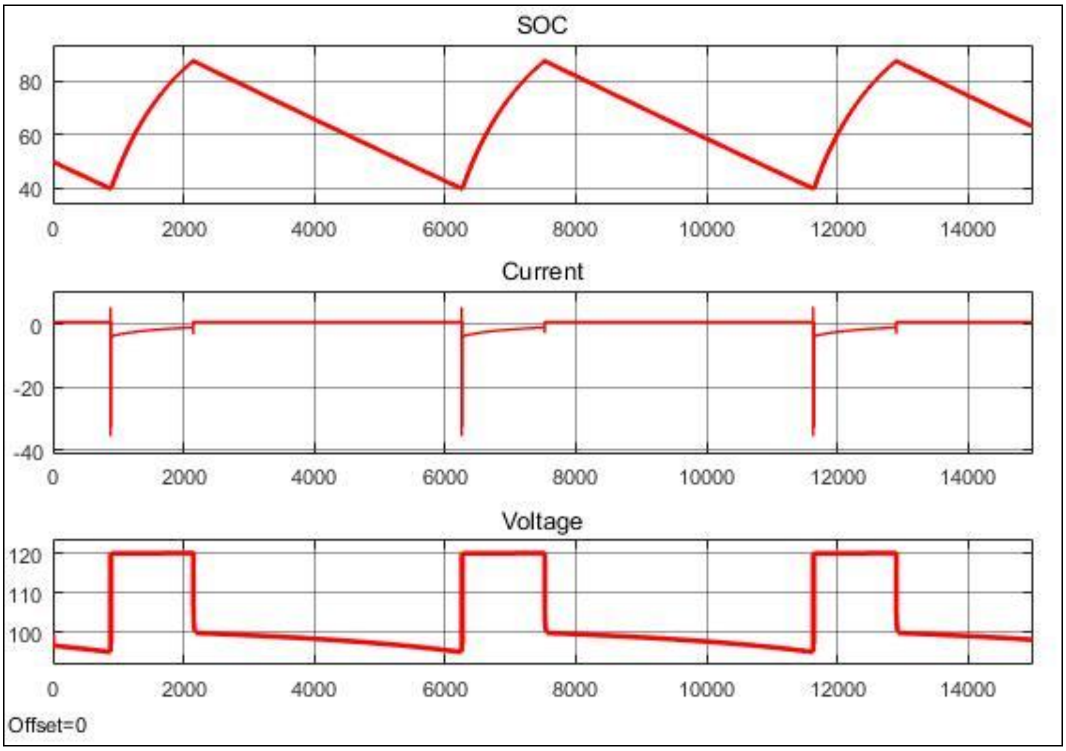


Fig. 7: *Advanced Lead Acid Battery Characteristics.*

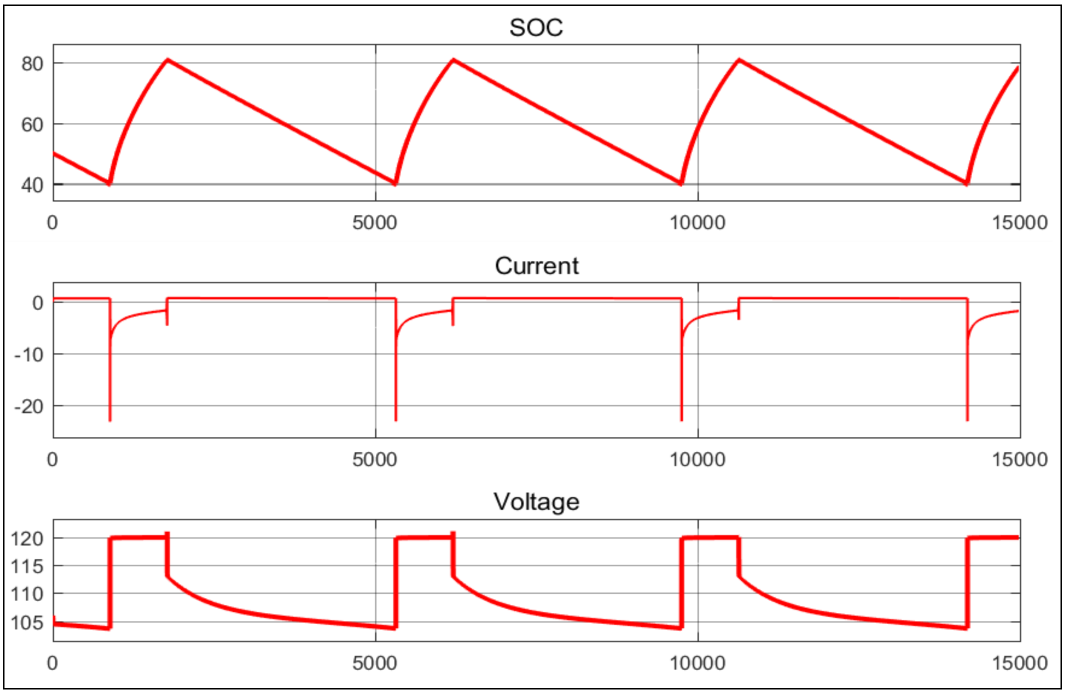


Fig. 8: *Nickel Cadmium Battery Characteristics.*

Variation of state of charge, voltage and current with respect to time for advanced Pb acid battery is recorded in Figure 7. It is seen that the SOC falls linearly when the power is drawn from the Pb acid battery and it rises non-linearly when the power is being delivered to the Pb acid battery i.e., when it is being charged. It has a fast charging time but a delayed discharging time in comparison to the lithium ion battery.

Figure 8 shows the variation of state of charge, current and voltage with respect to time for a Ni Cd battery. It is seen that Ni Cd battery runs the most number of cycles for a fixed amount of time. From the voltage vs. time graph, we see that the voltage decreases non-linearly as the SOC of Ni Cd battery decreases. Ni-Cd batteries require a charger with a higher voltage (compared to a lead acid battery charger). While these chargers exist, they are costlier. A fully charged 12 V battery bank can also go as high as 17 V, which could cause inverters to shut down. In addition, the charging efficiency of Ni-Cd batteries is generally rather low between 70 and 75%. In comparison, advanced lead acid batteries convert about 85% and lithium ion batteries convert about 90% electricity.

State of Charge

In case of discharging, from Figures 6 and 8, it is concluded that a fully charged Ni Cd battery lasts 1.11 times longer than Li ion battery. Also, from Figures 6 and 7, it is observed that a fully charged Pb acid battery lasts 1.27 times lesser than Li ion battery.

Taking the charging into consideration, Figures 6 and 8 suggest that an empty Li ion battery charges 2.88 times faster than Ni Cd battery.

Depth of Discharge

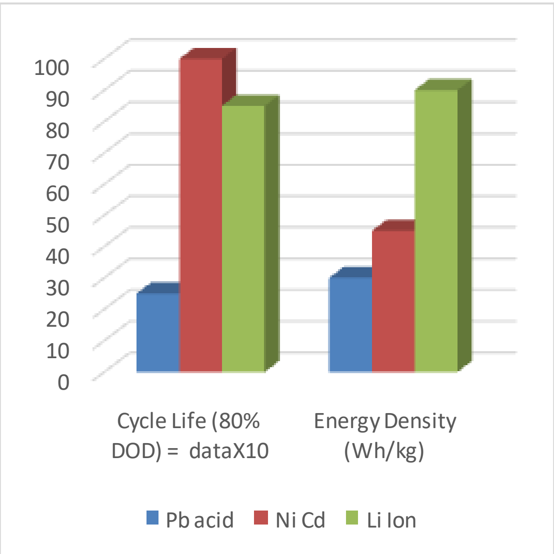
Depth of discharge (DOD) is also used to convey the percentage of energy left in the battery. Depth of discharge can be considered as the compliment of the state of charge of a battery. It is related to SOC by a simple equation:

Depth of Discharge (DOD) =100–State of charge (SOC)

It tells about the amount of energy that is already delivered by the battery to the load connected to it. When a battery is repeatedly charged and discharged through its life, its minimum depth of discharge slowly increases which lessens the capacity of the battery.

Specific Power and Charge/Discharge Efficiency

The specific power of Li ion battery is 1.96 times greater than Ni Cd battery and 1.63 times greater than Pb acid battery as shown in Table 5. The charge/discharge efficiency of Ni Cd battery is 94.1% of Li ion battery. The charge/discharge efficiency of Pb acid battery is 88% of Li ion battery as seen in Figure 9.



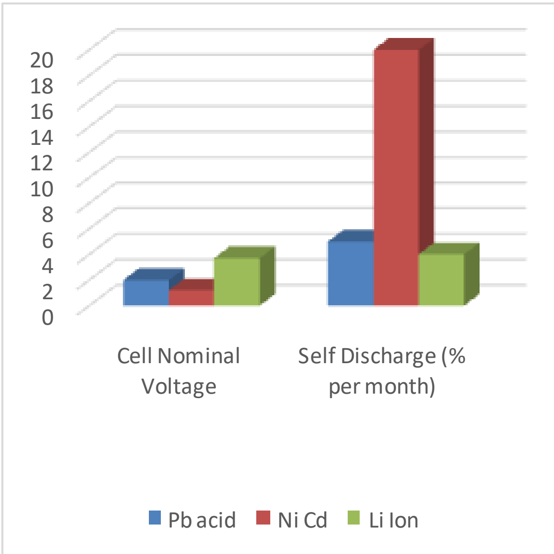


Fig. 9: *Graphical Representation of Performance Parameters.*

Table 5: *Comparisons of Battery Parameters for PV Applications.*

Factor	Advanced Pb Acid Battery	Ni Cd Battery	Li Ion Battery
Cell nominal voltage	2	1.2	3.7
Energy Density (Wh/kg)	30	45	90
Charge time	8–16 h	1–2 h	1–2 h
Self-Discharge/month (room temperature)	3–20%/month	10%	8% at 21°C, 15% at 40°C, 31% at 60°C (per month)
Overcharge tolerance	High	Moderate	Low. No trickle charge
Memory effect	Do not suffer from memory effect	Suffer from memory effect	Do not suffer from memory effect
Maintenance requirement	Does not need periodic discharge	Full discharge every 90 days when in full use	Maintenance-free
Safety requirement	Thermally stable	Thermally stable, fuse protection	Protection circuit mandatory
Toxicity	Very high, harmful to environment	Very high, harmful to environment	Low, can be disposed in small quantities
Recycle	Follow hazardous waste treatment and disposal	Follow hazardous waste treatment and disposal	recyclable
Cost	Low	Moderate	High

CONCLUSIONS

An off-grid PV system is modelled and simulated using MATLAB, Simulink environment. The model is tested using three different batteries: Lithium ion battery, Lead acid battery and Nickel Cadmium battery. The performance of the three batteries is recorded and the technical differences have been tabulated. It is found that the discharge time of lead acid battery is the highest followed by nickel cadmium battery and then lithium ion battery. This makes lithium ion battery most suitable due to its least discharge time.

In case of discharging, it is observed that a fully charged nickel cadmium battery lasts 1.11 times longer than lithium ion battery. On the other hand, a fully charged lead acid battery lasts 1.27 times lesser than lithium ion battery. Lithium ion battery charges at the faster rate as compared to nickel cadmium battery and lead acid battery. In terms of specific power, lithium ion battery is 1.96 times better than nickel cadmium battery and 1.63 times better than lead acid battery. Nickel cadmium battery is 5.9% less efficient than lithium ion battery in terms of charge discharge efficiency. On the other hand, lead acid battery is 12% less efficient than lithium ion battery in terms of charge-discharge efficiency. Hence lithium ion battery is most efficient while taking the charge-discharge efficiency into consideration. Lead acid battery and nickel cadmium battery pose as an environmental threat due to its toxic nature. This leads to an increase in usage of lithium ion batteries which are reasonably harmless and recyclable. Lithium ion batteries are low maintenance batteries that can be recharged before they are fully discharged without creating a “memory effect” and operate in a wider temperature range. Finally, it is concluded that lithium ion batteries have superior overall performance when compared to nickel cadmium and lead acid batteries.

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