Use of LiFePO$_4$ Batteries in Stand-Alone Solar System

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Abstract

In this paper the use of lithium iron phosphate (LiFePO$_4$) batteries for stand-alone photovoltaic (PV) applications is discussed. The advantages of these batteries are that they are environment-friendly, provide high safety, show long cycle life and hence relatively low lifetime costs. Different characteristics of batteries from various manufacturers have been studied in several battery testing experiments. Among the investigated properties are the relations of capacity, state of charge (SOC) and end-of-charge voltage as well as different charge-discharge durations. Differences between the capacities specified by manufacturers and the ones actually reached in experiments are reported. The tests show that LiFePO$_4$ batteries are an ideal choice for stand-alone PV systems due to their high efficiencies and long cycle life, provided that they are operated with a charge control algorithm specifically targeted for long charge durations as they are typical in solar PV applications.

Keywords: LiFePO$_4$ battery; stand-alone solar system; state of charge; end-of-charge voltage; charge-discharge rate

1. Introduction

Stand-alone photovoltaic (PV) applications provide an enormous benefit to places where no grid is nearby and the cost of PV systems have to be compared with those of bringing the grid to that location, which could be up to several thousands of US dollars per kilometre. In many remote areas, they also

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compete with gasoline or diesel-powered generators that often use subsidised fuel and for which users are charged on a “pay-as-you-use” base [1]. Apart from the much higher environmental benefits compared to diesel generators or individual kerosene lamps, the large-scale dissemination of stand-alone PV systems heavily depends on the lifecycle cost of the systems, which are mainly driven by the cost and the frequency of exchanging the batteries. This is addressed here by proposing a new type of battery for solar PV application: Lithium-iron-phosphate, LiFePO4.

In developing countries a small solar panel and a battery to run a few lights and a radio can change people’s life. Figure 1 illustrates a stand-alone PV system, which is very small in size so that even relatively poor families can afford it (< USD 100). The charge and discharge rates in these systems are typically very low, ranging from 10 hours to 100 hours for a full cycle. With the significantly decreasing costs for solar panels in the past few years, batteries are playing cost wise a more important role. Their limited lifespan compared to solar modules (20+ years) increases the total cost of the whole system correspondingly.

Fig.1. Stand-alone solar home system [2]

Lead acid batteries have been traditionally used for stand-alone systems, though they have many disadvantages, such as possible leakage of acid due to damage or spillage, noxious fumes given off during the charging process and their heavy weight [3]. Also the disposal of lead acid batteries often does not happen in a very environmentally friendly way, especially in remote areas, threatening the local people’s life for a long time. Another significant drawback of lead acid batteries is the fact that they age faster when kept in a low state of charge. Lead acid batteries need therefore to be frequently replaced due to this aging effect, which leads to additional system cost over time. Alternatively, in stand-alone system design, lead acid batteries can be over-sized compared to their nominal capacity, which then, however, increases the initial capital cost of the batteries significantly.

LiFePO4 batteries are widely used in electrical mobility applications, due to their advantages over other kinds of battery types: one key feature is its superior thermal and chemical stability, which provides better safety characteristics than lithium-ion batteries with other cathode materials [4]. Due to significantly stronger bonds between the oxygen atoms in the phosphate (compared to cobalt, for example), oxygen is not easily released and as a result, lithium iron phosphate cells are virtually
incombustible in the event of mishandling, and can survive high temperatures up to 85°C without decomposing [4].

The LiFePO4 battery is environmentally friendly, there is no hazardous or noxious substance inside the battery, which is also an excellent feature for stand-alone solar system application, because most of the end users are located in remote areas, where safety awareness is very low. The specific volume of a LiFePO4 battery is 65% of lead-acid batteries and the weight is 1/3 of that of a lead-acid battery [5], which also makes the battery more portable [5].

The total lifespan (cycles) is about 2000 cycles with the capacity still reaching 80%, which is 6-7 times higher compared to lead acid batteries over the entire lifetime. Moreover, it is maintenance free and does not get affected by longer durations in low states of charge, which allows for a higher utilisation of its capacity [5].

A comparison between various types of lead acid batteries, Li-Mg/Co batteries and LiFePO4 batteries for stand-alone solar system is shown in Table 1. It indicates that LiFePO4 batteries have a higher initial investment cost, but their lifecycle storage cost are lower than that of other kinds of batteries due to their higher numbers of cycles, higher usable capacity and higher energy efficiency. Thanks to all those advantages, LiFePO4 batteries are highly suitable for stand-alone PV systems. As the main application to-date is electromobility, few studies have been published on the use of this battery types for solar power systems. Therefore, detailed investigation of LiFePO4 batteries under such conditions are reported in this paper.

Table 1. Comparison of batteries for stand-alone PV systems’ design [3]

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Lead acid Flooded</th>
<th>Lead Acid AGM</th>
<th>Lead Acid GEL</th>
<th>Li-Mg/Co</th>
<th>LiFePO4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>2.12</td>
<td>2.12</td>
<td>2.12</td>
<td>3.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Lifespan [cycles]</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>2000</td>
</tr>
<tr>
<td>Energy efficiency [%]</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>90</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Usable capacity [%]</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>90</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Self-discharge rate [% p. month]</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cost [US$/kWh]</td>
<td>0.1</td>
<td>0.15</td>
<td>0.15</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Sizing rule [module]</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Sizing rule [days]</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Lifecycle storage cost [US$/kWh]</td>
<td>0.33</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>Environmental friendliness</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Overall evaluation</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>(+)</td>
<td>(+)</td>
</tr>
</tbody>
</table>

2. Investigation of battery characteristics

To study the characteristics of LiFePO4 batteries, thirty commercially available LiFePO4 batteries from six manufacturers have been tested with a professional battery tester (Maccor 4600). All batteries have a
nominal capacity of 1.4 Ah and a nominal voltage of 3.2 V. The investigated properties are: the relationship between the “end-of-charge voltage” (ECV) and the “state of charge” (SOC); the uniformity of battery samples from the same manufacturers as well as the efficiencies of batteries.

2.1 Characteristics of batteries from different manufacturers

The measurements are carried out by charging and discharging the batteries at 10 hours charge (discharge) duration from 2.0 V to different ECVs, ranging from 2.5 V to 3.7 V by steps of 0.05 V. Battery capacities and SOC are acquired with respect to each ECV. 100% SOC is defined as the nominal capacity (here: 1.4 Ah). Figure 2 shows the corresponding measurement results. The critical range for the charging process is from 3.3 V to 3.4 V, where SOCs sweep from 20% to 90%, which is equivalent to 70% of the battery capacity. Among six different battery manufacturers investigated, three do not reach the nominal capacity of 1.4 Ah (max 7% below), two manufacturers are very close to their specifications, while one is nearly 8% higher. This gives indication that the actual capacity for some LiFePO4 batteries may differ from the nominal capacity given by the suppliers.

2.2 Uniformity of batteries from the same manufacturer

To evaluate the uniformity of batteries from the same manufacturer, batteries are cycled at both 10 hours and 100 hours durations to determine their charge and discharge curves for comparison. Uniformity of samples from the same manufacturer also varies: some have almost identical behaviour, while others show significant differences. Figure 3 shows the battery charging voltage of two samples of manufacturer B (B1 and B2) as a function of corresponding capacity and SOC with virtually no discrepancy.
As an example for non-uniform behaviour, Fig. 4 shows the comparison of two batteries of manufacturer C, which had the biggest capacity difference in the test sequence (samples C1 and C2). It can be seen that both batteries have almost the same capacity when the charging voltage is below 3.4 V. Above 3.4 V, however, the battery capacities start to gradually deviate to 0.1 Ah, which is 7% of the total capacity. For instance at 3.4 V, battery C1 has a capacity value of 1.2 Ah, while battery C2 reaches 1.3 Ah. At the nominal capacity of 1.4 Ah, battery C1 is fully charged (and shows 3.7 V), while battery C2 has still not reached its maximum capacity and only shows 3.42 V.

In industry application, battery cells are generally connected in series to a battery pack. Due to the observed non-uniformity of individual cells, there is a risk that in a battery pack single cells will not get evenly charged. Especially detrimental is the potential overcharge of cells, which can lead to corrosion through a chemical reaction with the electrolyte [6], which would reduce the capacity of that cell, but -
through the series connection - also of the whole battery pack. Therefore, it is necessary to design a charge equaliser or charge controller circuit accordingly so as to protect the cells in a battery pack and prolong its lifespan.

2.3. Battery efficiency

The efficiencies of LiFePO₄ batteries are also investigated. By fully charging and discharging the battery at different current densities, the charge (discharge) energies are acquired. The efficiency is obtained by the ratio of discharge energy to charge energy. Table 2 shows the average battery efficiencies of six manufacturers. It indicates that battery efficiencies decrease with increasing charge and discharge currents. At a current density used for 100 hours charge duration, the efficiencies are found to be as high as 99%.

Table 2. Efficiencies of batteries from different manufacturers at different charge durations

<table>
<thead>
<tr>
<th>Charge duration</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
<th>Manufacturer D</th>
<th>Manufacturer E</th>
<th>Manufacturer F</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 h</td>
<td>92%</td>
<td>93%</td>
<td>92%</td>
<td>90%</td>
<td>87%</td>
<td>92%</td>
</tr>
<tr>
<td>10 h</td>
<td>97%</td>
<td>97%</td>
<td>96%</td>
<td>96%</td>
<td>95%</td>
<td>97%</td>
</tr>
<tr>
<td>100 h</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
</tr>
</tbody>
</table>

3. Summary

LiFePO₄ batteries have a number of advantages for stand-alone photovoltaic (PV) applications compared to lead-acid and other Li-ion batteries. The relations of capacity, state of charge and end-of-charge voltage, as well as battery efficiencies have been measured in extensive test series and discussed here. It turned out that the range from 3.3 V to 3.4 V is critical when charging LiFePO₄ batteries. Most batteries under investigation show good uniformity and reproducible measurements. For some batteries, however, measured nominal capacities and uniformity differ significantly across and even within manufacturers. This has to be taken into account when developing optimum charge algorithms for solar PV applications, which have relatively low charge/discharge durations of 10-100 hours, compared to electro-mobility, today's main application of the LiFePO₄ battery. At those low charge durations, LiFePO₄ batteries show excellent efficiencies of up to 99%, which makes them highly suited as storage solution for stand-alone solar PV systems.

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