Hybrid Battery Bank Application in Energy Storage System

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***Abstract*—This paper deals with the concept of a hybrid battery bank consisting of lithium and lead acid batteries. Lithium batteries offer various benefits and advantages over lead acid batteries however up-front cost is a significant difference. By using both types at the same time, the advantages of lead-acid and lithium batteries can be used at the same time. Lithium and lead acid batteries charging characteristics and discharge curves are different, also the technological voltage levels and the desirable depth of discharge rates are also different. This article shows in a practical manner, how to manage both when they are physically connected together, also following by some considerations of optimization possibilities.**

***Keywords*—hybrid battery bank, lithium and lead acid, adaptive active relay, hybrid energy storage system, battery degradation, energy management strategy, depth of discharge, state of charge**

I. Introduction

Renewable energy sources power outputs and energy consumption rates do not match usually, especially in an off-grid system, so an intermediate energy storage module is required. An energy storage module with a controlled or autonomous functions for example, state of charge, voltage, power monitoring, balancing, switching or converting capabilities, is an energy storage system. Hybrid energy storage system can increase the lifetime and the capabilities of energy storage elements by using both lead-acid and lithium batteries with supercapacitors. This solution can reduce the effect of microcycles and fitting the power capabilities of a hybrid energy harvesting system. The input power of solar, wind, other renewables or grid power can be stochastic and volatile, a correctly sized and controlled reliable energy supply system can handle these challenges.

A. Energy storage systems

Different types of energy storage technologies have different parameters, so they are most suitable for achieving different goals. The stored amount of energy depends on the needs of the load and the desired operating time [1]. The energy storage must also match the performance of the feeding energy source.

Short-term energy storage devices are designed to balance short-term loads (but longer than pulse-like loads), and these include supercapacitors [2]. They are able to serve a multiple of the operating load. The charge and discharge current and capacity of supercapacitors are much larger in proportion to their volume than those of conventional electrolyte capacitors. A typical field of application is to serve the increased current demand that occurs when loads are started.

Middle-term energy storage devices are designed to balance loads from nx10 minutes to days. The typical field of application of batteries is to serve the operational current requirements of loads.

Lithium batteries can provide power to a residential building to hours with reduced loads, in a reasonable price point. Lithium batteries can transform chemical energy to electrical energy with high efficiency, the energy density is relatively low and the cycle time is high [3], while maintaining technological disciplines [4].

Lead acid batteries used to provide power longer than lithium batteries (with higher capacity packs), but for less frequently use, to stay in the reasonable price point. They are widely used in uninterruptable power supplies and in renewables, however the life is limited. The gravimetric and volumetric energy density is much lower than lithium technology [5], the batteries are also well recyclable.

Long-term energy storage devices are designed to provide energy from days to months. Pumped hydro storages, electrolyzers and fuel cells [6] can be classified into the category.

B. Lead-acid batteries

The resting voltage of the lead-acid battery after charging and rest is around 12.6V and 12.9V – in case of a 6 cell battery. During discharge of the battery, the terminal voltage decreases linearly in accordance with the stored charge amount [7]. The charge and the discharging process of the battery has a significant effect for the present capacity over lifetime.

The Fig. 1 shows that increasing the charging voltage significantly increases the battery capacity in the short term, but reduces the battery life in the long term. Increasing the cell temperature also has an adverse effect on battery life. [8]

The number of cycles during battery life is highly dependent on DoD (Depth of Discharge), Fig. 2 shows the differences. An increased aging factor appears in the case of deeply discharged batteries. In the case of high available power supply systems, there is no detectable difference in degradation between 100% and 30% DoD in the case of flooded lead-acid batteries. Maintenance-free gel and AGM (Absorbent Glass Mat) batteries shows higher degradation ratings.

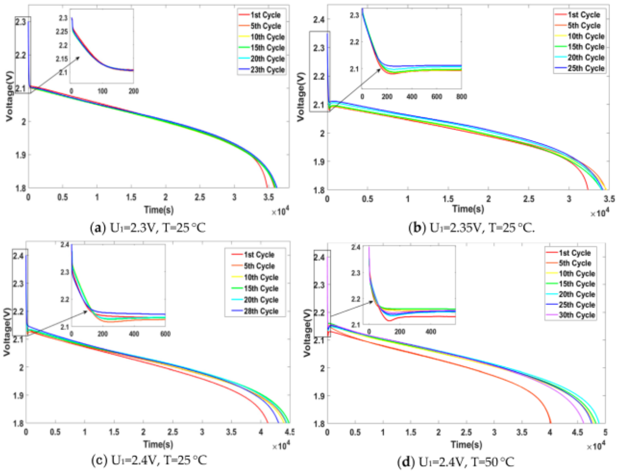

Figure 1. Lead-acid battery discharge curves under various conditions and cycle times under the same load [8]

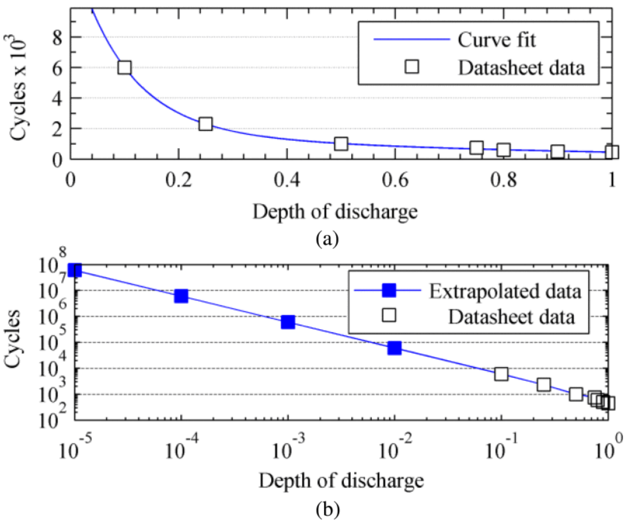

Figure 2. Lead-acid battery cycle life vs. depth of discharge curve in linear (a) and logarithmic (b) scale [9]

C. *Lithium-ion batteries*

The discharge voltage curve of a lithium battery is quite flat compared to that of a lead acid battery. When reaching a relatively high depth of discharge (~90% DoD), the slope of the voltage drop continues to increase as it approaches 100% DoD. In Fig. 3 typical discharge curves can be seen, depending on different load currents.

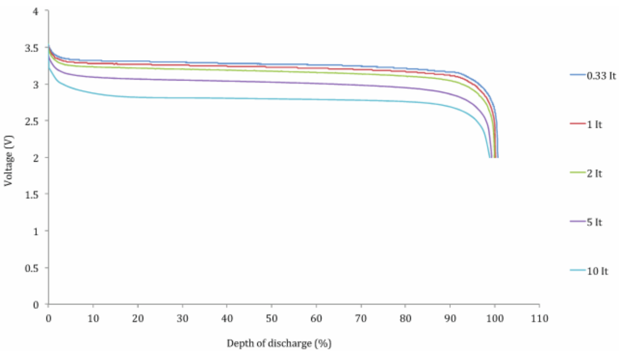

Figure 3. Lithium-ion battery discharge curve [12]

The measurement of the open circuit voltage in not accurate enough to estimate the state of charge level. Kalman Filtering and Fuzzy Logic methods can estimate the SoC (State of Charge) rating of the battery, the simulation and experimental results can be less than 4% [10]. Other electrochemical models and algorithms can improve the SoC calculation accuracy [11].

The exact measurement of the stored amount of charge is ampere-hour counting, where, the correct result can be obtained by adding the Peukert constant, see on Equ. 1. [12].

$$C_d = T_d \cdot I_d^k, \tag{1}$$

where C_d is the discharge capacity in [Ah], T_d is the discharge time in [s], I_d is the discharge current in [A] and k is the Peukert constant.

The Peukert number is dependent of the battery capacity and the discharge current. It is equal to 1, if the two parameter is independent from each other, it is higher than 1, if the discharge capacity is less than the applied current. [13]

In practice the Peukert constant is an empirical number, strongly depends on the used battery chemistry. In case of lead-acid batteries it is between 1.1 and 1.3, in case of lithium-ion batteries it is between 1.0 and 1.3.

D. *Hybrid battery bank*

Different modes of battery operation, depending on the application environment, charge the batteries in different ways. In the case of stationary batteries, for example in UPSs (Uninterruptible Power Supply), a rare and brief discharge is followed by a gentle charge, and then the equipment waits in an idle state for a significant part of its lifetime – more than 90% in average.

In the case of starter batteries, a short but high-current discharge that normally occurs several times a day is followed by a charge, and then the battery waits in an idle or partially charged state for a significant part of its lifetime – more than 70% in average.

The most intensive charge-discharge method in the case of electrochemical energy storage devices is the sequence of alternating discharge, charge and partially charged standby states that occur several times a day – for example EVs traction batteries. In off-grid systems, the battery burger is even more potent, since most of the idle period is taken up by a low-load discharge, and typically the charger and partially charger ratio is also lower.

Fig. 4 compares the main rechargeable battery technologies, with a decrease in DoD the number of life cycles increasing substantially, so a larger capacity partially discharged battery will last longer than a smaller capacity more discharged battery.

The charging and discharge current rates are also significantly affects the aging rate [15], it is strongly recommended to take into account the manufacturer's specifications.

For industrial and off-grid applications the use of advanced battery technologies (Lead Carbon, LiFePo4) has advantages in terms of longevity and safety [16]. The design of the hybrid system provides a flexible and easily parameterizable solution in case of incoming power [17], in a changing application environment. It can satisfy both economic and performance-oriented approaches [18]. Environmental issues also need to take into consideration, discharge can also be carried out under freezing temperature, but charging should be taken only at positive battery temperature [19].

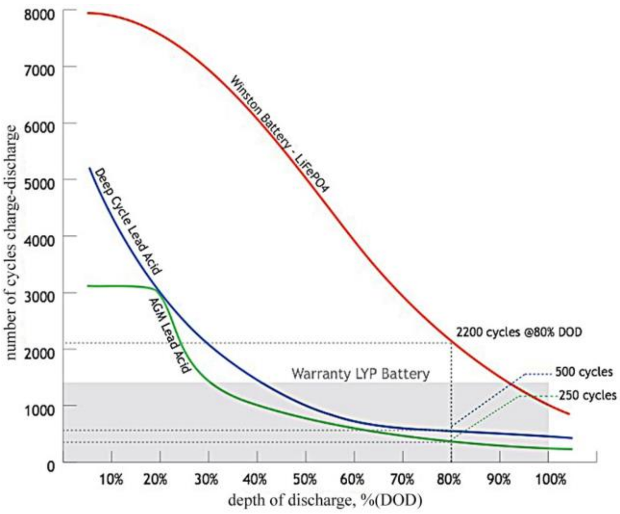

Figure 4. Service life of various chemical composition batteries depending on the depth of discharge [14]

E. *Pooling batteries*

According to the manufacturers datasheet, in the following table (see Table 1) is created for comparison of different battery technologies and types. The electric parameters are applied to 12V batteries.

TABLE I. BATTERY PARAMETERS

	Absorption [V]	Float [V]	Storage [V]	End of discharge [V]
Lead-acid	14.4	12.7	12.7	10.5
AGM - Deep Cycle	14.2 - 14.6	13.5 - 13.8	13.2 - 13.5	10.8
Gel - Deep Cycle	14.1 - 14.4	13.5 - 13.8	13.2 - 13.5	10.8
Gel - Long Life	14.0 - 14.2	13.5 - 13.8	13.2 - 13.5	10.8
Lead Carbon	14.1 - 14.4	13.5 - 13.8	13.2 - 13.5	10.8
Winston LiFePO4	14.6	13.2	13.2	11.2
Elerix LiFePO4	14.6	13.2	13.2	11.2
Victron LiFePO4	14.0 - 14.2	13.5	13.5	11.2
Lithium SuperPack	14.2 - 14.4	13.5	13.5	11.2

The lead-acid battery will settle down to a voltage of approximately 12.7V after being fully charged, which is 13.2V-13.5V for a lithium based battery. The end of discharge voltage for lead based batteries is 10.5V-10.8V, and 11.2V for lithium based batteries. Different manufacturers specifying their own parameters, but those electrical parameters are quite typical. There is a common subset on voltage levels, which is worthwhile for the realization of further operational possibilities.

In the case of the charged state of the energy storage, initially the lithium-based battery supplies the charges in the direction of the load. In the case of charging from a well-sized external renewable energy source, the battery performs a buffer function, which does not significantly reduce the lifetime of the lithium battery. With lithium batteries, self-discharge while idle proposed to be avoided [20].

II. System Architecture and Realization

Lithium based battery capacity is limited, so in order to increase capacity, lead based batteries are also implemented to the energy storage system. Lead based batteries can support lower currents for long time. In an off-grid application, when there is no, or there is low incoming renewable power, lead batteries are able to supply essential, low-power loads.

A. *Principle of operation*

In case of low DoD of the lithium battery, the lead battery can be connected as a parallel feed before the inverter. It is advisable to disconnect the different battery types after fully charging the lead batteries, this is the gentlest considering the life of the lead batteries.

It is recommended not to drain lead batteries below 50%, in critical and rare cases below 35% SoC. If this happens, their terminal voltage is already lower than the EoD (End of Discharge) voltage of the lithium batteries, the BMS (Battery Management System) switches off the lithium batteries (in order to prevent damaging the energy storage [21]) and the system can only rely on the lead batteries.

When charging, in the case of discharged lithium batteries, the lead batteries start charging first (taking into account the current limit due to their capacity), when their terminal voltage exceeds the EoD voltage of the lithium batteries, the adaptive active relay connects the different types of batteries in parallel again and they continue charging together. The operation can be seen in Fig. 5. The applied architecture is based the following articles [22-24], the developed firmware and control solutions are based the following articles [25-28], the setup is also capable for educational purposes [29-33].

B. *Hardware realization*

In the case of a more advanced architecture (see in Fig. 6), in the case of discharged lithium batteries, when charging, the different types of batteries should be separated and separately equipped with BMS and charged through them, so that the lithium battery can be used as a buffer, while the lead battery can be charged taking into account the current limit due to its capacity. In the practical implementation, a parallelizing adaptive active relay is no longer needed, but a similar characteristic contactor is required for each battery type.

For accurate power measurement, INA219 is a zero-drift bidirectional power monitor device, with I2C interface. The change of the programmable gain amplifier (PGA), the measurable current range can be adjusted.

Instead of regular DC contactors, it is proposed to use low energy consumption DC contactors or SSRs. This solution also enables the user to parameterize the different switchover DoD levels.

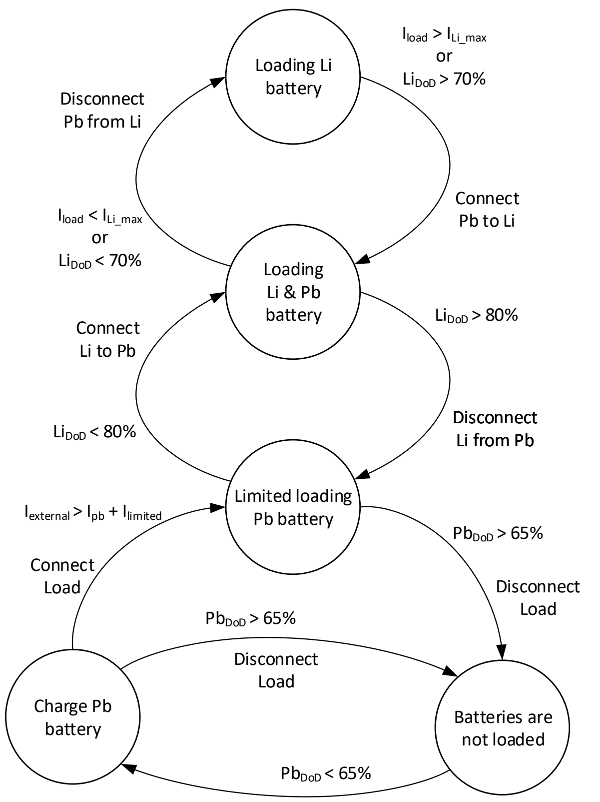

Figure 5. State diagram of the firmware

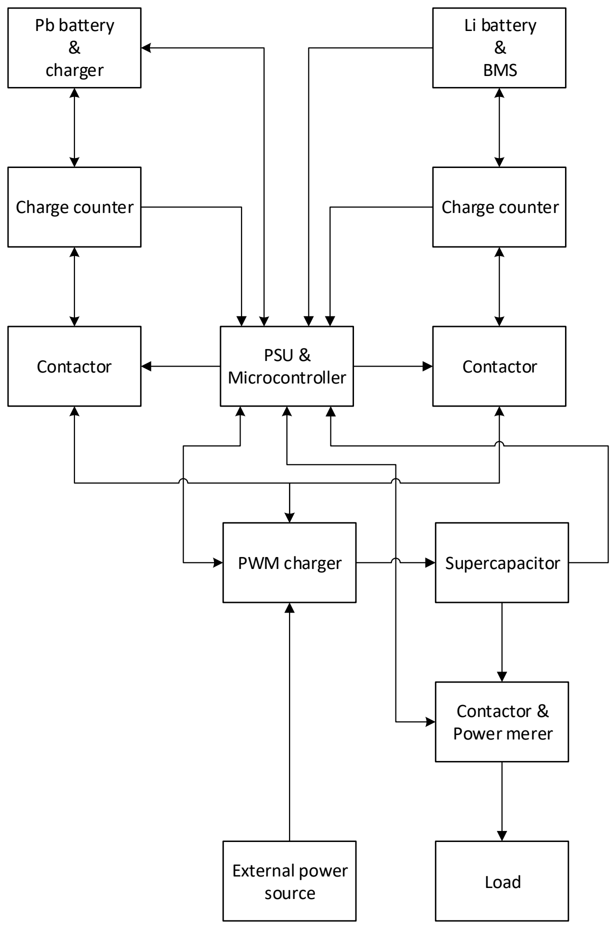

Figure 6. Architectural system design

In this realization, the PWM charger can limit the charging current for the batteries, there is a logic-level MOSFET based circuit for further supervision of the charging and discharging parameters of the lead-acid battery. The microcontroller handles the control tasks.

Contactors with low contact resistance capable of switching large DC currents are also suitable for combining batteries [34]. In order to avoid possible large currents arising from differences in internal resistance, it is recommended to insert a soft starter, supplementing the connecting relay.

In the case of lithium batteries, the measurement of the amount of charge flowing through provides a correct starting point for determining the SoC. In the case of lead batteries, it is possible to rely on the SoC estimation based on the terminal voltage, but in this case too, measuring the amount of charge is the correct solution.

Voltage fluctuations can be occurring because of battery switching, load changing or incoming power swings. For smoothing out voltage fluctuations of the energy storage system output, a supercapacitor bank is implemented [35]. This practical solution also can handle high short inrush currents due to for example electrical motor starting or capacitive loads, and reduce stress of the batteries [36]. A supercapacitor bank in parallel with a lithium battery, increasing the peak power capacity, the greater discharge life of the battery and reduce the power loss, while minimally impacting system volume and weight [37]. In Fig. 7 the prototype circuit can be seen, it is well purposed to test the setup and the developed algorithms.

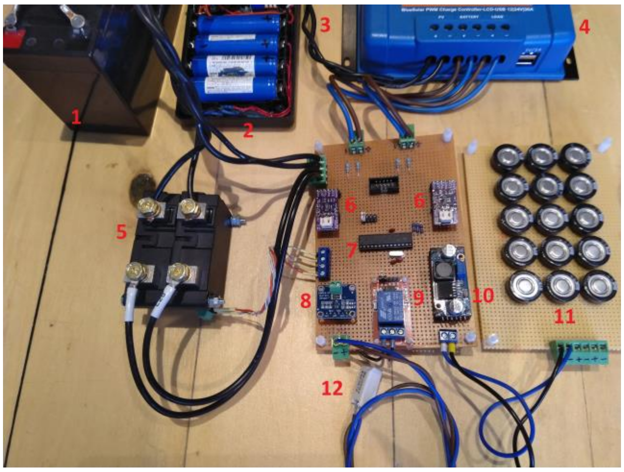

Figure 7. Prototype environment
(1 – Pb battery, 2 – Li battery pack, 3 – PV cable, 4 – PV charger, 5 – Contactors, 6 – Charge counters, 7 – Microcontroller, 8 – Power meter, 9 – Output relay, 10 – DC/DC converter, 11 – Supercapacitor bank, 12 – Artificial load)

C. *Economical considerations*

The result of the applied procedure is that most cycles load the lithium battery, which, in the absence of a complete discharge, lasts much better than lead-acid batteries, thus extending the life of lead-acid batteries [38]. The proposed solution is well usable in off grid or portable applications [39].

The battery life time is depending on a number of factors for example, charge voltage, DoD level, EoD voltage, charging and discharging current and temperature, cycle number, etc. In general, it can be determined that more expensive batteries with lithium technology are suitable for a higher number of cycles than batteries with lead acid technology.

At the overall lifetime cost the lithium technology could be cheaper than lead-acid technology per watt-hours, but it is a greater investment cost. A pure lead-acid battery setup is the cheapest, if the application is only for backup power, and for lower currents.

A hybrid battery setup gives an advantage to use higher load currents and faster, more efficient recharge cycles. For residential wan or boat applications, it is proposed to choose the lithium battery bank size 150%-200% of the average daily power need. The lead-acid battery bank size should be enough for additional 2-3 days of power, it means 4-6 times of the capacity of the lithium battery, in case of 50% DoD of the lead battery bank.

The reasonable payback time is around 3kWh usable backup power and above. Under this threshold level it is proposed to sticking to a single technology.

III. Conclusion

This article discussed the theory behind having lithium and lead acid batteries running and physically wired together. This paper went into details of the methodology and practice how to control a lithium and a lead acid battery bank when they are connected into one hybrid setup. The architectural concepts and algorithms are also proposed, optimization and economic considerations also added to the article.

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