# An Efficient Approach of Lengthening Battery Age and Working Hours through Redistributing Battery Packs

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**Abstract**— As electric vehicles and energy storage systems continue to develop and popularize, how to maximize the working time of batteries has become a major concern. For the sake of facilitating battery management, individual batteries are generally grouped to form battery packs by serial and parallel connections and a complete power supply system consists of those packs either in series or in parallel. However, the inconsistency of performances between different battery packs will seriously aggravates in the usage of batteries, resulting in a sharp reduction on the working time of batteries. In this paper, we propose a novel scheme of redistributing battery packs and design an appropriate system of managing the charging and discharging process of batteries, so that the lifetime of batteries can be greatly extended.

## 1. INTRODUCTION

The smart power management devices have wide applications in electric vehicles (EV) and energy storage systems. For the sake of facilitating battery management, individual batteries are generally grouped to form battery packs by serial and parallel connections and a complete power supply system consists of the battery packs in serial and parallel connections. Initially, the performance of each individual battery which constitutes battery packs is different and the difference between individual batteries will be gradually enlarged during the use of batteries, resulting in a significant degradation of the battery packs' performance [1, 2]. Because the released maximum power by a power supply system is determined by the minimum-power battery pack and the minimum-power battery pack will be seriously harmed if it continuously discharges and we must stop its discharging process. Similarly, if the maximum-power battery pack has a full charge, we must stop its further charge to prevent it from being harmed. When the difference of performance between battery packs is magnified, the working hours of power supply system will sharply reduce and the age of batteries will also be shortened greatly.

In this paper, we fully investigate a set of lithium-iron-phosphate batteries and propose an efficient approach for lengthening the working hours and age of the batteries by redistributing battery packs. The approach analyzes the data about the state of charge (SOC) and voltage of battery packs and then quantifies the level of their inconsistency between battery packs. The redistribution of battery packs will be automatically managed according to the level of inconsistency and we have designed a smart electronic device for controlling the process. The experimental tests show that the approach can significantly lengthen the working hours and age of batteries and we will show the details of design and testing results.

## 2. FACTORS IMPACTING THE REDISTRIBUTION OF BATTERY PACKS

Because of the advantages of high energy density, low cost, and safety, $LiFePO_4$ battery has become the first choice of mobile battery. From the point of usage, the performance parameters of $LiFePO_4$ battery include the capacity, battery voltage, internal resistance, charge-discharge scale, depth of discharge, and circular working life [3], etc.. The battery capacity includes the theoretical capacity, actual capacity, and SOC. The theoretical capacity is the capacity that allows all active substances in the interior of battery to take part in a chemical reaction and the total energy is calculated using Faraday's law. The battery capacity represents the maximum value of theoretical capacity and the battery discharge capacity is only a part of theoretical capacity. The actual capacity is defined as the electricity that allows the battery to be fully charged or reach the maximum capacity that can be given. The SOC is defined as the used battery's discharge in the rate of C/30 and in the temperature of 25 degree before the cut-off voltage can get the battery capacity.

The battery voltage includes the open-circuit voltage and operating voltage. The open-circuit voltage (OCV) of a battery is defined as the potential difference between two balanced electrodes of thermodynamics when the circuit is in an open-circuit state. The OCV is affected mainly by its material properties such as polarity and electrolyte materials [4]. The operating voltage (OV) is defined as the potential difference between two electrodes of the battery in a working state, which is also called terminal voltage. When the battery is in charging, the OV is bigger than the OCV. When the battery is in discharge, the OV is inferior to the OCV [5]. Because the internal resistance is difficult to measure, the cut-off voltage and SOC of charging and discharging in the battery packs are used as reference variables so that the redistribution of battery pack model can be simplified.

## 3. EXPERIMENTS AND RESULTS

### 3.1. Method of Redistributing Battery Packs

The redistribution of battery packs is determined according to the cut-off voltage and cut-off SOC of charge and discharge in a battery pack. The battery pack is formed by serial and parallel connections of individual batteries and its internal structure is shown in Figure 1.

If the cutoff voltage of charge in a batter pack is higher or closer to the voltage limit, then it means that individual batteries in a battery pack have a better performance and have a better consistency between different individual batteries because the individual battery has a higher voltage when its performance is better. However, as the usage of individual batteries increases and their aging aggravates, their performance will drop significantly and the voltage drop on the internal resistance of the batteries also increases. If the cut-off voltage of discharge in a battery is lower or it gets closer to the limit of discharge voltage, it simply reflects that the consistency of individual batteries in the battery pack is better. The SOC of battery packs is determined by the individual battery which has the least SOC.

We define the maximum cut-off voltage of charging as $V_i$ and the maximum cut-off SOC of charging as SOCj in a battery pack. We take an energy system which is shown in Figure 2 as an example. The system consists of four series-connect battery packs and three parallel-connection battery packs.

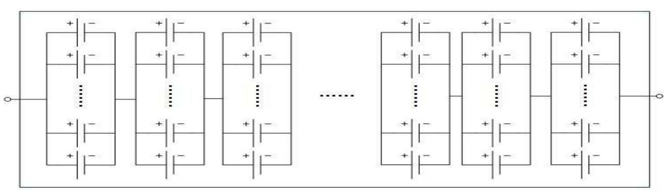

Figure 1: The internal structure of a battery pack.

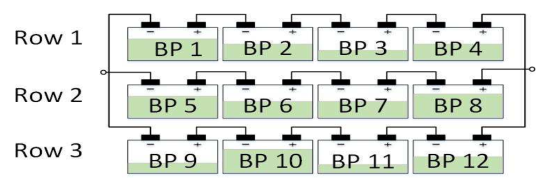


Figure 2: No redistribution of battery packs.

A low-voltage battery is charged by a high-voltage battery when they are connected in parallel and it will cause an energy assumption by the internal resistance of the battery. We define $V_{L1}$, $V_{L2}$ and $V_{L3}$ as follows.

$$V_{L1} = V_1 + V_2 + V_3 + V_4 \tag{1}$$
$$V_{L2} = V_5 + V_6 + V_7 + V_8 \tag{2}$$
$$V_{L3} = V_9 + V_{10} + V_{11} + V_{12} \tag{3}$$

In order to ensure that the battery pack will not charge each other, resulting in a waste of energy, we must ensure that $V_{s1}$, $V_{s2}$ and $V_{s3}$ are similar or equal to each other. Additionally, in order to ensure a maximum efficiency for the battery, we need to have a similar or equal maximum SOC in the battery pack of each row by the method of time-sharing work. The meaning of time-sharing work denotes that the battery pack of one row which has a large capacity will be charged by a switch when the EV needs a less power so that the battery pack's capacity in each row can be approached. All battery packs work when the EV needs an adequate power. So, the conditions of redistributing battery packs can be listed as follows.

1) $V_{L1}$, $V_{L2}$, and $V_{L3}$ are similar or equal to each other;

2) $SOC_1$, $SOC_2$, $SOC_3$, and $SOC_4$ are similar or equal to each other;

3) $SOC_5$, $SOC_6$, $SOC_7$, and $SOC_8$ are similar or equal to each other;

4) $SOC_9$, $SOC_{10}$, $SOC_{11}$, and $SOC_{12}$ are similar or equal to each other;

In order to decide the time of redistributing battery packs, we need to define the level of inconsistency in the battery packs and redistributing battery packs will happen when the level is exceeded. Table 1 shows the parameters of battery packs used for simulations.

Table 1: Parameters of battery packs.

| Battery pack | SOC | Voltage | Battery pack | SOC | Voltage |
|---|---|---|---|---|---|
| Battery pack 1 | 82% | 30 V | Battery pack 7 | 79% | 24 V |
| Battery pack 2 | 74% | 22 V | Battery pack 8 | 78% | 22 V |
| Battery pack 3 | 77% | 22 V | Battery pack 9 | 78% | 25 V |
| Battery pack 4 | 77% | 23 V | Battery pack 10 | 79% | 29 V |
| Battery pack 5 | 80% | 28 V | Battery pack 11 | 75% | 23 V |
| Battery pack 6 | 74% | 24 V | Battery pack 12 | 79% | 22 V |

### 3.2. Simulation Test and Analysis of Results

In order to complete the experiment and verify the method, we should first build a simulation test platform. The platform is set up through the object-oriented language — C sharp and it can simulate the discharge characteristics of the battery pack. Discharge rate is C/5 when the battery pack is discharging and the battery's working time is 11.15 h when the battery pack is not in a redistribution. The results are shown in Figure 3. According to the condition about the redistribution of battery packs, the battery's working time is 11.45 h when the battery pack is of redistribution. The results are shown in Figure 4.

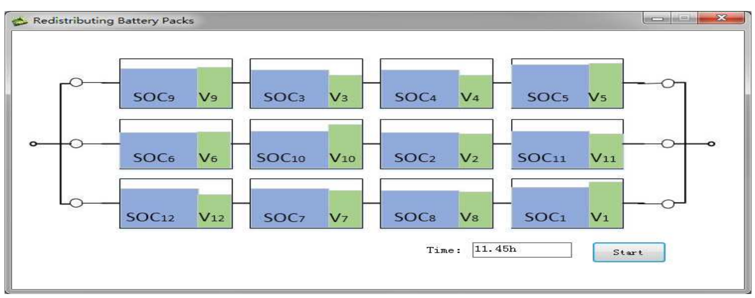


Figure 3: No redistribution of battery packs.

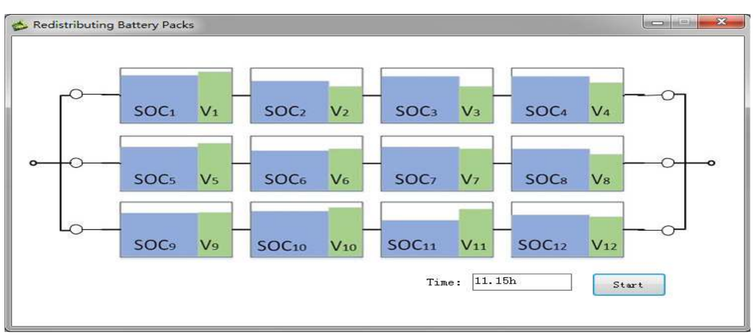


Figure 4: Redistribution of battery packs.

According to the results in Table 2, we can see that the prolonged working time of battery changes with different discharge rates when the battery pack status is the same and the prolonged working time is longer when the discharge rate is smaller. Therefore, the battery's working time is lengthened when the redistribution of battery packs happens.

Table 2: The simulation results.

| Discharge Rate | No Redistribution (unit: hour) | Redistribution (unit: hour) |
|---|---|---|
| C/15 | 33.45 h | 34.35 h |
| C/5 | 11.15 h | 11.45 h |
| C/3 | 6.69 h | 6.87 h |

## 4. CONCLUSION

In this paper, a redistribution scheme for battery packs has been presented based on the relationship between the battery pack voltage and SOC. The scheme is verified through a simulation test bench. Also, the experimental results show that the proposed scheme is effective and feasible.

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