Research of SOC Estimation Algorithm for $LiFePO_4$ Battery based on Differential Curves

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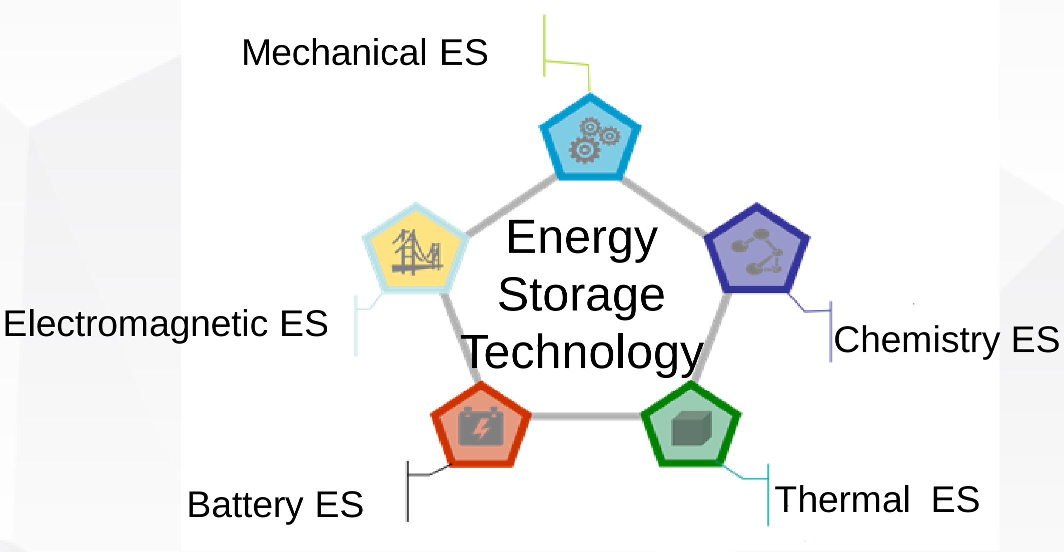
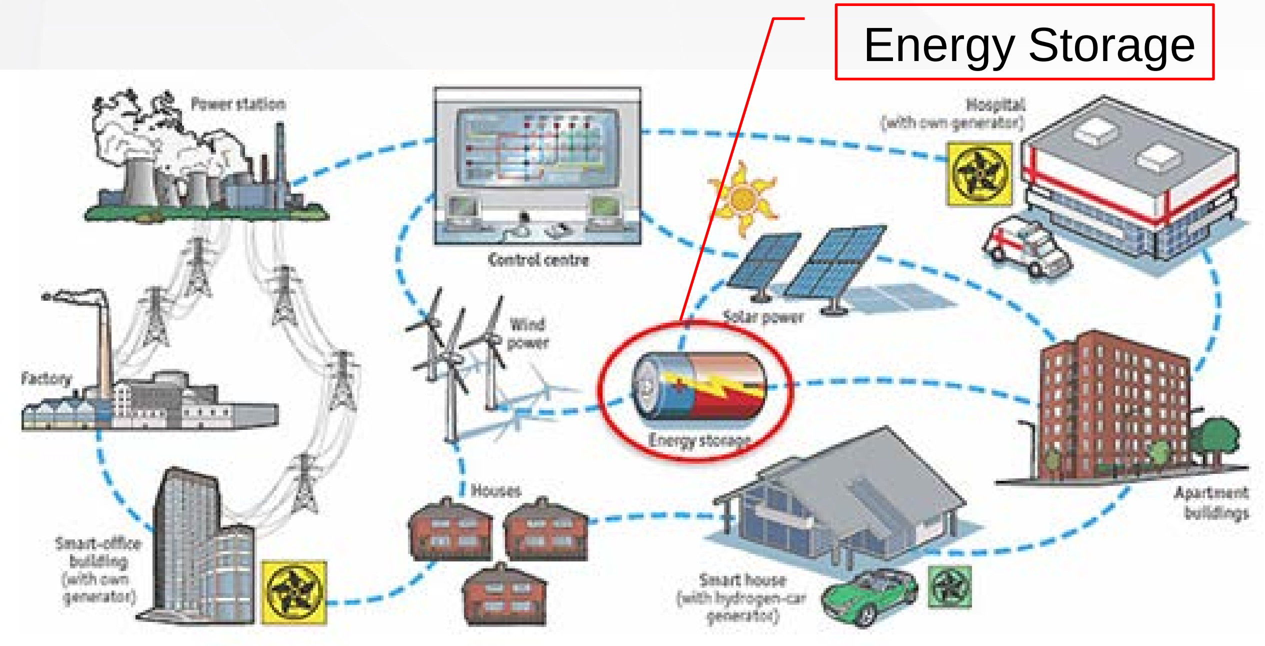
Contents

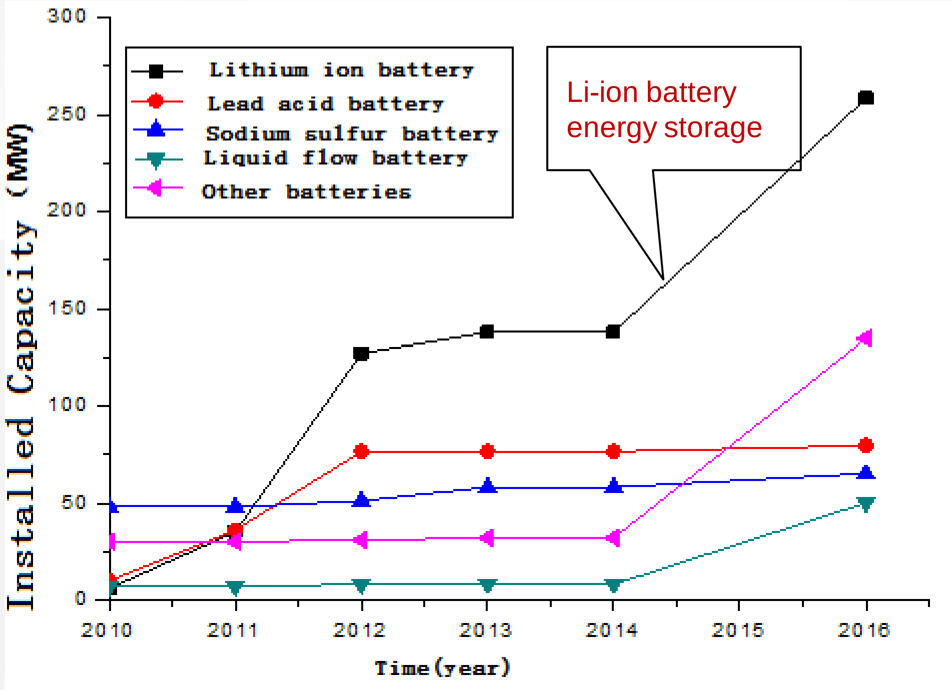
一 Background

- Energy storage technology is one of the key technologies of the Global Energy Interconnection.





- Energy storage technology is mainly divided into battery energy storage, thermal energy storage ,electromagnetic energy storage, chemistry energy storage and mechanical energy storage.
- Battery energy storage is the most widely used in the world now.



- In order to meet the requirements of voltage and capacity, the energy storage system consists of thousands of lithium-ion batteries.
- In order to ensure the safe operation of the energy storage system, the battery management must be carried out.
- SOC is the most important parameter of the battery, so it must be accurately estimated, and be provided to the battery management system as the reference basis.

✓ Lithium ion battery is the most commonly used in battery energy storage in the world because of its long life , high efficiency and safety.

二 The Algorithm of SOC Estimation

- Definition of SOC
- Theory of differential curve
- Algorithum of SOC Estimation

SOC(State of Charge):the ratio of the remaining capacity to the maximum available capacity of the battery.

$$SOC = \frac{Q_{remain}}{Q_{total}} \times 100\%$$

Q_{remain} ： the remaining capacity

Q_{total} ： the maximum available capacity

Here, Q_{total} is the capacity released from full charge to full discharge of the battery.
$Q_{total} \neq Q_n$, Q_n is the nominal capacity of battery.
The relationship between them can be expressed in SOH (State of Health)

$$SOH = \frac{Q_{total}}{Q_n} \times 100\%$$

$$SOC = \frac{Q_{remain}}{SOH \bullet Q_n} \times 100\%$$

- Compared with SOC, SOH changes slowly, and SOH is considered a constant when estimating SOC. Therefore, SOC is proportional to the remaining capacity of the battery.

Problems

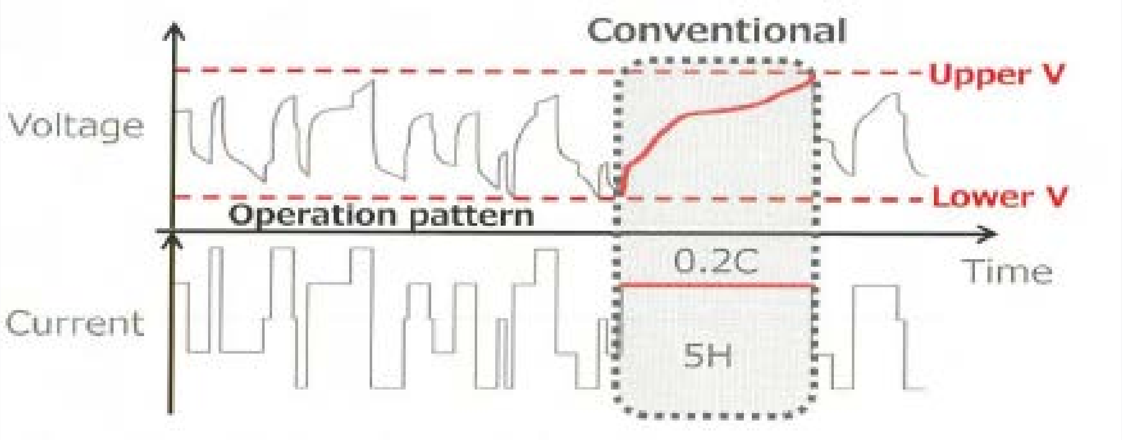
- Long measuring time
- Accelerate degradation
- Few chances to measure
- Large estimation error

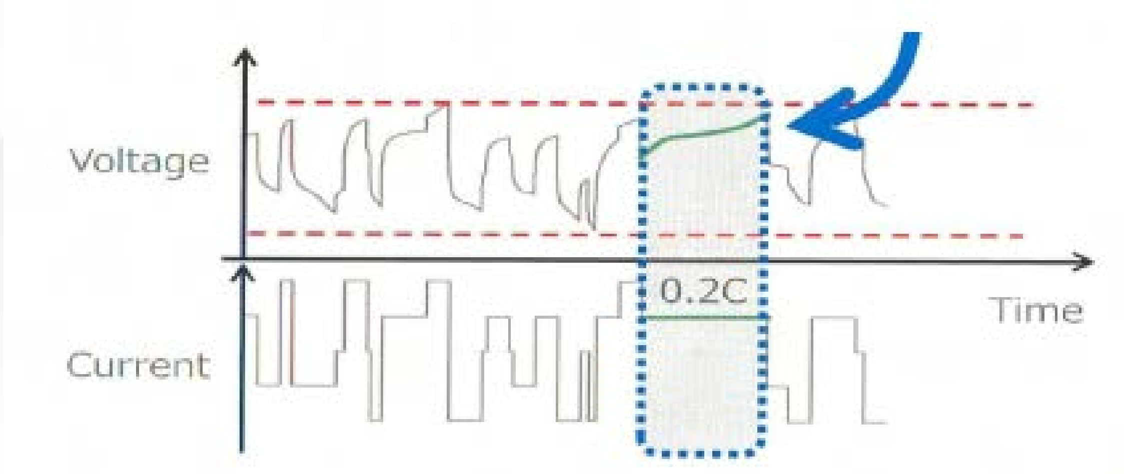
Purpose

- Short measuring time
- Simple
- Applicable during operation
- Small estimation error

↓

✓ Focus on derivation charge curve which reflects phase transition phenomena





DVA(Differential Voltage Analysis) is a method which widely used to highlight the different areas in a voltage profile where the voltage derivative with respect to capacity.

- The dV/dQ curve can reflect the ability of battery charge and discharge capacity at different voltage points based on the online measurement data.
- Considering a typical CC charging mode, the battery capacity Q (ampere hours, Ah) and voltage can be described using function:

$$\Delta Q = I \Delta t \quad \Rightarrow \quad \frac{dV}{dQ} = \frac{dV}{d(It)} = \frac{dV}{Idt}$$

From the equation dV/dQ is a function of V, at the same time, the current I is function of V also.

For the derivation, the battery voltage and capacity can be written:

$$V_n = V_0 + m \times \Delta V$$

$$Q_n = Q_0 + n \times \Delta Q = Q_0 + n \times I \times \Delta t$$

V_0:isthe voltage at the begin of battery charging.
Q_0: is the capacity at the begin of battery charging.
m,n=0,1,2……

When the battery voltage is V_k,

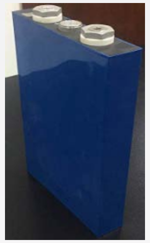
$$\left.\frac{dV}{dQ}\right|_{Q_{d,k}} = \frac{V_{d,k+1} - V_{d,k}}{Q_{d,k+1} - Q_{d,k}} = p\frac{\Delta V}{\Delta Q}$$

In constant current charging mode, p can be denoted by using the number of sampling point to denote.

Theory of differential curve

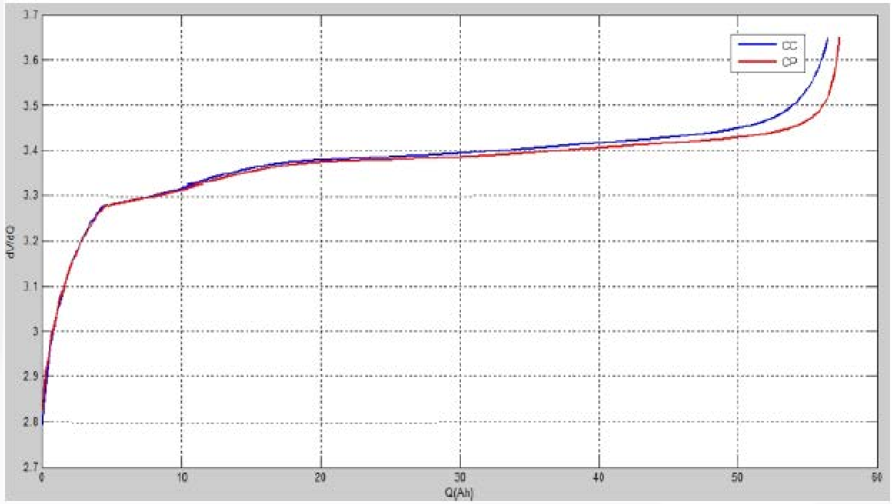
Test sample：

LiFePO4 battery
（Nominal Capacity： 65Ah）



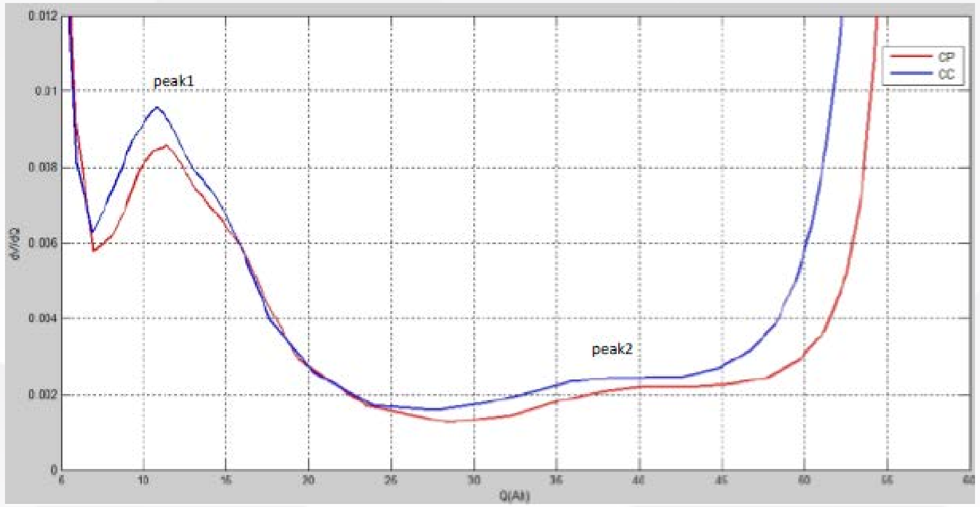
Test conditions:

- Temperature:25 ℃；
- Range of Voltage:2.5V ～3.65V ；
- Charge: CC: 0.5C; CP: Pn.
- Discharge: CC 0.5C.



CC and CP curves

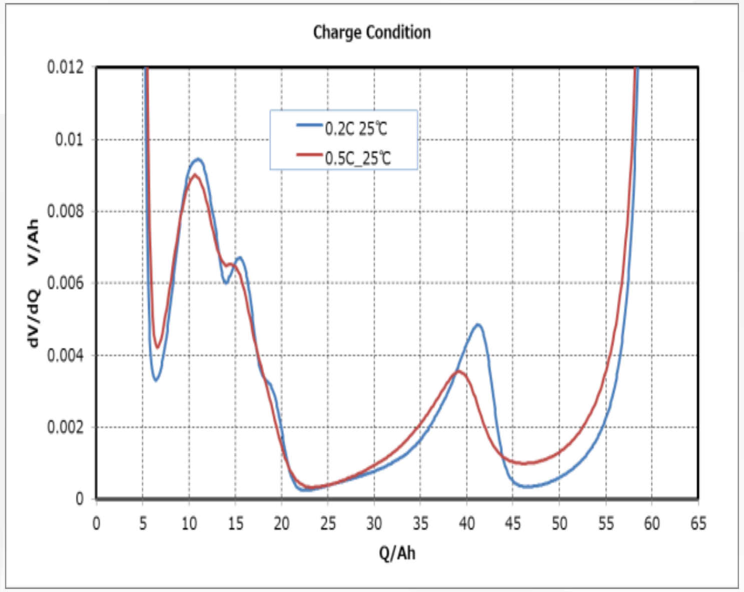
differential curve



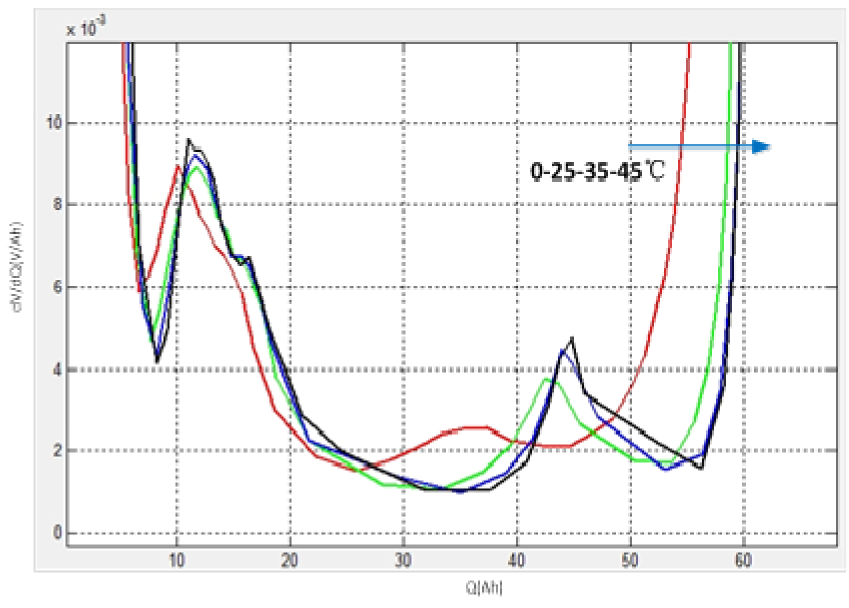
dV/dQ vs. capacity curves

- The differential curve of CC and CP mode is similar;
- The two peaks(peak1 and peak2)related to the two most significant voltage gradients in the charge curve;
- In the section of 15Ah-25Ah (SOC:25%-42%), the characteristic of derivation curve is stable, this can be used to calibrate the SOC and estimate the capacity of battery.

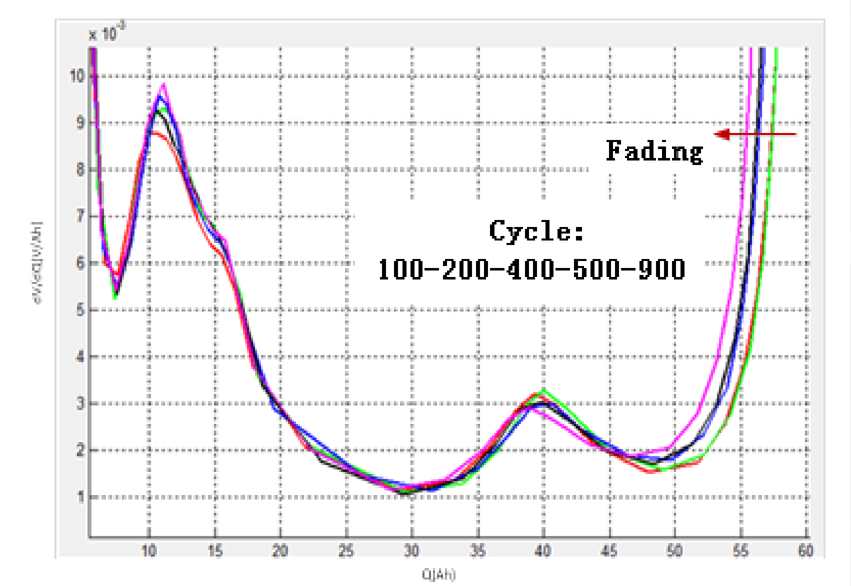
The dV/dQ vs. capacity curves under different working condition :



(a) Different charging rate



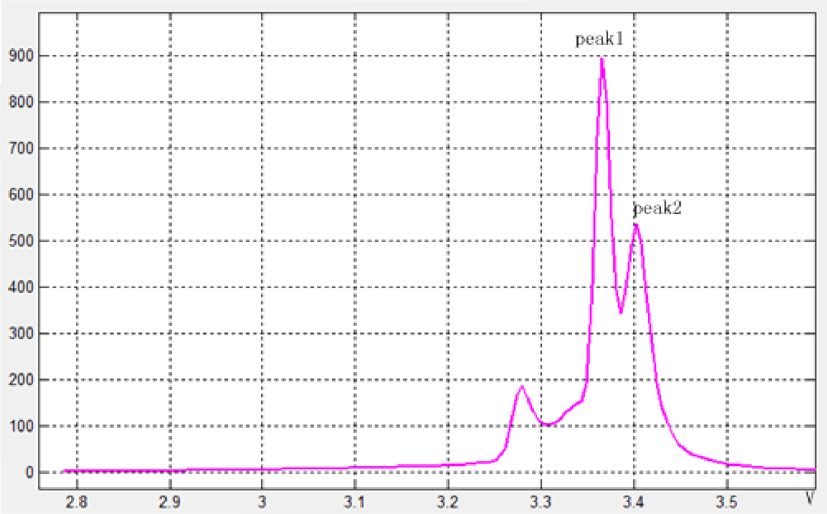
(b) Different temperature



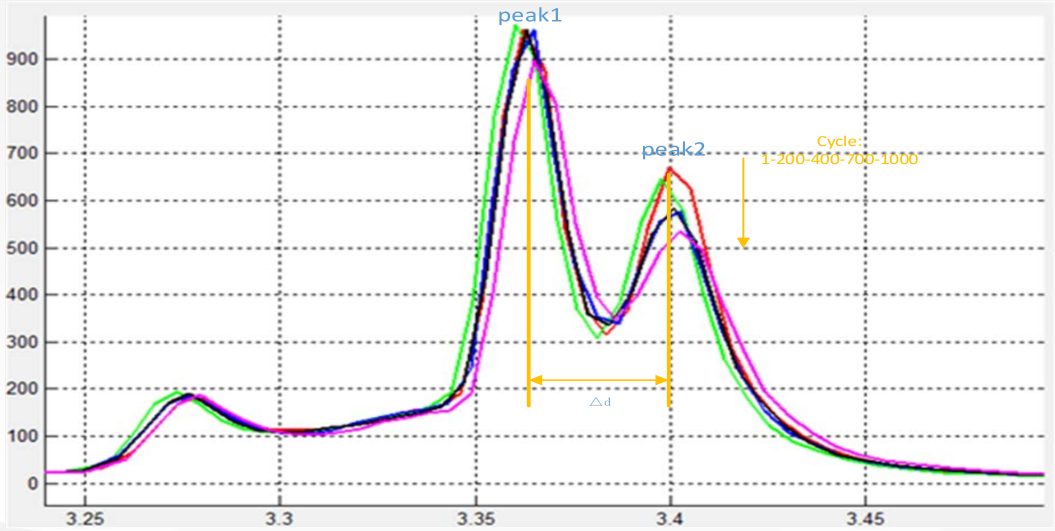
(c) Cycle aging

- The differential curve has good consistency with the remaining capacity of the battery.
- The dV/dQ curve within the battery capacity 15Ah ~ 25Ah (SOC:23% ~ 38%) is consistent.
- Shifts in the alignment of the electrodes due to side reactions seems to be the primary cause of capacity fade, the derivation curve has different trends under different working conditions, but the characteristic is similar in the selected curve section.

The dQ/dV vs. voltage curves under different working condition :



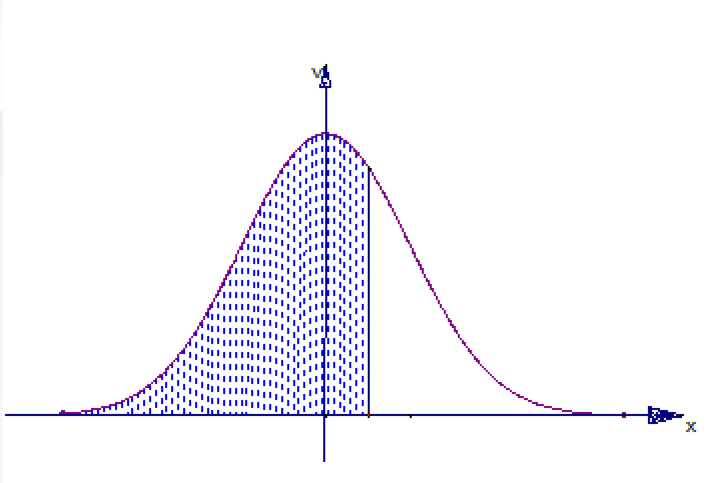
(a) The dQ/dV vs. voltage curve



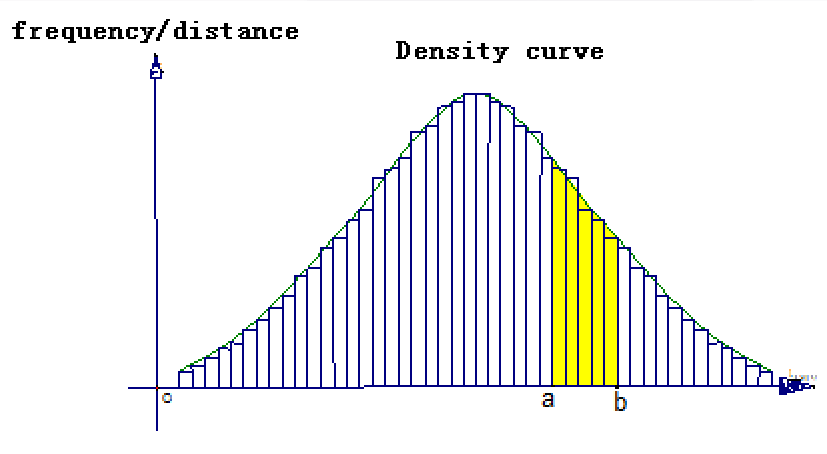
(b) The dQ/dV vs. voltage curves under different working condition

- The differential curve has two peaks, peak1 and peak2.
- With the fading of the battery capacity, there will lead to the distance Δd to be reduced between two peaks of peak1 and peak2, and the peak of peak2 will be decrease gradually, that is the peak amplitude will decrease with the increase of cycle number.

The normal distribution curve and its characteristics



(a)



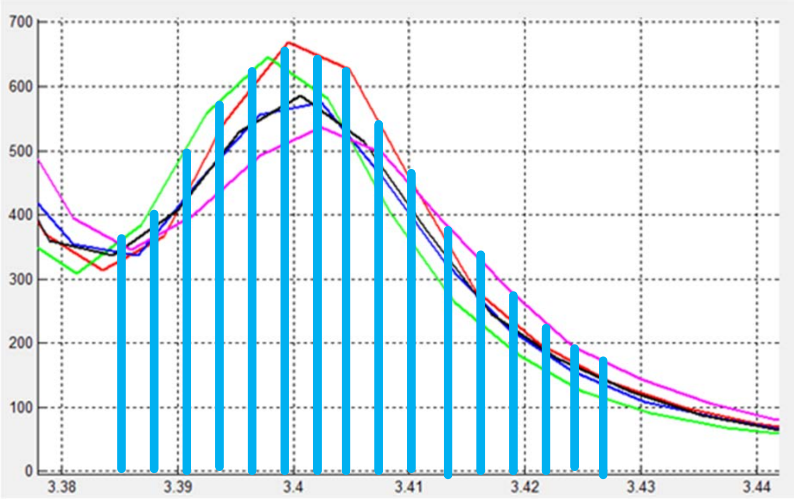
(b)

- Fig.(a) is the standard normal distribution curve, the area of the shadow part is probability.
- Fig.(b) is the practical application curve drawn by the sample, that is the sample histogram, which reflects the probability of the total value in each range. According to this curve, the probability of the total value in the interval (a, b) can be found to be equal to the population density curve.

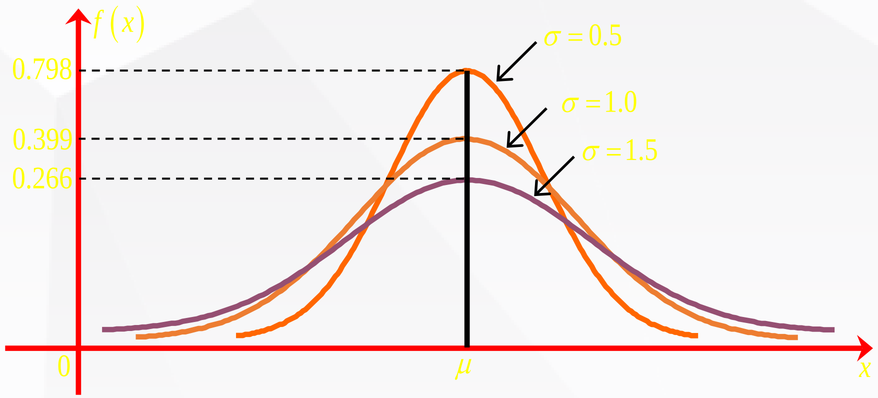
$$P(a < X \leq b) = \int_a^b f_{\mu,\sigma}(x)dx$$

- The battery characteristic curve conforms to the standard normal distribution curve characteristic at peak2.

The histogram of battery capacity fading



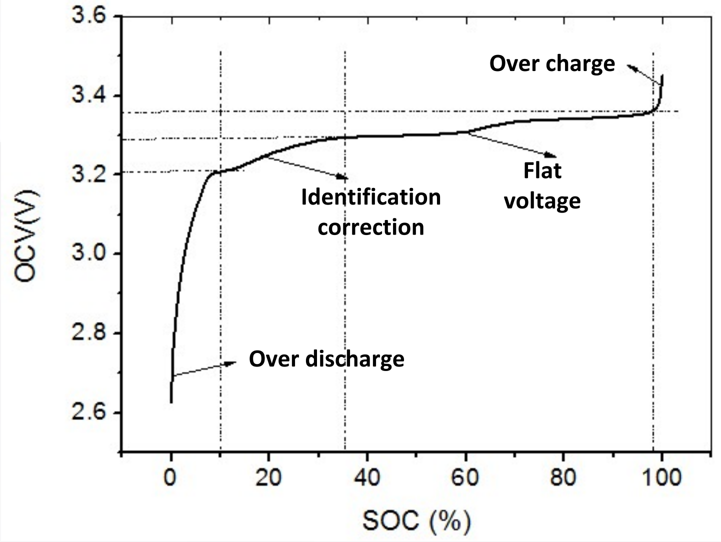
(a)



(b)

- Fig.(a) is the amplification of peak2 of the battery capacity fading curve.
- Fig.(b) is the the distribution graph of normal distribution curve in fixed expectation value μ and different standard deviation σ.
- The working range of the battery can be divided according to μ, and the σ is used as the magnitude of the battery capacity fading. Therefore, the relative value of the battery capacity can be calculated by the probability density of the normal distribution.

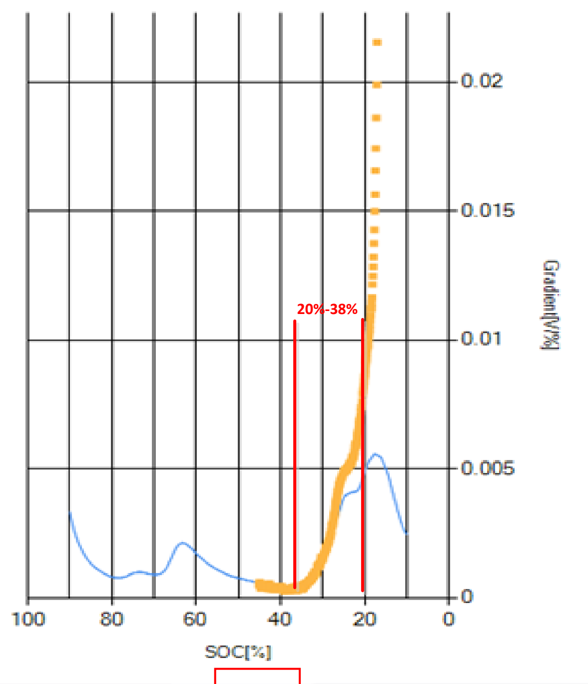
The division of battery working range.



(a)

AREA	PATTERN	OCV (V)	Δ OCV (V)	SOC (%)	Δ SOC (%)	Δ OCV/Δ SOC
OVER DISCHARGE	PATTERN 1	2.60～2.88	0.28	0～2	2	0.1400
IDENTIFICATION CORRECTION	PATTERN 2	2.88～3.28	0.40	2～32	30	0.0133
FLAT	PATTERN 3	3.28～3.36	0.08	32～98	66	0.0012
OVER CHARGE	PATTERN 4	3.36～3.50	0.14	98～100	2	0.0700

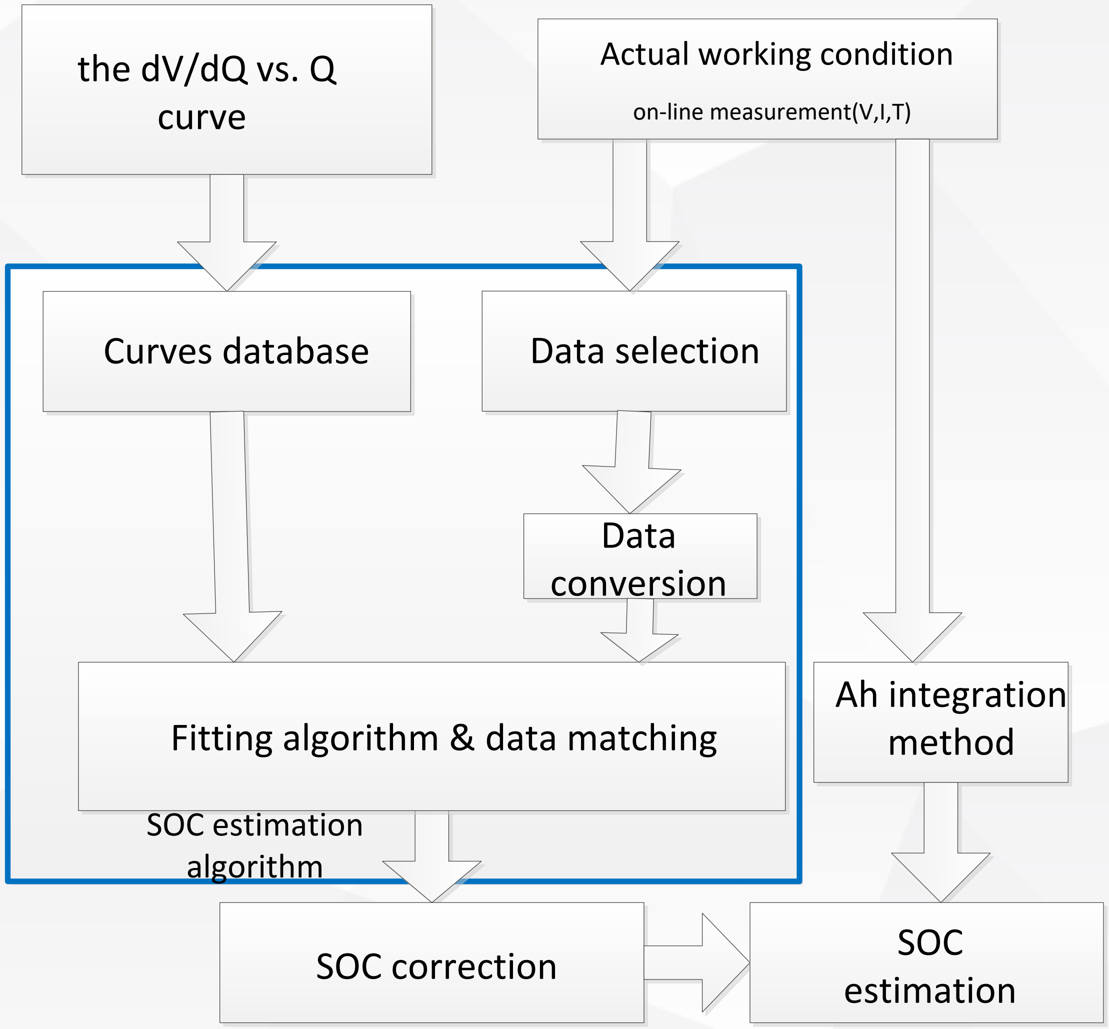
(b)



(c)

- The OCV-SOC curve of the battery can be divided into four working ranges.
- In the flat area of the battery, the performance of the battery is relatively stable, which is is helpful to calculate the battery capacity. So, we can choose the peak 2 as the interval of capacity calculation.
- The voltage of the battery in the identification area of the battery changes greatly, which can be used as the the battery SOC estimation range.

The SOC Estimation Algorithum



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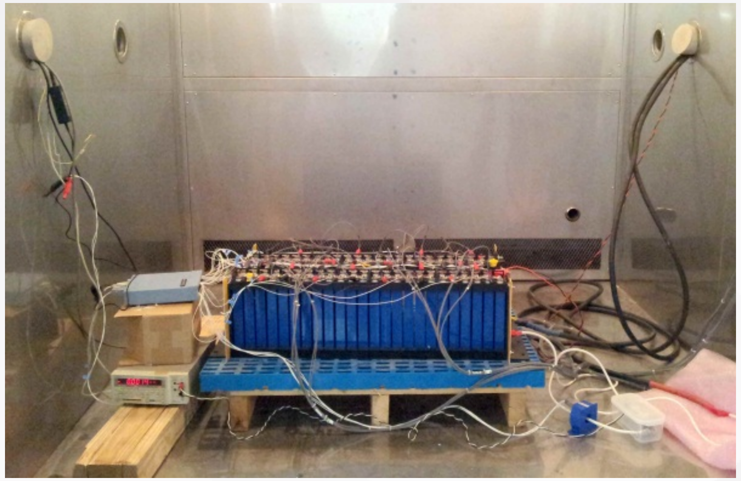
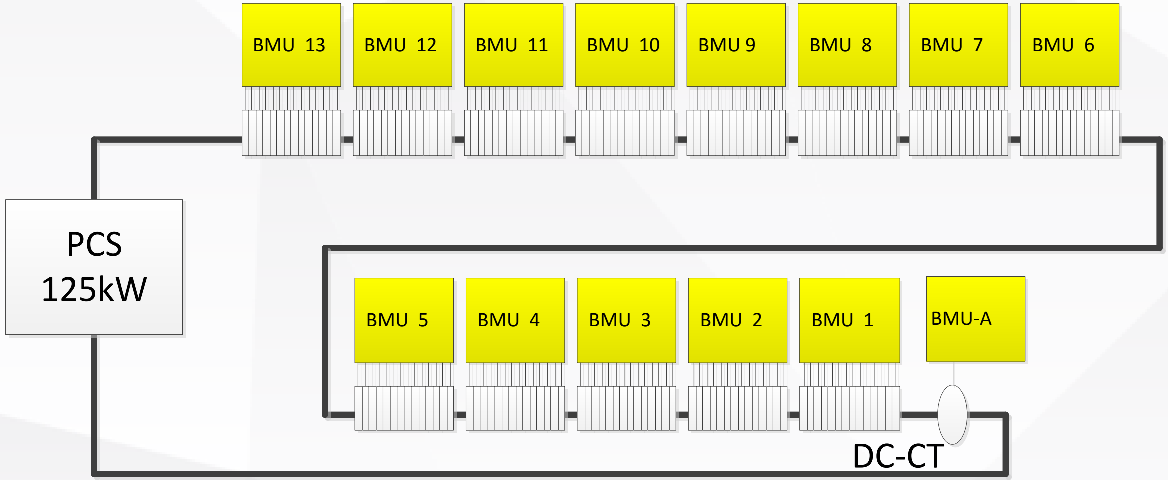
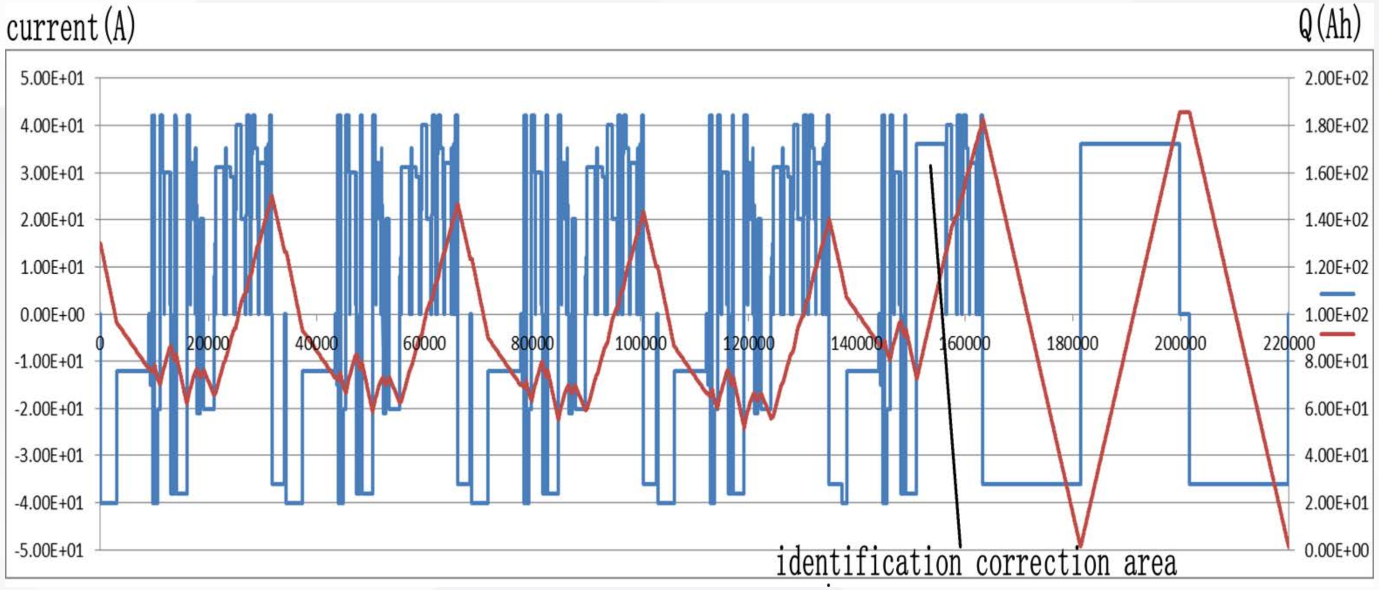
Experiment





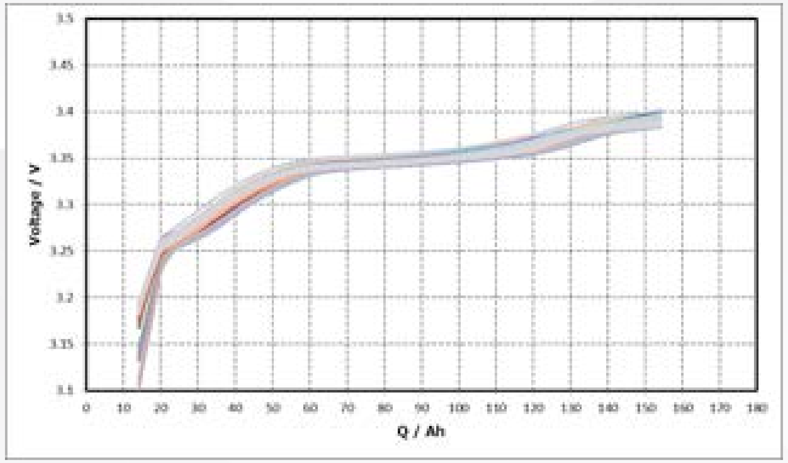
- ✓ The experimental battery storage energy system is made up of 13 packs in series, each pack is connected in series with the 16 battery, and the battery is connected in parallel with the 3 cells.
- ✓ The capacity of the battery is about 180Ah,and the temperature is 25℃.
- ✓ In order to verify the difference between the estimated value and the true value of SOC, the high precision current sensor and digital table is installed to record the current value, and the ampere hour integration method is used to calculate the actual charge and discharge capacity of the storage battery.

Experiment

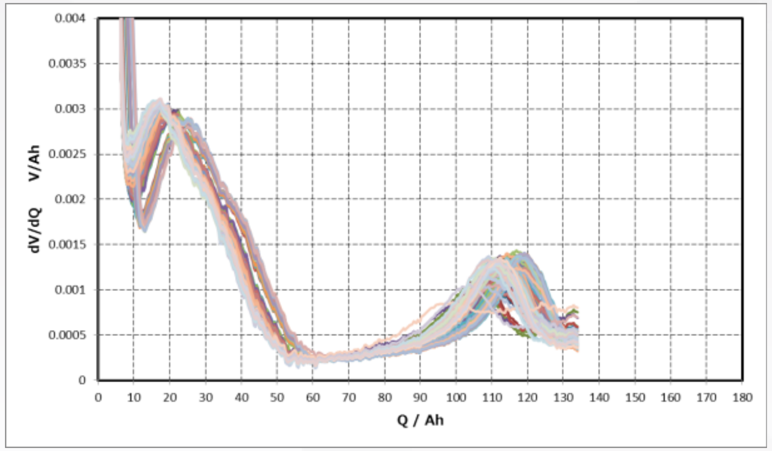


- ✓ Test cycle data: the actual energy storage battery system in a period of time (about 40000 seconds) of one wind farm for power tracking data.
- ✓ The experiment lasted for 5 test cycles.

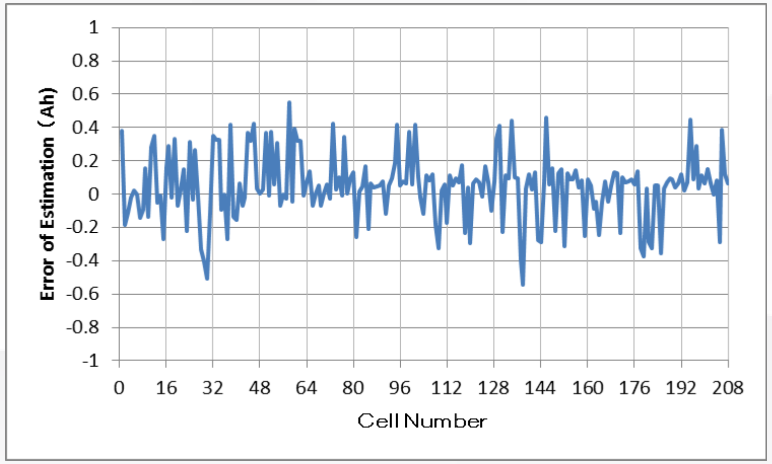
The experimental results



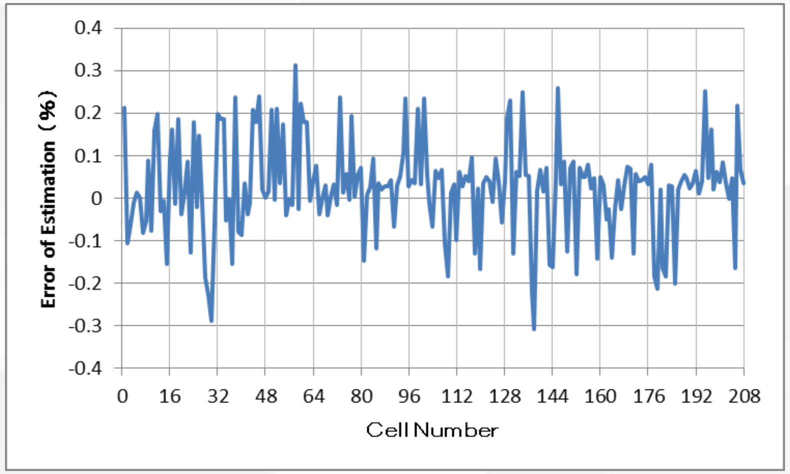
（a）the voltage-capacity curve



(b) the dV/dQ-Q curve



（c）the capacity error



(d) the SOC error

- ✓ the battery capacity is always between 22～160Ah in conversion, and the SOC is between about 10%～90%.
- ✓ Compared with the true value, the capacity error is controlled at ±0.5Ah, and the SOC estimation error is controlled at ±0.6%.

四 Conclusions

- ✓ The algorithm has a high precision after the system run about 55.55 hours continuously, and the SOC error can be controlled within the range of 1%. .
- ✓ The algorithm is feasible and applicable in the practical working conditions of the energy storage system.
- ✓ The algorithm is simple, and can shorten the measurement time.
- ✓ This algorithm can realize on-line estimation of battery .
- ✓ When the temperature is low, the estimation error will increase, and further research on the battery characteristics is needed.
- ✓ The accuracy of the algorithm needs to be further verified under longer and different working conditions.

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