Title
Experimental Validation of Voltage-Based State-of-Charge Algorithm for Power Batteries

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Experimental Validation of Voltage-Based State-of-Charge Algorithm for Power Batteries

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by

Zhuo Jia

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ABSTRACT OF THE THESIS

Experimental Validation of Voltage-Based State-of-Charge Algorithm for Power Batteries

by

Zhuo Jia

Master of Science in Electrical Engineering
University of California, Los Angeles, 2014
Professor Lei He, Chair

State-of-Charge (SOC) is a key to modeling and managing the battery system. Several algorithms have been developed to calculate the OCV (open-circuit voltage) based on the terminal voltage and terminal current of batteries. Then SOC can be obtained based on the monotonic mapping between SOC and OCV. Using the measured terminal voltage and current from an EV(electric vehicle) fleet, this thesis solves the following two problems: (1) how to develop a robust mapping between OCV and SOC; and (2) experimentally validate the accuracy of a voltage-based SOC algorithm that is universal to all battery types.

The thesis of Zhuo Jia is approved.

Paulo Tabuada

Sudhakar Pamarti

Lei He, Committee Chair

University of California, Los Angeles

2014

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Chapter 1

INTRODUCTION

Batteries are one of the most used energy storage mechanisms for clean vehicles, renewable energy harvesting, and smart grids. These batteries are often called power batteries to distinguish them from smaller batteries used in portable consuming electronics.

This thesis focuses on power batteries that are used in electrical vehicles (EV). How to model and manage such batteries is in fact mission critical, i.e., needs a high reliability. We will study the state of charge (SOC) problem in this thesis.

SOC measures how much energy a battery has. By definition, a fully charged battery has 100% SOC. One common way to obtain SOC is to first calculate the open circuit voltage (OCV) of a battery cell, and then derive the SOC of this cell based on the monotonic dependency of OCV on SOC. This type of approach is called voltage based approach in the literature. Another type of method is called current based approach, where SOC is calculated by integrating charging and discharging current. Current based approach is accurate in the lab setting. In EV applications, it however suffers from error accumulation and it is also difficult to recover from a sudden error during integration. Therefore, EV often uses a combination of current and voltage based methods to calculate SOC.

Several voltage based approaches have been developed recently. There still exist the following two open problems: (1) how to decide the monotonic relationship between SOC and OCV; and (2) how to validate the accuracy of a voltage-based SOC against the measured SOC. These two are the topics to be studied in this thesis.

The remaining of this thesis is organized as following. In Chapter 2, we introduce background of SOC calculation. In Chapter 3, we discuss how to measure battery terminal voltage and terminal current, and present measurement data. In Chapter 4, we discuss how to derive SOC and OCV relationship and validate the accuracy of a voltage-based SOC, both based measured voltage and current.

Chapter 2

BACKGROUND

2.1 Battery models to calculate SOC

SOC is expressed as a percentage, decided by the ratio between the remaining energy of a battery and the total energy when the battery is fully charged. By definition, SOC is 100% when a battery is fully charged.

SOC is needed for battery management. For example, the battery of hybrid car is often charged between 20% and 95% SOC [3]. It can also be used in dynamic power management [4], battery scheduling [5, 6], and efficient battery traffic shape and routing [7].

A general framework is presented in [10] for SOC estimation by combining voltage-based and current-based SOC estimations, where

$$\mathrm{SOC}=\alpha \mathrm{SOC}_c+(1-\alpha)SOC_v \qquad (1)$$

$$\mathrm{SOC}_c(t)=SOC_C(0)-\frac{1}{Q}\int_0^t I(t)dt \qquad (2)$$

where SOC_c is the Coulomb-counting (or current) based SOC and SOC_v is the voltage-based SOC. SOC_c is estimated based on the amount of charge that has been extracted from the battery, and can be simply calculated by (2). Q is a constant to relate the current with the charge. SOC_v is the estimated SOC based on the open-circuit voltage (OCV) of the battery.

It has been observed that the OCV has a monotonic dependency on the SOC. The dependency of OCV on SOC for a Lithium Ion battery is shown in figure 1 from [1, 13]. While SOC_c clearly has a dependency on the usage history, SOC_v does not depend on the usage history if the OCV calculation does not depend on the history. It is often the case that the OCV calculation only depends on a very short period of terminal voltage and current at the selected time point, therefore the voltage-based SOC can recover from an error quickly and it has no accumulation of errors.

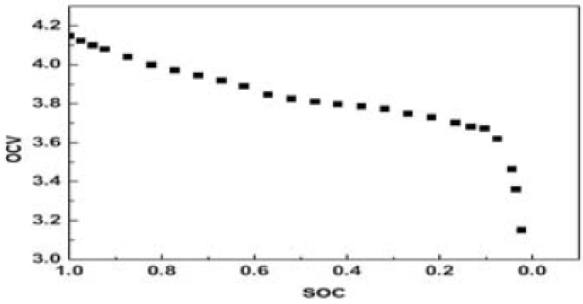
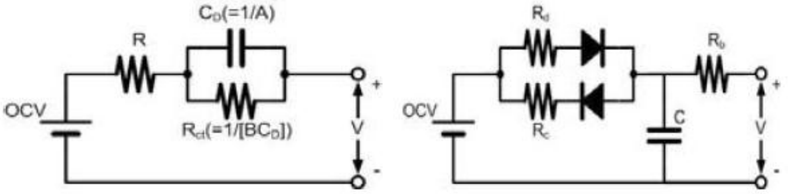
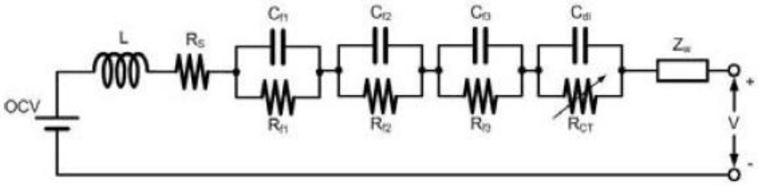


Figure 1: Dependency of OCV on SOC for a Lithium Ion Battery

In EV application, it is not feasible to measure the OCV of a battery by disconnecting the battery and the loading. Most of existing approaches calculate the OCV based on equivalent circuit models for batteries. In [2, 14], the models in Figure 2 are used. In general, these models are developed for specific types of batteries, and parameters need to be tuned for different battery models because their chemical processes are different.



(a) RC pair model. (b) Nonlinear model.



(c) RC network model.

Figure 2: Examples of battery models used in literature

Below, we will discuss an OCV algorithm, which does not assume an equivalent circuit model for the battery. Therefore, it applies to all batteries and can be called a universal model. This leads to the voltage-based SOC model to be validated in this thesis.

2.2 A Universal OCV Algorithm

The open circuit voltage is the voltage across the battery terminals when we disconnect the external load from the battery. According to [1], OCV can be calculated based on terminal voltage and terminal current without disconnecting load by a window based OCV extraction method. In a window of a short period of time, we can treat OCV and SOC as constants. This converts the problem from a time-varying nonlinear system to a time-invariant linear system. Therefore, instead of using time-discrete functions, we can use time continuous notations such as V(t) and express them for discrete times such as $V(t_1)$ and $V(t_2)$.

Applying the superposition theorem, we can decompose the terminal voltage V(t) into two parts given by

$$\mathrm{V(t)} = V_{zi}(t) + V_{zs}(t) \tag{3}$$

where the zero-input response related to the terminal voltage with no discharge current is $V_{zi}(t)$ and the zero-state response with regard to the terminal voltage V is $V_{zs}(t)$ The zero-state response of our system has a discharge current of i(t) with the voltage source shorted.

Since the battery is assumed to be linear and time-invariant in each time window, the system impulse response h(t) is linear and thus the zero-state response could be expressed as the convolution of the discharge current and the impulse response. Therefore, we have

$$\mathrm{V(t)} = V_{zi}(t) + \mathrm{i}(t) * h(t) \tag{4}$$

It is clear that for different battery models, most likely we end up with different system transfer responses. In this algorithm, instead of calculating the analytical function of h(t) for any specific battery model, we can directly extract the OCV without utilizing any equivalent circuit model.

Suppose the current time is t where $0 \leq t \leq t_w$ and we extract SOC during period $0 \leq t \leq t_w$. Under the assumption that the discharge current is always zero when t<0, the battery is disconnected from the load and the zero-input response is zero. However, when t>0, the zero-input response equals to the OCV if the self-discharge effect is not considered, which allows the further decomposition of the system equations as given in below.

$$V_{zi}(t) = OCV \times u(t) \tag{5}$$

$$\text{Where } u(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \tag{6}$$

We then apply the following time-discrete algorithm to calculate *f*(t) which satisfies

$$f(t) * i(t) = \delta(t) \tag{7}$$

$$\text{Where } \delta(t) = \begin{cases} 0, & t \neq 0 \\ 1, & t = 0 \end{cases} \tag{8}$$

Then we can get follow equations

$$f(t) * [V(t) - V(0)] = [i(t) * h(t)] * f(t) \tag{9}$$

$$\delta(t) = f(t) * i(t) \tag{10}$$

After we obtain *f*(t), we can then further decompose equation (1) step by step by the following equations,

$$V_f(t) = \mathrm{f(t)} * V(t) = \mathrm{f(t)} * (V_{zi}(t) \ + \ V_{zs}(t))$$

$$= \mathrm{f(t)} * (OCV \times u(t) \ + (\mathrm{i}(t) * h(t)$$

$$= \mathrm{OCV} \times u_f(t) + \ \delta(t) * h(t)$$

$$= \mathrm{OCV} \times u_f(t) + \ h(t), \quad 0 \leq \mathrm{t} \leq \ t_w \qquad (11)$$

According to measured response spectrum [1], the frequency domain response of the battery model is finite. Since the final value theorem [13] states

$$\lim_{\mathrm{t}\to\infty} h(t) = \ \lim_{\mathrm{s}\to 0} sH(s) = 0 \qquad (12)$$

Thus, $$\lim_{\mathrm{t}\to\infty} \frac{V_f(t)}{u_f(t)} = OCV \qquad (13)$$

With $\mathrm{t} \to \infty$, the system transfer response approaches zero and the open-circuit voltage could be calculated as $V_f(t)$ divided by $u_f(t)$ for the current time window. However, we can never approximate OCV at an infinite time window. To minimize the error brought by non-zero transfer response h(t), we extract the OCV at the time when $u_f(t)$ has the largest value within the current time window.

After extracting the OCV value for the current time window, the equation for h(t) could be derived as Equation (13).

$$\mathrm{h(t)} \ = \ V_f(t) - OCV \times u_f(t) \qquad (14)$$

Similarly, since we do not estimate OCV at t=∞ the impulse response will not hold accurate if t is very large or h(t) is close to zero. The impulse response is accurate only under the situation where t is relative small.

For the next time window, as the battery retains the steady state for some time, the discharge current from the previous window affects the zero-input response in the current time window. The assumption that the discharge current is always zero in the past is no longer true. In order to apply the same OCV extraction process for the next window, we need to modify the terminal voltage, taking into account the discharge current from the previous window. Since the impulse response from the previous window and the discharge current from the current window are known, we have

$$V'(t) = V(t) - \int_{t-t_e}^{t_w} i(\tau)h(t-\tau)d\tau \qquad (15)$$

Where t_e is the end time of the previous window. With the updated terminal voltage V'(t), we can apply the same OCV extraction procedure given in Equations (10)-(13).

There is a special case where the above algorithm cannot be used. When t approaches infinity, if $u_f(t)$ converges to zero, the algorithm could not be utilized to extract the OCV. In other words, suppose $u_f(t_{1,}\, t_{2,}\, t_n \dots)$ are the time-discrete samples for $u_f(t)$. If these samples equal to zero for n≥2, then the proposed algorithm does not work as in this case, the discharge current is always a constant. Fortunately in this case, the battery can be viewed as a simple resistive network. Therefore, we have

$$\mathrm{OCV} = \mathrm{V(t)} - I(t)R_e \tag{16}$$

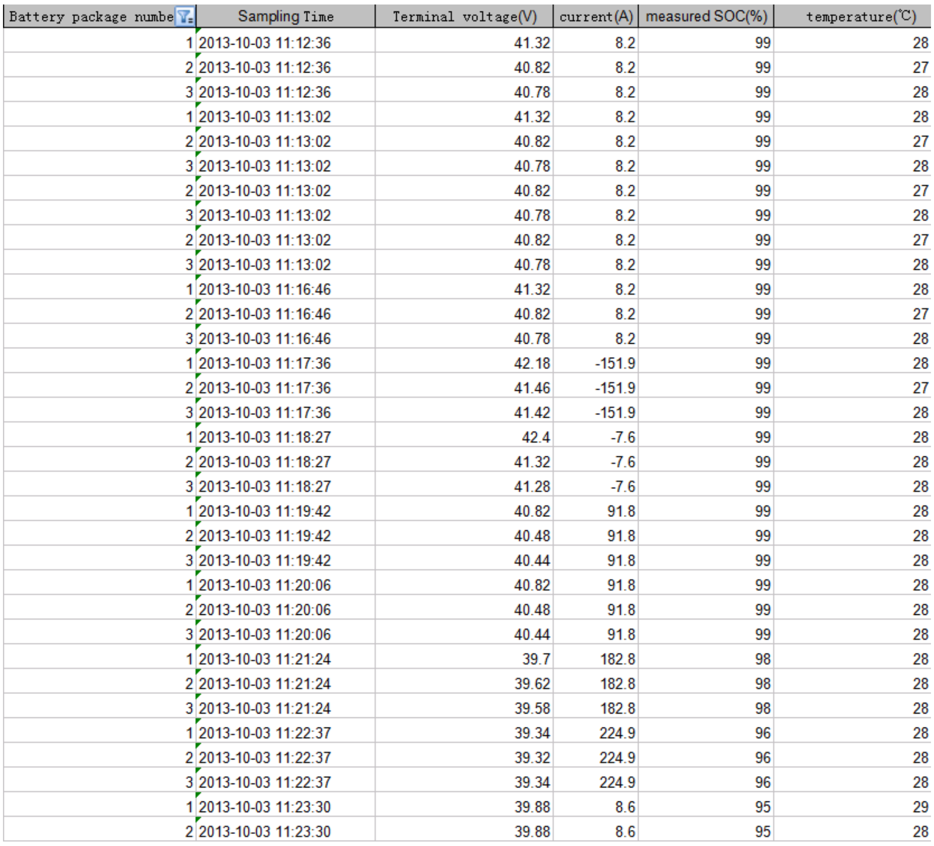
where R_e is the effective resistance for the battery.

Chapter 3

BATTERY MEASUREMENT

For our measurement, we used an EV fleet, and measured the terminal voltage, current and SOC of battery packs with real driving profiles. We also recorded battery working temperature.

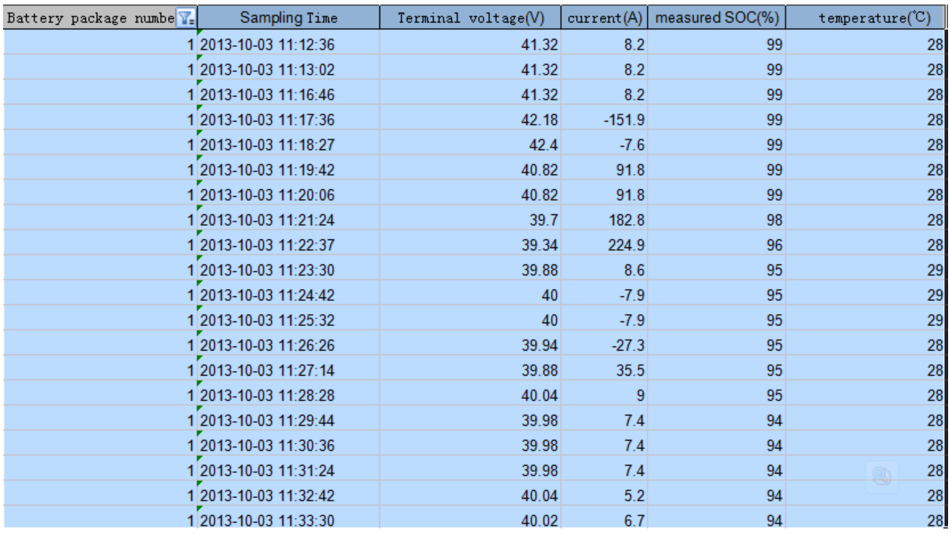
The battery used in experiment is one type of Lithium-Ion batteries with voltage around 3.5v. We measured eight battery packs in experiment. There are either 12 battery cells for each pack. We recorded data for one cycle of charging and discharging. Note that the batteries are not fully discharged in our experiment. The voltage and current were measured using voltage and current sensors. The measured SOC was provided by an industrial strength method with an error. The error information is confidential.



Battery package numbe	Sampling Time	Terminal voltage(V)	current(A)	measured SOC(%)	temperature(℃)
1	2013-10-03 11:12:36	41.32	8.2	99	28
2	2013-10-03 11:12:36	40.82	8.2	99	27
3	2013-10-03 11:12:36	40.78	8.2	99	28
1	2013-10-03 11:13:02	41.32	8.2	99	28
2	2013-10-03 11:13:02	40.82	8.2	99	27
3	2013-10-03 11:13:02	40.78	8.2	99	28
2	2013-10-03 11:13:02	40.82	8.2	99	27
3	2013-10-03 11:13:02	40.78	8.2	99	28
2	2013-10-03 11:13:02	40.82	8.2	99	27
3	2013-10-03 11:13:02	40.78	8.2	99	28
1	2013-10-03 11:16:46	41.32	8.2	99	28
2	2013-10-03 11:16:46	40.82	8.2	99	27
3	2013-10-03 11:16:46	40.78	8.2	99	28
1	2013-10-03 11:17:36	42.18	-151.9	99	28
2	2013-10-03 11:17:36	41.46	-151.9	99	27
3	2013-10-03 11:17:36	41.42	-151.9	99	28
1	2013-10-03 11:18:27	42.4	-7.6	99	28
2	2013-10-03 11:18:27	41.32	-7.6	99	28
3	2013-10-03 11:18:27	41.28	-7.6	99	28
1	2013-10-03 11:19:42	40.82	91.8	99	28
2	2013-10-03 11:19:42	40.48	91.8	99	28
3	2013-10-03 11:19:42	40.44	91.8	99	28
1	2013-10-03 11:20:06	40.82	91.8	99	28
2	2013-10-03 11:20:06	40.48	91.8	99	28
3	2013-10-03 11:20:06	40.44	91.8	99	28
1	2013-10-03 11:21:24	39.7	182.8	98	28
2	2013-10-03 11:21:24	39.62	182.8	98	28
3	2013-10-03 11:21:24	39.58	182.8	98	28
1	2013-10-03 11:22:37	39.34	224.9	96	28
2	2013-10-03 11:22:37	39.32	224.9	96	28
3	2013-10-03 11:22:37	39.34	224.9	96	28
1	2013-10-03 11:23:30	39.88	8.6	95	29
2	2013-10-03 11:23:30	39.88	8.6	95	28

Table1: Measured parameters of battery pack No.1 to No.3

We presented some of the measured data in Table 1. The battery packs (No. 1 – No.3) in Table 1 have 12 battery cells each pack. These packs are used for different EV models. Table 2 presents more data points for battery pack No. 1. As one can see, the sampling time difference is about one minute. Because the measurement was performed during road test driving, the current varies a lot for a small voltage range. In these tables, positive current means discharging, and negative current means charging. Batteries are charged when the EV is decelerated.



Battery package numbe	Sampling Time	Terminal voltage(V)	current(A)	measured SOC(%)	temperature(℃)
1	2013-10-03 11:12:36	41.32	8.2	99	28
1	2013-10-03 11:13:02	41.32	8.2	99	28
1	2013-10-03 11:16:46	41.32	8.2	99	28
1	2013-10-03 11:17:36	42.18	-151.9	99	28
1	2013-10-03 11:18:27	42.4	-7.6	99	28
1	2013-10-03 11:19:42	40.82	91.8	99	28
1	2013-10-03 11:20:06	40.82	91.8	99	28
1	2013-10-03 11:21:24	39.7	182.8	98	28
1	2013-10-03 11:22:37	39.34	224.9	96	28
1	2013-10-03 11:23:30	39.88	8.6	95	29
1	2013-10-03 11:24:42	40	-7.9	95	29
1	2013-10-03 11:25:32	40	-7.9	95	29
1	2013-10-03 11:26:26	39.94	-27.3	95	28
1	2013-10-03 11:27:14	39.88	35.5	95	28
1	2013-10-03 11:28:28	40.04	9	95	28
1	2013-10-03 11:29:44	39.98	7.4	94	28
1	2013-10-03 11:30:36	39.98	7.4	94	28
1	2013-10-03 11:31:24	39.98	7.4	94	28
1	2013-10-03 11:32:42	40.04	5.2	94	28
1	2013-10-03 11:33:30	40.02	6.7	94	28

Table 2 Partial data of battery pack 1

In Chapter 4, we will use the measurement data for battery packs 1 and 2 from Table 1 to calculate the relationship between OCV and SOC. Because the temperature during measurement is not constant, the resulted OCV and SOC relationship in fact takes into account the temperature impact implicitly. Because all battery packs have the same battery cell type, the OCV and SOC relationship is the same for all packs. We therefore will apply the resulted OCV and SOC relationship to the rest of battery packs, and validate the accuracy of the voltage-based SOC algorithm.

Chapter 4

VALIDATION OF VOLTAGE-BASED SOC ALGORITHM

4.1 Overview

Before validation, we separate the measured data into two groups. Group 1 is the measured data for battery packs 1 and 2, and group 2 is measured data for battery pack 3.

We begin with measured terminal current and voltage of battery group 1 to estimate the OCV based on the universal OCV algorithm developed in [1] and described in Chapter 2. We label the average value of OCV for a given SOC over battery packs 1 and 2 as OCV_{12}. We then find the monotonic mapping between OCV_{12} and the measured SOC, which is the OCV and SOC relationship to be used in this thesis. We call the relationship as $f(v)$.

We then use measured terminal current and voltage of battery group 2 to calculate the OCV using the same universal OCV algorithm and label it as OCV_3. We use OCV_3 and $f(V)$ to calculate the voltage-based SOC of group 2. Finally we compare the current-based SOC, the voltage-based SOC, and the measured SOC for group 2.

4.2 Calculating the relationship between SOC and OCV

Because the universal OCV algorithm assumes that battery is a LTI system in every time window and the length of the window is required to be small enough, actual data should be sampled at a high frequency. However, due to the limitation of actual sampling device and sampling procedure, the sampling interval is one minute per sample in our experiment. We applied the cubic interpolation in MATLAB to obtain more samples and used both measured and interpolated data in our post-measurement analysis to be presented below.

Using the universal OCV algorithm for batteries [1], we can calculate the OCV by the terminal voltage and the terminal current. Figure 3 plots the relationship between OCV and time for battery pack 1. The ideal OCV should be a smooth curve that decreases with time, but the curve in Figure 3 has lots of spikes. One reason for these spikes is that we do not have enough data points between five thousand and seven thousand seconds in our measurement. Moreover, the sampling rate of the measurement device is not high enough to capture the quick changes in current that yield these spikes in the OCV curve.

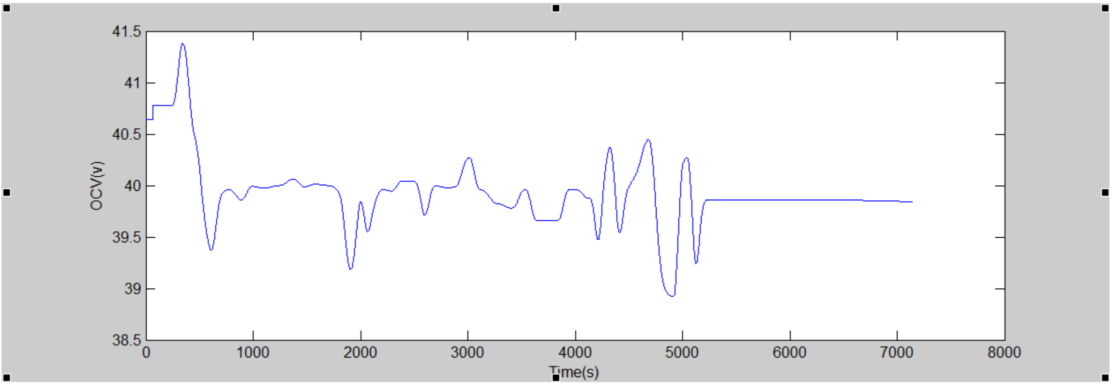
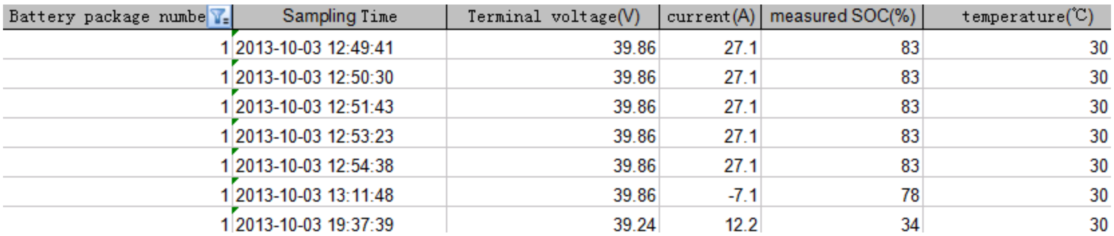


Figure 3: Calculated OCV of battery pack 1

Table 4 shows that there is no data sampled between 1:11pm and 7:37pm because the car is not driving. We did not perform any experiment during this period of time.



Battery package numbe	Sampling Time	Terminal voltage(V)	current(A)	measured SOC(%)	temperature(℃)
1	2013-10-03 12:49:41	39.86	27.1	83	30
1	2013-10-03 12:50:30	39.86	27.1	83	30
1	2013-10-03 12:51:43	39.86	27.1	83	30
1	2013-10-03 12:53:23	39.86	27.1	83	30
1	2013-10-03 12:54:38	39.86	27.1	83	30
1	2013-10-03 13:11:48	39.86	-7.1	78	30
1	2013-10-03 19:37:39	39.24	12.2	34	30

Table3: The last part of data of battery pack 1

Figure 4 presents calculated OCV and SOC for battery pack 1. One can see that there is a wide range of OCV values for a given SOC. In order to achieve a more smooth and more accurate *f(v)* curve, we decide to use the average value of OCV over battery pack 1 and 2 for a given SOC to decide the relationship between OCV and SOC.

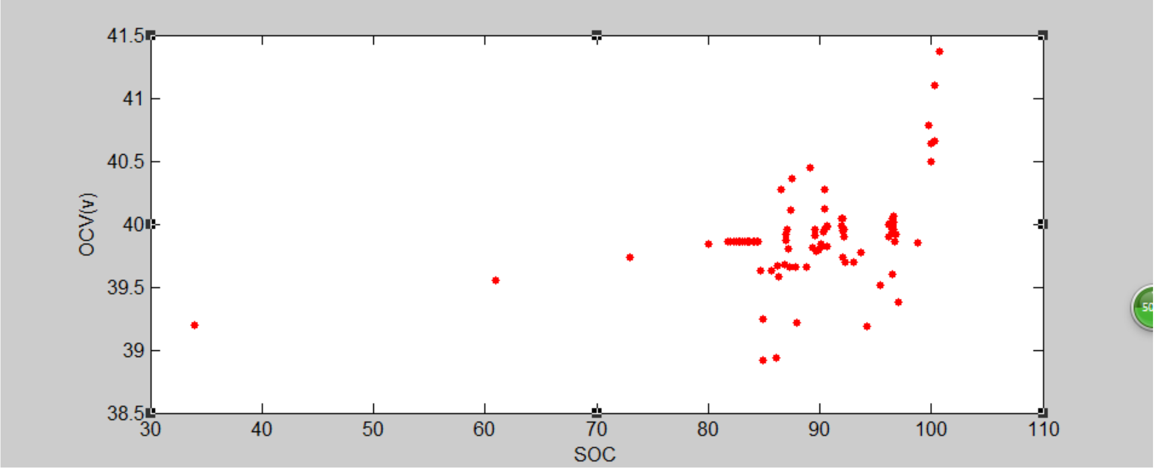


Figure 4: OCV vs. SOC of battery pack 1

The curve in Figure 5 is the resulted relationship between OCV_{12} and SOC (or so called *f(v)*).

The large stars in Figure 5 indicate these points that are far away from the rest of data points. These data points are regarded as abnormal (possibly due to mistakes in battery measurement) and are excluded for our curve fitting. We use CFTOOL in MATLAB to get the function *f(v)* based on non-excluded data points. CFTOOL is a MATLAB tool that performs automatic curve fitting to extract an analytic function from a set of data points.

As shown in Figure 5, the data points are grouped into two regions A and B, each with a different fitting function. We make sure that the two curves fitted for the two regions are continuous at the intersection of regions A and B. Below we use the resulted two-segment function *f(v)* to calculate the SOC of battery pack 3.

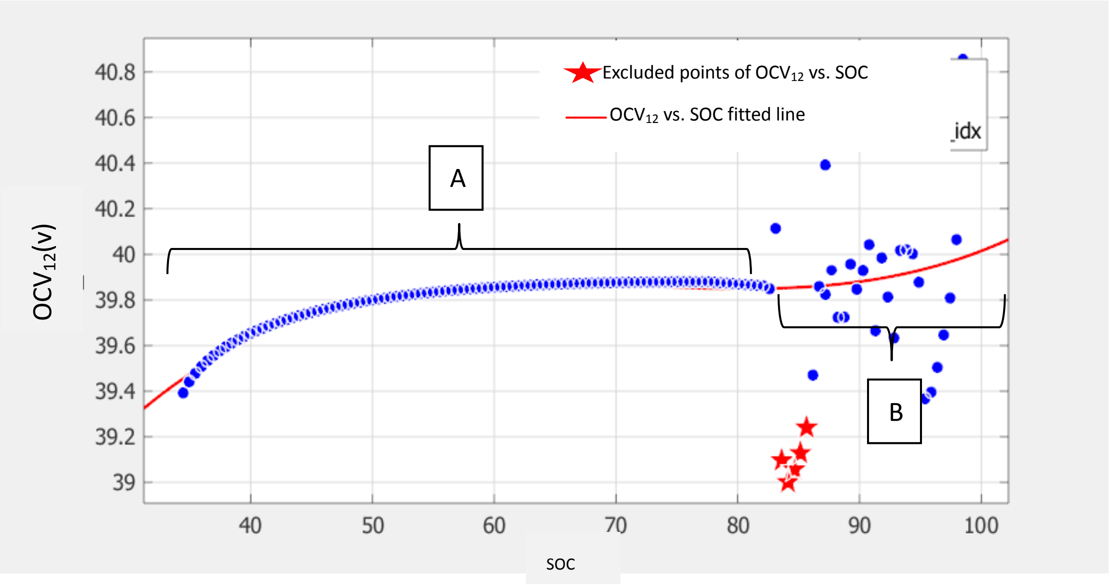


Figure 5: Two-region OCV_{12} and SOC relationship

4.3 Error of the Voltage-based SOC

Based on the universal OCV algorithm for batteries, we calculated the OCV of battery pack 3. Then we get the voltage-based SOC based on the calculated OCV and OCV-SOC relationship *f(v)* in Figure 5.

Figure 6 compares the voltage-based SOC and the measured SOC which is regarded as the golden case in our experiments. The maximum difference is 8.8%, the minimum difference is 0.007%, and the average difference is 3.1%.

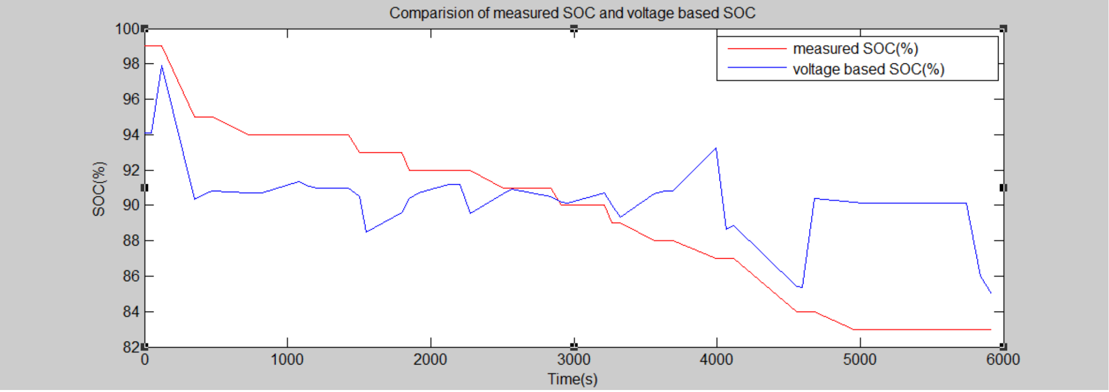


Figure 6: Comparison of measured SOC and voltage-based SOC

As one can see from Figure 6, the relative difference between the measured SOC and voltage-based SOC at the beginning and end of the curve is larger than the difference in the center section. When time is around four thousand seconds, the voltage-based SOC is increased suddenly. We speculate that this increase is due to the measuring tool having a relatively low sampling rate compared to the change of driving speed.

4.4 Error of the Current-based SOC

Figure 7 plots current versus time, and the current has no obvious trend. The discharge process of battery has a constant voltage, but the current changes frequently. We used current integration to calculate current-based SOC.

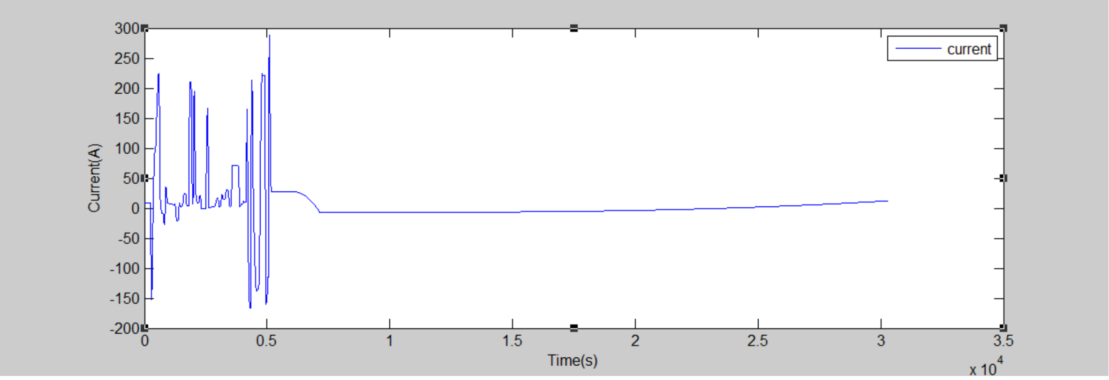


Figure 7： Discharging current vs. time

Current integration requires an initial state of SOC. In Formula (16) below, ‘SOC_current’ is the value of the current-based SOC. We have

$$\mathrm{SOC\_current} = (\mathrm{Cap}_0 - \mathrm{elapsed\_cap})/\mathrm{Cap}_0 \qquad (17)$$

Where Cap_0 is the initial capacity of the battery, and the elapsed capacity is the power consumption.

As we have introduced in Chapter 3, the initial value of battery capacity is 250Ah in our experiment. Then we get the below formula (17) after calculated elapsed capacity by integrating the terminal current. We use 3600 to divide the current(t) due to that the unit of time is second but the unit of capacity is Ah.

$$\text{SOC\_current} = (250 - \int_0^t \frac{current(t)}{3600})/250 \qquad (18)$$

In Figure 8, the blue line shows the relationship between the current-based SOC for battery pack 1 and time. One can see that the current-based SOC does not have a lot of noise. As we compare the measured SOC with the current-based SOC, the absolute error averaged over the time range given by Figure 8 is 3.6%

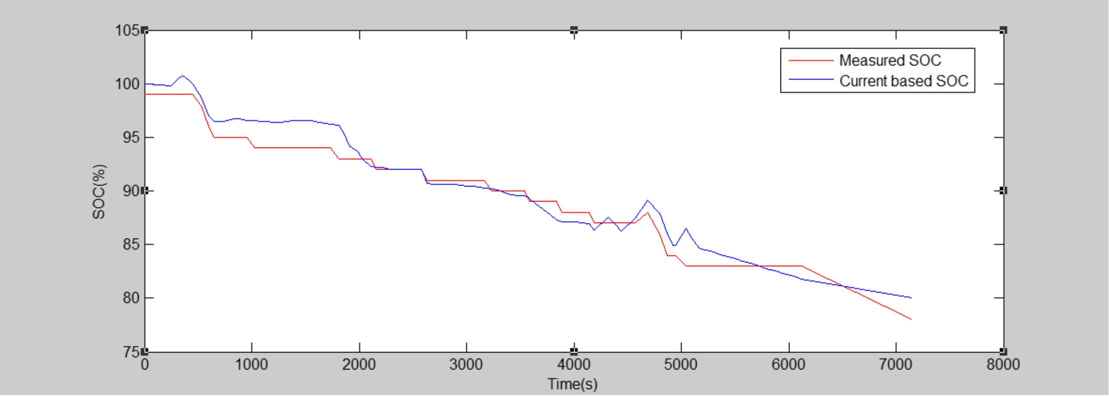


Figure 8: Comparison between Measured SOC and current-based SOC

4.5 Comparison between voltage-based SOC and current-based SOC

Figure 9 compares the voltage-based SOC and the current-based SOC for battery group 2. The line in the figure is fitted to minimize the errors to all data points in the figure. It is virtually 45 °, which indicates that the two types of SOC on average are almost equal as each data point is decided by one voltage-based SOC and its correspondent current-based SOC.

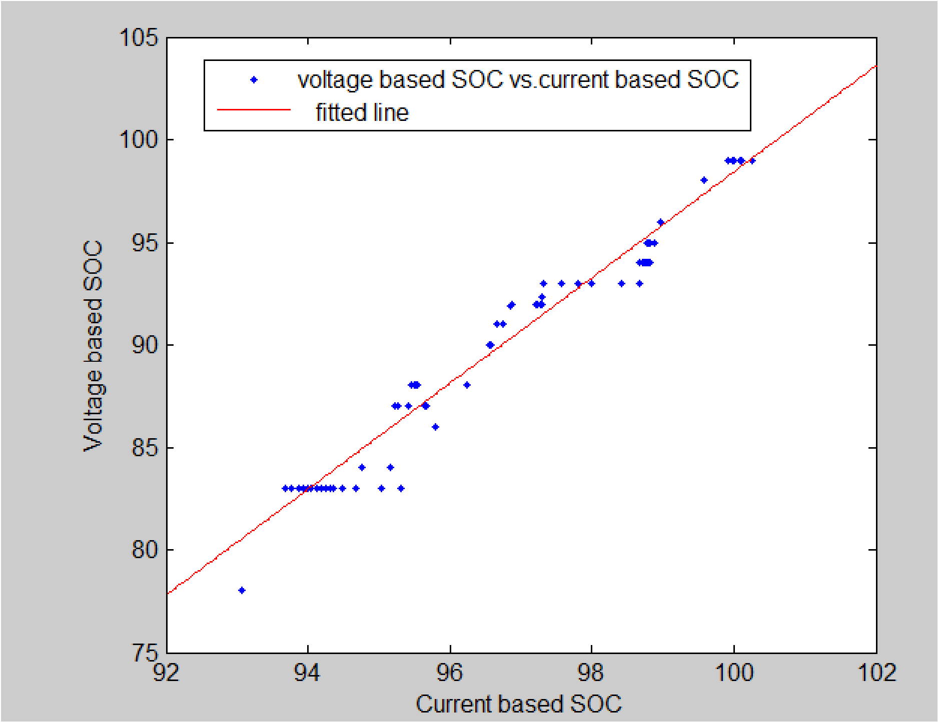


Figure 9: Comparison between the voltage-based SOC and the current-based SOC of battery pack 3

Chapter 5

CONCLUSIONS AND FUTURE WORKS

In this thesis, we have used the measured data to obtain OCV and SOC relationship. We have also compared voltage-based SOC with the measured SOC. The voltage-based SOC by the universal OCV algorithm from [1] has a good accuracy given that the relative error of 3.1% contributes only to a small difference of the total mileage an EV can drive, given that large relative differences often happen for lower SOC values. This little difference or error can be tolerated in practice by using a small error margin in terms of the absolute value for the estimated driving range.

Furthermore, we have also compared the current-based SOC with the measured SOC. The resulted error is 3.6% on average. As one can see, the accuracy of the current-based SOC is close to that for the voltage based SOC when there is no upset in the current measurement and no error accumulation in integrating the current as in our experiment. Note that it is doable to exclude current measurement upset and error accumulation in the controlled experiments, but it is often difficult to do in general (or in large scale deployment of EVs).

An alternative way to get a robust SOC and OCV relationship is to plot SOC (either measured or current-based) and OCV points for many battery packs, and then synthesize a curve to minimize the error with respect to these points. This may lead to smaller error compared to using the average OCV as in this thesis. Due to that this method needs more data points, it is planned as a future work when we are able to obtain more measurement for more battery packs. More battery measurement is in fact an ongoing work.

One potential way to improve the voltage based estimation method is using a higher sampling rate. We verify this by running Dualfoil, a software simulator for batteries. In our simulation, we generate one sample per second, each sample including terminal voltage, terminal current, and accurate OCV (ground truth). We then calculate OCV from terminal voltage and terminal current, and compare the calculated OCV with the ground truth. As shown in Figure 10, the two types of OCV are close to each other. Note that the initial value of OCV we used in simulation is 4.06v.

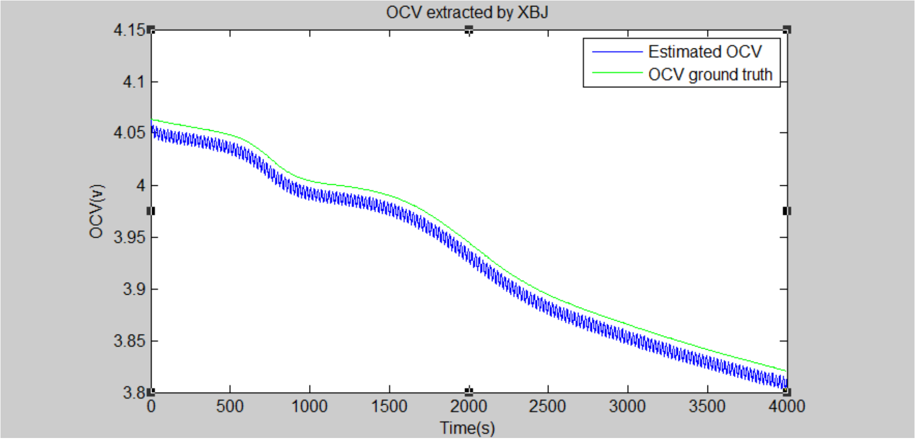


Figure 10: The OCV estimated with higher sampling rate

In the real scenario, the sampling rate cannot be that high due to the equipment limitation. A suitable sampling rate may be developed in the future to reach the required accuracy with constraints on sampling cost. In addition, it would be a good research to develop voltage-based SOC models using different ways of sampling methodologies such as compressive sensing.

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