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SOC Estimation Based on the Model of Ni-MH Battery Dynamic Hysteresis Characteristic

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Abstract

Accurate estimation of battery State of Charge (SOC) is essential for battery control and effective energy management of Hybrid Electric Vehicles (HEV). Taking the dynamic hysteresis characteristic of battery into account, an equivalent circuit model is built. Based on the Hybrid Pulse Power Characterization (HPPC) test data, the parameters was adopt by means of on-line least-square regression. The accuracy of SOC estimation algorithm was verified by the energy balance test, the energy consumption test, New Europe Driving Cycle (NEDC) test and real vehicle driving cycle test, respectively. The experimental results show that this method is with high accuracy and reliability.

Keywords: *Ni-MH battery, State of charge , Dynamic hysteresis characteristic , Equivalent circuit*

1 Introduction

State Of Charge (SOC) is a critical parameter for the control and energy management of battery systems. Accurate SOC value is essential to battery life and fuel economy, especially for hybrid electric vehicles (HEV). However, a battery SOC is not directly measurable during vehicle operation. Therefore, an efficient and effective algorithm is needed to estimate battery SOC from measured signals such as battery terminal voltage and current during normal vehicle operation. The importance and challenges of determining battery SOC have been discussed in [1-2].

Open circuit voltage of the Ni-MH battery and a battery SOC are related. A battery SOC can be estimated with open circuit voltage of the Ni-MH battery. In this paper, the equivalent circuit model is built through characteristics of the Ni-MH battery for SOC Estimation.

2 The open circuit voltage characteristic of Ni-MH battery

The relationship between VOC and SOC can be get though HPPC article [3]. The curve of the relationship has different tracks of the charging process or the discharging. The former always had higher VOC at the same SOC except SOC=1 or SOC=0. The two curves component a Hysteresis one (Fig.1).

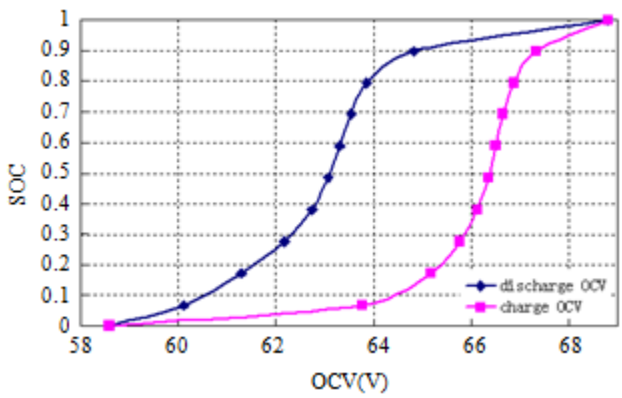

Fig.1: The relationship curve of open circuit voltage and SOC

A curve was provided to prove this characteristic by test. Under the condition of the battery venting, battery was charged to full with 1/3C current and

tabled for 1 hour. Discharged to SOC=0.1 with the same constant-current and tabled for another 1 hour. Charged to SOC=0.9 with the same constant-current and tabled for 1 hour. Following this rules and ending at SOC=0.5.
The curve describes this process in Fig.2. A conclusion can be proved that the right SOC depending on the whole charging-discharging process at the same VOC as a result of the Ni-MH battery's Hysteresis characteristic, which makes the Accurate estimation of SOC difficult.

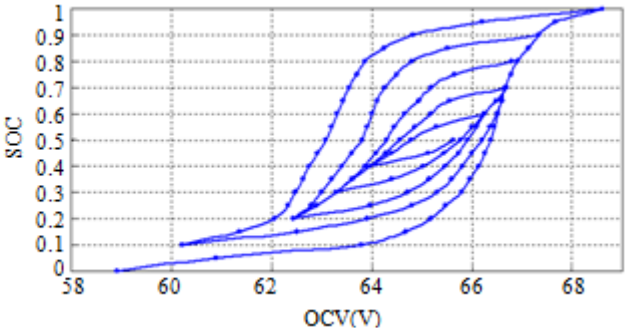

Fig.2: Hysteresis characteristic curve

3 Model and SOC Estimation algorithm

As open circuit voltage of the Ni-MH battery exits hysteresis characteristics, and obtaining the battery EMF by external characteristics of the battery directly is not possible, model of the Ni-MH battery Hysteresis is built. As illustrated in Fig.3, the electrical circuit model involves eight parameters, depicting a static resistance Ro, a static potential Uoc that represents the open-circuit voltage, and two dynamic processes that model the double layer effect and diffusion effect respectively. The OCV Uoc is the indicator of SOC. We use two RC pairs to describe the double layer effect for cathode and anode respectively. Double layer is a fast dynamic process with a time constant ranging from hundreds of milliseconds to several seconds. We use one RC pair with a varying diffusion resistance approximate the diffusion effect, whose time constant can be several seconds to hours. Getting the battery OCV by the battery voltage with the model, the battery SOC can be estimated by the battery OCV. Specific methods, see[4].
In this paper, a method of model of the battery Hysteresis combined Ah counting is proposed. The accuracy of model SOC depends on the accuracy of the model. The complexity of the battery has decided to establish precise and practical model is very difficult It is very difficult to establish precise and practical model, because the battery is a complex system. Ah counting method using current integral estimate the battery SOC. The method does not rely on the model, and guarantee high accuracy in a time.

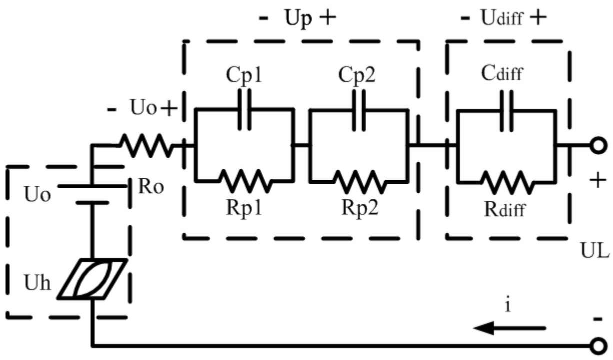

Fig.3: Model of the Ni-MH battery Hysteresis

To capitalize on the advantages of Ah counting method, we make it and model SOC combined. To prevent algorithm divergence, the model of battery is used to amend the error. The function can be described by

$$SOC(k) = [SOC(k-1) + \Delta SOC_I] \times \omega + SOC_V \times (1-\omega) \quad (1)$$

Where SOCV is model SOC, △ SOCI is the increasing of Ah counting method, ω is the weighting factor of the Ah counting method, 0≤ω≤1.

4 Algorithm Estimation

4.1 Energy maintains test

Energy maintains test can verify the precision of estimation of battery State of Charge (SOC) at one SOC point. During the experiment, battery was charge and discharged circularly with rapid macro current on the basis of maximum allowed charge-discharge power at one SOC point and the SOC should stay the same after every charge-discharge circulation.
With the Ah counting method, the current is measured by Digatron BTS-600 and considering the coulomb's efficiency, the true SOC value is acquired by Ah integration; Hysteresis model（Hysteresis SOC）contains the low resolution (LRH SOC) which is computed by MCU and the high resolution one (HRH SOC) by Matlab; Hysteresis and Ah counting method（Hysteresis & Ah SOC） is the combination of (Ah SOC) and low resolution. The three methods mentioned above are used respectively to estimate SOC.
At the beginning, the battery was discharged with 1C current to cutoff voltage, after that which tabled for an hour and then charged with 1C current for 36 minutes and tabled for an hour again. During the charge and discharge circulation experiment which was repeated 20 times, the battery was charged with 90(A) current for 10 seconds, tabled for 90 seconds and then discharged with 100(A) current for 9 seconds and

tabled for 90 seconds again. After that, the battery was discharged with 1C current to cutoff voltage. The curve of terminal voltage and open circuit voltage (OCV) of the battery are showed in the Fig.4, their Local amplification curves are in the Fig.5.

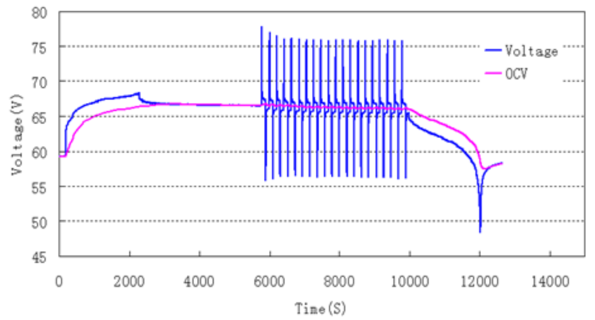

Fig.4: Energy maintain test

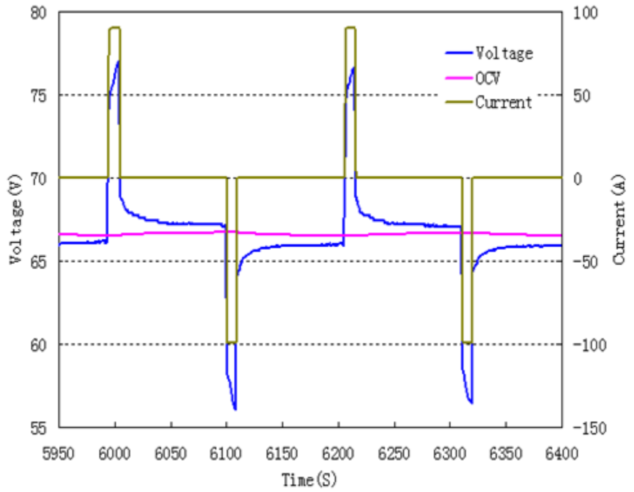

Fig.5: Local amplification curves

The curves of LRH SOC, HRH SOC, Ah SOC and Hysteresis & Ah SOC are showed in Fig.6, their Local amplification curves are in Fig.7 and their SOC error are in Fig.8.

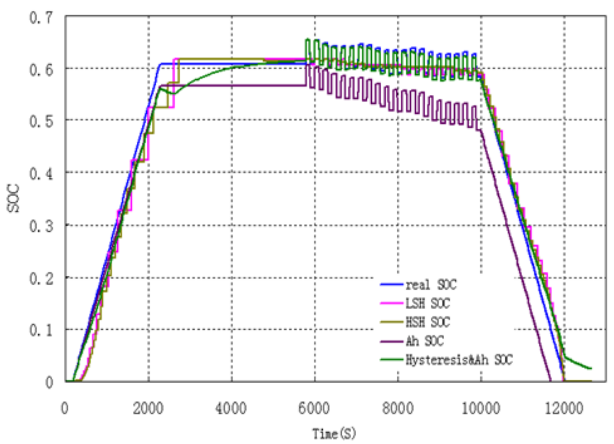

Fig.6: Four SOC algorithms comparison

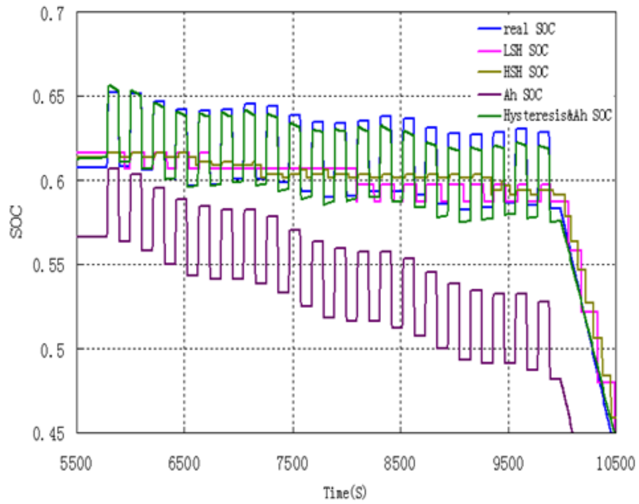

Fig.7: Local amplification curves

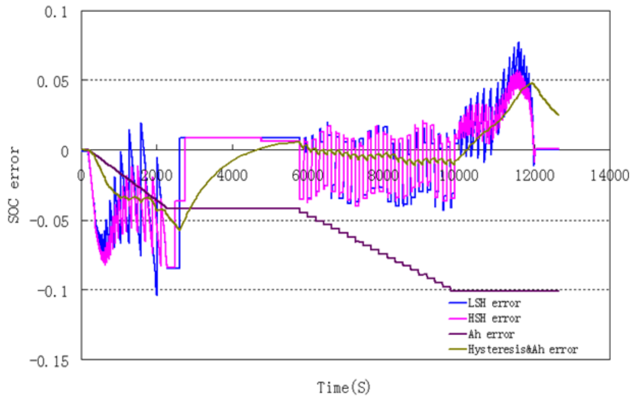

Fig.8: Four SOC algorithms error

The curves above demonstrates that the SOC error of Ah SOC becomes bigger and bigger and the SOC of Hysteresis SOC descended 0.03 after the 20th circulation while the Hysteresis and Ah counting method can not only estimate the dynamic SOC accurately, but also make accurate calibration after the experiment. The error comparison results are showed in the table 1.

Table 1: SOC error comparison of energy maintains test

	LRH	HRH	Ah SOC	Hysteresis & Ah SOC
Maximum error	0.041	0.040	0.101	0.007
Average error	0.013	0.011	0.072	0.004

4.2 Energy consumption test

Energy consumption test can verify the precision of estimation of Battery State of Charge (SOC) from SOC is equal to 0.4 to 0.7, which is a common range in the HEV. During the experiment, battery was charge and discharged circularly with rapid macro current on the basis of maximum allowed charge-discharge power at one SOC point and the SOC should descend about 0.01 after every charge-discharge circulation.

At the beginning, the battery was discharged with 1C current to cutoff voltage, after that which tabled there for an hour and then charged with 1C current for 42 minutes and tabled for an hour again. During the charge and discharge circulation experiment which was repeated 20 times, the battery was charged with 90(A) current for 10 seconds, tabled for 90 seconds and then discharged with 100(A) current for 12 seconds and tabled for 90 seconds again. After that, the battery was discharged with 1C current to cutoff voltage.

The curves of LRH SOC, HRH SOC, Ah SOC and Hysteresis & Ah SOC are showed in Fig.9, their Local amplification curves are in Fig.10 and their SOC error are in Fig.11.

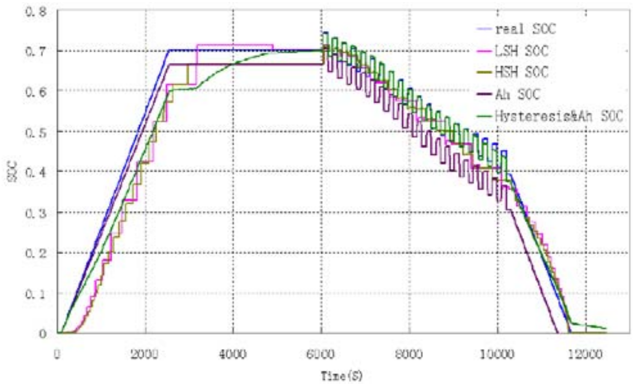

Fig.9 Four SOC algorithms comparison

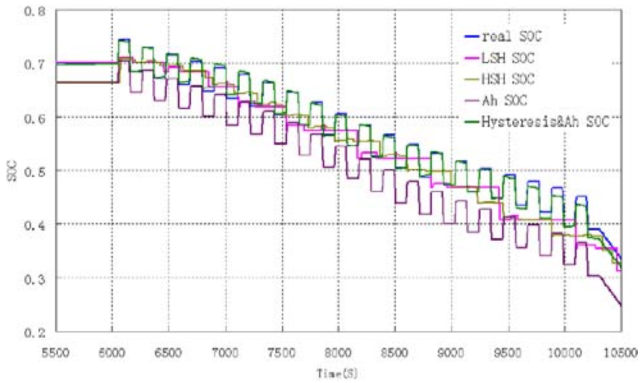

Fig.10 Local amplification curves

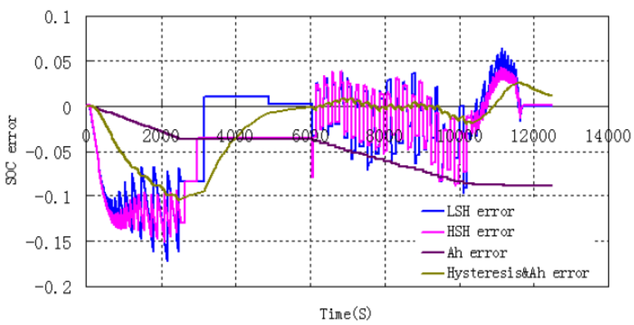

Fig.11 Four SOC algorithms error

The curves above demonstrate that the SOC error of Ah SOC becomes bigger and bigger, the LRH SOC descended 0. 36 and HRH SOC descended 0. 38 after the twentieth circulation while the Hysteresis & Ah counting method can not only estimate the dynamic SOC accurately, but also make accurate calibration after the experiment. The error comparison data is showed in the table 2.

Table 2: SOC error comparison of energy consumption test

	LRH	HRH	Ah SOC	Hysteresis & Ah SOC
Maximum error	0.091	0.079	0.088	0.017
Average error	0.020	0.019	0.063	0.002

4.3 NEDC cycle test

The New European Driving Cycle is a driving cycle consisting of four repeated ECE-15 driving cycles and an Extra-Urban driving cycle, or EUDC. The NEDC is supposed to represent the typical usage of a car in Europe, and is used, among other things, to assess the emission levels of car engines. It is also referred to as MVEG cycle (Motor Vehicle Emissions Group). It was shown in Fig.12.

It is the total for 1185 seconds. The first 800 seconds had relatively gentle condition with the current more than 45(A) and discharging with less than 0.1(Ah). The following 385 seconds appear macro current charge-discharge with the maximum discharge current for 74 (A), resulting in Ah increasing dramatically. The whole NEDC is a stable dynamic conditions after the first with the -0.6 Ah.

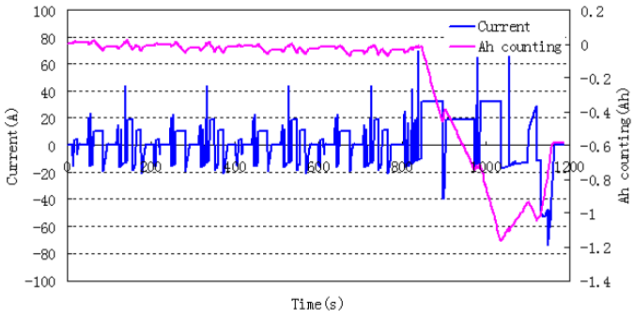

Fig.12 NEDC test data

In order to verify the SOC estimation algorithm in long time working cycle of accuracy and stability, this paper adopts NEDC cycle. Under the condition of the battery venting, battery was charged for 39 minutes with 1C current and tabled for 1 hour. Repeat NEDC cycle 10 times. The battery was charged for 370s between each cycle with 1C current, tabled for 1 hour again and then discharged to cutoff voltage with 1A constant-current. See Fig.13.

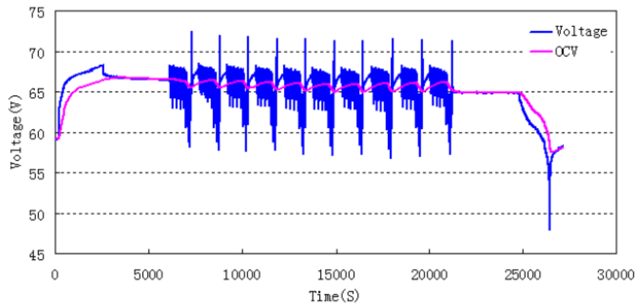

Fig.13 NEDC cycle test

LRH SOC, HRH SOC, Ah SOC and Hysteresis & Ah SOC are compared in Fig.14. Partial enlargement was shown in Fig.15. The deviation of every method was shown in Fig.16. The conclusions can be got: Ah SOC was losing accuracy with time, according to cumulative measuring deviation and the difficulty to estimating coulomb efficiency. Low and high resolution hysteretic algorithm with the beginning SOC of 0.61 and ending SOC of 0.48 have better anatomizes with the true value with the ending SOC of 0.46. Hysteresis & Ah SOC improved the dynamic characteristics of the former with the best maximum deviation of 0.04 in the whole process.

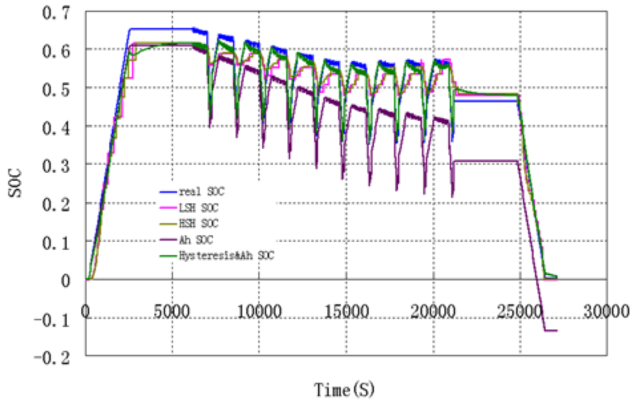

Fig.14 Four SOC algorithms comparison

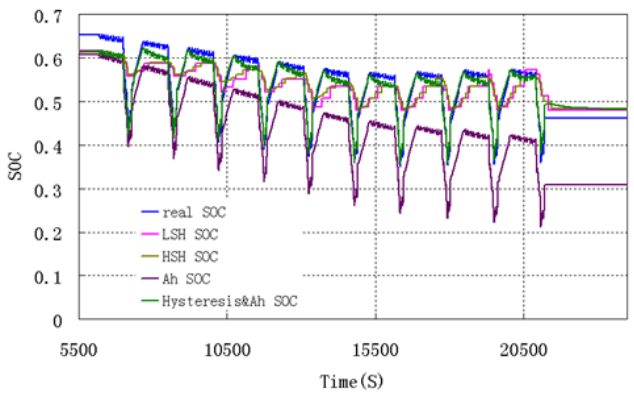

Fig.15 Local amplification curves

As showed in the table 3, the Dynamic error of LRH and HRH is larger, and their average error is smaller, therefore it can be used as Calibration basis of SOC. The maximum of SOC error of The Hysteresis and Ah counting method is 0.04 and its average error is just 0.002.

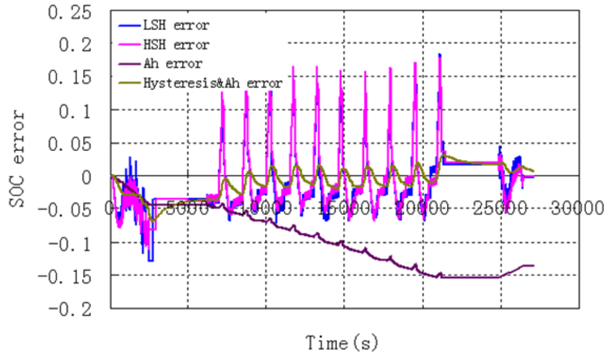

Fig.16 Four SOC algorithms error

Table 3: SOC error comparison of NEDC cycle test

	LRH	HRH	Ah SOC	Hysteresis & Ah SOC
Maximum error	0.18	0.17	0.16	0.04
Average error	0.003	0.002	0.110	0.002

4.4 Real Car driving cycle test

A actual working process was shown in Fig.17. The whole smooth condition was with 1121sec, maximum discharging current in 40A (6.7C), maximum charging current in 50A (8.3C) and -0.25Ah totally.

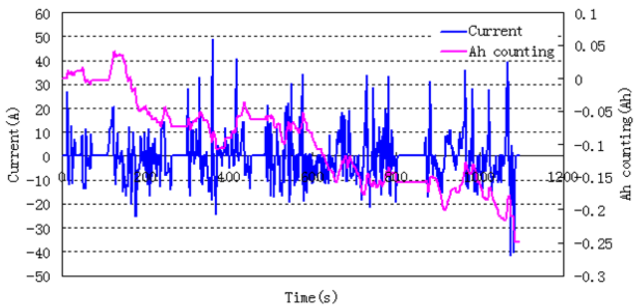

Fig.17 Real Car driving test data

In order to verify the SOC estimation algorithm in long time working cycle of accuracy and stability, this paper adopts NEDC cycle. Under the condition of the battery venting, battery was charged for 36 minutes with 1C current and tabled for 1 hour repeat actual cycle for 10 times. Between each cycle battery is charged 150s with 1C current for more times and tabled for 1 hour again, and discharged to cutoff voltage with 1A constant-current. See Fig.18.

The curves of LRH SOC, HRH SOC, Ah SOC and Hysteresis & Ah SOC are showed in Fig.19, their Local amplification curves are in Fig.20 and their SOC error are in Fig.21. The conclusions can be got: Ah SOC was losing accuracy with time, according to cumulative measuring deviation and the difficulty to estimating coulomb efficiency. Low and high resolution hysteretic algorithm with the beginning SOC of 0.61 and ending SOC of 0.56 have better anatomizes with the true value with the ending SOC of 0.59. Hysteresis & Ah SOC improved the dynamic characteristics of the former with the maximum error of 0.02 and average error of 0.01 in the whole process.

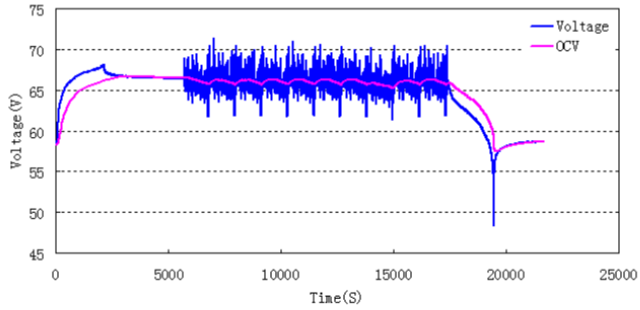

Fig.18 Real Car driving cycle test

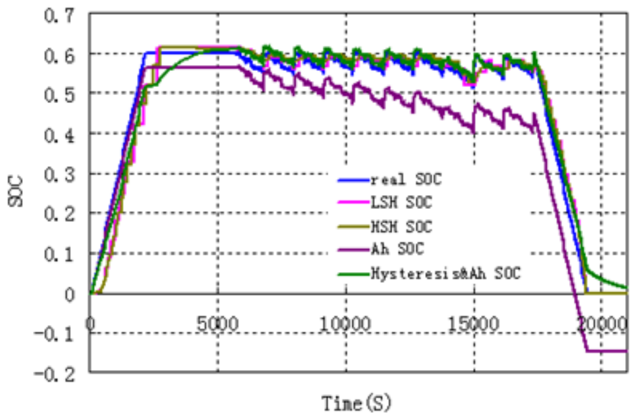

Fig.19 Four SOC algorithms comparison

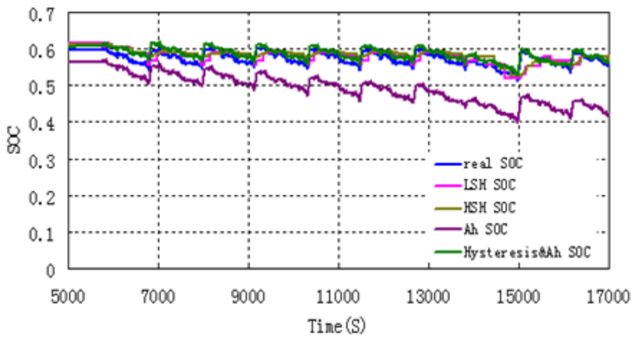

Fig.20 Local amplification curves

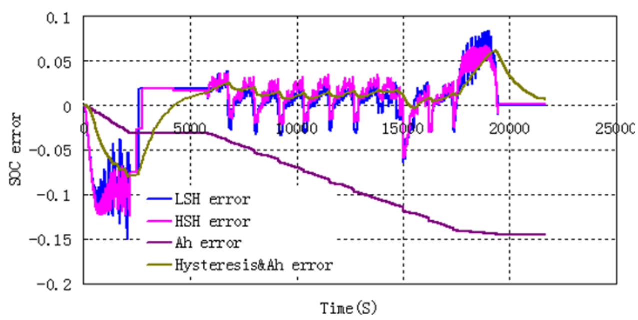

Fig.21 Four SOC algorithms error

The error comparison data is showed in the table 4.

Table 4: SOC error comparison of Real Car driving cycle test

	LRH	HRH	Ah SOC	Hysteresis & Ah SOC
Maximum error	0.06	0.05	0.14	0.02
Average error	0.009	0.004	0.084	0.010

5 Conclusion

The accuracy of the estimation of SOC was improved by Model method combination with Ah SOC which was used in the energy balance test, the energy consumption test, New Europe Driving Cycle (NEDC) cycle test and Real Car driving cycle test to make the error of SOC estimation less than 5% all the time. Therefore this method can meet the long-term requirements in the HEV.

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