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Dynamic SOC Compensation of an Ultracapacitor Module for a Hybrid Energy Storage System

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Abstract

The ultracapacitor module has recently been recast for use in hybrid energy storage systems (HESSs). As a result, accurate state-of-charge (SOC) estimation for an ultracapacitor module is as important as that of primary sources in order to be utilized efficiently in an energy storage system (ESS). However, while SOC estimation via the open-circuit voltage (OCV) method is generally used due to its linear characteristics compared with other ESSs, this method results in many errors in cases of high-current charging/discharging within a short time period. Accordingly, this paper introduces a dynamic SOC estimation algorithm that is capable of SOC compensation of an ultracapacitor module even when there is a current input and output. A cycle profile that simulates the operating conditions of a mild-HEV was applied to a vehicle simulator to verify the effectiveness of the proposed algorithm.

Key Words: Auxiliary energy system, Hybrid energy storage system, Ultracapacitor module, SOC compensation, State-of-Charge

I. INTRODUCTION

The energy storage systems (ESSs) for HEV, Plug-in HEV, and EV must be sized so that they can store sufficient energy and provide adequate peak power for a specified acceleration performance. They also need to have the ability to meet appropriate driving cycles. In addition, the energy storage devices must meet appropriate cycle and calendar life requirements [1]. According to these requirements, ESSs with high power and high energy, such as Ni-MH, Li-Ion and even lead-acid batteries for mild-HEV, have been developed and are being used. However, Ni-MH, Li-ion, and lead-acid batteries alone, integrated into the vehicular power train, are not always sufficient to supply vehicle propulsion power and they are not able to accept energy from regenerative braking. Thus, the capacities of such batteries should eventually be over-designed in order to provide peak power demands. For this reason, these vehicles may use an ultracapacitor module (bank) as a part of their auxiliary energy system (AES) that is able to receive regenerated energy and provide power during peak periods.

An ultracapacitor, also known as a supercapacitor, an electric double layer capacitor (EDLC), or a pseudocapacitor, uses electrodes with an extremely large surface area, along with

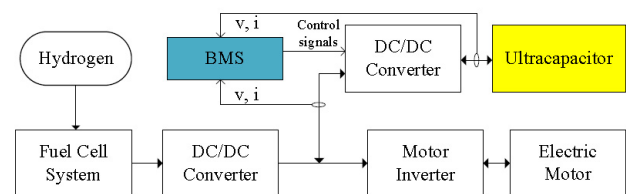


Fig. 1. Hybrid Fuel Cell - Ultracapacitor ESS.

electrolytes that can permit values of up to several thousand Farads per cell. Therefore, ultracapacitors have approximately 10-times the power density of a similar-sized battery, along with the ability to be being charged and discharged over 100-times faster than a normal battery. Also, ultracapacitors have a very long life span [7],[8].

Throughout the world, research has been conducted on hybrid energy storage systems (HESSs), which simply mean an ESS containing both a battery or fuel cell and an ultracapacitor, such as a Hybrid Fuel Cell-Ultracapacitor ESS or Hybrid Battery-Ultracapacitor ESS [2]–[6]. Fig. 1 and 2 show the layout of a HESS with an ultracapacitor module.

In order to effectively use not only a battery but also an ultracapacitor module as a HESS, an accurate state-of-charge (SOC) estimation must be performed using a battery management system (BMS) that manages and monitors the ESS. SOC estimation is one of the most important issues for application products that utilize an ESS. There are two

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case of a power assist, the switch or DC/DC converter is controlled in order to transfer energy to the battery.

The main function of the BMS controller is to calculate the SOC of the ultracapacitor module and VRLA battery in order to estimate the SOC of the HESS. For this reason, the BMS controller measures the current, the voltage, and the temperature required to calculate the SOC, transfers the HESS's available discharge and charge energy to the VCU, and manages the energy by controlling the switch.

Taking into consideration the cost and interface aspects, the current was measured using a Nikkohm $0.1\text{m}\Omega$ shunt resistor by amplifying the voltage across two shunt terminals. The voltage was dropped to a 5V level through resistance distribution. The temperature was measured using an NTC type thermistor, which is $10\text{k}\Omega$ at 25°C . Since the current and voltage are closely related to an accurate SOC estimation, a 16-bit ADC was used for increased precision. An information exchange between the BMS and VCU was implemented based on CAN2.0B. An Infineon 16-bit XC164CS controller was used for the vehicle application for fast algorithm computation.

III. SOC COMPENSATION

Accurate SOC estimation of an ultracapacitor module that involves a relatively small capacitance, enabling an easy change in the SOC even with small amounts of input and output current, is extremely important, as is a battery's SOC accuracy. Therefore, this paper proposes an algorithm that uses an ampere-hour counting method, but compensates the initial SOC with the OCV, and further compensates for the current integration error by using the relationship between voltage detection in a specified low-current region and the SOC-OCV. The SOC compensation described above shall be referred to as "dynamic SOC compensation" in this paper.

A. Initial SOC compensation

Accurate SOC estimation for a vehicle based on OCV is feasible when sufficient time has passed for stabilization after battery usage, and when all of the loads are open. For this reason, experiments regarding the SOC-OCV relationship must be conducted in advance when charging or discharging at different temperatures, and the resulting data must be compiled in the nonvolatile memory of the BMS. The stabilization time for the SOC-OCV experiment is applied for 30 minutes by considering the worst case conditions in this paper. Fig. 4 displays the SOC-OCV curves for charging and discharging at various temperatures. As the graph indicates, there are discrepancies in the SOC-OCV relationship for charging and discharging depending on the temperature.

For the initial SOC compensation, the stabilization time after the IG is turned off and before it is turned back on is first checked. When the IG is turned off, the BMS stores the SOC based on ampere-hour counting and the time based on the real-time clock (RTC) in the flash memory, and the power is then turned off. When the IG is turned on, the BMS measures the voltage of the ultracapacitor module and the ambient temperature, and retrieves the SOC_{OCV} , which corresponds to the voltage and temperature from the look-up

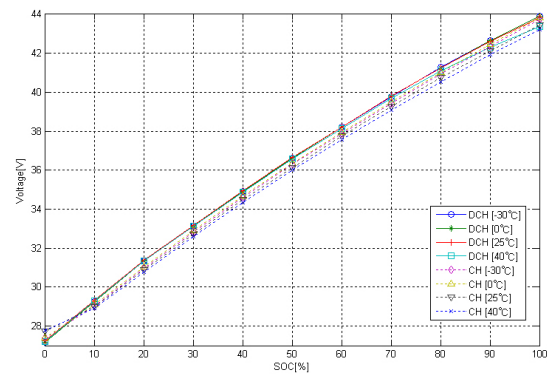


Fig. 4. Ultracapacitor module's SOC-OCV curves for charging/discharging at various temperatures.

table. The BMS then compares the RTC stored in the flash memory and the present RTC to determine the time required to stabilize the ultracapacitor module.

If sufficient time for stabilization has not yet passed, the BMS determines that the ultracapacitor module is not stable and uses the $\text{SOC}_{\text{Flash}}$ stored in the flash memory as the initial $\text{SOC}_{\text{Initial}}$. If sufficient time has passed, the BMS determines that the ultracapacitor module is stabilized and uses the SOC_{OCV} based on the OCV as the initial $\text{SOC}_{\text{Initial}}$.

The $\text{SOC}_{\text{Initial}}$ determined by the BMS is the initial SOC used for ampere-hour counting. As indicated by equations (4) and (5), since the capacitance of the ultracapacitor module is continuously integrated, the SOC (%) is converted into capacity (Ah) according to equation (1).

$$\text{AH}_{\text{Initial}} = \frac{\text{SOC}_{\text{Initial}} \times C_r}{100} \quad (1)$$

where, C_r is the rated capacity that was tested by discharging from a fully charged condition (44V) to the cutoff voltage (27V) through a constant current (4A).

Fig. 5 illustrates the flow chart for obtaining $\text{SOC}_{\text{Initial}}$.

B. Dynamic SOC compensation

If the input/output current has been maintained at 0 for a certain period of time for stabilization, or if the input/output current is not 0 but the current is below a specific value during charging/discharging, the dynamic SOC compensation of an ultracapacitor module involves calculating the SOC_V based on the voltage and comparing it to the SOC_{AH} , which is calculated according to ampere-hour counting to provide compensation.

Therefore, it is necessary to conduct charging and discharging tests for the current levels in order to determine how much input/output current should flow through the ultracapacitor module for a sufficiently small voltage error, which is the difference in voltage before and after a rest time, and to determine the discrepancy in the SOC value that corresponds to the voltage error. It is also necessary to check at what point compensation should commence when a conversion is made during charging/discharging under the current threshold.

For the first experiment, charging/discharging was performed at a predetermined current level for a specific duration

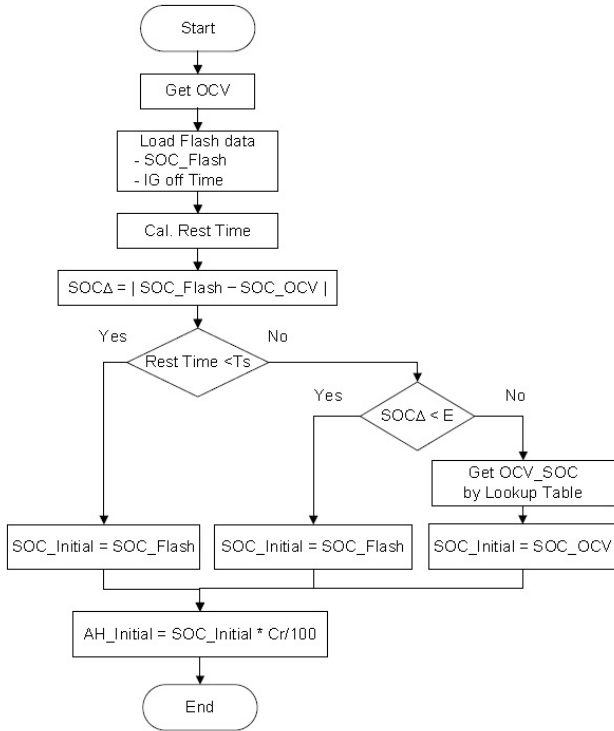


Fig. 5. Flow chart for calculating the initial capacity.

TABLE II
SOC_{ΔV} BEFORE AND AFTER STABILIZATION ON CHARGING (60% SOC).

Test Current [A]	Voltage @ 5sec [V]	Voltage @ 30 min [V]	Voltage difference [V]	SOC _{ΔV} [%]
+2.5	38.62	38.60	-0.02	-0.13
+5.0	38.86	38.78	-0.08	-0.51
+7.5	39.08	38.94	-0.14	-0.90
+10	39.26	39.10	-0.16	-1.04

(5 seconds), and the voltage was measured after stabilization (30 minutes) in order to select an appropriate current level that produces a small error. The experiment was conducted with an SOC of 60% at an ambient temperature of 25°C for 2.5A, 5A, 7.5A, and 10A of test current. Detailed experimental results are shown in Tables II and III.

The SOC_{ΔV}, which corresponds to the voltage difference before and after stabilization, can be obtained from equations (2) and (3).

$$\text{SOC}_{\Delta V} = \frac{\frac{1}{2}C(V_{\text{rest}}^2 - V_{\text{test}}^2)}{E} \times 100 \quad (2)$$

TABLE III
SOC_{ΔV} BEFORE AND AFTER STABILIZATION ON DISCHARGING (60% SOC).

Test Current [A]	Voltage @ 5sec [V]	Voltage @ 30 min [V]	Voltage difference [V]	SOC _{ΔV} [%]
-2.5	38.44	38.50	0.06	0.38
-5.0	38.42	38.50	0.08	0.51
-7.5	38.42	38.52	0.10	0.64
-10	38.36	38.52	0.16	1.02

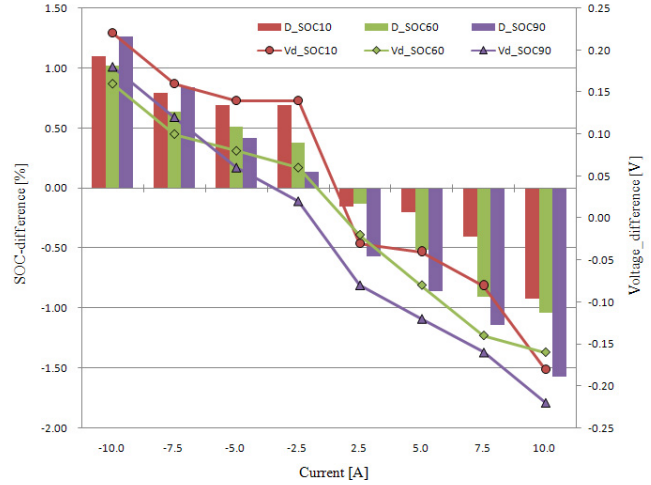


Fig. 6. SOC difference corresponding to the voltage difference before and after stabilization according to test current levels.

TABLE IV
SOC DIFFERENCE DUE TO THE CURRENT AND TIME

Initial Current [A]	Test Current [A]	SOC difference [%]			
		3 sec	5 sec	7 sec	10 sec
150	5	3.57	3.35	3.24	3.25
	2.5	3.09	3.1	2.86	2.87
	0	2.97	2.85	2.61	2.49
	-2.5	-2.48	-2.48	-2.36	-2.12
	-5	-2.6	-2.23	-1.99	-1.74
-250	5	3.22	3.01	2.7	2.6
	2.5	3.41	3.31	3.0	2.79
	0	3.61	3.4	3.3	3.19
	-2.5	3.82	-3.71	-3.59	-3.37
	-5	-3.92	-3.8	-3.79	-3.66

$$E = \frac{1}{2}C(V_{\text{max}}^2 - V_{\text{min}}^2) \quad (3)$$

where, C is the capacitance of 18 serially-connected 1700F capacitors, V_{rest} is the voltage after stabilization, V_{test} is the voltage at the termination of the experiment with a corresponding current, V_{max} is the fully charged voltage, V_{min} is the cutoff voltage, and E is the difference in energy between the maximum energy at the fully-charged voltage and the minimum energy at the cutoff voltage.

E is 56997.22 from equation (3). In the case of the 5A, 5 sec experiment shown in Table II, the SOC_{ΔV} before and after stabilization is 0.51% from equation (2).

The test results indicate that the SOC difference is proportional to the current, producing errors at around 0.5% and 1% at ±5A and ±10A, respectively.

In order to examine whether the SOC difference displayed similar tendencies outside of the 60% SOC region, additional tests were conducted for a 10% SOC and a 90% SOC. As shown in Fig. 6, the 10% SOC difference was smaller than the others for charging, but bigger than the others for 5A below the discharging region. It was also found that the SOC ratio for the voltage difference before and after stabilization for 5A of charging/discharging was less than ±1%.

Applying the results of the first test is problematic because there is no time for stabilization during actual vehicle operation. Therefore, in order to find a region that allows

for compensation during operation, a second experiment was conducted to examine whether the SOC comes within a desired error range if the test current ($0, \pm 2.5A, \pm 5A$) is maintained for a few seconds after the maximum charging/discharging. Taking into consideration the operating conditions of a mild-HEV (5kW cranking and regenerative braking of 3.3kW [2]), the maximum range of the charging/discharging current that can be applied to an ultracapacitor module was set at 150A for charging and 250A for discharging.

Table IV lists the SOC differences for voltage differences after charging for 5 seconds at 150A from a cutoff voltage of 27V; discharging for 4 seconds at 250A from a fully-charged voltage of 44V; maintaining the charge/discharge for 3, 5, 7 and 10 seconds at the test current; and after undergoing stabilization. The experimental results indicate that if the test current flows in the same direction as the initial current, the voltage difference becomes greater than in the case of the opposite direction. It can be deduced that the maximum difference would occur with 5A of current flowing in the same direction as the initial current, and that the average SOC difference would be around 3%. Therefore we set the stabilization current below $\pm 5A$ for dynamic SOC compensation.

The SOC difference caused by the maximum voltage difference (initial current : -250A, test current: 2.5A) that can occur with the current maintained below $\pm 5A$ decreases by up to 0.52% as the duration of the current held below $\pm 5A$ is increased from 5 to 10 seconds. However, the difference is not significant. Since designing the algorithm in such a way that SOC compensation occurs only when the duration of the current held below $\pm 5A$ exceeds 10 seconds reduces the number of SOC compensations, it is advisable to set the duration of the current maintenance at about 5 seconds.

Fig. 7 and 8 are voltage and current waveforms when the stabilization current is flowing in the same direction as the initial charging/discharging current generated when the SOC error is at its maximum. According to Fig. 7, when resting after charging at 150A for 5 seconds, and then charging again at 5A for another 5 seconds, the voltage at the end of the 5A charge is 36.42V, which drops down to 35.86V after 30 minutes of stabilization. Using equations (2) and (3), the SOC error becomes 3.35%. Likewise, according to Fig. 8, when resting after discharging at -250A for 4 seconds and then discharging again at -5A for another 5 seconds, the voltage at the end of the -5A discharge is 31.48V, which increases to 32.30V after 30 minutes of stabilization, yielding a SOC error of -3.8%.

In this study, if the current is maintained at 5A or below for 5 seconds or longer, the present voltage of the ultracapacitor module is measured to obtain the SOC_V based on the voltage. Compensation of the SOC only takes place when there is a difference of 5% or greater between the current value (SOC_{AH}), calculated by ampere-hour counting, and the compensation target value (SOC_V), calculated using the voltage. This takes into consideration the innate error (up to 3.8%) of the compensation mechanism which uses the present voltage. However, if the SOC_V based on the voltage is applied directly to the SOC_C as the compensation SOC

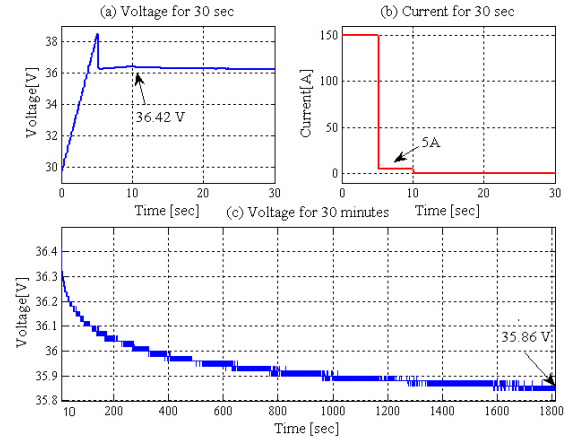


Fig. 7. Charging at 150A followed by charging at 5A.

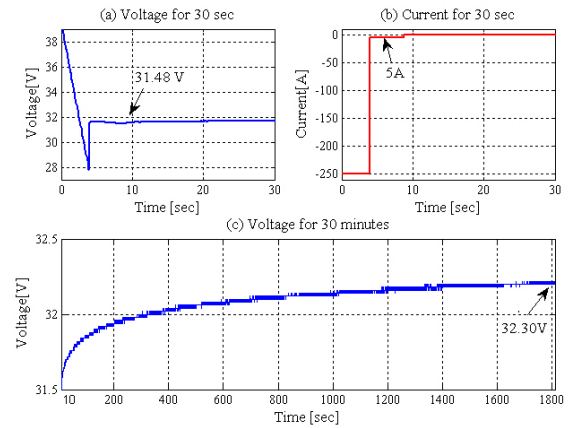


Fig. 8. Discharging at 250A followed by discharging at 5A.

value, an instantaneous SOC variation can cause instability. Therefore, it would be appropriate to perform small levels of (+) compensation during charging and (-) compensation during discharging for a specified compensation time (Δt_C) in a consistent manner.

The associated equations of a dynamic SOC compensation algorithm for the ultracapacitor module described earlier can be expressed as follows:

Step 1. After detection of the input/output current of the ultracapacitor module, calculate the SOC_{AH} via ampere-hour counting.

$$AH_t = \frac{AS_{t-1} + i_t \times t_s \times f_e}{3600} \quad (4)$$

Here, AH_t is the ampere-hour (Ah) accumulated up to the present moment, AS_{t-1} is the ampere-sec (As) accumulated up to the previous point, i_t is the amount of current at the present moment, t_s is the sampling time, and f_e is the charging/discharging efficiency.

$$SOC_{AH} = \frac{AH_{Initial} + AH_t}{C_r} \quad (5)$$

Here, $AH_{Initial}$ is the initial capacity when the ignition key is turned on, and C_r is the rated capacitance.

Step 2. If the magnitude of the input/output current ($|i_{cap}|$) is less than a predefined value (Δi), check if the current is maintained for a specified duration (Δt).

Step 3. If the magnitude of the current is maintained for a specified duration (Δt), calculate the SOC_V based on the voltage of the ultracapacitor module from the SOC-OCV table.

Step 4. Calculate the error of the remaining capacity with the present SOC_{AH} and the SOC_V based on the voltage.

$$SOC_{error} = SOC_{AH} - SOC_V. \quad (6)$$

Step 5. If the error of the remaining capacity is greater than the predefined error range ($\pm 5\%$), set the SOC_V as the remaining capacity (SOC_C) and perform continuous compensation for the accumulated error of the SOC_{AH} over a specified compensation time (Δt_C) in small amounts.

$$SOC_C = SOC_{AH} \pm \frac{SOC_{error}}{\Delta t_C}. \quad (7)$$

Step 6. Update from the SOC_C to the AS_t .

$$AS_t = \left(\frac{SOC_C \times C_r}{100} - AH_{Initial} \right) \times 3600. \quad (8)$$

Step 7. When compensation for the SOC_{error} is complete, once again monitor whether the input/output current is maintained below a specified current level (Δi) for a specified duration (Δt).

IV. EXPERIMENTS

A. Sensing accuracy test

The proposed algorithm for the dynamic SOC compensation of an ultracapacitor module is based on the current, voltage, and temperature measured by the BMS. Accordingly, the sensing accuracy used by the BMS to calculate the SOC is important. Sensing errors in the current measurement totaled about 1% in the $-250A \sim 150A$ range, and about 2% in the low current range ($-10A \sim 10A$). The voltage errors were within 0.5% in the $27V \sim 44V$ region. As for temperature, the errors were within 3% between $-40^\circ C$ and $90^\circ C$.

In order to minimize the errors associated with the external environment, all of the tests were conducted in a chamber at $25^\circ C$. For use as references to determine the accuracy of the algorithm explained below, we used a Yokogawa current transducer (751574), which is capable of measuring current with an error rate of less than 0.05%, and a NetDAQ 2640 to measure the voltage within an error range of 0.01%.

B. SOC accuracy test

There are generally no standard procedures for an accuracy test of SOC estimation during the development process of a BMS. Therefore, a manufacturer in the development of a BMS uses its own test procedure; it starts the test profile at a specific SOC in a state in which the capacity of the ESS is already known. It then discharges at the end of the test cycle until it reaches the cutoff voltage. Finally, the parameters are tweaked for SOC estimation if there is not an equally similar reference SOC for comparing the accuracy of the SOC

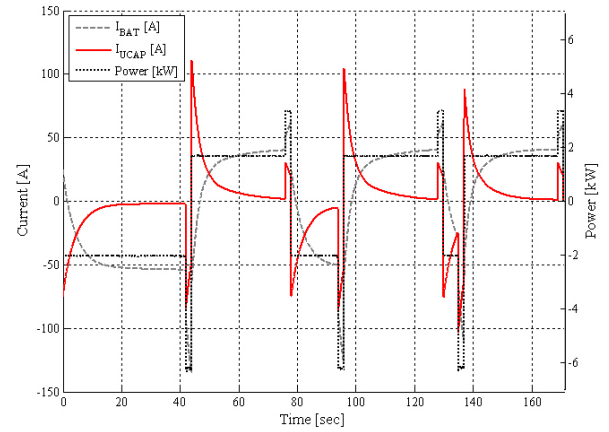


Fig. 9. Test cycle profile of ultracapacitor module.

estimation calculated in equation (9) and the last value of the SOC calculated by the BMS.

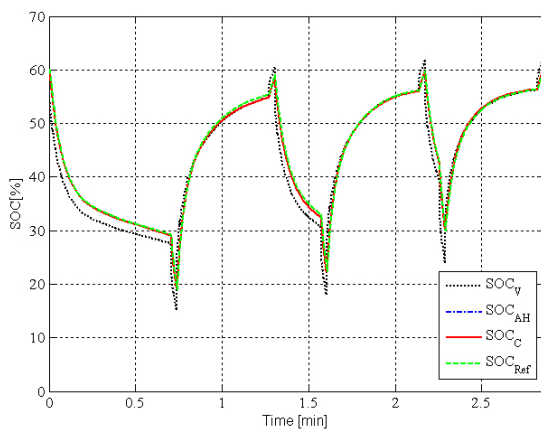
$$SOC_{remain} = \frac{AH_r}{C_r} \times 100 \quad (9)$$

where, AH_r is the remaining capacity at the cutoff voltage, and C_r is the rated capacity.

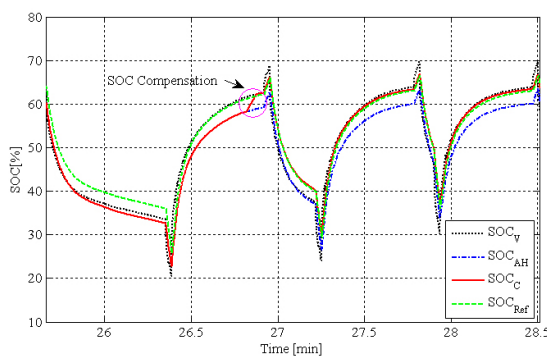
In order to examine how much the proposed algorithm affects the SOC accuracy of the ultracapacitor module of a HESS, a test profile reflecting the idle stop/start, regenerative braking, other phenomena that frequently occur during mild-HEV driving, and the extract current (I_{ucap}) of the ultracapacitor module from the parallel battery and the ultracapacitor module, was created as shown in Fig. 9 and put through a test of 100 cycles, after which the remaining capacity of the ultracapacitor module was checked. The original cycle profile was modified by adding a regenerative function to the ZPA (zero-power assist) efficiency and the life test profile from the "Freedom CAR 42V Battery Test Manual" published by INEEL and DOE [2],[14].

The 100-cycle test was started after fully charging the ultracapacitor module and then discharging it for two hours down to 4A and 60% of the SOC. The BMS measured the current, the voltage, and the temperature, and then it calculated the SOC of the voltage, the ampere-hour, and the dynamic compensation every 10ms.

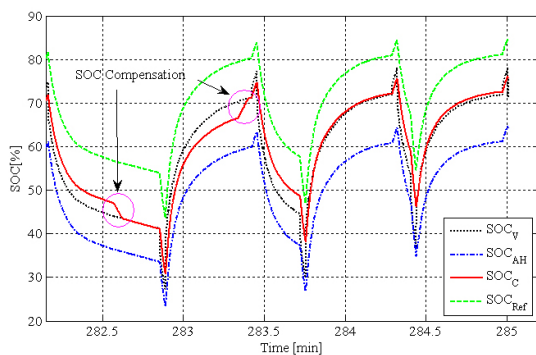
Fig. 10 shows the results of the SOC estimation at 1-, 10-, and 100-cycles, respectively. Figure (a) shows that all of the SOC (SOC_{AH} , SOC_V , SOC_C , SOC_{Ref}) are started under the same conditions and there is no critical SOC error in the first cycle. Figure (b) shows that the dynamic SOC compensation happens first based on the SOC_V when the current is below $\pm 5A$, and its condition is maintained for 5s or more. Figure (c) shows that the error rate comparing the SOC_{AH} and the SOC_{Ref} is increased gradually owing to an accumulation of current sensing error that is dependent over time. However, the SOC_C using the dynamic SOC estimation algorithm follows well the ampere-hour counting under a high current, and skillfully adjusts as a voltage method under a low current.



(a) 1 cycle.



(b) 10 cycles.



(c) 100 cycles.

Fig. 10. The results of SOC estimation.

When the test cycle was done, the ultracapacitor module was discharged at 4A to the cutoff voltage in order to examine the remaining capacity (SOC_{remain}), which is the reference accuracy of the SOC measured by a precision current sensor and data acquisition (DAQ). The SOC using the ampere-hour method was also calculated by using the current of the DAQ to compare the accuracy of the SOC during each cycle.

Table V shows the accuracy results of the SOC estimation for the cycle test. According to the test results, the difference between the remaining capacity, taken after the cycle test was calculated using the reference, and the SOC of the dynamic compensation of the BMS was 2.96%. This is within the general design specification of $\pm 5\%$ in HEV applications. The

TABLE V
THE ACCURACY RESULTS OF SOC ESTIMATION FOR THE CYCLE TEST

-	Reference		BMS		
	SOC_{remain}	SOC_{AH}	SOC_{V}	SOC_{AH}	SOC_{C}
SOC [%]	78.52	84.2	75.35	64.18	75.56
Error	-	5.68	3.17	14.34	2.96

results also show that it has a similar error rate when compared to the SOC_{V} , but a greater accuracy than the SOC_{AH} . Even if the difference in the SOC between the SOC_{V} and the SOC_{C} in the BMS is not large after the end of a cycle, the difference in the SOC between the SOC_{V} and the SOC_{Ref} is bigger under high-current situations such as engine starting and during the regenerative braking function of a HEV.

V. CONCLUSIONS

In order to improve the accuracy of the SOC estimation of an ultracapacitor module used in a HESS, this paper introduced a compensation algorithm that uses compensation by the OCV when the ignition key is turned on, as well as the ultracapacitor module voltage when the input/output current is below a certain level during operation. This study also verified the accuracy of the proposed dynamic SOC algorithm within 2.96% of the reference based on a modified cycle profile test that simulated mild-HEV driving conditions.

Even if the ultracapacitor module is modified in a HESS that uses the ultracapacitor module as a power source, dynamic SOC estimation can be accurately performed using a few sets of test data, as described in this paper.

APPENDIX

SOC :	State-of- Charge
ESS :	Energy Storage System
HESS :	Hybrid Energy Storage System
HEV :	Hybrid Electric Vehicle
BMS :	Battery Management System
ZPA :	Zero-Power Assist
ESR :	Equivalent Series Resistance

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