特集 Lithium-Ion Battery Pack for Stop & Start System*

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The automotive industry places a high importance on developing CO2 reduction technologies for powertrain. A dual power supply Stop & Start(S&S) System combined with energy regeneration is an effective technology to reduce CO2 emission. Compact size, low weight and high charge acceptance are very important characteristics for a power supply storage unit. A lithium-ion battery is the optimal power supply to meet these requirements. It has high charge acceptance per unit weight (power density). Furthermore, we developed a simple system that eliminates the DC-DC converter by adopting the lithium-ion battery with a voltage characteristic similar to that of a Pb battery. Lithium-ion batteries must be kept within an appropriate capacity range. Overcharge and overdischarge cause extensive damage to Lithium-ion batteries. Therefore, the detection of battery State Of Charge (SOC) is very important. We developed a method to detect Open Circuit Voltage (OCV) while driving. Charging and discharging profiles during driving makes SOC detection difficult because the dynamic nature of battery resistance makes modeling complicated. However, the S&S system is characterized by a constant current discharge during normal driving. The battery resistance is comparatively stable in this area. By performing the SOC calculation in this area and accounting for the frequency characteristic of the resistance of the battery, it is possible to accurately detect SOC.

Key words : Battery Pack, Lithium-ion, SOC (State Of Charge), Stop & Start

省電
工動
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1. ABSTRACT

Increased interest in global warming requires rapid improvements in CO2 reduction efforts. The automotive industry is placing high importance on CO2 reduction technologies.

Using Lithium-ion (Li-ion) battery pack Stop & Start (S&S) system with combined energy regeneration is an effective technology to reduce CO2 emissions.

Power supply storage is very important for the S&S system. High charging acceptance, low weight, and compact size are required. A Li-ion battery is the optimal power supply that meets these requirements. It has high charge acceptance per weight. Furthermore, we developed simple system structure which eliminates the need for the DC-DC converter. By utilizing a Li-ion battery that has voltage characteristics similar to the Pb battery there is no need for a converter to make adjustments between the two power supplies.

The Li-ion battery's range of capacity must be managed appropriately as overcharge and overdischarge causes extensive damage to the battery. Therefore, battery State of Charge (SOC) is very important.

We considered a method which detects open circuit voltage (OCV) while driving. The S&S system has a stable electric discharge area for a long time. The battery condition is stable in the area. By measuring in this area, and considering the frequency characteristic of the impedance of a battery, it becomes easier to detect SOC correctly even if the current sensor has an error.

2. INTRODUCTION

Fig. 1 shows an anticipated increase of CO2 emissions. This red line shows the present energy consumption. In 2030, CO2 emissions will become 1.4 times the present rate and the average temperature of the earth will increase 6 deg C. Therefore, the "CO2 concentration scenario of 450 ppm in the atmosphere" is proposed.

The S&S system which stops the engine while waiting at stoplights is an effective way to reduce fuel consumption.

Fig. 2 is an example of vehicles powertrain energy flow analysis. The technology of CO2 reduction is classified into three points, "Load reduction", "Energy regeneration" and "Engine efficiency". S&S system with combined energy regeneration is an effective technology to reduce CO_2 emissions.

We propose an improving S&S system.

First technology is an engine stop during deceleration. Conventional S&S system stops the engine after the vehicle stops. Our system stops during deceleration to cut down fuel consumption. In order to enable to stop the engine during deceleration, there must be capability to re-start the vehicle immediately even when engine is still rotating. DENSO's product "Tandem Solenoid Starter" [2] makes it possible.

Second technology is increasing regeneration. While braking, conventional vehicles waste kinetic energy as thermal energy. Regeneration is converting to electric energy for battery charging. We consider adopting a power supply of high charge acceptance to utilize more regeneration energy.

This paper reports on the power supply for improving S&S system. We considered an optimal power supply and the management system of it appropriately.

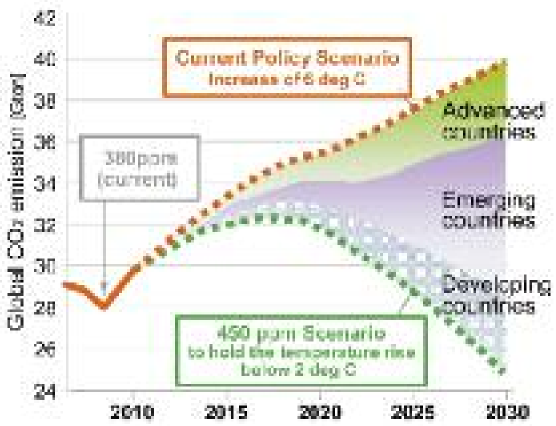

Fig. 1　World Energy Outlook 2010, IEA [1]

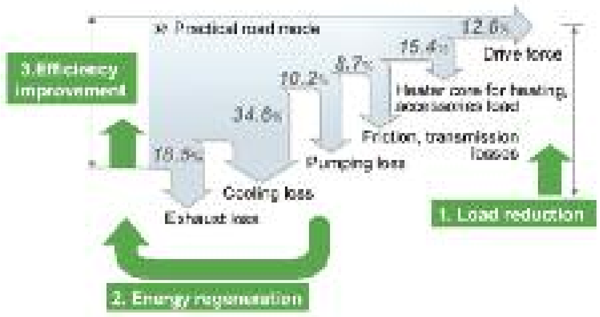

Fig. 2　Powertrain energy flow

Table 1　Comparison Power Supply

	Pb battery	Ni-MH	Li-ion battery	Capacitor
Acceptance (per weight)	Bad	Not Good	Very Good	Very Good
Energy density (per size)	Good	Good	Very Good	Not Good
Cost	Very Good	Good	Good	Bad ("Need DC/DC")

Very Good>Good>Not Good>Bad

3.　BEST POWER SUPPLY SELECTION

3.1　Best Power Supply for the System

This system's power supply requires three important things. First, high charge acceptance is required for charging much regenerative energy. Second, is low weight and compactness for simplifying installation and saving weight. Third, is low cost.

This is the result of carrying out the benchmark of various power supply storage. See **Table 1**. Pb battery should be kept at nearly full charge in order to prolong battery life. As a result, its charge acceptance is bad. Ni-MH is inferior in charge acceptance compared with a Li-ion battery or a capacitor. Capacitor needs a DC/DC converter for the voltage adjustment to Pb battery's voltage. A Li-ion battery is the optimal power supply that meets these requirements. It has high charge acceptance per weight.

Furthermore, to hold down the cost, we developed a simple system structure which eliminated the conventional DC-DC converter by adopting a Li-ion battery with a battery voltage characteristic similar to that of a Pb battery (shown **Fig. 3**).

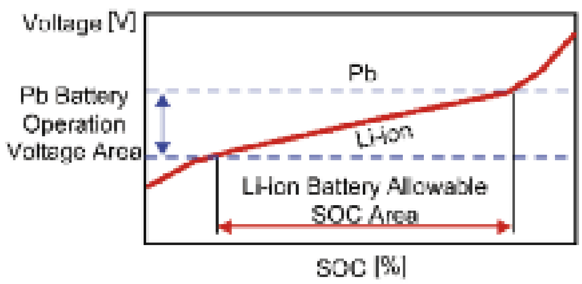

Fig. 3　Voltage Characteristics

3.2　Developed System Outline

Fig. 4-1 and **Fig. 4-2** show our proposal S&S system using Li-ion battery pack. The pack has Li-ion battery and control circuit. It is connected with the Pb battery in parallel, and it has two switches to separate each other. During deceleration, the controller turns on both switches, and regeneration power charges both power supplies. In this case the engine runs without consuming fuel. Then the controller turns off switch 1 and turns on switch 2. The charged power supply is connected to the protected electric load during driving or idling stop. It not only reduces fuel consumption during an engine stop, but during driving, since power generation of an alternator, i.e., the generation loss is lost, fuel consumption is improved and smooth acceleration is obtained. The pack provides an approximate 3% increase in fuel economy at NEDC.

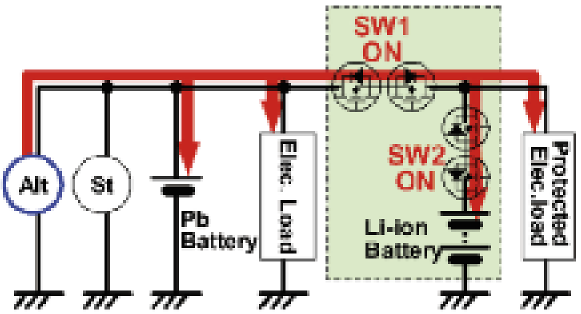

Fig. 4-1　Charge Mode (Deceleration)

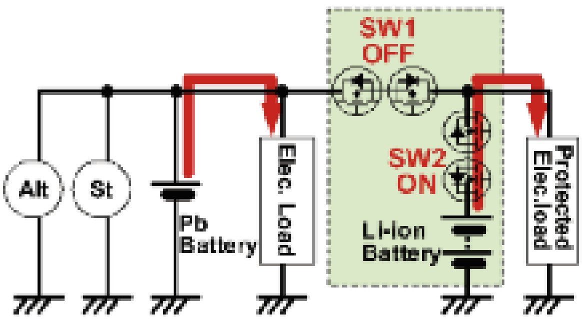

Fig. 4-2　Discharge Mode
(Idling/Acceleration/Driving)

4.　LI-ION BATTERY MANAGEMENT

4.1　Improvement of Detection of Battery State

State of Charge (SOC) is available battery capacity expressed as a percentage. The Li-ion battery's range of capacity must be managed appropriately. Overcharge and overdischarge causes extensive damage to the battery and worse emissions. Therefore, we have to detect SOC accurately.

The conventional methods of SOC detection are: "Open Circuit Voltage (OCV) method" and "Current Integration method". "OCV method" converts a battery voltage to SOC, using the known discharge curve (voltage vs. SOC) of the battery. "Current Integration method" calculates the SOC by measuring the battery current and integrating it in time.

These methods each have a problem. "OCV method" can't convert a battery's voltage to SOC during typical driving when normal charging and discharging of the battery are occurring. "Current Integration method" is not ideal because if the current sensor has an error, the error is also integrated. As a result, it is impossible to detect SOC correctly.

4.2　OCV Estimation while using Battery

We estimate OCV while using battery to correct integrated error. We can detect OCV while using battery, if the battery impedance is known. But battery impedance changes intricately in response to the influence of polarization by charging and discharging. To estimate OCV correctly, we focus on two points.

First point is the timing to estimate OCV. **Fig. 5** shows Li-ion battery current at driving. S&S system has a low and stable current discharge area for long time. So, the battery impedance is stable in this area, too. This area is suitable to estimate OCV.

Second point is the modeling of the impedance characteristic of the Li-ion battery. **Fig. 6** is the measured impedance characteristic of the battery. The portion of a semicircle can be denoted by a general equivalent circuit model. However, actually impedance is continuing to go up in a low-frequency region. The characteristic is called Warburg impedance [3]. Low-frequency region means continuous charge or discharge. Therefore, the impedance characteristic of a battery cannot be expressed with a simple model.

So, we adopt the model which has the map (time of charging vs. impedance) considering the frequency characteristic of the impedance of a battery (shown **Fig. 7**).

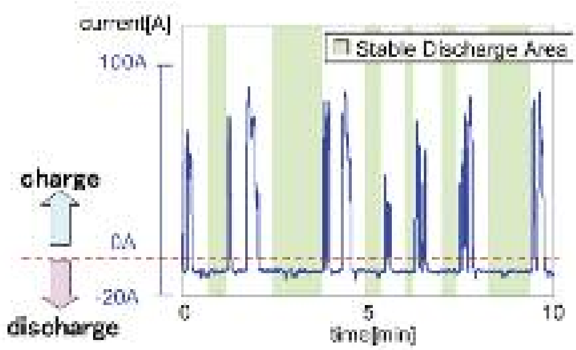

Fig. 5　Charging pattern on Li-ion battery

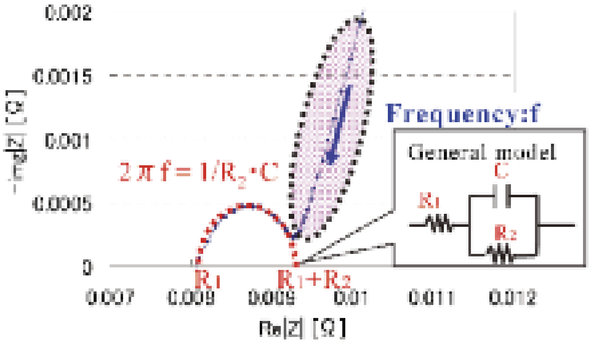

Fig. 6　Impedance of Li-ion battery (at 25deg C)

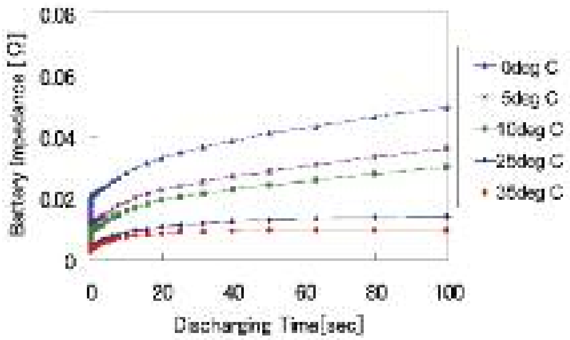

Fig. 7　Impedance map of Li-ion battery

4.3　Logic Construction

Fig. 8 is developed SOC calculation logic. At engine start, initial SOC (SOC_{init}) is detected by the OCV method. After start, SOC is calculated by addition of current integration method to SOC_{init}. It is the conventional logic so far (expression (1)).

$$SOC = SOC_{init} + \Sigma(ILi \cdot k) / C \tag{1}$$

SOC_{init}: Converts a battery voltage to SOC
ILi:Current of Battery
k:sampling rate
C:Battery Capacity

New logic has adjusting value which is calculated from the difference of present SOC and SOC_{est} (expressions (2) & (3)). The adjustment is performed only while Li-ion battery is discharging continuously.

SOC_{est} is converted from estimated OCV (OCV_{est}). OCV_{est} is calculated by battery impedance using the map of **Fig. 7**, voltage and current (expression (4)). The current and voltage are filtered in order to withstand noise or variation from the vehicle.

$$SOC = SOC_{init} + \Sigma(ILi \cdot k) / C + SOC_{adj} \tag{2}$$

$$SOC_{adj} = \{(\alpha - 1)SOC - SOC_{est}\}\ \alpha \tag{3}$$

α : correction coefficient

$$OCV_{est} = VLi_{flt} - ILi_{flt} \cdot Z \tag{4}$$

VLi_{flt}:Voltage of Battery (filtered)
ILi_{flt}:Current of Battery (filtered)
Z:Battery Impedance

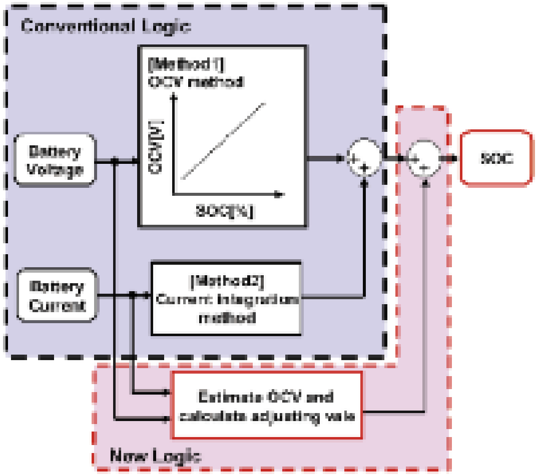

Fig. 8　Logic Construction

4.4　Evaluation Result

Fig. 9 shows the evaluation result. This graph expresses SOC at the time of driving by JC08 (Japanese Emission test cycle) repetition. At this time the current sensor has maximum error. The horizontal axis of this graph indicates time, and the vertical axis indicates SOC. The red line shows real value. The blue line is conventional logic output. By the conventional method, a sensor error will be integrated and an error will be 25% after the run for 1 hour. The green line is new logic output. It shows the effect of estimated OCV. Even if a current sensor has an error, the error is not integrated by correcting during electric discharge. The error is 2.5% at 25 deg C. Also low temperature which is strongly subject to the influence of polarization, the error was able to be suppressed to less than 5%.

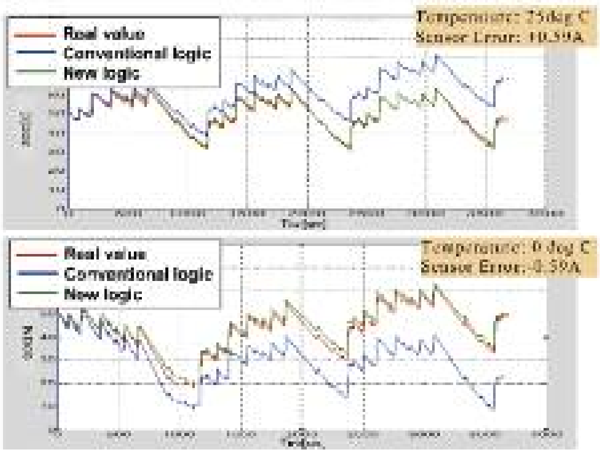

Fig. 9　Actual SOC detection performance

5. CONCLUSION

We have developed an improved S&S system using Li-ion battery pack. The system adjusts the same characteristic as Pb battery to make the system simple, and improves re-generation capability due to high charge acceptance. This system is an effective technology to reduce worldwide CO2 emissions (contributes to reducing fuel consumption 3% at NEDC).

In the calculation of Li-ion battery SOC, by measuring in the stable electric discharge area, and considering the frequency characteristic of the impedance of a battery, it becomes easier to detect SOC more accurately, even if the current sensor has an error.

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