Development of Battery Management System

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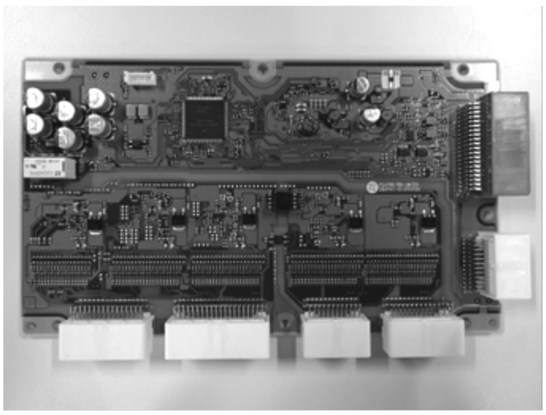

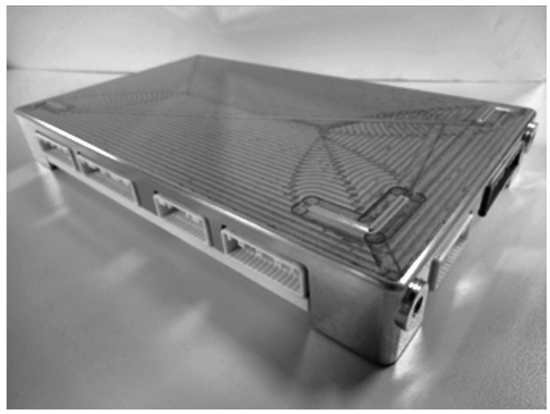

Abstract

Due to their high efficiency and high energy density, lithium-ion batteries have been adopted for mobile electronic devices and electric vehicles. They have been increasingly used further for various applications, such as small mobility vehicles (electric motorcycles, golf carts, etc.), stationary batteries for HEMS (Home Energy Management System), trucks/buses and industrial machinery. However, they have risks of fire hazard and electric shock if being used incorrectly. In order to use the highly efficient lithium-ion batteries safely and effectively, a battery management system (BMS) is needed. Among the BMS, technologies of the battery capacity estimation and the malfunction detection are important.

FUJITSU TEN has developed a universal BMS PF (platform) that can be used for a variety of applications. This paper elaborates the development concept, the safety design technology and the highly-accurate battery capacity estimation technology of the universal BMS PF.

1 Introduction

Among secondary batteries (chargeable batteries), lithium-ion batteries, with higher energy density, have been reduced in size and cost with more capacity due to higher environmental awareness and technological innovation. The market of the batteries is expected to grow about 20% annually from 2015 to 2025. Having the characteristics of no memory effect and small self-discharge as well as being compact and light-weight, they have been used as a power supply for mobile devices, such as cell phones and laptop computers, since 1990s. Their use has been expanding since 2009 when they were mounted on electric vehicles and hybrid vehicles.

In the future, the lithium-ion batteries will be increasingly employed in more various fields, for example,

- stationary batteries for HEMS (Home Energy Management System) for storing electricity generated at lower night rate or electricity generated by solar power
- power supplies for industrial machinery, such as construction machines and devices
- small mobility vehicles, such as electric motorcycles and electric carts, and
- commercial vehicles, such as large buses and trucks.

However, those lithium-ion batteries have a smoke/fire hazard and electric shock if they are handled incorrectly. Therefore, a battery management system (BMS) is important to secure safety.

The BMS plays the roles of:

- detecting malfunctions, such as overcharge, excessive rise of temperature and electric leak; and
- estimating state of charge at temperatures and in the charging/discharging environment

Thanks to those functions of the BMS, the lithium-ion batteries having large energy density can be used safely.

Fig. 1 illustrates a block diagram of the functions of an electric vehicle.

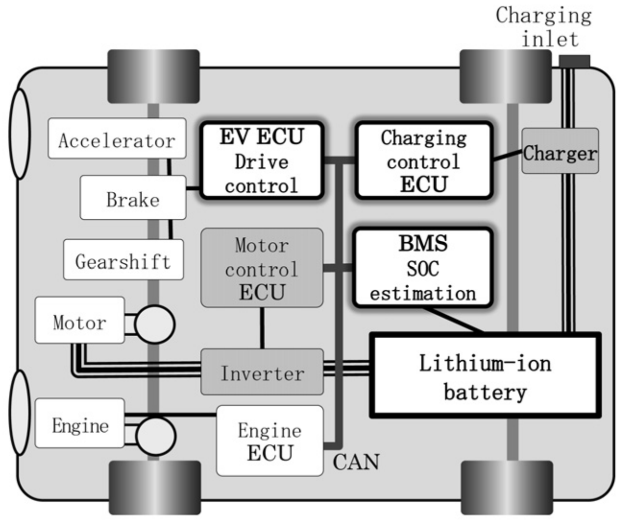

Fig. 1 Block Diagram of Electric Vehicle

The BMS estimates the state of charge (SOC) of the lithium-ion battery. The EV ECU controls a power supply amount (discharged amount from the power supply) and a regeneration amount (charging amount to the power supply) to/from the motor based on the estimated value and battery temperature information. Moreover, the charging control ECU controls a charging amount. Those collaborative controls can prevent overcharge of the lithium-ion battery so that the battery can be charged and discharged safely.

This time, FUJITSU TEN has developed a universal BMS platform (PF) with the aim that it will be used in wider fields having a possibility of using lithium-ion batteries, besides the automobile industry for which we have developed BMS before. This paper elaborates the development concept of the BMS, a safety design technology and a highly-accurate SOC estimation technology used for it.

2 Development Concept

2.1 Change in Development Process

Our conventional development process has taken a few years to develop a vehicle-mounted product for each vehicle in line with the development schedule of the vehicle, which means that we have tailored products based on customer requirements (**Fig. 2**).

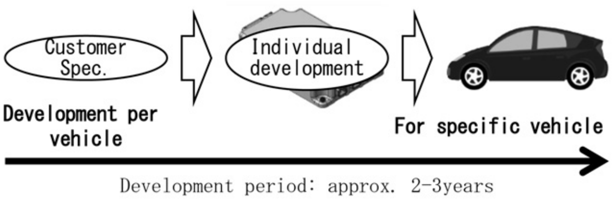

Fig. 2 Conventional Development Process

However, as described in the previous section, since the lithium-ion batteries have been adopted in more fields, if we develop products customized for each field like we did in our conventional development process, we will face a problem of an increase in development cost and resources. Therefore, as a measure for efficient development with limited resources, we adopted an advanced development process in which we first carried out preliminary research about BMS specifications such that the universal PF will be able to be used for a wider range of applications and then developed the "universal BMS PF" compatible with broader specifications (**Fig. 3**).

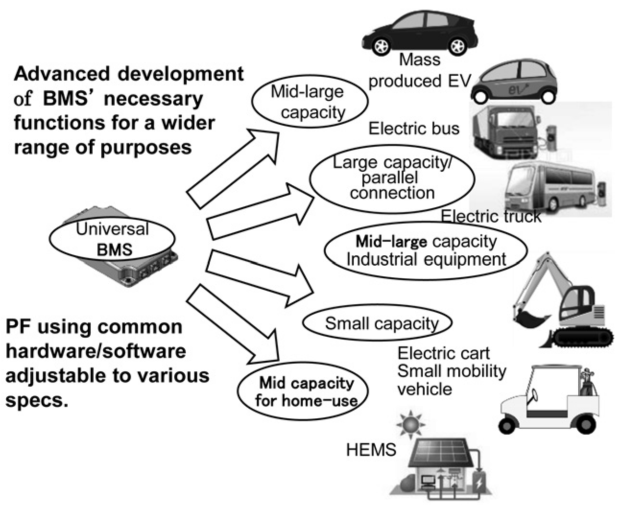

Fig. 3 Advanced Development Process for Widely-used PF

2.2 Development Specifications of Universal BMS PF

Fig. 4 shows an example of functions required for the BMS per purpose and specifications of the universal BMS PF. We decided the required functions per purpose based on ECU benchmarks of other companies, market trend research and survey by asking auto makers and system makers (battery makers).

One among examples for which the BMS is used is EVs of which sales volume is relatively large. However, the BMS is often used in variety of products of which sales volume is relatively low. If a BMS is designed and tailored for each of those products with a low sales volume, development cost will swell and thus the product price will increase. Therefore, we tried to achieve cost reduction by using same design specifications both for EVs requiring many functions and large capacity and for the high-variety low-volume products.

	EV	Bus/ Truck	Stationary batteries for HEMS	Small mobility vehicles	Universal BMS PF
Number of cells	96	96	32,48, 96	8,14, 28	8〜96
Parallel pack	×	○ (2,4)	○ (2,4,8)	×	○ (〜8)
Relay control	○ (3)	○ (3)	×	×	○ (5)
Current monitoring	○	○	○	○	○
Insulation resistance detection	○	○	○	×	○
FAN control	○	○	×	×	○
Temperature monitoring	○ (4)	○ (4+α)	○ (2)	○ (2)	○ (7)
Impact detection	○	○	×	×	○
General-purpose I/O	Extended capability for expected future requirements				○ (4)
General-PWM input					○ (4)

* Number of cells: Number of lithium-ion batteries in series

Fig. 4 Requirements per Purpose and Specifications of Universal BMS PF

Moreover, there is a possibility that the universal BMS PF including all currently-required functions will not be able to satisfy requirements that will be added in the future. Therefore, in addition to the requirements identified based on results from the research and the survey, we decided to include a general-purpose digital input/output terminal and a PWM input/output as an extension I/O for expected future requirements.

2.3 Method of Materializing Universal BMS PF

We materialized the universal BMS PF in a scalable structure to meet all the specifications by using the same circuit board and the same case.

Fig. 5 illustrates a functional block diagram of the 96-cell full function universal BMS that includes all the functions. Moreover, **Fig. 6** and **Fig. 7** illustrate functional block diagrams of the 48-cell universal BMS for stationary batteries for HEMS and the 20-cell universal BMS for small mobility vehicles, respectively.

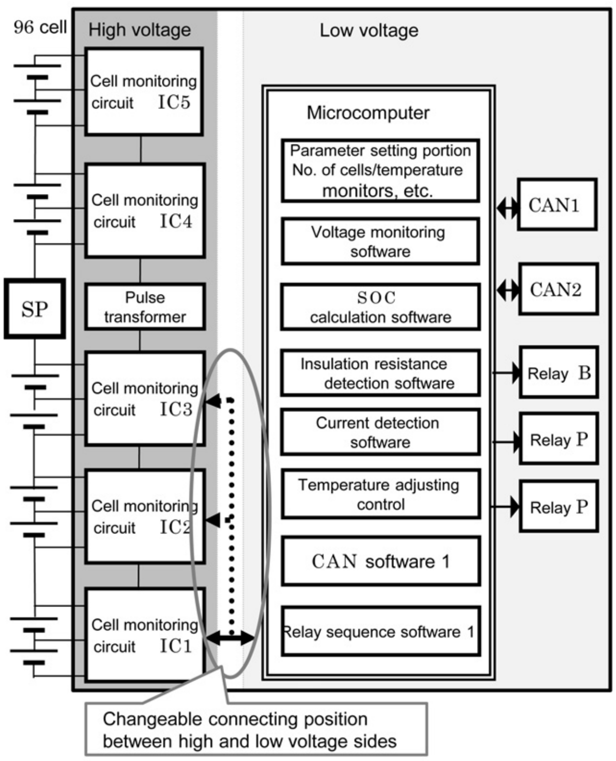

Fig. 5 Block Diagram of 96-cell Full Function Universal BMS

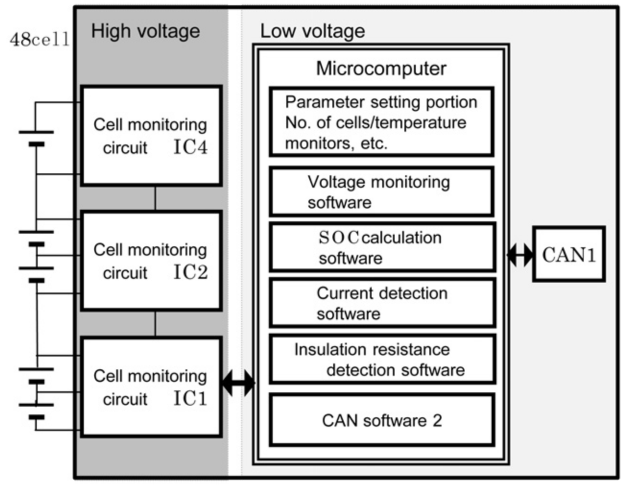

Fig. 6 Block Diagram of 48-cell Universal BMS for Stationary Battery for HEMS

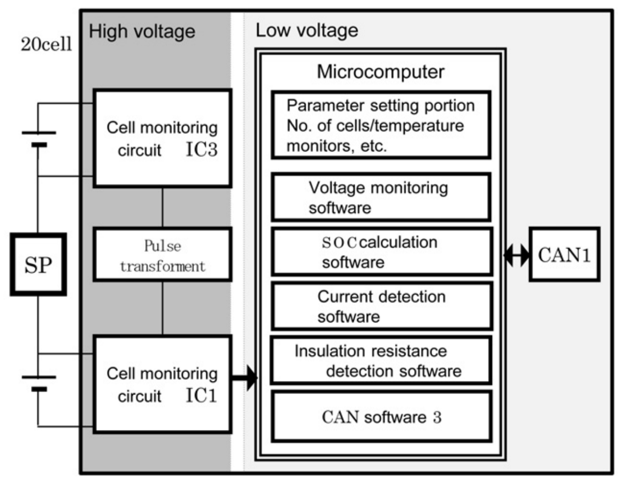

Fig. 7 Block Diagram of 20-cell Universal BMS for Small Mobility Vehicle

As for the hardware, we designed a circuit board including all the functions to realize the full-function specifications shown in **Fig. 5**. Moreover, only by adding or removing (mounted/unmounted) parts to/from the universal BMS PF's circuit board, the modified universal PF can be used for the stationary batteries for HEMS in **Fig. 6** and for small mobility vehicles in **Fig. 7**. In this manner, differences in specifications, such as the number of cells to be monitored, the number of temperature sensors and necessity/non-necessity of relay control, are overcome.

Similarly, the PF includes a parameter setting portion configured to change the numbers of cells, thermistors and current sensors such that it can manage differences in software specifications. Moreover, in this software structure, CAN software and relay sequence varying depending on customer specifications can be easily changed only by replacing software parts.

When the number of the cells is changed, a position of a service plug (SP) in a battery cell pack also needs to be changed (refer to **Fig. 5**). The service plug is an insulation plug for safety to protect service person from electric shock during maintenance work of the vehicle. When the service plug is detached, the current pathway is cut off so that safety can be ensured.

Normally, the SP is provided near the center of the battery cells connected in series. For the BMS circuit board, a pulse transformer should be provided for insulation of the circuit in accordance with the position of the SP. Moreover, communication from a microcomputer on the board to each cell monitoring IC is established via the lowest IC (the IC1 in case of **Fig. 5**). Therefore, when the circuit board is adjusted to a cell pack having a small number of cells, ICs are removed in a decreasing order of hierarchy. In order to materialize a board design flexibly adjustable to a cell pack having the SP as well as fewer cells, the circuit board can be designed so as to provide the pulse transformer between any two ICs. However, that will make the board larger and the cost will exceed the target.

Meanwhile, in the structure of the universal BMS, a location of the IC for the communication can be changed between the low voltage side and the high voltage side of the board, as shown in **Fig. 5**, so that the position of the pulse transformer for the circuit insulation can be fixed at one position. Accordingly, the structure is adaptable to the cell pack having fewer cells and a SP, as shown in **Fig. 7**, because the IC can be changed. Thus, the structure helps to realize a smaller-sized circuit board and a reduction in the board cost.

2.4 Satisfaction of Required Functions (Cell Balancing)

One of important functions of the BMS is cell balancing. It is a function of optimally using the battery cell capacities by eliminating differences in capacity among the battery cells, as shown in **Fig. 8**. If there are differences in voltages among battery cells in a cell pack, those cells cannot be charged or discharged to their limits. Thus, their practical capacities decrease. The cell balancing prevents this. In the case of a BMS having cells connected (packed) in series, this function is necessary to maximize performance of those cells.

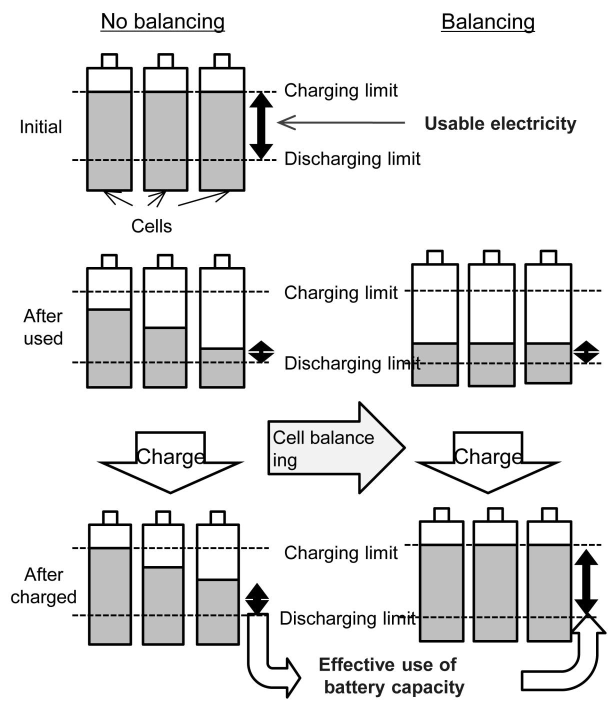

Fig. 8 Cell Balancing

The "passive cell balancing" is employed for our universal BMS PF. In the passive cell balancing, a discharging switch (SW) forcibly discharges battery cells having higher voltages. In a conventional structure, as shown in **Fig. 9**, one same pathway is used both for voltage monitoring and cell balancing current so that it is difficult to monitor an accurate voltage during the cell balancing because a voltage drops due to resistance and current of the pathway. Therefore, there is a problem of low accuracy of battery cell voltages measured during charging/discharging and travelling of the vehicle.

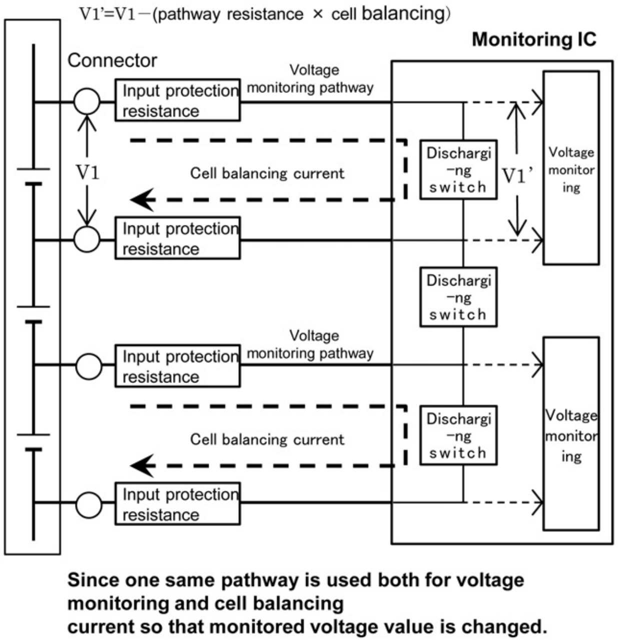

Fig. 9 Conventional Structure

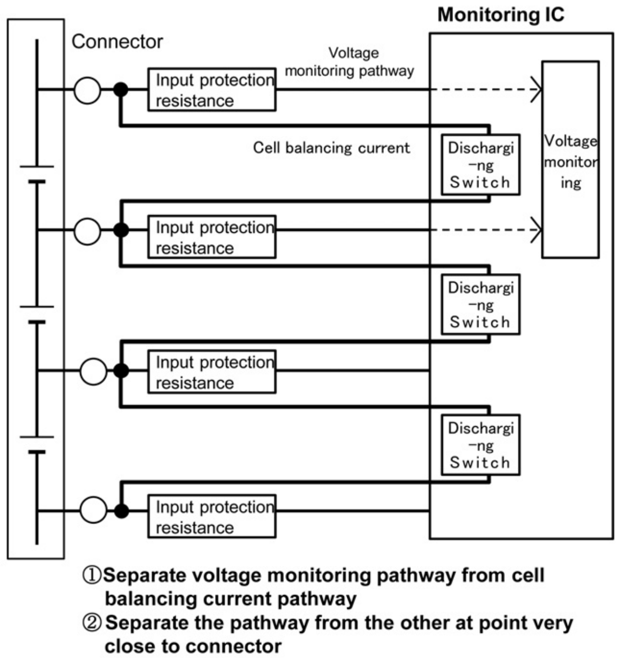

Fig. 10 Method of Achieving Cell Balancing during Operation

In order to solve this problem, the structure shown in **Fig. 10** is adopted for the universal BMS PF. The voltage monitoring accuracy required for the BMS is normally 10mV or less. Thus, the resistance of the board pattern needs to be considered. In the structure in **Fig. 10**, a voltage drop is prevented by separating the current pathway from the voltage monitoring pathway at a point very close to the connector. Therefore, it is possible to monitor more accurate voltage even during the cell balancing. (Now, it is possible to perform the cell balancing without lowering the accuracy of the cell voltage measurement even during charging/discharging operation and travelling of the vehicle.)

This function can be especially effective not only for vehicle-mounted devices but also for constantly operating systems, such as the stationary batteries for HEMS.

3 Safety Design Technology

3.1 Importance of BMS Safety Design and Compliance with Standard of Functional Safety

As cited earlier, there is a possibility that lithium-ion batteries cause a serious problem if they are handled incorrectly. Therefore, the BMS that monitors those batteries also need safety design. We designed our BMS, focusing on the risks listed below.

- ・Fire hazard from lithium-ion battery due to overcharge (**Fig. 11**)
- ・High voltage electric shock (**Fig. 12**)

Moreover, the automobile industry is preparing to apply the international standard ISO26262 (Functional safety) to all related products. The standard was established with the participation of many auto-related manufacturers to strike a balance between performance and safety of the automobile controlling function that has been increasingly computerized. The standard defines the automotive safety integrity levels (ASIL) from A to D, according to risk levels of phenomena possibly caused by malfunctions. As for the "fire hazard from lithium-ion battery due to overcharge," of which risk level is especially high, we developed the universal BMS PF based on the design specifications that comply with the level D of the ASIL.

This section explains the safety design distinctive to the universal BMS PF.

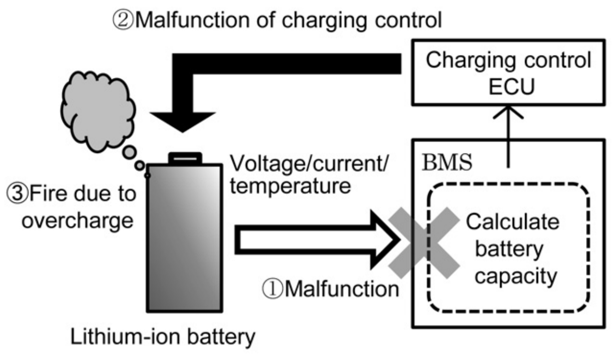

Fig. 11 Fire Hazard from Lithium-ion Battery

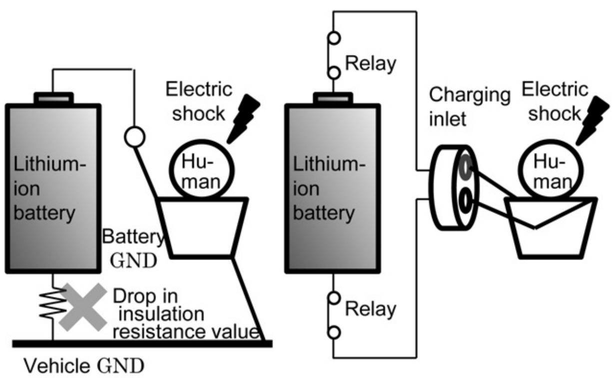

Fig. 12 High Voltage Electric Shock

3.2 Safety Design against Fire Hazard from Cell (Compliance with ASIL D, Functional Safety)

3.2.1 Design Concept

In order to prevent a fire hazard from the lithium-ion battery, the design concept of the universal BMS PF defines its main function (MF) as "controlling the charged/discharged states of the lithium-ion battery by monitoring its voltage, current and temperature."We added a safety function (first safety mechanism or 1st SM) that determines overcharge by detecting overvoltage and then turns off a relay to prevent the fire hazard from the cell in the case where charging is out of control due to a malfunction of the MF so that overcharge occurs. Further, we added another safety function (second safety mechanism or 2nd SM) that detects a malfunction of the 1st SM. Thus, the safety is ensured by the triple redundant design, the main function, the 1st SM and the 2nd SM (**Fig. 13**).

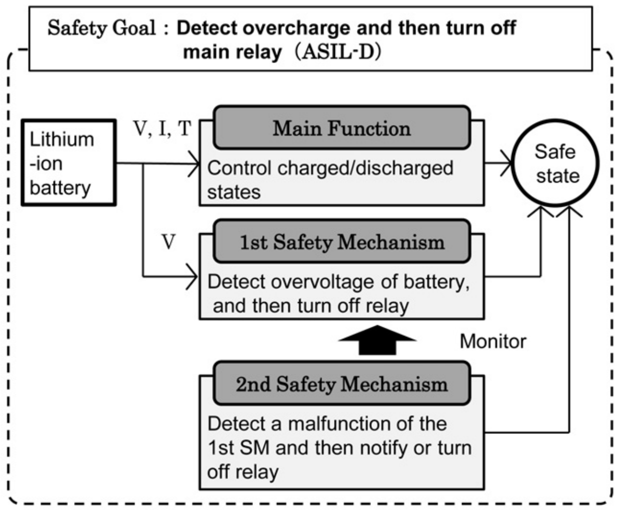

Fig. 13 Safety Design Concept to Prevent Fire Hazard from Battery

3.2.2 Design of First Safety Mechanism

The function of the 1st SM cited in the previous chapter is realized by configuring the hardware of the universal BMS PF as shown in **Fig. 14**.

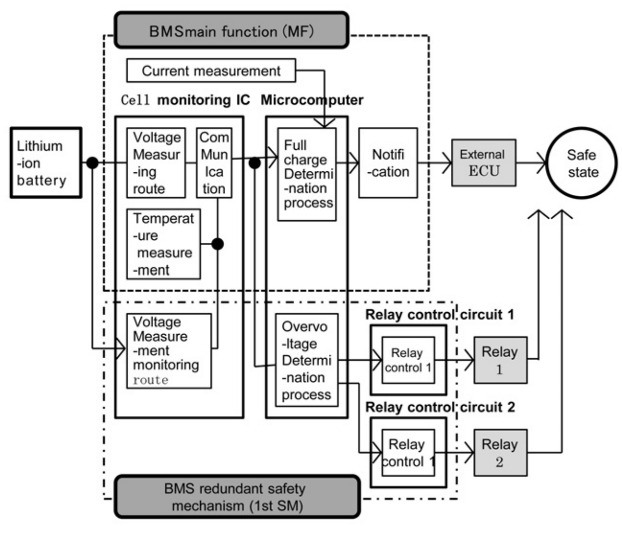

Fig. 14 1st SM Structure on Universal BMS PF

In this structure, the cell monitoring IC redundantly performs voltage measurements of the battery cells in two routes, one of which is a "measuring route" and the other is a "monitoring route." Moreover, the microcomputer determines whether overvoltage of the cells has occurred based on the measured voltages, and, if necessary, turns off the relays redundant by the two routes. Thus, dangerous malfunctions that may lead to overcharge of the cells can be detected at 99% or higher, the malfunction detection rate required for the ASIL D.

Both of the cell monitoring IC and the microcomputer are configured to include the MF and the 1st SM in the same devices. Therefore, measures are taken against malfunctions common to those safety functions. Some of those measures included in the design will be explained below.

(1) Measurements against malfunction common to cell monitoring ICs

Fig. 15 illustrates the internal structure of the cell monitoring IC. We adopted an IC including the voltage measuring route and the voltage measurement monitoring route. Each of those routes has a power supply, a MUX, an ADC, a data processor and a clock, and they are structurally separated from each other. In addition, the data communication line connected to the microcomputer is shared by the two routes so that problem detection is performed for the communication.

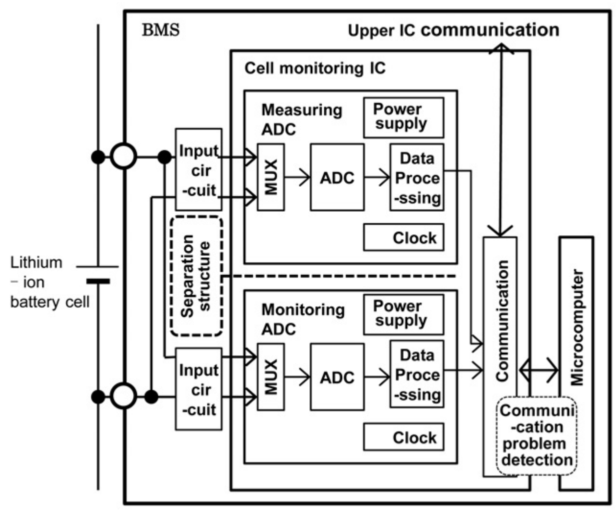

Fig. 15 Internal Structure of Cell Monitoring IC

(2) Measurement against malfunction common to microcomputers

We adopted a microcomputer including: the "dual core lock step" function that causes the processing core and the monitoring core to perform the same calculation and that confirms whether results from both the calculations are the same; and the "memory protection unit (MPU)" function that separates memory regions used for the MF and the 1st SM from each other. In the case where the calculation results are determined not to be the same by the dual core lock step function, there is a possibility that the microcomputer is in a state in which it cannot turn off the relay. Therefore, it is designed to send a notification of occurrence of the malfunction to the power supply IC. Once receiving the notification, the power supply IC can turn off the relay (**Fig. 16**).

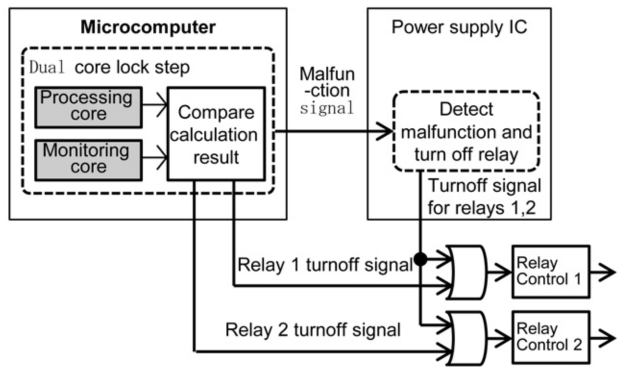

Fig. 16 Turning-off of the Relay by Power Supply IC in Case of Microcomputer's Malfunction

3.2.3 Design of Second Safety Mechanism

In order to detect a malfunction of the 1st SM, various diagnoses are performed as the 2nd SM. The diagnoses performed by the circuit blocks will be explained below.

(1) Diagnosis of cell monitoring IC (2nd SM)

It compares the cell voltage values individually measured by the voltage measuring route and by the voltage measurement monitoring route, and then diagnoses whether the measured values are correct.

(2) Diagnosis of microcomputer and power supply IC (2nd SM)

The diagnosis called the built-in-self-test (BIST) is performed. The BIST is a diagnosis method including test pattern generation through test result determination performed within the chip itself. It can diagnose logics, memories and analogue circuits.

(3) Diagnosis of relay control circuit and relay (2nd SM)

It diagnoses the relay control circuit and the relays to find a malfunction, by turning on and off the relays based on a predetermined pattern.

3.3 Safety Design against Electric Shock

Circuits for measuring an insulation resistance value and a voltage value at the charging inlet are provided to the universal BMS PF to protect a user from electric shock. The circuits will be explained below.

(1) Insulation resistance detection circuit

A ground of the vehicle is connected to a ground of the battery cell by coupling connection. An insulation resistance value is converted to a voltage value by applying a pulse voltage and then the converted voltage value is measured. A capacitor is used for the coupling connection. A short circuit of the capacitor directly leads to a decrease in the insulation resistance value. Thus, three capacitors are connected in series as safety design. Moreover, this circuit has a self-diagnosis function of inputting test signals to confirm whether the circuit is normal **(Fig. 17)**.

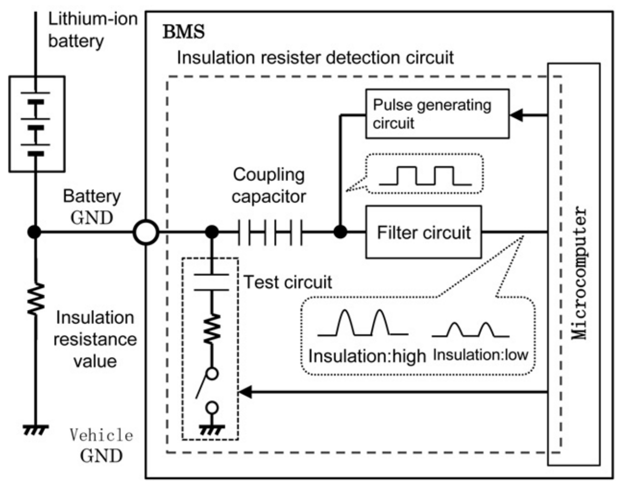

Fig. 17 Insulation Resistance Detection Circuit

(2) Voltage measuring circuit at charging inlet

When there is a possibility that the user touches the charging inlet, the voltage measuring circuit measures whether voltage comes out of the charging inlet. The circuit is configured with an input circuit connected to the positive side of the charging inlet and an input circuit connected to the negative side of the charging inlet. Two sets of those two input circuits are provided for redundancy. Thus, this design can perform a self-diagnosis by comparing the input logic from the circuits **(Fig. 18)**.

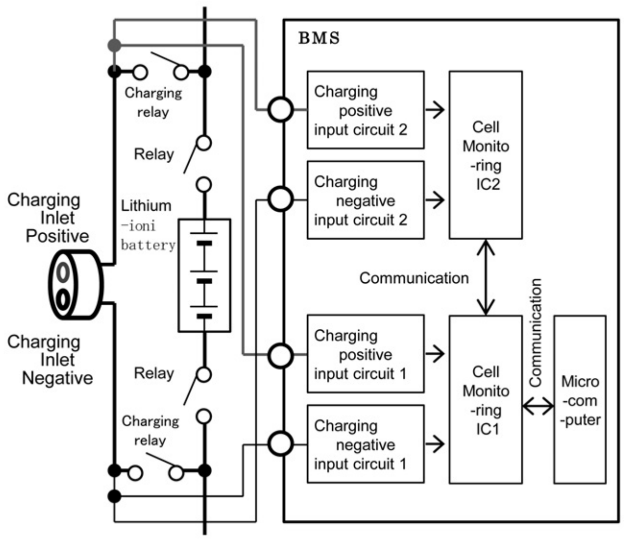

Fig. 18 Circuit for Voltage Measurement at Charging Inlet

4 Development of Battery Status Estimation Algorithm

4.1 Necessity for Accurate Estimation of Battery Status

Lithium-ion batteries have a region that is prohibited from being used because using the region carries a fire hazard and other risks. Therefore, a margin is set to the lithium-ion batteries to prevent the region from being used **(Fig. 19)**.

A size of the margin depends on accuracy in estimating the state of charge (SOC) of the battery. Therefore, an accurate estimation for the SOC makes the margin smaller and makes the usable capacity of the cell larger, which leads to better fuel efficiency of the vehicle and longer cruising distance. Therefore, accurate SOC estimation is very important to maximize the performance of the cell.

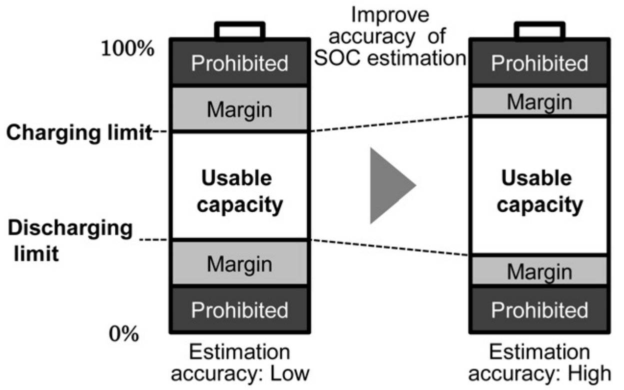

Fig. 19 Image of Battery Capacity

Generally, an estimation error of the SOC is regarded as 5% to 10%. We worked with FUJITSU Limited to develop an SOC estimation algorithm with an estimation error target of 3% or less.

4.2 Battery Status Estimation Algorithm

For estimating the SOC, it is important to measure an open-circuit voltage (OCV) of the battery because the OCV is closely related to the SOC. However, since the OCV means a terminal voltage measured when the battery is completely disconnected from a load and is in a stable state, it is difficult to measure the OCV while current is flowing. Therefore, in order to overcome this difficulty, we used the characteristics that a voltage at the battery terminal is equal to a sum of the OCV and an overvoltage caused by an internal resistance of the battery, while the current is flowing.

In our algorithm, once the internal resistance of the battery is calculated based on a battery equivalent circuit model, a terminal voltage is consecutively estimated. After the estimated terminal voltage is compared with an actually-measured voltage, the value is corrected by using Kalman filtering, a statistic method, so as to reduce the estimation error, and then the SOC is estimated.

4.2.1 Battery Equivalent Circuit Model

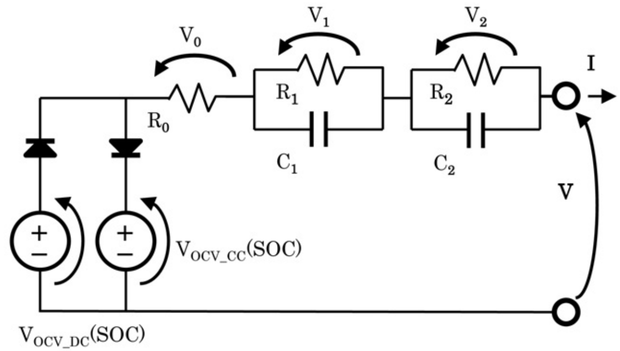

Fig. 20 Battery Equivalent Circuit Model

The battery equivalent circuit model, having resistances and capacitors as structure elements, is used to estimate the state of the battery (**Fig. 20**). The circuit model is derived based on inputs (current and temperature) and an output (voltage) to/from the battery.

The mathematical expression of the model is shown below.

$$x^{-}(k)=\begin{pmatrix} dV_1/dt \\ dV_2/dt \\ SOC(k) \end{pmatrix}=\begin{pmatrix} -1/R_1C_1\times V_1(k-1)+1/C_1\times I(k-1) \\ -1/R_2C_2\times V_2(k-1)+1/C_2\times I(k-1) \\ SOC(k)+(1/SCA)\times I(k-1)\times\Delta t \end{pmatrix}$$

$$OCV(k)=f(SOC(k)) \qquad k: \textit{Sample (data)}$$

V_1, R_1 and C_1 represent the voltage, the resistance and the capacity of the electrode surface, respectively, and V_2, R_2 and C_2 represent the voltage, the resistance and the capacity of the active material, respectively. R_0 represents the electrolyte resistance, and I represents the input current. SCA represents the full capacity. These parameters need to be defined whenever a type of the battery is changed. R_1, R_2, C_1 and C_2 are expressed by functions using R0 and the input current so that current dependency of the internal resistance can be considered.

The OCV of the battery is expressed in a mathematical equation based on curve fitting technique, using measured values of SOC and OCV, and is adjusted based on the temperature and the reduced capacity of the battery. Then, the dependency is reflected. Moreover, an OCV for a charging side (V_{OCV_CC}) is defined differently from an OCV for a discharging side

(V_{OCV_DC}), and they are switched based on a direction of the current input to the battery. By using this method, the SOC dependency of the OCV can be accurately expressed as a function so that the estimation error of the SOC can be reduced.

4.2.2 Structure of Battery Capacity Estimation Algorithm

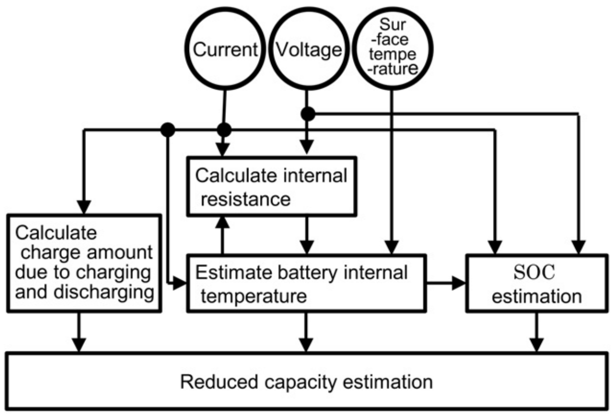

Fig. 21 Configuration of Battery Capacity Estimation Algorithm

In addition to the SOC, a reduced amount of the capacity of the battery also can be estimated by our battery estimation algorithm configured as shown in **Fig. 21**. The next section will explain an outline of each step of the process.

(1) Calculation of internal resistance

The internal resistance R_0 in the battery equivalent circuit model is calculated based on the equation below using a cell voltage and an input current at the time.

$R_0 = \Delta V(\text{cell}) / \Delta I(\text{input})$

Moreover, R_0 is calculated based on the actually-measured voltage and the input current. Therefore, this method allows the internal resistance to be derived, considering the temperature and the reduced capacity of the battery.

(2) Calculation of charge amount by charging and discharging

An amount of charge changed at each time of charging and discharging is calculated based on the input current.

(3) Estimation of internal temperature of battery

The internal temperature of the battery is estimated based on the flow from ① to ③.

①Calculate a rise in temperature (heat value) from the internal resistance and the input current.

②Calculate change in temperature (increase and decrease of heat) from a difference between the estimated internal temperature and the surface temperature.

③Estimate the internal temperature from ① and ②.

Temperature change = ① + ②

Estimated internal temperature of battery=previously estimated internal temperature of battery + temperature change.

(4) SOC estimation

The estimated battery terminal voltage V_p is calculated from the equation of the battery equivalent circuit model.

$$V_p = V_1(k) + V_2(k) + OCV(k) + R_0 \times I(k)$$

The estimated value is compared with the actually-measured terminal voltage V. Then, Kalman gain G, a weight coefficient for the estimation error, is calculated from the Kalman filtering, and then the estimated value is corrected. This process is repeated at every measurement of a value input to the battery.

$$y(k) = V_p(k) - V(k) \quad , \quad x(k) = x^-(k) + G(k) \times y(k)$$

$y(k)$:*Error between measured and estimated values*

$x^-(k)$:*Estimated value* $x(k)$:*Estimated value after correction*

(5) Reduced capacity estimation

The reduced capacity is defined by a sum of natural degradation that has a greater influence at a high temperature and current degradation that has a greater influence during charging/discharging at a low temperature.

The natural degradation is a function of temperature, SOC and time, and the current degradation is a function of temperature and moved charge amount.

4.3 Estimation Accuracy Evaluation

We evaluated accuracy of the SOC estimated by our battery estimation algorithm based on a charging/ discharging pattern obtained while the EV is travelling. As shown in **Fig. 22**, the estimation error between the estimated value and true value is 3% or less so that the estimation is highly accurate.

Moreover, we also evaluated the estimated reduced capacity of the battery (degradation to capacity). As shown in **Fig. 23**, we compared transition of the actually-measured value of degradation to capacity (true value) with transition of the value estimated based on charging/discharging evaluation of 112 cycles (approx. two months) to find that the values estimated by our algorithm are highly accurate.

5 Conclusion

As described above, this paper described the outline of our developed universal battery management system platform and the development technologies for it. The PF's specifications allow it to be used for various applications, and provided prototype samples of the PF have been received well. Thus, we believe that we have developed the PF as intended. However, we also believe that battery management systems will be continuously improved in performance and functions. Therefore, we will continue to enhance our battery management system with higher func-

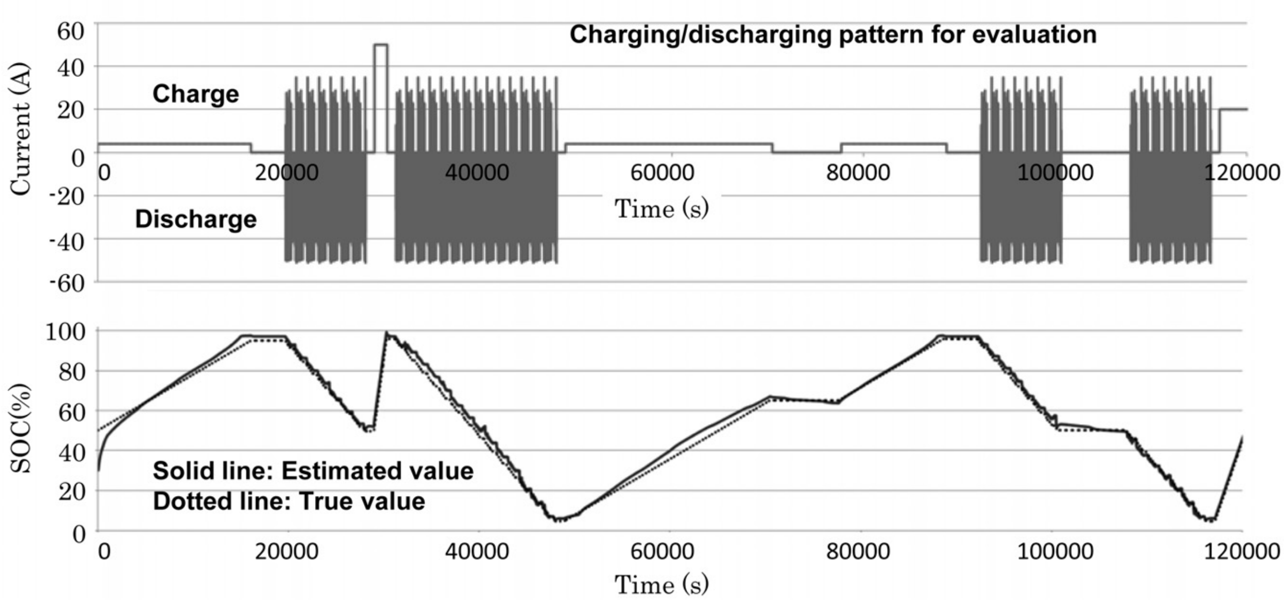

Fig. 22 Transition of SOC Estimated Value and True Value

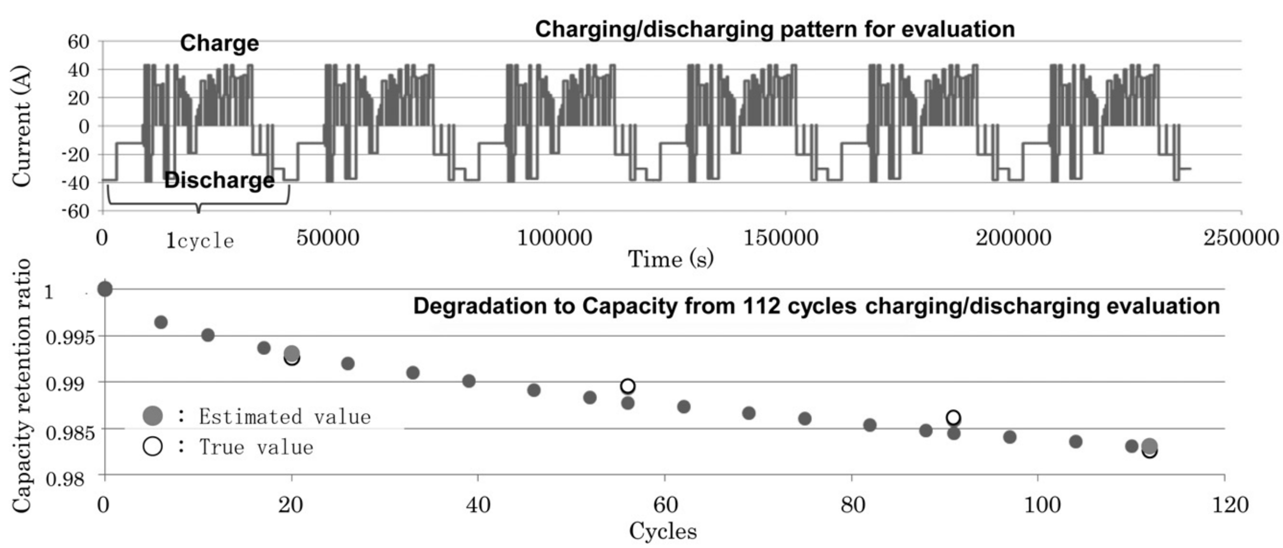

Fig. 23 Transition of Estimated Value and True Value of Reduced Capacity (Degradation to Capacity)

tions and more sophisticated performance at a lower cost by making the best use of the know-how gained in this development. For review and development of the specifications of this battery management system, we received kind cooperation from customers, parts suppliers and design companies. We would like to extend our sincere appreciation to our customers and all others who provided us with valuable advice and generous technical support for this development.

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