Development of an Auxiliary Power Supply System for Electric Power Steering and a High-heat Resistant Lithium-ion Capacitor

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To motorize the steering system of a full-size vehicle equipped with a 12 V power supply, JTEKT is developing an auxiliary power supply system for electric power steering (EPS) using a lithium-ion capacitor. In addition, as a result of working on expanding the temperature range of the lithium-ion capacitor in order to mount the system in a full-size vehicle free of a cooling-heating system, the world's first operating temperature range of -40 to 85 degrees C was achieved. The developed capacitor operates stably even in high temperatures exceeding 100 degrees C by restricting the upper limit of operating voltage.

Key Words: *energy storage device, lithium-ion capacitor, heat-resistance, low temperature output, EPS*

1. Introduction

Advanced Driver Assistance System (ADAS) and autonomous driving (AD) are two major topics concerning current and next-generation automobiles. The 2018 Public-Private ITS Initiative/Roadmaps issued by the Prime Minister’s Office set a goal of launching vehicles with autonomous driving level 4 as defined by SAE International J30162 (Sep 2016) on the market in limited scenes such as expressways by around 2025[1), 2)].

Even if some form of failure occurs in a vehicle, the AD function must continue to the extent that the vehicle can be guided in the front/back, left/right directions[3)-5)]. As such, it is essential that functional safety is improved in the steering systems equipped in vehicles with high AD levels. Particularly in regards to vehicles with AD level 4, where a human does not intervene with driving, there is a need for the steering system to continue operating even in the event of power failure/interruption, etc. during vehicle travel, therefore improving the functional safety of current steering systems is essential[6), 7)].

Moreover, in order to realize ADAS and AD functions, it is desirable to equip vehicles with electric power steering that enables steering control from an external ECU. However, hydraulic power steering systems are equipped in vehicles weighing 3 tons or more and large vehicles with a steering rack axial force requiring 14 kN or more. If electric power steering (EPS) is used in these large vehicles, during maneuvers such as stationary steering and sudden steering, it would not be possible to supply sufficient power demanded by the EPS, even for a brief period, from a 12 V vehicle power supply. In other words, it would exceed the maximum current able to be supplied from a lead storage battery, therefore creating a phenomenon where the steering wheel would be heavy during maneuvering. This phenomenon is called “insufficient assistance,” and in order to solve this phenomenon, JTEKT is developing an auxiliary power supply system for EPS utilizing a Lithium-ion capacitor for the energy storage device[8)-10)]. This system has high function expandability and can contribute to the aforementioned improvement of EPS’s functional safety. This is explained in detail in the next section.

Moreover, in order to make such a system low cost and more freely able to be equipped on a vehicle, it would be necessary to omit a cooling system. The operating temperature range of a conventional Lithium-ion capacitor was narrow at around -20 to 60℃, therefore non-conforming with vehicle temperature requirements and making the use of a cooling-heating system essential. As such, JTEKT also independently endeavored to expand the operating temperature range of Lithium-ion capacitors.

2. Auxiliary Power Supply System for EPS

2. 1 Concept

The auxiliary power supply system for EPS was developed with the aim of alleviating the power insufficiency problem that occurred when an EPS is mounted in a large vehicle, without the need to make changes to either the EPS or 12 V vehicle power supply.

Figure 1 shows an external view of a prototype for the developed system. As **Fig. 2** shows, this system is a separate device installed between the 12 V vehicle power supply and EPS system, and is configured from an energy storage device and a charge-discharge controller controlling the charging and discharging of the energy storage device. In situations where the vehicle power supply and EPS have low power consumption, power is stored in this energy storage device, then used in situations where the EPS requires a high amount of energy, such as during stationary steering. The charge-discharge controller and energy storage device must have the various reliable qualities demanded of a vehicle (mechanical stress, electrical stress, operating temperature range).

2. 2 Configuration and Overview

Figure 3 is a block diagram of an auxiliary power supply system for EPS. This system is installed between a 12 V vehicle power supply [A] and EPS system [B]. With consideration to charging/discharging speed, repetitive charging/discharging life, energy density, safeness and other factors, a Lithium-ion capacitor [C] was adopted for the energy storage device.

The Lithium-ion capacitor and 12 V vehicle power supply are connected by a charge circuit [D] and discharge circuit [E]. The central processing unit (CPU) of the charge-discharge ECU [F], monitors the status of the EPS and 12 V vehicle power supply and actuates the discharge circuit if a situation arises where the EPS requires power greater than the 12 V vehicle power supply can provide. By adding the Lithium-ion capacitor voltage to the 12 V vehicle power supply and increasing the supply voltage, the EPS can be made high output (x of **Fig. 3**). If the voltage of the Lithium-ion capacitor drops, the charge circuit is actuated and charging is performed from the 12 V vehicle power supply (y of **Fig. 3**).

2. 3 Circuit Operation

Figure 4 shows the detailed circuit operation of this system. When travelling straight, etc. in the case that the EPS power consumption is small, the FET1 and FET2 will close, and the EPS will only operate by the 12 V vehicle power supply. In situations such as stationary steering and rapid steering when the EPS requires a large amount of power, FET1 and FET3 will close, and the Lithium-ion capacitor will be connected in series to the 12 V vehicle power supply. The cell voltage of the Lithium-ion capacitor will be added to the 12 V vehicle power supply, and as a result of power supply voltage increasing, it will be possible to supply the EPS with a large amount of power. Increasing the number of Lithium-ion capacitors in series will increase the maximum output power of the system. If the system operates and the voltage of the Lithium-ion capacitor drops, FET4, FET5, and the coil will be used to recharge the Lithium-ion capacitor.

Fig. 1 External view of an auxiliary power supply system for EPS (W137×D83×H80mm)

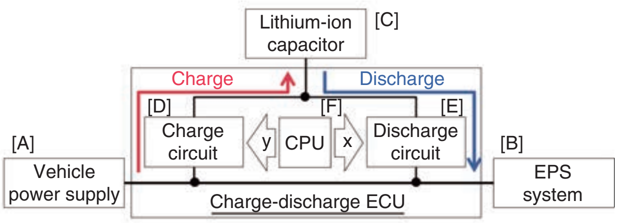

Fig. 3 Block diagram of an auxiliary power supply system for EPS

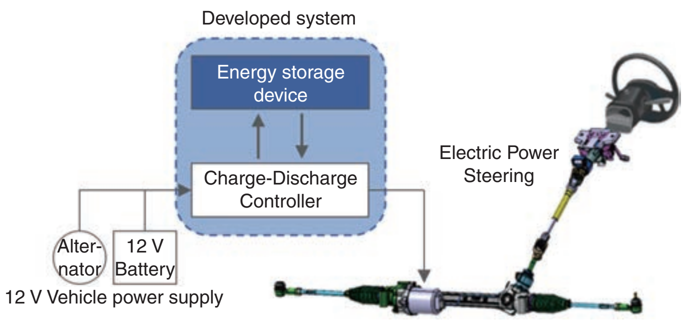

Fig. 2 System configuration

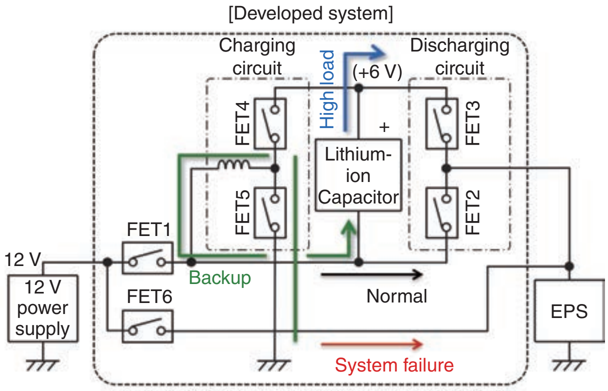

Fig. 4 Circuit operation details

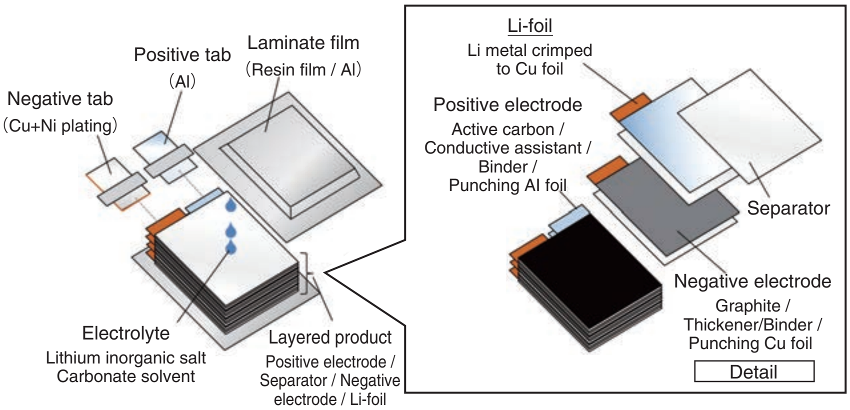

Fig. 5 General structure of a lithium-ion capacitor

Every Lithium-ion capacitor cell has an average operating voltage of 3 V, therefore 4 capacitors in series will create a 12 V power supply in the system internally. If a power failure occurs during travel, EPS will continue being driven by the 12 V power supply configured in this system due to FET3 and FET5 closing. This is a useful system for the realization of AD level 4, which requires the full fail-operational of EPS including power failure. Even in the unlikely event that some kind of problem occurred in the circuit or FET, the system can continue to drive the EPS with a bypass circuit due to FET6 closing. A feature of the system developed by JTEKT is the high expandability in a single circuit which enables a myriad of functions to perform, and the effectiveness of this system was verified in an actual vehicle evaluation, however a Lithium-ion capacitor with high heat resistance is necessary to equip this system on a vehicle without using a cooling system. As such, we endeavored to suppress the performance deterioration of the Lithium-ion capacitor in a high temperature environment.

3. Lithium-ion Capacitor

3. 1 Structure and Features

The Lithium-ion capacitor is a new energy storage device that has characteristics midway between a lithium-ion secondary battery and electric double layer capacitor, and comprises a lithium-ion secondary battery's graphite negative electrode and electric double layer capacitor's activated carbon positive electrode[11), 12)] (**Fig. 5**).

While retaining the features of an ability to instantly supply/regenerate a large amount of power and excellent repetitive charging/discharging resistance, which are the merits of an electric double layer capacitor, the Lithium-ion capacitor is an energy storage device with a volume energy density that is three to six times greater, therefore it is anticipated to be useful in various industrial domains[13)]. However, one issue that must be addressed in order to expand its scope of application, is the need for a wider operating temperature range, and it is essential that the performance deterioration occurring at temperatures above around 60℃ is suppressed.

3. 2 Grasping Deterioration Outside of Operating Temperature Range

Through a bibliographic survey and verification test, we elucidated the cause of performance deterioration in a Lithium-ion capacitor as a result of what kind of phenomenon occurring during operation at temperatures both higher and lower than the operating temperature range of a conventional Lithium-ion capacitor.

In the higher temperature range, irreversible increase in internal resistance and irreversible decrease in capacitance occurred due to thermal decomposition of the electrolyte. Decomposition gas of the electrolyte caused the capacitor to expand, and ultimately led to the cell rupturing (**Fig. 6**). It was observed that the decomposition of the electrolyte occurred due to the thermal decomposition of lithium hexafluorophosphate ($LiPF_6$), which is an electrolyte commonly used in Lithium-ion capacitors and lithium-ion secondary batteries[14].

(85℃, 100 hours)

Fig. 6 Lithium ion capacitor stored in a high temperature environment

In the lower temperature range, irreversible output reduction occurs in line with the increase in internal resistance, and once a temperature of -20℃ or below is reached, the electrolyte freezes, making it no longer possible to charge or discharge the Lithium-ion capacitor. The negative electrode of the Lithium-ion capacitor is the same material as a lithium secondary battery and uses a chemical reaction during charging/discharging. The speed of a chemical reaction depends on the ambient temperature, therefore if the temperature drops, the output of the Lithium-ion capacitor will also drop.

From the above study results, we confirmed that a major point in broadening the operating temperature range of a Lithium-ion capacitor was improving the electrolyte.

3. 3 Implementation Items

Table 1 shows the implementation items for improvement. We changed the electrolyte (lithium hexafluorophosphate) that was the cause of the electrolyte's thermal decomposition at high temperatures to an imide-type lithium compound with excellent heat-resistance. Furthermore, we revised the mixing ratio of the electrolyte solvent, etc. to a composition unique to JTEKT whereby it does not freeze at -40℃, nor boil at 100℃. We also used a unique improvement technique to control the compatibility of capacitor materials.

4. Evaluation Test Conditions

4. 1 Manufacturing of Lithium-ion Capacitors

Making a positive electrode by applying activated carbon to aluminum foil and a negative electrode by applying graphite to copper foil, we alternately layered positive electrodes and negative electrodes via a separator. With the below three criteria, we created a laminated Lithium-ion capacitor with an operating voltage of 2.2 to 3.8 V and a capacitance of 500F.

(1) Regular electrolyte (1.0 mol/L $LiPF_6$/ Ethylene carbonate (EC): Ethyl methyl carbonate (EMC): Dimethyl Carbonate (DMC) = 3: 4: 3)

(2) New electrolyte (high heat-resistant electrolyte/non-aqueous solvent with a high boiling point and low

Table 1 Implementation items

	Technical challenge	Implementation items
Heat-resistance improvement	Prevention of electrolyte liquid decomposition	Adoption of high-heat resistant electrolyte salt
	Prevention of electrolyte liquid boiling	Adoption of high boiling-point organic solvent
	JTEKT original improvements	
Improvement of low temperature output	Prevention of electrolyte liquid freezing	Adoption of low freezing point organic solvent
		Optimization of organic solvent mixing ratio
	Prevention of internal resistance rising	Affecter identification
		Changing of positive and negative materials

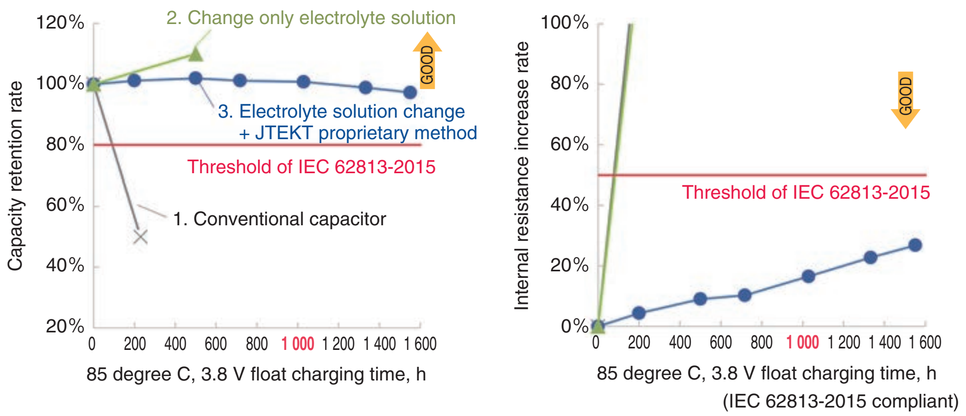

Fig. 7 Test result of float charging at 85 degree C

freezing point)

(3) New electrolyte + JTEKT's unique improvement

4. 2 Heat-resistance

The high temperature durability test for the Lithium-ion capacitor was a 3.8 V float charging test carried out in an ambient temperature of 85℃, as per the stipulations of IEC 62813-2015 [High temperature continuous rated voltage application test] of [Lithium-ion capacitors for use in electric and electronic equipment - Test methods for electrical characteristics]. This same standard requires that after 1 000 hours of float charging, the internal resistance increase ratio is 50% or less, and the static capacitance decrease ratio is 20% or less.

4. 3 High Current Charge/discharge Resistance

We investigated the durability of the developed Lithium-ion capacitor against large current charging/discharging. We confirmed performance deterioration of the capacitor by a charge/discharge cycle test where we changed the maximum temperature from 85 to 110℃ temperature in increments of 5℃. By gradually reducing the capacitor's upper limit voltage from 3.8 to 3.6 V, we performed the test approximately 10 000 times at a charging/discharging rate of approximately 900C. The charging/discharging mode is the CC (rated current) - CV (rated voltage) mode.

After the cycle test, we measured internal resistance and discharging capacitance in line with IEC 62813-2015, and set a performance deterioration of around 10% or higher as the pass/fail threshold for the test.

4. 4 Low Temperature Characteristic

We investigated the internal resistance increase rate in a low temperature environment based on the internal resistance at 25℃. The measurement method used conformed with IEC 62813-2015. We investigated the charge/discharge cycle performance of the developed Lithium-ion capacitor at -40℃. The operating voltage range was set from 2.2 to 3.8 V, CC-CV charging/discharging mode was used, and the charging/discharging rate was made 85C. For confirmation of Lithium-ion capacitor performance, after returning the workpiece surface temperature to 25℃, we measured internal resistance and discharging capacitance under conditions conforming with IEC 62813-2015.

5. Various Evaluation Results

5. 1 Heat-resistance

Figure 7 shows the results. For the conventional Lithium-ion capacitor, the deterioration of both the capacitance retention rate and internal resistance increase rate are significant. These values fell below the IEC standard's requirements approximately 100 hours after the test was begun. Gas was generated due to thermal decomposition of the $LiPF_6$ in the electrolyte, and the test was terminated due to significant cell expansion in the Lithium-ion capacitor.

In a capacitor where only the electrolyte was changed, the capacitance retention rate improved and the cell expansion problem was alleviated. However, no improvement was observed insofar as internal resistance increase rate. In a capacitor with a different electrolyte and JTEKT's unique improvement measure implemented, the capacitance retention rate and internal resistance increase rate requirements were satisfied even after 1 000 hours of float charging tests, as specified by the IEC standard[15]. From the above results, we elucidated that, in order to increase the heat resistance of the Lithium-ion capacitor, it was necessary to not only improve the heat resistance of the structural material, but also control the compatibility of materials so that each material could sufficiently perform.

Table 2 Internal resistance increase behavior

Test atomospheric temp., deg. C		Capacitor upper limit voltage, V				
		3.60	3.65	3.70	3.75	3.80
	110	24.6%				
	105	7.1%	5.7%			
	100	3.1%	1.8%	6.8%		
	95	0.3%	2.2%	3.7%	5.1%	
	90	0.7%	−0.2%	3.0%	2.1%	
	85	0%	2.1%	3.5%	3.5%	7.7%

Mesuring method: IEC 62813-2015

Table 3 Capacitance reduction behavior

Test atomospheric temp., deg. C		Capacitor upper limit voltage, V				
		3.60	3.65	3.70	3.75	3.80
	110	3.0%				
	105	2.3%	−0.3%			
	100	1.6%	−0.2%	0.7%		
	95	0.8%	0.5%	0.2%	0%	
	90	2.0%	0.9%	1.4%	0.6%	
	85	0.0%	0.8%	0.5%	1.4%	0.2%

Mesuring method: IEC 62813-2015

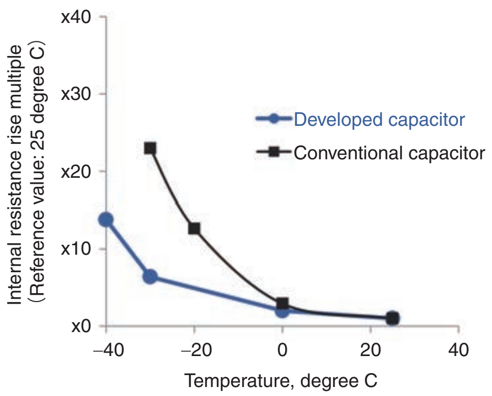

Fig. 8 Measurement result of internal resistance at low temperature

5. 2 High Current Charge/discharge Resistance

Tables 2 and **3** show the results. By changing the limitation on the upper limit voltage of the Lithium-ion capacitor from 3.8 to 3.6 V, even in a 100℃ environment, the change in Lithium-ion capacitor performance was very minimal at less than 5%. We elucidated that improving the heat resistance of the Lithium-ion capacitor would contribute to suppressing the deterioration caused by self-heat generation upon repeated large current charging/discharging.

5. 3 Low Temperature Characteristic

Figure 8 shows the measurement results for internal resistance. In contrast to the conventional Lithium-ion capacitor, whereby the electrolyte freezes at -30℃ or lower making charging/discharging impossible, the electrolyte of the developed capacitor did not freeze even at -40℃, and charging/discharging was possible. The internal resistance of the developed capacitor at a temperature of -40℃ was practically equal to the internal resistance of the conventional capacitor at -20℃.

Figure 9 shows the results of a charge/discharge cycle test conducted at -40℃. A 200 000 cycle test was conducted for the developed capacitor however the performance only deteriorated slightly. We confirmed that the merit of the Lithium-ion capacitor, a large current supply, was possible not only in high temperatures, but also in low temperatures.

6. Conclusion

The auxiliary power supply system newly developed for EPS, makes it possible to alleviate the problem of power insufficiency when equipping an EPS on a large vehicle, without the need to strengthen the 12 V vehicle power supply. Moreover, because the developed system has excellent function expandability and also functions as a redundant power supply during vehicle power outages or temporary power outages, we believe it will contribute to the realization of a level 4 advanced autonomous driving system which demands high functional safety.

Moreover, the Lithium-ion capacitor with a greater operating temperature range is helpful in realizing a system that can be equipped on a vehicle without using a cooling-heating system. We anticipate it will be used on a broader scale, in not only the auto industry, but also a variety of industrial domains.

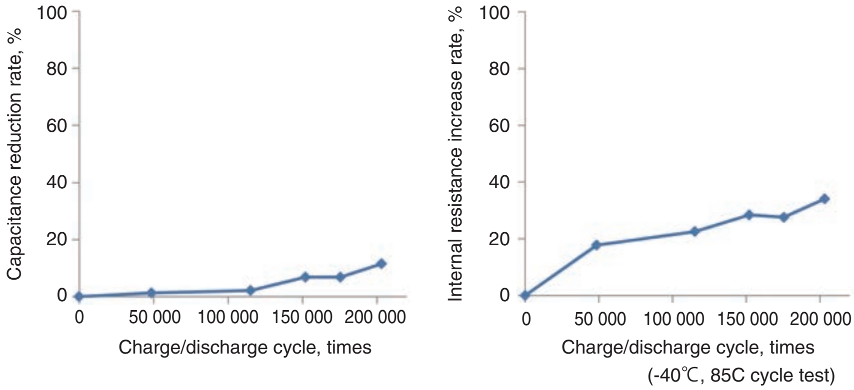

Fig. 9 Test result of charge-discharge test at low temperature

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