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Development of 36-V valve-regulated lead-acid battery

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Abstract

A 36-V valve-regulated lead-acid (VRLA) battery used in a 42-V power system has been developed for the Toyota Hybrid System-Mild (THS-M) vehicle to meet the large electrical power requirements of hybrid electric vehicles (HEVs) and the increasing power demands on modern automobile electrical systems. The battery has a longer cycle-life in HEV use through the application of ultra high-density active-material and an anti-corrosive grid alloy for the positive plates, special additives for the negative plates, and absorbent glass mat with less contraction for the separators.

Keywords: 42-V; Lead-acid batteries; Mild-hybrid electric vehicle; Power system; Valve-regulated

1. Introduction

Automakers are developing a variety of low-emission vehicles with reduced emissions of CO_2, NO_x, and other substances to mitigate global warming and other environmental damage. Accordingly, there has been a rapid growth in hybrid electric vehicles (HEVs), whose powerplants combine engines and battery-driven motors.

Conventional HEVs mainly have 200- to 300-V systems powered by nickel–metal-hydride or Li-ion batteries. Mild hybrid systems have 42-V power supply systems using 36-V batteries, and the simple mechanisms of the systems make it possible to use the batteries in a wide variety of vehicle types [1]. Meanwhile, international efforts are underway to change the voltage of the vehicle power supply from 14- to 42-V to cope with future increased loads on power supplies. The 42-V system adopted for the mild hybrid system has broken ground world-wide.

The functions of the 36-V battery include supplying power for electrical loads (such as air-conditioners) during idle stops and power to the motor when starting from a stop, as well as capturing regenerated energy when decelerating. Therefore, the batteries must have good input/output power characteristics. Other requirements for the wide use of batteries in HEVs include the ability to detect accurately the state-of-charge (SoC) and state-of-health (SoH), capability for operation across a broad temperature range, and low price. It is also important that battery materials are recycleable. Japan Storage Battery Company (JSB) has worked with Toyota Motor Co. Ltd. to develop jointly a 36-V lead-acid battery that fulfills the foregoing requirements [2].

This paper discusses the basic principles of lead-acid batteries, and describes the technology and performance of the JSB 36-V lead-acid battery.

2. Characteristics of lead-acid batteries

Lead-acid batteries have a history of more than 100 years, and have been used in many applications that include automobiles, motorcycle service, and telecommunications systems. Automotive batteries are used for starting, lighting and ignition (so-called 'SLI batteries') and are mostly of the 12-V flooded type.

2.1. Basic principles

The following equations express the charge and discharge reactions in lead-acid batteries.

At positive plate:

$$PbO_2 + 3H^+ + HSO_4^- + 2e^- \rightleftarrows PbSO_4 + 2H_2O \qquad (1)$$

At negative plate:

$$Pb + HSO_4^- \rightleftarrows PbSO_4 + H^+ + 2e^- \qquad (2)$$

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Overall:

$$PbO_2 + Pb + 2H_2SO_4 \rightleftarrows 2PbSO_4 + 2H_2O$$

The positive active-material is lead dioxide (PbO_2), and the negative active-material is metallic lead (Pb) in sponge form. The sulfuric acid electrolyte also serves as an active-material. The acid is consumed during discharge and produced during charge and, therefore, its concentration varies in accordance with the battery SoC. The involvement of sulfuric acid ions in charge and discharge reactions determines the characteristics of lead-acid batteries. Positive and negative active-materials are lead compounds, while the current-collectors are lead alloys. This composition endows lead-acid batteries with the characteristics of low cost and easy recycleability.

2.2. VRLA batteries

Batteries for hybrid vehicles are installed in places other than under the hood. Thus, and in the case of flooded designs, it is difficult to conduct water maintenance. Accordingly, hybrid vehicles use valve-regulated lead-acid (VRLA) batteries, which employ immobilized electrolyte absorbed and retained by absorptive glass-mat (AGM) separators and which do not require water replenishment. The JSB 36-V battery for hybrid vehicles is also of this type. In this battery, 18 cells are connected in series to yield 36 V, as shown in Fig. 1. Each cell has a rubber valve that opens when the internal pressure rises and, thereby, prevents build-up of pressure. The battery is also equipped with a thermo-sensor to allow proper control in accordance with battery temperature.

2.3. Recycleability

Battery recycling is important from the perspective of environmental protection. Due to the long use of lead-acid batteries in automobiles, recycling routes and processing methods have been established. At present, the recycling rate for automotive batteries is nearly 100%. It should also be noted that new lead-acid batteries can be made from recovered units.

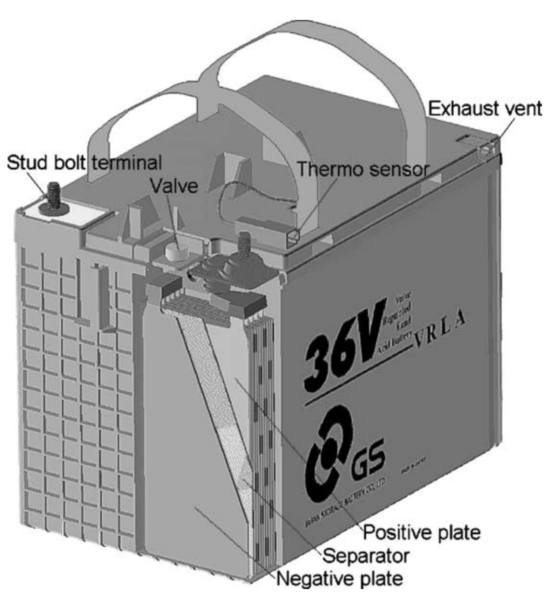

Fig. 1. Structure of 36-V VRLA battery.

Table 1
Specifications of 36-V VRLA battery

Nominal voltage (V)	36
Rated capacity (Ah, 5-h rate)	20
Dimensions	
Length (mm)	260
Width (mm)	173
Height (mm)	219
Mass (kg)	27
Specific energy (Wh kg^{-1})	27
Specific power at 50% SoC (W kg^{-1})	350

3. Characteristics of 36-V battery

The specifications for the 36-V battery are listed in Table 1. The aims in developing this battery are that it provides excellent performance under partial state-of-charge (PSoC) duty, and that it is highly reliable in vehicle service. The main features of 36-V battery are as follows.

(i) Battery size is JIS D26 (equivalent to Group 24 under BCI standards).
(ii) Peak specific power is 350 W kg^{-1} (50% SoC), which is higher even than that of lead-acid batteries (JSB model SER60) used for pure electric vehicles.
(iii) Cycle-life is excellent, even under high-temperature PSoC conditions.
(iv) Installing a thermo-sensor in the battery cover allows battery control in accordance with battery temperature.
(v) The use of stud bolt terminals prevents accidental connection to 12-V automobile batteries.

3.1. Input–output power characteristics

The relationship between the SoC of the 36-V battery and its input/output specific power indicates that specific output power declines and specific input power improves when the SoC decreases, as shown in Fig. 2. Because hybrid vehicle batteries must provide high output and efficiently accept regenerative energy, they are used in an appropriate SoC range that provides the correct balance between these two features.

The relationship between temperature and specific power (Fig. 3) shows that the lower the battery temperature, the lower both input and output power. Low-temperature characteristics below 0 °C exhibit a significant drop in input power, but the decrease in output power is less than that experienced in other types of battery.

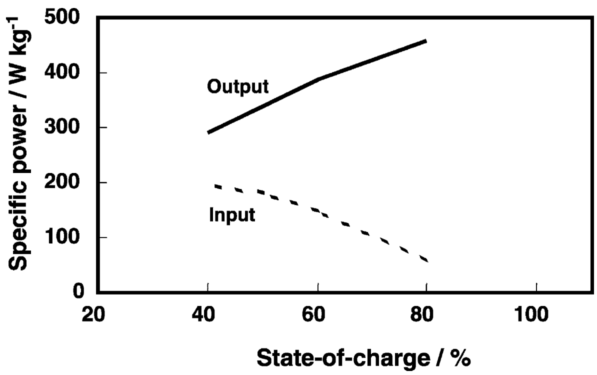

Fig. 2. Relationship between specific power and SoC for 36-V battery (25 °C, 5 s).

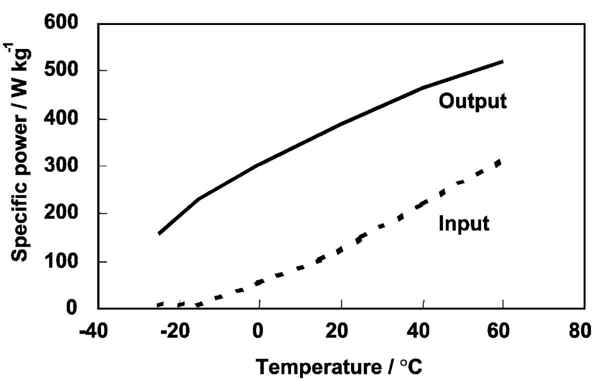

Fig. 3. Relationship between specific power and temperature for 36-V battery (60% SoC, 5 s).

3.2. Cycle-life characteristics

Primary failure modes of VRLA batteries are corrosion of the positive grid, dry-out due to excessive water loss, accumulation of lead sulfate in the positive active-material, and sulfation of the negative active-material. Plate materials and their compositions must be optimized to mitigate these failures. In life tests, assuming that vehicles have systems to stop the idling of engines, these failures are all suppressed and cycle-life performance is improved to three times that of conventional batteries, as shown in Fig. 4 [2], by using optimized positive-grid alloys, positive active-material, negative active-material and separators.

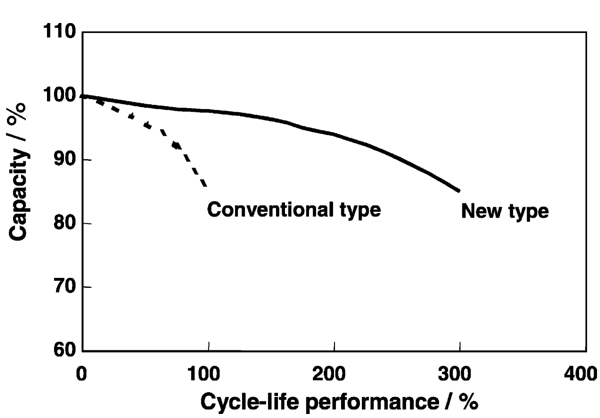

Fig. 4. Cycle-life of 36-V battery under ISS simulated cycle.

3.3. SoC and SoH detection

The proper control of charging and discharging is also effective in suppressing the failure modes of VRLA batteries. This means that accurate detection of both SoC and SoH is important for HEV batteries. Until now, however, these parameters have been difficult to determine without actually measuring discharge capacity.

To detect SoC and SoH, JSB has created a map based on data that has been accumulated to date (Fig. 5). Measurements of the open-circuit voltage (OCV) and internal resistance of the battery, and comparison of the values against the data in the map allows determination of the SoC and the SoH. This estimation method does not require history information such as integration of the amount of charge and discharge electricity. Thus, the SoC and the SoH of any battery type can be estimated simply by using equipment to measure internal resistance and voltage.

As a battery deteriorates, its internal resistance increases and plots that represent its measured value move upwards on the map. On battery discharge, the SoC moves along one of the dashed lines towards the left. Thus, if the deterioration level of the battery is divided into several zones, as in Fig. 5, it is possible to determine the SoH and inform the user of the extent to which the battery has declined in performance and when it should be replaced.

4. Technologies incorporated in 36-V battery

The JSB 36-V battery incorporates various new technologies to provide the maximum performance for hybrid vehicle use. These technologies are discussed in the following sections.

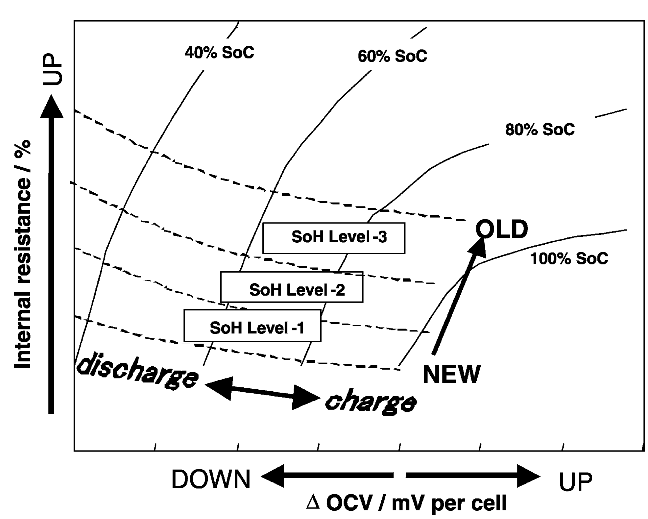

Fig. 5. Relationship between internal resistance, OCV, SoC and SoH of 36-V battery.

4.1. Positive plates

Positive-grid corrosion, which causes grid growth, is one of the main failure modes of lead-acid batteries. To improve corrosion resistance, a Pb–Ca–Sn alloy of optimized composition [3,4] is used for the positive grid. The grid design is also optimized to reduce its growth.

To reduce the rate of degradation of active-material caused by charging and discharging, positive active-material with a higher density than that used in conventional deep-cycle batteries is employed. Usually, high-density lowers the utilization of active-material, but the introduction of a new additive has made it possible to increase utilization during high-rate discharge.

4.2. Negative plates

The negative plates in lead-acid batteries are prone to failure by sulfation when operated under conditions. This phenomenon is due to accumulation of lead sulfate in the form of large crystals that give rise to inefficient charging. Under high-temperature operation, this failure is further accelerated by an increase in lead dissolution. In order to inhibit sulfation, highly conductive carbon is added [5,6] and active-material of high-density is employed. This results in the formation of a conductive network of carbon and lead in the active-material, and suppresses the accumulation of non-conductive lead sulfate. Further, optimizing the conventional negative-plate additives enhances the activity at reaction sites on the electrode, and improves the acceptance of regenerative charging.

4.3. Separators

Attaining superior cycle-life performance requires a high level of plate-group pressure, which must be maintained during battery operation. Additionally, attention has to be given to the prevention of short-circuits through the separators, because the battery increases power by using many more plates and by spacing the plates closer together than usual. Therefore, a special hybrid AGM is used for the separator [5,7]. This separator can maintain high compression because it contracts little both on adding sulfuric acid and after substantial water loss. The separator is also highly resistant to short-circuits.

4.4. Container, cover and cell arrangement

The outside dimensions of the battery conform to JIS D26 (equivalent to Group 24 under BCI standards). The cover is provided with handles to facilitate installation in (and removal from) vehicles, as well as handling during transportation. There are 18 cells in two nine-cell rows. The cells are connected in series in a U-shaped configuration.

4.5. Terminals

M8 stud bolts are used as the terminals to prevent accidental connection to 12-V automobile batteries.

4.6. Exhaust vent

Each cell has a safety valve of the type used in conventional VRLA batteries. A common exhaust vent is located away from the terminals. A ceramic filter helps prevent explosions and otherwise improves safety.

4.7. Thermo-sensor

Achieving the maximum performance from the battery requires control of charging and discharging with respect to temperature. The JSB battery is equipped with a thermo-sensor to measure battery temperature. Good accuracy is made possible by creating a depression in the center of the battery for the thermistor so as to bring it close to the plate group.

5. Summary

The configuration and characteristics of the new JSB 36-V VRLA battery are described. To the greatest possible extent, this battery incorporates technologies that have been developed to endow the battery with high output and long life. It has been designed for use under the conditions imposed by 42-V vehicle systems by having high output power characteristics and superior cycle-life under PSoC duty. A Toyota mild-hybrid using this 36-V battery is the first 42-V system in the world, and it seems likely that such systems will continue to evolve and diversify. Japan Storage Battery Company intends to develop even better 36-V VRLA batteries to keep pace with the expected changes in 42-V systems. It is firmly believed that the crucial basic technologies for batteries adapted to 42-V systems have been achieved through the development of the 36-V battery reported here.

Acknowledgements

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