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Development of VRLA battery for hybrid bus

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Abstract

Valve regulated lead–acid (VRLA) batteries named SEH65 series for hybrid vehicles have long been used in hybrid inverter-controlled motor and retarder system (HIMR) buses developed by Hino Motors Ltd. In order to elucidate the points for improving the battery performance, the battery performance, which were obtained during field use and by bench test, was analyzed in details. As the result, a new VRLA battery, with which longer life performance can be expected, has been developed by improving the positive grid corrosion resistance and adopting a new additive for the negative plates. In addition, it was found that estimation of residual life of the battery is possible by measuring the battery voltage in high-rate discharging during bus use and by adjusting it with the field use conditions.

Keywords: Battery; Cycle life; Hybrid electric vehicle; Lead–acid; Valve regulated; Low emission

1. Introduction

For environmental reasons, low emission vehicles (LEVs) have been developed by many organizations and institutes since 1990. There are many kinds of LEVs at present, such as electric vehicles (EVs), compressed natural gas (CNG) vehicles, methanol vehicles, liquid propane gas (LPG) vehicles, hybrid electric vehicles (HEVs), fuel cell electric vehicles (FCEVs) and so on. But almost all LEVs, except HEVs, require infrastructure to supply fuel or electricity. On the other hand, since HEVs can share completely the infrastructures with the conventional automobile, they have larger possibility to be used even in the remote areas.

The vehicles adopting hybrid inverter-controlled motor and retarder (HIMR) system made by Hino Motors are a kind of HEVs, and a power plant of the system consists of a diesel engine and an electric motor. In Japan, many diesel engines are used for most buses and trucks, but they emit NO_x, CO, and diesel exhaust particles (DEPs) while starting, accelerating, or hill climbing. On the other hand, the fuel efficiency of the diesel engine is better than that of gasoline engines, which can reduce emission of CO_2. Therefore, the HIMR system has been developed to utilize the advantages of the diesel engine while eliminating its demerits [1].

We have taken part in the development of the valve regulated lead–acid (VRLA) batteries for the HIMR track [2–4]. We also presented a new method for measuring and analyzing battery conditions on the HIMR bus [5]. It was proposed that the state of health and charge of the batteries could be estimated without removing them from the bus. In this paper, we report observed results of the VRLA battery during practical operation, in detail. In addition, whether a new VRLA battery for an HIMR bus can have a performance of 4 years.

2. Experimental

2.1. VRLA batteries for HIMR bus

Fig. 1 shows the appearance of a VRLA battery (65 A h/5 HR) named YUASA SEH65 for an HIMR bus. And the carrier-box with 25 batteries removed from the bus is shown in Fig. 2. Voltage sensors are put on all batteries. If the voltage of some battery reaches a lower regulated voltage, this is indicated soon at the cockpit of the bus. Thermal sensors are also set on a surface of the representative batteries. If the battery reach an upper regulated temperature, the fans installed in the battery room of the bus cool them.

The batteries have been developed in three steps mainly since 1993, and their specifications are listed in Table 1. Ver. 1 battery was first to improve the efficiency of regenerative charge acceptance with high-rate current. Therefore, the electrodes surface area of Ver. 1 was expanded with the plates number increasing to reduce the charging current

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Fig. 1. VRLA battery for HIMR (SEH65).

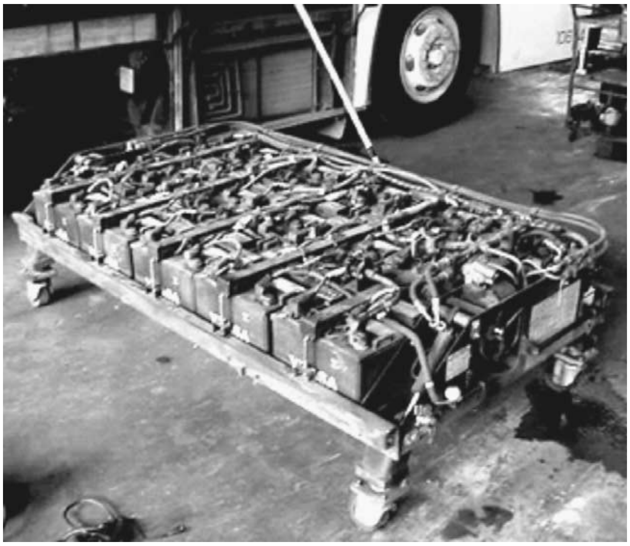

Fig. 2. Carrier-box with 25 batteries.

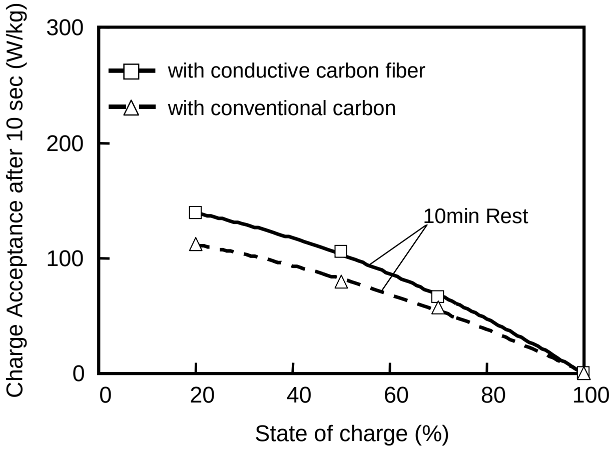

Fig. 3. Improvement of charge acceptance of VRLA battery with conductive carbon fiber additive.

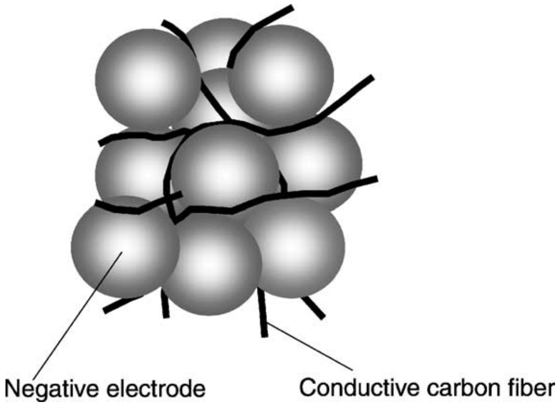

Fig. 4. Schematic illustration of conductive carbon fiber additive in the negative active material.

density to less than that of conventionally designed VRLA battery. Ver. 2 battery was developed through the second step in order to improve the charge acceptance by adding the conductive carbon fiber into the negative electrode (Figs. 3 and 4) [6]. And Ver. 3 battery was designed to improve the corrosion resistance of the positive grid by increasing the thickness of it with the plates number decreasing in the

Table 1
Specifications of three versions of SEH65 VRLA battery for HIMR bus

Battery type	Ver. 1	Ver. 2	Ver. 3
Capacity (A h/5 HR)	65	←	←
Nominal voltage (V)	12	←	←
Mass (kg)	27.5	←	←
Dimensions			
W (mm)	171	←	←
L (mm)	304	←	←
H (mm)	236	←	←
Number of plates (positive/negative)	7/8	←	6/7
Negative plate additives	Conventional	Conductive carbon fiber	Conductive carbon fiber with conventional
Positive grid mass (g)	540	←	600
Positive grid thickness (mm)	1.9	←	2.5

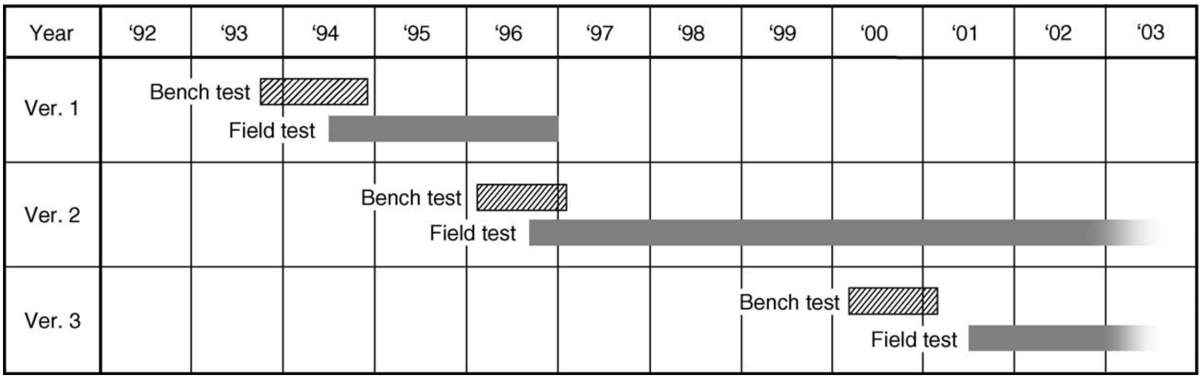

Fig. 5. Examination histories of three versions of SEH65 VRLA battery for HIMR bus.

third step. Since the surface area of the electrodes would be decreased on such plates design, conductive carbon fiber with conventional carbon was added onto the negative plate of Ver. 3 to suppress polarization of the negative plate at high-rate charging. The field use test for Ver. 3 battery is now on. The examination histories of these batteries are indicated in Fig. 5 including both of the field and the bench tests. Results obtained through each test on three versions of SEH65 VRLA battery are described in detail in the next sections.

2.2. Bench test procedure for cycle life performance examination

Cycle life performances of the batteries were examined by a bench test simplifying the charge/discharge conditions of the HIMR bus. The bench test was contrived to accelerate the sulfation phenomenon that can occur at the lead–acid batteries for HEVs. The sulfation is most serious degradation of the negative plate in lead–acid battery and occurs mainly under the insufficient charge condition. The bench test procedure is listed in Table 2, and also shown in Fig. 6.

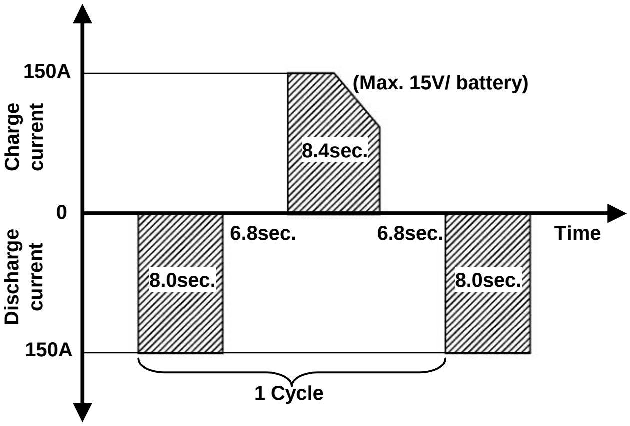

Fig. 6. Charge/discharge pattern of the bench test at 1 cycle.

Table 2
Bench test procedure

Cycle pattern (per 1 cycle)	
Discharge	150 A for 8 s
Standby time after discharge	For 6.8 s
Charge	150 A (up to 15 V) for 8.4 s
Standby time after charge	For 6.8 s
Interval of equalization charge	6.5 A for 8 h every 12500 cycles
Environmental temperature	30 °C
Judgement of the end of life	When the discharge voltage fell to 10.6 V
Cycles corresponding to 1 month	12500 cycles

3. Results and discussion

3.1. Ver. 1 and Ver. 2 batteries on the bench test

Discharge voltage transitions at 8 s and the end numbers of cycle life obtained by this bench test are shown in Fig. 7 and Table 3, respectively. Field life of Ver. 1 and Ver. 2 were estimated as 1.6 and 2.1 years, respectively. Thus the cycle life of Ver. 2 was 1.3 times as long as Ver. 1 by addition of the conductive carbon fiber into the negative plate. And it is considered that this conductive carbon fiber was very effective for suppression of the sulfation because the discharge voltages of Ver. 2 were higher than that of Ver. 1 through all the cycles.

Table 4 shows the percentage of accumulated lead sulfate in each plate of the batteries, which were observed by the disassemble analysis. Accumulations of many lead sulfates with sulfation were detected in the negative plates of both batteries, but little lead sulfates existed in the positives. These results mean that the failure mode of both batteries was caused by the negative plate sulfation, and this bench test certainly accelerates sulfation of the negative

Table 3
Results of Ver. 1 and Ver. 2 batteries after the bench test

Battery type	Ver. 1	Ver. 2
Cycle life ($\times 10^3$)	237.5	312.5
Total discharge capacity (C A h)	1218	1603
Estimated field life (years)	1.6	2.1

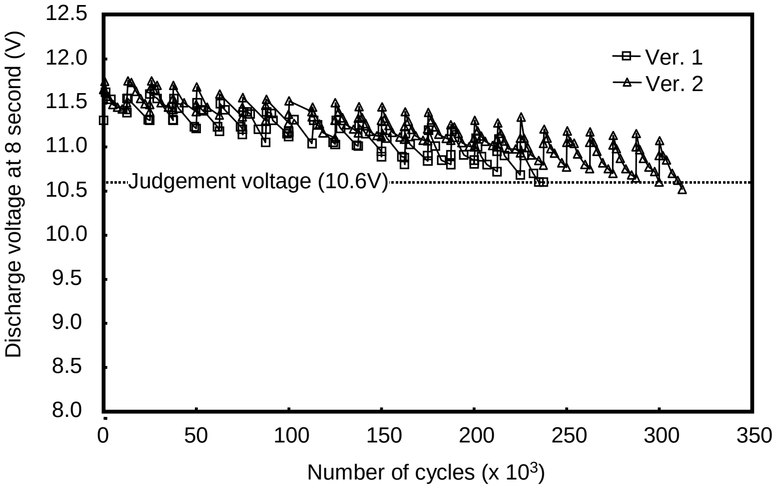

Fig. 7. Discharge voltage transitions at 8 s of Ver. 1 and Ver. 2 batteries during the bench test.

Table 4
Accumulated lead sulfate in the plates of Ver. 1 and Ver. 2 batteries after the bench test (%)

Polarity of the plates	Site of the plate	Ver. 1	Ver. 2
Negative	Upper	3	41
	Middle	44	44
	Lower	55	39
Positive	Upper	<1	<1
	Middle	<1	<1
	Lower	<1	<1

plate. And more accumulation of lead sulfate is found at Ver. 2, but this might be caused by function of the conductive carbon fiber. Namely, the additive would make possible the use of much active material with its high conductivity until the negative plate had come to such a state.

3.2. *Ver. 1 and Ver. 2 batteries on the field test*

HIMR buses are used by many bus companies in Japan and have been operated not only in the megalopolis such as Tokyo and Osaka but also in the mountain areas such as national parks. This report explains the results of the batteries in HIMR bus run in a hilly town area, because it is considered that the operational condition of HIMR system in this area has been relatively severe on the batteries.

Fig. 8 shows the residual capacity transition of Ver. 1 and Ver. 2 batteries used in the HIMR bus. The capacity of the batteries was measured with 5 h rate (5 HR) discharge and 2 C discharge close to the current required by HIMR system at its power assisting. Thus the field life of Ver. 2 became 1.15 times as long as Ver. 1, and the residual capacity of Ver. 2 also kept always higher than that of Ver. 1 through its life. And capacities of the batteries were decreased conspicuously at the early stage and the last stage of its field life, but the

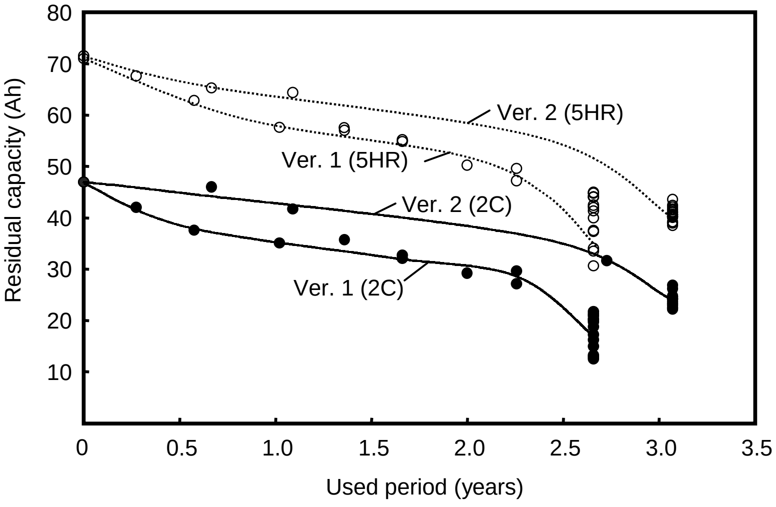

Fig. 8. Residual capacity transition of Ver. 1 and Ver. 2 batteries during the field use.

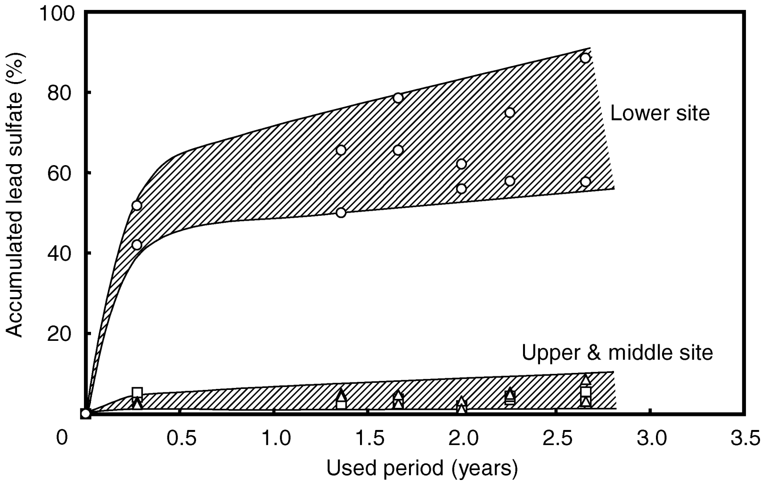

Fig. 9. Accumulated lead sulfate transitions in the negative plate of Ver. 1 battery during the field use.

capacity losses of the medium stage were in a plateau state. Such capacity loss trend did not concern the battery versions and the discharge rates.

It is considered that the cause of the capacity loss in such an early stage depended mainly on occurrence of the negative plate sulfation. For, the lead sulfate had been accumulated to the upper site of the negative plate at the corresponding stage in the field life of Ver. 1 as shown in Fig. 9. Therefore, the improved performance on 5 HR and 2 C discharge of Ver. 2 battery would be brought about by the conductive carbon fiber to the negative plate, which was supposed, like similar phenomenon, to affect on the bench tests.

Fig. 10 shows the transition of positive grid corrosion during the field tests. Fig. 11 shows photographs of the grid of Ver. 1 and Ver. 2, respectively, at the end of field test. Since available grid amount for discharge had been designed as approximately 60%, these were reasonable results for the batteries. From these results and analyses, it is considered that the conspicuous capacity decrease at the end of life was caused by such positive grid corrosion. Namely, the performances of both batteries would be gradually lost with thinness of the grid at the last stage, and the batteries would fail due to cut across the conductive route of the grid at last.

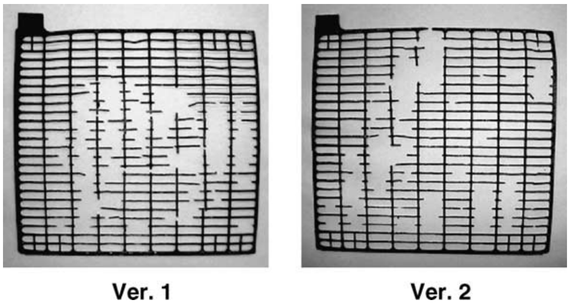

Fig. 11. Photographs of the positive grids of Ver. 1 and Ver. 2 batteries after the field use.

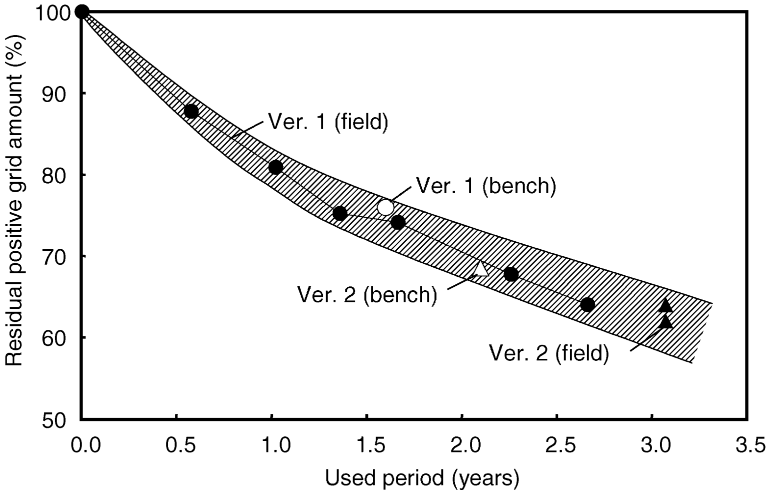

Fig. 10. Positive grid corrosion transition of Ver. 1 and Ver. 2 batteries during the field use (Residual grid amounts of each battery after the bench test are also plotted in it.).

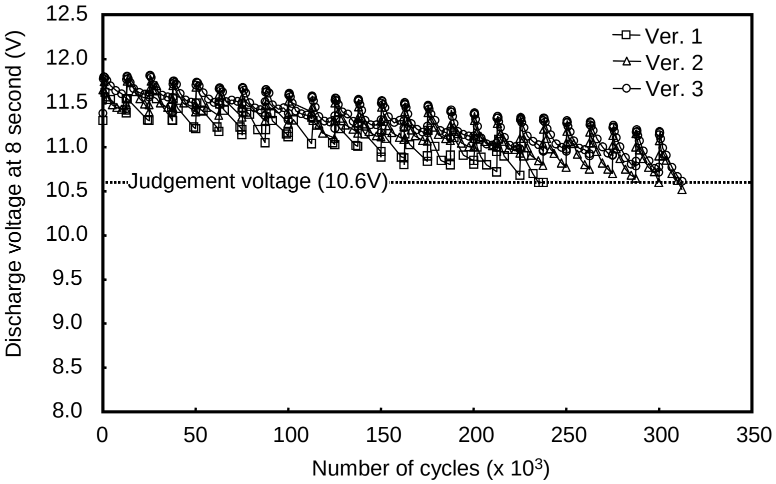

Fig. 12. Discharge voltage transitions at 8 s of Ver. 3 batteries during the bench test with the results of Ver. 1 and Ver. 2 batteries.

And positive grid corrosion amounts obtained in the bench tests are also plotted in Fig. 10. Because grid corrosion by the bench tests well agreed with results of the field tests, it was confirmed that the above-mentioned bench test pattern for this development is also proper to evaluate the grid corrosion.

3.3. Summary for Ver. 1 and Ver. 2 batteries

The results that were found with both bench and field tests of Ver. 1 and Ver. 2 batteries are summarized as follows:

1. The life performance and capacity transition of SEH65 battery for HIMR bus were improved by adding the new conductive carbon fiber into the negative plate.
2. It was confirmed that contrived bench test is suitable to evaluate charge acceptance of the negative plate because the lead sulfate accumulated in the negative active material at the end of the bench test.
3. The batteries used in the field failed mainly due to the positive grid corrosion, although sulfation occurred also in the negative plates. And it was found that the grid corrosion by the bench test well agreed with the trend of the field tests.

In further extension of the field life performance of SEH65, it was noted from these results that corrosion resistance of the positive grid should be improved, while the charge acceptance had to be kept in Ver. 2 level or above.

3.4. Ver. 3 battery on the bench test

Based on the above results of Ver. 1 and Ver. 2 batteries, the Ver. 3 battery was newly designed to improve the corrosion resistance of the positive grid by increasing its thickness with the plates number decreasing. Since the surface area of the electrodes would be decreased on such plates design, Ver. 3 adopts also additives for the negative plate

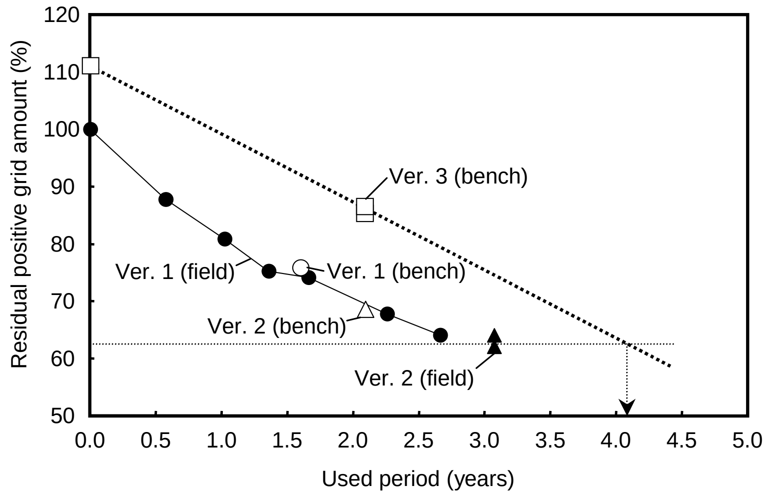

Fig. 13. Estimation of the field life of Ver. 3 using the positive grid corrosion data of the bench test (Positive grid amount of Ver. 1 and Ver. 2 before test is shown as 100%.).

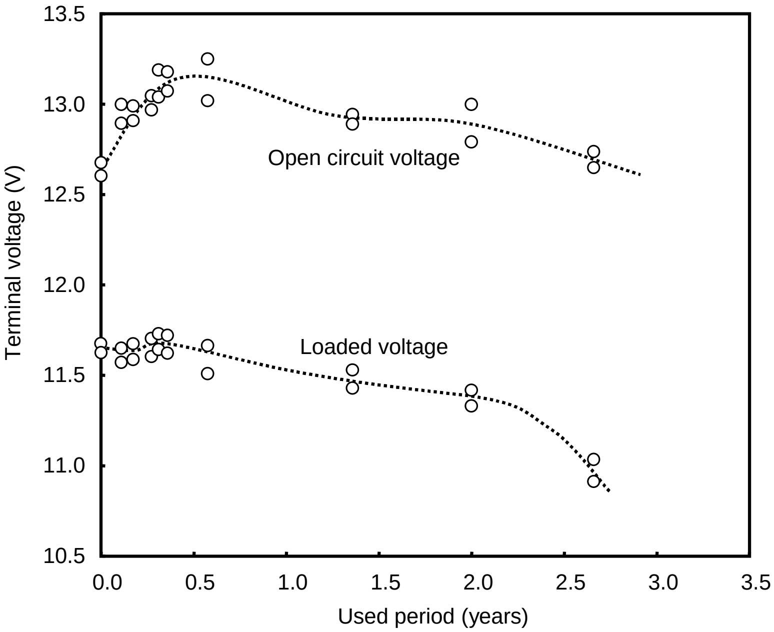

Fig. 14. Transitions of open circuit voltage and loaded voltage during the field use of Ver. 1 batteries.

to suppress polarization of the negative plate at high-rate charging. Fig. 12 shows the result of Ver. 3 battery under the same bench test with the results of Ver. 1 and Ver. 2. It is found from this figure that the charge acceptance per negative plate of Ver. 3 was improved as in the aiming by adoption of the additives formula, because its life was as long as Ver. 2. In Fig. 13, the positive grid amounts of Ver. 3 before and after the bench test were also plotted in Fig. 10. The life performance of this Ver. 3 battery in the field use would achieve over 4 years from this figure, if the battery failed with the grid corrosion like the previous batteries did. In fact, the field life performance of the Ver. 3 batteries has been examined without any trouble since 2001, as shown in Fig. 5.

3.5. State-of-health prediction of the battery for practical field use

Equalization charges are maintained once a month to the batteries for HIMR buses used for practical operation. Open circuit voltages and loaded voltages of the batteries have been also checked after charge at those opportunities. Transitions of these data are shown in Fig. 14. The loaded voltage means a high-rate discharge voltage at 5 s, and that discharge current corresponds to required current for HIMR system during its operation.

The open circuit voltage increased at the early stage, but then it gradually decreased during the field life. However, it is found that the loaded voltage declined little at the early and middle stage, but the voltage decline became larger obviously at the last stage. Therefore, it was found that state-of-health of the batteries can be predicted easily with not only the open circuit voltage check but also the loaded voltage check. Actually, this loaded voltage measurement has been applied as a simple way to check the state of battery by the bus users. And we have also monitored the loaded voltage with other users until now. As the result, it was confirmed that the loaded voltages for battery failure judgement are a little different in each user, because the output performance or capacity required for the HIMR bus are different because of its running condition (e.g. up-and-down route). This prediction is related to the contents presented by us in 2000 [5], and we expect that such a method makes it possible to easily detect state-of-health of the batteries in HIMR operaton.

4. Conclusions

Development of the long life VRLA battery for HIMR bus had aimed at improving charge acceptance of the negative plate at first. However, the corrosion resistance improvement of the positive grid was also considered from the middle of this development, because it was found by the analysis of practically used batteries that the grid corrosion was the main failure mode of the battery. As the result, we succeeded in developing a new battery whose 4-year life performance could be estimated by practical use. This life performance is 1.3 times as long as that of previously developed batteries. The bench test adopted for this development is a suitable way to simulate the practical condition of the HIMR bus. And the loaded voltage measurement in high-rate discharge is helpful to predict state-of-health of the battery. Thus, we confirmed that VRLA batteries, which are excellent in terms of cost performance and practicality, can be used for hybrid electric vehicles including HIMR.

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