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Development and testing of a bipolar lead-acid battery for hybrid electric vehicles [1]

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Abstract

An 80 V bipolar lead-acid battery was constructed and tested using hybrid electric vehicle (HEV) drive cycles. Drive cycles with a peak power of 6.7 kW, equal to 1/5 of the total power profile required for the HEV studied, were run successfully. Model calculations showed that the 80 V module constructed, which is at the moment 2.5 times heavier than required for the HEV operation studied, can be optimised to meet the requirements.

Keywords: Bipolar lead-acid battery; Hybrid electric vehicle; Drive cycles

1. Introduction

In two earlier papers, we presented the development of the bipolar lead-acid battery at TNO within the framework of the development of a high power battery for pulsed power applications [1] and for hybrid electric vehicles (HEV) [2].

The aim of the ongoing investigations at TNO is to develop a bipolar lead-acid battery technology for hybrid electric vehicles. In this application, there are generally requirements on both specific power (W/kg) and specific energy (W h/kg) [3]. The technology used for the bipolar battery should be as closely as possible connected to the production technologies for lead-acid starter or traction batteries. In order to achieve this, we have decided to use, as a first attempt, pasted battery plates, originally made for starter batteries, in the bipolar battery. In the near future, we will modify the method of construction of the bipolar battery. This paper will deal only with bipolar lead-acid batteries made using thin pasted starter plates.

The bipolar plate and the sealing of the bipolar cells are the crucial parts of the bipolar lead-acid battery, which have prevented so far the commercialisation of the bipolar lead-acid battery, e.g., for use as starter battery and for hybrid electric vehicles.

Therefore, we decided to make a thorough investigation of the materials that can possibly be used as a bipolar plate. Very recently, an excellent review article was published by Kao [4] who concluded that in fact only the silicides of Ti, Nb and Ta appear to be suitable fillers for plastic composite substrates. However, these materials do not show a proper bonding of the active materials and therefore cannot be used at the moment.

Other developments like the Ebonex material, using a sub-titanium dioxide Ti_4O_7, showing excellent corrosion stability [5–8], have not led to a commercially bipolar plate. Reasons are the high cost of the material, the problems of making a thin layer (brittle material) and the wetting of the material when used as a composite with polymers.

Developments reported in patents by LaFollette [9,10] of Bipolar Technology have attracted our attention because of the innovative approach used. The bipolar plate is made from a composite of long carbon fibers impregnated with a fluorinated polymer by first dissolving the polymer in an appropriate solvent. After a thermal cross-linking step at approximately 180°C, the bipolar plate is treated for increasing the over voltage for oxygen evolution. Finally, the bipolar plate is lead plated. The lead layer is used for making a thin active layer using the Planté corrosion process in a diluted sulphuric acid solution in the presence of, e.g., $NaNO_3$.

Partly based on these and other developments, we decided to develop our own technology for the bipolar plate

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and to design and build a battery based on that, for hybrid electric vehicle applications. Although we are still improving our bipolar plate technology at the moment, we wish to present here our results of an 80 V module, based on our own technology.

The main innovations we implemented will be discussed in this article, together with the recent results of tests with an 80 V bipolar lead-acid battery. In this 80 V battery, several improvements are included in order to prolong cycle life.

The development of this battery is related to a TNO project on the development of hybrid drive train and drive train components (e.g., an engine/generator set) for various drive train applications [11].

2. Experimental

2.1. Preparation of bipolar plate

The bipolar plates, used for the construction of the 80 V bipolar lead-acid battery and the battery itself, were made according to a process developed at TNO (patent pending). The bipolar plate is protected for corrosion using a thin coating of lead. The bonding of the lead layer to the bipolar plate was possible after a special treatment of the surface. The lead layer is necessary in order to obtain a good bonding with the active mass. The area resistance of the lead-plated bipolar plate is less than 0.04 $\Omega \cdot cm^2$ at a thickness of 0.7 mm which makes it very suitable for very high current density applications (> 1 A/cm^2).

2.2. Constructing and testing of the 80 V bipolar lead-acid battery

In order to test the bipolar technology developed, we constructed an 80 V bipolar lead-acid battery with a total pasted area of 420 cm^2/cell both for the positive plate (PP) and the negative plate (NP). This battery, with a total weight of 75 kg, including the casing and cooling elements, was made using pasted starter battery plates of 1.6 mm (PP) and 1.4 mm (NP) and an AGM (absorptive glass mat) separator of 2 mm. The end plates were made of a special aluminium alloy.

In order to keep the temperature of the battery within a safe region, three cooling elements were built into the battery. In this way, between every ten cells, a water-cooling element was present. In order to measure the temperature, in total 14 Teflon-coated Pt-100 resistors were built into the cells. The maximum allowable temperature of the battery in the tests was 40°C. All temperatures were measured using a 24-channel parallel data logger (Digatron).

Before sealing the battery, each cell was connected, using the bipolar plate, to a 48-channel parallel data logger (Digatron). This enabled us to measure all the cell voltages in order to protect individual cells from cell reversal.

The sealing of the battery was done before filling the battery. After sealing, the battery was filled with 37% sulphuric acid solution.

The battery was charged afterwards and was found to have an internal resistance of 80 mΩ. This resistance was measured using a calibrated milliohmmeter from Hewlett Packard, measuring at 1000 Hz (four-point measurement).

All measurements were done using the BTS-600 software (version 3.28) of Digatron, using 40 kW Digatron equipment connected with two parallel data loggers (24 and 48 channels).

Hybrid electric vehicle drive cycles were run on this equipment while having full protection of the 40 individual cell voltages and meanwhile measuring 16 different temperatures.

During all experiments, the cooling medium was kept at 18°C, which is the inlet temperature to the battery.

3. Results and discussion

In order to run drive cycles on the 80 V battery, initial charge/discharge tests were run. From these tests, we found that one of the important aspects in operating a bipolar battery configuration is to maintain the balance between the cells.

Without a proper balance, the individual cell voltages will diverge when discharging, making it very difficult to run drive cycles at high discharge current densities. Therefore, we started with drive cycles with low peak power (< 4 kW). All cells with deviating cell voltages, i.e., with voltages lower than average, were individually charged after charging the total battery. This resulted in an improved cell balance, which enabled us to go on with higher peak powers. Another very important method for improving the cell balance was using an equalisation charge. The internal resistance of the battery was maintained, at 100% of State of Charge (SoC), at 80 mΩ in this way. During the drive cycles, the individual cell voltages were continuously measured enabling us to detect weak cells.

In the tests, a number of drive cycles were run with increasing peak power. As an example, the performance in a hybrid electric vehicle (HEV) drive cycle is given in Fig. 1a–d where the power (W), battery voltage, current and capacity (charge, discharge and sum of both) are given as a function of the time (s), respectively.

Before running the drive cycle, the battery was partially discharged during 15 min in order to get a state-of-charge suitable for the HEV application. The power for acceleration has a peak of 6.75 kW. The drive cycle given corresponds with 1/5 of the total power required for the hybrid electric vehicle studied during that certain drive cycle. During regenerative braking, the battery is charged. However, at charging peaks with long duration, i.e., at approximately $t = 2000$ s, the charging current is limited by the maximum charging voltage of 99 V. The reason for limiting the charging voltage is to prevent heating the battery

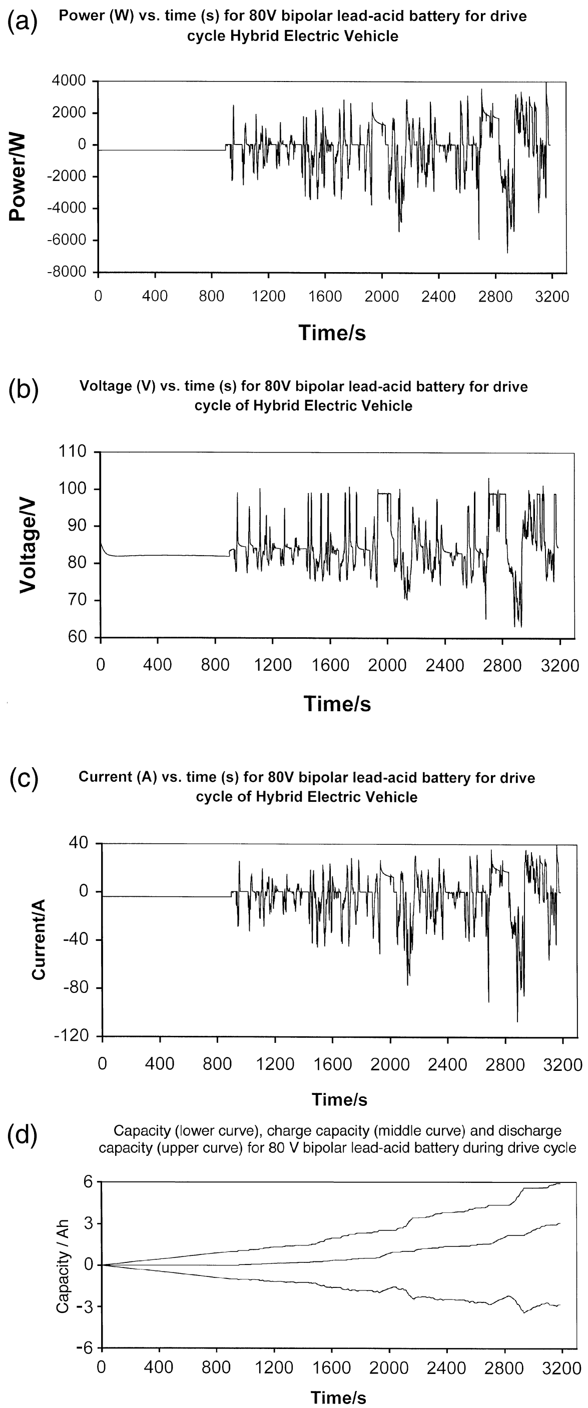

Fig. 1. (a) Measured power profile (W) of the 80 V bipolar lead-acid battery as a function of time (s) during a hybrid electric drive cycle. During the first 900 s, the battery is discharged at 4 A. Negative values of the power indicate discharging of the battery (acceleration of the HEV). (b) Measured battery voltage (V) of the 80 V bipolar lead-acid battery as a function of time (s) during the hybrid electric vehicle drive cycle. (c) Measured current (A) of the 80 V bipolar lead-acid battery as a function of time (s) during a hybrid electric drive cycle. (d) State of charge, discharge capacity and charge capacity during the hybrid electric vehicle drive cycle as calculated from the current-time curves. All values are relative to the initial SOC (time zero).

due to ohmic resistance and also to prevent water electrolysis (overcharging). This has hardly any negative influence on the energy efficiency because storing the energy of the higher peak powers (> 20 kW) during regenerative braking gives only a minor improvement of the fuel consumption of the HEV due to low occurrence of these high peaks. This means that, for an 80 V module, drive cycle equal to 1/5 of the total power, charge peaks > 4 kW can be ignored. The peak powers (see Fig. 1a) during charge had a maximum of approximately 3 kW.

The measured peak power during discharge of the 80 V bipolar lead-acid battery (acceleration of the vehicle) is identical to the power required for 1/5 the hybrid electric vehicle during acceleration. From Fig. 1b, we see that the minimum voltage during a peak power of 6.75 kW is equal to 63 V at a discharge current of 107 A (see Fig. 1c). The ohmic voltage drop at a discharge current of 107 A is equal to 8.6 V (80 mΩ internal resistance). This means that the battery voltage, corrected for the ohmic drop, decreased to 71.4 V (1.79 V/cell) during the most severe acceleration profile starting at approximately $t = 2830$ s and lasting to $t = 2930$ s approximately.

In this example, the charge current and power of the engine/generator set are, on average, less than the current and power consumed in the drive cycle, leading to net discharge of the battery.

The capacity decreases (compared to the initial value) first until -1 A h due to the discharge with 4 A during 15 min (900 s). At the end of the drive cycle, the capacity is decreased to -2.75 A h, compared to the initial value. The discharge capacity, ranging from 0 to 6 A h, starts at $t = 0$ s and rises to 1 A h at $t = 900$ s (initial discharge of the battery). During the drive, the discharge capacity rises with 5.9 A h, indicating a capacity of 4.9 A h used during the drive cycle. The charge capacity starts at $t = 960$ s during the first peak for regenerative braking and stops at 3.1 A h.

The ratio of the charge and discharge capacity is equal to 0.63, meaning that 63% of the capacity used during acceleration is returned to the battery during regenerative braking and/or supplied by the engine generator set. Improvement of this value is possible by lowering the State of Charge of the battery at the beginning.

From Fig. 1a–d, we conclude that the 80 V bipolar lead-acid battery, developed at TNO, is able to run the power profile (1/5 of total required for the HEV studied) without failures of any of the cells and without thermal problems.

4. Outlook for future developments and improvements

4.1. Hardware

What may be said about the goals of the bipolar lead-acid battery at this moment in terms of the acceptable weight and performance in case of a projected voltage of 320 V and maximum allowable weight of 150 kg?

From the weight of the 80 V battery (75 kg) and the drive cycle tested (1/5 of total power profile), we conclude that the weight of the 80 V bipolar lead-acid battery built and tested still must decrease by a factor of 2.5. It is a great challenge therefore to find possible ways to increase the performance of the constructed 80 V bipolar lead-acid battery module. Below we will go into detail what are the problems to be overcome in order to obtain such an improvement.

One of the first points for improvement is to lower the internal resistance of the battery. The internal resistance of the 80 V bipolar lead-acid battery was 80 mΩ at 100% SOC. This can be compared with the theoretical internal resistance using the conductivity of the bipolar plate material, the electrolyte, etc. The ohmic resistance, calculated from all individual contributions, is about 70 mΩ. This value is equal to the value measured two days after the battery was filled with electrolyte solution. This means that, although the compression of the battery can be improved, the actual internal resistance of 80 mΩ is only 10 mΩ higher than of the new battery. How is it possible to lower further the internal resistance? This can be done, by using a thinner separator. This in turn leads to the necessity of using thinner active layers (to keep an excess of electrolyte). At this moment, the active plates (1.6 m PP and 1.4 mm NP) are the thinnest pasted plates produced by the battery manufacturer involved in this project (Centurion Accumulatoren). However, it has been shown that pasted plates of half this thickness are possible. Therefore, the separator thickness can be decreased to 1 mm leading to a calculated module resistance of 40 mΩ. Compared with the ohmic resistance of 80 mΩ, this means an improvement of a factor of two.

Further, this decrease in thickness leads to a reduction in total weight of 30% of the battery.

Further reduction of the weight can be obtained by applying the active mass differently. In the current version of the 80 V bipolar lead-acid battery, the active mass is delivered by using pasted plates with an active mass to grid mass ratio of about 1:1. The rather high contribution of the grid to the active mass is because in a conventional starter battery the grid is used for two purposes: both for current conduction to the tab and for bonding of the paste. However, in a true bipolar battery, this grid can be skipped or be much lighter because the only function is to keep the paste on the right place. In the ideal case, the bipolar plates are directly pasted, this leads to a decrease of 20% in total weight.

Further weight reductions are possible in other components like sealing, spacers and cooling parts. When this is realised, this leads to an estimated module weight of about 40 kg, which is, assuming five modules are required, still too heavy (200 kg compared to the required 150 kg).

An important route to reduce the battery weight further is to examine the possibility to use four modules instead of five modules, leading to a total weight of 160 which is acceptable in terms of the weight for the hybrid electric vehicle. How can this be done? The key idea is increasing the high discharge rate performance of the battery. As shown above, one way to do this is to lower the internal resistance to approximately 40 mΩ for the 80 V module. Another, very promising way is to adapt the active paste in such a way that the high charge and discharge rate behaviour is improved. For advanced starter batteries, such improvements have resulted in better high discharge rate behaviour. Therefore, the active paste of the bipolar lead-acid battery has to be adapted for giving better high discharge and charge behaviour.

A project is going on together with a Dutch battery manufacturer (Centurion) to improve the aspects mentioned above of this bipolar battery.

We conclude that several improvements and modifications of the tested 80 V true bipolar lead-acid battery will make it possible to come to a state-of-the-art hybrid electric vehicle battery which meets the requirements.

These improvements will enable us to demonstrate further the feasibility of the lead-acid battery system for a new emerging and booming market of hybrid electric vehicles.

Within the coming year, we will implement several of the above mentioned improvements. Other improvements, like the use of an advanced battery management system, will be discussed in the next paragraph.

4.2. Battery management system

The successful performance of a bipolar battery system, under severe conditions like drive cycles for hybrid electric vehicles during long time, can only be performed successfully if an advanced battery management system is used which communicates with the individual cells.

Such a Battery Management System, described with the acronym ICOBAMS (Individual Cell Oriented Battery Management System), is essential in operating a complex system like an 80 V bipolar lead-acid battery and will be developed in parallel with the battery development.

Of course, each cell has to be protected both from overcharging and from cell reversal. Also, a lower limit for the individual cell voltages is important. However, this is not the only role for ICOBAMS. A very important role is the balancing of the cells after charging the battery. If the balance is not good, the cells will have different behaviour while discharging. In a worst case scenario, this leads to a very serious lifetime decrease.

Another important feature of ICOBAMS is to control the temperature of the cells. An active cooling strategy of the cells, i.e., to start cooling if the cells become too warm, prevents overheating of the battery.

The development of ICOBAMS is still in its infancy. Until now, we controlled the individual cell voltages of the 80 V bipolar battery using a 48-channel parallel data logger. Such a solution is of course of no practical interest, especially when individual cell charging is required. Of course, these chargers have to be controlled by a central computer. Development of ICOBAMS is not only limited to the bipolar lead-acid battery system, but can be used in, e.g., lithium battery systems with hundreds of cells in series, sodium–nickel chloride battery systems, nickel–cadmium battery systems, etc. In each of these battery systems, individual cells need to be controlled.

In the future, TNO therefore will continue not only further developing of the bipolar lead-acid battery, but also attention will be paid to a system which will enable us to charge (and discharge if necessary) individual cells. The availability of such a system will greatly enhance the performance of the bipolar lead-acid battery system and is also required to get a satisfactory life cycle.

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