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Measurement of the maximum charge and discharge powers of a nickel/metal hydride battery for hybrid electric vehicles

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Abstract

The determination of the maximum acceptable charge power and power output is of special significance in the development of hybrid electric vehicles. Theoretically, the maximum acceptable charge power and the power output can be defined as those relating to the maximum current levels before the occurrence of any side reaction. A new method has been developed to measure these maximum currents for nickel/metal hydride batteries used in hybrid electric vehicles. The method involves three step: (i) measurement of the transient voltage vs. current relation during charge or discharge by a sequence of pulse currents; (ii) calculation of the overall battery internal impedance at different times and current magnitudes; (iii) determination of the maximum current from the minimum point of the internal impedance. This method is based on the principle that, with increasing current level, mass transport becomes the rate-limiting step. Any extra increase in current can only cause the occurrence of a side reaction which will result in an increase in the battery internal impedance. The maximum current can thus be determined by the minimum internal impedance from a plot of this parameter against current. Experimental results show that the maximum current strongly depends on battery state-of-charge and also, battery structure. Increase in the surface area of the battery plates is an efficient way to increase the charge-acceptance and power output of the battery, and also to reduce the internal impedance. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Nickel oxide electrode; Metal hydride electrode; Battery; Charge and discharge; Hybrid electric vehicle

1. Introduction

The exhaust gases from internal-combustion engined vehicles are a major source of atmospheric pollution. The development of hybrid electric vehicles (HEVs) is aimed at increasing the energy efficiency of the vehicle and greatly reducing the emission of pollutant gases.

One design of HEV employs a small internal-combustion engine which works constantly at its highest efficiency and an auxiliary battery/motor system to adjust the power demands of the vehicle and to increase the energy efficiency of the fuel consumed. For this mode of operation, the battery is subjected to transient high-power charges and discharges. The battery is normally designed with a relatively low capacity but with a high power input and output capability. It is crucial to pre-determine the maximum acceptable charge power and the power output of the battery. This is because the occurrence of any side reaction can cause a lower charge efficiency and can cause low reliability in battery state-of-charge (SOC) control. A side reaction can also mean some kind of detrimental change in active material, that may shorten battery life.

Measurement of the maximum acceptable charge power has received little attention, only a few studies of the measurement of power output can be found in the literature. The conventional method is to measure the power output at the end of a high rate discharge pulse with a certain cut-off voltage. This method has been used to test automotive starting-lighting-ignition (SLI) batteries [1], as well as electric-vehicle (EV) batteries [2,3]. Corrigan [4] has proposed a one-pulse power test to evaluate the power performance of nickel oxide electrodes. This method is based on the condition that the voltage-current relation (V–I relation) is linear, in other words, ohmic resistance is the main part of the battery internal impedance. But this is not always the case in practical applications.

Recently, a method to evaluate both the maximum acceptable charge power and the maximum power output has been developed in our laboratory. This method in-

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volves the application of a sequence of pulse currents with different magnitudes to the battery, so that a more precise V–I relation can be obtained. A further calculation of the battery internal impedance based on the V–I relation at different current magnitudes and times results in a plot of internal impedance against pulse current, which shows a minimum point of the internal impedance at a certain current level. This current level can be considered to be the maximum acceptable charge current (for charge pulse–current test), or the maximum discharge current (for discharge pulse–current test). This paper discusses the application of this method to nickel/metal hydride HEV batteries.

2. Principle of test method

For an electrochemical cell, the electric current is carried either by electrons or ions depending on different sections of the battery. For an electrochemical reaction in a solid electrode, from the reaction site to the electrolyte, the current is carried by ion transport both in the solid active material and in the electrolyte. The electron transfer and the mass-transport steps are actually in series. Therefore, the rate-determining step can be electron transfer in low current range, but the mass-transport step in the high current range. The latter controls the maximum magnitude of the charge or discharge current. Any current level higher than the limit of the mass-transport rate will cause the occurrence of a side reaction [5,6]. In such a case, the battery voltage will change more greatly than normal.

The voltage difference (ΔV) between the transient voltage at any current and time (V_t), and the open-circuit voltage (V_{ocv}) can be defined as the general energy loss. Therefore, the general internal impedance (R_t) can be expressed as:

$$R_t = \frac{\Delta V}{I_t} = \frac{|V_t - V_{ocv}|}{I_t}. \quad (1)$$

R_t varies with the change of current and time while current passes through the battery, because it is composed of all the contributions from the positive and negative electrodes, the electrolyte, the separator, and the electric connectors.

As a direct current flows through the battery, the internal impedance of each electrode is the sum of four parts, the first is from the overpotential to overcome the activation energy barrier of the electrochemical reaction (R_1); the second is the ohmic drop due to the limited electric conductivity of the active material (R_2); the third is from the overpotential for ion conductance in solid material (R_3); and fourth, but not the least, is from the overpotential for mass transport in the electrolyte (R_4).

These four components of the internal impedance are not equally important but depend on the current magnitude and the time during which the current passes through the electrode. For a pulse current of a few seconds duration, R_2 can be taken as a constant; both R_3 and R_4 vary with time and current magnitude; but R_1 decreases with increase in the current magnitude, as shown by the Tafel relation [7–9]. In general, before a side reaction occurs, the internal impedance decreases while increasing the current magnitude when the current is lower than the limit of mass transport, but increases with the time.

On the other hand, when a side reaction occurs due to the rate limit of mass transport being met, the electrode overpotential will increase more rapidly with increase in current magnitude and, thereby, will cause an increase in the internal impedance. Thus, the minimum point in a plot of internal impedance vs. current indicates the maximum current level. For a charge process, this is the maximum acceptable charge current, but for a discharge process, it is the current determining the maximum power output. This mechanism applies to both electrodes; the power performance of a battery is finally determined by the electrode which has the lower power ability.

3. Experimental

A cylindrical type nickel/metal hydride (Ni/MH) battery with a sintered nickel oxide electrode and a pasted metal hydride electrode was used to evaluate the test method. Two different battery designs were used: A type and B type. Type B battery was designed in such a way that the geometric surface area of the electrodes was 50% larger than that of the electrodes in the type A battery. This gave a difference in power performance. Apart from this, all the other parameters were the same for both battery types. The nominal capacity of type A and B batteries was 6.5 A h and was limited by the positive electrode.

A charge–discharge unit (HOKUTO DENKO, Japan) with a PC computer was used to perform the charge and discharge purpose. Two current ranges were used, namely, 40 A and 400 A. The accuracy of the unit was 0.3% of the maximum. Data were recorded and processed by the computer. A temperature cabinet (LU-112T, TABAI, ESPEC, Japan) and a cooling fan were used to control the battery temperature; all experiments were performed at 25°C.

The maximum levels of charge and discharge current were measured at different initial battery SOCs. The initial SOC was established by using a current at the 0.8 C rate to the required level.

In the pulse–current sequence, the current magnitude was increased gradually. The duration of the pulse current was set at 10 s, which is long enough to cover most situations of HEV battery operation. After each pulse charge or discharge, the battery was discharged or charged with a 0.3 C current to compensate for the change in SOC, i.e., the initial battery SOC was recovered. With the whole sequence of pulse–current charge or discharge, the voltage was plotted against the current to obtain transient V–I relations. The change in transient internal impedance against the current could thus be obtained.

The charge and discharge efficiencies of the maximum current determined by the minimum of the internal impedance were verified by a constant-pulse current charge or discharge at 50% SOC, the pulse current has the same magnitude as the maximum. After that, the remaining battery capacity was measured by 0.3 C rate current discharge to a cut-off voltage of 1.0 V.

4. Results and discussion

4.1. Measurement of maximum charge current

In the Ni/MH battery, the main electrochemical reactions during charge can be expressed as:

$$\text{Positive electrode: } Ni(OH)_2 + OH^- \rightleftarrows NiOOH + H_2O + e^-, \quad (2)$$

$$\text{Negative electrode: } Me + H_2O + e^- \rightleftarrows MeH + OH^- \quad (3)$$

where Me denotes the hydride forming alloy.

The main side reactions are

$$4OH^- \rightleftarrows 2H_2O + O_2\uparrow \quad (4)$$

in the positive electrode, and

$$2H_2O \rightleftarrows H_2\uparrow + 2OH^- \quad (5)$$

in the negative electrode.

The charge process involves a change in chemical oxidation state from Ni(II) to Ni(III,IV) in the nickel oxide electrode, and the formation of metal hydride in the negative electrode, when only the main reactions occur. Any gas evolution as a side reaction inside the battery will reduce the charge efficiency. Several factors can influence the proceeding of the side reactions and, hence, can affect the charge-acceptance of the battery. One of these is battery design, i.e., when the negative electrode is configured with a much higher capacity and higher surface area than those of the positive electrode, reaction (5) can be avoided. This is the case in this study. Another factor is battery SOC. Qualitatively, a higher battery SOC results in a lower charge-acceptance. Therefore, from the point of view of battery SOC, the maximum charge-acceptance should be at the fully discharged state.

Fig. 1 shows the voltage vs. current relation of type A battery measured by pulse–current charge at 0% SOC. At any time of measurement, the V–I relation displays non-linear behaviour. Although the voltage varies with the current, it is not easy to see when a side reaction occurs.

The transient battery internal impedance can be calculated according to Eq. (1). The relation of R_t vs. current corresponding to the data of Fig. 1 is presented in Fig. 2. Three important points can be drawn from this Figure.

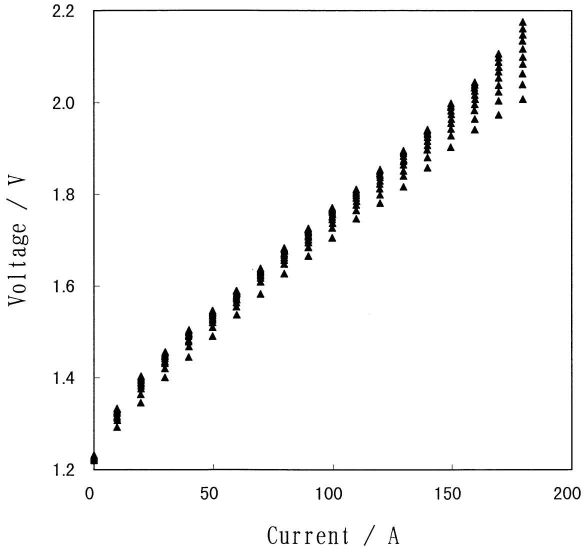

Fig. 1. Pulse current charge $V-I$ relation at 0% SOC for type A battery.

First, as the current magnitude increases, the internal impedance decreases to a minimum value. Second, the value of the internal impedance depends strongly on the charge time; at a shorter time, R_t has a lower value. Third, there is a minimum at a current level of 150 A in curve (c); this is shown more clearly in the insert. Higher currents at 10 s cause an apparent increase in the internal impedance, which indicates the occurrence of a side reaction. Therefore, 150 A can be considered as the maximum acceptable level of charge current.

A minimum does not appear in curves (a) and (b) of Fig. 2. This is because at shorter times, the mass transport rate is much higher, so a higher charge current level is acceptable. It is expected that the minimum point of R_t is reached at higher currents for curves (a) and (b).

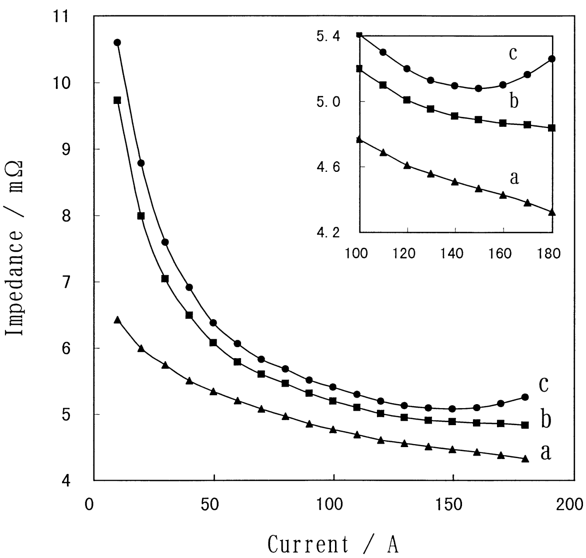

Fig. 2. Internal impedance vs. current at different times: (a) 1 s; (b) 5 s; (c) 10 s. Calculated from the data in Fig. 1.

The pulse–current charge behaviour of type A battery at other SOC states was also determined. Fig. 3 shows the V–I relations at 50% SOC (curve (a) and 90% SOC (curve (b)) at 10 s. A comparison of the V–I relations shows that a higher SOC causes a higher charge voltage.

The corresponding variation in internal impedance with current at these two SOCs was determined and is plotted in Fig. 4 where curves (a) and (b) represent the results at 50 and 90% SOC, respectively. From these data, it is obvious that, at 50% SOC and 10 s pulse time, the minimum value of R_t appears at 110 A. At 90% SOC, the minimum point appears at 90 A. Both of these currents are much lower than that in Fig. 2 for 0% SOC. These results clearly show that the charge-acceptance of the battery is drastically affected by the SOC: a higher SOC always relates to a lower charge-acceptance.

By comparing Figs. 4 and 2, it can be concluded that, in the low-current range, the battery internal impedance at the fully-discharged state is higher than those at all other SOCs. This was caused mainly by the Ni oxide electrode. It has been shown [10] that $Ni(OH)_2$, the main oxidation state in a fully-discharged Ni oxide electrode, has much poorer electric conductance than the Ni(III,IV) oxidation state.

The charge efficiency of the maximum charge current determined by the minimum R_t value was further confirmed by the following experiment. Initially, the battery was charged at the 0.8 C rate for 3.20 Ah from a fully discharged state, which was equivalent to 50% SOC. Then, the battery was charged with a 100 A pulse current for 1.00 Ah. Finally, the battery was discharged at the 0.3 C rate to 1.0 V. The discharged capacity was measured as 4.20 Ah. The results are shown in Fig. 5. Thus, it can be concluded that the side reaction at this current level can be ignored, in other words, the charge efficiency of a 100 A pulse current at 50% SOC can be taken as 100%.

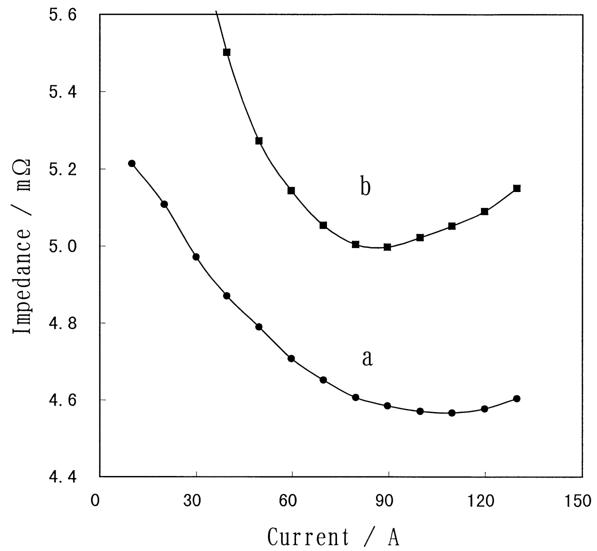

Fig. 4. Internal impedance vs. current at 10 s for: (a) 50% SOC; (b) 90% SOC. Calculated from the data of Fig. 3.

A current of 100 A is slightly lower than the maximum value (110 A) determined by the method of sequence pulse–current charge. This is because the battery nominal capacity is only 6.5 A h, but with 100 A pulse–current charging for 1.00 Ah, it results in a change in SOC from 50 to about 65%. Moreover, the charge-acceptance is reduced as the SOC increases.

Another experiment was performed similar to that shown in Fig. 5, except that the pulse current was 150 A and the pulse charge was 0.82 Ah (two pulses). The results are

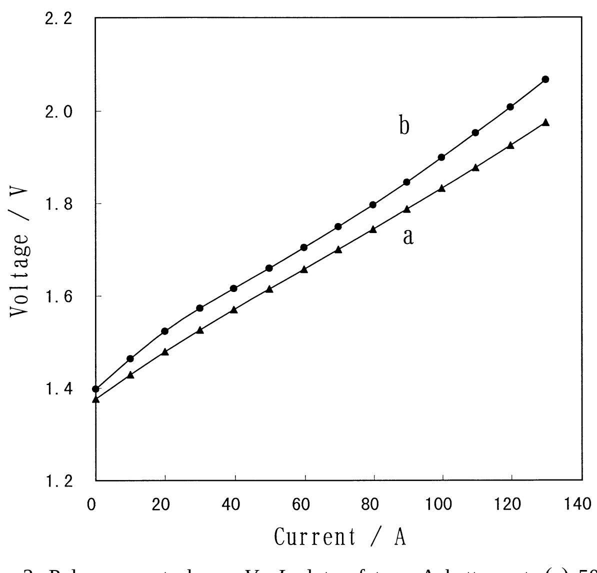

Fig. 3. Pulse–current charge $V-I$ plots of type A battery at: (a) 50% SOC and (b) 90% SOC, (10 s).

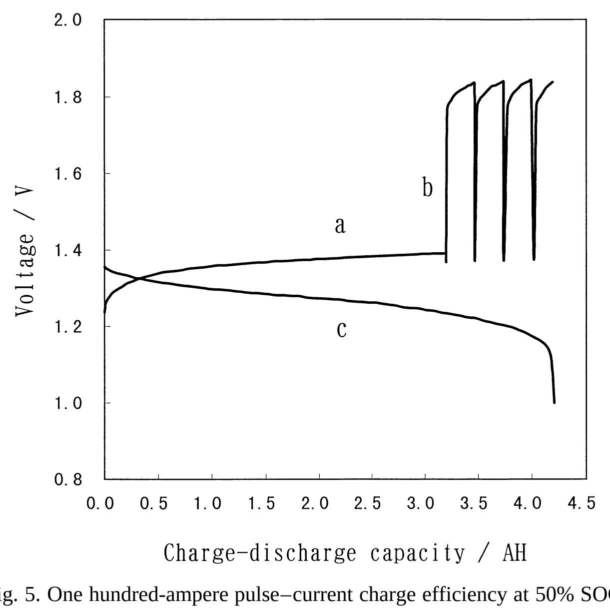

Fig. 5. One hundred-ampere pulse–current charge efficiency at 50% SOC for type A battery. Curve (a): 0.8 C rate charge 3.20 Ah; curve (b): 100 A pulse–current charge 1.00 Ah; curve (c): 0.3 C rate discharge to 1.0 V (discharge capacity 4.20 Ah).

given in Fig. 6. The total charge was 4.02 Ah (curves (*a*) and (*b*)), and the measured total discharge was 3.89 Ah (curve (*c*)). The difference in the total charge and discharge (0.13 Ah) could result from the low charge efficiency of the 150 A pulse current at 50% SOC.

To verify the validity of the method of pulse–current sequence charge for determining the maximum acceptable charge current level, a similar experiment was conducted on the type B battery. Fig. 7 shows the *V–I* relation at 50% SOC and 10 s (curve (*a*)). On comparing this with curve (*a*) in Fig. 3, it is apparent that the charge voltage of the type B battery is much lower than that of the type A counterpart.

Curve (*b*) in Fig. 7 is the relation of the internal impedance with the current at 10 s calculated from the data of curve (*a*) in the same Figure. Curve (*b*) shows clearly that a minimum point appears at a current of 210 A. When the current is higher than this level, R_t increases sharply. Therefore, 210 A can be considered to be the maximum acceptable charge current at 10 s for the type B battery. By comparison with the results for the type A battery, it can be concluded that a different battery design can change the battery charge acceptance significantly.

The charge efficiency of the 210 A pulse current for the type B battery at 50% SOC was verified by a similar experiment to that performed for the type A unit. The results are shown in Fig. 8. Initially, the battery was charged for 3.31 Ah (50% SOC) at the 0.8 C rate (curve (*a*)), then the battery was charged further by a 210 A pulse for 0.57 Ah (curve (*b*), one pulse). Therefore, the total charge was 3.88 Ah. Finally, the battery was discharged at the 0.3 C rate to 1.0 V (curve (*c*)). The discharged capacity was measured as 3.88 Ah. Thus, the maximum

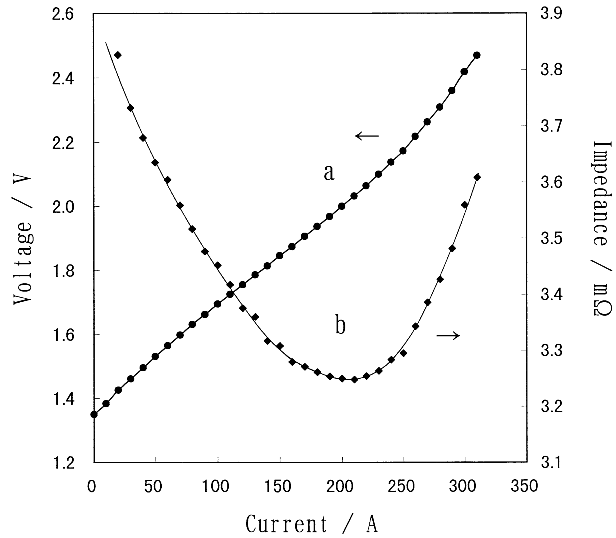

Fig. 7. Curve (*a*): pulse–current charge *V–I* relation for type B battery at 50% SOC and 10 s; curve (*b*): relation of internal impedance vs. current.

acceptable charge current for the type B battery is 210 A at 50% SOC.

The above experimental results clearly demonstrate that as a nickel/metal hydride battery is charged with high power, it is possible to identify a critical current level which separates the current range into two sections. When the current is lower than this level, the battery can be charged with high efficiency, but when the current is higher than this level, the charge efficiency can be reduced by the occurrence of a side reaction. This critical current level corresponds to a minimum in the transient battery internal impedance, as can be measured by experiment.

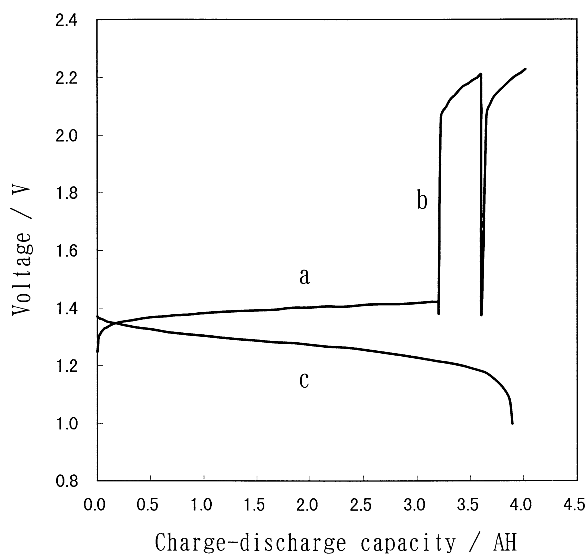

Fig. 6. One hundred fifty-ampere pulse–current charge efficiency at 50% SOC for type A battery. Curve (*a*): 0.8 C rate charge 3.20 Ah; curve (*b*): 150 A pulse–current charge 0.82 Ah; curve (*c*): 0.3 C rate discharge to 1.0 V (discharge capacity 3.89 Ah).

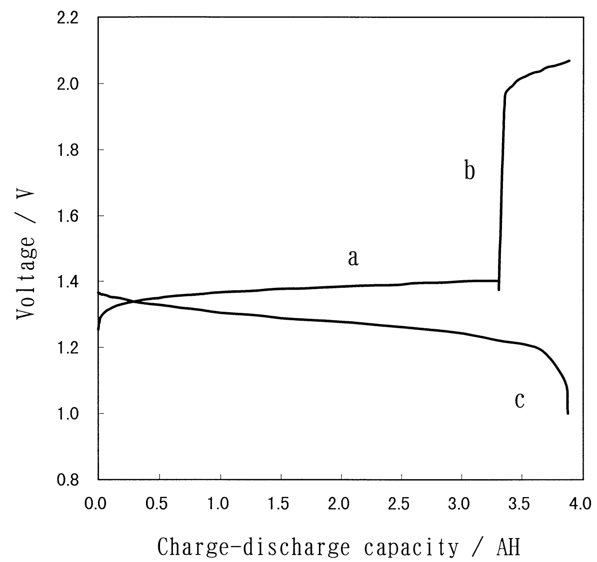

Fig. 8. Two hundred ten-ampere pulse–current charge efficiency at 50% SOC for type B battery. Curve (*a*): 0.8 C rate charge 3.31 Ah; curve (*b*): 210 A pulse–current charge 0.57 Ah; curve (*c*): 0.3 C rate discharge to 1.0 V (discharge capacity 3.88 Ah).

4.2. Measurement of maximum discharge current

The electrode reactions of the nickel/metal hydride battery during the discharge process are the reverse of reactions (2) and (3). The determination of the maximum discharge power is actually a measurement of the maximum current output ability. This ability varies with different battery systems, and also with different battery designs.

The same method used to determine the maximum acceptable charge power can be employed for the measurement of the maximum discharge current. Initially, the battery SOC was set at a certain level, then a sequence of discharge current pulses of predetermined duration and gradually increased magnitude was applied to the battery. Thus, a transient *V–I* relation was obtained. The overall internal impedance of the battery can be calculated from this relation. Finally, the maximum discharge current can be determined from the minimum point of the internal impedance.

Fig. 9 shows the transient discharge voltage vs. current relation for the type A battery at 90% SOC and different times (1 to 10 s). At 1 s, the *V–I* relation is more or less a linear one, but at longer times, deviation from the linear relation becomes obvious.

From the data in Fig. 9, the overall internal impedance at different current levels and times was calculated. The results are presented in Fig. 10, in which curves (*a*), (*b*) and (*c*) represent the results at 1, 5 and 10 s, respectively. It is clear that, basically, the internal impedance decreases with increase in the current magnitude, but long discharge times result in a higher internal impedance. From curve (*c*), which relates to a time of 10 s, a minimum in the internal impedance appears at the 120 A current level; higher currents than this caused an apparent increase in the internal impedance. Therefore, 120 A is the maximum discharge current ability at 90% SOC.

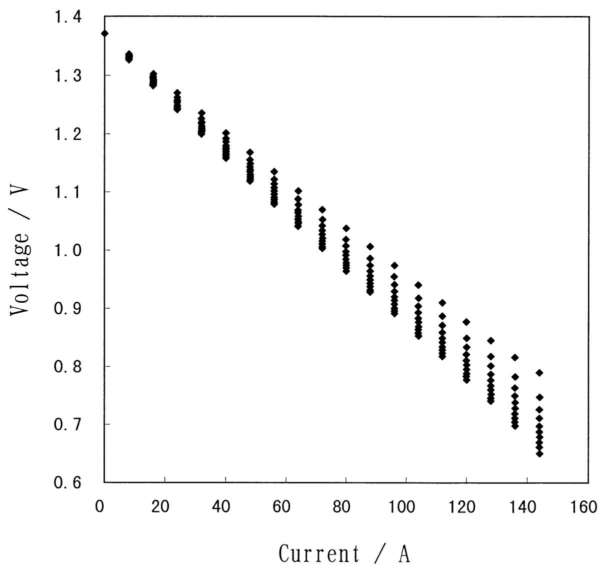

Fig. 9. Pulse–current discharge *V–I* relation at 90% SOC for type A battery.

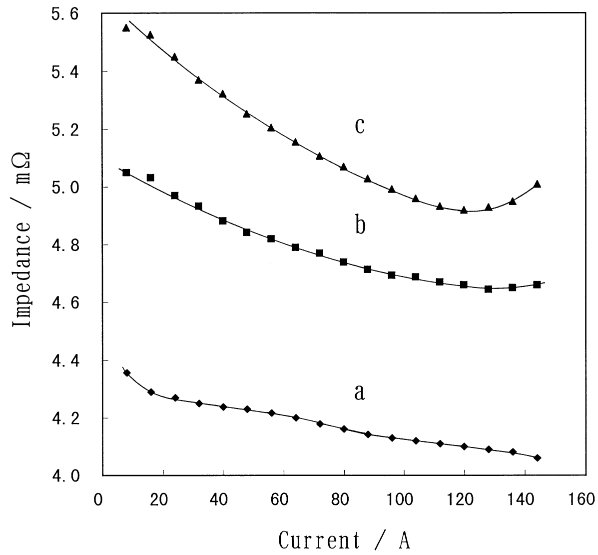

Fig. 10. Relations of internal impedance vs. current at different times: curve (*a*): 1 s; curve (*b*): 5 s; curve (*c*): 10 s. Calculated from the data in Fig. 9.

Similar studies were performed at different SOCs. The *V–I* plots at 10 s are given in Fig. 11 where curves (*a*) and (*b*) correspond to 20 and 50% SOC, respectively. From this data and also that of Fig. 9, it is seen that a lower battery SOC always relates to a lower discharge voltage. Moreover, all the *V–I* lines are non-linear.

The relationship between the internal impedance and the pulse–discharge current at 20 and 50% SOC were calculated from the data in Fig. 11 and are plotted in Fig. 12: curve (*a*) for 20% SOC and curve (*b*) for 50% SOC. Both curves show a minimum in internal impedance but at different current magnitudes. At 20% SOC, the current

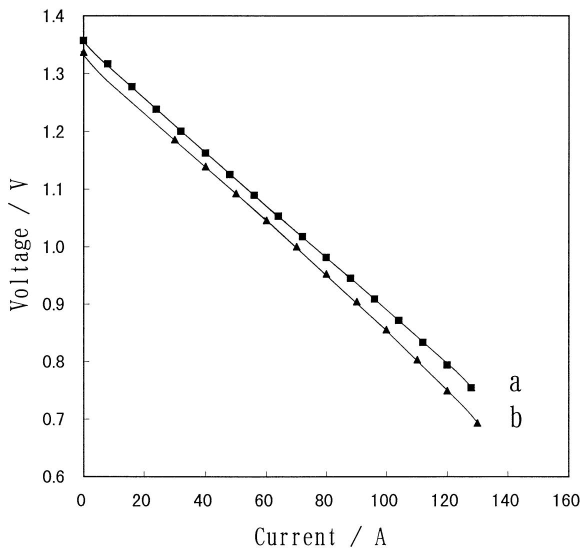

Fig. 11. Pulse–current discharge *V–I* plots for type A battery at: (a) 50% and (b) 20% SOC, (10 s).

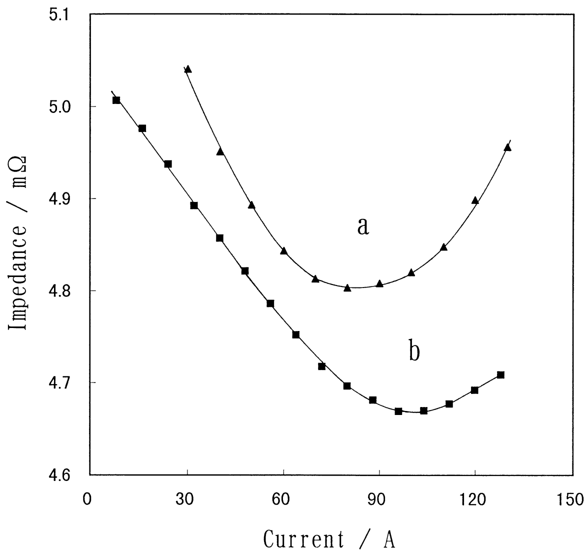

Fig. 12. Relation of internal impedance vs. current at 10 s and different SOC: (a): 20% SOC; (b): 50% SOC. Calculated from the data in Fig. 11.

level at the minimum point is 80 A, but at 50% SOC it is 100 A. These current levels can be taken as the maximum current output.

The discharge efficiency of a 100 A pulse current for the type A battery at 50% SOC is shown in Fig. 13. In the experiment, the battery was initially charged at the 0.8 C rate for 3.20 Ah, i.e., to 50% SOC (curve (*a*)). The battery was then discharged with a 100 A pulse for 1.00 Ah, followed by a further discharge to 1.0 V at the 0.3 C rate. The measured total discharge was 3.20 Ah. Thus, the discharge efficiency was 100%.

Interestingly, in another experiment similar to the one in Fig. 13, except that the pulse current magnitude was 140 A, i.e., much higher than the maximum current level determined by the minimum internal impedance, the measured total discharge capacity was also equal to the amount of charge, i.e., the discharge efficiency was 100%. This result indicates that the cause of the increase in the internal impedance in discharge process is not the same as that in the charge process. In the latter, it is certain that the occurrence of a side reaction which increases the internal impedance can simultaneously reduce the charge efficiency. In the former, however, the increase in the internal impedance is not accompanied by a reduction in the discharge efficiency. At present, it is not clear why the increase in the internal impedance is caused by the higher current discharge, but it is still reasonable to consider the current level relating to the minimum internal impedance as the maximum current output.

Sequence pulse–current discharge was also applied to the type B battery. The results at 50% battery SOC are shown in Fig. 14. Curve (*a*) in this Figure shows the *V–I* relation at 10 s. Compare with curve (*b*) in Fig. 11, it can be seen that, like the behaviour of pulse–current charge, during pulse current discharge, the discharge voltage of the type B battery is much higher than that of the type A at the same current level.

The change in internal impedance with current, calculated from the data of curve (*a*) of Fig. 14, is plotted as curve (*b*) in the same Figure. A minimum internal impedance appears at current level of 160 A, and R_t increases gradually as higher current is applied. Comparison of curve (*b*) in Fig. 14 and curve (*b*) in Fig. 12 shows that enlarging the surface area of the electrode plates is

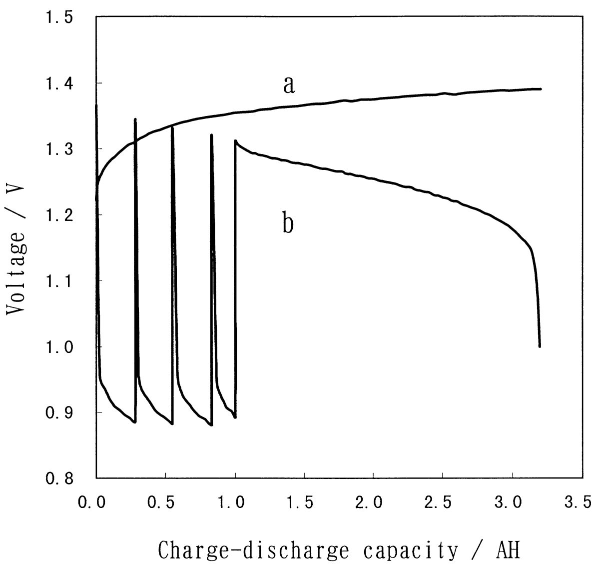

Fig. 13. One hundred-ampere pulse–current discharge efficiency at 50% SOC for type A battery. Curve (*a*): 0.8 C rate charge 3.20 Ah; curve (*b*): 100 A pulse–current discharge 1.00 Ah followed by 0.3 C rate discharge to 1.0 V (total discharge capacity 3.20 Ah).

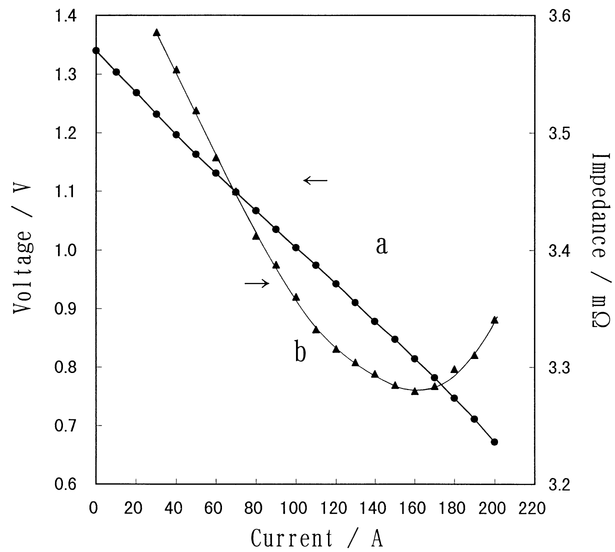

Fig. 14. Curve (*a*): pulse–current discharge *V–I* plot for type B battery at 50% SOC and 10 s; curve (*b*): relation of internal impedance vs. current.

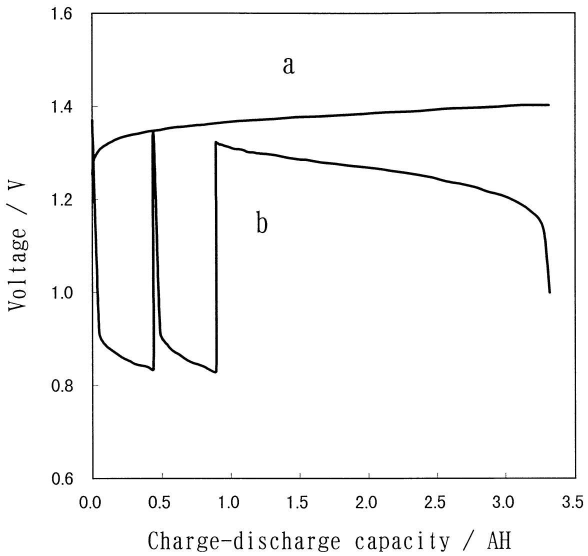

Fig. 15. One hundred sixty-ampere pulse–current discharge efficiency at 50% SOC for type battery. Curve (a): 0.8 C rate charge 3.31 Ah; curve (b): 160 A pulse–current discharge 0.89 Ah followed by 0.3 C rate discharge to 1.0 V (total discharge capacity 3.32 Ah).

definitely beneficial in increasing the power output of the battery.

The discharge efficiency of 160 A pulse current for type B battery at 50% SOC was also evaluated; the results are given in Fig. 15. In the experiment, the battery was charged initially at the 0.8 C rate for 3.31 Ah equivalent to 50% SOC (curve (a)), then it was discharged first by a 160 A pulse current for 0.89 Ah (two pulses), and then at the 0.3 C rate to 1.0 V which resulted in a discharge capacity of 2.43 Ah (curve (b)). The total discharge was therefore 3.32 Ah which is almost the same as the charged capacity with a minor difference (0.01 Ah). This result proves that, 160 A is the maximum current output for the type B battery at 50% SOC.

In the conventional method to determine the maximum power output, the cut-off voltage is an important parameter. From the above experimental results, however, no universal cut-off voltage exists even for different design of the same kind of battery. The first reason is that different battery designs can change battery internal impedance remarkably, so the voltage drop at the same discharge rate can be quite different. The second reason is that the current output ability can also be changed greatly. Third, current output ability also depends on battery SOC, there is no unique relation between current output ability and cut-off voltage. Therefore, an artificially decided cut-off voltage can probably put the battery into an improper operation. Thus, the maximum power output should be the one with highest current output without any side reactions. The latter could be one which can reduce the current efficiency like that in the charge process, and also one which does not reduce current efficiency but can increase the battery internal impedance like that in the discharge process.

5. Conclusions

For a nickel/metal hydride battery with capacity limited by the nickel oxide electrode, the maximum acceptable charge current is limited by the occurrence of a side reaction which reduce charge efficiency. The maximum acceptable charge current can be measured by the minimum change in the internal impedance derived from the V–I relation of a sequence pulse–current charge. At a current level as high as the maximum, the charge efficiency can reach 100%.

The maximum power output can be determined by measuring the maximum discharge current. This current level is limited by the occurrence of a side reaction which does not reduce the discharge efficiency but can result in an increase of internal impedance of the battery. The maximum discharge current can be obtained from the minimum of the internal impedance vs. discharge current plot.

This method, which applies a sequence pulse current to battery with a gradually increased current magnitude, measures the voltage response to obtain the transient V–I relation, and further calculates the internal impedance, is an effective way to determine the battery maximum acceptable charge power and maximum power output.

Both the maximum acceptable charge current and the maximum discharge current vary with battery SOC. Higher battery SOC results in a lower charge-acceptance but a higher power output ability. Conversely, a lower battery SOC causes a lower power output ability but higher charge-acceptance.

Increasing the battery surface area is an efficient way not only for reducing battery internal impedance, hence reducing energy loss, but also for increasing the battery charge-acceptance and power output ability.

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