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Measurement of short circuit current for low internal resistance batteries

S. OKAZAKI, S. HIGUCHI, N. KUBOTA, S. TAKAHASHI

Government Industrial Research Institute, Osaka Midorigaoka 1, Ikeda, Osaka 563, Japan

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A method of measuring short circuit current has been established for high power and low internal resistance batteries. The battery was forcibly discharged at a constant resistance much smaller than its internal resistance by a newly constructed short circuit switch. Current and voltage were then monitored by a digital memory scope. Pasted-type and tubular-type lead–acid batteries were used as samples in this work. Short circuit current was also observed for the batteries in various states-of-charge.

1. Introduction

In recent years a large amount of effort has been put into the development of electric power storage systems for the purpose of load leveling of commercial electric power systems. Research on various types of advanced secondary batteries has been carried out in order to realize a high power, large capacity, high efficiency and long life battery [1, 2]. When these batteries are utilized as high power sources, care must be taken in designing the system; one of the problems encountered is that of short circuit. In addition to an external short circuit, there is the possibility of inverting failure in the internal a.c.–d.c. inverter. Without a protective circuit, the short circuit current would cause great damage to the system as well as the battery itself. Thus, a protective circuit is indispensible to the system. The design of the circuit depends largely on the value of the short circuit current in relation to its capacity and response time, and the current withstand capacity of the total system. However, no published reports can be found dealing with short circuit current for high power and low internal resistance ($\sim$ mΩ) batteries. Thus, it is of considerable importance to establish an accurate measurement method for short circuit current.

There are two fundamental conditions in the short circuit current measurement. First, the external resistance has to be sufficiently small compared with the internal resistance in the closed circuit of the battery. Second, the circuit has to be closed rapidly. In other words, the time required to close the circuit ($R \approx \infty \rightarrow R \approx 0$) must necessarily be short (e.g. < 1 ms). Manual use of a knife switch to close the circuit takes too long and even when an electromagnetic breaker is used, a long chattering time exists. Furthermore, contact resistance is not negligible in these systems. The glow discharge just before the contact is also troublesome. It is thus clear that these switches are not appropriate for the measurement of short circuit current.

In order to solve the problems stated above, a new instrument was constructed and the measurement of short circuit current was carried out for commercially available lead–acid batteries.

2. Experimental details

The main part of the instrument was a short circuit switch, the block diagram of which is presented in Fig. 1. It was based on a conventional battery discharger at constant resistance and was made by Takasago Ltd. The current on resistance R_1 (or R_2, R_3) was regulated according to $I = E/(AR_1)$, where E and A are the terminal voltage of the battery between the probes and the amplification factor of the D/A converter type multiplier, respectively. In order to flow 1000 A at maximum, 200 regulating power

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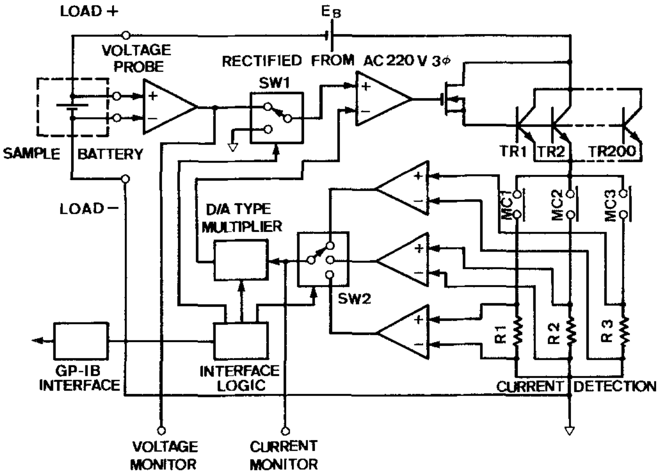

Fig. 1. Block diagram of the short circuit switch.

transistors, TR1 to TR200, were connected in parallel. To keep the collector–emitter voltage of the transistors above 1 V a d.c. power source, E_B, was used. Switch 2 selected current detecting resistance R_1, R_2 or R_3. This also corresponded to a selection of the range of the discharging resistance. Furthermore, the multiplier, which is controlled through a General Purpose Interface Bus (GP–IB), determined the actual value of the discharging resistance. Its minimum value was 10 μΩ which was sufficiently small compared with the internal resistance of the batteries (e.g. ~ mΩ for a lead–acid battery). The short circuit switch was triggered by switch 1. This was an analog switch based on MOS–FET and was able to switch on without chattering. The total response time, or switching time, of the total system was less than 1 ms (0 → 1000 A). Finally, the maximum power was 10 kW (10 V and 1000 A), which was sufficiently large to short circuit a conventional low internal resistance battery.

A battery connected to the power cable and the voltage probe was thermostatically controlled in air at 25 ± 2° C. It was forcibly discharged at a constant resistance by the short circuit switch. Voltage and current were monitored every 2 μs by a digital memory scope and the apparent external resistance was calculated from the voltage and current. Temperature was also measured at a point just under the meniscus of the electrolyte solution.

The instruments were controlled by microcomputer and the measurement data processing were carried out automatically.

3. Results and discussion

Commercially available lead–acid batteries

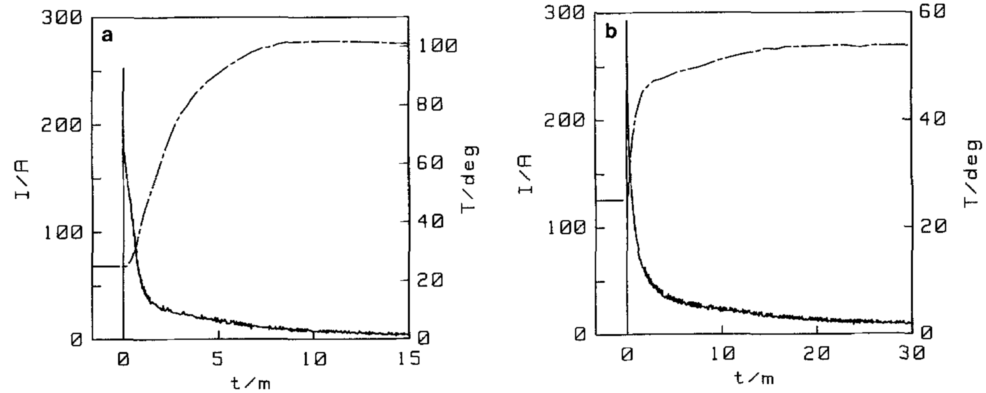

Fig. 2. Short circuit current (———) and temperature of electrolyte solution (— – —) as a function of time for commercially available (a) pasted-type lead–acid battery (6 V, 6 A h) and (b) tubular-type lead–acid battery (2 V, 15 A h).

were short circuited for a few tens of minutes. The results are shown in Fig. 2a for a pasted-type lead–acid battery (6 V, 6 A h) and in Fig. 2b for a tubular-type battery (2 V, 15 A h). Each of the batteries was in some state-of-charge. The curves represent the current and the temperature below the meniscus of the electrolyte solution when the batteries were discharged through a constant resistance, i.e. 10 $\mu\Omega$.

As shown in the figures, short circuit current decreased abruptly from its initial value for both the batteries. It decreased sharply from about 250 A for the pasted-type battery and from about 300 A for the tubular-type in a few minutes. The initial slope was particularly steep, which may be caused mainly by diffusion polarization. It shows that switching time is a very important factor in the measurement of initial short circuit current. This will be discussed later in more detail.

The temperature of the electrolyte solution rose due to the short circuit current. The initial power of the short circuit in the battery amounted to about 1.5 kW for the pasted-type battery and 0.6 kW for the tubular type. In particular, the temperature of the electrolyte solution of the pasted-type battery reached about 100° C and it began boiling 7–8 min after the short circuit. Since the measuring point was near the meniscus of the solution, there was a large time delay in the initial temperature rise at the probe due to convection. The temperature may become very high locally before boiling of the total solution occurs. After a short circuit of 15 min, one half of the electrolyte solution had been boiled off. There were small amounts of active material falling from the electrode as well as degradation of the separator. In the case of the tubular-type lead–acid battery the temperature reached as high as about 60° C. Though this was lower than that for the pasted-type battery and the electrolyte solution did not start boiling, both situations illustrate the damage which can be caused by short cicuits. In particular, the cycle life should be reduced substantially by the short circuit.

With regard to the measurement of the initial short circuit current, more careful treatment is required because of the surprisingly rapid decrease from the initial value. For this reason the electronic switch was used for short circuit current measurements instead of mechanical switches such as the knife switch, as stated in the previous section. Short circuit profiles of a millisecond time scale are presented in Fig. 3a and b for pasted-type and tubular-type lead–acid batteries, respectively. Apparent external resistance was calculated from current and terminal voltage and is also presented in the figures.

As shown in Fig. 3a, the short circuit switch was triggered at about 500 μs. External resistance decreased abruptly from infinity and took about 600 μs to reach less than 1 mΩ. The battery can then be considered to be short circuited since the value of the resistance, 1 mΩ, is sufficiently small compared with that of the internal resistance, i.e. about 25 mΩ, obtained from the a.c. impedance method and the d.c. step method.

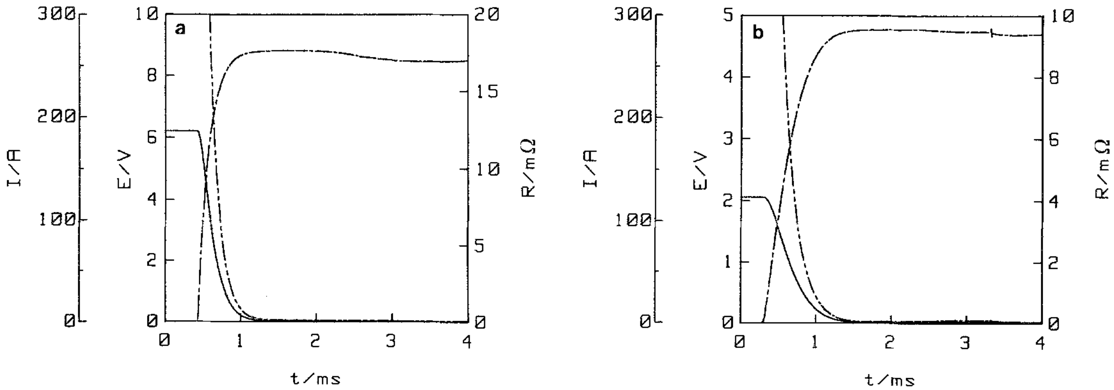

Fig. 3. Short circuit transient for commercially available (a) pasted-type lead–acid battery (6 V, 6 A h) and (b) tubular-type lead–acid battery (2 V, 15 A h). Apparent external resistance (— - - —) was calculated from short circuit current (— - —) and terminal voltage (———).

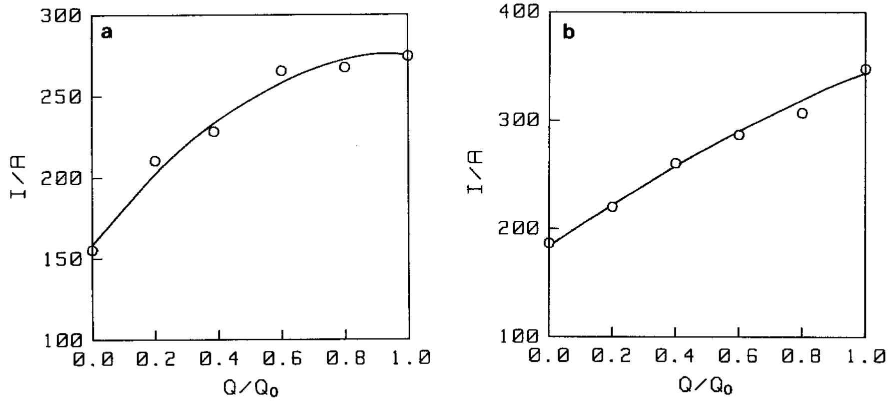

Fig. 4. Initial short circuit current as a function of state-of-charge for commercially available (a) pasted-type lead–acid battery (6 V, 6 A h) and (b) tubular-type lead–acid battery (2 V, 15 A h).

Thus in this case, the response time of the short circuit switch was in the range of several hundreds of microseconds. This is much faster than an electromagnetic breaker. Current also started flowing and increased abruptly at the same time. It took about 600 μs to reach a maximum value. Though the current decreased slowly owing to a decrease in the electromotive force itself and/or an increase in the internal resistance after the circuit was closed completely, the curve became rather flat over the subsequent time scale. This means that the initial short circuit current could be measured precisely and was 265 A in this case. Terminal voltage was negligibly small and could not be distinguished from noise after the circuit was closed.

The behaviour of the current, voltage and apparent external resistance for the tubular-type lead–acid battery is similar to that for the pasted-type battery, although it took a little longer to close the circuit completely. Thus it has been shown that precise mesurement of the initial short circuit current has been realized using the short circuit switch.

Short circuit current is shown in Fig. 4a and b for the two types of batteries as a function of state-of-charge. The abscissa represents the ratio of the residual charge, Q, to the original capacity, Q_0, defined by the cut-off voltages of discharge, 5.4 V (10 hour rate discharge) for the pasted-type battery and 1.75 V (5 hour rate discharge) for the tubular-type battery. As shown in the figures, the larger the residual capacity, the larger the short circuit current for both systems. The dependence on the state-of-charge is similar for both, although it shows a smaller curvature for the tubular-type battery than for the pasted-type battery. It is worth stressing that a considerable short circuit current flows even in a completely discharged state for these batteries.

Nominal capacity of the tubular-type battery is $2\frac{1}{2}$ times that of the pasted-type. However, their short circuit currents are comparable. This means that the power of the pasted-type battery is greater than that of the tubular one.

4. Concluding remarks

In this paper it was shown that initial short circuit current can be measured for the conventional lead–acid batteries using the short circuit switch. However, advanced secondary batteries used in [1], such as the sodium–sulphur battery, the zinc–chlorine battery, the zinc–bromine battery and the iron–chromium redox flow battery are considered to have several thousand amperes of short circuit current. This is too large to measure by the short circuit switch. We are now trying to establish a prediction method for such a practically immeasureable large short circuit current. This will be presented in a subsequent paper.

References

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