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Predicted and observed initial short circuit current for lead–acid batteries

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Initial short circuit currents have been observed using our electronic short circuit switch and also predicted from terminal voltage and ohmic resistance according to Ohm's law for several kinds of lead–acid batteries in various states-of-charge. Ohmic resistance was measured by the d.c. step and the a.c. impedance methods. The predicted and the observed values have been compared in order to establish a prediction method for initial short circuit current. A good agreement was obtained, the root mean square percentage deviation of the predicted value from that observed being only 2 ∼ 19%, which confirms the validity of the prediction method for the initial short circuit current.

1. Introduction

In electric power storage systems [1, 2], batteries are incorporated into commercial a.c. power systems through d.c.–a.c. inverters. Safety devices have to be considered in the design to protect against, for example, the invasion of small a.c. ripple currents containing higher order harmonics into the d.c. system as well as the switching surge which also enters into the battery side. In particular, the most serious trouble is the short circuit of the battery which is caused, not only by external trouble, but also by internal inverting failure. The batteries under discussion here have a large capacity and high power with very small internal resistance and extremely large short circuit current flows both in the batteries and the inverter. This large short circuit current results in battery damage with reduced capacity, energy efficiency, cycle life, etc. The overcurrent in the circuit also damages the inverter.

Hence a protecting device in the system is indispensable, the response time and current tolerance of which depend largely on the value of the short circuit current. The overcurrent withstanding ability of the inverter itself is also dependent on the protecting device. Accordingly, a knowledge of the value of the short circuit current is necessary in designing an electric power storage system.

These arguments also hold true in the case of electric vehicles, where a high powered battery is required. The relation between the battery and thyristor chopper in an electric vehicle is the same as that between the battery and the inverter in an electric power storage system.

In a previous paper [3], the measurement of short circuit current was reported for lead–acid batteries. The instrument constructed was capable of passing a current of up to 1000 A at potentials of up to 10 V, and some hundreds of amperes of short circuit current were measured. However, the practical short circuit currents, for example, in respect of the four kinds of 10 kW class of advanced batteries in the project in Japan [1], i.e. the sodium–sulphur battery, the zinc–chlorine battery, the zinc–bromine battery, and the iron–chromium redox-flow battery, are considered to be from several to tens of thousands of amperes. These are too large to measure directly by the practical short circuit. No power supply is able to recover such a large current on a millisecond time scale. Even if it is possible to short circuit the batteries, it is uneconomical to carry out such destructive tests since large-scale batteries are very expensive. Thus, in these cases it is very important to establish a nondestructive estimating method for the initial short circuit current.

The short circuit current I_{short} must be expressed formally as

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$$I_{\text{short}} = \frac{E}{R_{\text{int}}} \tag{1}$$

where E and R_{int} are the terminal voltage and internal resistance of the battery, respectively. R_{int} is divided into several components, i.e. ohmic resistance, R_{ohm}, reaction resistance, R_{react} and diffusion resistance, R_{diff}. Therefore, we can write,

$$R_{\text{int}} = R_{\text{ohm}} + R_{\text{react}} + R_{\text{diff}} \tag{2}$$

Of course, these terms are functions of time and it is clear that when $t \to +0$ then $R_{\text{diff}} \to 0$. Furthermore, in the case of the short circuit, overpotential is sufficiently large to consider $R_{\text{react}} \approx 0$. Thus the initial ($t = +0$) short circuit current should be described by the ohmic resistance R_{ohm} only, as

$$I_{\text{short}} = \frac{E}{R_{\text{ohm}}} \tag{3}$$

It is interesting to compare the observed initial short circuit current and that calculated from R_{ohm} and E. Initial short circuit current is observed by the short circuit switch based on a constant resistance power supply as stated in the previous paper [3]. Ohmic resistance is also measured by the a.c. impedance method and the d.c. step method.

In this paper, the establishment of a prediction method for the initial short circuit current is discussed and the relation between the observed and the calculated initial short circuit current is presented for three kinds of lead–acid batteries.

2. Experimental details

The ohmic resistance was obtained both by the d.c. step method and the a.c. impedance method. The d.c. step method is classified into the current step and the potential step method. These two are divided into two modes, the load-on and the load-off mode, each of which, furthermore, has two directions in the case of the secondary batteries, i.e. charge and discharge. Thus, there are altogether eight ($2 \times 2 \times 2$) kinds of measurements using the d.c. step method. The current step method in the direction of the load-off corresponds to the well-known current interruption method. Of course, in principle, there should be no differences between the results based on these eight methods. However, it is important to have an indication of the variance among the methods before starting a series of the measurements. The results of the eight kinds of step method were first compared for a pasted-type lead–acid battery in an unknown state-of-charge. In the measurements, the potentio/galvanostat, Toho Technical Research 2000S, was controlled by a function generator, Wavetek 175, which was able to step the signal in 10 ns. The current response time of the potentio/galvanostat was, however, from 6 to 20 μs. Voltage and current were monitored by a digital memory scope (DMS), Iwatsu Electric Co., Ltd DMS 6440, every 2 μs. The E–t and I–t curves were expanded by a microcomputer and ΔE and ΔI were read from the figures, and the ΔE was plotted against ΔI. Ohmic resistance was obtained from the slope of the ΔE–ΔI line fitted for three or four points of the ΔE–ΔI plot by the least squares method. The fitting equation was $\Delta E = R\Delta I + \Delta E_0$, where the fitting parameter ΔE_0 must be zero according to Ohm's law.

Alternating current impedance was observed by an integral type frequency response analyser, NF Electronic Instruments Company S5720. The power source was the same potentio/galvanostat as in the case of the step method, the maximum response rate being 20 kHz. The amplitude of the perturbation voltage was 10 mV r.m.s and the sweep frequency was 0.1 Hz to 20 kHz. The ohmic resistance was obtained as usual from

$$R_{\text{ohm}} = |Z|_{b=0} \tag{4}$$

where $|Z|$ and b are the absolute value and the imaginary part of the impedance. It was also read from an expanded Cole–Cole plot.

Short circuit currents were measured using the short circuit switch described in the previous paper [3].

Three kinds of lead–acid batteries were used as samples. They were: a pasted-type battery, nominally 6 V and 6 A h, and two kinds of tubular-type batteries, 2 V and 15 A h, and 2 V and 30 A h. The batteries were immersed in a water bath controlled at 25 ± 1° C when their ohmic resistances were measured and were then kept in air thermostated at 25 ± 2° C when the short circuit currents were measured.

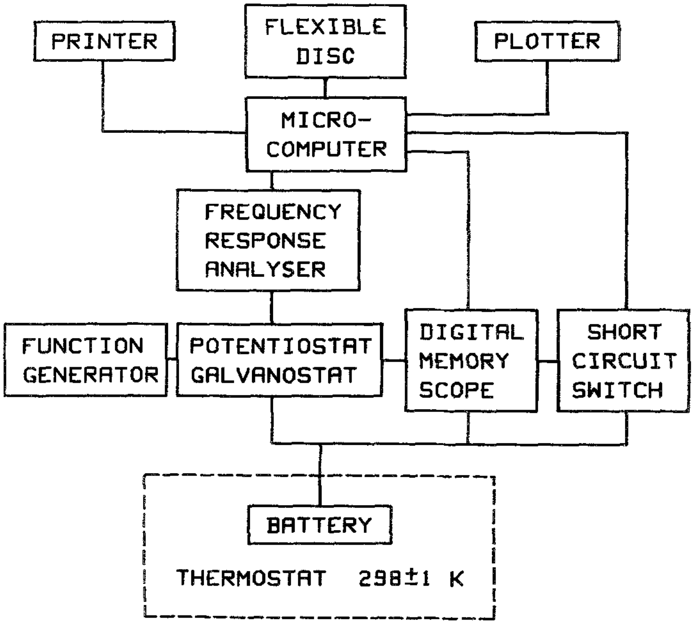

Fig. 1. Block diagram of the measurement system.

A set of measurements for one sample consisted of the first a.c. impedance measurement, the d.c. step measurement, the second a.c. impedance measurement, and finally the measurement of the short circuit current. The second a.c. impedance measurement was carried out in order to confirm that the equilibrium state or stability of the battery was not disturbed by the step current. The measuring instruments were all controlled by the microcomputer. A block diagram of the system is shown in Fig. 1. The short circuit switch and the DMS were used in the short circuit current measurement. The potentio/galvanostat, the function generator, and the DMS were for the d.c. step method. The frequency response analyser and the potentio/galvanostat were used in the a.c. impedance measurement. All of the results were stored on floppy disc and displayed by the plotter or on the cathode ray tube.

3. Results and discussion

3.1. *Ohmic resistance*

The d.c. step method, in general, tends to contain a large error, which is thought to be caused mainly by the slow response of the power sources, i.e. a kind of switching time. The response times were typically 6 to 20 μs for our measurements. Eight kinds of step method were tried and their results were compared for a pasted-type lead–acid battery in an unknown state-of-charge in order to confirm the precision of the measurement of ohmic resistance, R_{ohm}. The results are shown in Fig. 2, where each symbol corresponds

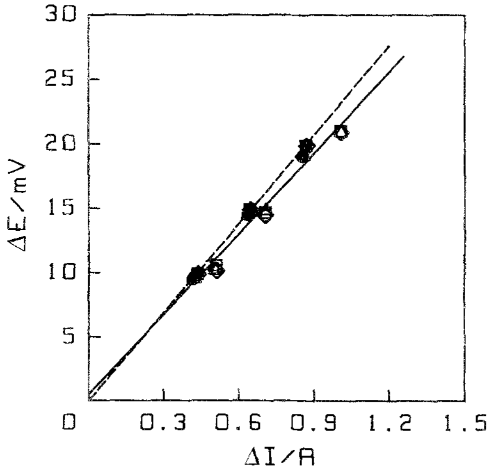

Fig. 2. ΔE–ΔI plots of eight kinds of the d.c. step methods for a pasted-type lead–acid battery (6 V and 6 A h) in an unknown state-of-charge. Each set of measurements consists of three points of the plot. The solid line represents the line fitted for a total of 24(3 × 8) plots of the measurements and the broken line corresponds to the ΔE–ΔI line according to the resistance obtained by the a.c. impedance method. Current step: (○) charge load-on, (△) charge load-off, (□) discharge load-on, (◇) discharge load-off. Potential step: (●) charge load-on, (▲) charge load-off, (■) discharge load-on, (◆) discharge load-off.

to each one of the eight kinds of measurement. The solid line in the figure is the result of the least squares method for all of the 24 plots and the broken line corresponds to the ΔE–ΔI plot according to the ohmic resistance obtained by the a.c. impedance method.

Resistances were obtained for eight sets of measurements by the least squares method for each three points of the ΔE–ΔI plot, respectively. Each set of plots was well represented by a straight line which crossed the ordinate at nearly zero. The averaged value of the eight resistances was 21.9 mΩ and its root mean square percentage deviation was only 3.6%. It is also shown in the figure that all of the 24 plots form a single straight line. It is clear from these results that the measurement is little influenced by the battery polarization or the capacity component of the electric double layer.

Thus, a high precision is achieved for the ohmic resistances measurement by the d.c. step method. Thereafter, only the current step method in the direction of discharge load-on was carried out.

However, as shown in Fig. 2, the data deviate somewhat from the broken line. This means that the ohmic resistance obtained by the d.c. step method differs slightly from that by the a.c. impedance method. The value by the latter method is 23.1 mΩ, which is larger than that by the former by about 5%. Though the difference is small, it seems to be a systematic one as will be shown in the next subsection. So, the ohmic resistance of the battery was obtained by both the d.c. step method and the a.c. impedance method and these two were treated independently and compared with each other.

3.2. *Predicted and observed short circuit current*

Observed initial short circuit currents, I_{obs}, were compared with the predicted ones, I_{cal}, for the three kinds of lead–acid batteries in various states-of-charge. There are two kinds of the predicted current as stated in the previous section. One is based on the resistance obtained by the d.c. step method and the other by the a.c. impedance method. The number of sample batteries were 12, 11, and 2 for 6 V and 6 A h pasted-type lead–acid batteries, 2 V and 15 A h tubular-type one, and 2 V and 30 A h tubular-type one, respectively. The data are plotted in Fig. 3a, b and c. Standard deviations and root mean square percentage deviations are also given in Table 1 for the first two kinds of batteries.

It is seen from Fig. 3a and Table 1 that the short circuit current can be predicted by the d.c. step method with an error σ_{p} of less than about 20% for the pasted-type lead–acid battery, though there are some exceptionally larger errors, i.e. ~30%. These errors are considered to be sufficiently small in view of the difficulty of large short circuit current measurement. The prediction from the a.c. impedance method is good, where the error σ_{p} is less than 10%.

As for the tubular-type lead–acid batteries the predictions are excellent. The error does not exceed 10% for both the d.c. step method and the a.c. impedance method in every measurement and the root mean square percentage deviation is only 2.3 and 6.5%, respectively, in the prediction of the initial short circuit current of the 15 A h battery. Further, the error is less than 5% in the case of the 30 A h battery. Thus, for the tubular-type battery the prediction is more precise than for the pasted-type battery. The cause may be the stability of the battery against the measurement perturbation, although the details are not clear yet.

The d.c. step method tends to give a larger prediction of the initial short circuit current than the a.c. impedance method. This holds true for both types of battery. However, the reason for

Table 1. Standard deviation and root mean square percentage deviation in the prediction of the initial short circuit current for pasted-type lead–acid battery (6 V and 6 A h) and tubular-type (2 V and 15 A h)

	σ/A	σ_p^*
Pasted-type		
d.c. step	46	18.9
a.c. impedance	21	8.7
Tubular-type		
d.c. step	7	2.4
a.c. impedance	20	6.5

$$* \ \sigma_{\text{p}} = 100 \left\{ \frac{\Sigma[(I_{\text{obs}} - I_{\text{cal}})/I_{\text{obs}}]^2}{n-1} \right\}^{\frac{1}{2}}$$

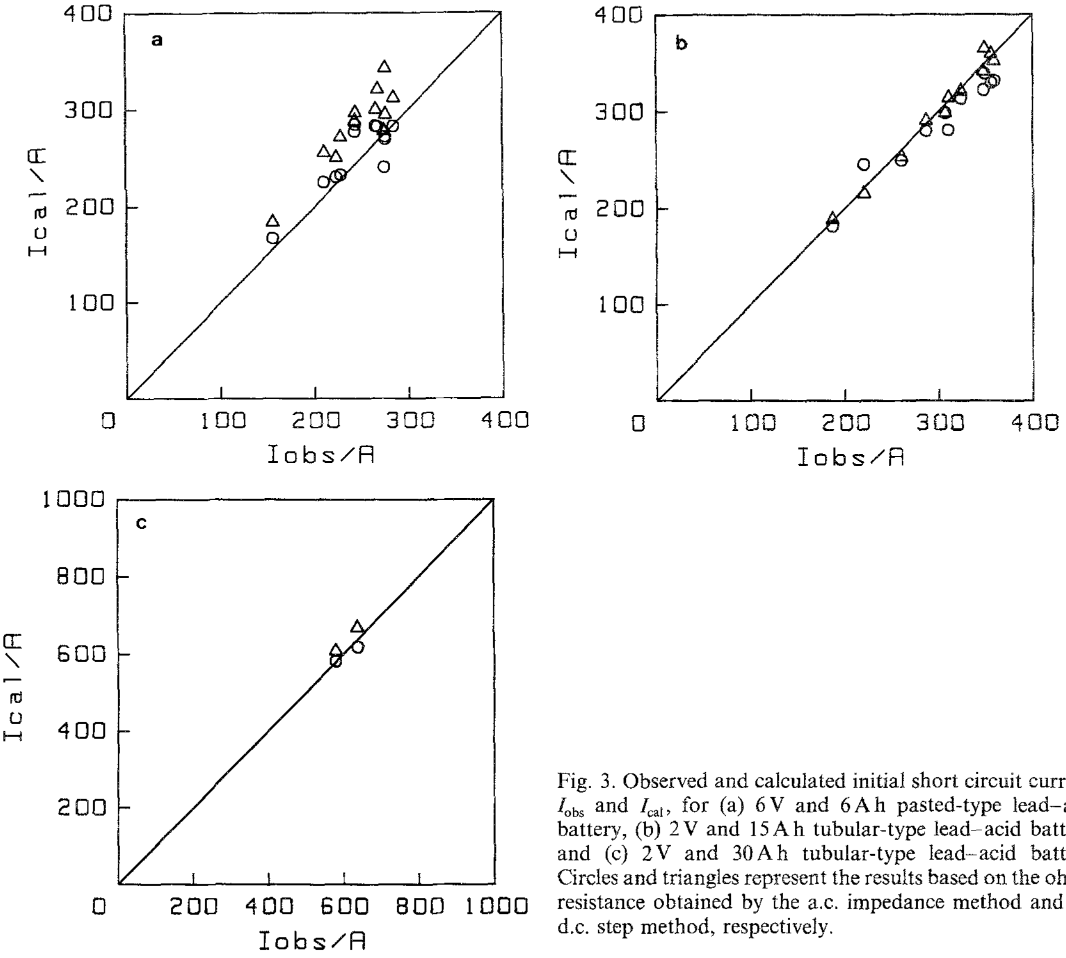

Fig. 3. Observed and calculated initial short circuit current, I_{obs} and I_{cal}, for (a) 6 V and 6 A h pasted-type lead–acid battery, (b) 2 V and 15 A h tubular-type lead–acid battery, and (c) 2 V and 30 A h tubular-type lead–acid battery. Circles and triangles represent the results based on the ohmic resistance obtained by the a.c. impedance method and the d.c. step method, respectively.

this is not clear at this stage. On comparing these two methods, the a.c. impedance method is found to be better than the d.c. step method for the pasted-type battery, while for the tubular-type battery the opposite holds true. It is considered that this situation is due merely to an accidental cause rather than an inherent one in the methods themselves.

As stated above, it is quite clear that the initial short circuit current can be estimated with an error of 10 to 30% for the pasted-type lead–acid battery and less than 10% for the tubular-type. The prediction is sufficiently precise to be used at least in the design of advanced battery electric power storage system. It is hoped that the method will be confirmed by its application to advanced batteries such as sodium–sulphur, zinc–chlorine, zinc–bromine, and iron–chromium redox-flow batteries.

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