FUNDAMENTAL STUDIES OF UTILITY REQUIREMENT FOR SECONDARY BATTERIES – LEAD-ACID BATTERIES

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Summary

The performance characteristics of lead–acid batteries in an electric power storage system have been studied. The superposition of 0.1 - 4000 Hz alternating current upon the d.c. charge/discharge current has been found to have little influence on battery capacity and cycle life. Observed short-circuit currents at various states-of-charge agree well with values calculated from ohmic-resistance measurements both using a.c. impedance and d.c. step methods. This information is important in designing safety devices against accidental short-circuits. Charging at constant power requires optimization; as a step towards achieving this, a linear correlation has been demonstrated between charging rates based on watt hours and ampere hours under either constant-power or constant-current operation.

Introduction

The Japanese National Research Project aims to develop a battery-based electric power storage (EPS) system with a load-leveling function, in which electric energy is stored during off-peak periods and delivered during peak demands.

An item of special concern is that the batteries in the EPS system will be subject to an a.c. influence, as the system will be operated on a power (watt) basis. Since it is the more common practice to regulate batteries on a current basis, data for optimizing the charging rate in relation to power output, rather than charge (A h) delivered, are scarce. In particular, a conversion coefficient from A h to W h will be required.

Use of an a.c./d.c. converter will cause line frequency as well as higher harmonics. However, information on the effect of a chopped current on the capacity of lead–acid batteries is only available for electric-vehicle applications. It is therefore necessary to study the influence of pulsed current in an EPS application.

Switching and lightning surges are both expected to affect the battery performance. Also, the occurrence of large short-circuit currents would reduce capacity, energy efficiency, cycle life, etc. Short circuits are caused by commutation failure and accidental external faults. Since batteries themselves have a large capacity and high power, protective devices are essential to the EPS system; a d.c. reactor and high-speed circuit-breaker are applicable to this purpose. Thus an estimation of the value of the short-circuit current will be important when designing the EPS system.

Experimental

(i) d.c. ripple and a.c. harmonics

Tubular-type (CS-15-6; 6 V/15 A h) and pasted-type (6N12; 6 V/12 A h) lead–acid batteries were used for the capacity and cycle-life tests respectively. Batteries were operated in constant-temperature water-baths at 25 ± 1 °C. The charge/discharge profiles were controlled using a Hokuto Denko HA-305 potentio/galvanostat, with a Wavetek 175 function generator. Alternating currents of 0.1 - 4000 Hz were superimposed on the battery d.c. current; the a.c. current amplitudes were 6 A (*C*/5 rate) and 3 A (*C*/8 rate) peak-to-peak in the CS-15-6 and 6N12 tests, respectively.

(ii) Initial short-circuit current

Three types of lead–acid battery were used for the tests: a pasted-type battery (6N6; 6 V/6 A h), and two types of tubular-type battery (CS-15-2; 2 V/15 A h, CS-30-2; 2 V/30 A h). The batteries were immersed in a water-bath controlled at 25 ± 1 °C for ohmic resistance measurements, and remained in air at 25 ± 2 °C for short-circuit current measurements.

The ohmic resistance was obtained using d.c. step methods and an a.c. impedance method. Two d.c. step methods, the current step and the potential step, were applied. The latter had two modes, load-on and load-off, each with two directions, *i.e.*, charge and discharge. Thus, eight (2 × 2 × 2) different measurements were made with the d.c. step method. Signals were stepped in 10 ns using a Toho Technical Research 2000S potentio/galvanostat controlled by the Wavetek 175 function generator. The current response time of the potentio/galvanostat was 6 to 20 μs. Voltage and current measurements were monitored at 2 μs by an Iwatsu Electric DMS-6440 digital memory scope.

The a.c. impedance was measured using an NF Electronic Instruments S-5720 integral-type frequency-response analyzer. The power source was the same as that used in the step method above, and had a maximum response rate of 20 kHz. The perturbation voltage was 10 m V rms and was applied over the frequency range 0.1 Hz - 20 kHz. The ohmic resistance was obtained by analysis of the complex impedance spectra.

(iii) Relation between A h charging rate and W h charging rate

Tubular-type (CS-60-6; 6 V/60 A h) and pasted-type (N200; 12 V/200 A h) lead–acid batteries were tested. They were maintained at 25 ± 1 °C, and charged and discharged for 8 h at either constant power or constant current. Each discharge was at 40 W and five different charging rates were selected. A Hokuto Denko P300 was used as the power source.

Results and discussion

(i) d.c. ripple and a.c. harmonics

The capacity and cycle-life performances of individual pasted-type lead–acid batteries were less reproducible than those for tubular-types. This situation was improved by averaging the data for a large number of batteries.

The ratio of the capacity before and after a test cycle was determined. For a 8 h charge/discharge rate, and with superimposed a.c. current, this capacity ratio was 1.00 in the a.c. frequency range 0.1 - 4000 Hz. In a similar experiment, but without a.c. superimposition, the capacity ratio was again 1.00. It is therefore concluded that d.c. ripple and a.c. harmonics have no influence on the capacity.

Figure 1 shows the dependence of cycle life on superimposed frequency [1]. The average cycle-life value for d.c. was 405(22). With 0.1 Hz, 100 Hz and 4000 Hz superimposition, the average values were 403(12), 382(19) and 446(17), respectively. The figures in parentheses are the root-mean-square (rms) percentage deviation. The reproducibility of the cycle-life tests was poorer than that of the corresponding capacity tests, and therefore, it is

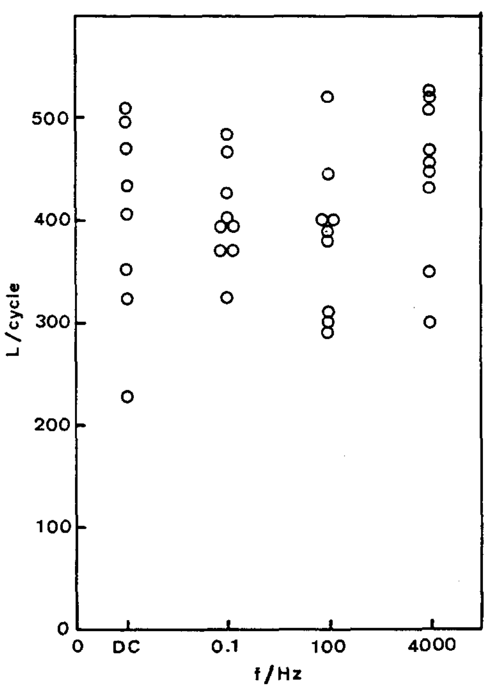

Fig. 1. Dependence of cycle life, L, on superimposed frequency, f.

difficult to interpret unequivocally cycle-life data. Nevertheless, cycle life is not expected to be influenced by a.c. superimposition.

(ii) Initial short-circuit current

A tubular-type lead–acid battery (CS-15-2) was short circuited. Figure 2 shows the time dependence of both the terminal voltage and the short-circuit current. A custom-built electronic switch [2] was employed and had an internal resistance of 10 $\mu\Omega$ (*cf.*, battery, ~ 10 mΩ) and a switching time of < 1 ms for 0 to 1000 A.

Figure 3 shows the short-circuit current as a function of the state-of-charge [3]. The horizontal axis represents the ratio of the residual charge, Q, to the original capacity, Q_o. It can be seen that the short-circuit currents increased with increase in residual capacity. Furthermore, the short-circuit current density of the pasted-type 6N6 battery was greater than that of the tubular-type CS-15-2 battery.

In order to confirm the precision of ohmic-resistance measurements, results from a pasted-type battery were compared for eight different step methods. Good agreement was obtained in the current-step range 0.4 - 1.0 A and the potential step-range 10 - 20 m V. The averaged value of the eight resistances was 21.9 mΩ with a rms percentage deviation of 3.6. The resistance was found to be independent of the current applied. The straight line obtained by the least-squares method for 24 different plots passed through the origin (within experimental error) in the current-step *versus* the potential-step representation. Thus, the method and the equipment employed are suitable for such investigations. Since the resistances obtained by all the step methods gave the same value, the current-step method in the direction of "discharge load-on" was employed in subsequent tests.

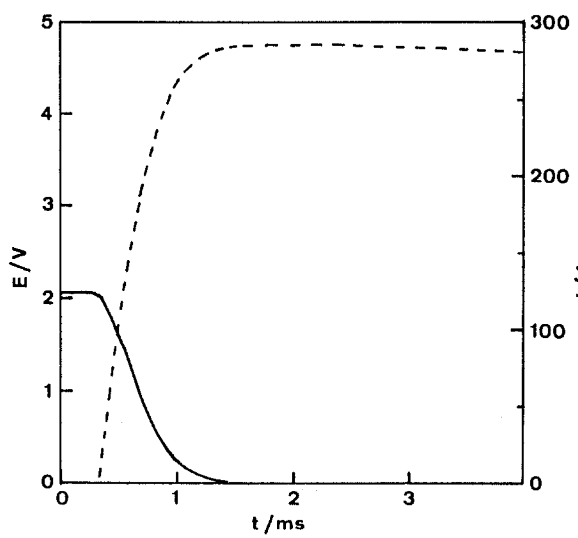

Fig. 2. Short-circuit transient of terminal voltage (——) and current (— — —).

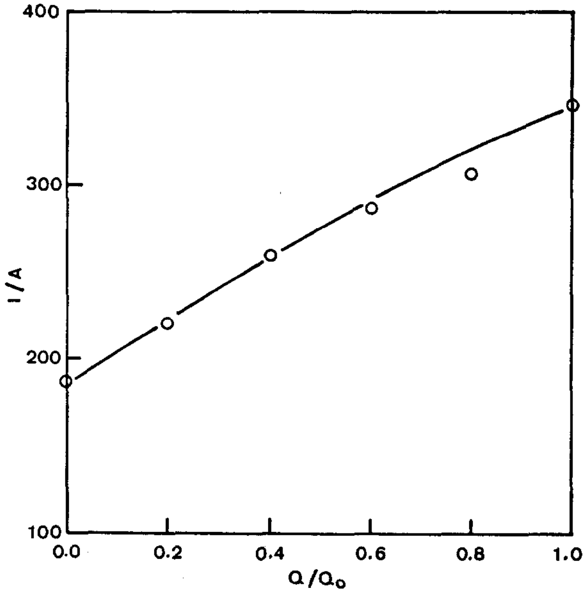

Fig. 3. Initial short-circuit current as a function of state-of-charge.

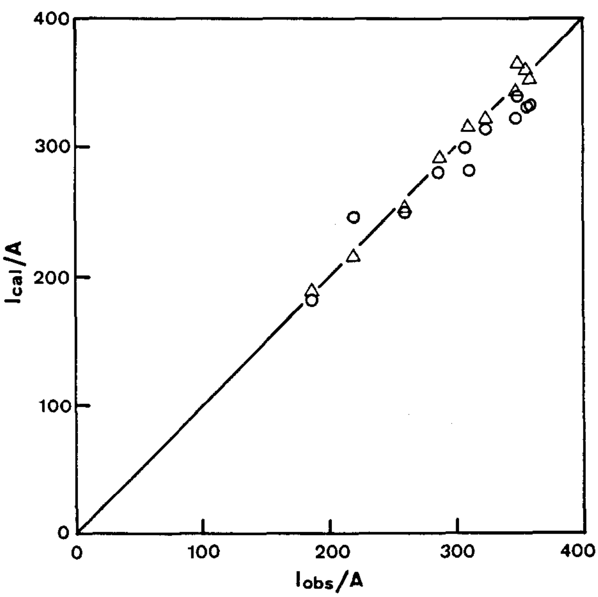

Fig. 4. Observed (I_{obs}) and calculated (I_{cal}) initial short-circuit current. I_{cal} are calculated from the ohmic resistances by a.c. impedance (○) and d.c. step (△) methods.

The ohmic resistance obtained by the a.c. impedance method was 23.1 mΩ, *i.e.*, only 5% greater than that determined by d.c. measurements (*viz.*, 21.9 mΩ). This difference, although small, appears to be a systematic error.

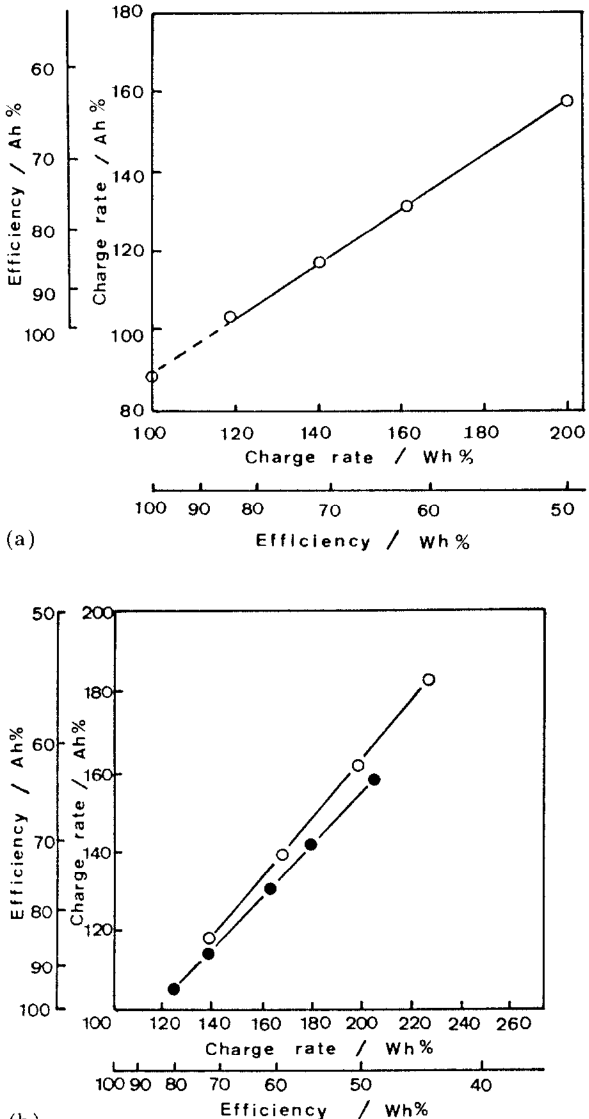

Fig. 5. Correlation between charging rates based on ampere hours and watt hours. (a) Battery CS-60-6 charged/discharged at constant power, (b) batteries CS-60-6 (●) and N200 (○) charged/discharged at constant current.

Figure 4 compares the observed (I_{obs}) and calculated (I_{cal}) initial short-circuit currents for CS-15-2 lead–acid batteries in various states-of-charge. Plots using twelve 6N6 data and two CS-30-2 data gave similar results. These approached the expected short-circuit current with an error σ_p of less than about 20% using the d.c. step method for the pasted-type lead–acid battery, although some showed exceptionally large errors of around 30%. Nevertheless, these errors are considered to be reasonably small, considering the difficulty in measuring large, short-circuit currents. The difference between I_{obs} and I_{cal} using the a.c. impedance method had an error of less than 10%. The corresponding errors for tubular-type lead–acid batteries were very small. For example, with the CS-15-2 battery, the error was less than 10% using either the d.c. step method or the a.c. impedance method, with respective rms percentage deviations of 2.3 and 6.5. The error was less than 5% for the CS-30-2 battery.

From these experimental results, we can estimate the initial short-circuit current to within an error of 10 - 30% for the pasted-type lead–acid batteries and to within less than 10% for the tubular-type batteries. The calculated values from the indirect method are, at least, sufficiently useful for designing the advanced battery EPS system.

(iii) Relation between A h and W h charging rates

Figure 5 shows charging results for tubular-type lead–acid batteries [4]. A charging rate based on watt hours gives a linear correlation with that based on ampere hours (Fig. 5(a)). This linearity enables an appropriate charging rate to be selected on a watt-hour basis from a given equivalent A h charging rate. The relation is always linear, even under different ambient temperatures or discharge rates. The linear correlation also holds for the constant-current test (Fig. 5(b)).

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