TRANSIENT RESPONSE OF 10-kW CLASS ADVANCED BATTERIES TO ABRUPT LOAD CHANGES

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Summary

A measuring system has been devised to evaluate the immediate availability and response properties of both lead/acid and advanced batteries (Na/S, Zn/Cl_2, Zn/Br_2, redox-flow) to abrupt load changes in an electrical energy storage system. It has been found that the response time of the charge/discharge equipment is proportional to the resistance of the load: the rise time of the output current is between 10 and 150 ms for a resistance between 10 and 200 mΩ. The rise and fall times of the current of the advanced battery systems are within 20 and 2 ms, respectively. It has been confirmed that the response properties of large-scale advanced batteries are sufficiently rapid to allow the use of these systems in electrical energy storage applications.

Introduction

Secondary batteries are attracting considerable attention for load-levelling applications in electric utilities [1]. They provide a promising alternative to either expensive gas-turbine or pumped-storage systems. The latter are location specific and suffer from many other limitations. If electrical energy (generated from coal, oil, nuclear or other prime energy sources) is stored (charged) during an off-peak period and is extracted (discharged) during a peak demand by using advanced batteries then generating equipment may be utilized efficiently and significant energy savings may be achieved.

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In Japan, a large-scale programme of research and development into advanced batteries — sodium–sulphur (Na/S), zinc–chlorine (Zn/Cl_2), zinc–bromine (Zn/Br_2), and redox-flow (Cr/Fe) — has been in force since 1980. Evaluation of the energy efficiency, self-discharge rate, cycle life, etc., of these systems has been carried out in the authors' laboratories between September and December, 1986. The results of the tests will be reported at a later date. Meanwhile, in this paper, data are presented on the transient response properties of the batteries.

When a large-scale secondary battery is employed for an energy storage system, the following conditions must be realized [1 - 3]:

(i) output power must be controlled as rapidly as possible, according to load fluctuations over a wide range;

(ii) energy efficiency must not decrease appreciably with marked variations in the load.

There have been no reports in respect of the transient characteristics of advanced batteries. As a consequence, a measuring system has been constructed in the authors' laboratories and used to study the transient response of 10 kW-class advanced batteries to abrupt load changes. Transient properties are most likely to be determined by electrode reactions and by cell design [4]. At this stage, determination of the electrode kinetics of the advanced batteries is deemed to be unnecessary because both the current and the electrolyte flows of the 10 kW-class modules are extremely complicated.

The main purpose of this work is to show the transient response curves of the 10 kW-class advanced batteries for large load changes. These curves depend on the response time of both the measuring system and the impedance characteristics of the batteries.

The measuring system consists of charge/discharge (C/D) equipment, a function generator, a digital storage oscilloscope, and a personal computer. Since battery charging and discharging was always conducted using the C/D equipment, the transient response property of that equipment was examined first. Subsequently, the response properties of the 10 kW-class advanced batteries were measured.

Experimental

The system used to measure the transient response of the batteries is shown schematically in Fig. 1. The C/D equipment (P30KN) was designed and constructed in collaboration with Hokuto Denko Co., Ltd.; it controls and measures battery voltage between 0 and 80 V, charge current between 0 and 500 A, discharge current between 0 and 1000 A, and battery power between 0 and 30 kW, all to an accuracy of ±0.1%. These specifications were set by the contractors developing the different 10 kW-class batteries.

The transient-response properties were determined precisely. In the measuring system, a function generator (Wavetek, 175) was employed to

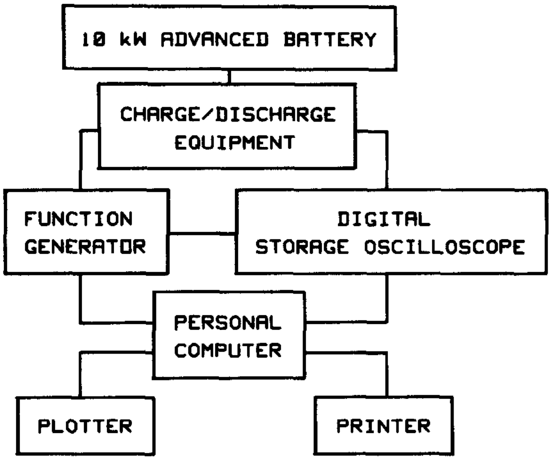


Fig. 1. System for measuring transient responses of advanced batteries to abrupt load changes.

cause a delayed signal from the equipment in measuring output current when necessary. Voltage and current data could be measured every 10 ns and stored in six memories of 1000 bytes in an 8-bit code by a digital storage oscilloscope (Gould, 4050). A personal computer (NEC, PC9801vm2) was used to control the system and store the data obtained from the oscilloscope.

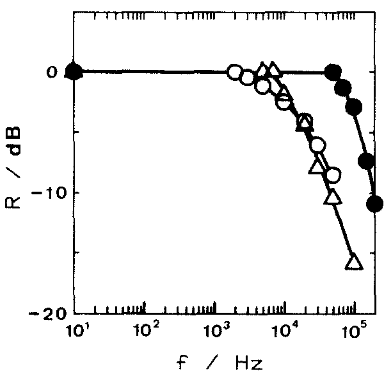
Since the purpose of the work was to clarify the response characteristics of the battery systems to large load changes, the rise and fall characteristics of both the current and the voltage were observed at the 8, 6, and 4 h discharge rates, and at the 8 h charge rate. The transient response was measured as follows (*cf.* Fig. 1). First, the personal computer sent sampling conditions to the function generator and digital storage oscilloscope. The C/D equipment instantaneously generates a trigger signal to the function generator immediately before the output current of the equipment increased or decreased. After a suitable delay, the digital oscilloscope measured the rise and fall characteristics of the battery voltage and current for a given sampling time. The personal computer then accepted and stored the data from the oscilloscope. The voltage and current were plotted as a function of time using an X–Y plotter (Hewlett Packard, 7470A) and were also recorded on a printer (Epson, VP80K).

Results and discussion

Response property of C/D equipment

The frequency property of the C/D detecting unit was determined by comparing the input data with the shunt resistance. As shown in Fig. 2, the current, voltage, and power responded perfectly up to 50 000 Hz, 7000 Hz, and 2000 Hz, for input signals of 100 A, 1 V and 100 W, respectively. Beyond these values, the response of the detecting unit gradually decreased with increasing frequency. These results indicate that the detecting unit responds accurately to the current, voltage, and power up to 0.02, 0.1, and 0.5 ms, respectively.

The frequency characteristics of the output current of the C/D equipment were the next to be determined. From the data shown in Fig. 3, it can be seen that the output current only responds accurately to set values of 800 A for discharge and 400 A for charge for frequencies up to several tens of Hz. This observation is attributed to the control unit of the output current and the power-transistor circuit, in addition to the detecting unit. Based on the above result, the transient rise time of the C/D equipment was estimated to be about 10 ms for output currents up to 800 A and 400 A for discharge and charge, respectively. The fall time of the output current (100 A) was also estimated to be about 0.1 ms; this is limited by the detecting unit.



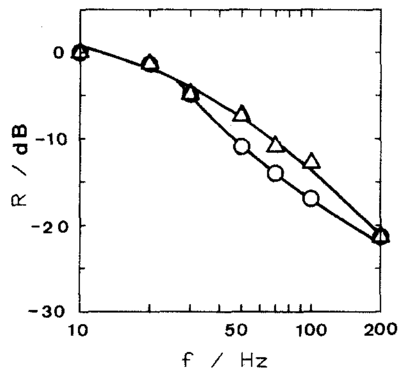
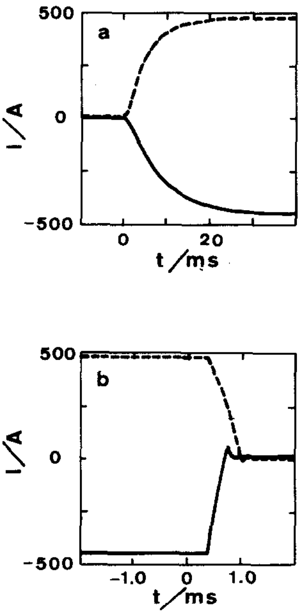


Fig. 2. Frequency characteristics of current (●), voltage (△) and power (○) detecting unit of C/D equipment for input of 100 A, 1 V and 100 W, respectively. $R = 20 \log_{10}(A_f/A_{10})$, where A_f = amplitude of measured current, voltage or power at frequency f.

Fig. 3. Frequency characteristics of output current of C/D equipment during charge (○) and discharge (△). Set values are 400 A (charge) and 800 A (discharge).

Since the rise time of the electrical system current is associated with the impedance characteristics of both the load and the equipment, the rise time was measured as a function of load resistance. Figure 4 shows that the rise time is proportional to the resistance and is between 10 and 150 ms for resistances between 10 and 200 mΩ, when a current of 100 A is applied. This finding is attributed to the fact that the C/D equipment includes a capacitor of 0.01 μF to stabilize the output current. Thus, the response time must be considered as that for the overall system consisting of the C/D equipment, cable, etc., as well as the battery itself.

The response characteristics of the 10 kW class lead/acid battery (15 modules, each of 12 V, 200 A h) were determined. The rise and fall times of



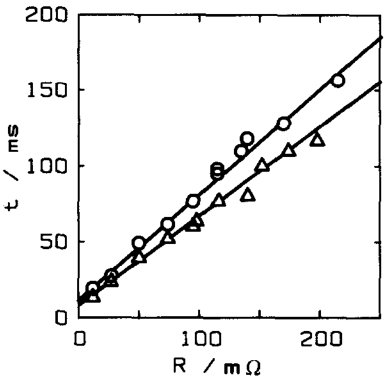


Fig. 4. Rise time of output current (100 A) *vs.* load resistance. ○, Charge; △, discharge.

Fig. 5. Transient response of 10 kW-class lead/acid battery during charge and discharge (15.0 kW, 30 V). (a) Rise character of current; (b) fall character of current. Solid line = charge; broken line = discharge.

the current and voltage were found to be about 20 and 1 ms, respectively (Fig. 5). The internal resistance was about 10 mΩ, as determined by an a.c. impedance method.

Response properties of 10 kW class advanced batteries

The specifications and internal resistance of the 10 kW (~80 kW h) batteries are summarised in Table 1. Battery current and voltage were measured as a function of time at the initial and final stages of an 8 h charge, and 8, 6 and 4 h discharges. (Figs. 6 - 9). The results are given in Table 2.

As mentioned above, the rise and fall times should relate closely to the impedance characteristics of the C/D equipment and the batteries. However, the data in Table 2 show little variation with either the type or the state-of-charge of the battery. These results are probably due to the following facts. The internal resistances of the four battery systems, excluding the C/D equipment and cable, are practically the same, being between 10 and 20 mΩ. Also, the values are not affected by the battery state-of-charge. This is due to the configuration of the unit cells [4], *i.e.*, the internal resistance results mainly from the electrical connectors and the electrolyte manifolds between the large number of unit cells used in the battery system. As a consequence, the rise and fall times of all the 10 kW-advanced battery systems are observed as about 20 and 2 ms, respectively. If the internal resistance of the batteries

TABLE 1

Specifications of 10 kW class advanced batteries

Battery	Na/S	Zn/Cl_2	Zn/Br_2	Redox-flow
Unit cell				
Area (cm^2)	495	2800	1600	6000
Current density ($mA\ cm^{-2}$)	50.5	22.0	13.0	30.8
Voltage (V)	1.8	1.95	1.67	0.9
Capacity (A h, 8 h rate)	200	495	166	1480
No.	280	96	288	60
Configuration*	(7s × 10p) × 4s	(24s × 2p) × 2p	(24s × 3p) × 4p	30s × 2s
Open-circuit voltage (V)	58.0	50.9	43.8	62.0
Charging power (kW)	15.0	14.9	12.7	12.8
Discharging power (kW)				
8 h rate	12.5	11.6	10.0	10.0
6 h rate	16.0	14.5	13.0	12.8
4 h rate	22.5	20.0	19.0	17.4
Internal resistance				
a.c. method (mΩ)	14	12	12	17
d.c. method (mΩ)	13	11	12	16
Contractor:	Yuasa Battery Co., Ltd. and NGK Spark Plug Co., Ltd.	Furukawa Electric Co., Ltd.	Meidensha Electric Mfg. Co., Ltd.	Mitsui Eng. & Shipbuilding Co., Ltd.

*Symbols s and p denote the cells are connected in series and parallel, respectively.

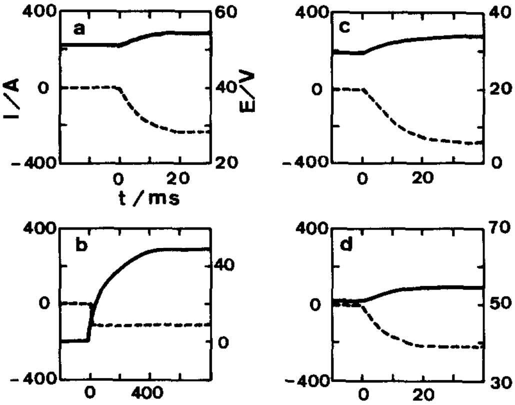


Fig. 6. Transient response at beginning of charge (8 h). (a) Na/S, (b) Zn/Cl_2, (c) Zn/Br_2, (d) redox-flow. Solid line = voltage; broken line = current.

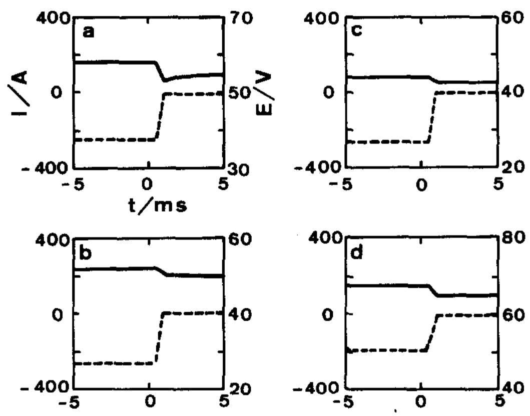


Fig. 7. Transient response at end of charge (8 h). (a) Na/S, (b) Zn/Cl_2, (c) Zn/Br_2, (d) redox-flow. Symbols as in Fig. 6.

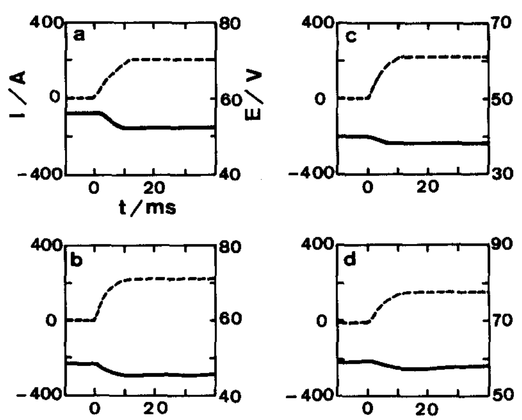


Fig. 8. Transient response at beginning of discharge (8 h). (a) Na/S, (b) Zn/Cl_2, (c) Zn/Br_2, (d) redox-flow. Symbols as in Fig. 6.

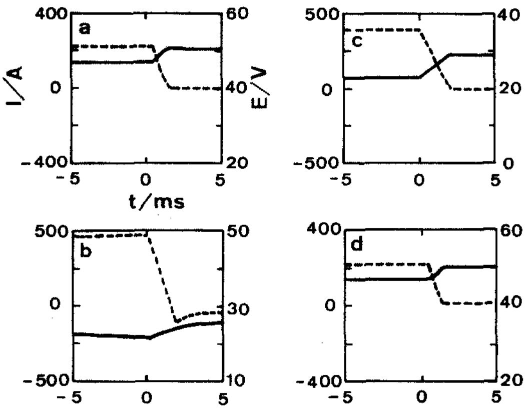


Fig. 9. Transient response at end of discharge (8 h). (a) Na/S, (b) Zn/Cl_2, (c) Zn/Br_2, (d) redox-flow. Symbols as in Fig. 6.

TABLE 2

Apparent response time of 10 kW class batteries

Measurement point		Response time[a] (ms)				
		Na/S	Zn/Cl_2	Zn/Br_2	Redox-flow	Lead/acid
8 h charge	rise[b]	14	8	19	13	18
	fall[c]	0.4	0.4	0.4	0.4	0.2
8 h discharge	rise	10	7	7	9	11
	fall	1	1	2	1	0.5
6 h discharge	rise	10	6	7	10	
	fall	0.7	2	3	0.5	
4 h discharge	rise	10	6	8	8	
	fall	0.8	2	2	0.8	

[a]Time for current change from 10 to 90% of rated values and that of C/D equipment.
[b,c]Rise and fall time measured at start and finish of rated charge and discharge, respectively.

consisted of pure resistance, then the rise time of the overall battery system should have been between 10 and 20 ms, according to the data of Fig. 4.

The transient curves in Figs. 6 - 9 have not been analysed in detail. The electrode kinetics of the batteries should be studied using much smaller unit cells, and under well-controlled conditions for which a theoretical model can be easily formulated.

The response times of the advanced batteries are much shorter than that of a hydroelectric plant the output power of which requires several minutes to become stabilized. The 10 kW class advanced battery systems now being developed in Japan respond within 20 ms to load variations between 0 and 20 kW when suitable C/D equipment is used. Thus, the storage and delivery of energy can be rapidly started or stopped using these advanced battery systems.

Acknowledgement

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