Journal of Power Sources, 7 (1982) 267 - 273

A NEW TECHNIQUE FOR DETERMINING BATTERY INTERNAL RESISTANCE: STUDIES ON LECLANCHE CELLS

J. A. HAMILTON

CSIRO Institute of Earth Resources, Division of Mineral Chemistry, P.O. Box 124, Port Melbourne, Victoria 3207 (Australia)

(Received August 15, 1981)

Summary

A new technique for determining the internal resistance of batteries (and fuel cells) is described. The measuring circuit employs recently released VMOS field-effect transistors. The measurements do not require a storage or differential-input oscilloscope, and they can be performed *in situ* during battery discharge. The determination is similar to the constant-current, square-wave technique but is easier to use and does not rely on the use of approximations. Batteries can be tested without significant discharge because the mark-to-space ratio of the discharge pulse can be 0.1%. Data obtained on Leclanché cells using this technique are presented, showing the variation of internal resistance with discharge current and temperature.

Introduction

The internal resistance of cells is an important parameter in realising the optimum energy density of a battery. This is because batteries with a high internal resistance are of limited use in applications that require large currents for short times (*e.g.*, to turn the starter motor in an internal combustion engined vehicle). High internal resistance is also detrimental to traction batteries which deliver moderate currents, because it produces internal heating which can have an adverse effect on battery life.

Several different techniques have been used in the past to measure the cell ohmic drop or resistive overpotential. The simplest method [1, 2] involves discharging the battery at different current levels, with the internal resistance being computed from the equation:

$$R_{int} = (V_{oc} - V)/I$$

where R_{int} is the internal resistance, V_{oc} is the cell open-circuit voltage, and V is the cell voltage at discharge current I. The cell resistance calculated with

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this expression includes a polarisation component and this can lead to inconsistencies in the application of this technique. An alternative procedure uses an a.c. bridge [3]. For many, this method is complex and time consuming, but it enables an operator to determine both the resistive and the reactive components of cell impedance.

High-speed oscilloscopes enable polarisation effects to be avoided. Glicksman and Morehouse [4] describe two methods — potential decay and potential recovery — for determining ohmic drop. The potential decay method has proved to be more popular. Current interruption is performed with microswitches mounted on cams and a square pulse of current is discharged from the battery through a resistor. The instantaneous potential drop is observed on an oscilloscope having a long-persistence phosphor screen. The cell resistance is the instantaneous potential drop divided by the magnitude of the current pulse.

The potential decay technique reported by Brodd [5] used a square-wave voltage generator in series with a cell and an external resistor; the latter was much larger than the cell resistance to ensure a constant current. A modification of this method by Tvarusko [6] included a d.c. blocking capacitor to prevent battery discharge through the pulse generator. Simultaneous continuous discharge through a resistor and square-wave pulsing were achieved by this method. A potential decay circuit incorporating a mercury-wetted relay has been advocated by Trachtenburg [7] for measurements of fuel cell polarisation. In a later paper [8], the relay was replaced with a power transistor switch in order to make the switching more reproducible.

A new technique for determining the internal resistance of a cell is presented in the work reported here. Several advantages can be claimed for this technique: (i) the current discharged is constant and does not depend on an external resistor; (ii) the duty cycle of the discharge pulse can be 0.1% and therefore it is possible to test batteries with negligible current drain; (iii) a high repetition frequency enables a non-storage CRO to be used to display potential increments; (iv) predictable, fast switching is achieved with VMOS transistors.

The effects of load current on the internal resistance of Leclanché cells has been a subject of continuing debate in the literature. For example, Glicksman and Morehouse [4] found that the internal resistance of a Leclanché cell is greater at low continuous current drains than at high continuous current drains. They attributed the increase in cell resistance to either a hydrogen film or an oxide coating on the zinc anode. On the other hand, Brodd [5] did not observe any change in cell internal resistance as the magnitude of the load current was varied. However, this author found that the internal resistance increased with time at constant load current. From this observation, it was suggested that internal resistance might be used to estimate the life expectancy of a cell. The findings of Tvarusko [6] agree with those of Brodd, namely, the internal resistance of cells does not change with discharge current. However, the range of discharge currents employed by Tvarusko was small, varying only from 1 to 20 mA. Further, the slow rise time of the CRO (3.5 μs) used in studies by Tvarusko would have limited the discrimination between polarisation and pure ohmic resistance. Brodd and De Wane [9] attempted to use the change in internal resistance during discharge to estimate the capacity of cells, but met with only limited success. These authors further found the internal resistance of Leclanché cells to be the same no matter whether pulse methods or a.c. bridge techniques were used.

The influence of load current on Leclanché cell internal resistance has been examined using the new VMOS switching technique and the results are presented below.

Circuit details of VMOS switching technique for measuring internal resistance

Figure 1 shows a circuit diagram of the active loads. Active loads AL1 and AL2 discharge currents at rates of v_1/R_1 and V_2/R_2, respectively. (In this paper, lower-case letters denote transient values, whereas capital letters denote steady-state values.) During each test, voltage v_1 is a narrow, square wave pulse with a duty cycle of about 0.1%, whereas voltage V_2 is held steady. Therefore, the battery is both pulse discharged with current i_1 and continuously discharged by i_2.

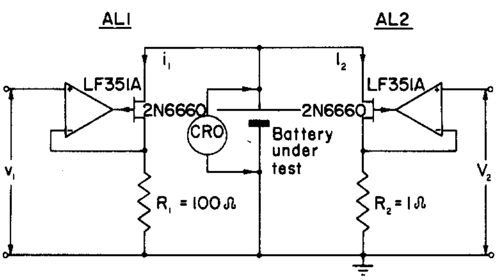

Fig. 1. Circuit diagram of the active loads (AL) used to determine the internal resistance of cells (CRO = Tektronix 466).

Figure 2 shows the circuit which was designed for pulsing the active load. Although a commercial pulse generator can be used, it is more convenient in the method employed here to use a specifically designed unit. The pulse repetition frequency and the pulse width are varied to produce a suitable trace on an oscilloscope, and the pulse height is adjusted to produce the required discharge current. The discharge currents obtained with this method are truly constant rather than approximately constant as in previous techniques. Also, it is not necessary to use a storage or differential-input type of CRO.

The 2N6660 VMOS FETs are almost ideal switches. With no minority-carrier storage time, they are extremely fast, having rise-times of about

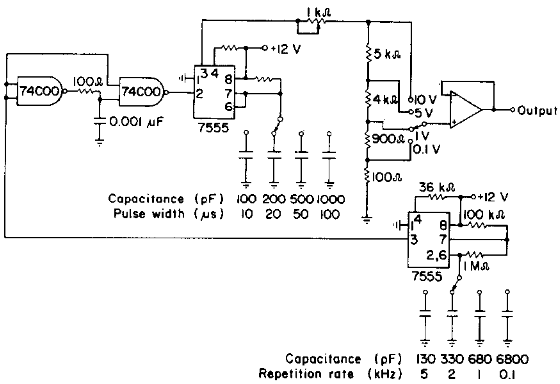

Fig. 2. Circuit diagram of the pulse generator used with AL1 in Fig. 1.

2 ns and requiring negligible gate currents. If pulse discharge currents of more than 2 A are required, then higher powered VMOS FETs can be used (*e.g.*, the 30 A-rated IRF131). Although bipolar transistors can be employed, the performance of these components is inferior to the VMOS FETs.

If the battery being tested is to be discharged to a predetermined potential, then volatge v_1 should be equal to, or less than, this value, so that AL1 will be an accurate current sink. A digital ammeter, connected in series with the drain of the FET in AL2, is helpful in checking constant current discharge conditions.

Layout is important. In order to suppress spurious signals being generated by the active loads, leads should be kept as short as possible. This is particularly important in testing large capacity lead–acid batteries with pulse discharges of more than 10 A. Also, the equivalent parallel capacitance of some batteries can make the active loads unstable at high discharge currents.

Examination of Leclanché cells using VMOS active loads

Some typical results achieved with the above technique are given in Figs. 3 and 4. Figure 3 shows the response of a 12 V Leclanché battery with a steady discharge current of I_2 = 10 mA, and Fig. 4 shows a similar measurement for a lead–acid SLI battery. In the latter case, the width of the discharge pulse was 1 μs with a repetition frequency of 100 Hz, with the result that the average current drain was low. Polarisation was negligible because of the short pulse width.

An experiment was performed on a size C Leclanché cell to test whether the internal resistance varied as a function of discharge current. Results showed that the internal resistance remained constant for discharge currents in the range 0 - 150 mA.

In other tests, four different size C cells were discharged to 0.75 V at discharge currents of I_2 = 25, 50, 100, and 150 mA, respectively. The

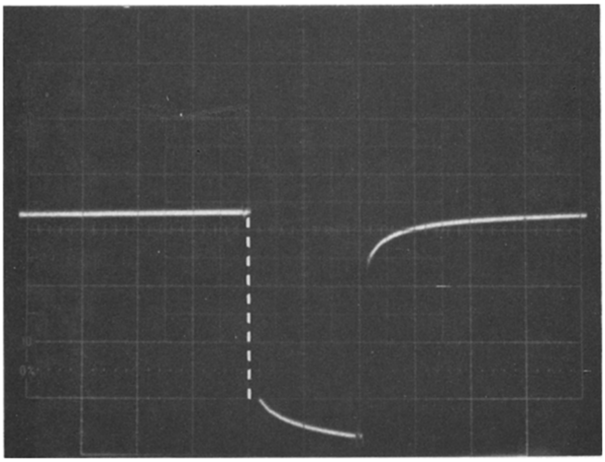

Fig. 3. i_1R_{int} drop (dashed line) for a No. 2582 Leclanché battery discharged at a steady current of I_2 = 10 mA. The horizontal grid scale is 5 μs per division and the vertical grid scale is 20 mV per division, hence the i_1R_{int} drop is 0.067 V. The pulse current was i_1 = 100 mA and the repetition frequency was 10 kHz. Since i_1R_{int} = 0.1 R_{int} = 0.067 V, then R_{int} = 0.67 Ω.

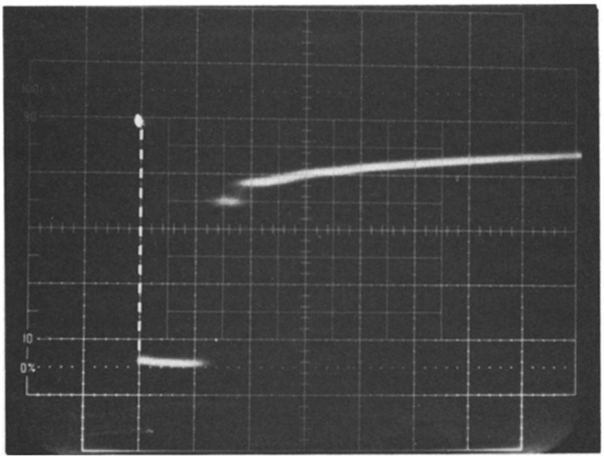

Fig. 4. i_1R_{int} drop (dashed line) for a lead–acid SLI battery with I_2 = 0 A. The horizontal grid scale is 1 μs per division and the vertical grid scale is 5 mV per division, hence the i_1R_{int} drop is 0.22 V. The transfer function of the pulsed active load was changed so that the 1 mV input discharged the battery at 1 A. Here, the pulse current was i_1 = 3 A and the repetition frequency was 100 Hz. Since $i_1 R_{int}$ = 3 R_{int} = 0.22 V, then R_{int} = 0.0733 Ω.

corresponding initial internal resistances ranged from 0.24 to 0.4 Ω. Cell voltages were plotted on a recorder and the i_1R_{int} drop was determined at various times during discharge. Figure 5 shows plots of internal resistance *vs.* discharge time for three consecutive experimental runs. These data were then replotted to show internal resistance *vs.* the capacity discharged from the cells (see Fig. 6).

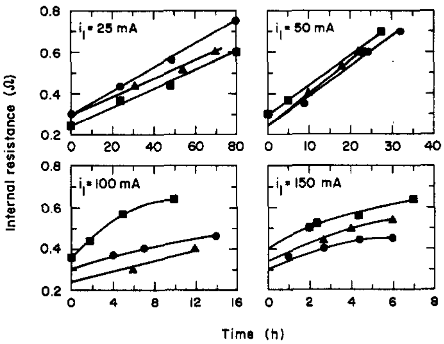

Fig. 5. Plots of cell internal resistance *vs.* discharge time for size C Leclanché cells discharged to 0.75 V at the indicated discharge currents (●, run 1; ■, run 2; ▲, run 3).

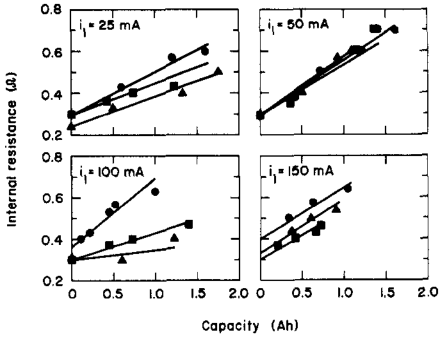

Fig. 6. Plots of cell internal resistance *vs.* capacity for size C cells discharged to 0.75 V at the indicated discharge currents (●, run 1; ■, run 2; ▲, run 3).

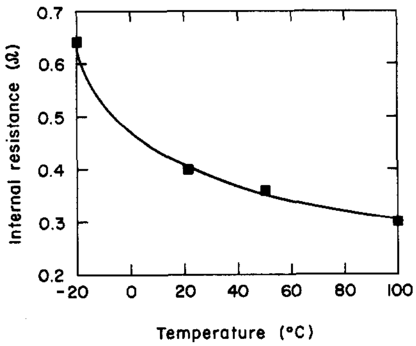

Fig. 7. Plot of cell internal resistance *vs.* temperature for a size C cell discharged at 50 mA continuous. The data were recorded 30 min after discharge at 21 °C.

Further tests confirmed that larger cells have a lower internal resistance. Size D cells had initial internal resistances of about 0.26 Ω, whereas size AA cells had initial internal resistances of about 0.44 Ω.

Finally, the dependence of internal resistance on temperature was determined. Figure 7 was obtained by immersing a size C cell in a temperature-controlled bath and noting the variation of initial internal resistance.

Discussion

The new technique outlined above is ideal for determining battery internal resistance, and it should also be applicable to fuel cells. In studies on Leclanché cells, results obtained with this technique support the findings of Brodd [5], Tvarusko [6], and Sieh [10]. It is possible that earlier investigations [1, 2, 11] include polarisation effects, although it is usually claimed in these papers that the presence of a hydrogen film at the zinc electrode is responsible. Most previous experiments have not discharged cells at a constant current, but rather through fixed resistors, usually 4 Ω. As the cell terminal voltage falls, so does the discharge current.

Recently, published work by Karunathilaka and Hampson [12] has shown that the resistive component of cell impedance is the dominant factor in determining the residual capacity of a cell. Although this was suggested as early as 1963 by Brodd and De Wane [9], an instrument to measure the residual capacity of a Leclanché cell has eluded researchers. From the data presented here, it can be seen that the initial internal resistance of a cell must be known if the residual capacity is to be accurately measured. Also, the residual capacity depends on temperature. A state-of-charge meter based on internal resistance needs this information to achieve sufficiently accurate results.

Acknowledgement

The author is grateful to Dr S. Fletcher for useful discussions.

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