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Journal of Power Sources 64 (1997) 189–192

JOURNAL OF POWER SOURCES

Nonstationary analysis and modelling of battery load performance

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Abstract

A method for the modelling of battery performance under nonstationary load is presented. For the purpose of description of battery dynamic behaviour a new equation with fractal exponent is used. The applicability of the proposed battery model consisting of five parameters, all dependent on the battery state of charge, is demonstrated.

Keywords: Battery modelling; Battery dynamic performance

1. Introduction

The knowledge of nonstationary load performance is of great interest in the assessment of the battery quality. The difficulties of the direct experimental measurement of the nonstationary battery characteristics are related with the complexity of the processes taking place during the discharge.

Most of the electrochemical methods used for battery investigations, such as measurement of the volt–ampere (load) characteristics, capacity determination, impedance spectroscopy, etc., gives information on their properties under stationary conditions. Since the battery state-of-charge is changed during the measurement it is better to use the term quasi-stationary instead of stationary conditions.

In order to evaluate the evolutive quasi-stationary and dynamic properties of the battery studied a special microcycle test is applied repeatedly during the discharge cycle (Fig. 1). The microcycle contains two current steps and a pause followed by a linear sweep segment [1].

2. Experimental

The measurements are carried out on a 140 Ah, 12 V lead/acid traction tubular-type battery using computerized test facility made in the authors' laboratory, CLEPS. The discharge current is 35 A. The test microcycle was applied at every 31 min corresponding to 13% change of battery degree of discharge. The test microcycle profile ensures the same quantity of electricity as in the case of a constant-current discharge for the same time.

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PII S0378-7753(96)02520-7

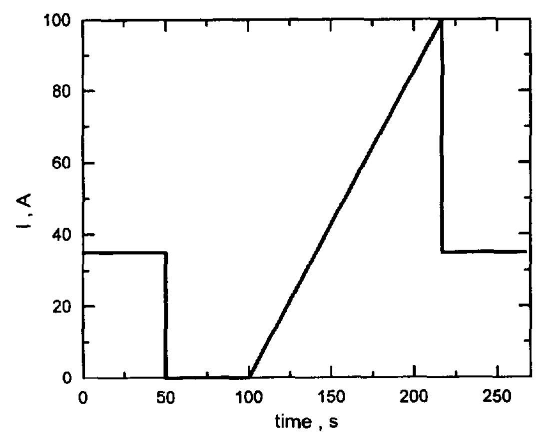

Fig. 1. Profile of the test microcycle.

3. Quasi-stationary analysis

The voltage responses corresponding to the linear current sweeps represent a family of volt–ampere load characteristics, measured at continuously progressing state of discharges (Fig. 2). This data set can be processed by the technique of three-dimensional analysis [1], which takes into account the change of the state of discharge during the measurement. As a result the deviation of s during the measurement is avoided and a new set of instantaneous volt–ampere characteristics is produced. These characteristics can be approximated by linear equations of the following form

$$U(I,s) = U_0(s) - IR(s) \qquad (1)$$

This linear kernel of the approximation contains a reduced open-circuit voltage $U_0(s)$ and an effective internal resistance $R(s)$, both function of s (Fig. 3). As it can be seen from Fig. 3, the open-circuit voltage, U_0, changes slightly

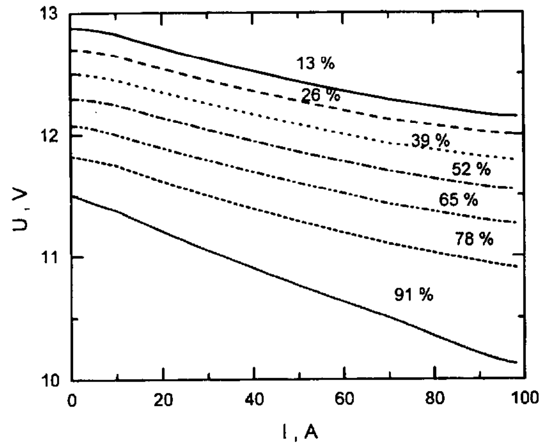

Fig. 2. Measured volt–ampere characteristics at different states of discharge.

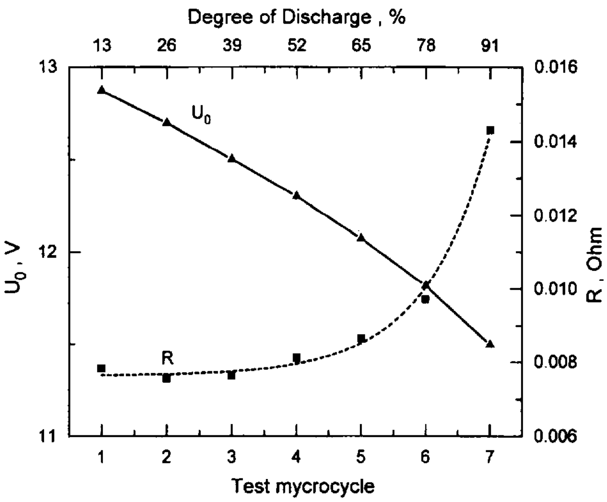

Fig. 3. Dependence of U_0 and R from Eq. (1) on the state of discharge.

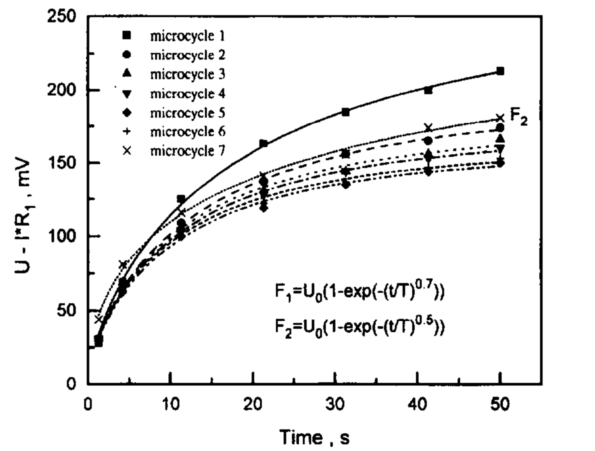

Fig. 4. Voltage relaxation after current step at different states of discharge approximated with function F_1 except microcycle 7 fitted with F_2.

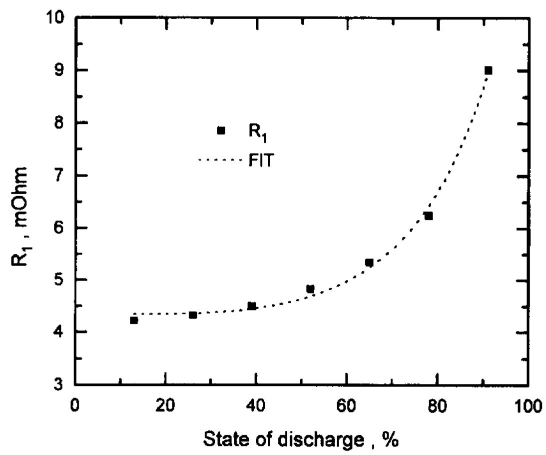

Fig. 5. Dependence of R_1 on the degree of discharge.

with the degree of discharge. Its value decreases with only about 10%, almost linearly with s, while the effective internal resistance, R, depends on the exponential degree of discharge and increases about two times. Nevertheless, this parameter could not be used directly for the estimation of the battery state-of-charge, since there is an initial period of 'activation' during which R decreases. The simple model, see Eq. (1), is an effective tool for modelling and simulation of the quasi-stationary battery performance and its evolution with progressing state of discharge.

4. Dynamic analysis

The dynamic properties depend also on the state of discharge. Fig. 4 represents the voltage responses of the current steps in the microcycles. In order to overcome the difficulties related to the classical analysis of these data a model with fractal exponent is selected

$$\Delta U(s) = U_1(s) + U_2(s)\{1 - \exp[-(t/T(s))^{n(s)}]\} \qquad (2)$$

where t is the time and T is time constant.

Assuming linearity, the voltage transient can be presented as

$$\Delta U(s) = I[R_1(s) + R_2(s)]\{1 - \exp[-(t/T(s)^{n(s)})]\} \qquad (3)$$

where $R_1(s)$ represents the initial voltage step and $R_2(s)$ the total effective relaxation process.

The quality of the fit of Eq. (2) to the experimental data, also processed by a three-dimensional analysis, is quite good and shows stable values of $n = 0.7$, changing only at the end of discharge to $n = 0.5$. It is known from the theory of topochemical reactions that such kind of equations are typical for processes limited by diffusion in the space with a variable dimension [2].

The resistances R_1 and R_2 also depend on the state of discharge. These dependencies could be modelled by empirical equations with the following structure

$$R_1 = -0.36634 + 4.71132 \exp(s^{4.0466}) \qquad (4)$$

$$R_2 = -315.2 - 188.9s^2 + 143.6$$
$$\exp(s) + 167.8 \exp(-s) + 0.6597s^{-1} \qquad (5)$$

where R_i is in mΩ and s is in parts of unity.

These dependencies are shown in Figs. 5 and 6. The dependence of the time constant, T, on the state-of-charge is described by an empirical equation with the following structure

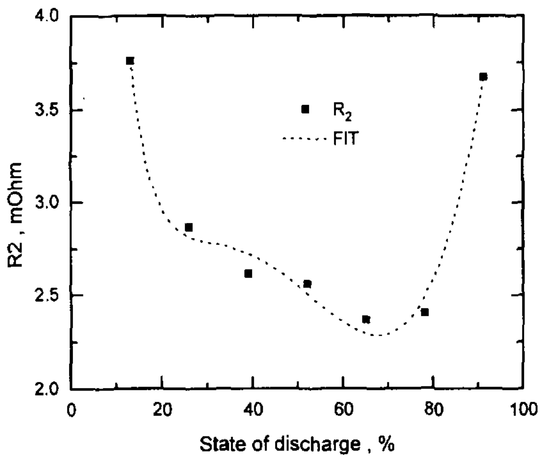

Fig. 6. Dependence of R_2 on the degree of discharge.

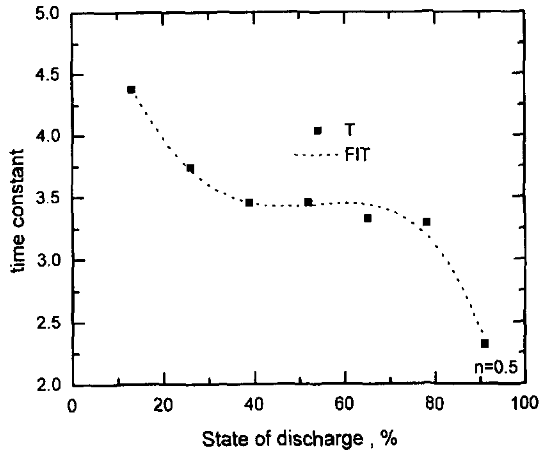

Fig. 7. Dependence of the time constant, T, on the degree of discharge.

$$T = 189.1 + 108.4s^2 - 86.16\exp(-s) - 97.35\exp(s) \quad (6)$$

where s is in parts of unity.

The dependencies of R_2 and T (Fig. 7) on s are quite complex while that of R_1 is relatively simple. Obviously, the value of the resistance R_1 could be used for estimation of the battery state-of-charge.

5. Discussion

The knowledge of the evolution of the parameters with the state-of-charge provides for a simulation of the battery behaviour under loads with different profiles.

The simplest way of battery modelling is the quasi-stationary approach. Quasi-stationary model contains the relation between battery voltage and current (and as a result gives the open-circuit voltage by Eq. (1)) under stationary conditions. Combining it with the so-called 'Ragone' diagram (presenting specific energy versus specific power) it is possible to determine the battery abilities to supply energy under different load profiles. This approximation is based on the assumption of the 'additivity' of the 'Ragone' diagram. This approach is useful for relatively fast comparison of different

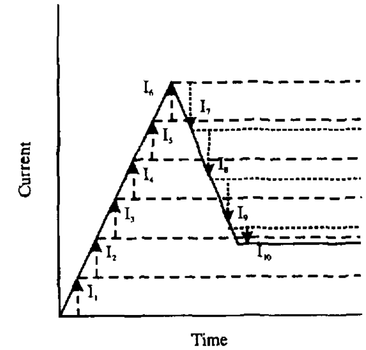

Fig. 8. Replacement of the current profile by a sum of current steps.

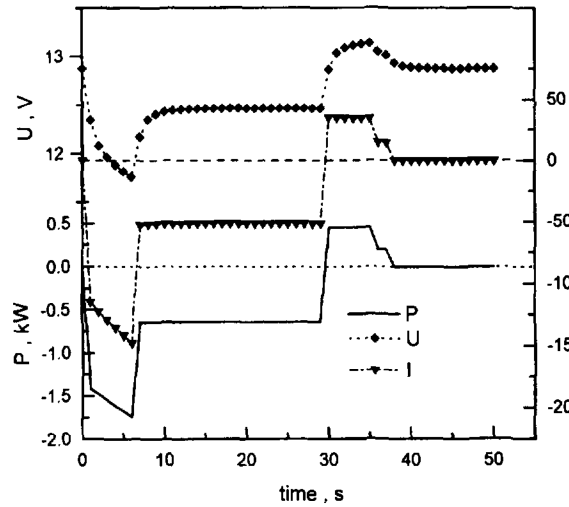

Fig. 9. Simulated values of U and I for the 1 microcycle under plotted load.

batteries without long and expensive experimental work. Unfortunately, this assumption is not really true.

One possibility to avoid this problem is the improvement of the battery model by adding a new dynamic kernel. Assuming linearity of the battery behaviour and following the integral of Duamel cited in Refs. [3,4], each load profile can be presented as a sum of current steps

$$I(t) = \Sigma I_k \quad (7)$$

where I_k are step functions.

This procedure is schematically shown in Fig. 8. The change of the battery voltage, as a function of time, caused by the kth current step can be calculated using the equation with structure similar to Eq. (3)

$$\Delta U_k(t_k,s) = I_k[R_1(s) + R_2(s)]\{1 - \exp[-(t_k/T(s))^{n(s)}]\} \quad (8)$$

Then the overall battery voltage is given by

$$U(t,s) = \Sigma\Delta U_k(t_k,s) + U_0(s) \quad (9)$$

where $U_0(s)$ is the battery open-circuit voltage calculated from the Eq. (1) at the respective state of discharge.

Fig. 9 represents the simulated voltage and current behaviour of the battery studied discharged by a power profile showed in it at 13% degree of discharge.

The evolution of the battery voltage as a function of the degree of discharge under the above load is shown in Fig. 10.

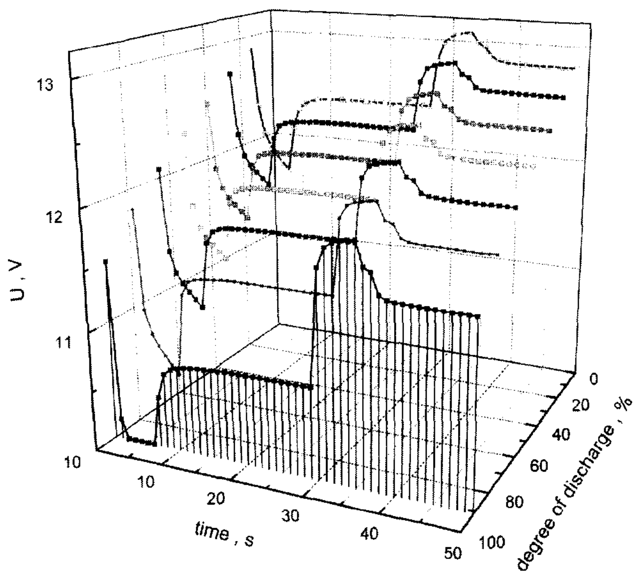

Fig. 10. Simulated voltage evolution during discharge.

It is clear that the open-circuit voltage (the first points of the different curves) changed quite slower than battery voltage under some load (for example the second points of these curves).

In deep-discharge (91%) the battery still can follow the power profile but its maximum cause the battery voltage to fall to about 9 V. Such small levels can cause fast battery degradation. For this reason battery discharge is normally limited to about 10 V for six cells batteries. With this limitation the battery cannot follow the power profile at high degree of discharge (Fig. 10).

6. Conclusions

The battery behaviour under complex load profiles depends on five parameters, each of them being a function of the battery degree of discharge

$$BB[U_0(s),R_1(s),R_2(s),T(s),n(s)] \qquad (10)$$

The above model takes into account not only the stationary characteristics of the battery but its dynamic properties as well.

A special computer software based on Eq. (9) is developed for simulation of electric vehicles batteries studied under different test profiles including standard 'Euro'93' test profile.

Acknowledgements

This investigation is partially sponsored by the National Fund for Scientific Research under contract no. X-425.

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