Journal of Power Sources, 30 (1990) 249 - 254

MODELLING OF THE COLD-CRANKING PERFORMANCE OF AUTOMOTIVE LEAD/ACID BATTERIES

M. T. LOPONEN* and P. JALAS

Neste Oy Technology Centre, Corporate R&D, Physics Research, P.O. Box 310,
SF-06101 Porvoo (Finland)

Introduction

In Northern climates, the cold-cranking (CCA) behaviour of an automotive battery is of primary interest. Therefore, optimization of the cranking properties is required. Also, it is important that the battery properties can be adjusted with regard to the applicable standards such as the SAE, DIN and IEC specifications. The CCA performance of an automotive battery depends on several parameters such as: plate area, thickness and pitch; mass density; separators; grid weight and design.

Models have been published [1 - 4] to allow the calculation of the cold-cranking behaviour of automotive batteries. These models, however, either require quite extensive use of high-power computers or have limitations with respect to the possible geometry of the grids. Although the price of computing has decreased dramatically, the complete optimization of an automotive battery with arbitrary grids using brute-force calculation is still a few years away.

In order to obtain results quickly and with limited calculation, simplified models have been developed. These were compared with full-scale calculated results in order to gain an insight into the drawbacks of the approximations.

The aims of the modelling work were to:

- optimize the grid design and battery construction with regard to the various standard specifications (SAE, DIN, IEC);
- obtain the dependence of cold-cranking performance on various battery parameters;
- compare the properties of active materials manufactured with different production parameters.

Simplified battery model

The main problem in solving the full current/potential equation of an automotive battery during a cold-cranking discharge is the large size of the

---

*Author to whom correspondence should be addressed.

0378-7753/90/$3.50

matrices required. Also, since the current distribution has to be found by repeated iteration during the discharge, the required calculation work is increased by orders of magnitude. Such calculations are by no means impossible, however, and have been performed in the authors' laboratories to assess the simpler model. The feasibility of such work is presently limited by the slowness of the calculation stages.

The basis of the model simplification is the change from the x and y dimensions of the grids to one dimension, the lug-to-lug resistance, R. This is achieved by measuring (or calculating, if working with new grid designs) the resistance maps $R_+(x, y)$ and $R_-(x, y)$ of the grids from the lugs to the (x, y) points. Thereafter, the maps of the positive and negative grids are combined in order to obtain the distribution of (+) lug to (−) lug resistance. This is essentially carried out by integrating $(R_+(x, y) + R_-(x, y))$ over the grid area as a function of R. The distribution of capacity as a function of R, thus obtained, can be divided into suitable steps, corresponding to lug-to-lug resistance intervals R_i, from R to $R + \Delta R$. Each of these steps has a corresponding capacity, C_i. Thus, a one-dimensional model is set up for the battery, with capacities C_i coupled to each other via effective grid elements with a resistance ΔR. Solving the current/potential equations for such a simple system can be done readily, even with a personal computer.

Unfortunately, the approximation does not exactly reproduce the true effect of the grid. Thus, the rest of the battery data cannot be taken from first principles, but must be fitted to the model so that the measured cold-cranking curves can be reproduced. This is essentially the case with the remaining internal resistance of the battery, namely, that in the electrolyte and the active masses.

With regard to the dependence of the cell potential on the depth of discharge (DOD), it was found that the relation used earlier [1] was not sufficiently accurate at lower voltages. Thus, a more complex empirical formula was adopted (the voltage was assumed to drop with the eighth root of (1-DOD), although there is, of course, no theoretical justification for this dependence). With this approach, a more accurate reproduction of the discharge curves was possible down to 6 V.

The cumulative decrease of the DOD as a function of the capacity discharged is calculated with the power-law dependence of the capacity *versus* current. This reproduces the observed decrease in the capacity at higher currents. Also, when the plate dimensions are changed, the effect of the cold-cranking behaviour can be taken into account.

Advanced model

Although the simplified model described above yields reasonable fits to the measured data with minimal calculation effort, it suffers from certain inherent drawbacks. One is the limitation to existing grid geometries, where the resistance maps can be measured and only weight can be scaled up or down during the calculation. A more serious problem is the over-emphasis of the grid resistance, which requires too low values for the other resistances in the battery to be used in the calculation.

In order to get a more realistic picture of the cold-cranking behaviour of a battery, we have developed a more exact model in which the actual grid resistances are used. The situation is, in practice, complicated by the conical shape of modern grids. Consequently, the nodes in the positive and negative grids do not correspond to each other.

In practice, the solution of the complete battery equation with about 400 × 400 matrices requires such a lengthy computation time that it is not feasible without efficient mainframe computers or workstations. Although the situation is rapidly changing, it may take a couple of years before automotive battery optimization with complete equations for arbitrary grids becomes routine.

Combination of the models

There is a possibility of combining the accurate calculation with the simplified model in order to obtain both the speed and precision required. Although the solution of the complete electrochemical and ohmic equations for the battery cannot be obtained in a reasonable time to simulate the full discharge as a function of time, it is relatively easy to calculate the resistance map of any grid.

The remaining problem is to eliminate the over-emphasis of the grid resistance. This is best done by calculating the average voltage drop in the grid at a small current and by scaling down the grid resistance in the simplified model accordingly. The other resistances that have been used as fitting parameters so far can now be scaled up to their real values.

Thus, the combined model yields an efficient means of analyzing both the CCA performance of an arbitrary battery (with arbitrary grids) without developing one, and determining the resistance in the active material from the fit of the model and the measured battery curves.

Modelling results

As an example of the use of the model, a 95 min reserve capacity battery (Super Power 854) was fitted to the model. The grid resistance maps from the grid to the lug were measured, and the lug-to-lug resistance distributions were determined at steps of 0.5 mΩ. The parameters in the equation describing the discharge voltage as a function of current and DOD were then determined so that the discharge curve at 200 A was produced. As shown in Fig. 1, the discharge curves at higher currents (up to 500 A) are also produced with high accuracy.

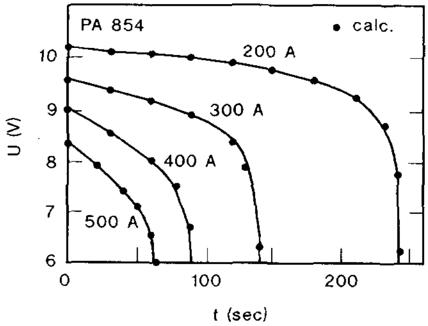

Fig. 1. Comparison of measured and calculated discharge curves of the Pakkasakku Super Power 854 battery.

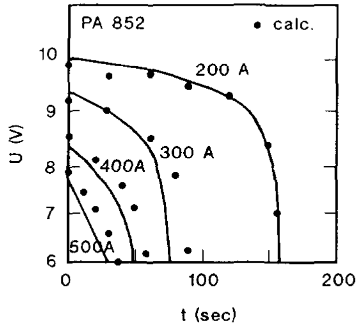

Fig. 2. Comparison of measured discharge curves of Pakkasakku Super Power 852 battery with those calculated from the model using the parameters obtained from the fit to the Super Power 854 battery (see Fig. 1) and the ratio of the plate areas in these two batteries.

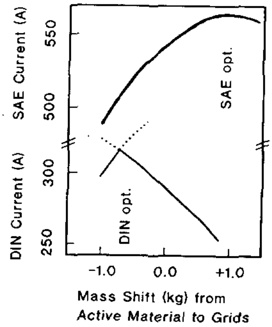

Fig. 3. Results from *simplified* model concerning effect of changes in mass distribution in Pakkasakku Super Power 854 battery. SAE and DIN cold-cranking currents are given as a function of mass shift of active material to the grids.

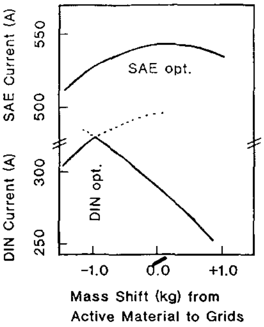

Fig. 4. Results from *combined* model concerning effect of changes in mass distribution in Pakkasakku Super Power 854 battery (Fig. 3). Average resistance due to grids is calculated exactly, and resistance distribution is scaled accordingly. This model yields a much broader optimum for SAE cold-cranking current. Both SAE and DIN optima are reached with somewhat lighter grids than in simplified calculation of Fig. 3.

As a further test, the model was applied to another battery, Super Power 852, that had 9 plates per cell instead of 11 in Super Power 854. It was found that the duration of the cold-cranking discharge at relatively small currents (typically 200 A) can be expressed as a function of the effective active-mass volume and area. The calculations were based on the fit to the Super Power 854 data and the ratio of the plate areas. The fit is still reasonable, as shown in Fig. 2.

As an example of possible ways to utilize the model, we show in Fig. 3 the results of calculations where lead is moved from the active mass to the grids, keeping the total weight of the battery constant. Both the SAE and DIN ratings for CCA are shown. The result is as expected, *i.e.*, better (heavier) grids benefit the SAE CCA rating, whereas the optimum for the DIN cold-start current is at heavier active material, that is, at higher capacity. These results have been calculated, however, with the simplified model that has too great an emphasis on the grid resistance. If the average grid resistance is taken from the exact calculations and the resistance distribution is scaled accordingly, the results shown in Fig. 4 are obtained. It can be seen that now the SAE and DIN optima are reached with somewhat lighter grids than predicted by the simplified model. Also, the SAE optimum is much broader. Actually, the battery appears to be rather well optimized with regard to the SAE specification. The DIN optimum would be reached for about 1 kg lighter grids and heavier active material.

Conclusions

It is possible to develop models for automotive batteries that yield results following limited calculations. Thus, the effect of various modifications to the battery performance can be estimated approximately, even with a PC computer. Exact calculations, with full matrix equations describing the potential distribution in arbitrary grids, will be possible only after reductions in the price of computing.

The calculations discussed here show, as expected, that optimum DIN cold-cranking currents are obtained with a smaller ratio of grid weight to active-material weight than in the case of the SAE optimum. Using this battery model, it is thus possible to optimize automotive batteries with regard to the required performance.

References

1 W. G. Sunu and B. W. Burrows, *J. Electrochem. Soc.*, *129* (1982) 688; *131* (1984) 1.
2 H. Gu and T. V. Nguyen, *J. Electrochem. Soc.*, *134* (1987) 2953.
3 E. C. Dimpault-Darcy, T. V. Nguyen and R. E. White, *J. Electrochem. Soc.*, *135* (1988) 278.
4 Y. Morimoto, Y. Ohya, K. Abe, T. Yoshida and H. Morimoto, *J. Electrochem. Soc.*, *135* (1988) 293.