

## TEMPERATURE CONTROLLED FORMATION OF LEAD/ACID BATTERIES

M. BUNGARDT

*Digatron Industrie-Elektronik GmbH, Templehofer Strasse 12, 5100 Aachen (F.R.G.)*

### Summary

At present, standard formation programs have to accommodate the worst case. This is important, especially in respect of variations in climatic conditions. The standard must be set so that during the hottest weather periods the maximum electrolyte temperature is not exceeded. As this value is defined not only by the desired properties and the recipe of the active mass, but also by type and size of the separators and by the dimensions of the plates, general rules cannot be formulated.

It is considered to be advantageous to introduce limiting data for the maximum temperature into a general formation program. The latter is defined so that under normal to good ambient conditions the shortest formation time is achieved. If required, the temperature control will reduce the currents employed in the different steps, according to need, and will extend the formation time accordingly. With computer-controlled formation, these parameters can be readily adjusted to suit each type of battery and can also be reset according to modifications in the preceding processing steps. Such a procedure ensures that:

- (i) the formation time is minimum under the given ambient conditions;
- (ii) in the event of malpractice (e.g. actual program not fitting to size) the batteries will not be destroyed;
- (iii) the energy consumption is minimized (note, high electrolyte temperature leads to excess gassing).

These features are incorporated in the BA/FOS-500 battery formation system developed by Digatron. The operational characteristics of this system are listed in Table 1.

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### Introduction

Whenever possible, the initial charging of lead/acid batteries should be conducted directly after their assembly. The increasing market for maintenance-free automotive batteries, and similar products in the industrial field, has opened further possibilities for formation procedures. However, irrespective of process history or the intended application, the problems to

TABLE 1

## Advantages of BA/FOS-500 computer-controlled formation system

*Save up to 20% electrical energy*

- Saves energy by eliminating overcharging of batteries. Companies often build in unneeded 10% contingency factor.
- Avoids using energy during peak-rate periods.
- Charging circuits can be loaded and started at a pre-determined time to avoid peak-power rates.
- Peak-power rate penalties can be avoided by energy-load management.
- The energy alarm signal can come from either the energy company telephone or an in-plant alarm.
- When energy cutback is required, partially formed plates (*i.e.*, less than 50% charged) are saved by not reducing current to those plates. The energy reduction is applied only to plates that are sufficiently formed.

*Save as much as 15 - 30% on formation time*

- Charge batteries for only the minimum required amount of time.
- No unnecessary charging for contingencies or unknowns.
- Since up to 45 steps can be programmed in a formation schedule, the optimum charging curve can be established. This saves time when compared with a two- or three-step charging program.
- Avoid damage by overheating of plates or batteries. Optional thermocouple probe senses and feeds back signals to the charger to terminate runaway formation step. Formation program automatically advances to next step. It has been reported that as many as 10% of batteries have been damaged in a typical battery plant.

*Production management*

- Immediate knowledge of which circuits are ready, or soon to be ready, for formation disconnection and reloading.
- Computer summarizes formation program station.
- Available idle circuits are easily identifiable on the computer screen.
- Individual circuit control is standard, not an option. Competitive systems use four circuits, thus giving less flexibility.

*Record management*

- Printed records of formation data are available.
- Recorded data can be analysed to improve formation program.
- Recorded data can be given to customers to assure quality.
- Recorded data provide supporting information for warranty claims. It is even possible to review files of other batteries produced at same time, or with same program, to determine the extent of potential warranty liabilities.

*Battery distribution management*

- Inventories of available batteries are immediately known for shipment to customers.
- Inventory overstocking can be eliminated.
- Delivery forecasts to customers can be made accurately. Rush orders can be promised and met.

*Reliability*

- Uninterrupted formation — should host computer go down, or be removed from the system, memory devices built into the rectifier's interface keep the system operational.
- Multiplex system design not used. There is no device between host computer and formation rectifier. Failure of a multiplex unit could put many circuits out of operation resulting in the possible loss of hundreds of batteries.

*(continued)*

TABLE 1 (continued)

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- IBM Personal Computer model AT, or clone computers, are used. Low maintenance compared with larger process computer used in other systems. Expensive service contracts not required.

*Production proven software*

- Software is user friendly — software does not need to be customized at the factory.
- Simple to use — no programming knowledge necessary.
- Software does not need to be returned to factory for customizing.
- Program features battery terminology.

*Flexibility*

- As an OEM, interfaces are built into new Digatron rectifiers.
  - Almost all existing rectifiers can be retro-fitted.
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be solved during formation are essentially the same. The jar formation of automotive batteries might be taken as a typical example. The process is complicated and involves the parallel operation of a large number of independent circuits. For process optimisation, the partly conflicting goals are: (i) full battery power according to specification; (ii) lowest possible energy consumption; (iii) shortest possible formation time; (iv) high reliability of the system.

Since all batteries should show full cranking-power and full capacity, the formation process should effectively even out any variations in either the starting materials or the production steps. Differences in the quality of the leady oxide, in the physicochemical characteristics of the cured plates, and in the types of separators being used, all present problems in the manufacture of automotive batteries.

The time required for battery formation should be kept to a minimum, otherwise there would be an increase in both the number of charging circuits and the space requirement. Good electrochemical efficiency, and effective dissipation of both heat and acid fumes, represent one set of objectives, suitable  $\alpha$ -PbO<sub>2</sub>/ $\beta$ -PbO<sub>2</sub> phase chemistry in the formed plates represents another set. Such contradictory requirements need compromise. The optimum formation conditions are not the same for all types of batteries.

This paper describes a formation system developed by Digatron that is applicable to a wide variety of batteries and has easy access, good reliability, and precise temperature control. The latter is especially important in tropical climates.

## The temperature problem

### *Scientific background*

For simplicity, consider first the end of formation when virtually all the current is used for evolution of hydrogen and oxygen. With a charging current equivalent to the 20 h rate, each cell exhibits an overvoltage close to 1.5 V which may be represented as:

$$C_{20}R_1 = 30 \quad (1)$$

where:  $C_{20}$  represents the nominal capacity at the 20 h rate and  $R_i$  the internal resistance. The energy is converted into heat:

$$Q_f = I^2 R_i \quad (2)$$

where:  $I$  = charging current. This energy has to be removed from the battery to the surrounding air:

$$Q_e = \frac{dT}{dt} a C_{20}/c \quad (3)$$

where:  $dT/dt$  represents the temperature gradient,  $a$  the heat capacity (approx.  $0.35 \text{ W h kg}^{-1} \text{ K}^{-1}$ ), and  $c$  the specific capacity ( $\sim 15 \text{ A h kg}^{-1}$ ). The temperature gradient can be represented by the ratio of the temperature difference between electrolyte,  $T(\text{bat})$ , and air,  $T(\text{air})$ , and a time constant,  $\tau$ , representing the overall heat-transfer coefficient. Thus, eqn. (3) becomes:

$$Q_e = \frac{T(\text{bat}) - T(\text{air})}{\tau} a C_{20}/c \quad (4)$$

At equilibrium, the heat generated inside the battery is equivalent to that transferred to the surroundings, *i.e.*,

$$I^2 R_i = \frac{T(\text{bat}) - T(\text{air})}{\tau} a C_{20}/c \quad (5)$$

Using the approximate values given above and eqn. (5):

$$T(\text{bat}) - T(\text{air}) = 1.3 \times 10^3 \tau (I/C_{20})^2 \quad (6)$$

or by taking

$$I_{20} = C_{20}/20 \text{ and } I = a I_{20}$$

eqn. (6) simplifies to:

$$T(\text{bat}) - T(\text{air}) = 3.2 \tau a^2 \quad (7)$$

This relationship can be used to obtain information about the time constant for each type of battery. However, the value is not very reliable because of the approximations that have been made for the parameters.

The next step is to consider the situation where the formation is not fully complete and electrochemical transformation of lead sulfate to  $\text{PbO}_2$  and lead is still taking place. The effective internal resistance is then much smaller. For example, at a state with a voltage per cell ( $U_i$ ) of 2.40 V, a charge current of  $4I_{20}$  and no visible gas evolution, it can be assumed that the open-circuit voltage ( $U_o$ ) is 2.1 V and:

$$C_{20} R_i = (2.40 - 2.10) \times 20/4 = 1.5. \quad (8)$$

This value is much lower than that for the gassing state (*cf.* eqn. (1)) and, therefore, batteries may be charged with high currents as long as the voltage is low, *i.e.*, below the gassing voltage.

When gassing consumes a minor, but still significant, part of the total current, a mixed potential exists. As a fairly good approximation, the voltage difference can be used to determine the heat evolved, *i.e.*, for each cell:

$$Q_f = (U_t - U_o)I \quad (9)$$

At this non-equilibrium state, the temperature increase is given by:

$$dT/dt = (Q_f - Q_e)c/(aC_{20}) \quad (10)$$

Substituting  $Q_f$  and  $Q_e$  by the expression given in eqns. (9) and (4), respectively, yields:

$$dT/dt = (U_t - U_o)Ic/(aC_{20}) - \frac{T(\text{bat}) - T(\text{air})}{\tau} \quad (11)$$

In principle, all parameters in eqns. (10) and (11) can be determined experimentally, but in practice the procedure is very complicated. While the first term uses data which can be assumed with sufficient accuracy to be applicable to all types of automotive batteries, the value of  $\tau$  in the second term is very sensitive to design and overall size.

### Control process

A universal value of  $\tau$  is required for temperature control. This can be seen by the following discussion.

Instead of the time constant,  $\tau$ , an average value for temperature equalization of the batteries might be assumed to be  $6 \text{ K h}^{-1}$ . If, for example, the temperature increase is measured as  $2 \text{ K h}^{-1}$ , then the ohmic heat evolution is equivalent to  $8 \text{ K h}^{-1}$ . In order to avoid further increase in the battery temperature, the control unit should reduce the heat evolution by:

$$100 \times 2/(2 + 6) = 25\% \quad (12)$$

Using Ohm's law and eqn. (1):

$$I_{\text{new}}/I_{\text{old}} = (6/(2 + 6))^{1/2} = 0.87 \quad (13)$$

But Ohm's law is not valid in electrochemical processes; rather, the Tafel equation should be used:

$$U - U_o = p \times \lg(I/I_o) \quad (14)$$

which means, the new relative power losses  $[6/(2 + 6)]$  are:

$$6/(2 + 6) = (I_{\text{new}}/I_{\text{old}}) \times (U_{\text{new}}/U_{\text{old}}) \quad (15)$$

If  $p$  was a constant and universal value for the lead/acid battery, then it would be a simple matter to employ a computer to conduct iterative calculations with the logarithms and have a 'perfect' current adjustment. Unfortunately  $p$  is not only different for the chemical transformation and gassing reactions but is also different for the positive and the negative plates. Thus,

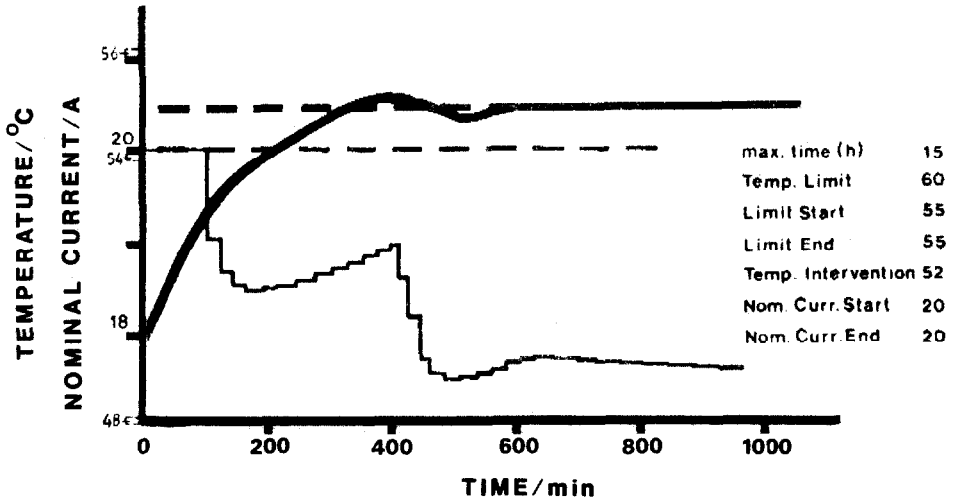


Fig. 1. Operation of BA/FOS-500 battery formation system.

all that can be achieved is to determine whether the square-root function of eqn. (13) is sufficiently accurate.

In the heat evolution expression given by eqn. (14), only the overvoltage (*i.e.*, the difference between actual and open-circuit voltages) need be considered. As  $p$  is between 100 and 200 mV, the actual current is at least one order of magnitude higher than the exchange current,  $I_0$ , except in the initial stage where the overvoltage is low when starting the formation with low currents.

In the first stage of formation, most of the heat is evolved by the chemical reaction of the active mass with the electrolyte:



The overvoltage is low, and reducing the current may cause an over-proportional response in the overvoltage. This means an over-reaction compared with Ohm's law and is exactly what is needed because the chemical reaction includes heat evolution as well as the Ohmic losses.

Later on in the formation process, the overvoltage will increase and the chemical reaction will become negligible. This is the stage in the formation where temperature problems may exist. The evolution of heat rises again when gassing accounts for a significant proportion of the current. At this point, the overvoltage will be high and the voltage response to change in the current will be under-estimated. This means that the control unit will not reduce the current to the required extent. In practice, this is not a problem, provided the temperature control reacts before a preset maximum temperature is reached. Under the conditions, a stepwise reduction in the current will result in a stepwise reduction in the temperature gradient leading asymptotically to zero, as shown in Fig. 1.