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Improvement of intelligent battery controller: state-of-charge indicator and associated functions

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Abstract

A few hundred electric vehicles have been field tested by 'Electricité de France' for several years. Most of them are equipped with valve-regulated lead/acid batteries. It is well known that the battery is the weak element of electric vehicles. Analysis of operation problems during field tests and laboratory investigations has led to the consideration that this situation could be improved by the use of an efficient battery-management system. An on-board management device has been developed with the Intelligent Electronic Systems company. Commercialized under the name Intelligent Battery Controller (IBC), its main features are: rapid and normal charge monitoring, data recording, state-of-charge indication and help for maintenance. First prototypes produced up to now have no state-of-charge indication. The battery management during driving was limited to the indication of charge/discharge Ah, and orange and red alarms related to deep depth-of-discharge. The upgraded version presented here is mainly characterized by a state-of-charge indicator that is corrected for temperature, rate of discharge, and ageing of the battery. © 1997 Elsevier Science S.A.

Keywords: Gauge; State-of-charge; Battery management; Electric vehicle; Lead/acid batteries

1. Introduction

To improve the service quality of its fleet of several hundreds electric vehicles, 'Electricité de France' (EDF) has initiated a study with a view to producing an on-board battery-management system. This automatic device, developed in co-operation with the French company Intelligent Electronic Systems (IES) and designated Intelligent Battery Controller (IBC), was the subject of a publication in 1995 [1].

Designed for management of valve-regulated lead/acid (VRLA) batteries, today's application is particularly applicable to batteries comprised of 6 V, 160 Ah modules. The main functions of this system are the following: data storage of measurements carried out on the battery, control of an on-board charger for normal charging, control of an external charger for fast charging at *C* rate, 'orange' and 'red' end-of-discharge alarms, identification of faulty battery cells.

The initial version of the IBC was not fitted with a gauge; it only displayed a simple count of Ah. Moreover, to avoid reversal of cells at the end of discharge, the polarization of all modules of the battery was measured and compared with a threshold viewed as characterizing incipient reversal. A 'red alarm' was triggered when this threshold was reached, to indicate that further discharge could be detrimental to the service life of the battery. Since the appearance and meaning of this alarm is quite abrupt, it was decided to have it preceded by an 'orange alarm', triggered upon a polarization threshold equal to about half the red alarm threshold. Appearance of the orange alarm indicated that the batteries retained only a few percent of capacity before triggering of the red alarm; the latter was a mandatory stop signal.

These two alarms constitute a very basic rough approach to a gauging function. Analysis of operation has shown that the reserve of energy framed by the two alarms was not constant. As expected, variations of this value

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were mainly attributable to current variations but, also, to other parameters, notably, the heterogeneity of capacity of the cells. The concept of the function designated G_3 in this article is based on this observation.

2. Organization of the gauge

The gauge displays a value that is decremented according to the number of Ah discharged and estimates of the remaining available capacity of the battery. The available capacity is corrected by means of three gauge functions that are based on different principles. The reliability of these three gauge functions varies differently during the course of discharge, the impact on calculations is weighted during discharge according to the respective reliability.

During charge, i.e., before the start of discharge, the energy available in the battery is calculated according to the maximum possible performance of the battery and its state of recharge. The gauge is then initialized at the start of discharge, according to the energy available in the battery. The gauge display indicates 100 when the battery is fully charged and its estimated performance corresponds to nominal. When the estimated performance of the battery is degraded, for example because of ageing or when its temperature is low, the gauge indicates a value smaller than 100 at the start of discharge, even if the battery is fully charged. On the other hand, the gauge may display a value in excess of 100 if the estimated available energy is higher than nominal.

During the first part of discharge, which corresponds to about 30% of usable capacity, it appears that polarization measurements are not sufficiently sensitive and reliable to enable interpretation. Accordingly, corrections of residual capacity estimates are solely based on measurements of temperature and discharge rate, by means of an algorithm that is designated 'gauge function G_1'.

During the second part of discharge, polarizations of the cells are higher and their measurements are more reliable. Correlations between polarization, discharge current and charge status are high enough to be usable. Two values are significant during this second part of discharge: (i) polarization of the weakest cell, i.e., the one that displays the highest polarizations; (ii) the difference in polarization between the weakest cell and the strongest cell. The algorithm associated with the first value is designated 'gauge function G_2' and that associated with the second value is designated 'gauge function G_3'. The estimates obtained through these two algorithms are used, together with the estimates from G_1, for correction of residual capacity. In a first stage, G_2 is more reliable that G_3. In a second stage and up to the end of discharge, G_3 progressively overcomes G_2. On stopping, the display is modified according to the duration of the pause and to the temperature variations taking place during the pause.

As soon as charging starts, the sum total of Ah discharged previously and the latest estimate of residual capacity are used to evaluate the maximum possible performance of the battery during the forthcoming discharge.

3. Calculation of the value displayed by the gauge

The value displayed by the gauge is termed G herein. This value is decremented through a method based on Ah metering. CE is the initial capacity, i.e., the capacity available at the start of discharge, estimated by the gauge according to the past performance of the battery, its state of recharge, and its temperature. An estimated residual capacity, termed CER, is calculated from the start of discharge through decrementation of Ah:

$$CER = CE - \Sigma\text{Ah} \quad (1)$$

where ΣAh is the sum total of Ah discharged since the start of discharge. The gauge display is proportional to CER:

$$G = G_0 \times CER/CE \quad (2)$$

where the initial value displayed by the gauge, G_0, is the ratio in percent between CE and a reference capacity that corresponds to full discharge of the battery in the new condition at 30 °C temperature and at the usual mean rate of discharge of the electric vehicle. In the application discussed here, the batteries have 160 Ah nominal capacity at the 5 h discharge rate and a reference capacity in the order of 125 Ah.

Such operation translates into uncertainty that increases during discharge. Gauge error often reaches unacceptable values during the final part of discharge, when the electric vehicle user requires an accurate indication of the energy remaining in the battery.

The gauge is characterized by re-estimating the residual capacity periodically during discharge, through another method, simultaneously with calculation of the value of CER used for the gauge display. This new estimate, termed CER_N, is the weighted sum total of estimates CER_1, CER_2 and CER_3 carried out by three gauge functions based on different principles. The respective weighting coefficients are P_1, P_2 and P_3. The following calculation is carried out at each step of 1 Ah:

$$CER_N = P_1 \times CER_1 + P_2 \times CER_2 + P_3 \times CER_3 \quad (3)$$

This new estimate CER_N is compared with the estimate of CER during use for calculation of the gauge display. If the difference exceeds a given threshold, set to 2% in the current version, CER assumes the value of CER_N. This operation, depicted at point I of Fig. 1, gives a new slope of decrementation of Ah. Calculation of the gauge display is then carried out as follows:

$$G = G_i \times (1 - (\Sigma\text{Ah} - \Sigma\text{Ah}_i)/CER_i) \quad (4)$$

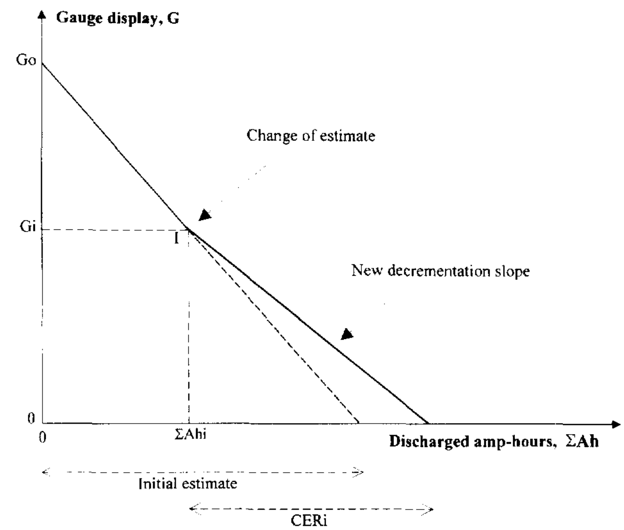

Fig. 1. Variation of gauge display G and impact of correction of residual capacity estimation. At point I the new estimate of residual capacity CER_1 translates into adoption of a new gauge decrementation slope according to the number of Ah discharged.

where G_i is the value of G at the moment when the value of $CERN$ is taken into account; $\Sigma \mathrm{Ah}_i$ is the value of ΣAh at point I; CER_i is the value of CER_N at point I.

3.1. Gauge function G_1

This function calculates residual capacity CER_1 through application of rate and temperature corrections to CER:

$$\Delta CER_1 = CER \times k_r \times k_\theta - CER$$

where k_r and k_θ are rate and temperature correction coefficients, respectively.

These corrections are added up from the last time G took into account a new estimation of residual capacity CER_i. Calculation of CER_1, at time t, is then carried out as follows:

$$CER_1 = CER + \Sigma_{t_i \to t}(CER \times (k_r k_\theta - 1)) \quad (6)$$

In order to carry out rate corrections, a mean discharge current is calculated at a frequency that increases with the depth-of-discharge. Each new value of this mean current is compared with the value calculated previously; Δi is the difference between these two values. The discharge rate correction coefficient is calculated by means of an equation:

$$k_r = 1 - \Delta i a(1 - G/G_0) \qquad \text{if } \Delta i > 0 \quad (7)$$

or

$$k_r = 1/(1 + \Delta i a(1 - G/G_0)) \qquad \text{if } \Delta i < 0 \quad (8)$$

where a is a coefficient that depends on the battery type. In the present application, $a = 0.0058$.

The temperature difference, $\Delta\theta$, between two successive calculations is defined similarly. The temperature correction coefficient is calculated as follows:

$$k_\theta = 1 + \Delta\theta(b + cG/G_0) \quad (9)$$

or

$$k_\theta = 1(1 - \Delta\theta(b + cG/G_0)) \quad (10)$$

according to the sign of $\Delta\theta$ and depending whether the measured temperature is higher or lower than 30 °C, and where b and c are parameters, whose value depends on the temperature range. Temperature correction stops are implemented when the measured temperature exceeds 50 °C. A temperature alarm is triggered at 60 °C.

3.2. Gauge functions G_2 and G_3

Algorithms G_2 and G_3 are initiated when both the value of ΣAh is more than 5% of the reference capacity of the battery and the residual capacity CER drops below 80% of this same reference capacity. The measurements used are the current i and the voltages $U_{[j]}$ of the various modules that constitute the battery. Voltage measurements are filtered according to the discharge current value, i.e., only voltage measurements that correspond to a discharge current situated between two given values are taken into account. In the present application, these two values are 70 and 130 A.

The mean voltage, over 5 Ah, of each battery module, $U_{\mathrm{moy}[j]}$, is calculated first. Then,

$$U_{\mathrm{ref}[j]} = U_{\mathrm{moy}[j]} + 0.25 \quad (11)$$

The values $U_{\mathrm{ref}[j]}$ calculated for each module are stored and constitute voltage references to which voltages measured subsequently will be compared.

The following are calculated every 20 measurements, i.e., every 4 s:

(i) for each module $[j]$:

$$\Delta U_{[j]} = U_{\mathrm{ref}[j]} - U_{[j]} \quad (12)$$

(ii) for gauge functions G_2 and G_3:

$$G_{2_t} = \left(i^{0.7}/\mathrm{Max}(\Delta U_{[j]})\right) \quad (13)$$

$$G_{3_t} = \left(i^{0.5}/\left[\mathrm{Max}(\Delta U_{[j]}) - \mathrm{Min}(\Delta U_{[j]})\right]\right) \quad (14)$$

The mean values of G_{2_t} and G_{3_t} are then calculated over 10 Ah, and used as initial values for exponential smoothing of G_{2_t} and G_{3_t}. The smoothed values are termed $G_{2\mathrm{liss}_t}$ and $G_{3\mathrm{liss}_t}$, respectively:

$$G_{2\mathrm{liss}_t} = 0.06(G_{2_t} - G_{2\mathrm{liss}_{t-1}}) + G_{2\mathrm{liss}_{t-1}} \quad (15)$$

$$G_{3\mathrm{liss}_t} = [(\Sigma \mathrm{Ah}_t - \Sigma \mathrm{Ah}_{t-1})/3](G_{3_t} - G_{3\mathrm{liss}_{t-1}}) + G_{3\mathrm{liss}_{t-1}} \quad (16)$$

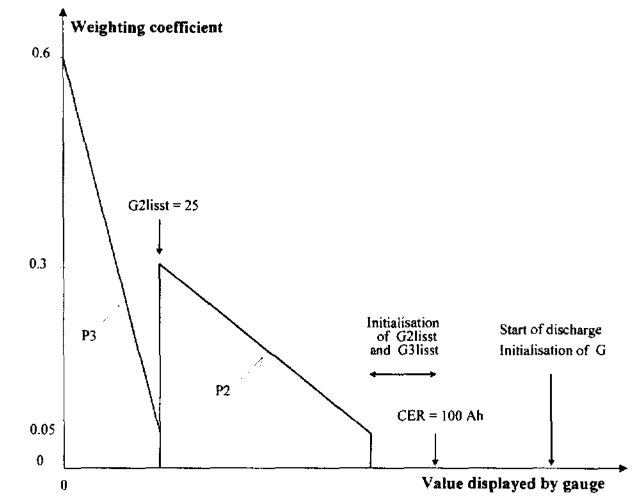

Fig. 2. Variation of weighting coefficients P_2 and P_3 assigned to corrections of residual capacity estimates by gauge functions G_2 and G_3. Weighting coefficient P_1 for corrections of gauge function G_1, not shown in this chart, is the complement to one, i.e., $P_1 = 1\text{-}(P_2 + P_3)$.

The residual capacity estimate CER_2 is calculated at each step of 1 Ah:

$$CER_2 = (G_{2liss_t} - 15)(\Sigma \mathrm{Ah}_t - \Sigma \mathrm{Ah}_{t0})/(G_{2_{t0}} - G_{2liss_t}) \quad (17)$$

where $\Sigma \mathrm{Ah}_{t0}$ is the value of $\Sigma \mathrm{Ah}$ at the first calculation of G_{2liss_t}, and $G_{2_{t0}}$ is the first value of G_{2liss_t}.

Estimation of residual capacity CER_3 starts when G_{2liss_t} becomes smaller than 25. Calculation of CER_3, carried out at each step of 1 Ah, is similar to that of CER_2 except for the initialization values:

$$CER_3 = (G_{3liss_t} - 10)(\Sigma \mathrm{Ah}_t - \Sigma \mathrm{Ah}_{t0})/(G_{3_{t0}} - G_{3liss_t}) \quad (18)$$

where $\Sigma \mathrm{Ah}_{t0}$ is the first value of $\Sigma \mathrm{Ah}$ when G_{2liss_t} becomes smaller than 25, and $G_{3_{t0}}$ is the first value of G_{3liss_t} when G_{2liss_t} becomes smaller than 25.

3.3. Variation of weighting coefficients (see Fig. 2)

At the start of discharge, the residual capacity estimate CER is only corrected by gauge function G_1. The values of the correction weighting coefficients are as follows until gauge functions G_2 and G_3 start to act: $P_1 = 1$ and $P_2 - P_3 = 0$.

The weighting coefficients are modified as follows from the first calculation of CER_2 on

$$P_2 = 0.05 + 0.25[(G_{t0} - G)/(G_{t0} - 20)] \qquad P_1 = 1 - P_2 \text{ and } P_3 = 0 \quad (19)$$

where G_{t0} is the value of G at the first calculation of CER_2.

Gauge function G_3 takes over from G_2 when G_{2liss_t} reaches a value of 25. The weighting coefficients then become:

$$P_3 = 0.6 - 0.55(G/G_{t0}) \quad (20)$$

$$P_1 = 1 - P_3 \text{ and } P_2 = 0$$

where G_{t0} is the value of G at the first calculation of CER_3.

3.4. Pause time

Pauses during a discharge are taken into account to estimate the associated gain of capacity. This gain is calculated according to a decreasing exponential function of time. It also depends on the value G displayed by the gauge. Variation of temperature during the pause is also taken into account to carry out the correction. Accordingly, a pause may have a positive or negative impact on the vehicle range depending on its duration and on the associated temperature variation.

4. Battery ageing and associated functions

4.1. Consideration of ageing by the gauge

The loss of performance associated to ageing of the battery is taken into account through evaluation of its effective capacity at each charge/discharge cycle. This effective capacity is evaluated and stored for discharge at 30 °C and at the reference rate. A new value is calculated at the start of each charge, based on the value stored previously and on the behaviour of the battery during the last discharge. Indeed, at the end of discharge, an evaluation of total capacity of the battery can be obtained through adding the Ah discharged $\Sigma \mathrm{Ah}$ and CER. The result thus obtained is all the more reliable as the value displayed by the gauge at end of discharge is lower. Correction of the stored capacity is thus weighted at each cycle according to the value displayed by the gauge at the end of discharge. This new stored capacity, when temperature corrected, gives value CE which is used to initiate the gauge.

4.2. Gauge variations during charges

The capacity value stored is used for evaluation of the maximum available capacity that can be expected at the end of charge. During charging, the gauge indicates a value that depends on the value displayed at the end of the preceding discharge, on the capacity value stored, on the number of Ah charged and on the temperature. As the battery ages, reduction of the capacity value stored causes the gauge to display a value smaller than 100 at the end of charge. This indication informs the user about the degree of degradation of the performance of the battery.

4.3. Specific electric treatments

IBC carries out two types of electric treatment automatically, whenever required. The first of these is a specific charge complement and the second is a controlled deep-discharge at low current. When performance losses are not irreversible, these treatments enable the battery capacity to be restored to an adequate value, often close to that when new [2].

Charge complement is carried out in a fully automatic way, transparently for the user. Its maximum duration is 6 h. This procedure can be interrupted at any time without any detrimental consequence, for instance when the vehicle is to be used. The decision for implementation of this charge complement is based on two criteria: a given number of cycles — such as 50 — or a performance loss level. Behaviour of the battery is analysed during this treatment and the results of this analysis are used to modify the capacity value stored and, thus, the value displayed by the gauge at the start of discharge.

Deep-discharge at low current is used when the charge complement treatment is not sufficient to restore acceptable battery performance. This procedure is lengthier than the preceding one and cannot be interrupted. It requires immobilization of the vehicle for about 36 h. Because of this constraint, an authorization to proceed is requested when the IBC estimates that such a treatment is needed. The user can then wait for an appropriate time, such as a weekend, to grant this authorization. As in the case of charge complement, the measurements carried out during this operation lead to modification of the stored capacity value. After a deep-discharge treatment, priority reverts to the charge complement treatment in the event of a drop in performance.

4.4. Management of faulty modules

When these two types of treatment do not properly restore battery capacity, the module(s) to which loss of performance is attributable is(are) stated as 'to be replaced' by the IBC. In this case, the gauge disregards the behaviour of the weakest module. This results in an increase of the values displayed by the gauge and into loss of power at the end of discharge, and communicates the fact that the weakest module is no longer protected against polarity reversals by the gauge; this weakest module is then deemed as being lost. As long as the faulty modules have not been replaced, the IBC displays a message that identifies the modules to be replaced and indicates their respective level of performance loss.

5. Conclusions

The gauge described in this study has required two years of research, in co-operation with the Montpellier II University. It will be fitted to the IBC versions to be marketed in 1997. Two gauge-associated functions, not described in this article, are nearing completion and should also become operational within a few months. These functions are detection of faulty connection elements and thermal management of the battery.

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