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Integral condition monitor for valve-regulated lead–acid batteries

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Abstract

A battery condition monitor is described that can be integrally mounted within a valve-regulated lead–acid (VRLA) battery. The device continuously monitors battery voltage, temperature and elapsed time. These parameters are processed to identify the status of the battery in terms of charge, discharge or resting modes. The state-of-charge is determined based on voltage and temperature measurements taken during resting periods, when the battery components adequately approach equilibrium conditions. The resulting whole-life record, built from the integration of instantaneous readings, is compared with a simple life model, based on the number and the depth of the discharges performed. Laboratory tests and ongoing field trials indicate that this approach can provide cost-effective and convenient monitoring of VRLA batteries in specific types of application.

Keywords: State-of-charge; Lead–acid battery; Cyclic application; Monitor; Valve-regulated; Golf trolley

1. Introduction

In many cases, the only available indication that a battery has reached the end of its useful life is when it fails to perform its intended purpose. To the user, the effects of this situation can range from inconvenient to life-threatening, depending on the application. Often, the replacement of the battery is a distress purchase that may result in the use of an inappropriate battery or an unduly expensive one. A variety approaches to the modelling of battery life have been proposed [1]. Because of the range of failure modes and the very diverse operating conditions of lead–acid batteries, a generally applicable model is necessarily complex. In many consumer applications, the processing power required to calculate remaining life based on a continuous supply of information would require hardware and software development that would presently be cost-prohibitive. To avoid this complexity, the mobility type of cyclic application, for example with a wheelchair, scooter or golf trolley, was chosen to test the feasibility of life monitoring. In this case, the battery is discharged relatively frequently and charged soon after use. This mode of use can be reproduced quite closely in laboratory conditions and values for battery life based on the number and the depth of the discharges are published in product literature. Typically, battery life, in cycles, reduces as the depth-of-discharge (DoD) increases, see Fig. 1. A major part of the work reported here has been to test whether the values indicated in Fig. 1 are valid for duties that consist of cycles of varying DoD in discontinuous, stop–start operations.

The choice of parameters to be measured to characterize the battery and its mode of operation was strictly limited by cost considerations. Two of the most useful features are measurement of current flow [2] and impedance [3,4]. These have been proposed by other workers. Nevertheless, to achieve useful resolution of these characteristics, in all operational modes, we consider such approaches to be prohibitively expensive for consumer applications. Thus, minimum parameters selected to provide the data for the cycle-life model were voltage, temperature and time.

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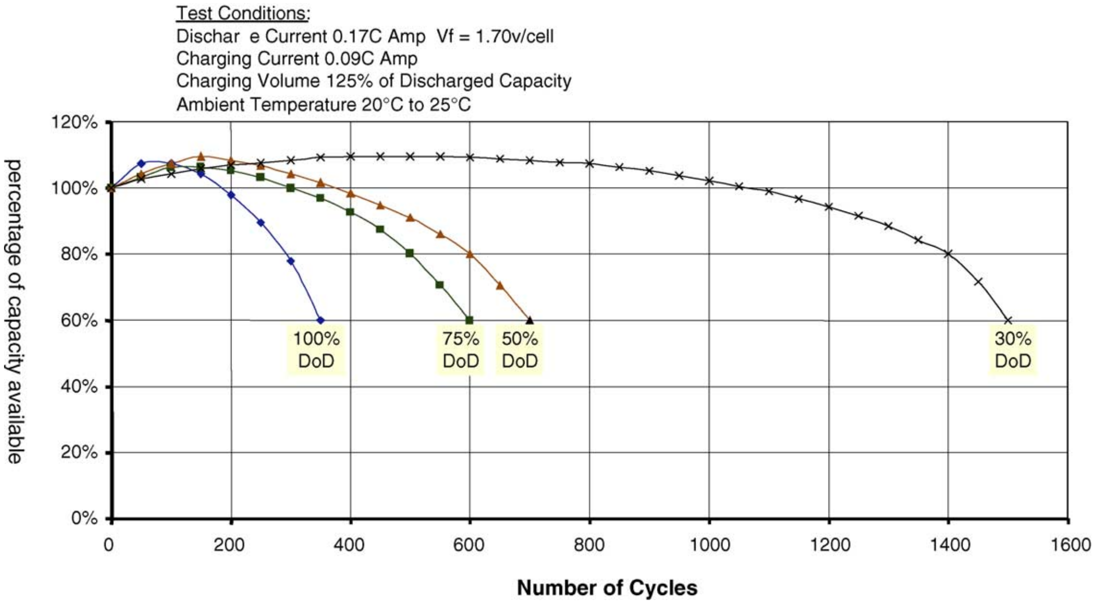

Fig. 1. Published cycle-life in relation to depth-of-discharge.

2. Experimental

2.1. Definition of duty cycle

An electrically-powered golf trolley was taken as a convenient example of a cyclic application. The unit was powered by a 24-Ah 12-V valve-regulated lead–acid (VRLA) battery, to move the trolley and golf bag. Measurements of terminal voltage and discharge current were measured during 18-hole rounds of golf using a portable data logger (Data Electronics Pty Ltd.; Datataker model 505). This information was used to define a pattern that could be simulated in the laboratory, Fig. 2. A simplified version of the duty cycle was developed based on an initial high current discharge, to simulate breakaway and acceleration, followed by decreasing current steps for steady motion and deceleration, Fig. 3. Three versions of this duty cycle were employed and used different current values to simulate changes in payload weight and

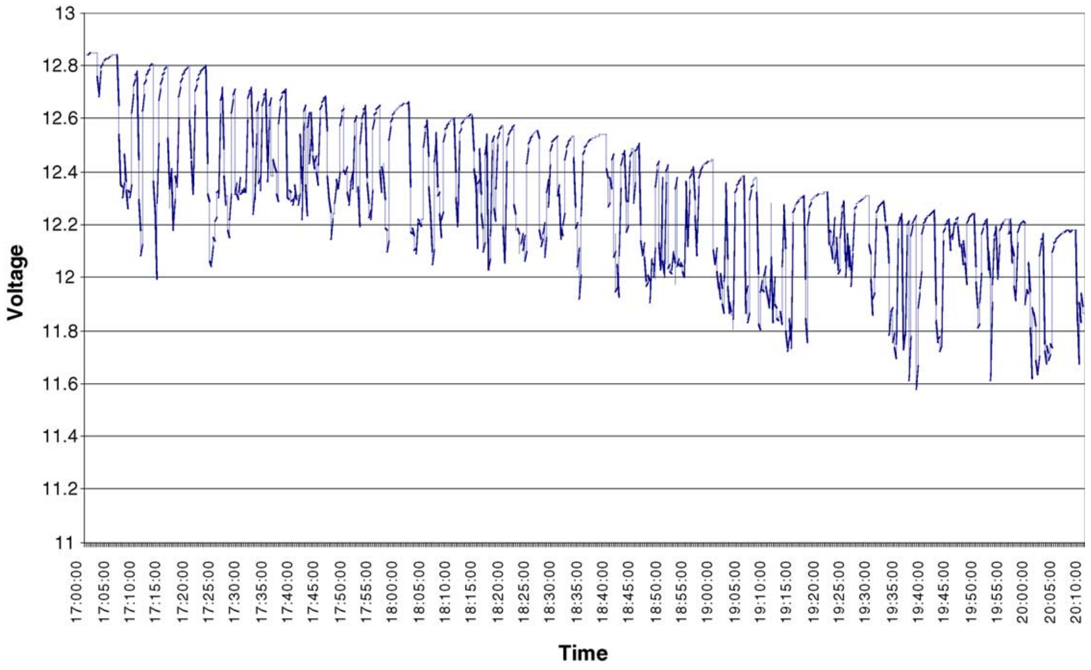

Fig. 2. Battery voltage profile during a round of golf.

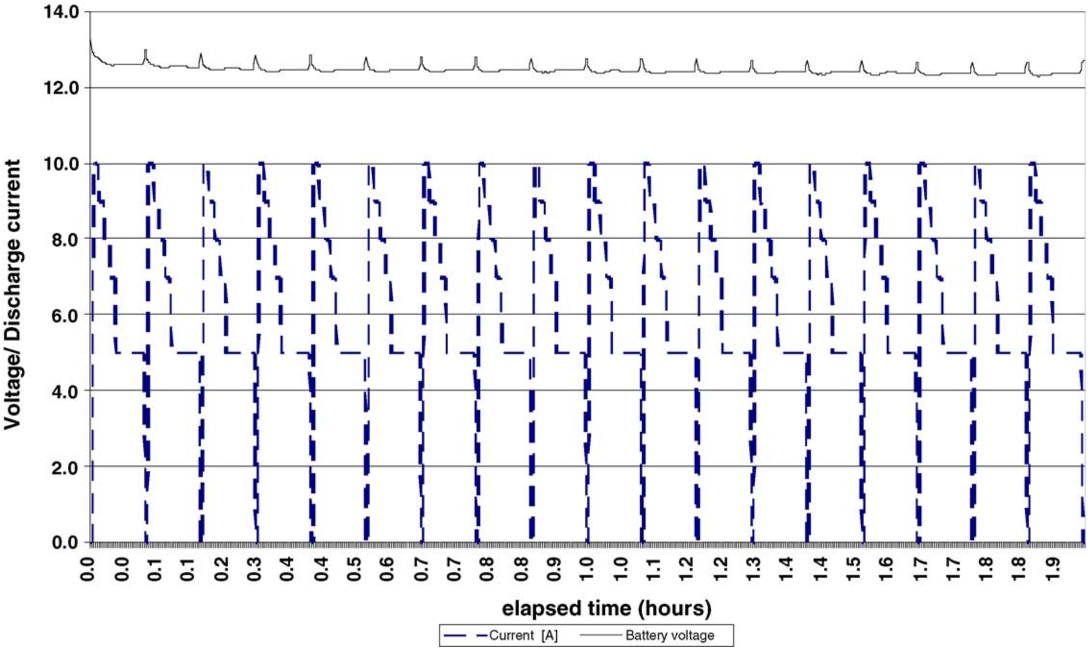

Fig. 3. Laboratory discharge cycle giving 20% DoD.

course steepness that can lead to variations in battery DoD at the end of a round. The individual discharge schedules were designed to give about 20, 40 and 60% DoD, respectively, during discharge periods of 2.5 h (Table 1).

A period of 30-min rest was applied at the end of each discharge pattern, during which the battery monitor identified the battery state-of-charge (SoC). The batteries were recharged using a current limit of 6 A and a voltage maximum of 14.7 V for a period of 9 h. This allowed two charge–discharge cycles to be performed each day. The different cycles were applied in three permutations (Table 2), which provided average DoDs over 10 cycles of approximately 40, 40 and 60%, respectively.

Table 2
Cycle permutations at single or mixed DoDs

Cycle no.	Type 1 uniform 40% DoD cycle	Type 2 mixed 40% DoD cycle	Type 3 uniform 60% DoD cycle
1	B	B	C
2	B	C	C
3	B	B	C
4	B	A	C
5	B	C	C
6	B	B	C
7	B	A	C
8	B	C	C
9	B	B	C
10	B	A	C

2.2. Monitor construction and connection

The battery monitoring employed a micro-controller chip with 10-bit analogue-to-digital conversion configured to provide a measuring resolution of 10 mV in an operating range from 8 to 18 V. Temperature measurement, timing and memory facilities were included in the single device. This was mounted within a recess in the battery lid, prior to battery

Table 1
Discharge–charge cycles based on stop–start applications for three different DoDs

Step type, duration		Cycle A	Cycle B	Cycle C
1	Discharge, 5 s	10 A	20 A	30 A
2	Discharge, 5 s	9 A	18 A	27 A
3	Discharge, 5 s	8 A	16 A	24 A
4	Discharge, 5 s	7 A	14 A	21 A
5	Discharge, 150 s	5 A	10 A	15 A
6	Pause, 230 s			
7	Perform 1–618 times			
8	Pause, 30 min			
9	Charge, 9 h	6 A to 14.7 V limit	6 A to 14.7 V limit	6 A to 14.7 V limit
	Discharge capacity	4.6 Ah	9.6 Ah	13.8 Ah

assembly, and potted in transparent epoxy resin. Connecting leads were passed through the lid and attached to the positive and negative terminals of the battery to provide power to the electronic circuit and act as the voltage measuring channel for the monitor. The SoC was indicated by a series of light emitting diodes (LED) numbered from one, full charge, to eight, zero charge. These were used to record the DoD after each cycle in field trials. More detailed information, stored within the device memory, was transmitted to a data reader via a serial interface at intervals during the testing programme.

2.3. Laboratory testing conditions

For each test, two 24-Ah, 12-V VRLA batteries were connected in series and attached to a programmable charge–discharge controller (Digatron BTS500) that was capable of performing the cycles defined above in Section 2.1. The temperature was maintained at 20 ± 2 °C throughout the tests. At intervals of 50 cycles, the schedule was interrupted and a capacity test performed at 18 A to 1.5 V pre cell (0.75C rate).

2.4. Field testing conditions

A 24-Ah, 12-V VRLA battery was provided to each of 18 users of electrically-powered golf trolleys. The players were based in locations throughout the UK and were chosen to represent a wide range of different modes of use, i.e., frequency of use, course conditions, ability and trolley weight, that may affect the form of the duty cycle. Each battery contained the integral monitor described above in Section 2.2.

The player was supplied with a record sheet to log use of the battery to show the DoD at the end of the round, date and duration of use, and the charging period between rounds. This information was used to check the accuracy of the data recorded within the monitoring device, and was monitored at the beginning of the trial and then after 6 months and 12 months of use. The recording is continuing through the life of the batteries.

The capacity of the field trial batteries has been measured, at the six monthly intervals, with a portable discharge unit (Astratech model 39). This is a fan cooled resistor load bank with a resistance of 0.6 Ω and allows discharges to be performed at similar rates to the laboratory tests to an end point of 1.5 V per cell.

Between rounds, the battery was recharged by means of the commercial charging unit provided with the golf trolley. The unit had a maximum output of 4 A with a voltage limit of 14.7 V. The charger maintained the battery at the 14.7 V level for 8.5 h after reaching this maximum level, and then reduced its output to 13.8 V that was maintained until the charger was disconnected. The standard instruction to players is to keep the battery on charge at all times while not in use. This is to ensure that the battery is kept at a high SoC, in the absence of any other means to confirm this status.

3. Theory/calculation

3.1. Mode identification

For the purposes of identifying the number and depth of the discharges throughout the life of the battery, it was sufficient to identify only two types of battery status, namely, the charging mode and the open-circuit mode. When a charging mode was identified, this marked the end of a cycle and signalled the life account to be updated. The charging mode was identified by setting a voltage threshold within the monitor, and at a level that could only be attained when the battery was connected to the charger.

The open-circuit mode was detected based on the rate of change of the voltage at the battery terminals. The slope, of voltage versus time, decays exponentially when current ceases to flow within the battery. This is mainly due to the diffusion of sulfuric acid within the electrodes and separators, that acts to achieve a uniform distribution of electrolyte concentration. When a uniform distribution of electrolyte is achieved, the SoC can be calculated from the voltage at the battery terminals. Even where small discharge currents continue to flow, an acceptable indication of the SoC can be achieved because diffusion rates are sufficiently great to prevent a significant shift from equilibrium.

In mobility applications, the discharge current is rarely uniform for long periods. This accentuates the voltage changes, which are observed under discharge conditions in lead–acid batteries, and clarifies the distinction between discharge and open-circuit modes.

3.2. State-of-charge calculation

The state of charge of a lead acid battery is directly proportional to the equilibrium open circuit voltage (OCV) over most of its charge range. The actual slope and intercepts of a plot of SoC versus OCV (Fig. 4) depends upon the design parameters of a particular battery type. Most significant of these parameters are the strength of sulfuric acid in the fully-charged state and the ratio of positive, negative and acid active-material contents. In this investigation, the relationship of SoC to OCV was determined empirically, by discharging a battery in stages of 2 h duration at I_{20} current. Between each stage, the battery was allowed to rest for 12 h before the OCV was recorded.

The SoC–OCV relationship was stored in the memory of the battery monitoring device in the form of a look-up table. The basic relationship was determined at 20 °C. The battery temperature was measured continuously by the monitoring device and a factor of $0.2\,\mathrm{mV\,K^{-1}}$ per cell was applied to the measured voltage readings before the SoC was calculated [5]. This was considered to be an acceptable approximation as the typical DoD in field trials was in the 40–60% range.

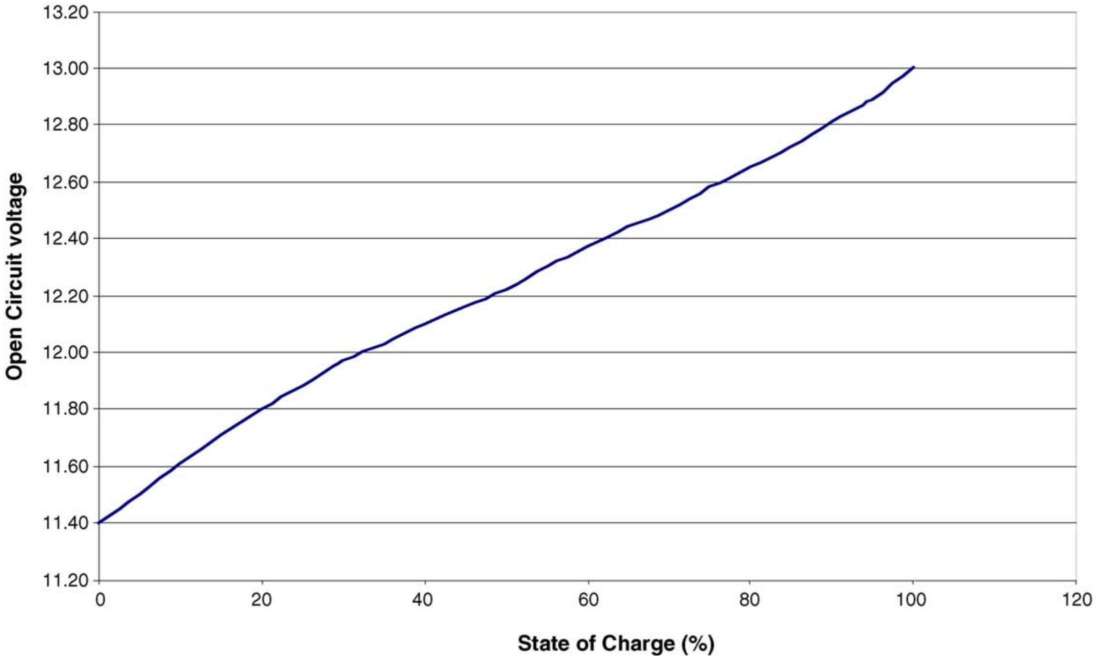

Fig. 4. Relationship of open-circuit voltage to state-of-charge for NPC type battery.

3.3. *Life account calculation*

The memory of the monitoring device was initialized at the first time of applying power with a value of 65,536 units as a life account. As each cycle of discharge and charge is identified during the life of the battery, the value of this account was reduced. The size of each debit was calculated, based on the SoC value most recently written to another location within the micro-controller, during periods of open-circuit. For the field trial, the debit values were interpolated from the published cycle lives (Fig. 1), and stored as a look-up table for use within the monitoring algorithm.

4. Results

4.1. *Laboratory cycle simulation*

The change in capacity of six test batteries, during simulated golf-round cycling, is shown in Fig. 5. The calculated

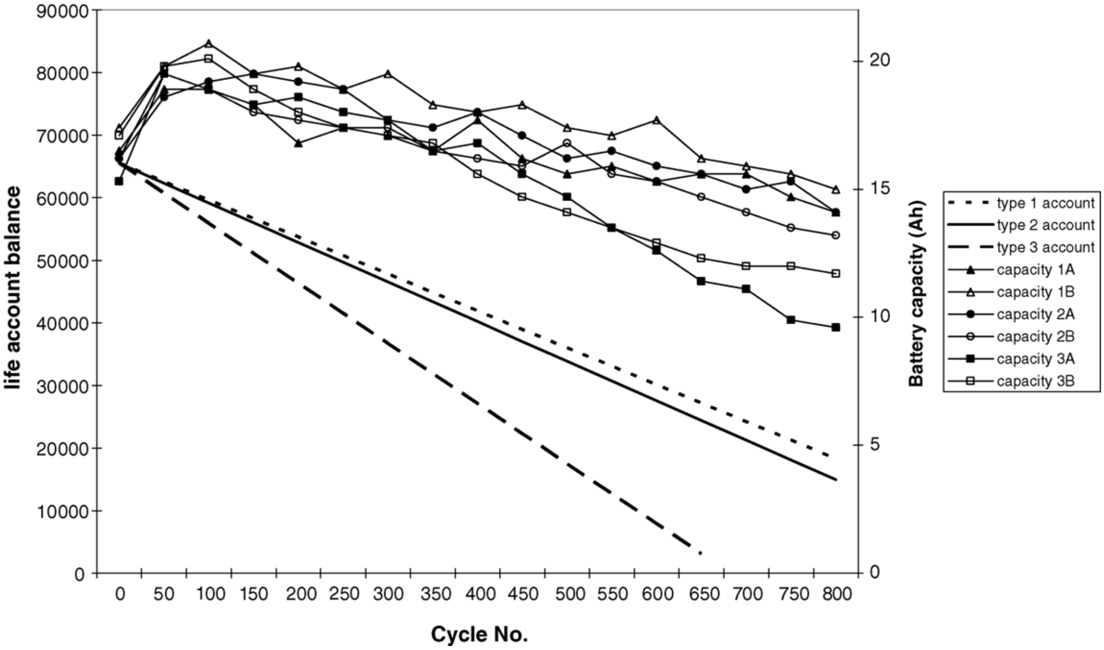

Fig. 5. Laboratory cyclic performance compared with calculated life-account values.

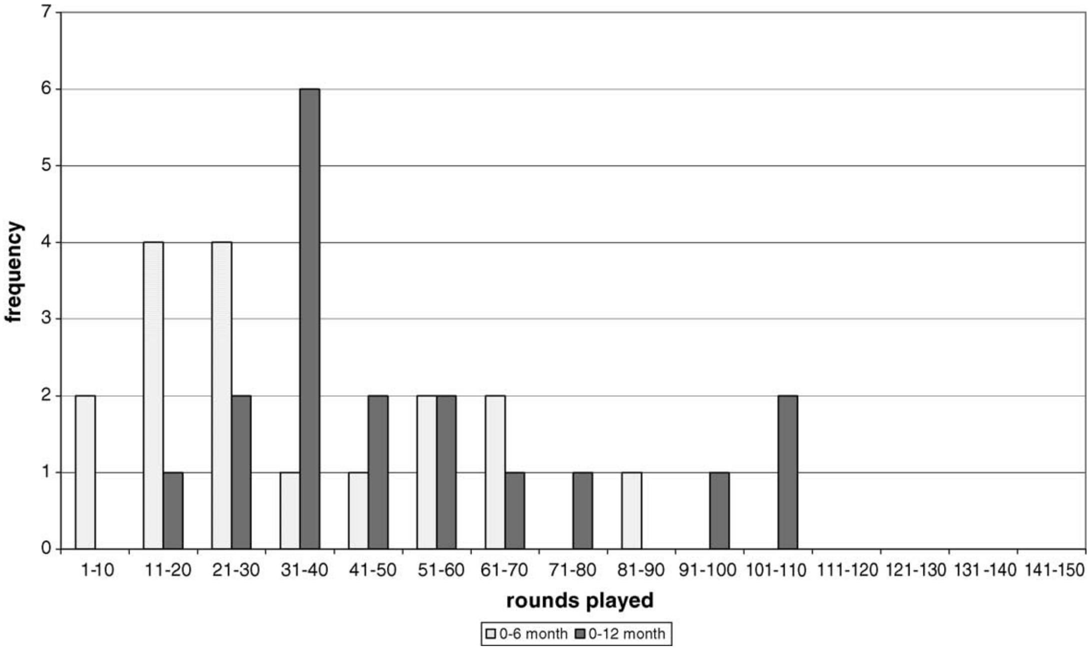

Fig. 6. Distribution of discharge cycles performed during first 6 and 12 months of service.

progression of elapsed life is also plotted. The uniform and mixed cycling regimes, giving the same average discharge of approximately 40% DoD, yield a different calculated life progression. This is because the relationship between cycle life and DoD is exponential rather than the linear averaging used in the schedule selection. In practice, the performance of the batteries exhibit enough variation to make the difference in capacity evolution between the mixed and uniform tests indistinguishable.

The batteries on the 60% DoD cycle showed a faster reduction in capacity, as anticipated. The results of this trial indicate that the stop–start form of discharge does not sig-

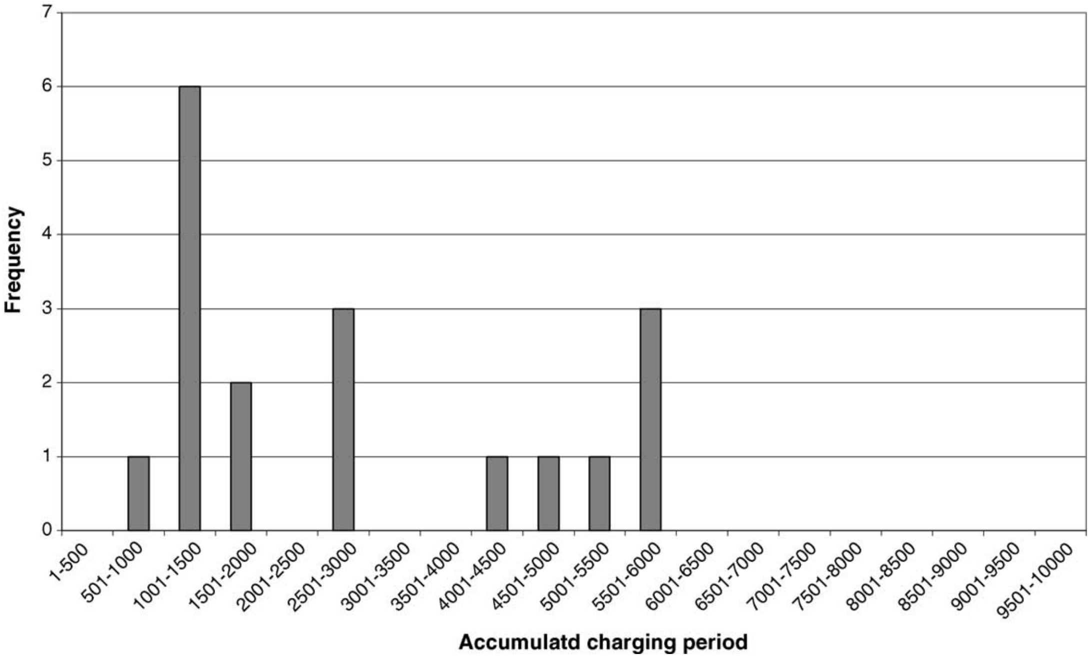

Fig. 7. Distribution of accumulated charging time during first 12 months of service.

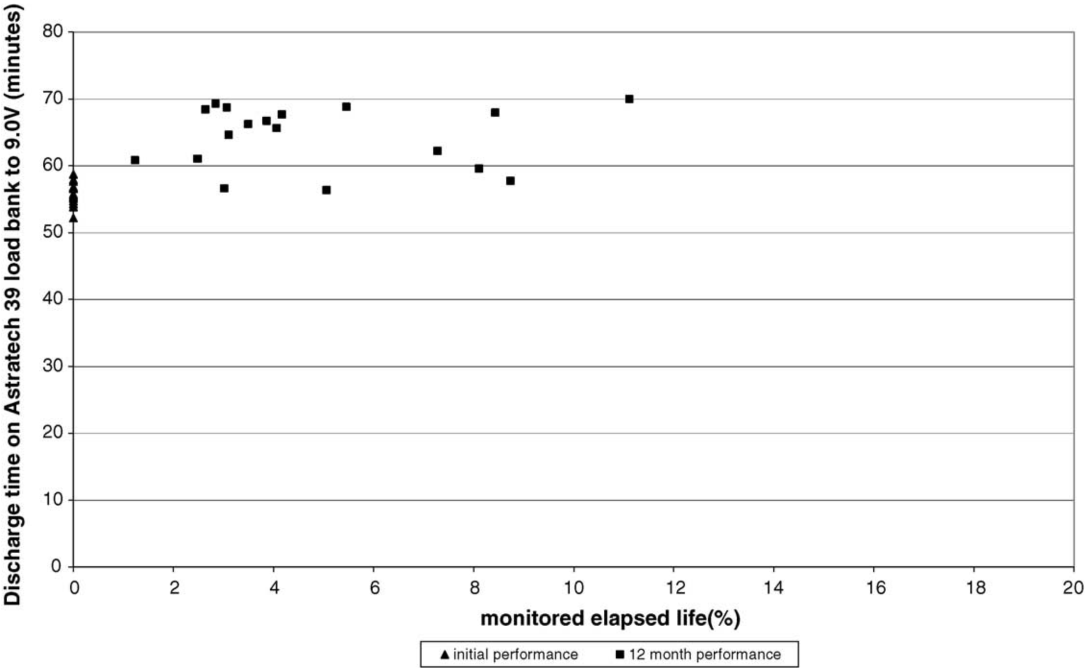

Fig. 8. Change in discharge performance during first year of service vs. elapsed life based on recorded cycle service.

nificantly affect the validity of the published cycle data that was used to program the battery monitoring device used in the field trials.

4.2. Variability in electric trolley application

The most striking difference between the laboratory simulations and field trials is the far greater variability in conditions of use found in the latter. The number of discharges performed in 6- and 12-month periods are presented in Fig. 6. The data show a 10-fold variation from the minimum to maximum usage. In all cases, the frequency of use was much lower than that assumed for laboratory simulations.

Another major source of variation was the charging period of the batteries. The users manual for the trolley recommends that the batteries are left attached to the charger when not in

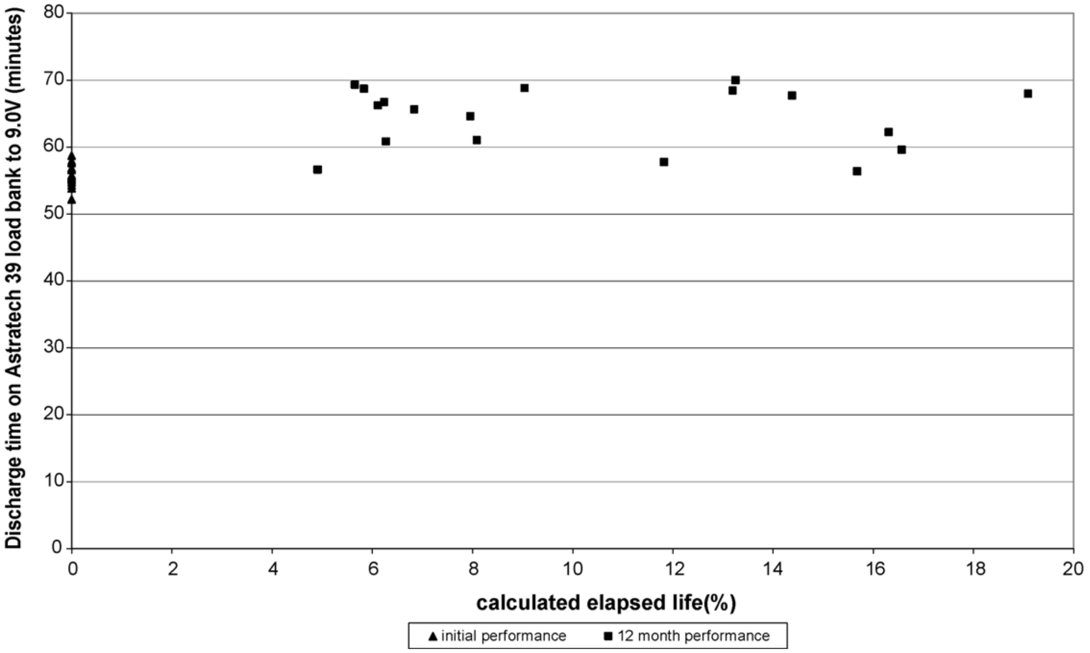

Fig. 9. Change in discharge performance during first year of service vs. elapsed life based on recorded cycle service and charging period.

use. This allows full charging to be maintained by a constant-voltage float charging mode after the initial recharge period. The distribution of accumulated charging times during the first year of service is given in Fig. 7. Again, there is a 10-fold variation across the sample range. Examination of the individual records reveals that the charging period is not related to the amount of use. Some users habitually disconnect the charger as soon as the battery is recharged, while others follow the instruction to leave the charger attached. A spectrum of behaviour between these extremes was observed.

4.3. Evolution of capacity in field trials

Because of the low frequency of use compared with laboratory trials, the field trials are continuing and none of the batteries have reached end of life. The capacity of the test batteries recorded at the start of the test and after approximately 12 months in service is given in Fig. 8. This performance has been plotted against the monitored elapsed life of the battery, calculated from the number and depth of the individual discharges. The same data are presented in Fig. 9 but the elapsed life calculation has been calculated externally to the monitoring system, to include a factor for the charging period experienced by each battery.

5. Conclusions

A low-cost monitoring device has been developed and is capable of continuously monitoring battery voltage, temperature and elapsed time. This has been mounted integrally to batteries to enable data to be collected in laboratory and field trials based on electric trolley applications. Laboratory simulations have confirmed that published cycle-life data are compatible with stop–start discharges of mixed depth over the range typically experienced in the golf trolley application. Even in applications where the discharge characteristics are reasonably predictable, the overall pattern of use may be much more variable than laboratory simulations suggest. The applicability of battery life models needs to be carefully defined with respect to the actual conditions of use. The ongoing field trials reported in this work can be analysed in terms of the cycle number and depth-of-discharge, as well as with respect to charging periods, if this significantly improves the model of battery life.

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