AN ON-BOARD CAPACITY ESTIMATION METHOD FOR PBA BATTERY

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ABSTRACT

Lead-acid (PbA) batteries have served as standard electrical energy storage devices in vehicles and other applications for nearly 100 years. Their role have expanded well beyond their original duty of engine cranking to include supplementing the alternator's power output during load transients and provide energy for deep cycle applications. In this work, we focus on applications where PbA batteries are used to provide electrical energy while the engine is off. An extended aging and characterization activity was carried out on large, deep discharge PbA batteries aimed at assessing the battery performance degradation process along battery life and to develop algorithms suitable for the determination of the battery state of health during its operation. The paper presents a novel capacity estimation method used within a capacity prediction framework. Results show that the battery monitoring technique and state of health evaluation algorithm have the potential to be run on-board vehicles in real time.

INTRODUCTION

Today, in most automotive applications, PbA batteries are used as a starter battery and to act as a buffer between the alternator and the vehicle electrical system when the engine is on, when the electrical power short-term electrical system demands exceeds what the alternator is able to provide [4]. There are also applications in which PbA batteries are asked to provide long-term energy, as for example, in military vehicles such as silent watch missions where the batteries are used to provide continuous power to operate surveillance equipment with the engine off from extended periods of time ranging between 4 and 72 hours. The focus of this paper is the investigation of the aging and characterization properties of PbA batteries for diagnostics/prognostics purposes for a silent watch application. Online battery life estimation algorithms could be used to warn on declining battery performance to assist for replacement prior to failure. In conventional and hybrid-vehicle applications capacity is often the primary metric of interest to assess the State of Health (SoH) of the battery. This paper is structured as follows: development of duty cycle statistically representative of the silent watch missions; implementation of a reproducible synthetic duty cycle that mimics the actual one and age batteries according to this protocol; assessment of aging and capacity degradation; development of methods and algorithms for capacity estimation to assess capacity loss in operation; and finally, development and validation of the capacity prediction algorithm.

AGING AND CHARACTERIZATION ACTIVITY

The PbA battery used to perform the aging experiments was a VRLA 12 V, 120Ah HAWKER ARMASAFE Plus battery as shown in Fig. 1. In the field application, the battery routinely undergoes a deep discharge to 100% Depth of Discharge (DoD), at an elevated temperature.

Figure 1 - 120 Ah ARMASAFE+ Battery

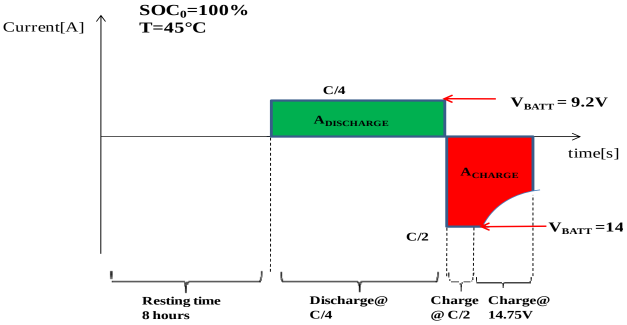

Figure 2 - Synthesized Aging Profile

The synthetic duty cycle that mimics this application is shown in Fig. 2. The aging activity starts by first bringing the battery to a constant temperature of 45°C over a period of 24 hours in an environmental chamber. A full SoC is then achieved by charging at constant current of 70 A (almost C/2 rate) until the voltage reaches 14.75V, followed by a constant voltage hold at 14.75V. Then the battery is allowed to rest for 8 hours before starting the aging profile. After the rest period, the discharge is stated at a constant rate of 30A (C/4 rate) until a terminal voltage of 10.5V is reached. After that, the battery is rested for 30 minutes and then charged back to 100% following the procedure described above. All these operations (discharge, charge, rests) are done while maintaining the battery temperature to 45°C. This aging profile is then repeated 5 times within an aging set and five aging sets form an aging campaign (25 deep discharges). At the end of each aging campaign, the assessment activity takes place, which consists of capacity test at C/5 rate and at 25 ºC and EIS test.

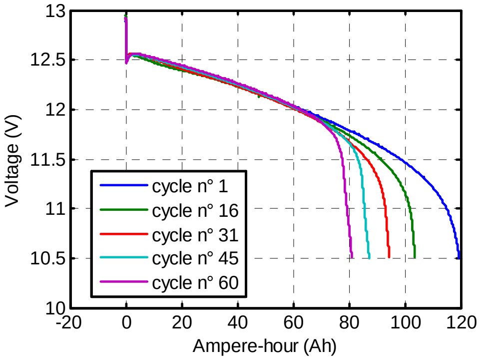

Figure 3 - Voltage *versus* Energy Removed (Ah) at Various Aging Stages

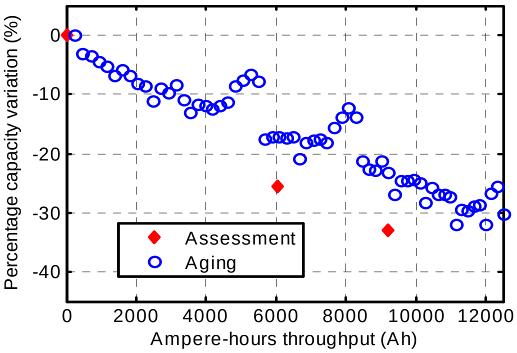

Figure 4 - Percentage Capacity Variation *versus* Total Ah Throughput

Results of aging and assessments tests are shown in Fig. 4, where the percentage capacity variation is plotted versus the total Ah throughput, showing a decreasing trend.

CAPACITY ESTIMATION METHOD: RESERVE CAPACITY TEST

The ultimate goal of this work is to design an on-board implementable algorithm for capacity estimation which is described in this section. Examination of the discharge curves at various ages (Fig. 3) reveals an inward progression of the 'knee' of the curve at low SoC. As the battery ages, less capacity is available and the voltage knee moves inwards. As a general observation, the voltage knee is typically be encountered within the final 5-10 Ah before full discharge. The idea behind the reserve capacity methodology is to correlate the rate of voltage drop under a given load to the remaining capacity at that given discharge rate ('time to run'). This correlation is established as follows. Each discharge curve through the life of the battery is examined. Starting from the fully discharged condition and moving backwards, the voltage drop over a given amount of time (100 sec in this paper) is calculated and correlated to the Ah remaining until fully discharged conditions. These local slopes (*(dV/dt)*$_{100}$, *i.e., dV/dt* averaged over 100 sec.) were evaluated at Ah remaining ranging between 2 and 40 Ah. The 100 sec interval length was chosen after some preliminary investigations as a compromise between evaluating a 'local' slope and noise immunity. This process is shown for a given cycle in Fig. 5. This same process is then applied through the life of the battery. The results obtained by the plotting capacity versus *(dV/dt)*$_{100}$ are shown in Fig. 6.

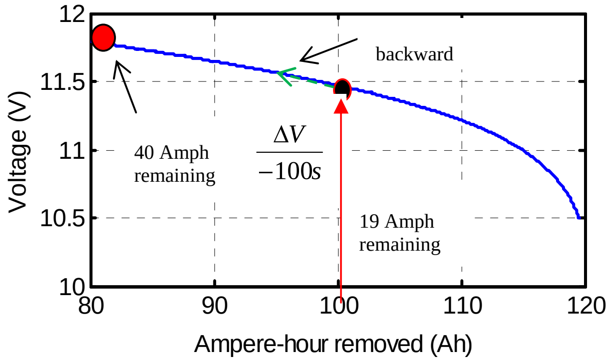

Figure 5 - Analysis of the Discharge Voltage for Reserve Capacity Estimation Method

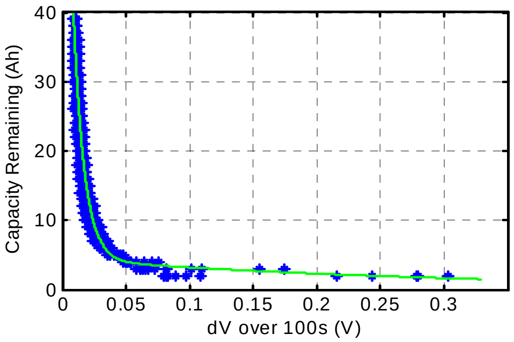

Figure 6 - Remaining Capacity *versus* Voltage Drop over a 100 Second Interval, (dV/dt)$_{100}$

Figure 6 shows that there is a clear correlation between the voltage slope and the remaining discharge capacity. Furthermore, this curve does not appear to change as the battery ages despite the fact that capacity decreased by more than 30% over the life (see Fig. 4). Clearly, as the voltage slope increases, estimates of the remaining capacity (or time-to-run at that current) become more accurate. For example, if the voltage drop measured over a 100 second period is 50mV, the remaining capacity is approximately between 4 and 6 Ah. This technique was first developed and presented in [2], and is referred to as the Reserved Capacity method. In the following section, this method is used to design an algorithm to predict the battery capacity without fully discharging the battery (*i.e.*, measuring the battery capacity).

CAPACITY PREDICTION

A capacity prediction algorithm is proposed in this section based on the Reserve Capacity method. This algorithm is based on the average correlation shown in of Fig.6 (green curve). This method ca potentially be run on-board of the vehicle. The various steps in the implementation of the algorithm are described as follows.

Step 1: Set the threshold amount of Ah remaining at which to start the algorithm which corresponds to $Amph_{remaining}(t_0) = \left(\int_{t_0}^{T} i(t)dt \right)_{estimated}$

Step 2: From the threshold set in Step 1 and using the correlation of Fig. 6, determine the corresponding reference voltage slope at time t$_0$, *i.e.* $(dV/dt)_{100,ref}(t_0)$. We refer to this value as the *reference slope* during the discharge phase at which to perform the evaluation of the remaining capacity.

Step 3: As the battery starts discharging, data are being collected and the actual drop $(dV/dt)_{100,act}$ is recorded. The actual slope is compared to the *reference slope* at each time, until the condition $(dV/dt)_{100,act} \geq (dV/dt)_{100,ref}$ is met, which occurs at *t$_0$*. The energy removed out of the battery from *t=0* (beginning of discharge, SoC = 100 %) to *t$_0$* are calculated by integration of the current.

Step 4: The capacity estimate at time t_0 is then given by $\tilde{C}(t_0) = Amph_{removed}(t_0) + Amph_{remaining}(t_0)$

The steps of the capacity estimation algorithm are graphically summarized in Fig 7.

Validation tests have been conducted on different automotive battery samples and results show high accuracy in the estimation. The correlation between the actual capacity and the estimated capacity is shown in Fig. 8 for different values of the threshold at which to perform the capacity estimation. As expected, the prediction is more and more accurate as it occurs closer to fully discharge conditions.

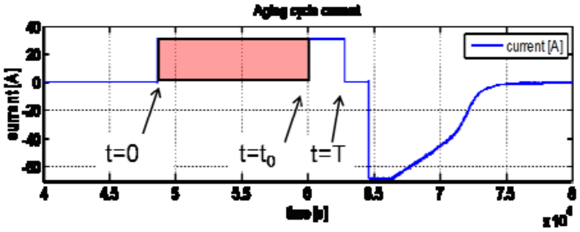

Figure 7 - Capacity Estimation at Time t_0

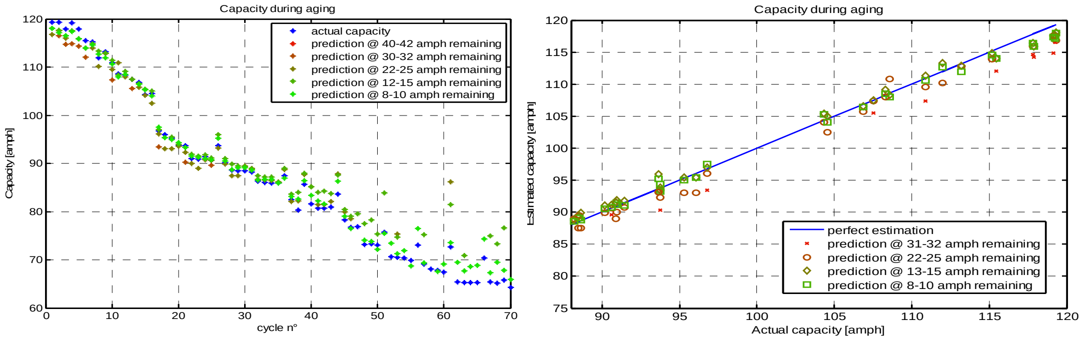

Figure 8 -Validation results of Capacity Estimations Throughout Life when Discharged at C/4 at 45 °C.

However, the results are reasonable as early as 30 Ah from fully discharged conditions (SoC=25% for a new battery, and earlier for a degraded battery), hence providing an early estimate of time-to-run at that current level. Furthermore, the algorithm performs equally well as the battery ages and its capacity degrades.

CONCLUSIONS

A capacity estimation method for PbA battery for on-board capacity prediction during actual operation and throughout the battery life was presented. This method can provide reasonably accurate capacity estimates without ever fully discharging the battery (*i.e.*, measuring the capacity). These results under restricted conditions (constant load and single temperature) are very promising and the results are currently being extended for different temperatures and varying currents.

ACKNOWLEDGMENTS

The authors would like to thank the US Army - TARDEC for its financial support under which the majority of the work presented here was conducted.

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