NEW PbA BATTERY MODELING STRUCTURE AND VALIDATION CAPTURING THE PEUKERT EFFECT

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ABSTRACT

The higher the discharge rate, the lower the energy that can be extracted out of a battery. This is the well known Peukert effect which describes how the battery apparent capacity is directly affected by the current at which it is discharged and it is particularly important for lead-acid batteries (PbA). In many applications it is essential to predict the remaining capacity of a battery reliably, accurately and simply. This paper discusses experimental validation results of a novel battery model (proposed by the same authors in [3]) to predict the Peukert effect in deep-discharge PbA battery applications. Validation results show the effectiveness of the calibrated model to accurately estimate the proper capacity as a function of the discharge load current.

INTRODUCTION

Despite the fact that new battery chemistries are available nowadays for use in electric and hybrid vehicles, PbA batteries still play an important role in automotive and stationary applications. Thanks to their low cost and their ability to supply high power, they are still extensively used as automotive starter batteries and deep cycle batteries. This paper focuses on PbA batteries used in deep cycle applications such as military ground vehicles, all-electric vehicles such as fork lift and tow motors, renewable energy storage and power backup systems. The battery capacity represents the maximum amount of energy that can be extracted out of the battery and deep-cycle PbA battery applications are such that the battery is designed to be regularly discharged to most of its capacity. Thus, predicting the remaining battery capacity is an essential requirement for the successful of such applications. One of the main factors, though, which influence the battery capacity, is the discharge current. The goal of this paper is to present new experimental results aimed at validating a novel battery model structure [3] capable of rationally capturing the Peukert effect for PbA batteries. While many complex electrochemical battery models exist, accurate and simple phenomenological models (Randle-type equivalent circuit models) can provide insightful information and used in real time in applications for estimating SoC and SoH. These models are calibrated from data obtained from laboratory testing and they can be applied to an extensive range of operating conditions. This novel battery model structure [3] is based on a two-buffer approach and is validated here against experimental data carried out on 120Ah deep discharge PbA batteries.

PEUKERT EFFECT

Although PbA batteries have been extensively used for more than a century, some interesting phenomena are still not completely understood and correctly modeled. One such effect is the Peukert effect which describes the apparent capacity reduction at high current discharge rates. It is heuristically described by the Peukert equation [1,2]:

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[1] Antonio Manenti has conducted this work while was a visiting scholar at Center for Automotive Research at Ohio State University.

$$I^n T = const = C_1 \text{ [Ah]} \tag{1}$$

which maps the capacity de-rating as a function of the load current (considered constant) as a power law with an experimentally determined coefficient, the Peukert exponent. In Eq. (1), C_1 indicates the capacity that the battery can provide when discharged with a constant discharge current I of 1A, T is the discharge time (in hours) and n is Peukert exponent, empirically determined. The Peukert equation should be interpreted with care. Equation (1) does not mean that when a battery is discharged 'fully' (*i.e.*, down to a minimum voltage) at a high discharge current, it is completely empty. In fact, a seemingly empty battery discharged at high current will still have some available capacity at a lower discharge current after some resting time. This phenomenon is known as the capacity recovery effect. In this paper, we only discuss results regarding experimental validation of the novel battery model to predict Peukert effect, while a full investigation of the capacity recovery effect and modelling has been carried out by the authors and discussed in detail in [4].

MODEL STRUCTURE TO REPRESENT THE PEUKERT EFFECT

The novel battery model is based on an equivalent electrical circuit presented in ([3, 4]) and recalled here for sake of completeness. It is structured specifically to be able to accurately reproduce the Peukert and capacity recovery (not described here) effects. This model is built upon the rich literature on simple equivalent electrical circuit models, but rationally extends them to explicitly capture the phenomenological behaviour described by the Peukert effect. The new model structure is based on the equivalent electric circuit shown in Fig. 1.

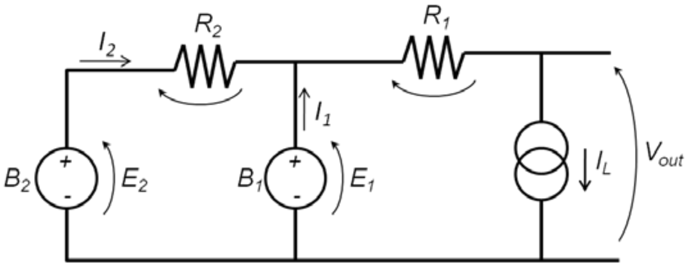


Figure1 - Battery equivalent circuit to model 'Peukert effect'.

The main idea behind the model design is to split the total capacity C_n of the battery into two energy buffers. A first energy buffer B_1 (directly observable at the battery terminals) is only a (large) fraction of the total capacity. Its voltage E_1 depends on its state of charge (SoC_1).

The additional buffer B_2 (internally connected to the first one and invisible at the terminals) is added. In the limit of vanishingly small R_2 (or small currents), this models behaves like a single energy buffer. In the limit of large currents, the first buffer gets emptied before the second (inner) one and the battery appears to be empty (but recovers after some time, as the two buffers equilibrate). This is a very coarse 2 term approximation of diffusion-driven phenomena (sometimes modelled as transmission lines from an electrical stand point). Accordingly, the total capacity is split into the two buffers through the parameter β ($0 \leq \beta \leq 1$):

$$C_{b1}(0) = C_{b10} = \beta C_n \tag{2}$$

$$C_{b2}(0) = C_{b20} = (1-\beta) C_n \tag{3}$$

where positive current indicates a current that flows out of the buffer (as in Fig.1). Differentiating (2) and (3) gives $\dot{C}_{b1}(t) = -I_1$ and $\dot{C}_{b2}(t) = -I_2$ and Kirchhoff's law at the node gives: $I_1 = I_L - I_2 = I_L - \frac{E_2 - E_1}{R_2}$ where I_L is the load current. For every β, the input-output proper battery behaviour is guaranteed if the voltage across each buffer is an increasing monotonic function of their SoC, that is, $E_1 = f(SoC_1) = f\left(\frac{C_{b1}(t)}{Cb_{10}}\right)$ and $E_2 = f(SoC_2) = f\left(\frac{C_{b2}(t)}{C_{b20}}\right)$. Moreover, the total capacity depleted from the battery (capacity available starting from time $t=0$ until time t_f when energy buffer 1 gets empty) is given by $C_{av,model} = \int_0^{t_f} I_L(t)dt$. The fundamental parameters of the model presented are β and R_2 which, while independent of load current and SoC, are in general non linear functions of the temperature, T, and aging or SoH:

$\beta = f_\beta(T, aging)$ and $R_2 = f_{R_2}(T, aging)$.

In what follows, the experimental setup is presented, aimed at performing the calibration of the two model parameters β and R_2 at constant temperature and for new batteries.

EXPERIMENTAL SETUP

Experimental tests are performed on two new 120Ah PbA ArmaSafe+ batteries manufactured by. Hawker [9] in order to calibrate the model parameters and validate the model itself. In particular, two sets of experiments are carried out. The first, aimed at identifying the Peukert exponent, consisted in discharging the battery with different constant currents I_T = 6A (C/20), 10A, 20A, 40A, 80A, 120A (1C). All the experiments were performed at ambient temperature (25°C). Before each test, the batteries were fully charged as recommended by the manufacturer. The nominal capacity of the battery was assessed through capacity tests[2]. The second series of tests then was aimed at analyzing and track the recovery phenomenon and it consisted in applying a second discharge current of a smaller amplitude than the one used to perform the first discharge, after a resting time period of 6 hours after the first discharge. A total of seven experiments have been conducted on two new PbA batteries. For Experiment #1, due to the very low current used in the first discharge phase, a second discharge was not possible, while Experiment #7 at the highest current allowed for a third discharge phase after two resting periods of 6 hours each.

DATA ANALYSIS

Experiments were conducted on two new batteries. The averaged results are shown in Fig. 2. The interpolation curve yields a Peukert exponent *n=1.1536* that is actually really close to the value provided by the manufacturer (*n=1.1565*).

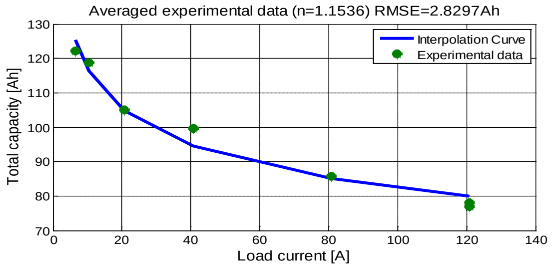
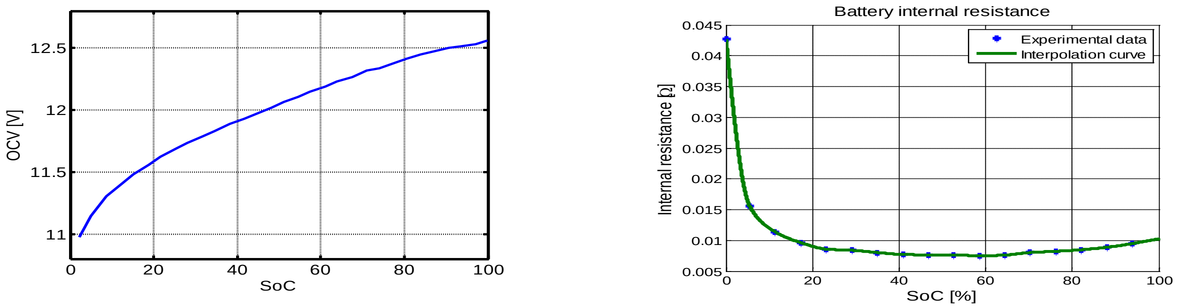


Figure 2 - Available capacity at different discharge rates.

MODEL CALIBRATION AND VALIDATION

The model parameters, namely, open circuit voltage, E_1 and E_2, of the two buffers and the internal resistance R_1, were identified from another series of experiments.



Open circuit voltage curve for ArmaSafe+ batteries

Battery internal resistance (R_1) vs. SoC

Figure 3- Model parameters from experiments.

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[2] This test, according to the "Freedom car manual" [5] consists in a complete discharge at C/20 (6A in this case).

Details on the tests carried out and procedure used to identify the parameters are fully documented in [4] and representative results only are shown in Fig. 3.

Once the model was tuned, the calibration parameters R_2 and β were obtained through an optimization process ([6], [9]) that minimizes the cost function:

$$\varepsilon = \sqrt{E\left(C_{exp} - C_{model}(\beta, R_2)\right)^2}$$

which resulted in $R_2 = 0.065\Omega$ and $\beta = 0.6$.

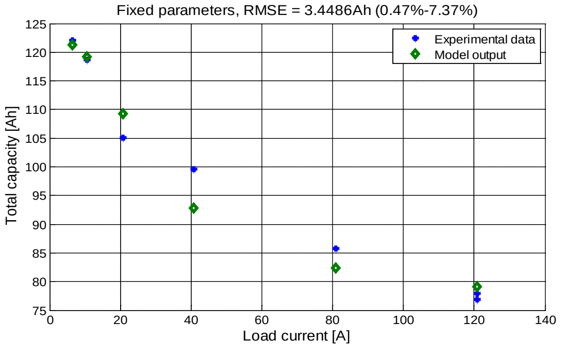

Figure 4 - Comparison between measured and predicted capacity for various discharge rates.

The calibrated model was then exercised to determine the battery capacity under different load conditions. Results from the model and the experimental tests are represented on Fig. 4 which shows how the model outputs (which do not rely on an empirically determined of a Peukert exponent!) are accurately close to the experimental values (with an overall RMSE of about 7.4%).

CONCLUSIONS AND FUTURE WORK

Test results were presented which show the effectiveness of a novel battery model proposed in [3]. The capacity recovery effect paper was also fully investigated by the authors and presented in [4], with comparable success. This new battery model aims at predicting both the Peukert and capacity recovery effects for real arbitrary variable load current profiles (involving both charging and discharging with variable magnitudes). Due to its simplicity, it can easily be incorporated into real time applications to predict SoC and time to run, which is essential for mission-critical applications (military, telecom, hospitals). Furthermore, the model structure is easily generalizable to more than 2 energy buffers. Further investigations are currently carried out to model both phenomena occurring with aged battery and over a range of temperatures and will be reported elsewhere.

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