A simple yet accurate model for battery State of Charge prediction.

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***Abstract*—A comprehensive model for the prediction of the state of charge (SoC) of a battery, based upon a model for the prediction of the SoC of a hot water vessel was introduced in [1]. In this work the proposed model is improved and verified using various measurements on lead-acid batteries, as well as predictions using the KiBaM model. The resulting model is simple yet accurate, and can be used in model predictive control of energy usage in grid simulations.**

***Index Terms*—Battery, State-of-Charge, Prediction, Smart grid, Energy management**

I. Introduction

On the one hand, batteries get more and more an important part of the future energy systems. Examples include using a battery for emergency situations, using a battery to store electricity generated by pv-panels during the day for usage during the night, and charging an *electric vehicle* (EV). On the other hand, simulations are used to predict for example weak points in existing grids [2] or to explore the possibility of new types of grids [3]. To accurately simulate the energy usage in a grid, accurate models are needed for all devices connected to the grid. To describe the behavior of batteries many models are available [4], [5]. However, some of the available models are too complex to be used in energy-grid simulations, while other models are simple but not accurate enough.

A simple yet accurate model was created in [1] to predict the battery *state of charge* (SoC). The model is based upon a model for the SoC prediction in thermal energy storage, developed by van Leeuwen et al. [6]. In this work the model outlined in [1] is further developed and verified with data obtained from measurements done on lead-acid batteries.

A comprehensive model for battery SoC prediction

The model in [1] predicts the *state of charge* (SoC) at any given time using Equation 1, in which the state of charge (SoC_t) is calculated by summing the previous SoC (SoC_{t-1}) and the change in SoC.

$$SoC_t = SoC_{t-1} + \frac{U_t \cdot I_t \cdot \Delta t}{E_{max}} \tag{1}$$

The change in SoC is the sum of the energy that was put in, or retrieved from the battery in the previous time step divided by the maximum energy contents of the battery (E_{max}). To calculate the SoC_t values, the initial SoC (SoC_{start}) and E_{max} are needed, next to the current at each time (I_t), which is known as this is what is applied to or demanded from the battery. Finally also the voltage at each time (U_t) is needed. To calculate these voltages the model uses four states of the battery: discharging (2a), idle time after discharging (2b), charging (2c) and idle time after charging (2d). For each state a different function to determine the voltage applies.

$$U_t = U_{t-1} + \alpha \cdot I_{t-1} \tag{2a}$$

$$U_t = U_{t_0^*} + (U_{max} - U_{t_0^*}) \frac{t - t_0^*}{\beta \cdot (t - t_0^*) + \gamma} \tag{2b}$$

$$U_t = U_{t-1} + \frac{\delta}{I_{t-1}} \tag{2c}$$

$$U_t = U_{t-1} \tag{2d}$$

When the battery is discharged (2a) is used, in which the voltage (U_t) is calculated from the current (I_t) and a constant α. When the battery is idle, after a discharging step, (2b) applies, in which the voltage (U_t) is calculated from the voltage at the beginning of the idle step ($\text{U}_{t_0^*}$), the starting time of the idle step (t_0^*), the maximum voltage the battery can reach (U_{max}) and constants β and γ. When the battery is charged, (2c) applies, in which the voltage (U_t) is calculated using the current (I_t) and a constant δ. When the battery is idle after charging, (2d) is used. For (2b) and (2d) it is assumed that the idle time is short enough so that there are no self-discharge effects.

The parameters α, β, γ and δ are specific for a battery type and can be determined from voltage measurements during the charging and discharging of the battery with a constant current [1]. Several measurements using various charge and discharge currents and idle periods should be done to obtain accurate values for these parameters.

II. Results

The model (1) + (2) is applied to simulate the behavior of a 6V, 2.5 Ah *lead acid battery* (pb-acid) in a realistic situation. The battery is charged and discharged periodically, with a certain idle time after each discharging step. The results of this simulation are compared to the results of a simulation of the same battery under the same conditions using the well established *kinetic battery model* (KiBaM) [7], [4]. The parameters used for the prediction with both the proposed model and the KiBaM model are listed in Table I. Furthermore the simulation results are compared to measurements done on a pb-acid battery under the same conditions.

TABLE I: Settings for the proposed model and the KiBaM model

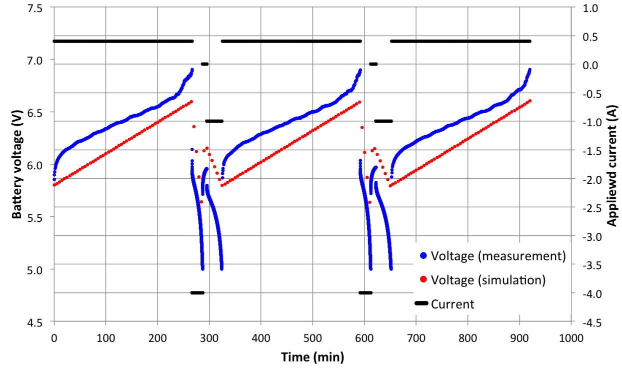
Proposed			KiBaM		
α	1.79	10^{-4}V/A	C	15	Wh
β	1.8	-	C_{start}	1.9	Wh
γ	1.18	min	c	0.248	-
δ	1,2	10^{-3}V/A	k'	0.094	-
E_{max}	15	Wh	SoC_{start}	0.13	-
SoC_{start}	0.13	-			

The measurements and simulation results are displayed in Figure 1. In Figure 1a the battery voltage predicted with the proposed model is compared to the measured voltage. The predicted voltage follows the pattern of the measured voltage, but the predicted voltage deviates from the measured voltage over the whole prediction, though the deviation is never larger than 0,5 V (or 10%). However, note that the goal of this model is not to give an accurate prediction of the battery voltage, but rather give an accurate prediction of the SoC.

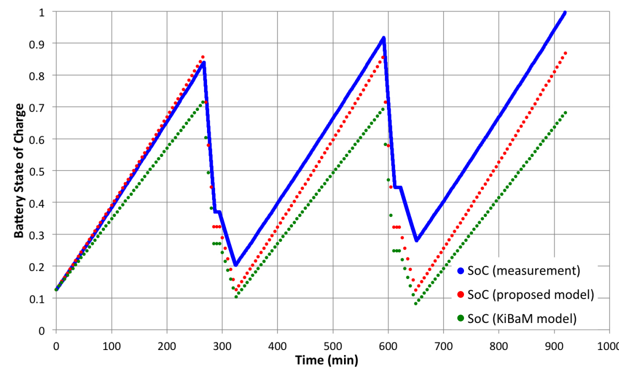
Therefore, the measured SoC is compared to the SoC predicted with the proposed model in Figure 1b. In the first charge / discharge cycle (0 - 320 min) the predicted SoC follows the measured SoC precisely, but in the next discharge cycle (320 - 650 min) and subsequent charge step (650 - 950 min) the predicted SoC deviates from the measured SoC. The deviation seems strongest after the discharging steps and appears to be cumulative over subsequent (dis)charge steps. To decrease these deviations, the part of the model that deals with discharging steps (Equation (2a)) should be improved. This is part of in future work.

The predicted SoC is also compared to the SoC predicted with the KiBaM model [7] (see also Figure 1b). As the KiBaM model directly predicts the SoC, no comparison between the predicted battery voltages could be made. The SoC predicted with the KiBaM model follows the measured SoC less closely than the SoC predicted with the proposed model, however, in both models the deviations become larger in the second charge / discharge cycle and last charge step. In this case the predictions done with the proposed model are slightly better than those done with the KiBaM model. A possible explanation for this is that the KiBaM model is less suitable for predictions regarding aged or degenerated batteries.

While the proposed model is a work in progress, and far from perfect, it is comprehensive and relatively simple. In terms of accuracy the proposed model is comparable to the well-established KiBaM model.



(a) Applied current and resulting voltage of the Pb-acid battery, both measured and calculated with the proposed model. Positive currents represent charging steps, negative currents represent discharging steps.



(b) Resulting SoC of the Pb-acid battery, calculated based on measurements, and simulated with the proposed model and the KiBam model.

Fig. 1: Measurement data and simulation results of the usage of Pb-acid battery in a realistic situation.

III. Future Work

In the full paper the following issues will be addressed:

- An improvement of the part of the model that deals with discharging.
- A validation of the model with experiments on additional battery types.

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