

Evaluation of the simulation of lead-acid batteries in MATLAB Simulink and measurement-based optimization of model parameters

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Abstract—This paper evaluates the simulation of lead-acid batteries in MATLAB Simulink, where the model parameters are determined using measurement data from battery tests. For the simulation, a simple Simulink model is used, in which the model parameters are approximated by an optimization algorithm in order to simulate the battery's voltage curve based on input values. The effectiveness of this method is assessed by comparing the simulation results with real measurement data. The conditions under which the Simulink model can provide valid results, and its limitations, will also be investigated.

Index Terms—Lead acid battery, MATLAB Simulink, battery model, parameter optimization,

such a model in MATLAB/Simulink, which is parameterized by experimental tests. Two essential tests, the Continuous Discharge Test (CDT) for forming lookup tables and the Pulse Discharge Test (PDT) for the equivalent variables, are used to determine the battery models. Even if lithium batteries are considered there, the principles of modeling are comparable to those of lead batteries. Another method used in Simulink is described in [4], where a highly complex Kalman filter-based calculation is used for parameterization.

I. INTRODUCTION

Simulating lead-acid batteries is important for predicting their behaviour under real operating conditions. Despite the increasing prevalence of modern technologies, lead-acid batteries remain relevant due to their cost-effectiveness and robust performance. In this context, they can find applications in hybrid storage systems, where battery simulation is essential to coordinate the interaction of different storage technologies and optimize overall system efficiency [1]. A key challenge in practice is the complexity of the simulations and the difficulty of accurately approximating the model parameters. The following presents a method for tuning the model parameters in MATLAB using real measurement data from a 48-volt lead-acid battery module. The battery is discharged and charged in pulses several times under certain conditions. The focus is on using an optimization algorithm to adjust the model parameters to provide a realistic representation of the voltage curve as a function of the initial state of charge (SOC) and the input current. Finally, the comparison of the simulated values with the real values provides information about the accuracy of the model.

II. RELATED WORK

Typically, battery simulation models are developed based on an equivalent circuit that includes a DC voltage source, a series resistor and parallel RC networks to simulate the dynamic characteristics of the battery. The basis for this equivalent circuit is presented in [2]. Building on this, [3] presents

III. MATERIAL AND METHODS

Before the actual simulation, measurement data for the behavior of a lead-acid battery must first be recorded. The initial point for the measurements is a PSB110000-40 laboratory power supply unit from Elektro-Automatik. This power supply unit is a bidirectional device that is capable of charging and discharging batteries and feeding energy back into the grid. The battery module under investigation consists of eight 12V lead batteries, four of which are connected in series and two in parallel, resulting in a nominal voltage of 48 V. According to the manufacturer, the batteries are specified with a capacity of 80 Ah. In Figure 1, the schematic setup of the hardware is shown. All measurements were taken at an ambient temperature of 25 °C.

In this work the measurement data is recorded with MATLAB and the simulations are performed with MATLAB Simulink, using parts from the Simscape library.

IV. IMPLEMENTATION

A. Measurement data acquisition

Communication with the power supply unit, which operates the battery, takes place via a Modbus TCP interface. This is a widely used industrial communication protocol that enables simple and reliable data transfer between devices. The MATLAB Modbus Communication Toolbox is used to implement IP-based communication with the power supply unit. This toolbox provides functions that make it possible both to send control commands, i.e. to write to registers, and to retrieve register values. This allows the output to be controlled in source

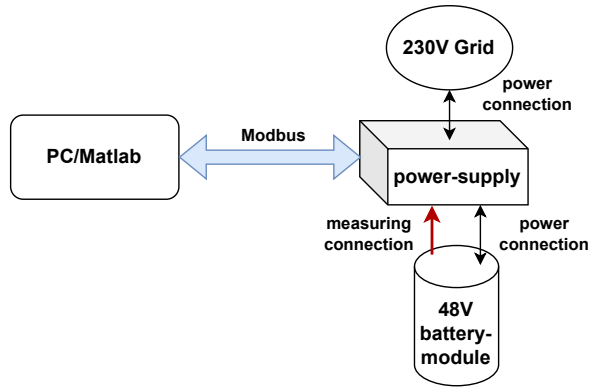


Fig. 1. Hardware Setup with components for measurement data recording

and sink mode, and the measured variables (current, voltage, power, energy and capacitance) to be queried. A MATLAB script runs an automated procedure to perform discharge and charge cycles on the battery module. This script controls the tests with predefined parameters including voltage, current, power, duration, and the number of cycles. The sequence is organised by different phases, including "start delay", "discharge", "pause" and "charge". The duration of each phase and the pauses between cycles can be defined individually. The continuous discharge test or the pulse discharge test can be done using this. The parameters can be entered via a MATLAB app developed for this purpose. The measured values are sampled at 1 Hz and displayed graphically simultaneously. Errors are also shown in the app and troubleshooting is made possible. The system is constantly monitoring for errors. The test process is aborted if the current, voltage or power limit values are exceeded, or if connection problems or errors occur during phase changes or parameter configuration. For safety reasons, the power supply unit is automatically set to sleep mode and the connection is disconnected to prevent hardware damage in the event of an error.

B. Simulation

The model and optimization is based on a parameterized equivalent circuit implemented in MATLAB/Simulink according to [5]. It simulates the electrical behavior of the battery under current excitation, taking into account both static and dynamic properties. The simulation setup is shown below (Figure 2).

a) Battery Model: The lead-acid battery is modeled with the block `Battery` from the Simscape Electrical Toolbox. The model has a limited *battery charge capacity*, which enables a charge-dependent voltage characteristic [6] that varies with the state of charge (SOC):

$$V(SOC) = V_{nom} \cdot \frac{SOC}{1 - \beta(1 - SOC)} \quad (1)$$

Here, V_{nom} is the nominal voltage, and β is a correction coefficient internally computed to ensure that the model passes

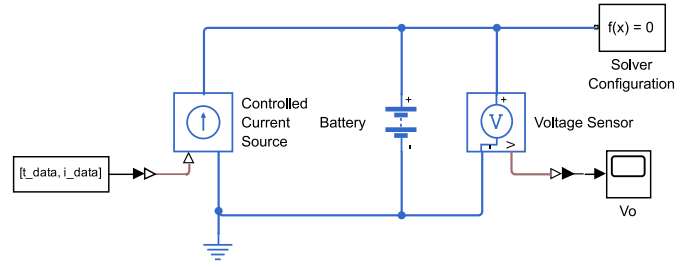


Fig. 2. Simulation Setup- Simulink lead acid battery model

through a specified user-defined data point $[AH_1, V_1]$, which characterizes the voltage drop at a given discharged capacity.

The model includes a second-order dynamic behavior using two parallel RC networks. This captures transient effects such as polarization and internal ion diffusion. The dynamic charge behavior is determined by two time constants, τ_1 and τ_2 , which are responsible for the current-voltage dynamics and the resistances R_{p1} and R_{p2} .

b) Model Parameters: The table below summarizes all parameters used in the model (Table I):

Parameter	Description
V_{nom}	Nominal voltage of the battery [V]
R_1	Series internal resistance [Ω]
Ah	Total charge capacity [Ah]
V_1	Voltage at reference discharge point [V]
Ah_1	Discharged capacity corresponding to V_1 [Ah]
R_{p1}	1. Parallel resistance in dynamic model [Ω]
τ_1	Time constant of the 1. RC circuit [s]
R_{p2}	2. Parallel resistance in dynamic model [Ω]
τ_2	Time constant of the 2. RC circuit [s]
Ah_0	Initial battery state-of-charge-capacity [Ah]

TABLE I
BATTERY MODEL PARAMETERS

c) Excitation and Measurement: The battery block is triggered via a controlled current source that feeds a time-varying current into the model. The current signal is provided by the data set from the battery test measurements.

- t_{data} : Time vector
- i_{data} : Corresponding current values

This allows the simulation to emulate real load cycles. The terminal voltage is monitored with a Voltage Sensor block, which enables the comparison of simulated and measured voltage curves.

d) Solver Configuration: The solver is responsible for the numerical integration of the differential equations that describe the dynamic behavior of the battery. In this model, it calculates how the state of charge and the terminal voltage develop over time in response to a time-varying current input. The solver ensures that both electrical transients (e.g. due to RC dynamics) and algebraic constraints (e.g. voltage-charge relationships) are handled. This enables a time-dependent simulation of the battery behavior.

C. Parameterization

Before the first optimization, the initial values of the parameter list are set. This is important to run the first simulation.

The values are partially selected from the battery's datasheet or are based on estimates. For subsequent simulations, the initial state of charge (SOC) of the battery at the first measurement of the dataset is also relevant. By using the relationship between the Open Circuit Voltage (OCV) of the lead-acid battery and the SOC, the initial SOC can be determined through a lookup table [7]. This assumes that the battery has rested for at least 4 hours before recording the measurement series, as the OCV continues to change for an extended period after load due to the chemically induced sluggish behavior of lead-acid batteries.

The parameters of the battery model are then adjusted using an optimization algorithm:

a) *Objectivefunction*: The objective function is used to adjust the model parameters so that the simulation results match the real battery measurement data as closely as possible when current is applied. This is achieved by minimizing the difference between the simulated voltage values and the measured values. The difference is calculated in the form of the sum of squared deviations, which serves as an error measure for the optimization.

The function is basically called to integrate the actual parameter values into the Simulink model. The model parameters are extracted from a list and transferred to the simulation model. These parameters include various properties described in Table I. After the parameters in the model have been updated, a simulation of the model is carried out to simulate the battery behavior. The difference between the simulated voltage values and the measured values of the battery is then calculated. These differences are summed as squared deviations to obtain an overall error measurement that quantifies the degree of agreement between the simulated and real values. If unexpected errors or invalid parameters occur during the simulation, the function is designed to return an invalid error value. This prevents erroneous parameters from entering the optimization process and ensures that only valid parameters are used for model fitting.

b) *Optimization*: The optimization of the battery parameters is carried out in two steps: the optimization of static parameters and dynamic parameters.

Initially, the static parameters such as nominal voltage (V_{nom}), internal resistance (R_1), capacity (Ah), and voltage coefficient (V_1) are considered. During the optimization process, these parameters are changed iteratively until the minimal deviation between the measured values and the simulated values is found. The optimization takes place over the complete measuring range.

The second step focuses on the dynamic parameters, which describe the charging behavior of the battery. Here, parameters such as the resistances (R_{p1} , R_{p2}) and time constants (τ_1 , τ_2) are optimized. To determine these parameters, relevant current pulses are extracted from the measurement data. The complete measuring range is not optimized, but only one pulse is considered.

After identifying the pulse data, the time section and time steps are calculated, and the dataset is adjusted for optimization. However, dynamic parameters not only affect the

charging behavior but also influence the discharge behavior. This allows for optimization of the discharge pulses as well.

The Parameter optimization is a nonlinear optimization problem that can be solved with various optimization algorithms, which were tested in this paper [8]. Due to its susceptibility to local minima, *fmincon* was found to be less suitable. In comparison, both the Genetic Algorithm and *fminsearch* produced comparable results. However, due to better runtime performance, *fminsearch* was preferred for the optimization. The stopping criterion is defined such that the optimization will terminate if the optimization variables do not change by more than 10^{-3} .

V. RESULTS AND DISCUSSION

The results of the parameter optimization are shown in the following. As described in the implementation section, dynamic optimization is designed to optimize either charging or discharging pulses. The charging and discharging processes are therefore considered separately here.

First, the measurement data and the simulation data based on the initial simulation parameters are compared in Figure 3 for discharge- and Figure 6 for charge-data.

The simulation parameters are then optimized using the measurement data. The result after optimization is shown in the Figure 4 and Figure 7. For validation, a test is carried out with a specified current profile and initial SOC and the simulation is compared with the measured values. This is shown in Figure 5 and Figure 8.

A. Optimization and validation based on discharge data

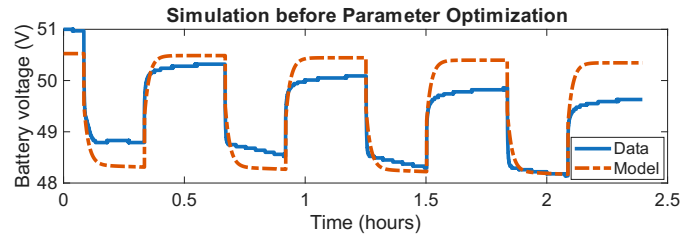


Fig. 3. Simulation based on discharge data before optimization

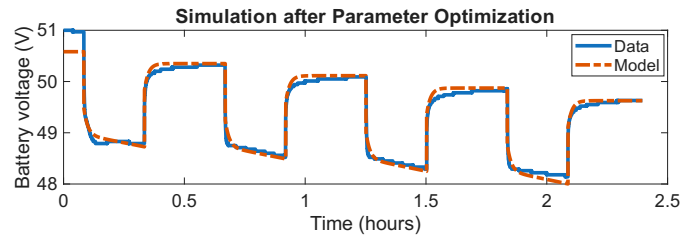


Fig. 4. Simulation based on discharge data after optimization

The comparative result shows that the voltage curves of the simulation and the test results match reasonably well. The RMS error of the voltage in discharge test is 164.6 mV, which corresponds to 0.34 % of the nominal battery voltage (Figure 5).

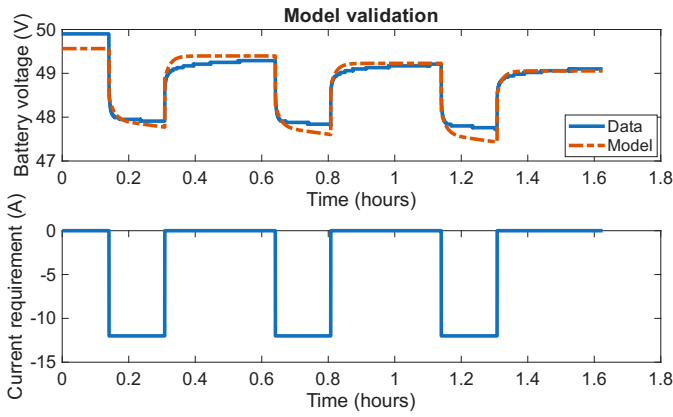


Fig. 5. Comparison between simulation and measurement results of discharge current profile test

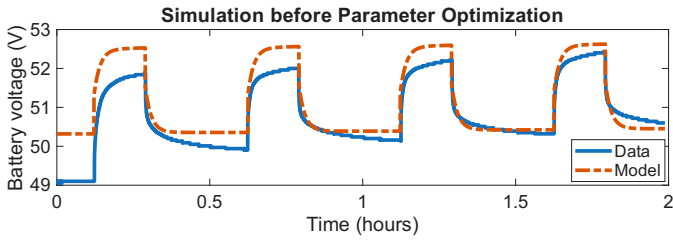


Fig. 6. Simulation based on charge data before optimization

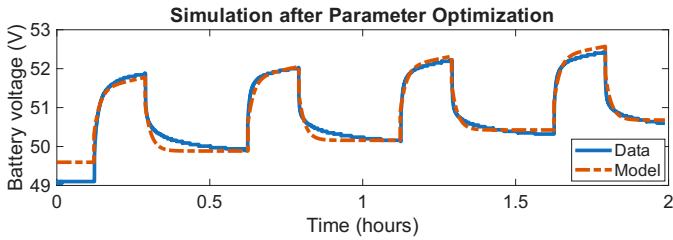


Fig. 7. Simulation based on charge data after optimization

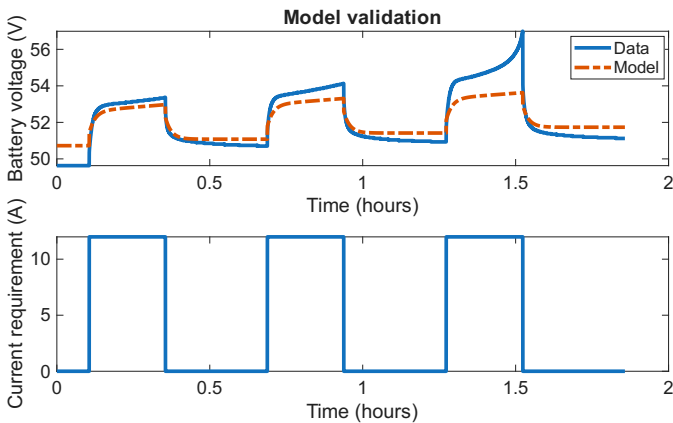


Fig. 8. Comparison between simulation and measurement results of charge current profile test

B. Optimization and validation based on charge data

To demonstrate the model's limitations, a start SOC just before the end-of-charge voltage was selected for the charging

test (Figure 8). As the battery saturates, the voltage rises more sharply until the constant voltage phase is reached. While the first charging pulse is simulated well, the steep voltage rise near the end-of-charge voltage cannot be captured by the model. The RMS error in this case is 723.4 mV, corresponding to 1.51% of the nominal battery voltage.

VI. CONCLUSION

This work demonstrates that the lead-acid battery model can be parameterized for a specific operating range through optimization. The results show that the simulated voltage curves match the experimental data well in certain ranges, which indicates the effectiveness of the proposed method.

However, the model cannot fully represent the entire battery behavior and is mainly suitable for either charging or discharging, not both simultaneously. The model's limitations are evident when simulating the charging process, especially near the end-of-charge voltage, where the steep voltage rise due to chemical effects cannot be captured accurately.

These results show that although the model is suitable for simulating specific battery behavior, it still needs to be extended to fully represent the complex dynamics of the charging and discharging processes.

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AUTHOR'S STATEMENT

Authors state no conflict of interest.

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