Lead-acid Batteries and Lithium-ion Batteries in parallel Strings for an Energy Storage System for a Clinic in Africa

Christiane RAHE[1,2]

[1] Chair for Electrochemical Energy Conversion and Storage Systems, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Jaegerstrasse 17-19, 52066 Aachen, Germany
[2] Helmholtz Institute Münster (HI MS), IEK-12, Forschungszentrum Jülich, Jägerstrasse 17/19, 52066 Aachen, Germany

Christiane.Rahe@isea.rwth-aachen.de

Abstract. *The aim of this paper is to develop an energy storage system for a clinic in Nioki, Africa. Caused by the difficulties of non existing infrastructure, the clinic needs its own power supply. Therefore, a simulation model combining lead-acid and lithium-ion batteries was developed and validated. The system under observation works with two different battery types in parallel without an energy management system. As input data the model uses weather data and load data. To be able to distribute the current correctly between the two batteries, the behaviour for each cell has to be calculated in every time step. A 14-V-system was built to validate the simulation model. The results of the simulation model and the measurement are compared and evaluated by comparison of the voltage and current curves of the batteries. The results show that the curves of the graphs for both, the measured data and the simulated data, are close enough to accept the simulation model as validated for the presented application.*

Keywords

batteries in parallel, lead-acid battery, lithium-ion battery, electricity supply Africa

1. Introduction

The lack of electricity infrastructures is a common problem in African countries. The problem has significant consequences for medical facilities such as hospitals: Patients cannot be treated adequately without modern equipment and light. To improve living conditions, power supplies have to be installed. The given solar radiation can be used to produce needed energy. High expenses are the main barrier hindering the application of conventional grids. Low priced, easy-to-use, solar-powered island networks are better suited than conventional grids that expand over larger regions. Two basic requirements have to be met for a basic power supply in Africa: The energy supply has to be guaranteed 24 hours a day and it has to be durable and cheap. Due to sunless periods, the renewable energy has to be stored in batteries. The system itself has to be easily repairable due to missing experts for power electronics and battery storage systems on-site.

Typically lead-acid batteries or lithium-ion batteries are utilized as storage systems for island networks. Both energy storages have (dis-)advantages: Lithium-ion batteries have a high energy density and high cycle stability, but are expensive. Lead acid batteries are cheap but offer a low energy density and low cycle stability. These disadvantages can be compensated by combining a lead-acid battery as long-term storage and a lithium-ion battery for the short cycles [1].

To predict the performance of this system and its long-time behaviour a simulation model is needed.

Simulation models combining different cell types such as lithium-ion and lead-acid already exist: They depend on energy management systems (EMS) that coordinate the energy flow. To simplify and make the island network cost-efficient, the batteries can be connected in parallel without EMS. The focus of this work is to develop an appropriate simulation model that is validated with a real system. At the end the simulation model can be used to fit the best combination of sizes of the storage system and the solar plant.

1.1 Related Work

Some approaches focus on applying different types of batteries to supply enough power for varying applications such as very-large-scaled integrated (VLSI) chips [2], telecommunication applications [1] and renewable energy storages [3]. The actual power requirements decide on which battery is used. Low-rate cells and high-rate cells for the power consumption of a VLSI chip are combined in [2] in order to extend the life-time of the power supply. The current-capacity characteristics of the two cells differ. The result of the experiment was that it is essential to respect the current-voltage characteristics to prolong the service life.

Another application which has already been tested with a mixed battery-storage system is telecommunication. In [1]

lithium-ion batteries and flooded VRLA batteries are used to extend the storage capacity of existing lead-acid-battery-storages. The results indicate that mixing battery technologies can be economically interesting for service providers as alternative to site expansion or full battery system replacement. A variable storage system with three types of batteries for wind and solar energy is built up in [3]. In this application an optimization algorithm was used to find the best battery combination for the load. The load can have any profile for example a household or a radio mast.

In all approaches described above the batteries are connected to an EMS. An EMS brings the negative impact of additional costs and complexity. The advantage of an EMS is the active control of the energy flow [4]. The rules for the energy flow can be set individually e.g. for cost optimization. A battery management system is needed as well for a successful EMS. Otherwise there is no basis for energy flow decisions. A simulation model without EMS is missing yet.

2. Experimental Setup

2.1 Simulation model of a Lead-Acid and Lithium-Ion Battery

For the battery simulation the battery models described in [5] and [3] were used as basis. Both models can be divided in an electrical model and an ageing model. The electrical model of the lead-acid battery is based on the shepherd equations [6]. For the ageing model of the lead-acid battery the ageing model of [6], which is based on physic-chemical processes (corrosion and degradation), was used instead of the ageing model of [5], which is specialised on one battery type.

In the electrical model are two equations: one for charging (Equation 1) and one for discharging (Equation 2). These equations have fitted parameters to simulate the actual used battery type. The parameters for the charge and the discharge equations differ, resulting in discontinuities in the voltage curve when one battery is changing its status from charging to discharging. This might be acceptable if the current is known before entering the battery model. However, for calculating the input current in the branch of the lead-acid battery model one actual battery state is needed. It is impossible to calculate the input current in case the equations answer both true or false for the next incoming current. An error-free simulation requires an answer depending on XOR logic for every case. One solution is to change the Shepherd equations for calculating the current in each branch as well as the ageing model of the lead acid battery in the model of [5].

$$U(t) = U_0 - g * DoD(t) + \rho_c(t) * M_c \frac{I(t)}{C_N} * \frac{SoC(t)}{C_c - SoC(t)} \qquad \forall I(t) > 0$$

Equation 1: Shepherd equation for charging (c) [5] (1)

$$U(t) = U_0 - g * DoD(t) + \rho_d(t) * M_d \frac{I(t)}{C_N} * \frac{DoD(t)}{C_d - DoD(t)} \qquad \forall I(t) \leq 0$$

Equation 2: Shepherd equations for discharging (d) [5] (2)

Variables: U [V] cell voltage, U_0 [V]: OCV, g [V]: electrolyte proportionality constant, SoC: state of charge, DoD: depth of discharge, ρ [Ω Ah]: aggregated internal resistance, I [A]: applied current, C_N [Ah]: nominal capacity, M: charge transfer overvoltage coefficient, C: normalized capacity, index c: charging, index d: discharging

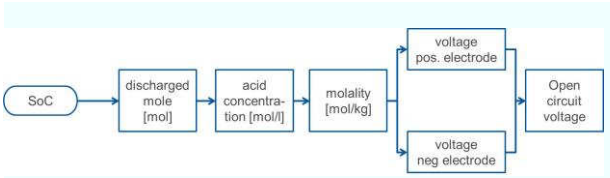

Fig. 1. Sketch for calculation open circuit voltage.

Changes to the Shepard Equations: The first two parts of the equations calculate the open circuit voltage (OCV). The OCV is changed to be calculated by a chemical model (Fig. **1**) which uses the link between the OCV and the acid concentration in the electrolyte, following the equations given in [7] and [8]. The result is given back to the shepherd equation as a value for the variable OCV. This new electric lead-acid battery model is used for further tests.

Changes to the ageing model of the lead acid battery in the model of [6]: For the state-of-charge calculation it was decided to use a value range from zero to one also during ageing. To take ageing into account the actual capacity will be adjusted. With these changes the OCV of the lead-acid battery is calculated by the acid concentration and the resistance by the last two parts of the Shepherd equation (Equation 1 or Equation 2). To prepare the model to the validation application the Shepherd equation is fitted to a charging/discharging curve of the later used battery.

The lithium-ion simulation model is an impedance based model [9], [3]. The battery resistance is calculated by the internal resistance and the resistance of the ZARC elements. The OCV is directly given in the model. An ageing model is included as well.

Thus, the two battery models deliver all needed values (resistance, OCV) for the current division for a parallel connection.

2.2 Modelling the parallel Connection

The most basic battery model is suggested (Fig. **2**) for the parallel connection of the batteries: a resistance and a voltage source. The resistance comprises the internal

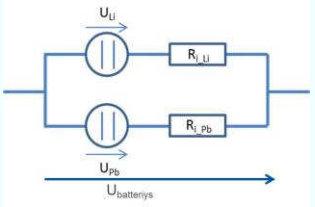

Fig. 2. Parallel connection of two batteries.

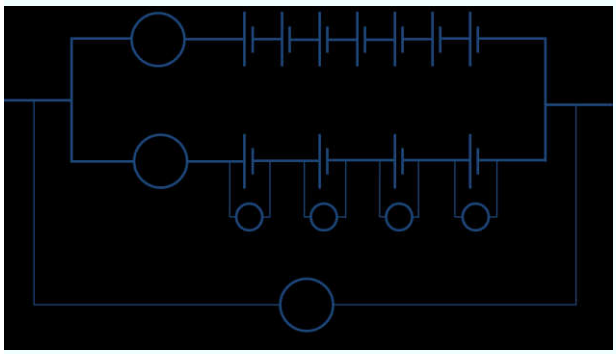

Fig. 3. Circuit diagram of the test setup.

resistance of one battery as well as the ohmic part (measurable at 1 kHz) [10]. The SOC dependent battery open circuit voltage is represented by a voltage source. Using this equivalent circuit model with elements derived from the formerly described equations and models, the current distribution in between the batteries and each battery voltage under load can be calculated.

Additionally the charging current has to be controlled in the simulation model: The maximum charging currents are given in the datasheets of the batteries. So the maximum charging current is limited to these values in the model. In normal use conditions these limits were never reached during testing. Just in the following explained case these limits save the system to behave as normal. The simulation is based on recursive steps lasting 10 minutes due to the required processing time of the weather data and the simulation time. In contrast to an instantly reacting actual battery, the simulation model is discontinuous. Each value for the current division model (Fig. **6**, in this part of the complete simulation model the input current will be divided in the two branches (lead-acid battery and lithium-ion battery)) is calculated with the parameters of the battery model from the state of the last step. Consequently, the behaviour of the batteries might be different than predicted due to already reached limits in case of huge value changes in the input data. This can lead to an excessive charging current for the new situation (because of a too late rising charging resistance) which may result in exaggerated ageing. Effectively this current charging restriction is just a

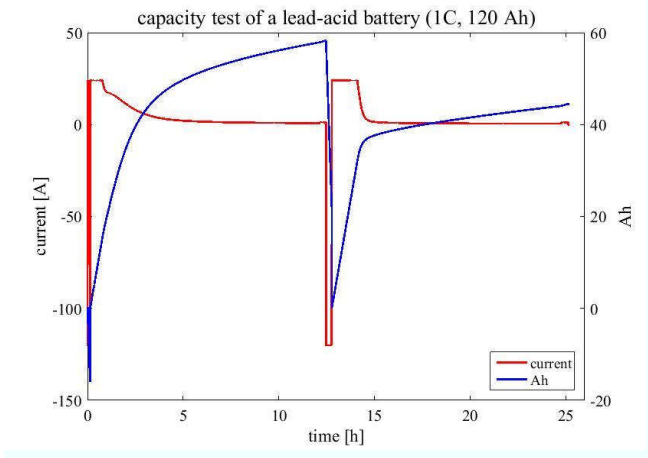

Fig. 4. Capacity test of a lead-acid battery.

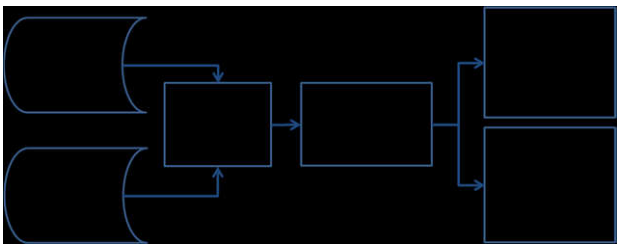

Fig. 6. Complete Simulation Sketch.

safety rule to prevent simulation errors. In the lead-acid battery model a fast increasing resistance is included in the shepherd equations (part 4 of Equation 1) in order to prevent the battery from overcharging.

2.3 Validation Application of the Model

As already mentioned the application of this battery system is a clinic in Nioki, Africa. Concerning the application the model is validated based on a real-life scenario: In Africa, many countries are without infrastructure. However, in most regions the high potential for solar-energy technology has not yet been exploited. Nevertheless, it is not possible to install solar plants additionally to given energy suppliers like in European countries. The efficient use of solar energy in Africa as main energy source depends on the storage system, e.g. batteries. A tool for cost calculation and cost optimization already exists at ISEA. In this tool, a solar plant, different battery types and an energy management system are integrated [3] using MATLAB/Simulink. Into this framework a new simulation block for battery parallelizing has been added. In this case an African hospital is simulated as load. In this hospital, a fridge, some lights and an operating lamp have to be supplied with energy. To simplify the load profile fourteen hours working time and ten hours rest time are assumed. As input data the weather conditions (temperature and solar radiation) and an estimated daily load profile are taken into account. The weather data are provided for two years in ten minute steps by [11]. For this application solar energy is the only energy source. The battery data for modelling the system are adapted to the used batteries in the validation setup. Caused by time limits the ageing parameters could not be fitted to the used batteries. This should not have consequences for the electrical validation in short time periods.

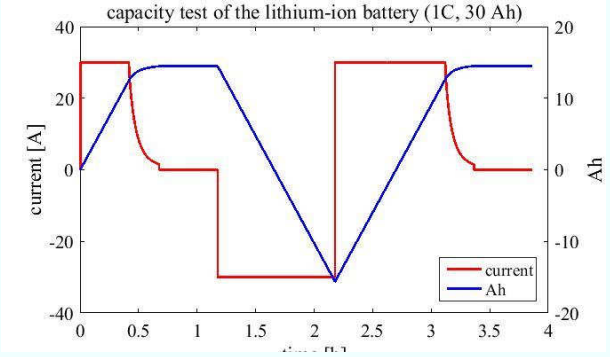

Fig. 5. Capacity test of a lithium battery.

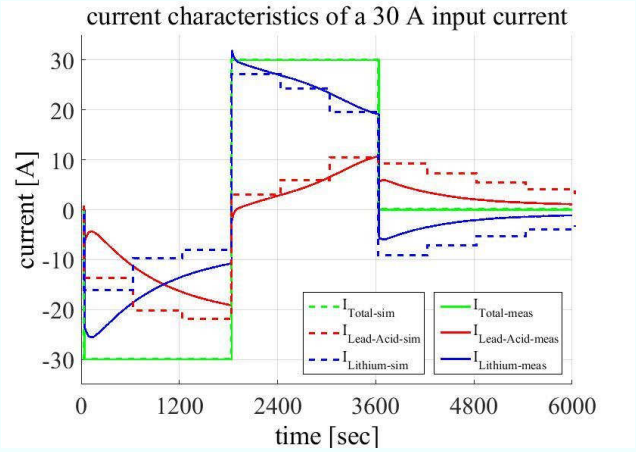

Fig. 7. Current characteristics with a 30 A input current.

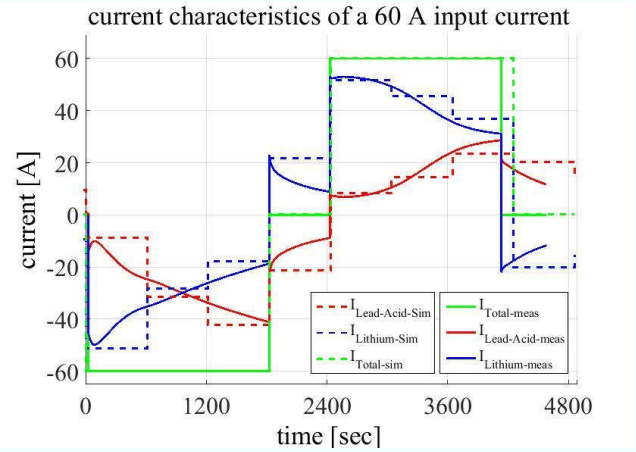

Fig. 9. Current characteristics with a 60 A input current.

In this work the electric model of the parallel use of batteries is validated. The ageing model is not validated caused by time. For additional calculations (e.g. cost calculations) the given parameters of the "old" batteries are used to bypass the validation of the ageing models.

2.4 Validation setup

A 14 V setup was built out of seven lead-acid traction-batteries (deu-batt, 2V/cell, 120 Ah) and four lithium-ion batteries (Kokam SLPB, pouch-bag, 3,6V/cell, 30 Ah) for validation. The cells of the same technology were connected in series. In this configuration a capacity test was conducted (Fig. **4** and Fig. **5**). The capacity test is performed with a 1C current. According to [12], the full capacity value is not expected for the lead-acid battery, because of the direct link between capacity and current rating (Peukert equation (Equation 3)). For ideal batteries v

$$i^v * t = C \tag{3}$$

Equation 3: Peukert equation (i:current, v: constant, t: time, C: capacity) [9]

(Peukert coefficient) is 1. For lead-acid batteries v is a value between 1.01 and 1.4.

Afterwards the two battery strings were connected in parallel. Every branch was equipped with a current measurement and a voltage measurement (Fig. **3**). For security reasons every lithium-ion cell was equipped with a voltage measurement and a temperature measurement. The whole system has a capacity of 150 Ah.

Validation criteria: The energy division in between the battery types should always be the same in the simulation and the test-system. Therefore the current courses of different test-setups are compared. To quantify the results the energy balance for each battery is calculated.

2.5 Results

The input current is shown in both diagrams (Fig. **4**, Fig. **5**) as red curve and the accumulated amp-hours as blue curve. Positive current implies charging and negative current implies discharging the battery. The capacity was tested with a 1C current. The lithium battery was discharged by 30 Ah (nominal capacity). The lead-acid battery delivered just 58 Ah. That is equivalent to half of the nominal capacity. This result can be explained with the high charging and discharging current of 1C (Equation 3). The value of the Peukert-constant would be 1.1 in this case.

Six tests were performed to validate the model. The first two tests were focused on different input currents. At the beginning of the tests, the batteries were completely

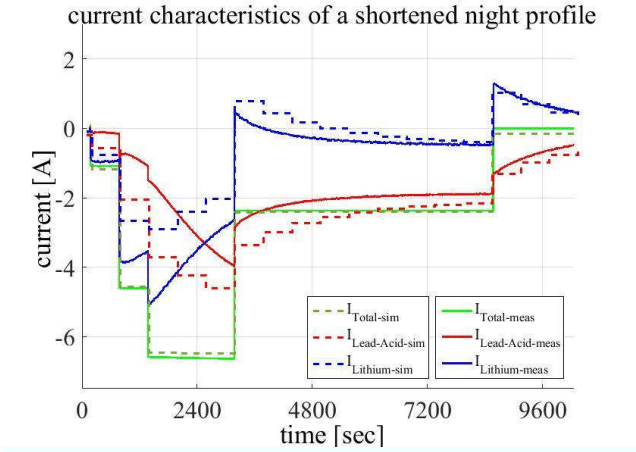

Fig. 10. Current characteristics of a night profile.

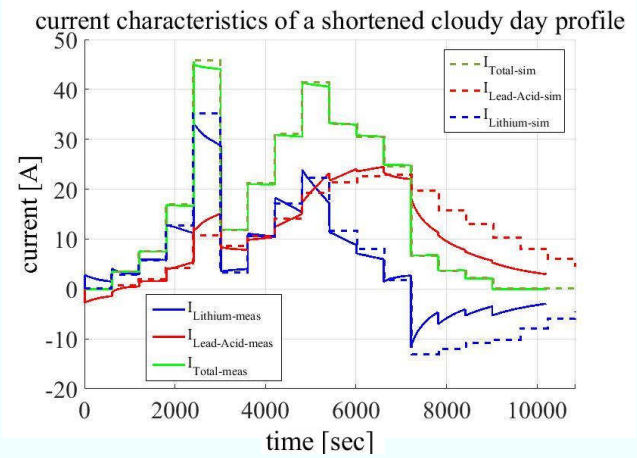

Fig. 8. Current characteristics of a shortened cloudy day.

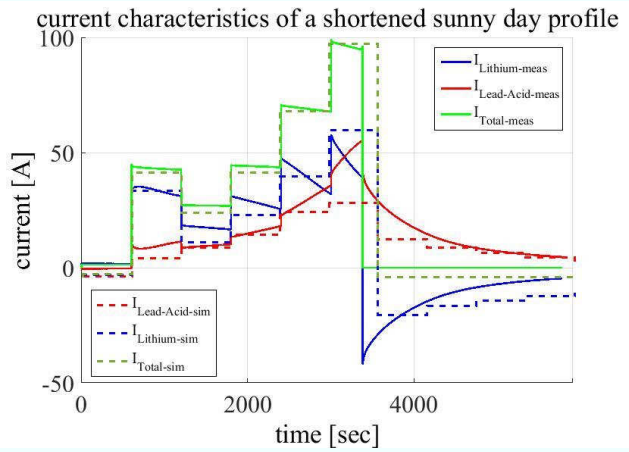

Fig. 12. Current characteristics of a shortened sunny day.

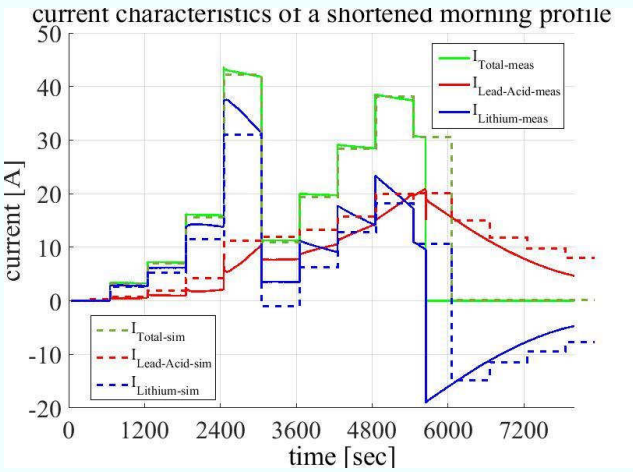

Fig. 11. Current characteristics of a shortened morning profile.

charged. During the tests, the batteries were discharged with 30 A (60 A) for twenty minutes and afterwards recharged with the same current. The measured (meas) and simulated (sim) data are given in Fig. **7** (Fig. **9**). The simulation results are shown in dashed lines and the measured results in solid lines. The green line shows the pack-current. The branch current is shown by the red line for the lead-acid current and the blue line the for the lithium-ion batteries current. The measured values are recorded at least every 10 seconds. As mentioned before, the simulation calculates a data value only every 10 minutes for computation speed reasons. This explains the discontinuities in the simulated data in comparison to the measured curves. This leads to a discontinuously shaped curve and complicates the direct comparison of the simulated and measured curves. The reason for using a discontinuous system is the input data: The weather data acquired by [11] can only be each ten minutes. Furthermore, the simulation is faster if fewer steps need to be calculated.

The current courses regarding to decreasing or increasing shape over time are equivalent for the simulation model and the measurement. In Fig. 9 the measured curves end before the simulated ones due to a reached voltage limit set in the test program. The quantitative comparison between experiment and simulation is more difficult due to different resolutions. A comparison of the figures shows that most of the values correspond.

Afterwards, more complex profiles were tested. This model was built for a solar model. Therefore, the fixed input quantity was changed from current to power. The tests focused on current profiles for different time periods (morning (Fig. 11), afternoon, night (Fig. **10**) and corresponding lighting conditions (sunny (Fig. **12**), cloudy (Fig. **8**), dark). Due to limited testing time the day profiles are reduced to 3 hour test profiles. The shapes of the current curves in the simulation model and the experiment are similar. However, the fixed power value in combination with the step-wise simulation model results in curve differences between the simulation and the measurement. These differences are also visible in the total current curve. The changes during one time step cannot be reproduced in the simulation model. The reduced day and night profiles imply power steps due to missing intermediate steps: The profiles are more dynamic than in reality. The current step size from one simulation step to the next step is big. In these moments the simulation model reaction is not fast enough for a real time simulation. After a few time steps the simulated curves have adapted themselves again in relation to the measured curves.

In reality the sun should be a more constant energy supplier than modelled in the profiles suggesting that this case can be excluded from the analysis.

The earlier ending of the measured data is already explained by voltage limits during charging for security reasons.

The Ah balance was drawn up (**Tab. 1**), to verify the visual comparison. All summed up values of the measurements are smaller than the simulation results. This is connected to losses during the tests due to side reactions, which are not modelled in this simulation.

Profile	Measurement			Simulation		
	Ah Lead-acid	Ah Lithium	Sum	Ah Lead-acid	Ah Lithium	Sum
30 A	-2,4	2,3	-0,1	-2,18	2,18	0
60 A	-4,04	2,43	-1,61	0,15	-0,15	0
Night	-5,13	-2,66	-7,79	-7,12	-0,94	-8,06
Cloudy day	29,53	16,615	46,14	32,51	14,02	46,53
Sunny day	24,45	16,27	40,72	22,05	23,3	45,36
Morning	17,88	11,49	29,37	21,69	8,8	30,48

Tab. 1. Ah-Balance of different current/power profiles.

3. Discussion

The best results were reached in the first test-setup. Here a constant input current was used for three time-steps. Caused by the independent input signal the input variable has exactly the same value in the simulation model and the test-setup. Furthermore the simulation model has enough time to respond to system changes. The current curves for the day and night profiles are of adequate quality. The resolution in time is not sufficient for exact simulations. The simulation model reports just one value for every 10 minutes. So the voltage change as well as the current change during ten minutes cannot be reported. The missing accuracy during a ten minute time-step speeds up the simulation. This advantage is quite important for a long-term forecast.

The results show that the curves of the graphs for both, the measured data and the simulated data, are close enough to accept the simulation model as validated for an application like prognosis on system costs for stationary systems. These results are good enough and better-than-expected. With this model it is possible to predict the costs for a stationary battery system with two cell technologies in parallel for a lifetime of e.g. 20 years. A simulation period of 20 years is suggested, because of the predicted lifetime of solar cells. Of course the batteries have to be replaced during such a long time period. The implemented cost calculation uses the present value method. So the economic efficiency, all costs for the whole system including all battery replacements, can be calculated and compared as costs transferred to today.

To complete the parameter set for the here used test setup the ageing parameters have to be extracted. The more extracted parameters from the batteries the better the simulation results will be. Further research is needed considering the development of other battery models to extend the range of possible applications. At the moment car profiles cannot be simulated because of missing dynamic battery models.

4. Conclusion

The aim of this work was to build up a simulation model for a power supply suited for a clinic in Nioki. Therefore, battery storage with different cell technologies in parallel was used. The approach of a battery combination without an EMS improves the system selection for standalone energy supplies. The simulation model is validated via a 14V-storage system. The current distribution between the two branches could be reproduced reasonably as well as the behaviour of each battery. For battery types with already known ageing behaviour a forecast of the long-time system behaviour and the costs can be achieved.

For further applications, the ageing model of the used battery has to be known in any case.

In follow-up studies, the battery ageing models applied in this approach during testing have to be validated. Another interesting field of application could be electric cars. Therefore, the battery models have to reproduce the dynamic behaviour of batteries. At the moment the battery reaction of the first seconds, used e.g. during cranking, is not represented. The dynamic profiles of cars cannot be simulated.

Acknowledgements

Research described in the paper was supervised by Prof. D.U. Sauer, Chair for Electrochemical Energy Conversion and Storage Systems, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University in Aachen, Germany.

The author wants to thank Dipl.-Wirt.-Ing. Julia Badeda for her support during this thesis.

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About Author...

Christiane RAHE was born in Bavaria and studied Electrical Engineering and Business Administration at RWTH Aachen University. During her studies she was a student research assistant at ISEA. The subject of her master thesis was "System analysis for a lead-acid -lithium-ion battery pack for off-grid PV-Systems under consideration of optimized cycle life", which is presented here. Since November 2015 she has been PhD Student at RWTH Aachen University in the area of battery technologies.