Final report

Project title: **Measurement based temperature dependency analysis of electrochemical energy storage systems**
Project identifyer: NKFIH 120422
Duration: September 1, 2016 - October 31, 2019

1 Aim of the research

The use of electrochemical energy storage systems is getting more and more widespread nowadays due to the growing number of electrical vehicles. The proposed project is aimed towards the modeling and state/parameter estimation of thermal battery models.

A key property of electrochemical storage devices is the temperature dependency of their operation parameters (e.g. voltage, state of charge, etc.). Temperature dependency is particularly important in the case of electric vehicle batteries because they are operated in a wide temperature range between $-40°C$ and $60°C$. Different approaches to modeling the thermal behavior of electrochemical energy storage devices can be found in the literature. These are typically linear, (e.g., [13]) or LPV models [14].

The advent of hybrid and plug-in hybrid electric vehicles has created a demand for more precise battery pack management systems (BMS). Among methods used to design various components of a BMS, such as state-of-charge (SoC) estimators, model based approaches offer a good balance between accuracy, calibration effort and implementability. Excellent design of a thermal management system requires good understanding of the thermal behaviors of power batteries [15], [16].

The primary aim of this project wa the measurement based modeling and identification of the temperature dependency of electrochemical energy storage systems. The obtained results can be used as a part of a prognosis and health management system that takes the environmental circumstances (temperature) into account. It is also possible to integrate the results into a complex energetic model including domestic size renewable sources and EV batteries [17].

The finished project was a continuation of the PhD work of P. Görbe [18] where the temperature dependent experimental data driven model has been developed. *The results of the project will serve as a basis for a following NKFIH project (131501), where the development results of the present project will continued towards battery management.*

2 Personal and institutional background

The University of Pannonia was the host institute of the project that provided a good general research infrastructure and an inspiring research atmosphereduring the research.

The team members are mostly affiliated to the University of Pannonia (PE), Prof. K. M. Hangos is affiliated to SZTAKI.

Senior researchers supervised the work packages each according to their background and expertise. Prof. K.M. Hangos (SZTAKI) was responsible for WP1 where she closely worked together with Dr. A. Magyar (senior researchers of PE) and A. Pózna (PE), a PhD student (PE). Dr. A. Göllei lead WP2 where he worked with Dr. P. Görbe (PE, a senior researcher) and Dr. A. Magyar. Finally, WP3 was coordinated by Dr. A. Magyar, who cooperated with Prof K. M. Hangos and R. Bálint who is working on his PhD thesis in this area.

3 Summary of the scientific results

3.1 WP1: Thermal modeling of electrochemical storage devices

Modeling the thermal behavior of electrochemical storage devices is crucial prerequisite of precise battery pack management systems.

Thermal modeling of electrochemical storage devices. As the first step of the research, LiFePO4 batteries already being available in our department has been investigated. Batteries can be modeled by several modeling techniques, for example electrochemical, equivalent electrical circuit, empirical and black-box models. The equivalent electrical circuit model type is selected from the potential modeling methodologies to describe the time and temperature-dependent behavior of the investigated LiFePO4 battery. According to the literature and our experiments a first-order RC circuit model already gives sufficiently small modeling errors. It is well known that battery performance and parameters vary with environmental and operating conditions. One of the most important factors of the battery performance is the environmental (operating) temperature, which has a great impact on the battery performance because reaction rate of chemical reactions taking place in the battery are influenced by the temperature. Within the limits of operating temperature the performance usually improves with the increasing temperature. In conclusion the temperature has impact on lots of parameters thus it can be a good candidate as a parameter of parameter-varying model. A nonlinear parameter varying model has been proposed to serve as the basis of the further research which is a temperature dependent generalization of the first order equivalent circuit model of the battery [1]. As a further direction, internal resistance based aging models was investigated and used as a basis of state of health estimation methods. Moreover, as the aimed application is to be implemented in Battery Management Systems model simplicity implies low computational complexity which is crucial. The temperature dependence of the battery is modeled by static temperature-dependent characteristics for all the key battery parameters in order to keep the model complexity easy to handle [2].

3.2 WP2: Experiment design and measurement of electrical vehicle batteries

The developed models in WP1 need to be verified, calibrated and validated using measured data from real batteries. These have been be carried out in two steps by solving the tasks below.

The first, preliminary set of measurements has been carried out without the climate chamber due to delays in the administrative steps necessary for the purchase. The first approach was to examine only the charging process of the battery. The charging current was kept at a constant value during the charging period, while the actual state of charge value was integrated from the current signal. Charging with constant voltage was not examined because only the charging current was controllable in the proposed experiment configuration [2]. The purchased climate chamber has also been installed and a set of test experiments has been carried out with success [3]. The measurements are controlled and recorded by computer to evaluate the results obtained. The temperature change is achieved with a climate chamber controlled by a Dixell XH360 temperature and humidity controller. XH360 communicates with the computer via RS-485 with ModBus protocol, which only adjusts the temperature of the climate chamber. During the measurements, the battery is charged and discharged at different temperature profiles [4]. As a next step, LiFePO4 batteries was be investigated by means of temperature dependent behavior. An optimal design of battery charge-discharge experiment has been presented in the conference paper [5]. The base of the method is a nonlinear charge and a discharge model and two possible input signal families, PRBS charging current and CC-CV cycle, respectively. The optimality of the experiment design has been investigated with respect to the estimated trace of the covariance matrix and the measure of unbiasedness of a nonlinear least squares parameter estimation.

The results show that the different modes of the hybrid model perform differently. The preliminary results clearly shows, that the discharge model can be used with a higher estimation accuracy.

The second important question was the excitation performance of the two possible input signal families, PRBS, and CC-CV. It was apparent that the estimator is biased for both inputs.

A set of experiments has been performed to analyze the statistical properties of the estimator for different parameters of the two excitation signal families. The results show, that the estimate of the covariance matrix trace norm does not really depend on the excitation parameters neither in the PRBS, nor in the CC-CV case. However, the CC-CV excitation gives an average value for the trace norm of 0.12 as opposed to the average 0.14 for the PRBS excitation. The Euclidean distance between the actual parameters (R and Q) and the estimate for different excitation parameters has also been generated as an indicator of the unbiasedness of the estimator. The results show, that the only parameter that has any effect on the unbiasedness is the maximal current in the CC-CV cycle. So it can be stated that the CC-CV excitation outperforms the PRBS input in both criteria (covariance and unbiasedness).

The experimental measurements involving the climate chamber and the battery charger-discharger has been continued. [6] The measurements are controlled and collected by a computer-based data acquisition system which is described in details in During the measurements, the battery is charged and discharged at different temperature profiles [7], [8], [9].

As a secondary thread of this research, batteries as part of a THD reduction framework have also been utilized. Measurements has been carried out that show how the main elements of a computer system (memory, GPU, HDD, CPU) effect the nonlinear behavior of the system as a whole causing nonlinear distortion. As a further step, the usage of DC microgrid system utilizing a battery pack might be investigated as a possible way to eliminate nonlinear distortion.

Parallel work is devoted to investigating the current nonlinear distortion of IT devices linear and switching mode power supplies. A software package is developed suitable for separate varying degrees load of functional parts of personal computers. Based on the collected voltage and current harmonic analysis serious distortion is stated in current time functions in automatic power factor compensating devices, too. Enormous distortions are observed in simple structure power supplies low power consumption consumer electronic devices. The consequences and effects of this behavior are described, and possible solutions are adumbrated in detailed conclusion with the integration of domestic size complex energetic systems consisting of renewable energy sources, battery storage, and single and three-phase current inverter parts, especially in the development of direct current bus systems in computer system applications [10].

Another parallel, but connected research was done in the field of Model-based Power Generation Estimation of Solar Panels based on Weather Forecast data. This is connected to batteries by means of the optimal placement and sizing of battery banks next to a renewable source in order to ensure the continuity of electrical power. [11]

A possible future direction is to involve other parameters to the experiment design since they can also hold information about battery health.

3.3 WP3: Parameter and state estimation of electrochemical storage devices

The proposed temperature dependent nonlinear model (see WP1.) has been selected for the use of parameter estimation investigated by means of parameter sensitivity analysis. Afterwards a Least Squares based parameter identification method has been performed based on the measurement data obtained in WP2. It has been shown that charging the battery with constant current yields an insufficient excitation current input that results in linearly dependent parameters [12]. It has been shown that that the battery model is highly sensitive for the battery constant voltage, and it is sensitive for parameters capacity and internal resistance as well. The poor sensitivity for the exponential parameters is probably due to the fact that the battery was half charged at the beginning of the experiment and the exponential term has its highest impact for the fully charged case [12]. Since the followed method is valid only at one point of the battery life, it cannot even be stated that the same input signal is the best for a half-used battery than that for a new one. That is why further experiments was to be performed to analyze this phenomena along the battery life.

Afterwards, an optimization-based lithium-ion battery parameter estimation method has been developed in this year that is capable of describing the thermal behavior of batteries. The base of the method is a nonlinear charge and discharge model which describes the temperature dependency as a parametric function of temperature as an external variable. Parameter sensitivity analysis has been carried out on the model to find the parameters to be estimated, that are the electrode potential, the battery capacity, and two polarization constants. The internal resistance was found to be non-sensitive to the model output, thus it was not estimated. The proposed parameter estimation method contains two steps. At first, the key battery parameters are estimated from measured data of charging/discharging at different constant ambient temperatures. In the second step, the temperature coefficients of these parameters are estimated. The proposed parameter estimation method is verified by a set of simulation experiments on an electrothermal battery model capable of describing the energy balance (i.e. the thermal behavior) of the battery. The temperature-dependent parameter characteristics obtained generated by the proposed method can be used as a computationally effective way of determining the key battery parameters at a given temperature. The novelty of the method is that the temperature-dependent parameter characteristics can be estimated from charging profiles by the proposed method can be used as a computationally effective way of determining the key battery parameters at a given temperature. The proposed parameter estimation method is verified by simulation experiments on a more complex battery model that also describes the thermal behavior of the battery. A journal paper is submitted about this topic [2].

As further research direction, time varying charging current has been used for the estimation of internal resistance that might be the basis of a health diagnostic (state of health estimation) system.

4 Publication summary

The data of publications already published or accepted in final form and related to the project are summarized in the following table:

Type	*Number*
Journal papers with impact factor	3
Q1 papers	1
Refereed journal papers without impact factor	1
Conference papers	4
Conference lectures with abstract	1
Total number of publications	12
Sum of impact factors	4.85

In addition, three of our PhD students and candidates (L. Neukirchner, R. Bálint and A. Pózna) started to write their PhD dissertations in this period, all of them will defend their theses in the spring 2020.

References

[1] A. I. Pózna, K. M. Hangos, and A. Magyar, "Design of experiments for battery aging estimation", *IFAC-PapersOnLine*, vol. 51, no. 28, pp. 386–391, 2018.

[2] A. I. Pózna, K. M. Hangos, and A. Magyar, "Temperature dependent parameter estimation of electrical vehicle batteries", *Energies*, vol. 12, no. 19, p. 3755, 2019.

[3] A. I. Pózna and A. Göllei, "Analysis of the lifespan of the energy storage units connected to the renewable energy systems", in *Klímaváltozás - Energiatudatosság - Energiahatékonyság (KLENEN 18) Gárdony, Hungary.*

[4] A. Göllei and A. Magyar, "Temperature dependence study of electrochemical storage systems", in *2019 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET)*, IEEE, 2019, pp. 1–5.

[5] A. I. Pózna, K. M. Hangos, and A. Magyar, "Design of experiments for battery aging estimation", *IFAC-PapersOnLine*, vol. 51, no. 28, pp. 386–391, 2018.

[6] A. Göllei, P. Görbe, S. Veronika, and F. Attila, "Megújuló energiák integrációs lehet?ségeinek vizsgálata a pannon egyetemen", *Energiagazdálkodás folyóirat*, vol. 58, no. 1-2, pp. 36–39, 2017.

[7] Z. Kovács, "Elektrokémai rendszerek h?mérsékletfüggésének vizsgálata mérések alapján", Master's thesis, PE MIK Intézményi Tudományos Diákköri dolgozat, 2018.

[8] A. Göllei and A. Magyar, "Temperature dependency measure system for automotive batteries", in *1th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik (Croatia).*

[9] A. Göllei, "Villamosenergia tárolók élettartam elemzésének eredményei", in *Klímaváltozás - Energiatudatosság - Energiahatékonyság (KLENEN 19) Siófok, Hungary.*

[10] V Szücs, A Fodor, A Göllei, and P Görbe, "Examination of nonlinear distortion of it power supplies in low voltage grid from the current quality point of view", *Acta Physica Polonica, A.*, vol. 134, no. 1, 2018.

[11] R. Bálint, A. Fodor, and A. Magyar, "Model-based power generation estimation of solar panels using weather forecast for microgrid application", *Acta Polytechnica Hungarica*, vol. 16, no. 7, pp. 149–165, 2019.

[12] A. I. Pózna, A. Magyar, and K. M. Hangos, "Model identification and parameter estimation of lithium ion batteries for diagnostic purposes", in *Power Electronics (Ee), 2017 International Symposium on*, IEEE, 2017, pp. 1–6.

Related references

[13] A. Vasebi, M. Partovibakhsh, and S. M. T. Bathaee, "A novel combined battery model for state-of-charge estimation in lead-acid batteries based on extended kalman filter for hybrid electric vehicle applications", *Journal of Power Sources*, vol. 174, no. 1, pp. 30–40, 2007.

[14] Y. Hu and S. Yurkovich, "Linear parameter varying battery model identification using subspace methods", *Journal of Power Sources*, vol. 196, no. 5, pp. 2913–2923, 2011.

[15] S Panchal, I Dincer, M Agelin-Chaab, R Fraser, and M Fowler, "Thermal modeling and validation of temperature distributions in a prismatic lithium-ion battery at different discharge rates and varying boundary conditions", *Applied Thermal Engineering*, vol. 96, pp. 190–199, 2016.

[16] J. Li, L. Wang, C. Lyu, H. Wang, and X. Liu, "New method for parameter estimation of an electrochemical-thermal coupling model for licoo2 battery", *Journal of Power Sources*, vol. 307, pp. 220–230, 2016.

[17] P. Görbe, A. Magyar, and K. M. Hangos, “Reduction of power losses with smart grids fueled with renewable sources and applying ev batteries”, *Journal of cleaner production*, vol. 34, pp. 125–137, 2012.

[18] P. Görbe, “Áram minoség optimalizálása kisfeszültségu nemlineáris torzított hálózatokban megújuló energiaforrások komplex integrációjával”, PhD thesis, University of Pannonia, 2013.