Qualification and Verification of High-Power Battery Systems

for Traction Application under Dynamic Load Conditions

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HBM Test and Measurement

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Before a traction battery is introduced in the market, a qualification and verification of those systems is inevitable. A suitable test bench has to cover a high voltage and current range as well as a high dynamic and it should be able to execute the necessary tests as realistically as possible and in an application-oriented manner. For this purpose, the measurement techniques have to be highly precise and dynamic. Based on the description of high-power traction battery designs and the requirements for testing those systems, the paper presents a unique high-performance test bench and a possible solution for the instrumentation with the data acquisition system GEN3i. Finally, different measurements will be presented.

1. Introduction

The increasing demand and the need for electrical energy storage systems in several diverse applications makes it necessary to continually develop new battery systems and explore new battery technologies. This progressive evolution leads to continuously increasing energy and power densities. Thereby, keeping the mechanical characteristics such as weight or size constant, the storage capacity of the batteries can be increased. This results, inter alia in the field of traction applications, into even greater distances and, thus, paves the way for the advancement of electric mobility. Especially for use in mobile traction applications, battery storages must meet high requirements. Criteria such as energy storage capacity and size of the battery, characterized by the energy or power density, as well as the implemented safety concepts, serve as a basis for the first valuation of the storage systems and, hence, as a selection criteria for the planned application. Therefore, already during the development process, qualified testing of the necessary, application-specific requirements is inevitable. To achieve meaningful results, there is a compelling need to execute all these test procedures as realistically as possible and in an application-oriented manner. Only then can statements be made about the behaviour of the battery system in the later-intended application. Therefore, a modern test bench has to flexibly meet the high and unique test requirements. Especially for high-power battery systems, the test bench also has to be highly dynamic and it must cover a high power range. High requirements for the instrumentation of the test environment also have to be considered. The measurement techniques have to be highly precise and dynamic. They must ensure live monitoring as well as post-process editing and evaluation.

2. High-Power Traction Battery System

The following considerations only refer to the lithium-ion battery, because this technology has the potential to fulfil the demands of energy and power density today for its application in electric vehicles (EVs) [1]. As figures 1 and 2 reveal, a battery system consists of various complex subsystems. These individual components have to be closely coordinated with each other to guarantee a safe and optimum operation. With the interconnection of the single electrochemical cells, high system voltages and capacities can be achieved. To reach the total voltage and current requirements of the battery pack, the pack contains many discrete cells connected in series and parallel. For the application in traction batteries, the packs can contain several hundred single cells. Typically the large stack of cells is grouped into smaller stacks called modules. Within each module, the cells are welded together to complete the electrical path for the flow of current. Several of these modules are placed into the battery pack. The modules can also include cooling mechanisms, temperature monitors, and other devices like cell balancing. Cell balancing is important for the life of the battery system because without the balancing system, the individual cell voltages will drift apart over time. This result in a rapid decrease in the capacity of the total pack [2].

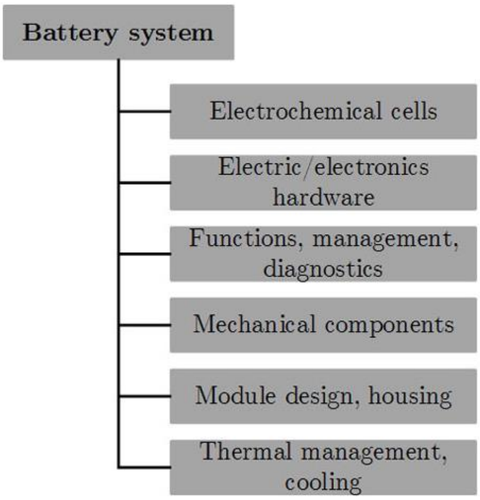

Fig. 1: Variety of subsystems of a traction battery

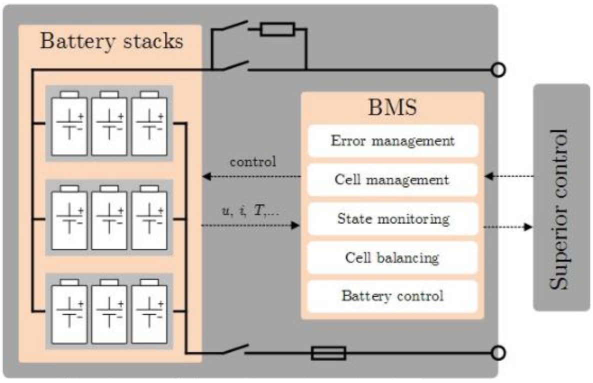

Fig. 2: Typical setup of a battery for traction application

As preferred by the battery manufacturers, the applied battery cells can differ in their chemistry, physical shapes and dimensions. This leads to a first clear distinction of the different battery system designs. Besides the interconnection of the single cells and modules, a battery system consists of further mechanical and electrical components which permit the operation of the system. For an optimal operation, these components have to be closely coordinated with each other and with the intended application. To limit the current of the pack under a short circuit condition, the battery pack is equipped with a main fuse. The single stacks as well are usually equipped with a module fuse to interrupt internal over-currents. Often a “service plug” is placed within the electrical path of the battery, which can be removed to split the battery stack into two electrically isolated halves. Also, the battery contains relays, or contactors, which control the distribution of the battery pack’s electrical power to the output terminals. In most applications, there will be a minimum of two main relays which connect the cell modules to the main positive and negative output terminals of the pack. Some battery designs further include alternative current paths for pre-charging the drive system with a limited current or for powering an auxiliary bus. In addition, often batteries used for traction application contain a brake chopper. This unit is necessary to prevent the battery from overcharging while the EV is recuperating. For a battery fully charged to 100 %, the brake chopper unit converts the excess energy into thermal energy during recuperation. This prevents the battery from overcharging. Every traction battery system also contains a variety of temperature, voltage, and current sensors. The collection and analysis of data from the cell/pack sensors and the control of the contactors and the entire battery system is conducted by the Battery Management System (BMS). With the collected data, the BMS takes over the task of state monitoring like state-of-charge (SOC) determination and error management. Hence, the BMS is a complex and essential electronic system that manages the performance and safety of the battery pack and the high electrical energy stored within, an extensive BMS test is thus inevitable.

As described in the previous paragraph, to build a safe and reliable battery system for traction application, all of the individual components have to be optimally coordinated. The complexity of the individual components leads to a complex interaction, and therefore, to a highly sophisticated battery system. Thereby exists the absolute necessity for a realistic verification of the interaction for the intended application. Altogether, which tests are performed at each step is a different matter and depends on the specifics of the process and the device as well as the intended application. Since every battery pack design is unique and testing requirements differ from the respective intention of use, a test bench has to flexibly fulfil the individual battery testing challenges.

3. Requirements of Appropriate Test Procedures

To meet the unique requirements of the automobile industry, it is inevitable to design specific test procedures for the battery systems and its individual components. Standard ISO 12405 provides specific test procedures for lithium-ion battery packs and systems, specially developed for propulsion of road vehicles. It specifies such tests and related requirements to ensure that a battery pack or system is able to meet the specific needs of the automobile manufacturer. Performance and reliability tests as well as abuse tests are some of the many necessary investigations [3].

Finally, to build a safe, reliable and also standard-conforming battery system the respective test procedures have to be executed and the results have to be analysed. However, in addition to the standard test procedures, realistic and application-oriented tests have to be executed. This means the battery system has to be investigated according to the conditions in the application. The unique test procedures have to verify that the system works in a safe and reliable manner, and fulfils the application-specific features. The variety of investigations include, among others, the verification of: the reliable interaction between the single components, the correct interaction between the BMS and the vehicle, the compliance of the application-specific safety requirements, the load behaviour for specific temperature ranges, the strain of the battery for peak currents, system behaviour for different temperatures. Only after conducting this qualification and verification process, a battery system is enabled for use in the application.

4. High-Performance Test Bench for Traction Battery Systems

In accordance with the high and individual requirements of high-power traction batteries, a corresponding test bench has to fulfil the high requirements for the test procedures. A test stand has to cover the high voltage and power range of the future battery systems. In addition to this, the main focus of a test bench is to provide the most flexible and highly efficient test execution. The execution of the test procedure has to be as realistic and application-oriented as possible. Besides the testing of the performance-related parameters like capacity and power, this means that the test bench has to simulate application-oriented operating conditions as well as the possible cases of faults. Because of the individuality of the different battery systems, the test bench has to have the flexibility to adapt on the respective threshold values and given conditions for testing the safety concepts and also the functionality of the entire system. Equally, a safe operating environment has to be guaranteed for the device under test (DUT) and the operating staff. Considering the high requirements for the process of qualification and verification of a high-power traction battery system, a unique high-performance test bench for these systems and their individual components is presented in this section.

The power electronic interface of the test bench consists of two two-level converters, connected via the shared dc-link. The three half-bridges of the output dc-dc converter are controlling the battery charge/discharge current, while the grid side converter controls the common dc-link voltage and the grid current. With this configuration, the test bench allows a bidirectional power flow between the DUT and the grid, with a maximum operating power of 250 kVA. This ensures high-power and energy-efficient charge and discharge experiments.

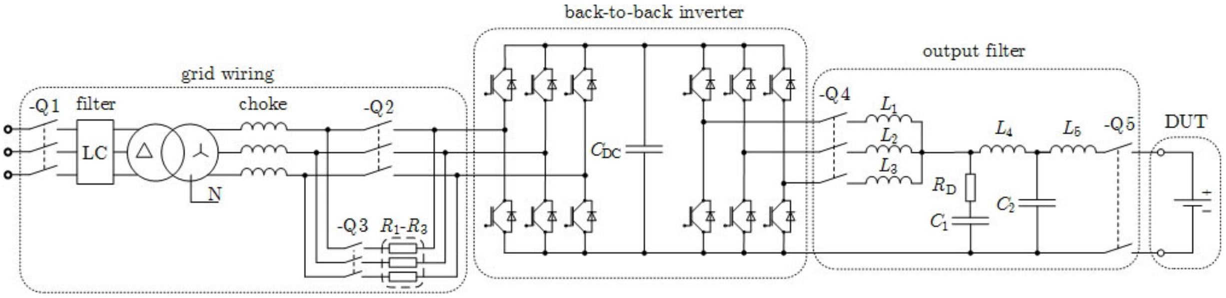

Fig. 3: Principle wiring diagram of the presented test bench

Figure 2 presents the principle wiring diagram of the power connections. The grid connecting components include the grid circuit breaker, the grid filter and choke, the isolation transformer for potential isolation and a dc-link pre-charge circuit. With the circuit breakers Q1-Q5, the galvanic isolation between the test bench and the grid as well as the DUT is accomplished. Table I lists the electrical characteristics of the presented test bench.

Table 1: Electrical characteristics of the presented test bench

Grid voltage	400 V
Output voltage range	0 – 750 V
Maximum output current	± 800 A
Maximum output ripple current	≤ 1 A
Maximum system power	250 kVA

To ensure accurate investigation results and to not strain the DUT unnecessarily, it has to be charged/discharged with a low ripple current. As a result, it is guaranteed that the DUT is solely charged/discharged with the predefined and standardized load profiles, so the reaction of the DUT is obviously attributable to them. Therefore, the three output half-bridges are built to a multiphase current-sharing converter. The load current is consequently divided on the three single phases. This current-sharing scheme will prevent an individual module from suffering excessive current stress in steady state operation, and during line/load transient conditions. Also, very high battery currents can be achieved. As a result of the approach to switch the three phases interleaved, for a phase shift of exactly 120 °, the inductor ripple currents tend to cancel each other, resulting in a smaller ripple current flowing into the output capacitor [4]. The frequency of the output ripple current is tripled as well. Under certain conditions, it is possible to eliminate the ripple current at the output node. The phase relationship in Figure 4 shows how ripple current cancellation at the output works.

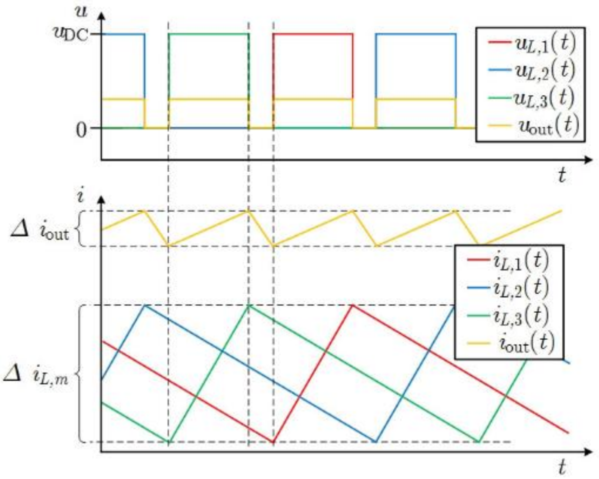

Fig. 4: Inductor voltages and currents for three phase interleaved switching, D = 0.75, m = 1, 2, 3

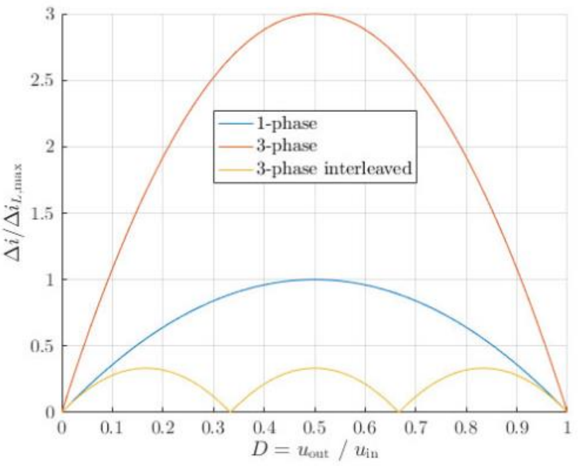

Fig. 5: Normalized peak-to-peak output ripple current vs. duty cycle

To quantify the output ripple current amplitude in an m-phase circuit, a closed-form expression was developed [4]:

$$\Delta i_{\text{out}} = \begin{cases} \dfrac{u_{\text{in}} \cdot D \cdot (1-D)}{f_{\text{s}} \cdot L}, & \text{for } m = 1 \\[2ex] \dfrac{m \cdot u_{\text{in}} \cdot D}{f_{\text{s}} \cdot L} \cdot \dfrac{\prod_{i=1}^{m} \left|\frac{i}{m} - D\right|}{\prod_{i=1}^{m-1} \left(\left|\frac{i}{m} - D\right| + \frac{1}{m} \right)}, & \text{for } m = 2, 3, \dots \end{cases}$$

The dependency between the output ripple current and the duty cycle for the three phase application is shown in Figure 5. For a duty cycle of D = [0, 1/3, 2/3, 1], the current cancellation leads to 0 A output ripple current. Within the entire range, the maximum peak-to-peak output ripple current is minimized by a minimum factor of three, in comparison to the maximum possible current ripple in a single phase.

Furthermore, to minimize the output ripple current for all operating points, an individual filter network is developed. For achieving a high damping slope, the low-pass filter is designed as a multistage filter. Because of the interleaved switching with 8 kHz per half-bridge, this filter is optimized on the resulting frequency of 24 kHz. As a result of all these measures, the output ripple current over the entire output voltage range of the test bench is minimized below 1 A. Figure 6 shows the presented test bench including the data recorder GEN3i and an appropriate DUT.

Fig. 6: Proposed High-Performance Test Bench, GEN3i, Pb Traction Battery

Along with the extremely low ripple current and the high voltage and current range, the test bench offers the possibility to execute realistic and application-oriented test procedures. The test bench can flexibly adapt to the specified test conditions and battery systems. Thereby the different safety measures like over- and under-voltage protection can be verified. For this, the test bench can adapt to the respective threshold values to execute the specified tests and can do so in a safe manner. In addition, with the possibility of executing standardised and manufacturer-specific load profiles and pulse tests, the battery system can be tested for use in the later-intended application. Such tests are necessary to achieve meaningful statements about the behaviour of the battery in the intended application.

Moreover, the battery configuration can also be verified. So it can be tested if the individual components and also the interaction of these work properly. Also, the test bench offers the possibility to execute common test procedures like determining the storage capacity or cycle tests, as well as more complex investigations like the automated determination of the internal DC and AC resistance with an electrical impedance spectroscopy. In addition to testing a complete battery system, the test bench also provides the option to test the single components like the individual cells/modules or integrated power electronics. Due to the high degree of flexibility, the test bench is also suitable for other DC test applications. Furthermore, the test bench is equipped with special safety measures to guarantee a safe test environment. For example, an isolation monitoring system tests the test bench and DUT against isolation faults.

5. Instrumentation

Another important aspect of setting up a test environment for the qualification and verification process of traction batteries is the selection and optimisation of appropriate measurement equipment. This is necessary to achieve reliable results, based on which, precise statements about the behaviour of the battery system in the later-intended application can be made. So the reaction of the DUT during a test procedure has to be recorded in a highly precise and dynamic manner. The variety of different measurement signals for a traction battery test includes the battery terminal voltage/current, the cell or module voltages/currents and temperatures at different spots. For understanding and verifying the battery behaviour under different conditions, the discrete signals have to be synchronized. Only with this synchronization, the state of the battery at certain operating points can be analysed. According to the different signal types and ranges, a suitable data acquisition system has to flexibly adapt to the specific conditions. Besides measuring the high battery terminal voltage with high precision, the instrumentation also has to guarantee the measurement of the individual “low” cell voltages with the same accuracy. Just as important as the adaptation to the different signal levels, is to ensure that the huge number of different signals can be recorded simultaneously. Furthermore, it is necessary to ensure online-monitoring of the signals, especially the critical signals. So in case of critical conditions or unforeseeable faults, the test staff can manually interrupt the test procedure. For further analysis and documentation of the test procedure, a simple post-process editing and evaluation should be possible.

The HBM GEN3i is especially suited for this high requirement of data acquisition and transient recording. The GEN3i data recorder enables synchronous acquisition of all important quantities in energy-related systems with a large number of channels and high sampling rates [5]. With this data recorder, the easy commissioning of the test bench as well as the data acquisition during test procedures can be accomplished. Easy test measures like determination of capacitance as well as more complex measures like electrical impedance spectroscopy can be executed. Post process, the data can be analysed and further processed. This results in the generation of accurate statements about the battery system.

The entire instrumentation consists of:

- GEN3i data recorder for data acquisition, transient recording, live monitoring, post-process editing of: battery current/voltages/temperatures, inverter voltages/currents
- LEM IT 700/1000 S with high-precision measuring shunts, HBR 2.5/10 for measuring phase and battery currents
- Artificial star for measuring grid side voltages
- Thermocouples Type K

Figure 7 shows in a diagram format the measurement acquisition of system quantities which are sent to the GEN3i data recorder. For testing a traction battery system, only the measurement of the battery quantities is necessary. This includes the battery terminal voltage and current, the individual cell or stack voltages, as well as temperatures at different spots. However, for the commissioning of the test bench, a lot more signals have to be analyzed. For implementing and optimizing the grid control, the grid phase currents and voltages as well as the DC link voltage has to be measured. Based on the optimized grid control, the output control for charge/discharge experiments have to be set up. For this, the output converter and filter quantities have to be measured. With the dynamic measurement of the output quantities, different control strategies for the output side can be easily analyzed.

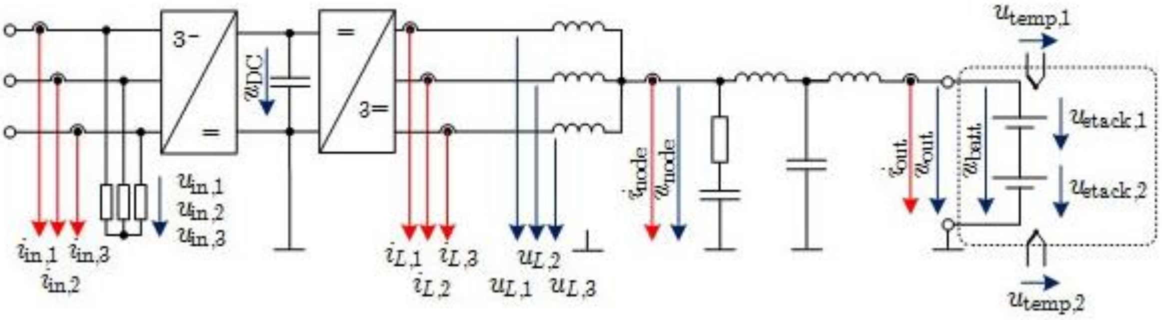

Fig. 7: Measured system quantities

6. Measurement Results

6.1. Methods for the Ripple Current Reduction

The first example indicates how the ripple current cancellation due to interleaved switching works. The measurement also shows the effects of the low-pass filter on the output ripple current. Therefore, the phase currents/voltages of the multistage converter as well as the resulting node current/voltage and output current/voltage are measured. The measurement in Figure 8 shows the principle of the interleaved switching method. The three phases are switched with a phase shift of 120 °. As a result of the switched phase voltages, the currents are phase-shifted as well. Due to the ripple current cancellation effect for interleaved switching, explained in section 4, the ripple currents tend to eliminate each other. This results in a reduced current ripple in the node point. Furthermore, the filter network is final damping this ripple current below 1 A.

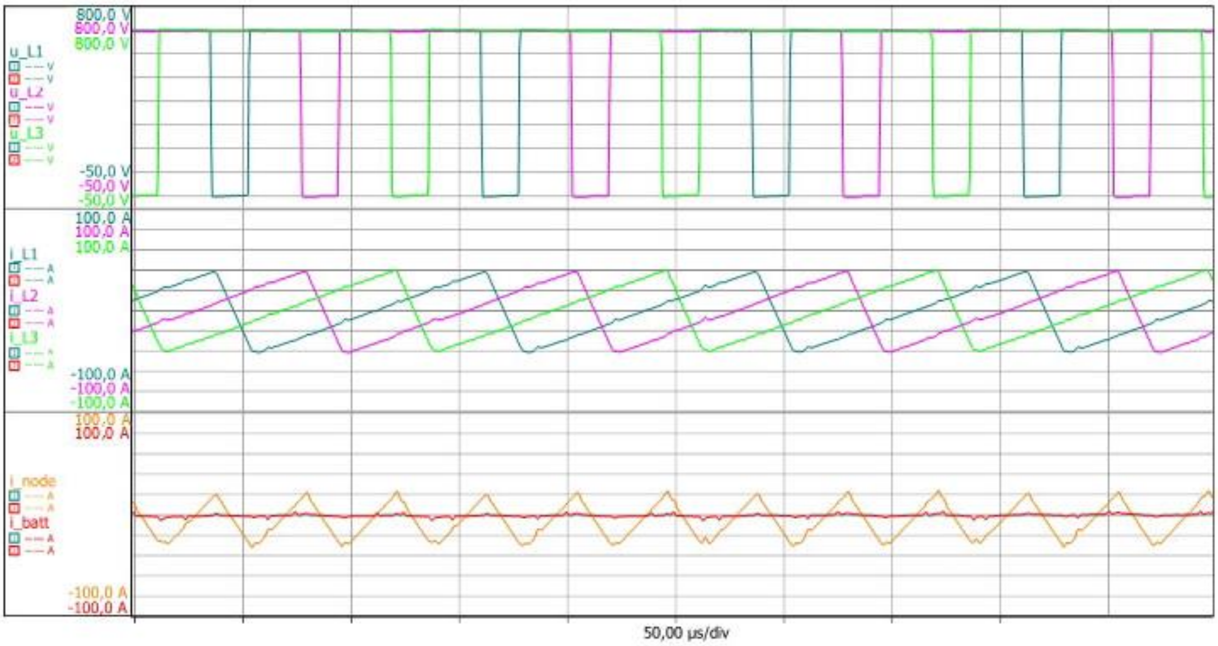

Fig. 8: Interleaved Waveforms for D=0.85

6.2. Constant-Current Constant-Voltage (CC/CV) Charging

The charge method CC/CV is used for charging lithium-ion batteries and battery systems, which may be vulnerable to damage if the upper voltage limit is exceeded. This method consists of two stages. In the first stage, the battery is charged with a constant current. The specified current charging rate is the maximum charging rate which the battery can tolerate without getting damaged. Before the cell voltages reach their upper limits, the charging method switches to constant voltage. Within this stage, with rising SOC, the battery current decreases. Finally, if the current falls below a specific limit, the charge process is finished and the SOC reaches 100 %. Figure 9 presents the proposed charge method. In the beginning, the DUT is charged with a constant current of 100 A. When the upper threshold voltage (115 V) exceeds, the charge method switches to the constant voltage stage. In this stage, the DUT is charged with the constant voltage of 115 V till the threshold current has exceeded and the charge process has ended.

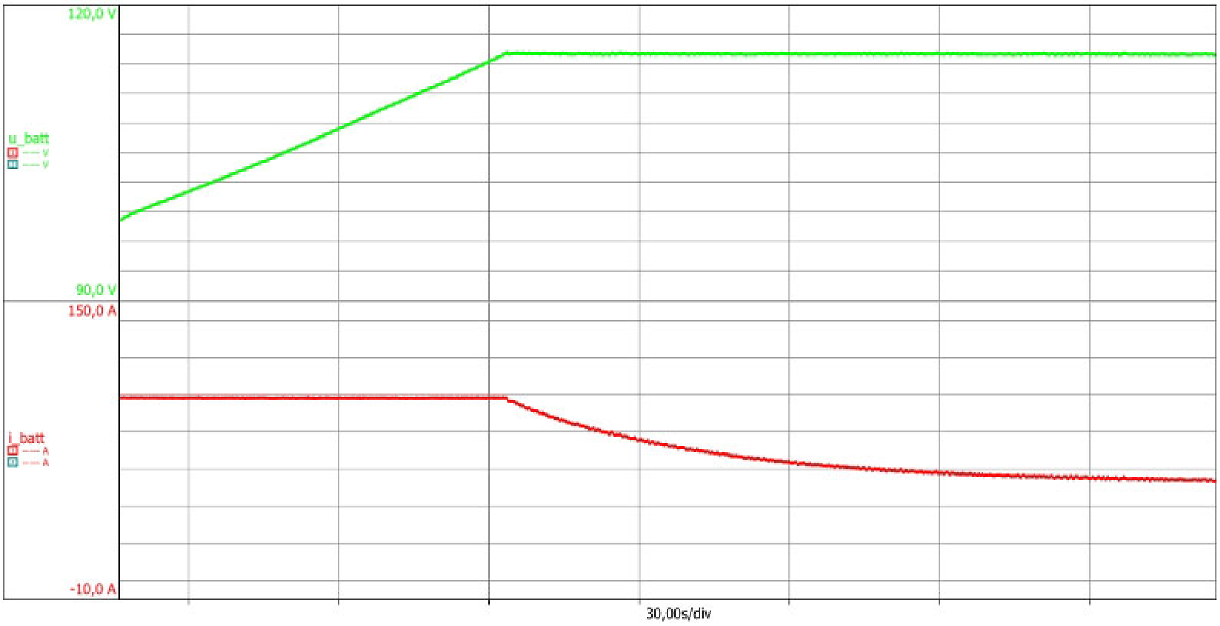

Fig. 9: CC/CV-Charging Example

6.3. Determination of the Internal DC Resistance

Besides the capacity of a battery system, internal resistance is also one of the major battery parameters. The lower the resistance, the lesser the restriction the battery encounters in delivering the needed power spikes. Batteries with large internal resistance show poor performance in supplying high current pulses. Internal resistance also increases as the battery discharges and the battery ages. The following measurement presents a technique to measure the DC resistance of a battery pack/cell. This method is based on the voltage change during a current pulse. Ideally, the current jumps from a small value (e.g. 0.1 C-Rate) to a high value (e.g. 2 C-Rate). After a defined duration, the voltage drop is measured. Following this, the voltage change is divided by the current change. The result of this calculation is the internal resistance of the DUT. [6]

Figure 10 presents the measurement for the determination of the internal resistance of a traction battery system. In the first stage, the DUT is discharged with a small current of about 21 A. If a stationary condition is reached, a current step is performed. The discharge current jumps to 400 A. Equally, the battery voltage drops. After a specific duration, the discharge process of the battery is completed and the calculation of the internal resistance can be carried out. The internal resistance of the DUT is determined as follows:

$$\Delta R_{\mathrm{i}} = \frac{u_{\mathrm{start}} - u_{\mathrm{end}}}{i_{\mathrm{start}} - i_{\mathrm{end}}} = \frac{\Delta u}{\Delta i} = \frac{93.77\,\mathrm{V} - 75.45\,\mathrm{V}}{-21.41\,\mathrm{A} - (-400.3\,\mathrm{A})} = 48{,}4\,\mathrm{m}\Omega$$

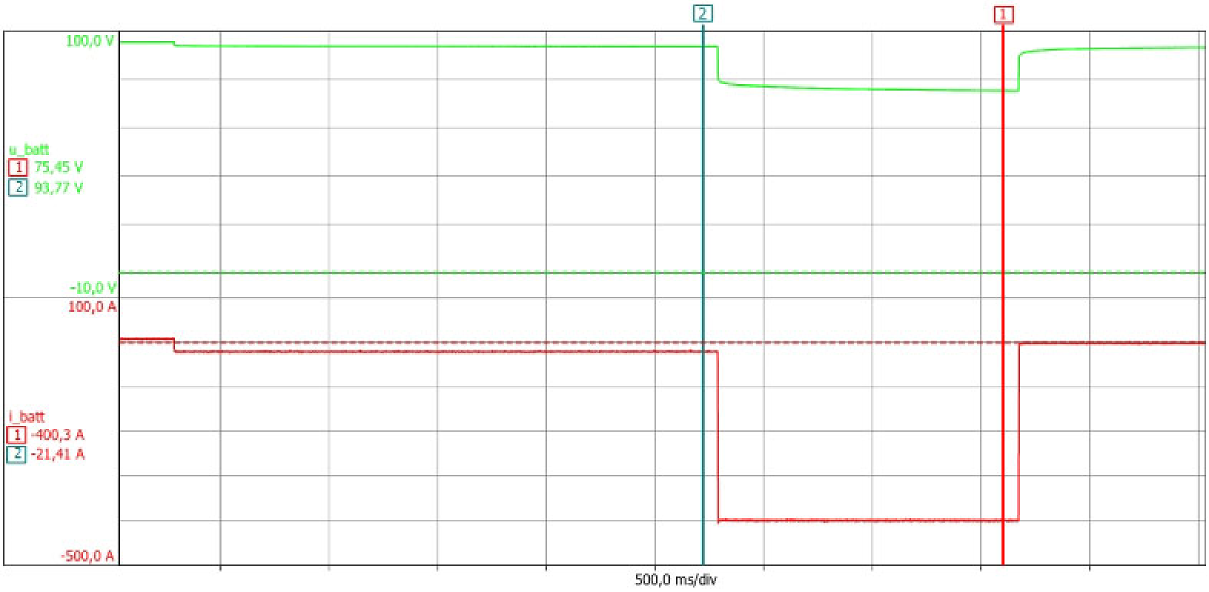

Fig. 10: Test Method for Determining the DC Resistance

7. References

[1] International Electrotechnical Commission (IEC): Electrical Energy Storage, White Paper, December 2011.

[2] Cao, J.; Schofield, N.; Emadi, A.: Battery Balancing Methods: A Comprehensive Review. In: IEEE Vehicle Power and Propulsion Conference (VPPC) (2008), DOI: 10.1109/VPPC.2008.4677669.

[3] ISO 26262 (all parts), Road vehicles – Functional safety.

[4] ISO 6469 (all parts), Electrically propelled road vehicles – Safety specifications.

[5] Linear Technology Corporation: High Efficiency, High Density, PolyPhase Converters for High Current Applications. cds.linear.com/docs/en/application-note/an77f.pdf. Release: 1999.

[6] Eberlein, D.; Lang, K.; Teigelkötter, J.; Kowalski, T.: Electromobility in the fast lane: increased efficiency for the drive of the future. Proceedings of the 3rd conference of Innovation in Measurement Technology, May 14, 2013.

[7] Jossen, A; Weydanz, W.: Moderne Akkumulatoren richtig einsetzen. First edition, Untermeitingen: Inge Reichardt Verlag, 2006. ISBN: 3-939359-11-4.