

Innovative Measurement Technology Solutions for Thermal and Mechanical Testing of HV Batteries

Dipl.-Ing. (FH) Timo Eich¹

¹ CSM Computer-Systeme-Messtechnik GmbH, Raiffeisenstr. 36, 70794 Filderstadt, Germany

Abstract

HV batteries have to endure multiple mechanical and thermal stresses when in service, which have to be extensively examined already in the development phase to prevent battery failures or even vehicle fires caused by thermal runaways. Thermal and mechanical simulations depend on real field data for creating reliable models and verifying such in later development phases against reality. For this reason field testing of HV batteries utilizing measurement technology is key. Unfortunately, testing under high-voltage conditions poses a lot of challenges on the measurement equipment, particularly when acquiring data from sensors like strain gauges, accelerometers and temperatures. In this presentation Timo Eich shows, how CSM GmbH mastered those challenges and solves the needs of car and battery manufacturers for mechanical and thermal testing worldwide with innovative measurement technology solutions.

Key words: High-voltage safety, battery testing, strain gauge measurement, acceleration measurement, temperature measurement

Mechanical stresses on HV batteries

In modern electric and hybrid vehicles, high-voltage traction batteries not only serve as energy storage units, but also perform structural and load-bearing functions in the vehicle, particularly in the passenger car sector, due to their proportion of the vehicle mass and their size and shape (skateboard architecture). This means that - at the latest when HV batteries are integrated into their respective target vehicles - they are confronted exposed to the conditions of the respective vehicle environment. On-road or even off-road environments in particular induce multiple stress influences during driving due to vibrations, impacts and shocks as well as deformations caused by the forces that occur when cornering or, for example, when driving over curbs (torsional forces). These forces, vibrations and deformations not only occur at the outside and surface of the battery housing, but also propagate into the inside of HV batteries with great effect. This results in some high forces on load-bearing elements such as struts, but also mechanical loads on busbars, for example, which connect individual battery modules relatively rigidly and can be subjected to high loads due to their relative movements to each other.

At the same time, the operation of lithium-ion batteries causes swelling, an expansion of the

individual battery cells due to electrochemical and thermal effects, which occurs particularly in prismatic cells. While the major reason for irreversible cell-swelling is the degrading of battery cells, reversible swelling mainly stems from thermal expansion of electrolytes.

Thermal stresses on HV batteries

The performance of HV battery systems heavily depends on the ambient temperature as well as on self-heating effects caused by high currents and electronic and thermal resistances. Effective battery management and the associated sophisticated temperature management are crucial here, especially when it comes to battery safety. This is one of the reasons why thermal testing of HV batteries is of such importance to battery and vehicle manufacturers. While end customers demand performance and a long range in all seasons, manufacturers must also ensure the safety of the battery and thus of the vehicle and its occupants. Above all, worst-case scenarios such as thermal runaways must be avoided.

Testing with measurement equipment is vital

All the effects and phenomena listed above require comprehensive investigations and tests of HV batteries, both in the development phase of batteries and in the near-series testing of

complete vehicles. Thermal and mechanical simulations can already provide valuable insights here - if the corresponding models are reliable and based on real data from road tests. Ultimately, however, even the best simulations cannot fully cover the countless small and large influences of the real world.

This means that testing of HV batteries and complete vehicles with analog measurement technology is crucial in several phases of vehicle development. On the one hand, to create a data basis for modeling and simulation and, on the other hand, to check the simulation results against reality and to improve and refine the models. Road tests are of crucial importance here, as even test benches only reflect the reality of the road to a certain, fixed degree.

Challenges when testing HV batteries with analog measurement equipment

In order to gain comprehensive insights into the physical and thermal processes in HV batteries, they must be equipped with sensors to record vibrations, strains, forces, pressures, deformations and, above all, temperatures. However, there are numerous challenges to overcome when performing measurements in HV batteries. Firstly, the space available for comprehensive instrumentation of HV batteries is very limited, as the batteries are usually very densely packed. Secondly, comprehensive instrumentation of the battery may also have adverse side effects on the actual operation and behavior of the battery, not least due to the numerous breakthroughs required for cables for sensor supply and signal lines. And finally, the measurement technology and sensors are directly confronted with the system voltage, which in HV batteries usually amounts to several hundred volts.

Challenges when measuring in high-voltage environment

The high battery system voltages pose two challenges for the measurement technology: the acquisition of the smallest sensor signals at HV potential and the safety of the measurement equipment and its operators.

Sensors such as accelerometers, force and pressure sensors, but in particular strain gauges and temperature sensors, provide extremely small measurement signals in the millivolt and microvolt range. These fine signals must be measured, digitized and transmitted by the respective measurement amplifier in a high-voltage environment with several hundred volts of potential without interference or superposition. This requires extremely good common mode rejection (CMRR), which is

effective over the entire required frequency range of the physical measured value acquisition.

Current HV safety regulations for HV battery testing

High voltages also pose a particular challenge for the safety of measurement equipment and its operators. Therefore, comprehensive safety measures must be taken under all circumstances to prevent damage to material and personnel. Measurement devices for high-voltage applications must be certified in accordance with DIN EN 61010 and thus have to provide a comprehensive HV safety concept. On the one hand, this concerns the circuit design, which must be implemented with double or extended insulation. On the other hand, sensor cables, connectors, cable sockets and the device housing must also comply with the strict regulations set out in DIN EN 61010.

Insulation and galvanic decoupling demands

Fiber optic cables are only a very limited alternative for two reasons. Firstly, fiber optic cables do not allow the transmission of energy for the sensor supply, which is essential for the operation of bridge-based sensors such as strain gauges, acceleration sensors and resistance thermometers as well as active sensors with conditioned output. On the other hand, fiber optic cables pose a risk of breakage due to the tough mechanical requirements of the road test.

Wireless transmission of the signals is also difficult due to the shielding nature of the HV battery housing. It is therefore necessary to route the supply and signal lines for the corresponding sensors into and out of the battery, also meaning that galvanic decoupling must take place in the measurement device.

CSM's high voltage safety concept

CSM GmbH has developed a comprehensive measurement device concept for use in high-voltage environments, which is based on DIN EN 61010. After 10 years of continuous extension, CSM's HV-safe product line covers almost all physical measured variables to be acquired at high-voltage potential. The core of the HV-safe measurement devices is the analog part of the measurement amplifier circuit, which is designed separately for each measurement channel and is electrically isolated from the digital part of the measurement device by reinforced insulation. This ensures that high voltage reaches the measurement device but not its power supply circuit or the bus system for measurement data transmission, let alone the device housing.

High-voltage connectors specially developed for CSM and a special potting of the plugs and sockets enable an insulation strength of 1,000 volts in the smallest of spaces. In this way, the device housing can be designed very compactly and the required air gap and creepage distances are still maintained – a significant factor in field tests.

CSM's HV safety concept also includes robust and high-voltage-safe special cables that carry sensor signals into the measurement device in an insulated manner and consist of several layers of insulation. It is important that individual signal cables are available for each measured value, which meet the requirements of the respective measured value. For example, signal cables for thermocouples are designed as a sum cable for four sensors in the respective thermocouple material combination, whereby the thermocouple pairs are individually insulated and the sum cable as a whole then has additional insulation.

The following section outlines four applications in the field of mechanical and thermal battery testing that CSM customers have performed with measurement devices from the HV-safe product line.

Battery drop test with acceleration measurement

According to the Korean Motor Vehicle Safety Standard (KMVSS), traction batteries for vehicles must undergo a standardized test in order to be certified for the Korean market. The test involves dropping the HV battery from a height of 4.90 meters onto a hard surface such as concrete. Acceleration signals on the outside of the housing and inside the HV battery are to be measured. The aim is to acquire and document the shock amplitudes of the acceleration transducers and to gain insights into the propagation of the shock wave through the battery. Both objectives require a very high temporal resolution and, in addition, extremely good temporal synchronization of all measurement signals.

In this case CSM's customer utilized a combination of HV-safe and non-HV-safe measurement modules, which were connected via EtherCAT® and clock-mastered by a CSM XCP-Gateway. CSM's HV IEPE3 FL100 measurement device was used for the acceleration signals within the battery, which allows the acquisition of one triaxial or three uniaxial IEPE sensors with a sampling rate of up to 100 KHz per measurement channel. The HV IEPE3 FL100 supplies the IEPE sensor(s) electrically isolated with an impressed current of 3.5 mA. The acceleration measurements on the

surface of the battery, which are not required to be high-voltage safe, were carried out with a CSM AD4 IE1000, which allows the acquisition of four IEPE measurement channels with up to 1 MHz per channel.

By using the EtherCat® bus system and the CSM XCP-Gateway, the measurement signals could be synchronized with an accuracy of 1 microsecond and thus valuable conclusions could be drawn from the measurement data regarding the propagation of the shock waves through the battery.

Vibration measurement on busbars

In corresponding HV battery variants, the individual battery modules move relative to each other under driving conditions. This in turn affects the busbars connecting them, which are exposed to considerable vibrations and forces. In the worst case, the busbars can break and lead to malfunctions or even battery failure. CSM customers therefore wanted to measure how great the accelerations are directly on the busbars within the HV battery. In this case, piezoresistive acceleration sensors are used, which require different signal processing than IEPE sensors. CSM's customer used the HV AD4 IF1000 measurement module, which enables the acquisition of active sensors under HV environmental conditions. The acceleration sensors are supplied with an electrically isolated power supply from this measurement module and the sensor signals are measured back separately and isolated with sampling rates of up to 1 MHz per channel. In this way the safe use of standard sensors in HV environments gets possible.

Strain gauge measurements in HV batteries

Measurements with strain gauges under HV conditions are a particular challenge. Their measurement signals are vanishingly small compared to the battery system voltages, usually only a few microvolts. CSM's customer wanted to apply strain gauge sensors to the surface of the battery in order to measure strain, compression and torsion while driving. On the other hand, strain gauges were also to be attached to the struts between the battery modules in order to investigate the swelling effects. A major challenge here is the different materials for which the measurement device must be able to provide the appropriate measurement ranges, as well as the possibility of subsequently adjusting the measurement ranges and sensor supply voltage after the strain gages have been applied.

CSM was able to solve these requirements with the HV STG4 pro BS20 measurement module. It allows the connection of four strain gauge full

or half bridges with a sense line on both sides. Quarter bridges can also be realized with special external supplementary resistors. The special feature of the measurement module is the bridge supply voltage unit, which can be set individually for each channel between 1 and 10 volts and thus optimally adapted to the material to be measured. In addition, the bridge supply voltage is measured by the measurement module in parallel with the bridge voltage (=measurement signal) itself, so that the measurement signals are not negatively influenced by potential fluctuations in the bridge supply voltage and are therefore extremely accurate and unsusceptible to interference.

Temperature measurement in HV batteries

While battery management systems generally only have a manageable number of temperature sensors, dense temperature monitoring is necessary in the development phase of batteries in order to reliably detect even the smallest anomalies. This requires measurements at cell, module and system level, which can often lead to a total of over 500 temperature measurement points in a battery.

Currently, measurements are often carried out using thermocouples, but these have two major disadvantages. Firstly, the best thermocouples (class 1) with a measurement accuracy of at best 1.5 Kelvin or 0.4 % of the measured value are not accurate enough for many applications such as the verification of temperature models. On the other hand, measurements with many thermocouples also require many feedthroughs through the battery housing, even with cable glands that are suitable for several cables.

Resistance thermometers are more accurate than thermocouples, but only if they are operated in a 4-wire circuit. This means that twice as much cabling is required for the same number of thermocouples. This is not only unfavorable with regard to the necessary openings in the battery housing, but also with regard to the cable routing of the sensor lines within the battery. In addition, they are difficult to position exactly and reproducibly in the same places on several battery cells. Furthermore, the identification of the individual measurement points and their assignment in the measurement data acquisition is prone to errors with large numbers of channels in analog measurement setups. In addition, the sensor signals on analog lines within the battery are exposed to massive fields and interference. Finally, the acquisition of such a large number of sensors also requires many measurement channels and thus measurement modules outside the battery, which consume limited space, especially in road tests.

To meet these challenges, CSM has therefore developed a digital multi-channel temperature measurement system for testing HV components, especially HV batteries. The HV DTemp measurement system consists of digital temperature IC sensors as well as small, compact controller units and a single central unit. The system can measure up to 512 temperatures with an accuracy between 0.1 to 0.25 Kelvin (total system accuracy). Only a single digital cable is routed from the central unit into the battery housing to supply and organize the controllers and sensors and to transmit the measurement data to the central unit.

Thanks to the digital architecture, the sensors can be precisely identified and assigned. The individual sensors each occupy an area of just 1 x 1.5 mm and measure the temperature on the underside with pinpoint accuracy between -40°C and +125°C. Thanks to their low height of 0.5 mm and their robust design, they can also be pressed between battery cells, for example. They are soldered onto ultra-thin, flexible foils, which provide the connections for the cabling and are covered with Kapton foil, thus offering contact reliability of 1,000 volts. Thanks to the direct digitization of the measured values in the sensor, the measurement signals are extremely immune to interference, as no analogue signal lines are used within the system.

The sensors can be designed as individual sensors or combined as sensor assemblies and thus individually adapted to the application. For measurements on cells in particular, custom-designed foils with up to 20 precisely positioned sensors are available, which can then be inserted between battery cells and thus reproducibly measure the temperatures of different cells at exactly the same positions.

The controller units allow the connection of up to 16 sensor modules with 4 sensors each and can therefore manage a total of 64 measurement channels. With their small dimensions of 80 x 10 x 56 mm, they can also be placed in tight battery housings. Their ports are available with different insulation strengths of up to 1,000 V. A total of up to eight controllers can be connected in series, enabling a total of 512 temperature channels. The measurement data from the 512 measurement channels is then fed from the battery to the central unit using just a single sensor cable.

The central unit takes over the supply and management of up to 512 measurement channels on one or two ports (e.g. with different potentials for two test specimens) and then

makes them available for forwarding on a CAN bus connection.

The HV DTemp system thus represents a highly innovative, minimally invasive and precise measurement method for multi-channel temperature measurements for HV batteries. It is already being used extensively by CSM's customers in the automotive industry as well as in electrified aviation.

Conclusion

CSM's HV device family allows almost complete coverage of mechanical and thermal measurements under high-voltage conditions with proven and common standard sensors such as strain gauges and accelerometers as well as with digital temperature ICs. This also enables comprehensive physical tests to be carried out in a safe environment in general electromobility.