Large Lithium-Ion Battery-Powered Electric Vehicles - From Idea to Reality

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***Abstract*—Lithium-Ion batteries have become the standard for powerful electrical energy supply at mobile applications. Safety is a decisive issue, not only energy per mass or cost. Moving up into energy ranges beyond 100 kWh we have to implement measures against general thermal run-away destruction inherently included in Lithium-ion battery design. In order to gain experience for a hybrid-power locomotive (catenary or battery) a demonstrator was established and successfully tested in 2017. Limited by maximum axle load (21 tons) and the requirement to use as far as possible the existing locomotive (1.6 MW peak, voltage source dc-link, PWM inverter for each of the 4 induction machines; a design of 1980) with its power train, 200 kWh of Lithium-ion batteries could be established. The batteries form 2 strands at 1000 V rated dc voltage each. The battery management system and safety design was based on experience from battery destruction tests of same battery type. Charging of batteries is done over catenary, locomotive main transformer, and existing rectifier by adding a simple resistive current limiter. Battery voltage is directly dc-link voltage for off-catenary operation. The original drive train remains unchanged. In design stage there is a catenary and battery powered large mining truck with over 100 tons payload. Such trucks generally use Diesel engines (about 1000 horse power) and big full-load-capable switchgear and a powerful retarder. The innovation step employs fully electric operation only. Electric energy is used from a special catenary for defined up-slope routes. Hereby, this e.g. 500 kWh Lithium-ion battery (subdivided into e.g. 6 strands) is charged up to the required level. Limited up-slope movement and horizontal driving discharges the batteries. Down-slope driving moves additional charge into the batteries by active braking.**

Keywords—Lithium-ion traction battery, very large electric vehicle, battery safety design

I. Introduction

A. Lithium-Ion Battery Properties and Effects

Lithium-ion batteries are the general and widely accepted power source for mobile applications due to their high energy per mass ratio while accepting high power delivery and exhibiting good efficiency. However, diesel in a combustion engine provides over 20 times the energy per mass ratio compared to Lithium-ion batteries. Therefore, a continuous industrial usage in 24/7 mode requires a clever power and safety design for Lithium-ion battery powered large vehicles. Safety precautions go beyond the accepted risk management for lower energy applications. Based on chemical design of Lithium-ion batteries, destruction finally ends up with thermal runaway and open fire. Especially with access of external oxygen, heat generation from thermal runaway of one single cell usually heats up the adjacent cells and causes thermal runaway also here. Fire may expand quite quickly. Understanding the specific reaction of a certain used battery type on short circuit, external excessive heat, overcharging, and mechanical penetration, counter-measures in design and equipment against the disastrous consequences can be developed. However, an internal battery failure leading to the same thermal runaway destruction is possible, too. Presently, the knowledge base in handling batteries on fire is rather thin, especially when it comes to large battery units over 100 kWh installed on a single vehicle.

B. Innovation Process

Creating something new is generally done in several steps. Feasibility and design studies in paper or computer environment are a first step but do not deliver the experience of a real system tested in practical operation. In a new approach, the practical start can be a demonstrator created at low costs from a running system by adding batteries in a power extension and an adapted battery monitoring and management system. Emphasis is set to safety design. Limits are cost, space, mass, and a reasonable expenditure to have the unit working. The experience from the demonstrator shall lead to a prototype. Definitely higher expenditure in the prototype allows fast modifications or variant study. This yields a system which can be used like the prospective series vehicle but is out of scope for series production because of single unit cost. Final test of such a prototype vehicle goes up to the limits of design and material. This provides the way towards a field test small series where target cost and good fabrication feasibility is considered strongly. Based on results of extensive field tests a review is carried out. Finally, series production can start.

Unfortunately, all problems found out only at later steps require high expenditures through re-design and re-test. Safety is a decisive issue, thus consequences in limiting the effects of burning batteries must be considered as early as possible. New approaches in drive train design and battery management are necessary for large Lithium-ion powered electric vehicles. While standard electric cars exhibit about 20 to 50 kWh of stored energy in the Lithium-ion batteries we consider definitely larger amounts for future mobile usage, e.g. 200 kWh up to 1000 kWh on a single and, therefore, rather heavy vehicle.

C. Demonstrator Basis Vehicle

Our demonstrator basic unit is an electrical locomotive of Austrian Federal Railways (OeBB) 1063.038 (a design from 1980) running on 16.7 Hz / 15 kV catenary employing main transformer, controlled rectifier, voltage source DC-link and 4 PWM inverters supplying induction motors at 1600 kW total peak power and includes an auxiliary drives system providing 400 V 50 Hz three-phase voltage for compressor and fans for traction motors. The sideboards are nicely suited to add the amount of 200 kWh of Lithium-ion batteries yielding a final total locomotive mass of 84 tons (Fig. 1, 2).

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Fig. 1. Demonstrator locomotive OeBB 1063.038, here with 6 open racks of added Lithium-ion batteries (8.4 kWh per rack), in total 24 racks at locomotive, under construction, rack cabinets removed, unit cabinet (visible in front of locomotive) removed, decoratiove appearance added

Fig. 2. Demonstrator locomotive OeBB 1063.038, here with 6 + 6 open racks of added Lithium-ion batteries (8.4 kWh per rack), at disassembling; battery balancer and battery cell measurement boards mounted

II. BASIC CIRCUIT SCHEMATICS

A. Original Locomotive

The electro-mechanic power section of the standard OeBB 1063 locomotive contains a power transformer, one semi-controlled rectifier and one diode rectifier for the DC link, 4 PWM inverters for traction induction motors (asynchronous machine, ASM), and an auxiliary drives converter for powering the 3-phase induction machines for traction motor cooling fans and an on-bord air compressor (Fig. 3, black). The original human-machine-interface is kept in operation. Handling of locomotive shall be the same when the battery add-on is implemented (Fig. 3, black).

B. Battery Operation Add-Ons

For battery operation, the available additional mass of slightly over 2 tons was exploited for mounting the defined 200 kWh Lithium-ion battery onto the sides of the locomotive. A clear safety process demanded all-pole turn-off capability of the batteries, inclusion of fuses, and subdivision in modules, racks, subunits and strands. 2 parallel sections of the battery system allow continuation of driving even when a failure occurs in one half which can be switched off individually (Fig. 3, red). For simplicity and weight considerations, the power interface between dc-link and battery is kept extremely simple: As charging of batteries is accomplished directly from dc-link, a resistor acts as current limiter for charging. A braking resistor of the original locomotive was used. A diode switching element bypasses this resistor for driving.

The battery system is equipped with balancing and supervision circuits. Simple signal interfaces to the original control system and human-machine interface are added (Fig. 3, red).

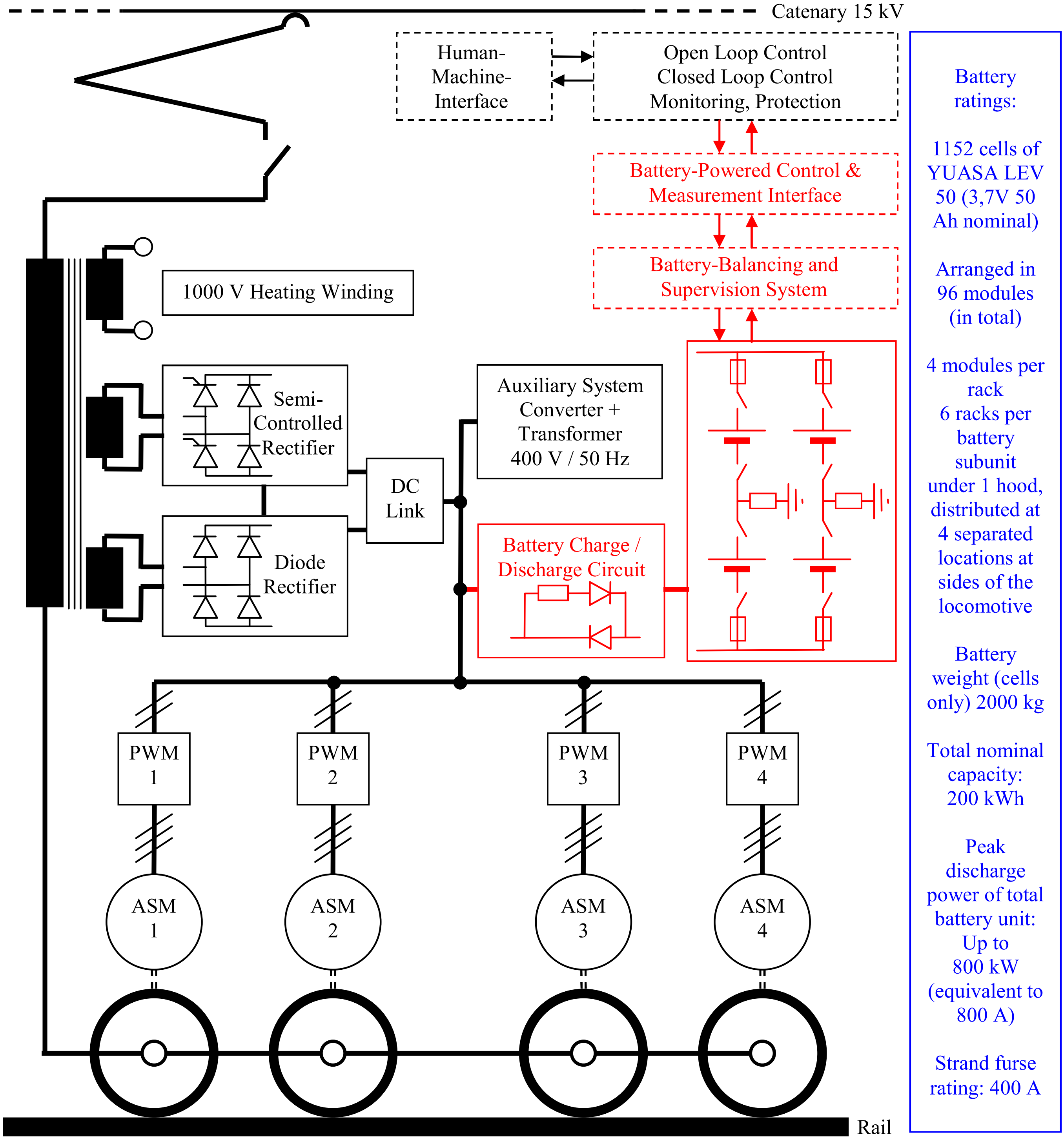

Fig. 3. Simplified circuit schematics of traction power equipment of demonstrator locomotive
black: original locomotive as designed in 1980 red: battery system extensions

III. Battery Details

A. Battery Origin

For cost reasons, using new batteries was out of scope. Used batteries obtained from a recycling company were available in unknown condition with unknown preloading. All 96 modules involved (plus some for spare parts) were tested in a charge/discharge routine before mounting.

B. Mechanical Safety Design

As a matter of fact, it appears impossible to gain a 100% safety in electrochemical batteries. We might be able to avoid destruction of Lithium-ion batteries from outside origin. However, we cannot prevent that eventually such battery destruction starts from internal failure. From experience, different battery types behave differently under destructive conditions. Before getting the permission to implement the designated batteries onto the locomotive, an intensive test series was done. Modules of the finally mounted type have been subjected to destruction by fire, by short circuit, by overcharging, and by mechanical damage. The highest energy content released by the battery comes at destruction by overcharging. From these life experiments (the modules did not survive) we derived the final design of the mechanical arrangement and housing on the locomotive. We used the original modules produced for mobile usage in electric cars. Unlike the arrangement of modules in an electric car with all modules in a single case, we only mounted 4 modules in one case forming a battery rack. A number of 6 racks define a battery subunit which got an additional cover.

C. Battery Balancing and Battery Managements

An advanced approach to system safety was implemented also in order to learn for a successive prototype. While standard mobile applications consider it being sufficient to measure module temperatures e.g. at two corner locations we implemented a temperature check for each cell directly at the positive pole. We measure each cell voltage directly at the cell terminals rather than over some extra wires. We implement not only supervision and balancer control but also a protection arrangement: A positive signal (everything is OK) must be delivered. In case not, we also detect supervision failures through this protection design. Safety circuits are kept as simple as possible. We did not employ a digital program for this reason. Figure 4 explains the battery safety environment.

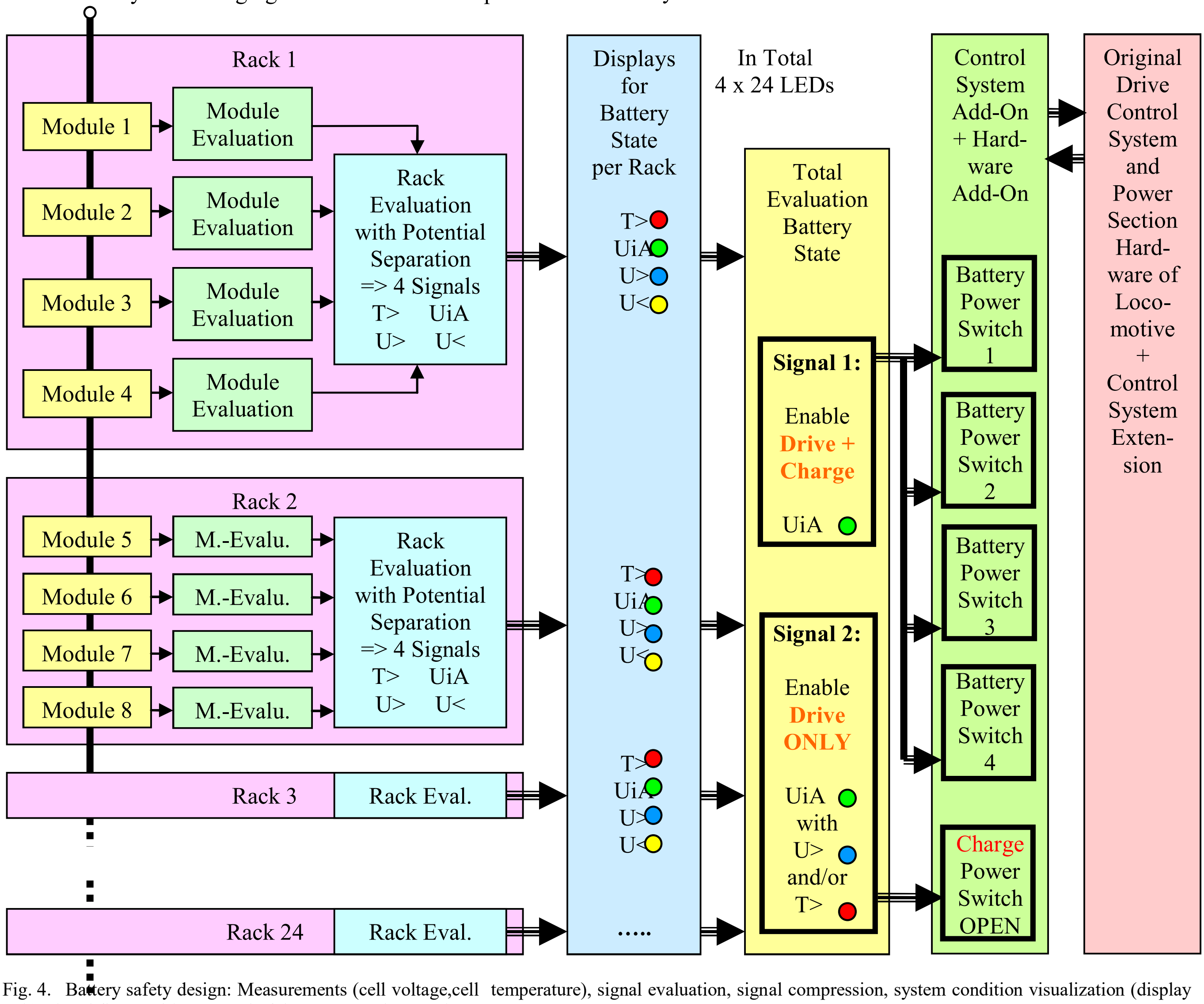

Fig. 4. Battery safety design: Measurements (cell voltage,cell temperature), signal evaluation, signal compression, system condition visualization (display unit), signal flow to drive control of demonstrator locomotive OeBB 1063.038

IV. All-Electric Mining Truck

A. Motivation and Electrical System Layout

In design state is a 100 tons payload mining truck. Such a today`s standard 110 t payload truck generally uses a Diesel engine (about 1000 horse power) and impressive full-load-capable switchgear and a powerful retarder (Fig. 5).

Fig. 5. Mining truck in operation

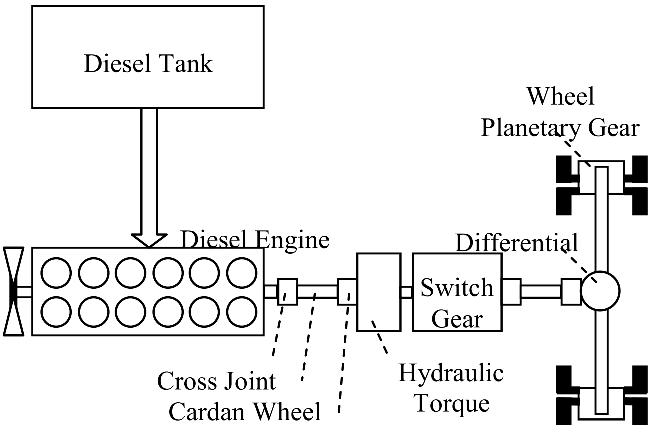

Fig. 6. Power train of standard Diesel engine ining truck

One can imagine the amount of hot air created when this truck moving downslope, and also the amount of Diesel burnt and carbon dioxide produced (Fig. 6).

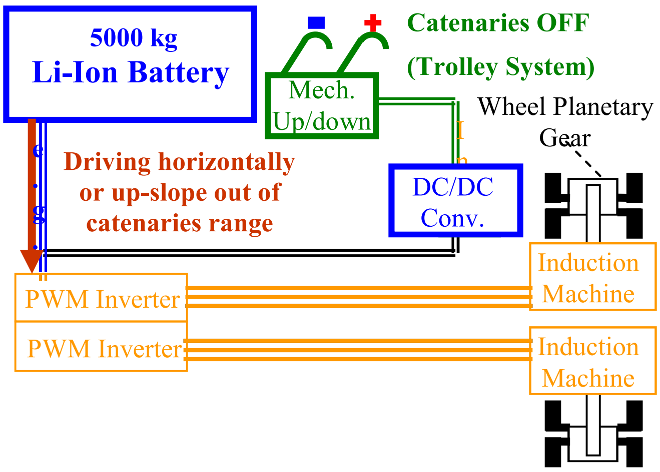

Fig. 7. Taking power from battery when driving horizontally or up-slope

The innovation step employs fully electric operation only. Electric energy is directly used from a special catenary for certain and limited up-slope routes. Hereby, this e.g. 500 kWh Lithium-ion battery (subdivided into some strands) is charged up to the required level. Limited up-slope movement and horizontal driving discharges the batteries (Fig. 7).

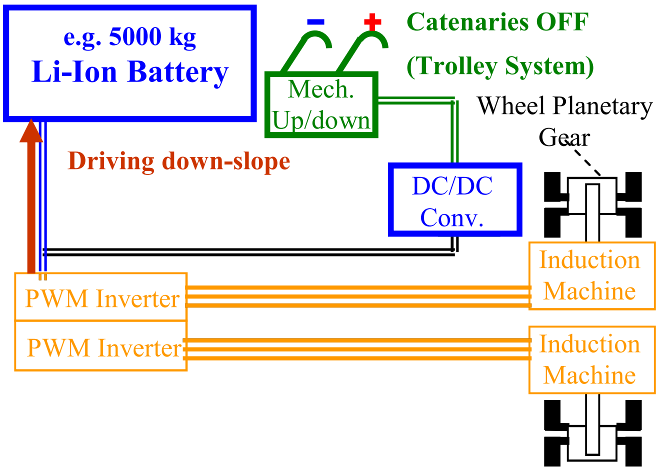

Fig. 8. Regenerative braking when driving horizontally or up-slope

Down-slope driving charges the batteries by active braking. Efficiency of recuperation (=active braking) is about 75%.

B. Battery Considerations

Fig. 9. Final reaction of Lithium-ion battery module (12 cells) after overcharging destruction test.

We have to keep in mind that Lithium-ion batteries might destroy themselves from internal failure in heavy fire (Fig. 9). The general safety concept needs to be implemented accordingly. We recommend a subdivision of the total battery unit into several mechanically separated containers. Exclusion from external air access in case of fire reduces fire intensity. Due to the pressure relieve valve at the cell, a pressure pulse will occur. An automatic closing vent at the rack should be part of the mechanical design.

Results

By today, demonstrators and even prototypes for large Lithium-ion battery powered vehicles can be implemented.

References

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