Charged in a flash

Optimization of batteries for a flash-charged bus

TIMOTHY PATEY, RETO FLUECKIGER, JAN POLAND, DAVID SEGBERS, STEFAN WICKI – With its six trolleybus and four tram lines, transportation in the Swiss city of Geneva already makes extensive use of electric traction. As a further step towards making its public transportation system carbon-neutral, the city has announced it will replace the diesel buses used on line 23 by a battery-powered electric bus fleet.

1 TOSA

ABB Review 4/2013 featured an article on the TOSA bus demonstration in the Swiss city of Geneva.

Following a successful conclusion of the demonstration, Geneva's public transportation operator, TPG, decided to convert its route 23 to the mode. The order for 12 TOSA buses and 13 charging stations was confirmed in July 2016. ABB's scope of delivery includes converters, motors and the charging stations.

2 Bus stop with flash charging station. The bus' batteries receive a 15 second 600 kW boost while at the stop.

ABB was recently awarded orders totaling more than $16 million by Geneva's public transport operator, Transports Publics Genevois (TPG), to provide flash charging and on-board electric vehicle technology for 12 TOSA (Trolleybus Optimisation Système Alimentation) fully electric buses → 1. Their operation can save as much as 1,000 tons of carbon dioxide per year (compared with the existing diesel buses).

ABB will deliver and deploy 13 flash-charging stations along the route → 2, as well as three terminal and four depot feeding stations. The flash-charging connection technology used will be the world's fastest: It will take less than one second to connect the bus to the charging point. The onboard batteries can then be charged by a 600 kW boost lasting 15 seconds using time that the bus is at the bus stop anyway. A further four to five minute charge at the terminus will enable a full recharge of the batteries.

Title picture
Geneva (Switzerland) is to replace a presently diesel operated bus line by flash-charged battery buses. In this view the bus is receiving its 15 second top up charge at a flash charging station similar to that which will be installed at 13 intermediate stops of route 23.

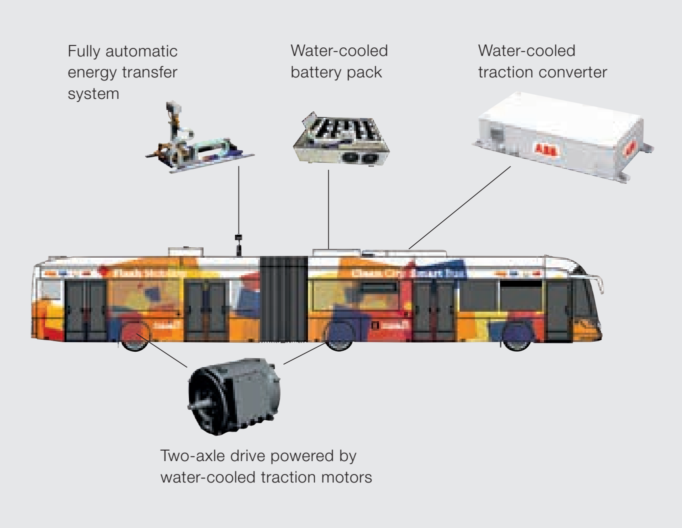
ABB will deliver and deploy 13 flash-charging stations along the route, as well as three terminal and four depot feeding stations.

ABB solutions for the electrification of public transportation

ABB has developed a modular platform for the electric drive train of city buses → 3. This caters to all e-bus applications ranging from the traditional trolleybus to DC fast-charged or flash-charged battery buses. At the heart of this are ABB's highly efficient water-cooled permanent-magnet traction motors as well as the extremely compact BORDLINE CC200 → 4 traction and auxiliary converter. The converter can drive up to two traction motors and all the auxiliary consumers of the bus.

On a flash-charged bus, the converter also handles the flash and opportunity charging at bus stops and the DC fast-charging at the end of the line. On an electric trolleybus, it is supplemented by a double-insulated DC-DC input converter. Adding a battery to this drive train enables the bus to operate free of catenary lines (overhead lines).

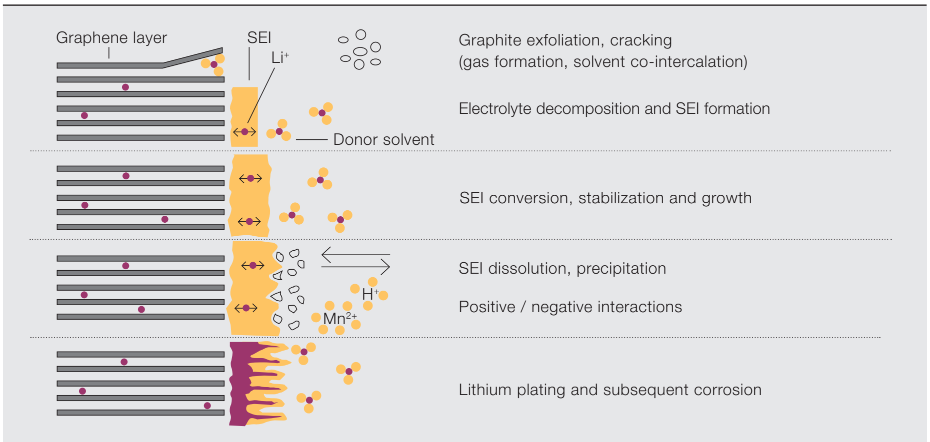
3 Key technology components of the TOSA bus.



4 ABB's BORDLINE CC200 traction an auxillary converter.

As every mobile phone user knows, availability of battery power is essential if the device is to fulfil its function.

5 Physical and chemical degradation mechanisms of graphite within a Li-ion battery[1].



SEI is the solid electrolyte interphase formed as a consequent of electrolyte decomposition and related side reactions.

Charging matters

As every mobile phone users know, availability of battery power is essential if the device is to fulfil its function. The same applies to an electric bus or tram. However, after a certain time and usage, a battery needs to be replaced. A challenge for ABB engineers is to predict when this will occur, and to create specifications that ensure availability of power through the product and system's life.

A model informed by experiments

A battery "dies" because it fails to deliver the power required for the specified timespan. More specifically, the decline in capacity (Ah) and rise in internal resistance (Ω) are simultaneous processes that compromise the battery's ability to deliver power. This is due to chemical and mechanical decomposition of the materials inside the battery (example of graphite degradation are shown in → 5).

A key challenge in battery integration lies in predicting the rate at which the battery will degrade. One approach is to test the batteries: The batteries are charged and discharged under various conditions to quantify the decline in capacity and rise in resistance. However, this method alone cannot cover all the use cases of the electric bus. There are too many variables, including temperature, state of charge, depth of discharge / charge, and current. The time and sheer number of experiments required to cover all the use cases is simply too high.

The solution to estimating battery lifetime is to make a model informed by experimental results and a fundamental understanding of the key physical and chemical processes of the battery. This approach is semi-empirical, in that it relies partly on empirical/experimental results. Models based purely on physics are not suitable as the high number and complexity of the various physical and chemical interactions are too numerous to run computations efficiently. It is more time efficient to conduct a series of well-designed experiments and use the results to create a model. The key to building a good model is to design the right experiments.

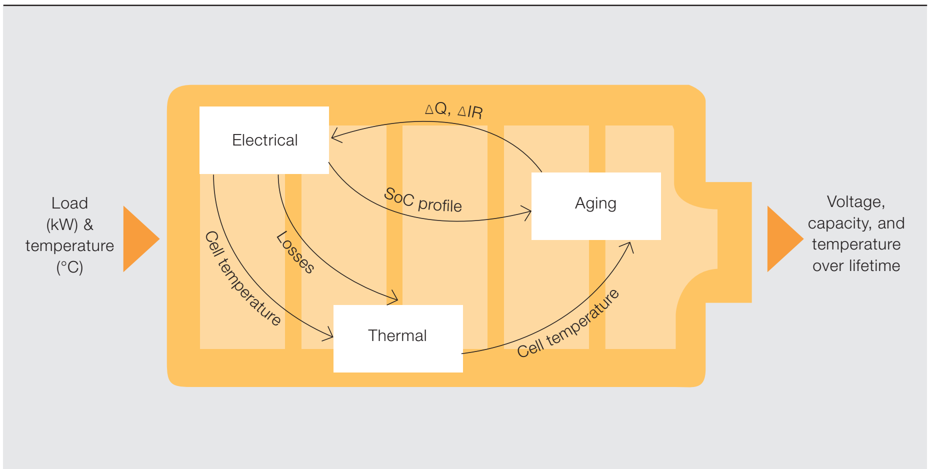
Step 1: Design the right experiments

In this phase, the temperatures, depth of discharge, state of charge, and current are varied in a series of battery tests. The

Footnote

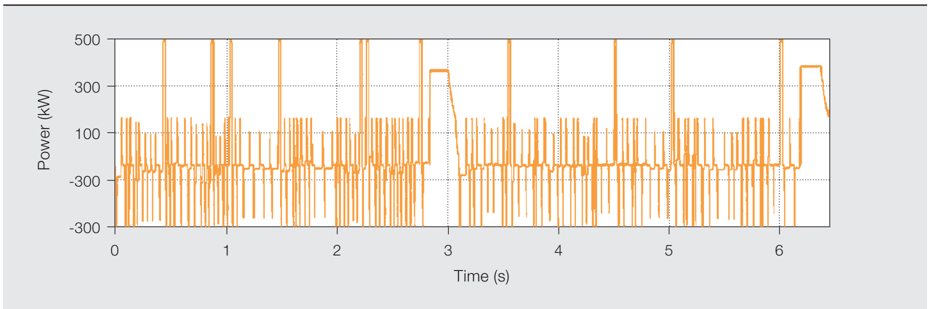
1 Vetter, J., *et al.*, *Ageing mechanisms in lithium-ion batteries.* Journal of Power Sources, 2005. 147(1–2): p. 269-281.

6 Simple representation of an electrical, thermal, aging model of a Li-ion battery



Key operation concept is the interplay of variables between models: e.g. change in capacity (ΔQ) and internal resistance (ΔIR) modify the electrical model, which varies the state of charge (SoC) profile that modifies the aging model.

7 Example of a battery load profile for one return trip of a 12km route with 13 flash charging and 2 terminal charging sections



A key challenge in battery integration is predicting the rate at which the battery will degrade.

capacity decline and resistance rise are measured. This will later enable a prediction of how certain charge/discharge events of the battery would impact the battery aging over time and use.

Step 2:
Develop an electric, thermal, aging model

The internal electrical architecture of a Li-ion battery is complex, but electrical response is approximated with a number of resistive and capacitive components. Heat and age modify these components, as informed by the thermal and aging models.

As electric buses are power applications, Joule heating (i^2R) is the dominant type of energy loss and dictates the battery cell's wall and core temperatures during operation. These temperatures are essential for accurate electrical and aging models.

The aging model is based on the results of experiments, and quantification of the decline in capacity and rise in resistance expected from the many possible charge / discharge events.

The resulting battery model combines the electric, thermal, and aging submodels. The interplay of these sub-models enables the prediction of the change in capacity and resistance under a given load and temperature over time → 6.

Step 3: Verify the model

Experiments at cell level inform and verify the model using realistic load profiles. This is an iterative process involving further refinement.

The key to building a good model is to design the right experiments.

Step 4: Apply the model

Once the model has been generated and verified, it becomes an important tool in scenario analysis. The battery's temperature, voltage, energy, and peak power all affect how a battery system should be dimensioned. While this process is not the final say in how big a battery should be, modelling informs decision makers and designers on how key variations in battery size and cooling influence bus performance.

Scenario analysis

The following scenario analysis considers a 25 ton articulated bus with a maximum passenger capacity of 80 people. There are 13 flash charging stations distributed along the route of 12 km length, providing a charging power of 600 kW for 20 seconds. The terminal charging uses 400 kW and takes four to five minutes. A typical load profile of such a bus is shown in → 7.

Key battery requirements for this electric bus include:

- 10 year lifetime
- minimum charge voltage of 600 V (to assure sufficient power is available for the motor and auxiliary systems and to match the charging infrastructure)
- cell temperature of max. 60 °C (to ensure safe operation, as the electrolyte evaporates above 80 °C)
- charging power of 600 kW for 20s (to allow for rapid charges), and 400 kW for 5 minutes
- an energy of 46 kWh (to complete a journey in one direction, with backup power for exceptional circumstances).

Parameters for three configuration scenarios are presented in → 8.

8 Overview of three possible battery designs for a 12 km urban route (with flash charging)

Design criteria	"Small energy"	"Strong cooling"	"Large energy"
Cell chemistry	LTO	LTO	LTO
Max. C-rate permitted (continuous)	6	6	6
Max. C-rate permitted (for 20s)	8	8	8
Cells in series / in parallel	314 / 4	314 / 4	375 / 4
Energy content [kWh]	58	58	69
Minimum voltage [V]	630	630	750
Nominal cont. power [kW]	400	400	480
Nominal 20s power [kW]	580	580	690
Battery weight incl. cooling system [kg]	~1600	~1600	~2000
Coolant temperature [°C]	25°C	15°C (active)	25°C

C-rate is the rate at which a battery discharges, with 1 C-rate equal to a complete discharge in 1 hour, and 10 C-rate 1/10th of 1 h, (ie, 6 minutes).

9 Overview of the model calculation for the three possible battery designs for a 12 km urban route (with flash charging). BOL = beginning of life, EOL = end of life

	"Small Energy"		"Strong Cooling"		"Large Energy"	
	BOL	EOL	BOL	EOL	BOL	EOL
EOL	-	6 y	-	12 y	-	10 y
Capacity	100%	83%	100%	80%	100%	80
Resistance	100%	200%	100%	170%	100%	185%
Energy content	58 kWh	48 kWh	58 kWh	46 kWh	69 kWh	55 kWh
Voltage range	690 - 850 V	590 - 850 V	690 - 850 V	630 - 850 V	840 - 1010 V	770 - 1010 V
C-rate terminal (continuous)	5.3	6.2	5.3	6	5.4	5.6
C-rate flash (for 20 s)	8	8.5	8	8.3	6.8	7
Peak core cell temperature	57 °C	86 °C	43 °C	58 °C	44 °C	57 °C
Battery efficiency	90%	80%	90%	85%	92%	86%

The three battery scenarios were analyzed using the thermal, electric and aging battery model to forecast the lifetime and the end of life (EOL) properties. Here the EOL is defined as 80 percent of the initial capacity or 200 percent of the initial resistance. The results of the model analysis shown in → 8.

For the case of the "small energy" battery, flash charging the battery at 600 kW would not be possible at end of life as it is beyond the power limit of the battery pack (with a C-rate limit of 8). It would be able to power the bus for some time using terminal charging only, but the rise in resistance would be too great (210 percent), resulting in an eventual unsafe temperature (T > 80°C, internal to the cell) and as well as minimum voltage of less than 600 V, which is insufficient to power the motor and auxiliary systems.

For the case of the "strong cooling" battery, the battery would be fine for terminal charging only. However the flash charging of 580 kW is beyond the limits of the battery pack. The lower coolant temperature, however, is sufficient to maintain healthy voltage and temperature ranges throughout the battery's lifetime of 12 years. This is a clear demonstration that battery temperature matters for system lifetime performance.

The "large energy" battery is the only one of the three considered that could fulfill both the flash-charging and terminal charging requirements. For flash-charging, the additional cells in series is simply needed to raise the voltage and lower the current to meet the power requirements thronghout the battery's life. Additionally, this configuration (375s4p) would ensure healthy temperature window for the entire 10 years of the required battery life.

Use of the battery model on these three battery cases is a simple means to demonstrate battery design impact on maintaining a reliable system performance at end of life. Further design iterations would be done to find the optimum solution, while mitigating all risks through system analysis.

Furthermore, the battery model informs the public transportation operator on the battery design impact of choosing flash charging or terminal charging. The bus line operators know their cities and its needs, and are in the best position to decide whether terminal or flash charging is most suited. The battery model is a support tool to inform them of the battery design consequences of their system choices.

Timothy Patey
Reto Flueckiger
Jan Poland
ABB Corporate Research
Baden-Daettwil, Switzerland
timothy.patey@ch.abb.com
reto.flueckiger@ch.abb.com
jan.poland@ch.abb.com

David Segbers
Stefan Wicki
Discrete Automation & Motoion
Turgi, Switzerland
david.segbers@ch.abb.com
stefan.wicki@ch.abb.com