EVS38
Göteborg, Sweden, June 15-18, 2025

Model-based and Health-adaptive Charging of Electric Vehicles

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Executive Summary

Volvo Cars and Breathe Battery Technologies (Breathe) are collaborating to enhance the electric vehicle charging experience through the implementation of Breathe Charge. This model-based and health-adaptive software optimises fast charging by actively controlling the anode potential of all cells in the pack to avoid lithium plating. Benchmark tests comparing Breathe Charge to a well-calibrated multi-stage constant current protocol on Volvo Cars' in-house developed battery management system show significant improvement in charging performance and robustness without compromising battery health. Furthermore, the charge strategy enables a reduction in thermal pre-conditioning of the battery, which improves overall charging efficiency. The results have been demonstrated in a Volvo ES90 on a public charging station.

Keywords: Electric Vehicles, Battery Management System, AC & DC Charging Technology

1 Background

Charging performance is an important attribute in the customer buying decision for electric vehicles. Today, it is common to specify charging time for 10-80% state of charge (SOC) to enable comparison between vehicles. While useful for comparison, data from Volvo Cars' internal fleet of company cars indicates that this is not fully representative of real-world usage. In Figure 1, the distribution of starting SOC for over 9000 fast charging events on 700 vehicles is plotted. It shows the most common starting SOC is 15-20%, and the average starting SOC is around 30%. It also shows that approximately half the events use thermal preconditioning. Based on this, assessment of charging experience should consider a wide range of starting conditions and be evaluated for an extended set of key performance indicators (KPI).

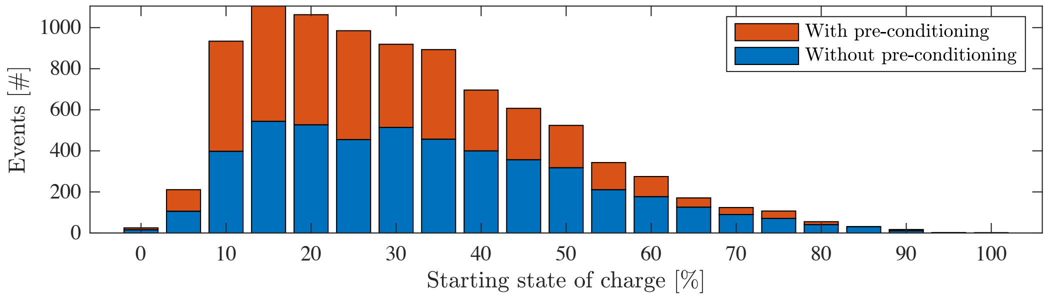

Figure 1: Distribution of starting SOC for 9000 fast charging events in Volvo Cars' internal fleet.

Charging performance is a complex attribute, and many parts of the electric propulsion system interact to provide the vehicle's final charging performance. Charging inlet and interaction with infrastructure, on-board electrical distribution, thermal system with cooling and heating, battery pack geometry, and battery cells must all be designed and controlled effectively to provide users with a robust and reliable charging function. Specifically, the battery management system (BMS) has two major functions that impact charging performance (i) pre-conditioning of the battery cells to accept a high charge current, and (ii) determining the maximum allowed charge current without excessive degradation effects on the battery cells.

Thermal pre-conditioning is effective in improving charging performance by securing that the battery cells are at an ideal temperature to accept charging power. However, pre-conditioning may consume several kWh of energy, and for this reason, performance that can be achieved without the need for pre-conditioning is preferred. The second function, determining maximum charge current, is where Breathe specialises. They develop advanced functions for battery management and their product, Breathe Charge - a model-based, health-adaptive software function - dynamically optimises fast charging, considering parameters such as battery state of health (SOH), ambient temperature, and user driving patterns.

Volvo Cars and Breathe are now collaborating to implement Breathe Charge into Volvo's in-house developed BMS platform. The implementation of adaptive charging not only benefits consumers by providing more reliable and faster charging but also supports the broader adoption of electric vehicles by addressing common concerns related to battery longevity and charging convenience.

This article is structured so that Section 2 provides context on Volvo Cars' battery and charging management. Section 3 introduces Breathe Charge and the topic lithium plating protection. In Section 4 results from testing and comparison of Breathe Charge and a multi-stage constant current profile are presented. Finally, Section 5 concludes the article and summarise key findings.

2 Volvo Cars' Battery and Charging Management

As described in the introduction to this article, charging an electric vehicle is complex and has multiple objectives. A charging session can be divided into four stages according to:

- **Planning:** First the charging event (or trip) is planned with routes and charging stations. This requires predictions about what conditions the battery may be at (SOC and temperature) when arriving at a charging station, and what charging time is expected based on the power performance of the charging infrastructure.

- **Preparation:** Based on the performance of the selected charging station and predictions about conditions of the battery at arrival, thermal pre-conditioning may be used to secure that the battery can accept the charging power. The pre-conditioning must balance the trade-off between charging performance and energy consumption, and any energy used for pre-conditioning must later be added back during the charge event. This is particularly important when considering the KPI of energy added per unit time. It is also worth noting that there seems to be a common misconception that batteries are always warm when used. Many vehicles are equipped with heat-pumps that can use the battery thermal energy to heat the cabin during driving in cold ambient conditions. This is good for overall energy efficiency but may impact charging performance and need for pre-conditioning.

- **Charging:** During the charging event, the current is maximised into the battery considering limitations from cells but also other components like contactors and busbars. The thermal system is used to cool the battery to stay inside temperature limits. Also, the driver is provided with updated information about charging performance and remaining charging time through the display in the car and via mobile app.

- **Post-conditioning:** After charging is ended, the battery may be hotter than optimal and therefore needs cooling to get back to long-term healthy temperatures. In warm climate, this normally must be balanced with needs from other systems like cabin climate that may share cooling system.

Coordinating these activities necessitates a system with functions distributed within the vehicle software stack. The primary functional blocks are illustrated in Figure 2. Volvo Cars is developing most of these functions in-house to achieve optimal system performance.

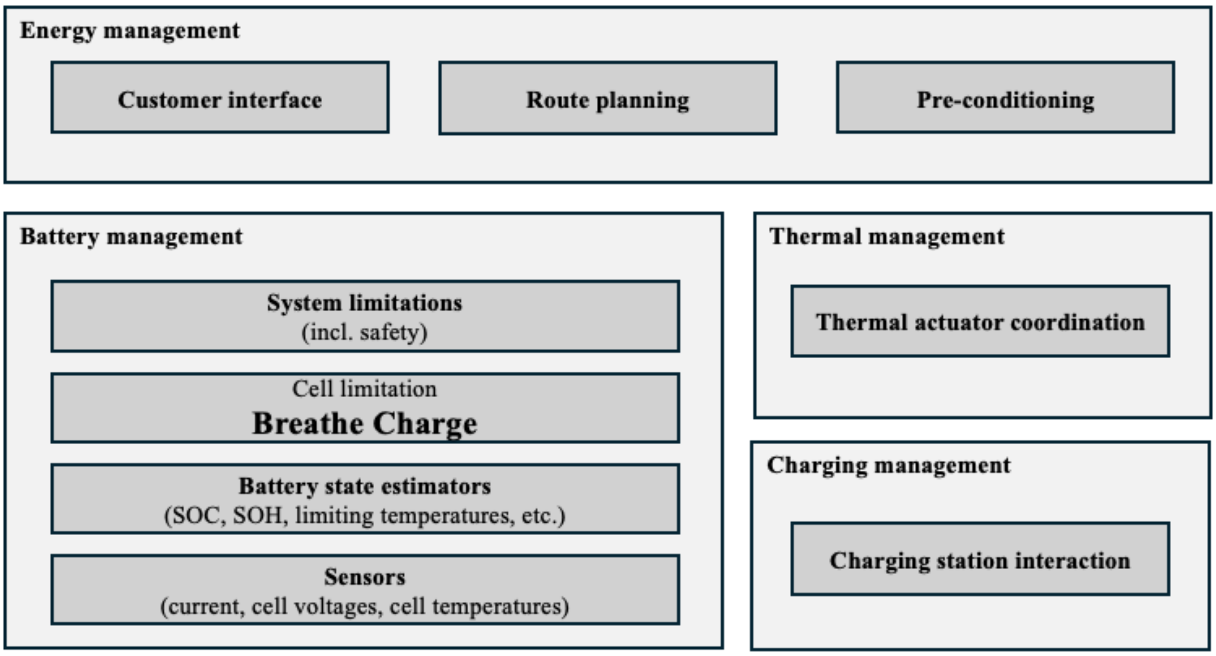

Figure 2: Parts of Volvo Cars' propulsion system software stack relevant to charging.

Volvo Cars' Battery Management System

The objective of the BMS is to enable optimal, reliable, and safe operation of the battery system. It includes a limited number of actuators for active control, such as contactors, but other systems rely on data provided by the BMS to maximise battery usage. Consequently, information generated by the BMS significantly influences vehicle performance, including charging capabilities. Volvo Cars has an in-house developed BMS platform that comprises over 100 software components spanning from AUTOSAR software stack configuration, device drivers and sensor management, safety protocols, and cell state estimation. Key functions relevant to charging include:

- **Sensing:** The primary sensors used for charging are pack current, individual voltage of all cells, and temperature that is measured on some of the cells in the pack. All sensors are monitored for accuracy and correctness to comply with automotive safety standards.

- **SOC estimation:** The SOC cannot be directly measured, instead it is estimated based on measurements of current and voltage together with a cell model. The SOC is estimated for all cells in the pack.

- **Cell temperature estimation:** Since not all cells has temperature monitoring and there are temperature gradients both across the pack and inside each cell, the temperature to use for charging control is normally not measured but estimated. The limiting cell is usually the coldest cell in the beginning of charging and the hottest cell towards the end of charging.

- **Safety limits:** Battery protection against over-charge, over-temperature, and over-current is ensured via a parallel path through the software. This way the charging function only needs to manage performance and degradation aspects of the battery.

- **Battery pack thermal management:** The BMS communicates how battery performance is affected by its temperature to the vehicle energy and thermal management to optimise the thermal system during the charging event and pre/post-conditioning.

- **Battery pack current limitation:** There are multiple components inside the battery pack that needs consideration during fast charging. The cells will be the main topic of the rest of this article, but also other components like busbars and contactors may need monitoring not to over-heat in certain edge cases.

3 Breathe Charge

Breathe Charge is an adaptive charging software designed for integration into an automotive BMS. In Volvo Cars' BMS platform it plays three fundamental roles: (i) to limit charging current to optimise charging speed without causing lithium plating in any cell, (ii) to provide input to thermal management and pre-conditioning, and (iii) to provide input to remaining charge-time estimation.

Lithium Plating Protection

A major limitation for fast charging comes from a cell-level degradation mechanism called lithium plating, which is thermodynamically and kinetically favoured over lithium intercalation when the potential of the battery anode drops below 0V vs. Li/Li^{+} [1]. Lithium plating deposits metallic lithium on the anode surface that subsequently react with the electrolyte. This consumes available lithium and forms additional passivating layers that reduce reaction and ionic transport efficiency. Consequently, this leads to rapid reduction in battery capacity and power capability, and in severe cases, plated lithium dendrites can cause a cell-internal short circuit.

It is well known that higher SOC reduces the anode potential and that higher charge currents, lower temperature, and reduced state-of-health (SOH) of the cell all increases kinetic losses (overpotential), thereby reducing the margins to lithium plating. Even though anode potential is a good indicator for risk of lithium plating, it cannot be measured on production ready cells. Therefore, detecting lithium plating during fast charging is challenging. Non-destructive methods, like detecting a voltage plateau during relaxation [2] or changes in battery impedance during charging [3], have been proposed in academic literature. Still, the sensitivity and reliability has not been verified on full-scale battery packs.

A common strategy to prevent lithium plating in automotive applications is to use multi-stage constant current (MSCC) protocols. These pre-defined look-up tables specify the maximum allowed charge current based on SOC and temperature. Derived through models and laboratory tests, these protocols are optimized around fixed starting conditions. Despite straightforward implementation, their static nature and simplifications of the underlying electrochemistry mean they cannot precisely control anode potential in real-time. Instead, they must be conservative to effectively protect against lithium plating under all conditions throughout the battery's lifespan. As a result, MSCC neither offer optimal charge time nor cycle life.

Advanced strategies for lithium plating protection using anode potential estimation and control have also been proposed in academic literature, often employing electrochemical models [4, 5] and Kalman-filter algorithms for state and parameter updates [6]. These model-based approaches better adapt to real-time changes in battery states like SOH and hysteresis compared to predefined MSCC. Despite demonstrating anode potential control in laboratory conditions, integrating these algorithms into automotive applications faces significant challenges including: (i) validating long-term performance at various temperatures, (ii) executing within limited computational resources in automotive BMS, and (iii) scaling to pack and vehicle levels considering cell-to-cell variations and thermal management. Breathe Charge manages to overcome these challenges through a proprietary physics-based model.

Breathe Charge Functions

The main function blocks of Breathe Charge are illustrated in Figure 3, and further explained below:

- **Anode potential estimator:** The anode potential estimator is built upon a reduced-order, physics-based battery model that calculates electrode thermodynamics and kinetics in real-time from inputs like battery current, voltage, temperature, and SOC. Internally, it also estimates SOH, hysteresis, and state-of-lithiation. The anode potential is estimated for all cells in the pack and processed through an arbitration algorithm to determine the pack-level anode potential. The parameters are application independent and obtained for a specific cell type through electrode-level characterisation and electrochemical measurements.

- **Adaptive current controller:** The estimated anode potential is provided to the adaptive current controller, which outputs the maximum allowable charging current without the anode potential dropping below a pre-defined threshold for any cell in the pack. The charge controller is calibrated to meet application specific requirements for charge-time and cycle-life, and to handle disturbances like cell-to-cell variability and inhomogeneity [8]. It can also be further configured to account for system-level constraints in cooling power or limitations from other components. Since charge control settings needs to be application dependent, they are calibrated both during cell-level testing, prior to BMS integration, and then further refined in the vehicle BMS during pack-level testing.

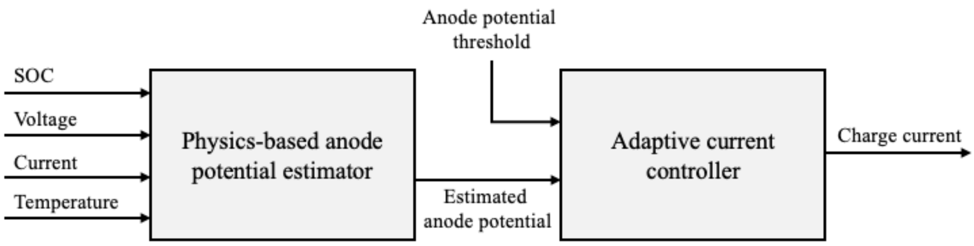

Figure 3: Schematic illustration of anode potential charging control in Breathe Charge.

Calibration workflow

The complete workflow for calibrating Breathe Charge uses both cell and pack-level testing together with simulations, as summarized in Figure 4.

- **Cell-level performance simulations:** Initially, the parameterised physics-based cell model is used to pre-select a set of calibrations predicted to meet charging performance and cell durability requirements.

- **Cell-level calibration:** The pre-selected calibrations are validated to fulfil durability requirements by conducting numerous (hundreds) charge/discharge cycles until a target SOH or cycle count is reached. The tests are repeated for multiple (at least three) cells to secure reliable results.

- **Pack-level robustness simulations:** Before final settings are selected for integration in the BMS, pack-level robustness simulations are used to assess how cell-level results will scale to pack. This is an efficient way to verify robust pack-level current control under different scenarios in thermal distribution, initial SOC distribution, charger power limit, and other edge-cases.

- **BMS integration:** Breathe Charge is integrated in Volvo Cars' in-house BMS platform. The delivery format is two object files, one for the algorithm and one for its calibration. This means Breathe Charge respects the major variation points and versioning used by Volvo Cars and reduces validation efforts for different pack variants.
- **Pack-level calibration:** In the battery pack level, Breathe Charge is tested in Volvo Cars' battery laboratory across a diverse combination of initial temperatures, SOC ranges, and cooling rates to ensure that the charging control remains robust and meets charge-time requirements under all conditions. Fine-tuning of calibration settings is typically necessary at this stage to accommodate the impact of cell-to-cell variability and the distinct thermal and electrical environments between the pack and cell levels (e.g., busbar resistance).

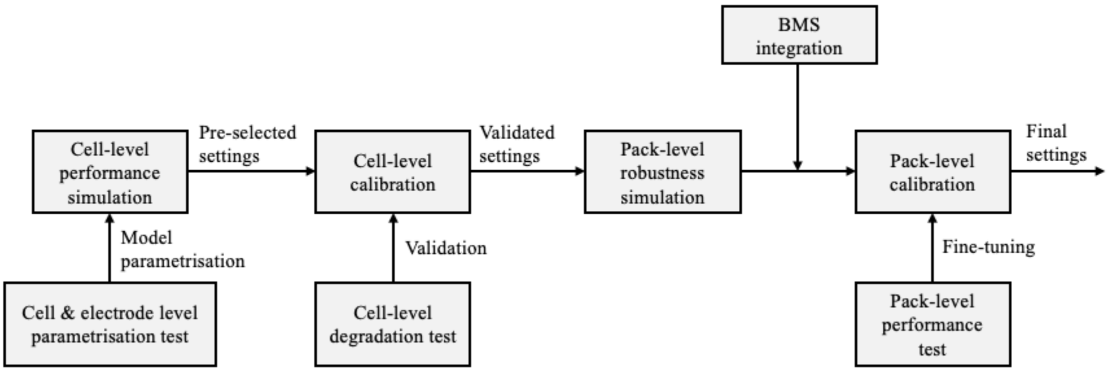

Figure 4: Breathe Charge settings calibration and validation workflow.

4 Results

In this section, results from calibration and validation of Breathe Charge on the new Volvo ES90 are presented. The results are divided into three parts for cell, pack, and vehicle levels.

Cell-level calibration & validation

The target for Breathe Charge was to reduce charging time between 10-80% SOC while maintaining the same degradation trajectory as the existing MSCC protocol for at least 600 full charge cycles. To make the test results representative of the application and to minimise later calibration efforts, the tests were carried out with mechanical compression and liquid cooling representative of the battery pack's mechanical and thermal environment.

Example trajectories of estimated anode potential during cell-level testing are shown in Figure 5 for charging at different temperatures and SOH. As expected, the estimated anode potential reaches the threshold at an earlier SOC when charging the cell at a temperature of +10°C compared to at +35°C due to larger cell impedance at lower temperatures. At both temperatures, the anode potential is kept close to the threshold value via adaptive current control. It can be noted that the anode potential briefly dips below the threshold at the beginning of charge in +10°C. This is due to larger cell impedance and slower kinetic response to current change. It should be noted that the threshold is set with margin to lithium plating conditions to handle these cases. Also, this is typically addressed by fine-tuning charge-control settings. Figure 5 (b)-(c) compares estimated anode potential and charge current (normalised to the peak value) observed during the first and the 500^{th} cycle of the degradation test. The aged cell reaches anode potential threshold earlier due to increased impedance, and the charge current is correspondingly lower. Overall, Breathe Charge effectively keep anode potential close to the pre-defined threshold at different thermal and aging conditions.

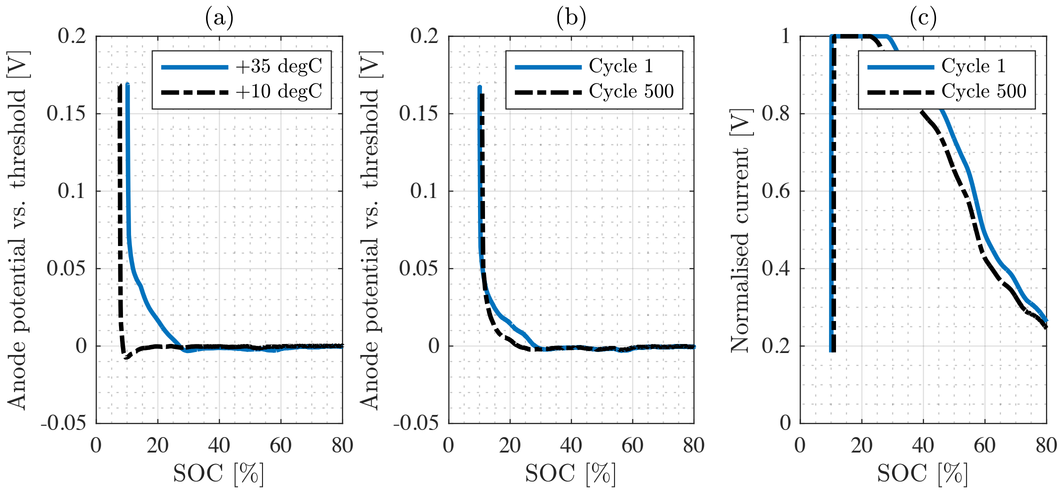

Figure 5: (a) Difference between estimated anode potential and threshold during fast charging at +10 and +35°C. Difference between (b) estimated anode potential and threshold, and (c) normalized current, at beginning of life and after 500 charge cycles at +35°C.

In summary, the cell level testing indicated improvements of around 15-20% on charge time from 10-80% SOC with negligible difference in battery health compared to the benchmark MSCC profile over 600 cycles of cell-level degradation test. In fact, the differences were similar to what two consecutive benchmark tests show.

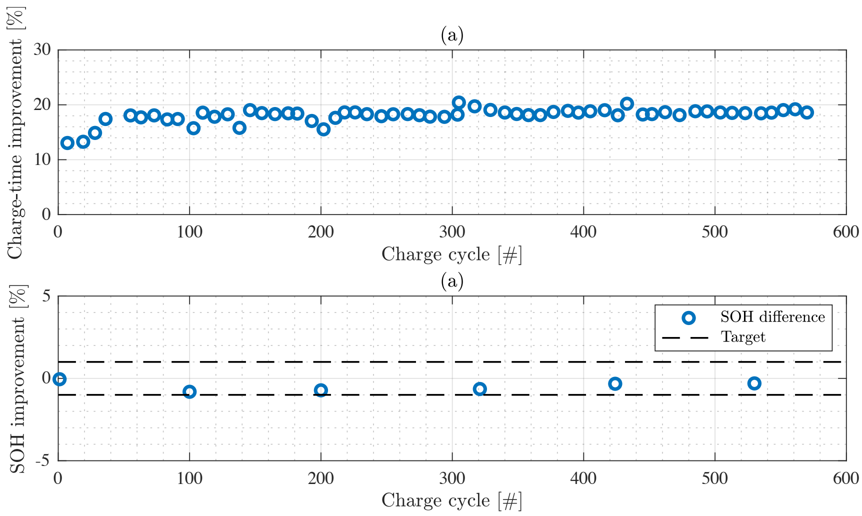

Fig.5: (a) Charge-time reduction (10 to 80% SOC) using Breathe Charge, and (b) SOH deviation between Breathe Charge and benchmark MSCC protocol.

Pack-level benchmarking

To further benchmark the performance of Breathe Charge compared to the MSCC protocol, pack tests were conducted in Volvo Cars' battery laboratory. In the tests, the pack is installed in a climatic chamber with a pack cycler simulating the charging station and a liquid thermal system to mimic the conditions in the vehicle. The test setup takes inputs from the BMS where Breathe Charge and MSCC protocol are implemented.

Two SOC ranges, 10-80% and 30-80% were tested for battery temperatures from +10 to +35°C. Lower temperatures than +10°C were already evaluated to have too poor performance and warmer than +35°C triggered other thermal limitations for both Breathe Charge and MSCC. In all cases, the battery started by being soaked to the climatic chamber temperature. After the test was started, the thermal system was active as it would be in the vehicle providing cooling and/or heating as requested. For each test, the charging time together with the amount of energy charged during the initial 10 minutes were recorded, and the results are found in Figure 6.

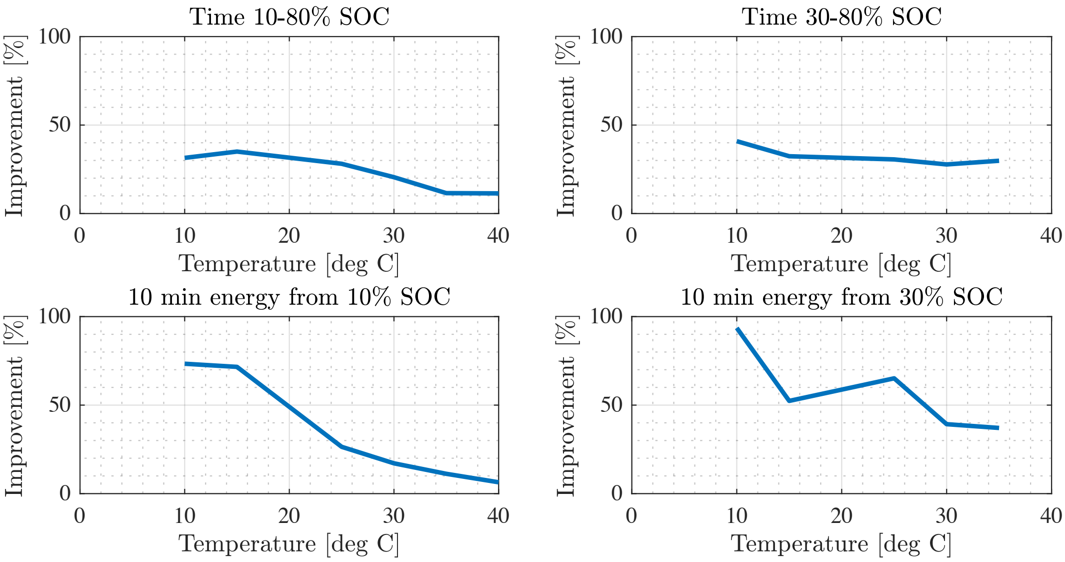

Figure 6: Charging performance improvements as tested in a battery pack in lab conditions using Breathe Charge compared to a well-calibrated MSCC protocol.

All cases showed improvements using Breathe Charge. The smallest differences were seen when the battery started optimally preconditioned. The main reason is that the MSCC is very well tuned to these conditions. The major improvement for lower temperatures means less energy is needed for pre-conditioning of the battery. That saves customers costs, time, and battery durability. The major improvement in colder temperatures is a combination of factors, first it is not as well calibrated in the MSCC due to the time-consuming calibration of such protocols. Secondly, the higher initial current with Breathe Charge has the secondary effect of increasing heat generation and thereby enabling even higher currents. Similar to the effect of non-optimal starting temperatures, Breathe Charge improved charging time at other starting conditions than 10% SOC better.

Vehicle validation

Ultimately, what matters is how charging performs in a real-world application. The results in Figure 7 come from testing of a pre-series Volvo ES90 with Breathe Charge implemented. The charging session was conducted at a public 300kW DC charging station in the north of Sweden. The conditions are typically difficult for battery charging, with ambient temperature of –5°C and the coldest cell in the battery pack starting at a temperature of around +17°C. With these conditions, the charging session from 10-80% SOC took around 21 minutes, which is only one minute above rated charging performance of 20 minutes, achieved with battery preconditioned to around +30°C.

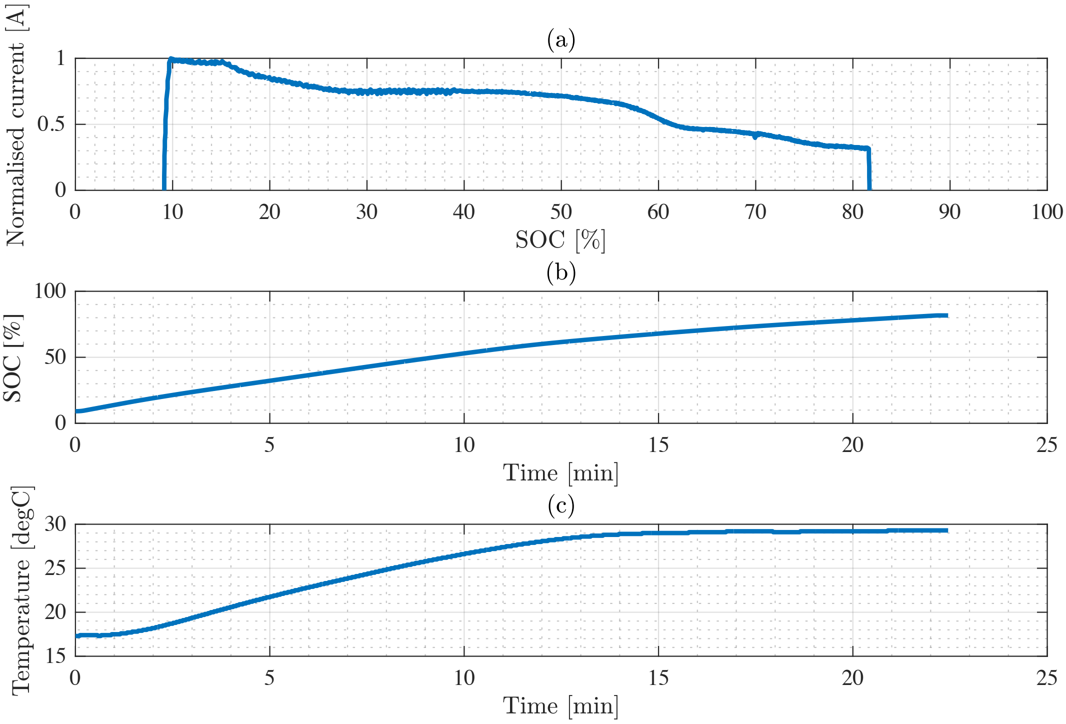

Figure 7: Charging between 10-80% SOC at –5°C ambient temperature after pre-conditioning to +17°C: (a) normalised pack current, (b) pack SOC, and (c) minimum cell temperature in the pack. The total charging time is around 21 minutes.

5 Conclusions

This article explores the charging performance improvements achieved by integrating Breathe Charge on Volvo Cars' in-house BMS. Breathe Charge replaces the conventional multi-stage constant current protocol with an adaptive current controller that manages to reduce charging time without compromising battery lifetime. It does so by estimating risk of lithium plating for all cells of the pack in real-time and adaptively adjusts the charging current accordingly. The results have been verified in a range of tests, from cell to final vehicle integration. The tests show 15-20% charge time reduction for optimal starting conditions without impact on battery degradation. When charging is started outside of optimal conditions, e.g., lower temperature, Breathe Charge manages to reduce charge time even more. This has secondary effect of reducing the need to thermal pre-conditioning making the charging more efficient.

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Presenter Biography

Dr Björn Fridholm, Technical Specialist in Battery Management at Volvo Cars

Björn has a M.Sc in Electrical Engineering and PhD in Automatic Control, both from Chalmers University of Technology. He has worked in the automotive industry for more than 20 years with simulation and control in different systems. Since 2011 he focused exclusively on battery management and currently has a role at Volvo Cars as technical specialist in the field.

Dr Yan Zhao, CTO & Co-founder at Breathe Battery Technology

Yan began his research focusing on lithium-ion battery design, thermal management, and simulation at Imperial College London, where he graduated with a PhD in battery engineering. He has over 10 published papers and has created software for cell design that is now used internationally. As CTO and co-founder of Breathe, Yan is responsible for Breathe's engineering, development and product strategy.

Dr Jingyi Chen, Head of Battery & Projects at Breathe Battery Technology

Jingyi has a PhD in Materials Research, focused on Solid Oxide Fuel Cells, from Imperial College London. Following the completion of her PhD, she stayed at Imperial as a Research Associate where she worked on battery degradation diagnostics and prognostics for battery management systems in EV and HEV applications. Jingyi currently leads Breathe's battery teams.