Durability effects of high frequency pulse charging

#12098

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Sammanfattning

Detta projekt undersöktes hur livslängden hos Li-Jon battericeller påverkas av pulsladdning. Till skillnad från konventionella metoder för konstant ström eller konstant spänning levererar pulsladdning energi i högfrekventa pulser följt av korta relaxationsperioder. I projektet testades litiumjonbattericeller med 100 % hälsotillstånd (SOH) under högfrekventa pulsladdningsförhållanden (10 mHz–125 Hz) för att bestämma deras hållbarhet och prestanda. Projektet analyserade högfrekventa pulsers förmåga att minska litiumplätering som uppstår när litiumjoner avsätts på anodytan under snabbladdning. Litiumplätering kan leda till kapacitetsminskning, ökat inre motstånd och säkerhetsrisker. Testerna införlivade olika arbetscykler (25 % och 50 %) för att ge viloperioder mellan pulserna för en mer enhetlig diffusion av joner, vilket bidrog till att bevara elektrodens strukturella integritet. Variationen av arbetscykler och frekvenser visade högre kapacitetsretention än en konstant referens under de totala cyklerna för olika tester. Till exempel hade pulsladdning med 50 Hz-frekvens vid 50 % arbetscykel ≈38 % högre kapacitetsretention än den konstanta referensen efter 300 cykler. Arbetscykeln visade sig vara en mer dominerande parameter än frekvensen, eftersom celler laddade med 25 % arbetscykel hade 95 % absolut kapacitetsretention medan den var 80 % för celler som drivs med 50 % arbetscykel för samma frekvens efter 300 cykler. Detta stöder direkt längre batterilivslängd och mer tillförlitlig prestanda över upprepade laddningscykler. Projektet drevs i samarbete mellan Volvo Cars och Chalmers.

Summary

This project investigated High-frequency Pulse for a Li-Ion battery. Unlike conventional constant-current or constant-voltage charging methods, pulse charging delivers energy in high-frequency pulses followed by short relaxation periods. This project tested lithium-ion battery cells with 100% State-of-health (SOH) under high-frequency pulse charging (10 mHz- 125 Hz) conditions to determine their durability and performance. The project analysed the ability of high-frequency pulses to reduce lithium plating that occurs when lithium ions deposit on the anode surface during fast charging. Lithium plating can lead to capacity fading, increased internal resistance, and safety risks. The testing incorporated different duty cycles (25% and 50%) to provide rest periods between pulses for a more uniform diffusion of ions, which helped to preserve the structural integrity of the electrode. The variation of duty cycles and frequencies demonstrated higher capacity retention than a constant reference throughout the total cycles of various tests. For example, the 50 Hz frequency pulse charging at 50% duty cycle had ≈38% higher capacity retention than the constant reference after 300 cycles. The duty-cycle proved to be a more dominant parameter than frequency, as cells charged with 25% duty cycle had 95% absolute capacity retention compared to 80% for cells operated at 50% duty-cycle for the same frequency after 300 cycles. This directly supports longer battery lifespan and more reliable performance over repetitive charging cycles. The project was a cooperation project between Volvo Cars and Chalmers.

Background

Electrifying vehicles is the key to decarbonizing road transport, a sector that accounts for around one-sixth of global emissions, (IEA 2024). Even though there is a slight reduction in electrification pace during the last year, sales have increased by a factor of three since 2022, and according to WardsAuto (2023), the share of electric vehicles can reach 86% of global vehicle sales by 2030. A key feature to continue to make electrified vehicles an important competitor to combustion engine vehicles is to ensure that the battery health can be kept well during the lifetime of the vehicle, during the first 10 years. High currents are known to degrade batteries, and in particular during charging, high currents could be needed to reduce stop time at fueling stations. A mitigation to this ageing that has emerged is to use high-frequency pulse charging. This charging methodology has emerged as one of the potential technologies that can revolutionize the customer's charging experience by faster and more efficient charging while degrading the battery cell's life less than constant-current charging. Accordingly, investigations on this subject are of high importance.

Furthermore, there are also other applications where pulsed waveform into battery cells can happen. Multilevel converters are slowly gaining interest in the automotive industry. One concept it the cascaded H-bridge set-up where the AC-voltages for the machine are built up by series-connected battery modules or cells. Here the cells are exposed to current waveforms of a pulsed shape. Volvo Cars, as a premium automotive car brand, aims to utilize the advantages of high-frequency pulse charging with this novel upcoming technology, Volvo SmartCell. SmartCell can perform high-frequency pulse charging without the need for any additional external hardware and software (Forssell et al., 2025).

The purpose of this project conducted by Volvo Cars, along with Chalmers and the Swedish Electromobility Centre (SEC), was to test and validate the promises of high-frequency pulse charging. Furthermore, a goal was to increase the experience of high-frequency pulse charging, which generates rapid pulses for a short period of time, followed by a short relaxation period, unlike conventional constant-current or constant-voltage charging methods, on the durability and performance of lithium-ion cells.

General project description

In this project a large test matrix was formulated to investigate the impact of pulsed charging, in total 54 cells were tested. Pulsed discharging was also incorporated since this is an operation that will occur in an MMC-set-up (Forssell et al., 2025) implemented in an electrical vehicle. Various pulse frequencies as well as duty cycles of the pulses were implemented utilizing various battery testers. The resulting capacity was then determined as a function of energy throughput.

Results

The primary testing performed in the project involved a testing campaign conducted to investigate the durability effects of pulsing charge currents, as indicated in the literature to be potentially beneficial for cell longevity (Geslin et al., 2024; Huang et al., 2024). The results from literature were however, inconclusive with regards to the most beneficial frequency for the square wave pulsing, with some papers indicating that high frequencies were required to get strong positive durability effects, with middle frequency range even being potentially detrimental to durability (Huang et al., 2024), and other showing that any frequency above 10-100 mHz were beneficial (Geslin et al., 2024; Frenander & Thiringer, 2023) and that higher frequency ranges had little to no effect on the durability (Bessman et al., 2019). The resulting test matrix is shown in Table 1.

Table 1 Summarized test descriptions and test IDs.

Test condition	Test ID	$I\_avg\ [A]$
Pulse charge, pulse discharge	PC-PD	2.5
Pulse charge, no pulse discharge	PC-NPD	
Constant current reference	CC-ref	
Pulse charge, 50 % duty cycle	PC-PD-50	3.5
Pulse charge, 25 % duty cycle	PC-PD-25	
Constant current reference	1C-ref	

To obtain comparable data for the relevant frequency ranges, the test matrix was designed to sweep frequencies from 10 mHz to 125 Hz. Due to tester limitations with regard to maximum charge current, the frequency sweep was split into two distinct categories based on average current: lower frequency testing with an average current of 2.5 A, dictated by the maximum current of 5 A and 50 % duty cycle and the higher frequency range with average current of 3.5 A corresponding to 1 C for the cells under test. Each test group had a corresponding constant current reference test, with the corresponding average current of 2.5 A and 3.5 A, respectively.

The tests were thus split into two groups with a variation of duty cycle of the square wave pulse for the higher frequency range and a variation of frequencies for the lower frequency range, see Tables Table 1 through permeability where an increase in k indicates a less permeable SEI layer. This can be indicative of formation of Li plating leaving a residual SEI layer with higher tortuosity on the negative electrode compared to the normal formation of SEI.

Table 2 Frequencies tested for 2.5 A average current cases.

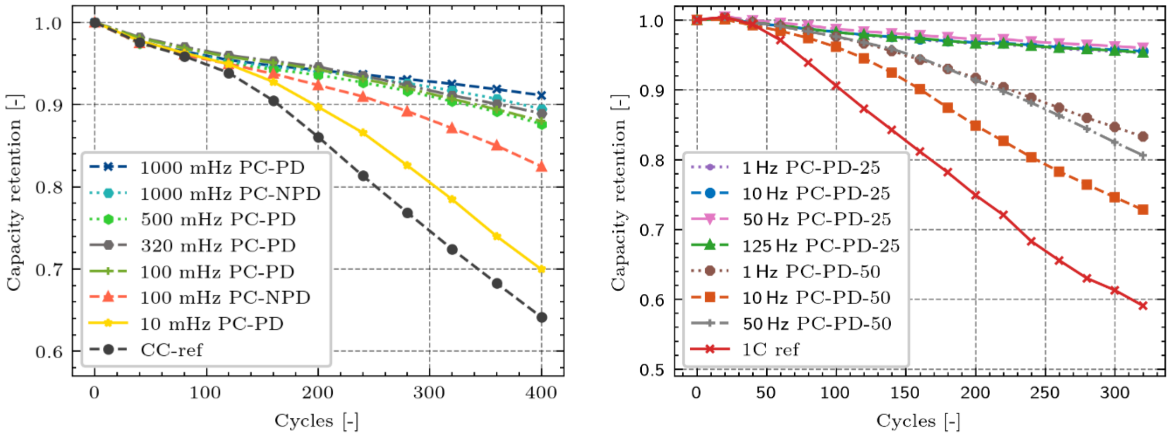
Test condition	Frequencies
PC-PD	10, 100, 320, 500, 1000 mHz
PC-NPD	100, 1000 mHz

All cycle testing included a recurring performance test to measure cell capacity and impedance by performing an intermittent current interrupt (ICI) test. ICI was chosen due to the ability to extract high value information from a fast and low effort test (Geng et al., 2022). From the ICI test it is also possible to extract both incremental capacity as well as differential voltage analyses (ICA/DVA), which was done following the method detailed in Geng et al. (2022). The ICI tests also allow for calculation of the diffusion related resistance k is calculated as $k = -(1/I)(dU/(d\sqrt{t}))$ during the intermittent rest steps, which is a good indication of the resistance of the solid-electrolyte interphase (SEI) layer's permeability where an increase in k indicates a less permeable SEI layer. This can be indicative of formation of Li plating leaving a residual SEI layer with higher tortuosity on the negative electrode compared to the normal formation of SEI.

Table 3 Frequencies tested for 3.5 A average current cases.

Test condition	Frequencies
PC-PD-25	1, 10, 50, 125 Hz
PC-PD-50	1, 10, 50 Hz

The main result to assess the benefits of pulse charging is to compare the capacity decay of the cells as the testing progresses, where the overall results are displayed in Figure 1. From these results it can be observed that for low frequency 2.5 A testing, there is a clear grouping of all cells that have a pulse frequency more than 100 mHz display a slower degradation compared to the ones with lower frequency and constant current cases. There is also a clear saturation effect, where the influence of pulse frequency is clearly reduced above 100 mHz. The effect is similarly pronounced for the higher frequency cases with 3.5 A average current and 50 % duty cycle cases, with some separation, but given the large spread between individual samples this can be attributed to stochastic effects rather than trends in the results. In both cases the constant current reference representing the most common charging strategy in today's vehicles is performing the worst from a durability perspective.

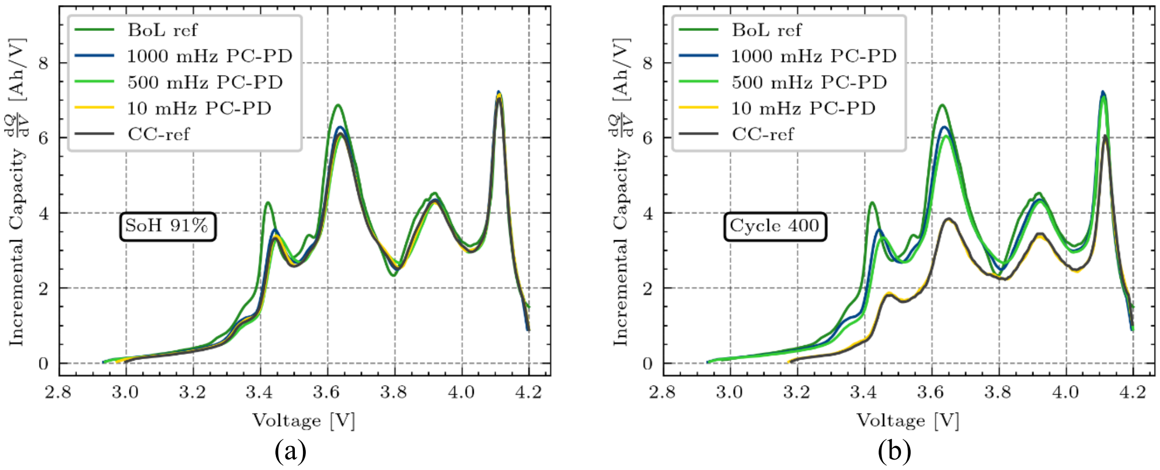


(a) (b)

Figure 1 Capacity decay curves of all tests in the project. Sub-figure (a) shows the 2.5 A average current, and (b) the 3.5 A average current.

There is also a clear trend for the higher frequency 3.5 A average current testing, that the 25 % duty cycle is outperforming the 50 % duty cycle, but this might be an effect of the higher current pulses required to achieve similar average current on 25 % duty cycle means that the cut-off voltages are reached earlier in the testing compared to the 50 % duty cycle, meaning that the average current in this case is actually significantly reduced as a final effect.

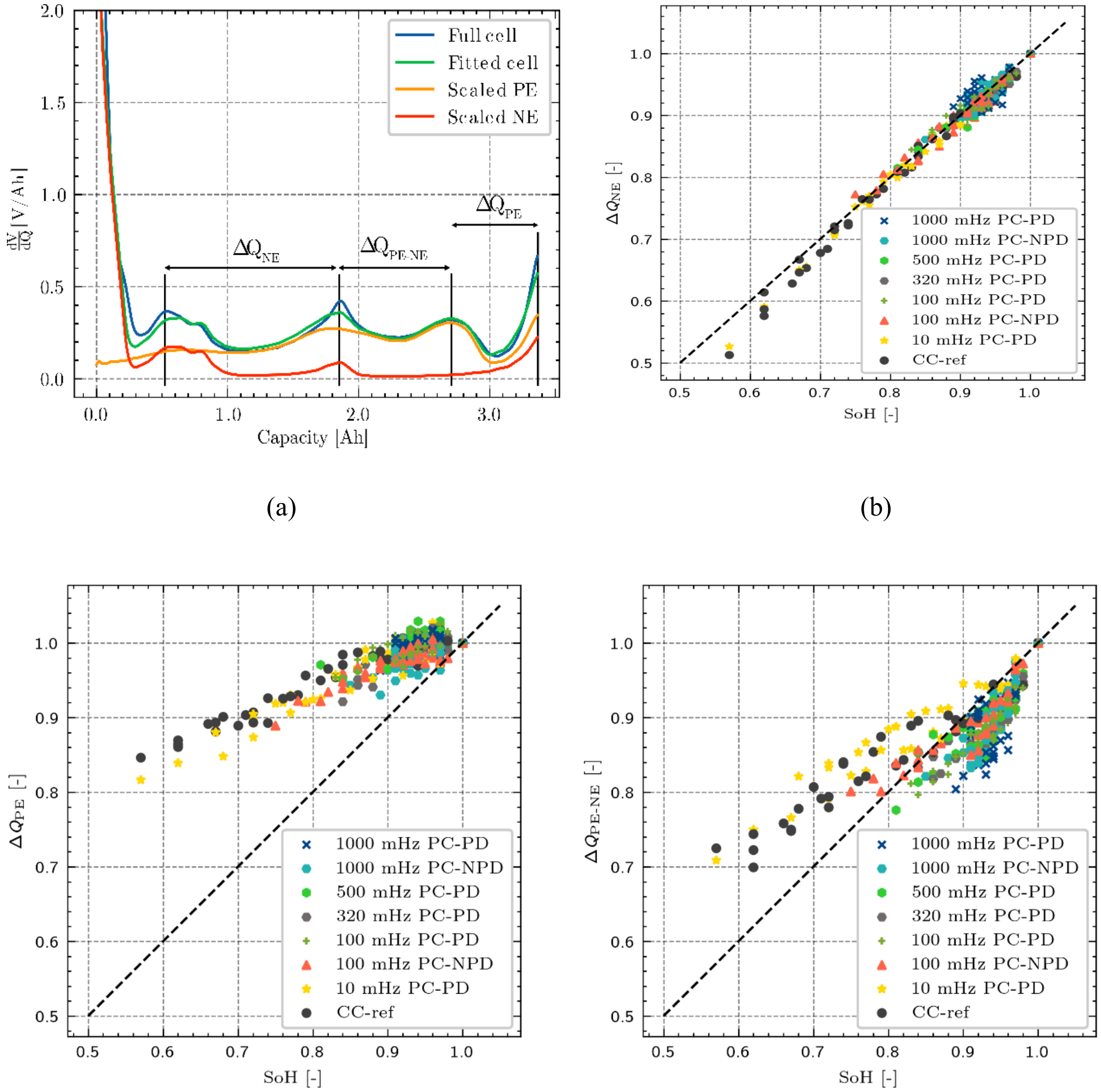
Attributing this difference in ageing to internal processes is attempted using the data from the electro-chemical characterization testing. By analyzing the ICA traces of the cells, it can be seen that the ICAs are showing very similar patterns when compared at similar State of Health (SoH) levels, Figure 2 (a), indicating that the ageing that is happening at constant current and low frequencies is not qualitatively very different from the ageing happening at higher frequencies, it just happens at different rates, which is also clear from Figure 2 (b) where the traces are clearly separated between the higher frequency cases and the constant current and low frequency cases.



(a) (b)

Figure 2 Comparison of ICA curves of cells aged with different cycling conditions. Sub-figure (a) shows cells at similar SoH level, whereas (b) shows ICAs performed after the same number of cycles.

Through utilizing the DVA traces of the cells to trace the distance between different peaks in the DVA, three ageing proxies can be defined to characterize the ageing of the individual electrodes as illustrated in Figure 3(a). By comparing the distance between the two negative electrode peaks a clear metric for the capacity retention of the negative electrode is obtained. It can be seen from Figure 3(b) that this data aligns very well with the overall cell degradation, but in the lower frequency cases it is generally below the trendline, indicating faster decay of negative electrode than overall cell. When comparing the distance between cell cut-off and the positive electrode peak at high voltage a proxy for the positive electrode ageing ΔQ_{PE} is obtained which is displayed in Figure 3(c). From this result, it is clear that the positive electrode is losing capacity at significantly lower rate than the negative electrode, regardless of pulse frequency, even the constant current case aligns well with the trend of the pulse charged cells. This shows that the main effect from pulse charging is seen at the negative electrode, raising the suspicion that it could serve to mitigate Li plating and SEI (re)formation, considering these are ageing effects known to mainly affect the negative electrode. This is further reinforced by analyzing the slip between the electrodes ΔQ_{PE-NE} which trace the distance between two peaks uniquely attributed to the respective electrodes, displayed in Figure 3(d). From this figure it can be noted that the trend for low frequency and constant current is for the distance to increase faster than cell capacity loss, which indicates a rapid loss of capacity on the negative electrode. Thus, this analysis provides indications that pulsing the charge current has clear benefits for the ageing of the negative electrode, while the positive electrode is less affected.



(a)

(b)

(c)

(d)

Figure 3 Ageing mode proxies as identified from DVA traces. As the trends are plotted versus SoH, the dashed diagonal lines indicate equal degradation of full cell and ageing proxy. (a) Details the identified proxies, (b) displays the negative electrode ageing ΔQ_{NE}, (c) is the positive electrode ageing ΔQ_{PE} and (d) the relative decay between electrodes ΔQ_{PE-NE}.

To assess whether this can be related to Li plating. the k-values for different ageing conditions are compared while controlling that the diffusion is still clearly Fickian in nature, ensuring that like-for-like comparisons can be drawn for the k-values. As seen from Figure 4, despite the cells losing significant amounts of capacity the 45° angle of the diffusive tail in the EIS is maintained throughout, so Fickian diffusion can still be confirmed. This also enables further analysis of the k-values for diffusive resistance.

By comparing diffusive resistance in a similar way to the incremental capacity traces, it can be noted that diffusive resistance is diverging even at similar SoH levels, see Figure 5(a). The higher diffusive resistance for constant current reference could be indicative of a more tortuous SEI being formed in the cells cycled with constant current or low frequency pulsing. This could in turn be the effect of re-occurring Li plating happening in these cells, as SEI will form on the plated Li metal and with stripping and intercalation of plated Li it is possible that a denser SEI would form on the negative electrode.

Due to lower resolution on the data from the tester the trend of higher k-value is less obvious from the 2.5 A mean current data, compared to 3.5 A mean current data. This can also be affected by the fact that they have not reached as low in SoH as the 3.5 A testing, however, if an average is calculated for the different cases the average value for k in constant current and low frequency testing is still about 8 % higher compared to the higher frequency tests, showing that the trend of higher diffusive resistivity is reproducible in all tests.

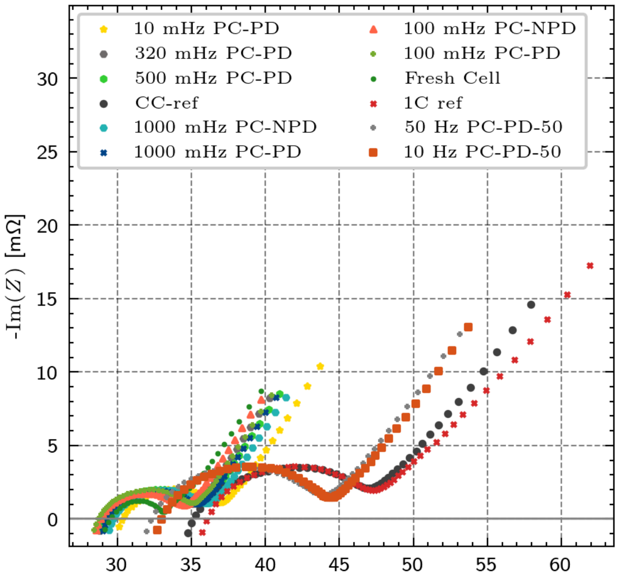
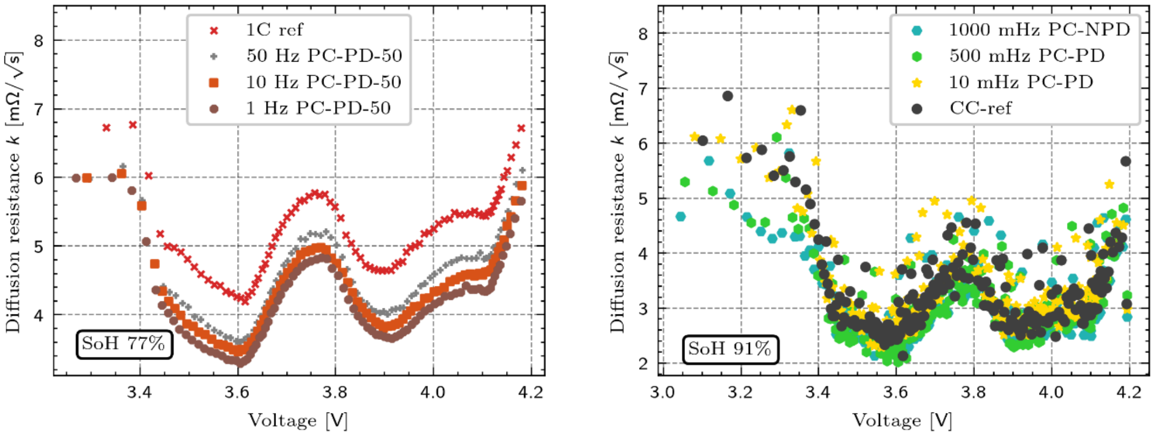


Figure 4 EIS sweeps of cells after ageing campaign completed. 45° angle of diffusive tail is verifying Fickian diffusion in all cases.



(a) (b)

Figure 5 Diffusive resistance plotted versus voltage for cells at similar state of health levels. Sub-figure (a) shows 3.5 A mean current high frequency tests, and (b) displays 2.5 A low frequency tests.

Conclusions

The project demonstrates that high-frequency pulse charging can improve the durability of lithium-ion cells compared to conventional constant-current charging. The results show that pulse frequencies above roughly 100 mHz reduce degradation rates, with clear grouping effects where all frequencies above this threshold outperform both low-frequency pulsing and constant-current references. This indicates that the benefit of pulse charging saturates above a relatively modest frequency level, making the benefits easy to achieve on a SmartCell platform.

Electrochemical analysis supports the conclusion that the primary improvements are linked to reduced ageing of the negative electrode. Incremental capacity and differential voltage analysis show that the negative electrode exhibits faster deterioration under low-frequency and constant-current operation, while higher-frequency pulsing slows this process. The observed trends in diffusive resistance further reinforce this interpretation. Higher k-values for constant-current and low-frequency cases suggest a more tortuous SEI, potentially linked to recurring lithium plating, whereas higher-frequency pulsed cells maintain lower diffusive resistance. Together, these findings indicate that pulse charging mitigates processes associated with lithium plating and SEI (re)formation, although full confirmation would require post-mortem analysis outside the scope of this study.

While the mechanisms underlying the reduced degradation require further clarification, the combined cycling and electrochemical data points towards a consistent trend, appropriately chosen pulse-charging strategies can slow negative-electrode ageing without introducing additional system complexity. This aligns with broader goals of improving battery lifetime and charging performance in practical applications, as highlighted in the project's utilization context.

Overall, the results confirm that high-frequency pulse charging is a promising approach for enhancing lithium-ion cell durability. The findings provide a basis for further refinement of pulse-charging strategies, improved modelling of plating-related ageing, and future validation through post-mortem studies. The benefits demonstrated offer clear potential for integration into emerging battery technologies such as Volvo's SmartCell platform, supporting more reliable and long-lasting electric-vehicle battery systems.

Utilization of results

The success of high-frequency pulse charging technology can be one of the major enablers for EV adoption, as it provides a faster and more efficient charging experience, along with enhancing battery cells' life. This new way of charging brings various questions, like charging performance, efficiency, but more importantly, its impact on the cell's life, and other than that, is there any relevant infrastructure or technology that can utilize its advantages? Volvo's SmartCell, which can generate AC or direct-current (DC) voltage directly from battery cells without a big conversion, is the true enabler for high-frequency pulse charging. SmartCell, through its cascaded H-bridge multi-level inverter system, can directly provide high-frequency pulses for charging without additional external hardware and software. SmartCell is a software-driven battery management platform substituting traditional power electronics systems like inverter, on-board charger (OBC), battery management system (BMS), and many more, which saves cost, weight, material, CO_2 footprint, and packaging constraints (Forssell et al., 2025). These advantages of SmartCell come with the question of the impact of high-frequency pulses on the cell's durability over time. The result of this project provides valuable insights on durability effects of high-frequency pulse charging on a battery cell's life. The test results validate that high-frequency pulses are beneficial for cells' life as they increase capacity retention and can enhance the charging experience. The test results are utilized for enhancing EV battery reliability, safety, and customer charging experience while using Volvo SmartCell. The test results provide insight into various advantages of high-frequency pulse charging and a platform for rigorous testing of cells under these conditions to unlock their full potential and ensure reliable, safe deployment in future electric mobility systems.

Targets

General SEC Objectives:

SEC Objective 1 – Interdisciplinary project - accomplished
This project had its base in thematic group 3 Energy storage but also stretched into thematic group 2 Electric Drives and Charging, linking the battery with the operation of its power electronic converter.

SEC Objective 2 – Interdisciplinary research environment - accomplished
The electrochemical and the electrotechnical disciplines have cooperated in the project, with researchers from both disciplines.

SEC Objective 3 – Scientifically competitiveness – accomplished/ongoing
Unique results regarding the ageing effect of rapid pulse charging and discharging have been achieved. A journal publication has been obtained on this subject.

SEC Objective 4 – Dissemination of knowledge & research findings – accomplished/ongoing
The results have been spread within SEC and to the participating partners.

SEC Objective 5 – Collaboration – accomplished
The present work has been a cooperation between Volvo Cars and Chalmers. It has continued the path of cooperation between the two entities into a new area, power electronics impact and possibilities on prolonging lifetime in Lithium-Ion batteries.

SEC Objective 6 – Competence supply – accomplished
At both Volvo and Chalmers, the project has led to a deepening of the subject of advanced experimental and measurement techniques, needed for studies of lifetime prolongation.

The expected technical results were:

All technical targets set out in the application of this project were achieved.

- Internal Resistance at various frequencies: By analyzing the voltage response to applied current pulses, one can calculate the internal resistance, which is critical for assessing power efficiency and heat generation. **Achieved**
- SoC Dependence: The test helps us understand how performance metrics like internal resistance change with the battery's state of charge. **Achieved**
- Assessing Dynamic Response: Evaluation of the battery's ability to quickly supply and absorb power. This is vital for applications requiring rapid power fluctuations. **Achieved**
- Durability: The impact of high frequency and power demand on cell State-of-Health and aging. **Achieved**

Industry contribution

Volvo Cars has defined the scope of the project to find valuable insight into the durability effect on battery cells' life from high-frequency pulse charging. Volvo cars have contributed to defining the test sequence and matrix, which included the important parameters and boundary conditions like frequencies, duty-cycles, temperature, state-of-charge (SOC), and c-rates based on real-world driving scenarios. Also, Volvo Cars has supported the preparation of the testing rig and provided additional support for adding cooling infrastructure so that cells boundary temperature can be maintained. The industry also supported the analysis of the test results and utilization of those results to optimize pulse charging strategies.

Dissemination of knowledge

Through cooperation with the industrial partners and the reference group information about the findings has spread from academia to industry as well as in reverse direction. Furthermore, a journal article has been published.

Papers & Publications

K. Frenander, D. Jutsell Nilsson, T. Thiringer, "Extending battery lifetime by pulsed charging", npj Clean Energy', (2026) 2:4

Abbreviation	Meaning
AC	Alternating Current
BMS	Battery Management System
CC	Constant Current
CCref	Constant Current Reference Test
CV	Constant Voltage
DVA	Differential Voltage Analysis
DC	Direct Current
EV	Electric Vehicle
EIS	Electrochemical Impedance Spectroscopy
Hz	Hertz
ICI	Intermittent Current Interruption
k	Diffusion related resistance factor
Li	Lithium
Li-ion	Lithium ion
NE	Negative Electrode
OBC	Onboard Charger
PC-PD	Pulse Charge – Pulse Discharge
PC-NPD	Pulse Charge – No Pulse Discharge
PC-PD-50	Pulse Charge – Pulse Discharge, 50% Duty Cycle
PC-PD-25	Pulse Charge – Pulse Discharge, 25% Duty Cycle
PE	Positive Electrode
SEI	Solid Electrolyte Interphase
SoC	State of Charge
SoH	State of Health
U	Voltage

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