38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Volvo SmartCell
A New Multilevel Battery Propulsion and Power Supply System

Jonas Forssell*, Markus Ekström, Aditya Pratap Singh,
Torbjörn Larsson, Jonas Björkholtz

Volvo Car Corporation, Göteborg, Sweden, *jonas.forssell@volvocars.com

Executive Summary

This research paper introduces Volvo SmartCell, an alternating-current (AC) battery technology. SmartCell is a combination of modular multilevel converters (MMCs) and cells for the propulsion and power supply of electric vehicles. This novel technology replaces conventional electric driveline components while enhancing efficiency and redundancy. Volvo's in-house developed SmartCell system integrates widely available components and features a new communication protocol for robust motor and charging controls. Key benefits include improved system efficiency, reduced cost and complexity, and increased safety through redundant power supplies and self-protection mechanisms. The SmartCell system also supports active balancing of battery cells and offers high degrees of freedom in cell chemistry and size utilization. Challenges such as wireless communication bandwidth and cost optimization of Cluster Boards are being addressed to fully realize the advantages of this novel technology. Successful rig testing has been performed and further development is ongoing.

Keywords: Electric Vehicles, Batteries, Electric Motor Drive, Power Electronic Systems, Advanced Control of EVs

1 Introduction

Electric vehicles have demonstrated their viability as an alternative to traditional internal combustion vehicles due to better driving experiences, lower environmental impact, and many more reasons, despite the higher initial purchase cost. To achieve widespread adoption of electric vehicles, it is imperative to further reduce costs. As the automotive industry evolves into the implementation of the third and fourth generation electric driveline, the transition presents a significant opportunity to reduce both cost and complexity at the same time. The trends in electrification include the integration of inverters in electric machines, the relocation of the charging and battery monitoring functions to the battery itself, and the enhancement of the auxiliary power supply options with 48 V systems [1]. Currently, the exploration of multilevel converters also provides the opportunity to improve efficiency. Taking these trends collectively into account, there is a potential to replace all these systems with a multi-level cell-based battery system, achieving even greater benefits. This approach not only reduces the number of complex components in the propulsion system but also possibly simplifies the software complexity due to the substantial synergies between the traction and charging control. This research article elucidates the primary design, functionalities, and benefits of the combination of MMC and cells for propulsion and power supply, termed the Volvo SmartCell [2, 3].

2 SmartCell Concept Description

SmartCell is a Cascaded H-bridge (CHB) battery system [4]. The main component is the Cluster Board which controls a group of battery cells referred to as cluster and primarily includes the H bridge and the DC / DC converter as shown in Figures 1 and 2. The Cluster Boards are in constant communication with a Master Board where the primary controller resides.

2.1 System Overview

SmartCell system comprises three independent parallel strings in which several Cluster Boards are connected in series as illustrated in Figure 1 and explained in Section 2.2. The cells through the Cluster Boards are connected to the electric machine to provide propulsion power. The Cluster Boards are connected in series in three independent phases X with each cluster having a unique identifier X:Y highlighted in Figure 1 (1:1, 2:2 and 3:3...). The output from the strings is routed via a Master Board where the total voltage and current for each string can be monitored. Radio transceivers are used for communication between Cluster Boards and Master Board.

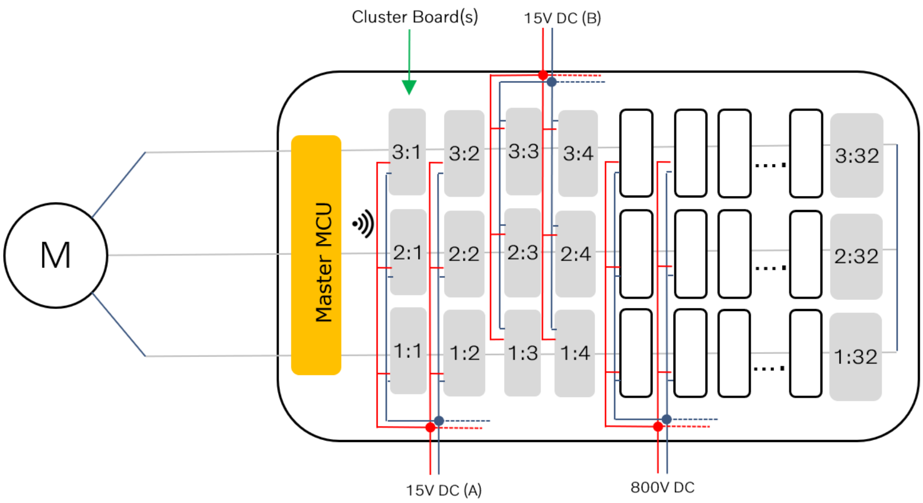


Figure 1: Overview of SmartCell battery pack

The entire communication is based on radio up-link as it is cost-effective and robust. Also, because of the varying potential of the clusters, this communication is isolated. We have configured the up-link on existing wireless Battery Monitoring System (BMS) technology complemented with a customized protocol to achieve the required bandwidth and clock synchronization between the clusters. Each cluster also has a second output from the DC/DC converter on the Cluster Board. This is an isolated output of the peak power $\approx$ 400 W and is available in two options: The first is a 15 V output, which is used to power the vehicle auxiliaries such as onboard computer, lamps, steering power assist, etc. This output is available in two independent branches that comply with high Automotive Safety Integrity Level (ASIL)[5]. The second output option is an 800 V DC supply for power climate loads such as an AC compressor and heater. Since, these loads are not classified for safety, hence there is no requirement for two independent branches for it. These loads are also predictable, which is not the case with 15 V loads. The DC/DC's in each branch are connected in parallel and are controlled to balance the load between them.

2.2 Cluster Board

The Cluster Board is the heart of the system, and it is very critical that this component is cost-effective and highly efficient to provide the utmost advantages of the SmartCell system. In SmartCell a few cells are grouped together in series to form a cluster which is controlled by their respective Cluster Board. The formation of cluster allows to use high-current switches that are rated for low voltage in the H-bridge, and puts the stepping stone for more advanced, efficient and cost-effective electric driveline solution than traditional available systems. Figure 2 illustrates the electrical components and flow of communication between them inside the Cluster Board. The DC/DC converter is isolated and has its own controller for ASIL functionality. The controller monitors the DC/DC converter's output voltage and turn-on the converter if it's voltage drops below the requested voltage. The requested voltage can be set by the local controller block which helps to prevent to turn-on all the DC/DC's at the same time if the load on the system is low. The BMS monitors the cluster's voltage, current, and temperature and keeps constant communication with the Master Board through the wireless up-link in a so-called black channel. The BMS also has a strong safety override to the gate driver. This override can force the H-bridge into bypass mode and thereby disconnect the cluster from the main system during any hazard.

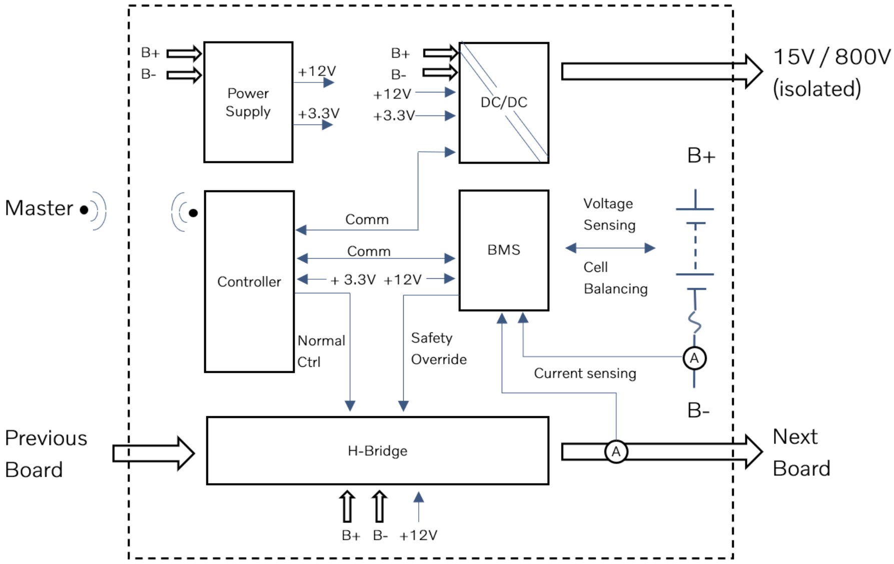


Figure 2: Main components of the Cluster Board

The controller is a traditional Main Controller Unit (MCU) with integrated wireless radio up-link. The controller runs the control firmware for the H-bridge which allows the clusters to generate an AC-voltage via PWM switching. The H-bridge will control the connection of the cluster to the main system. The full H-bridge allows the cluster to connect the cells with positive or negative polarity and also to keep them in bypass mode.

2.3 Master Board

The Master Board is responsible for configuring the main processing power, sensing, and vehicle interface components. Figure 3 illustrates the primary components of the Master Board. To ensure system safety, the board is powered by two independent low voltage branches. The microcontroller is rated for system safety, enabling end-to-end communications through the wireless black-channel.

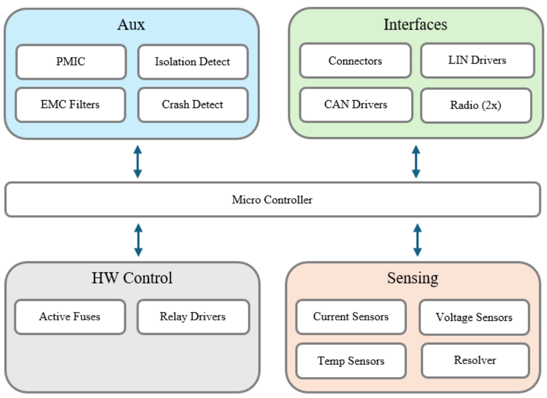


Figure 3: Master Board block diagram

3 SmartCell System for an Electric Vehicle

This chapter describes the primary advantages of the SmartCell system and its ability to significantly reduce the number of various components, enabling tighter integration of the remaining parts into a Master Board and several Cluster Boards. This integration allows for the incorporation of almost the entire propulsion system within the battery pack itself, resulting in a completely flat pack.

3.1 System Design

The core of the system comprises the Cluster Boards, which are connected to various ports as depicted in Figure 4. The AC-charging input is located on the left, where each phase is connected to a separate string, and the neutral is connected to the common top side. Several auxiliary relays enable the synchronization of clusters with the grid prior to initiating charging. The system is capable of handling one-, two-, or three-phase AC charging using the same hardware. On the left, the DC-charging mode is illustrated, where the three strings operate in parallel and are configured to match the DC-charging voltage. If the battery pack is designed for 800 V per string and the vehicle is to be charged from a 400 V charger, the clusters can be adjusted to reduce the string voltage to match the charger voltage. The DC/DC converters output two independent low voltage supplies, indicated in red, while a high voltage supply is shown in yellow. This high voltage supply is connected to the climate system and other non-safety critical loads. Finally, isolation checks are performed at critical points, as indicated in green.

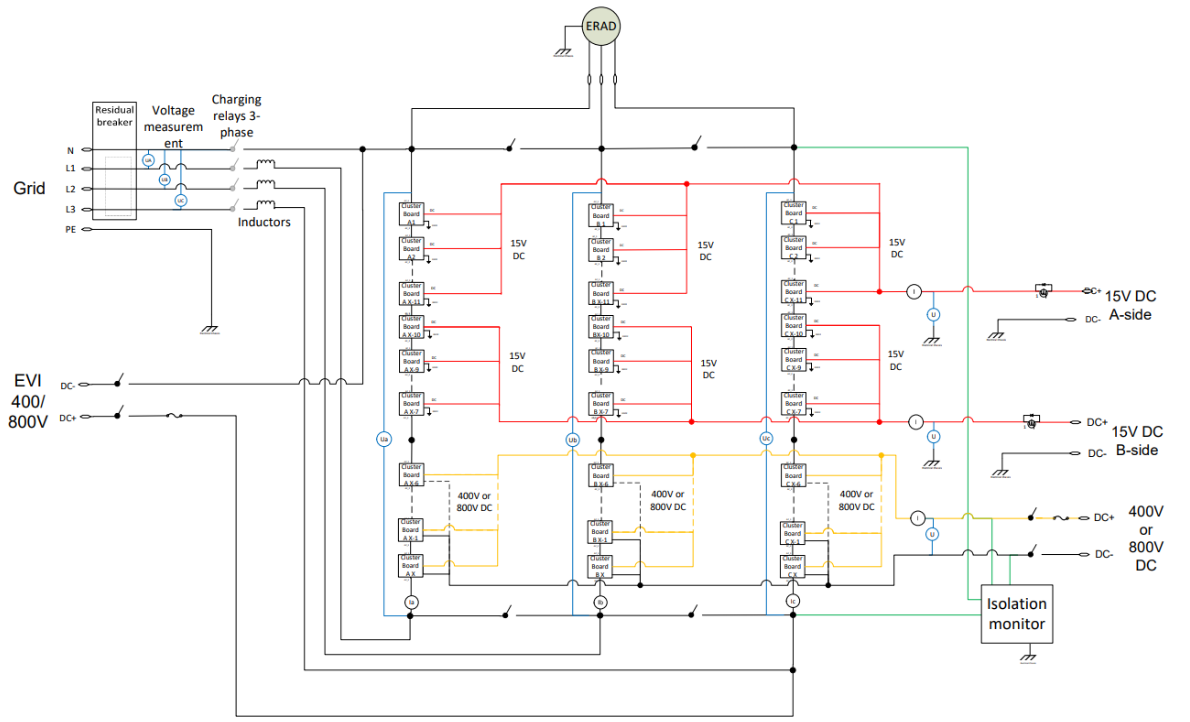


Figure 4: SmartCell schematic

3.2 System Safety

It is imperative that the system complies to highest level of safety standards. Hence, system safety principles have been integrated from the start of the SmartCell concept. The highest requirements specify that cells operate within specified limits and maintain a stable and secure power supply to the vehicle, which is particularly crucial with the introduction of autonomous driving. The main processor is compliant with system safety standards and supports wireless communication. This wireless communication is secured through two redundant channels, ensuring fail-safe communication in the event of a failure in one channel. Additionally, the main phase current measurements are backed up by secondary current measurements on each Cluster Board. The clusters are programmable and can be shutdown via controls. However, as a backup, large current relays can be activated to disengage the clusters.

3.2.1 Self-Protection

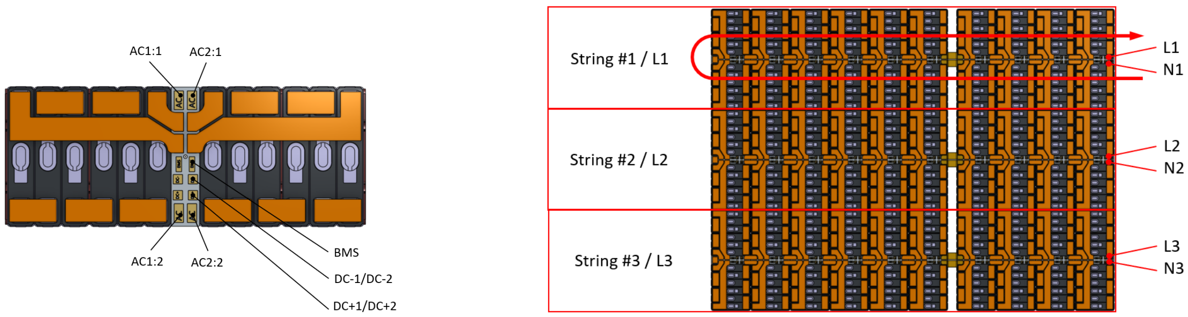
The H-bridge on each Cluster Board controls the connection of each cluster to the entire system. In the default mode, the H-bridge is disconnected to ensure no external voltage from the cluster. Many hazards can be addressed via the by-pass mode, for example, if any of the cells inside a cluster reaches a critical lower voltage during use, the cluster can take the decision to protect itself. This mechanism is hardwired to protect the cluster from over-voltage, under-voltage, over-current and over-temperature.

3.2.2 Separated Power Supplies

The power supply to the vehicle is achieved by two independent branches which complies ISO 26262 and can support safety-relevant vehicle functions necessary for automated driving levels 3-5 [6]. The output of the DC/DC converter of each cluster is connected in parallel to the others. Since each branch consists of multiple DC/DC converters and each with its own independent power source, the redundancy becomes very high. Each DC/DC has its own controller with constant monitoring of the voltage in the system, which allows the DC/DC to continue running even if the communication to the master is interrupted or there is a hardware or software failure in the controller of the Cluster Board.

3.3 Reduction of AC Electromagnetic Interference (EMI)

The flow of current through a conductor induces a significant magnetic field around it [7]. To mitigate the high AC magnetic fields generated by the SmartCell and comply with the relevant directives [8], the busbar layout is engineered to include a counteracting current path in close proximity. This design effectively cancels out the magnetic field around the conductor, as depicted in Figure 5. The same principle is used throughout the design to minimize EMI. In a normal DC battery this is not an issue, but since the SmartCell generates AC current in the battery itself, there are strict requirements on the allowed field and the SmartCell design fulfills these requirements [8].



(a) Cluster (b) Battery pack

Figure 5: Current path for canceling EMI

3.4 Higher Degree of Freedom

SmartCell allows for individual control of the clusters in the system. This opens up for more degrees of freedom compared to a traditional system. The duty cycle of a cluster can be controlled in such a way that all the clusters are actively balanced, for example, if a cluster has a lower state-of-charge compared to the other clusters, then it can be actively balanced through charging via other clusters or by utilizing less during driving until it's capacity is balanced. This active balancing can be made during driving, charging, or even in standby conditions. This active balancing can be taken one step further when combined with different cell characteristics. SmartCell empowers to use mixed cell size and chemistry according to the requirements. For example, the SmartCell system can utilize a cell having a chemistry with high energy but high internal resistance (low power capacity) during low power requirements and can use high-power cells with low resistance (low energy capacity) during the need of high instant power. Another possibility is to combine cells of different sizes in the same pack and enhance space utilization.

4 Communication and Control

One of the primary challenges with the SmartCell system was identifying a cost-effective, non-galvanic communication interface between the Master Board and the Cluster Boards. Various communication technologies were evaluated to determine the best fit for the interface requirements, which are complex due to the need to synchronize the Cluster Boards within a microsecond and continuously transfer critical data. Among the technologies considered, wireless communication was selected for its ability to meet the criteria of cost-effectiveness, non-galvanic properties, and high-speed communication. Additionally, wireless BMS have become widely available from several suppliers, aligning with SmartCell interface requirements. This section explains the wireless communication interface and control mechanisms between the Cluster Boards and the Master Board.

4.1 Wireless Communication Protocol

A dual broadcast interface protocol is developed through which the Master Board transmits at a fixed interval to all the Cluster Boards as illustrated in Figure 6. The communication is strictly downstream and no confirmation is sent by the Cluster Boards about receiving the information from the Master Board. The Master Board broadcasts resolver angle, resolver velocity, and other critical parameters at 1 kHz to the Cluster Boards to generate the required voltage profile. The Cluster Board also sends data like state-of-charge to Master Board at 1 kHz but one Cluster Board at a time. The consequence of this is that the upstream communication is significantly slower than the downstream and, directly related to the number of clusters in the system.

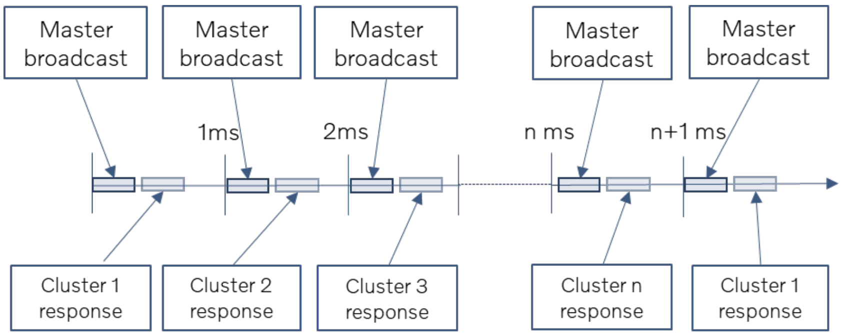


Figure 6: Communication protocol

The Cluster Boards can extrapolate the next means of action based on earlier received data up to five consecutive transmissions during transmission failure. The Cluster Boards goes into the self-protection if they do not receive information from the Master Board even after five successive extrapolations and comes to the active mode once the communication is restored.

4.2 Power Control

In SmartCell a unified control principle for both AC charging and traction control has been developed, termed Power Control. The Master Board senses current, voltage, and resolver data, which serve as inputs to a Park-Clarke transformation to derive the direct and quadrature axis currents (Id and Iq). A proportional-integral (PI) regulator acts on these values to generate a voltage request for each string (U_{string}), as depicted in Figure 7. This request is expressed in vector format to ensure consistency and predictability in wireless control values. The resolver angle, along with resolver velocity (O_{omega}), enables the clusters to predict future angles in the event of a communication message loss.

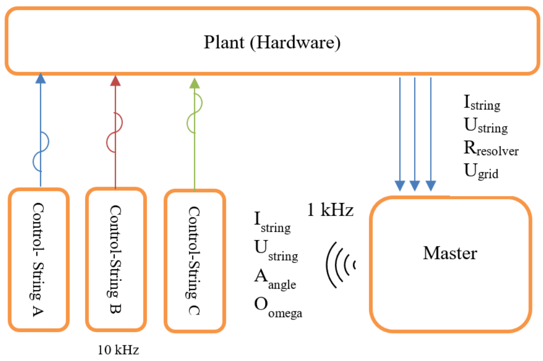


Figure 7: Power control interface

Each Cluster Board utilizes data from the Master Board to determine the precise timing for the generation of a sinusoidal voltage with the correct amplitude and frequency. This timing decision is based on an internal clock within each Cluster Board, synchronized with a common time reference. Additionally, each Cluster Board is equipped with internal current sensing for the string, which facilitates the operation of an internal closed-loop correction algorithm at a high frequency. The Power Control algorithm addresses deviations from the request from the Master Board and transient disturbances. As the same algorithm operates on each cluster and the sensed current is consistent throughout the string, all cluster Boards reach to the same conclusion simultaneously to ensure that corrective actions affect the entire string uniformly.

4.3 DC/DC Control

In order to fulfill system safety requirements, the DC/DC converter boarded on each Cluster Board operates on their own and has no communication between them. Each DC/DC converter has a target voltage and operates accordingly. The DC/DC converter maintains the requested voltage by increasing or decreasing its power output. Figure 8 illustrates the control logic to engage the right number of DC / DC converters by programming different target voltages to meet the vehicle load requirements. On the other end of the spectrum, when a vehicle is parked and in a low state of power consumption, only one or a few DC/DC converters are turned on to provide the needed power. The configuration on how to distribute the DC/DC target voltages is subjected to optimization because it is a trade-off between efficiency and transient response.

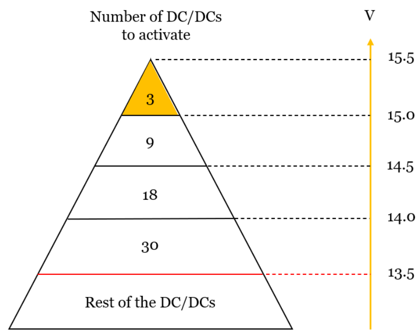


Figure 8: DCDC control

5 Results

SmartCell is a multi-level cell-based battery propulsion and power supply system. It leverages the full capabilities of various functionalities and components, such as H-bridges, wireless communication, and small, independent DC/DC converters, to meet all system requirements with high efficiency and enhanced control. The fundamental distinction between SmartCell and conventional systems lies in the operation and control of battery-pack voltage. SmartCell builds voltage by stacking the voltage of individual clusters according to the power (voltage) requirement, whereas traditional inverter-based systems operate on the full DC voltage to achieve the target voltage. The results of this innovative method of combining MMC and cells to simplify controls and eliminate the need for various components like an inverter, an on-board charger, and to enhance overall system efficiency are presented in this chapter.

5.1 Traction

Figure 9 shows the test results for the utilization of clusters during a segment of the worldwide Harmonized Light Vehicle Test Cycles (WLTC) drive cycle. The top graph shows the engagement of the clusters to supply current for the required torque, as highlighted in the second graph. The number of active clusters depends upon the requested voltage, which varies with electric machine speed as shown in third plot. The negative amplitude of the current illustrates the discharge of the clusters to achieve the requested propulsion torque whereas the positive amplitude of the current is depicted during regeneration, as shown in the first graph. The last graph represents the total phase current delivered to the electric machine, where the current frequency depends on the fundamental frequency of the electric machine.

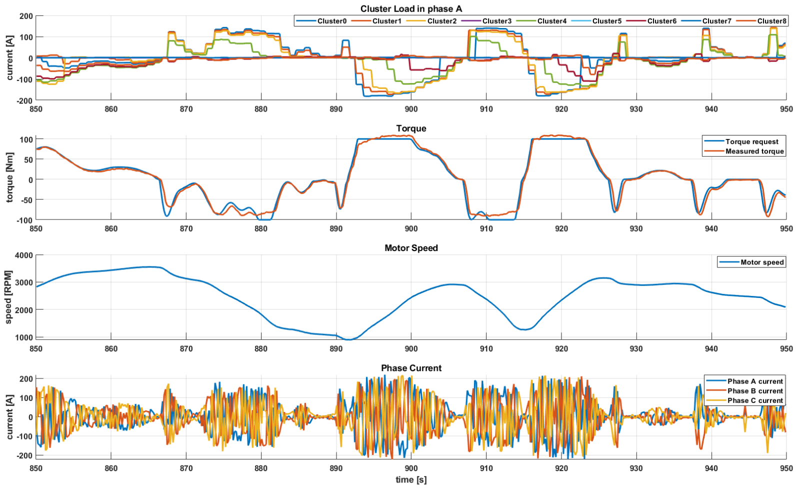


Figure 9: Cluster usage during traction

5.2 Grid Charging

Figure 10 shows the test results for single-phase AC charging of the SmartCell clusters. The green line graph represents the incremental addition of SmartCell clusters in a stepwise manner, resulting in an increase in the charging voltage. The clusters create a partial voltage by the use of PWM. The pink line graph illustrates the sinusoidal phase charging current, which exhibits some disturbances originating from the grid, which the charging control system attempts to mitigate and provide a smooth current waveform. The cluster current, denoted as $I_{cluster}$ indicates the current from the first connected SmartCell cluster, which remains in phase with the charging voltage and has the same polarity all the time with no reactive power.

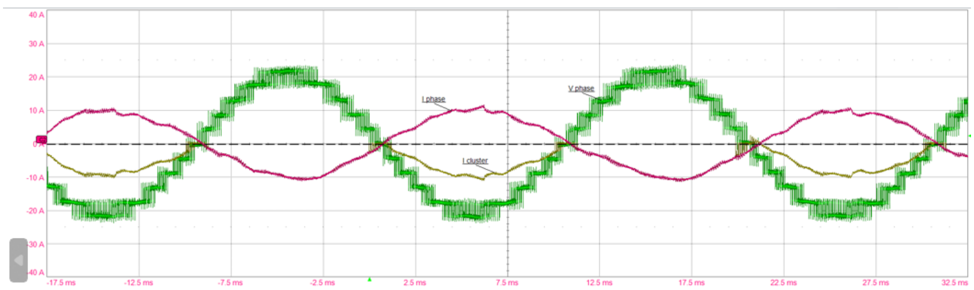


Figure 10: AC charging

5.3 DC/DC Control

Figure 11 shows the test results for the operation of DC / DC converters subjected to a sinusoidal load. The cluster Boards are programmed with different target voltages, where cluster 0 has the highest target voltage. At the time of minimum load, only one DC/DC converter is active to deliver power. According to Figure 11, as load increases, more Cluster Boards are engaged to provide the requested power. Another interesting benefit of this approach can be seen in the last sinusoidal peak where cluster 0 is shutting down and is replaced by cluster 4 due to high voltage dip at that instance. The target voltages for the clusters can be adjusted to equally distribute the load to various DC/DC converters according to power requirements.

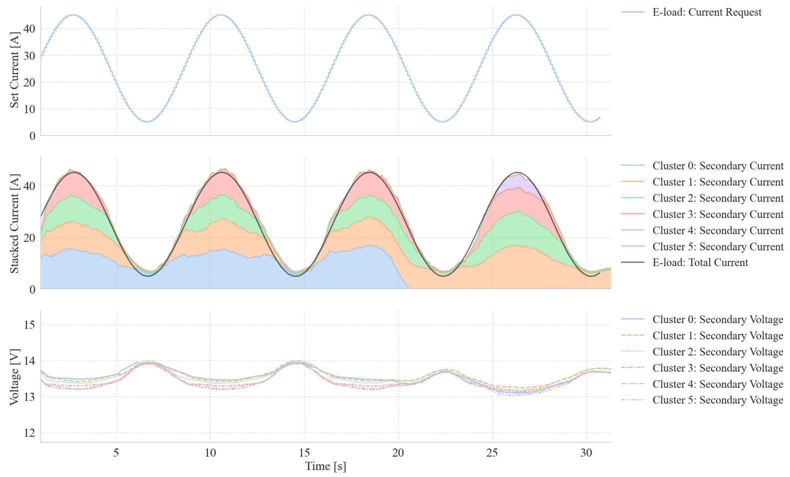


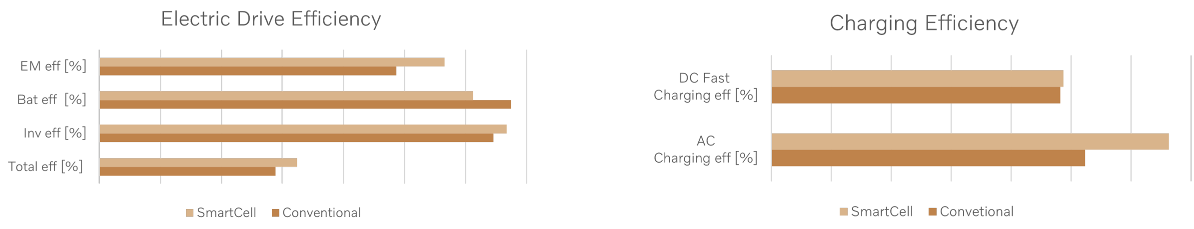
Figure 11: DC/DC load response

5.4 System Efficiency

Extensive simulations have been conducted of the system to determine efficiency. It can be seen that the losses in the SmartCell system are distributed differently versus a traditional inverter-based propulsion system. Battery cell losses are increased due to higher AC-currents through the cell. On the other hand, the CHB switching losses in SmartCell are reduced compared to the traditional inverter since the multi level approach allows the clusters to spend more time in pure conduction mode. In addition, losses in electric machines are reduced due to the many conversion levels. This provides smoother AC excitation in comparison to the conventional system, which helps to reduce core losses in the electric machine and increase overall efficiency [9]. Figure 12a illustrates electric driveline efficiency simulated over WLTC for SmartCell and conventional electric driveline.

In a traditional system, there is an on-board charger which converts the AC in the grid to DC in order to charge the battery. These on-board chargers experience high losses primarily due to the inefficiencies inherent in the many stages in the AC to DC conversion process. Additionally, power factor correction (PFC) and filtering stages, which are essential for stabilizing the DC output, contribute to further inefficiencies. The SmartCell system allows connection of the battery cells directly to the grid which eliminates several stages of conversion and allows for higher efficiency than traditional system as illustrated in Figure 12b .

SmartCell technology facilitates the utilization of the same switches for both traction and charging. This capability enables exceptionally high charging capacities, ranging from 100 to 200 kW, contingent upon the grid's capacity. If cell-based multilevel systems become the automotive standard, a high-power AC infrastructure could be developed as a cost-effective complement to existing DC fast charging stations. Furthermore, SmartCell incorporates advanced current control mechanisms to internally heat the cells. This internal heating reduces the cells' internal resistance, which typically increases as temperature decreases, thereby enhancing efficiency [10, 11]. Traditionally, cells are heated by warming the battery coolant, which then transfers heat to the cells which is significantly less efficient due to substantial heat loss along the coolant path.



(a) Electric Drive Efficiency

(b) Charging Efficiency

Figure 12: SmartCell vs Conventional system simulated efficiency

6 Conclusion

SmartCell introduces a novel and efficient technology to control the electric propulsion system, with the potential to become an industry standard. It offers significant benefits to automotive companies by simplifying the driveline and reducing the number of components, streamlining the supply chain with large volumes of identical components, and providing customers with high driveline and charging efficiency at a lower cost. SmartCell provides further advantages to the customers such as extended range, faster and more efficient charging, high redundancy, increased space, and lighter vehicles. However, there are several challenges to be addressed or validated to harness all the advantages of this novel AC battery technology. The limited bandwidth of the wireless system can constrain control of the cluster which we are trying to eliminate through on-going development of an advanced control system. SmartCell's ability to connect the high voltage system directly to the grid without intermediate isolation could lead to current leakage to the ground. Therefore, extensive simulation and physical testing are on-going to ensure no leakage current occurs with non-isolated grid charging. Despite the system's simplicity in terms of number of different components, the cost of numerous Cluster Boards becomes a critical factor in the overall system cost. The cost of power MOSFETs, which constitute a significant portion of the Cluster Boards cost, must be further optimized along with the entire Cluster Board through innovation, simplification and integration. At Volvo, our purpose is to provide freedom to move in a personal, sustainable and safe way. Hence, keeping that in mind we are working further to make SmartCell, the most sustainable, safe, efficient and cost-effective electric driveline solution.

Acknowledgments

We acknowledge the contributions made by the SmartCell project team members and supporting contributors at Volvo Cars.

References

[1] M. Eaker, "48V Automotive Systems: Why Now?," Texas Instruments, Feb. 2025. [Online]. Available: https://www.ti.com/lit/wp/slyy243/slyy243.pdf

[2] O. Josefsson, "Investigation of a Multilevel Inverter for Electric Vehicle Applications," PhD Thesis, Dept. of Energy and Environment, Chalmers Univ. of Technol., Göteborg, Sweden, 2015.

[3] F. Helling, J. Glück, A. Singer and T. Weyh, "Modular multilevel battery (M2B) for electric vehicles," 2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Karlsruhe, Germany, 2016, pp. 1-9, doi: 10.1109/EPE.2016.7695480.

[4] O. Theliander, A. Kersten, M. Kuder, E. Grunditz and T. Thiringer, "LiFeP04Battery Modeling and Drive Cycle Loss Evaluation in Cascaded H-Bridge Inverters for Vehicles," 2019 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 2019, pp. 1-7, doi: 10.1109/ITEC.2019.8790460.

[5] ISO, "ISO 26262-1:2018 Road vehicles – Functional safety – Part 1: Vocabulary," ISO, Geneva, Switzerland, 2018. [Online]. Available: https://www.iso.org/standard/43464.html.

[6] Verband der Automobilindustrie e.V. (VDA), "VDA Recommendation 450: Electrical Power Supply System regarding automated driving in the context of ISO 26262," April 2023. [Online]. Available: www.vda.de.

[7] J. Hu et al., "Impact of Magnetic Substrate on Dynamic Loss and Magnetization Loss of HTS Coated Conductors," in IEEE Transactions on Applied Superconductivity, vol. 32, no. 4, pp. 1-5, June 2022, Art no. 8200405, doi: 10.1109/TASC.2022.3143783.

[8] United Nations Economic Commission for Europe, "Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility," ECE Regulation No. 10, Revision 5, Oct. 2014.

[9] P. Rasilo, A. Salem, A. Abdallh, F. De Belie, L. Dupré and J. A. Melkebeek, "Effect of Multilevel Inverter Supply on Core Losses in Magnetic Materials and Electrical Machines," in IEEE Transactions on Energy Conversion, vol. 30, no. 2, pp. 736-744, June 2015, doi: 10.1109/TEC.2014.2372095.

[10] Y. Ji and C. Y. Wang, "Heating strategies for Li-ion batteries operated from subzero temperatures," Electrochimica Acta, vol. 107, pp. 664-674, 2013. doi: 10.1016/j.electacta.2013.03.147.

[11] Y. Liu, Y. G. Liao and M. -C. Lai, "Effects of Depth-of-Discharge, Ambient Temperature, and Aging on the Internal Resistance of Lithium-Ion Battery Cell," 2021 International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town, South Africa, 2021, pp. 1-5, doi: 10.1109/ICECET52533.2021.9698495.

Presenter Biography

Jonas Forssell, M.Sc. in Mechanical Engineering from Chalmers University of Technology. He has been a developer at Volvo Car Corporation since 1995 with a focus on advanced engineering in the field of mechanical and electrical engineering. He has background in body structures, platform design and most recently solutions in hybrid and electrical propulsion systems.

Markus Ekström has done Electrical Engineering from Lund University. He has been working at Volvo Cars since 2011. During his initial years he has focused on engine management systems. Lately, he has been working on motor controls and energy functions in electrified vehicles and has been in the SmartCell project from its inception.

Aditya Pratap Singh, M.Sc. in Vehicle Engineering from KTH Royal Institute of Technology. He has been working as a Propulsion System CAE Engineer at Volvo Car Corporation since 2021. He has background in electrical machine design and battery modeling. His focus area for the SmartCell project is electrical system design, system controls and simulations.

Torbjörn Larsson, M.Sc. in Electrical Engineering from Chalmers University of Technology. He has been a developer at Volvo Car Corporation since 2000 with focus on the development of power supply systems within the electrical and hybrid propulsion systems. Currently, he works as electrical system architect for SmartCell.

Jonas Björkholtz, M.Sc. in Mechanical Engineering from Chalmers University of Technology. He has been a developer at Volvo Car Corporation since 2000 with focus on advanced engineering in the field of combustion engines, mechanical, and electrical engineering. He has background in combustion engines, hybrid propulsion systems and electrical propulsion systems.