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DCDC Power Conversion System in Electric Vehicle-Part 1: System Design, and Future Trends

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Executive Summary

The automotive industry is currently driven by megatrends such as electrification and automated driving. As complexity of electrical/electronic systems increase, new failure modes and new requirement emerge, making need for safe power conversion systems essential. This paper presents a study of the different power conversion systems for battery-electric-vehicle (BEV) from a system and subsystem perspective. Important aspects of system design for power conversion are elaborated. Failure modes and protection methods of power conversion systems are introduced with respect to both high and low voltage sides. Finally, new challenges and future trends related to automotive power conversion systems will be demonstrated.

Keywords: battery-electric-vehicle (BEV), failure mode, power conversion, system design, future trends

1 Introduction

Environmental concerns and increasingly stringent regulations are driving industries to reduce carbon dioxide (CO2) emissions. In the automotive sector, a major contributor to CO2 emissions, vehicle electrification has emerged as the most effective solution for aligning with environmental standards [1].
With increasing electrification and the rapidly growing autonomous driving (AD) systems respectively advanced driver assistance systems (ADAS), the complexity of the network will increase significantly in the coming vehicle generations. Furthermore, the operation of critical functions such as the brake-by-wire or steer-by-wire must not be compromised under any circumstances. It means that AD and critical loads will require power supplies with higher automotive safety integrity level (ASIL), to ensure high reliability and safety. Considering the typical electrical architecture of electric vehicles, the DCDC power conversion unit (DCDCPCU) plays an indispensable role.
On the other hand, to enhance energy efficiency by reducing vehicle costs, improving payload, and reducing logistics-related CO2 emissions, vehicle manufacturers are interested in decreasing the size of heavy lead-acid LV batteries. DCDCPCUs can support different ranges of LV voltage (e.g., 12V, 24V, and 48V). This raises the question of whether an LV battery will be needed in the upcoming future. In the case of removing LV batteries, redundancy will be an urgent and stringent requirement, from the high voltage energy battery system to the LV system. To comply with such requirements, it is crucial to design automotive DCDCPCU in accordance with international standards like ISO 26262 or VDA 450.
The range and lifetime of an electric vehicle are limited by the battery system. To maximize the energy delivered by the battery system, emerging technologies like HV batteries with active balancing are desirable [2]. These innovations will have major influences on the design of DCDCPCU to supply the LV network.
This paper presents a comprehensive study of the different power conversion systems for battery-Electric-

Vehicles (BEV) from system perspective. First, ASIL decomposition between the LV battery and DCDCPC unit is explained which will impact on selection of power conversion topologies, components, and control strategies. Second, different protection methods are introduced with respect to the various potential faults that may occur at both HV and LV sides. Finally, new challenges and future trends related to automotive power conversion systems will be demonstrated.

2 System architecture design of DCDCPCU

Currently, there is no specific standard approach within the automotive industry to ensure functional safety specifically for power supply systems in BEV applications. To fill this gap, this section will demonstrate functional safety with a focus on power supply system including ASIL allocation and ASIL decomposition of safety requirements. Input requirements to the technical safety concept of power supply systems are usually technical safety requirements (TSRs). TSR receives functional safety requirements from different Function Realization (FR) groups, including Steering, brake, and body electronics, and allocates TSRs to Subsystems. As an example, fault tree analysis (FTA) for a typical LV load with ASIL C is shown in Figure 1. In this FTA, short circuit faults are assumed as internal failure of DCDCPCU while a large LV battery can supply power to the LV loads during short time with an open circuit fault in DCDCPCU. Physical architecture in Figure 2 shows the electrical view of a DCDCPCU connected to other subsystems [2].

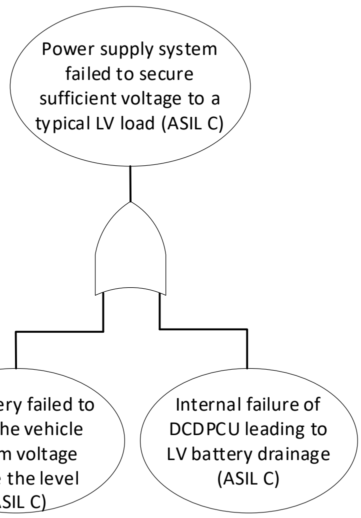

Figure 1: FTA for typical LV load with ASIL C.

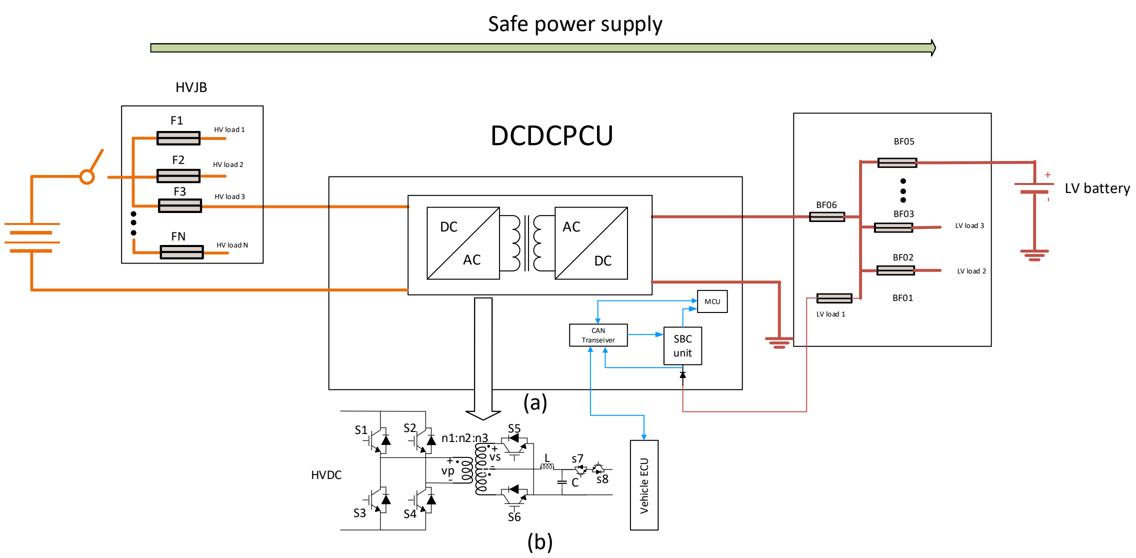

Figure 2: (a) Generic system architecture of power conversion. (b) A typical topology of DCDCPCU [2].

On the high-voltage (HV) side, the DCDCPCU is connected to the HV energy storage system via the HV distribution box and HV contactors. As such, the HV operating range of the DCDCPCU must be defined based on its availability. If the HV voltage falls outside the specified range, power conversion must be halted.
On the low-voltage (LV) side, the DCDCPCU connects to the LV loads and the LV battery. It is important to note that both the DCDCPCU and the LV battery serve as primary sources for supplying power to the LV loads. The DCDCPCU output is regulated based on the LV battery voltage, which varies depending on temperature and state of charge (SoC) defined by the LV power management system.
These two power sources work together to maintain the LV system voltage above a critical threshold across all operational scenarios, including both normal driving and high transient load conditions.
Under normal operating conditions, the DCDCPCU receives a set-point voltage from the vehicle ECU and operates in the voltage mode control, as illustrated in Figure 3. The vehicle ECU can wake up the DCDCPCU via the CAN transceiver block. This transceiver subsequently wakes up the microcontroller (MCU) and the single basis chip (SBC), which ensures safe and efficient operation of the DCDCPCU. Additionally, the SBC regulates voltage for both the MCU and other associated circuitry.

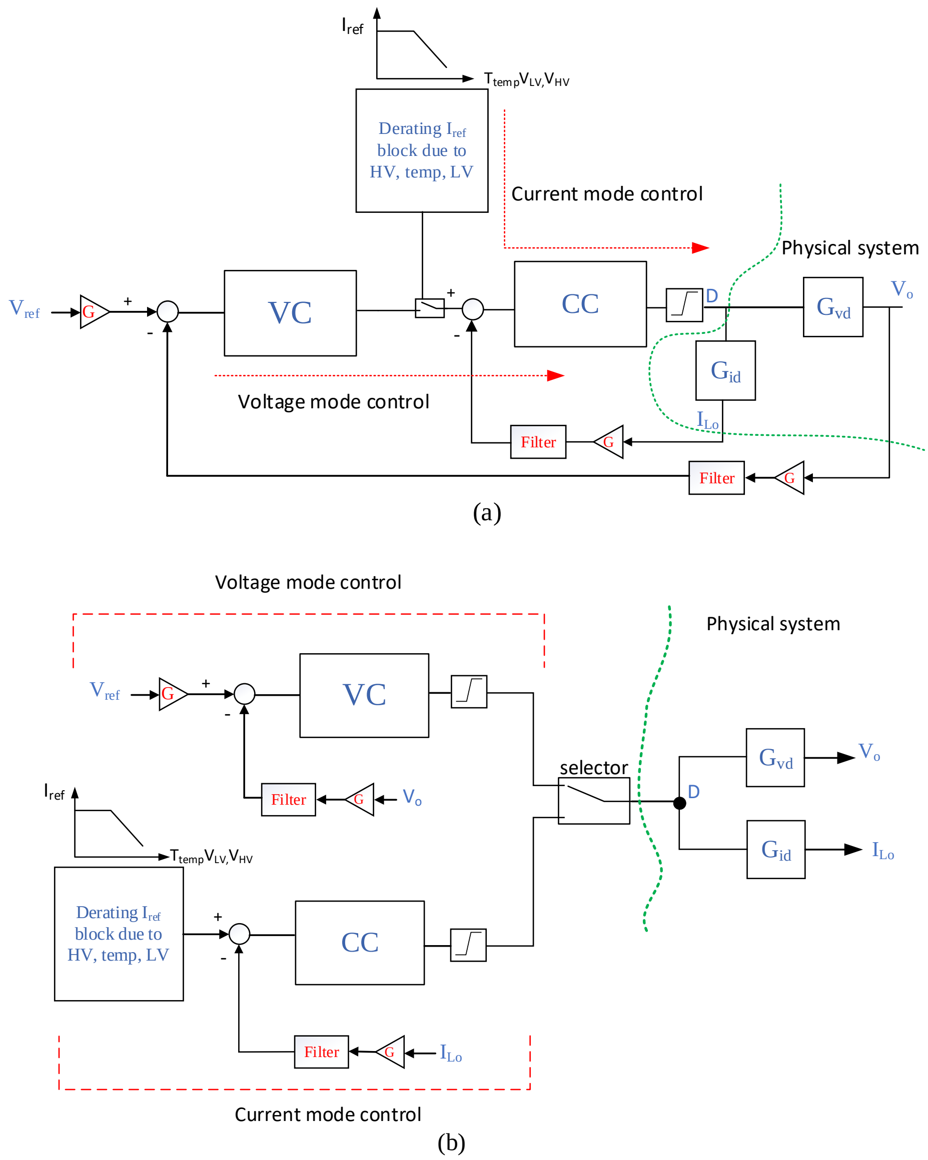

Figure 3: Different control system design for the DCDCPCU. (a) Classical cascaded control. (b) separated control system.

It is worth noting that the control strategy designed in the DCDCPCU depends on the selected DCDCPC topology due to its dynamic characteristics and the maximum load variation requirements defined by the LV system management. The conventional cascaded control method—featuring an inner current control loop and an outer voltage control loop—typically offers a slower dynamic response compared to the separated voltage and current control loops, as illustrated in Figure 3(a) and 3(b). In addition, to improve dynamic response to the load changes, the feedforward control strategy can be implemented.

2.1 DCDCPCU failures

2.1.1 External LV short circuit

When the LV of DCDCPSU reaches V_{min}, as shown in Figure 4, the DCDCPSU enters the overload area, therefore, DCDCPSU will provide max current to the LV system using the current control mode as depicted in Figure 3. When the voltage reaches V_{min_drate}, the DCDCPSU stops the power conversion. In should

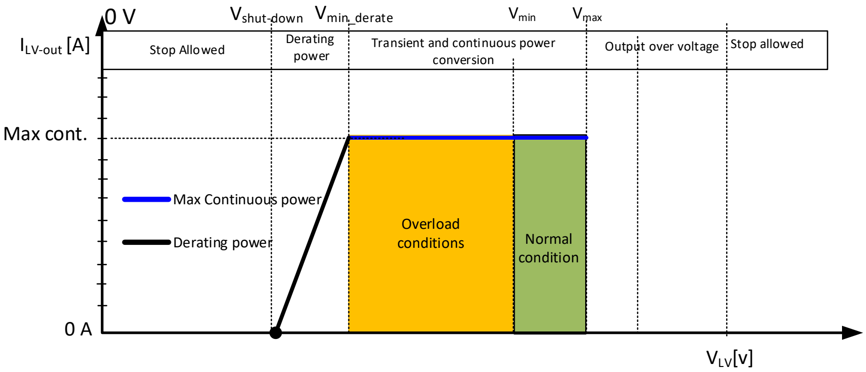

Figure 4: A typical LV power management of DCDCPSU in normal and overload conditions.

2.2.2 Internal LV short circuit

In the event of an internal short circuit on the low-voltage (LV) side of the DCDC power supply unit (DCDCPSU)—for example, in the LV MOSFETs, as illustrated in Figure 2 for a typical isolated DCDC converter—the LV battery may experience significant discharge, leading to a sharp drop in the LV system voltage. To mitigate this, the DCDCPSU must respond rapidly by isolating the internal fault using the MOSFET S_8, as shown in Figure 2(b) [3].

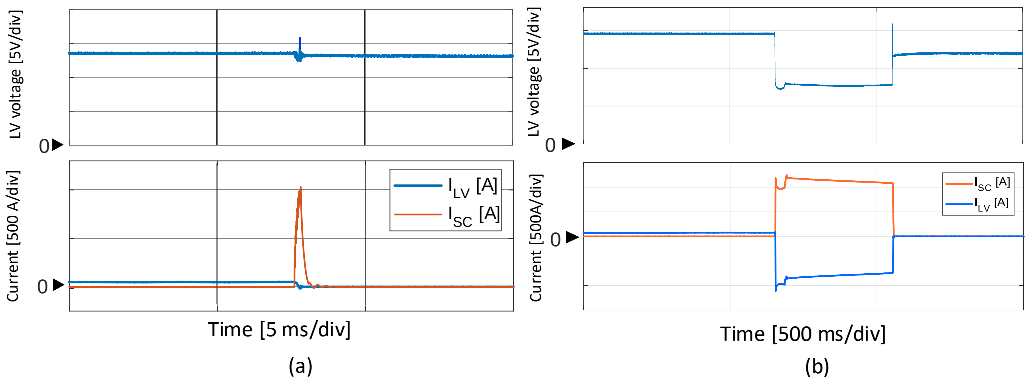

Figure 5: Internal short circuit on LV side. (a) Protection with MOSFET. (b) Protection with LV fuse.

Figure 5 compares the impact of short-circuit protection using MOSFET S_8 versus traditional LV fuses. The MOSFET provides a much faster response, isolating the fault within 300 µs. As a result, the voltage drop on the LV side is minimal compared to the drop observed when protection relies on an LV fuse. As seen in Figure 5(b), the LV fuse takes approximately 400 ms to detect the fault. During this delay, the LV voltage drops to 7 V, and the LV battery discharges significantly due to the ongoing short circuit. Consequently, many critical ECUs in the vehicle can be turned off since the LV voltage is dramatically decreased. It is worth noting that cable impedance plays a significant role in the occurrence of overvoltage faults, as illustrated in Figure 5(a). Longer cables introduce higher inductance, which leads to greater overvoltage during switching events. Therefore, snubber circuits are necessary to mitigate the overvoltage caused by fast switching transients.

2.2.3 Reverse polarity faults

In the case of a reverse polarity connection to the LV battery, body diodes in the LV MOSFET will conduct and provide a short circuit path to the LV battery which may damage the LV MOSFETs. To protect the DCDCPSU against reverse polarity event, MOSFETs S_7 must be implemented to isolate the fault [3]. It should be noted that a diode can be considered as reverse polarity protection for power supply of SBC and communications blocks, as shown in Figure 2(a).

2.2 DCDCPSU design challenges

According to ISO262622, Functional safety analysis has a direct impact on the DCDCPS topology selection, especially for higher ASIL requirements. According to the decomposition of ASIL target level of power delivery, redundancy might be needed where different power conversion topologies should be considered due to independency between decomposed DCDCPSUs.

DCDCPC topologies can affect failure modes differently. For example, in the cases of center-tap topology selection for secondary side of DCDCPSU, a short circuit fault on secondary side's MOSFETs will result in the LV battery drainage, as shown in figure 2(b). With the full-bridge topology in the LV side, a short circuit on one of the LV MOSFETs may not result in a large LV battery drainage if the DCDCPCU can detect the fault quickly.

The DCDCPSU can be designed as single stage or multiple stage. Multiple stage converters can be also designed as cascaded- or -parallel-connected DCDCPCUs. For example, in the case of parallel-connected DCDCPCUs, one DCDCPCU will operate as the master voltage mode control and the rest of DCDCPCUs are configured as slave current mode controllers.
To be able to compare cascade- and parallel-connected DCDCPCUs, various parameters should be considered. The system safety, reliability, cost, efficiency, power density and EMI performance are some acceptance criteria which will be elaborated in Paper-Part 2.
As power electronics applications continue to push for size reduction by increasing switching frequencies, a key design challenge is optimizing the trade-off between achieving higher power density and maintaining reliable power delivery across wide operating ranges. Notably, increasing the switching frequency allows for a reduction in the size of passive components, typically the largest and most material-intensive parts of the converter, often dependent on critical raw materials. This frequency-driven miniaturization significantly contributes to a more compact converter footprint, enhancing both efficiency and sustainability in system design.
Life cycle analysis enables designers to evaluate the environmental impact of key components such as aluminum housing, PCBs, transformers, and MOSFETs that are often associated with high carbon footprints [4]. Sustainable design approaches aim to reduce the bill of materials, optimize voltage ratings, and minimize overall system weight. Crucially, achieving true sustainability goes beyond individual component choices, requiring a holistic, system-level perspective that considers operational use cases, energy efficiency, and long-term reliability.

3 DCDCPCU future design and trend

With the DCDCPCU in the vehicle, the LV power supply to the LV loads can be possible. This raises the question of whether an LV battery will be necessary in the vehicle. The LV Lead-acid batteries, being the conventional technology automotive, are widely used for automotive applications and comparatively big and bulky. Although the use of the lead-acid battery is currently covered by an exemption in the restriction of hazardous substances (RoHS) and end-of-life vehicles (ELV) guidelines for vehicles, these must be reviewed every few years [2]. So, the exemption might expire sooner or later. By then at the latest, the lead-acid battery would have to be replaced with a Li-ion battery, which would lead to additional costs due to battery management monitoring system and expense of cells. For this reason, there are considerations to simply remove the LV battery altogether. However, this requires completely new battery pack and power conversion concepts. Therefore, the redundant DCDCPCUs are required so that they provide isolated power supply to the high ASIL LV loads. At the same time, weight and space can be reduced, which in turn improves vehicle efficiency. In addition, scalable vehicle platforms can be realized that address both affordable market

segments and high-performance vehicles. It should be noted that since LV loads will not be distributed symmetrically, an active balancing circuit in the system is required [2]. The load balancing can be designed in the LV or HV sides. Figure 6 shows the balancing strategy between two battery packs on the HV side.
Due to the need to increase the lifetime of battery cells and ensure power supply redundancies for high ASIL LV loads in electric vehicles, modular approaches with active cell balancing will be a promising approach in future, as shown in Figure 6(b). Therefore, redundant DCDCPCUs are required so that they provide isolated power supply to LV functions like ADAS and by-wire functions. At the same time, weight and space requirements are reduced, which in turn improves vehicle efficiency. In addition, scalable vehicle platforms can be realized that address both affordable market segments and high-performance vehicles.
It should be noted that the HV short circuit scenarios need to be considered since the HV will dramatically fall within a short duration if a short circuit will occur in the HV loads and the DCDCPCUs must continue the power conversion without presence of the LV battery. It means that the DCDCPCUs requires a wide input voltage range which has a significant impact on DCDCPCU topology selection and design.
In future, HV smart switches based on semiconductor technology can detect faults very fast. Furthermore, by new development of battery cells, the voltage characteristics of cells will change in future which will affect the battery pack voltage during short circuit scenario.

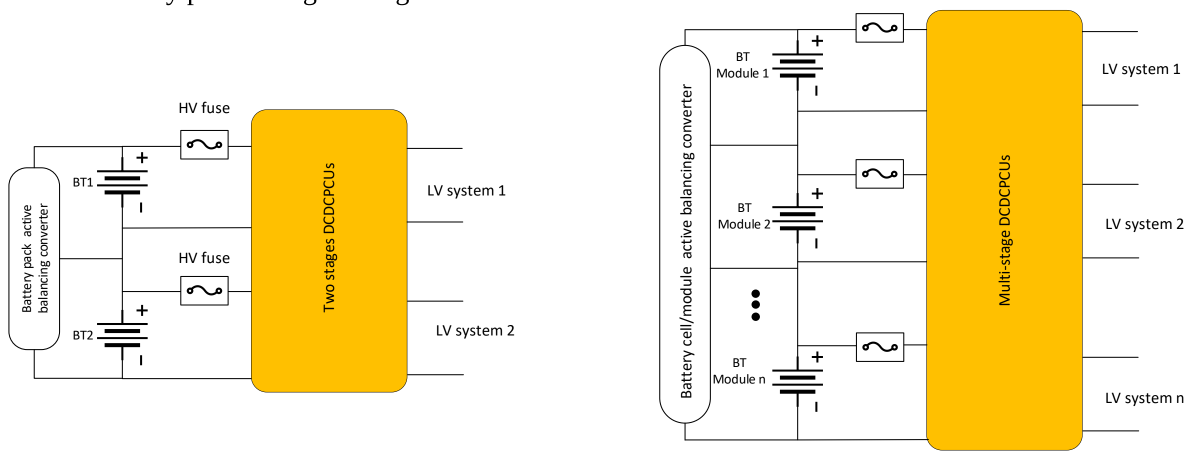

Figure 6: Generic DCDCPC system design for future of BEV [2]-[5]

Within modular approach and active cell balancing to enhance battery lifetime, the battery cell/module could generate not only DC but also alternating current AC via fast semiconductor switches to control the electrical motor directly [6-8]. With this electrically integrated approach, electric motor drive systems can be integrated with active cell balancing and power conversion functions, as shown in Figure 6. In such an integrated intelligent power system, redundancy is already included, and scalability is readily available [2]. Furthermore, it is easier to support a sustainable life cycle, as well as maintenance and repairability. While we cannot yet predict the exact direction of future developments, we may see this drivetrain evolution: from a single main battery to two main batteries to an intelligent multi-string battery.

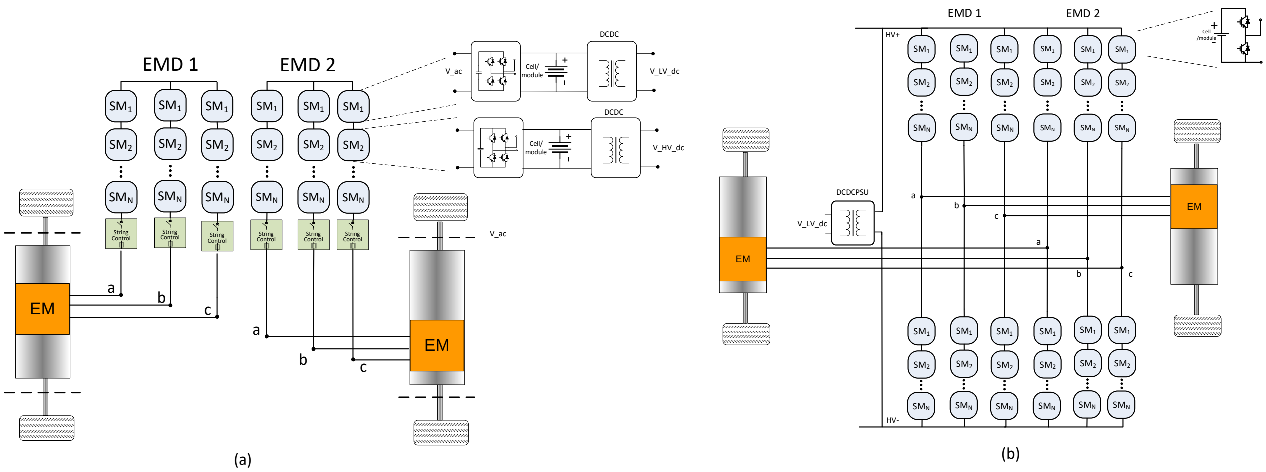

Figure 7: Power electronics architecture for HV battery design with active balancing [6-8].

As it can be seen in Figure 7(a) two isolated AC systems are required for two electrical motor drive systems without an HVDC link whereas Figure 7(b) show a common HVDC link give possibility to connect HV component to HVDC link. Therefore, we need multiple DCDCs to supply LV and HV loads shown in Figure 7(a) or additional HV batteries in the power conversion architecture.

4 Conclusions

This paper has presented an overview of various power conversion systems for battery electric vehicles (BEVs) from a system architecture perspective. Key aspects of power conversion system design, including system safety, as well as HV and LV architectures have been discussed in detail. Control strategies for the DCDCPC system under different operating conditions were introduced and compared. Systematic faults, their impacts, and corresponding protection mechanisms for fault detection were examined on both the HV and LV sides. Finally, emerging challenges and future trends in automotive power conversion systems were highlighted, offering insight into ongoing developments in this critical area.

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Presenter Biography

Amir received his B.S. and M.S. degrees in Electrical Engineering from the Azad University, Science and Research Branch, Tehran, Iran, in 2004 and 2008, respectively. He earned his Ph.D. in the Power Conversion Laboratory at the Department of Electrical Engineering, Yeungnam University, South Korea. From 2016 to 2018, he was a postdoctoral researcher at Chalmers University of Technology. Amir has over 10 years of experience in various industries. He is currently a Specialist System Architect and Concept Leader at the Electromobility Center, Volvo Group Trucks Technology, in Gothenburg, Sweden.