DC MICROGRIDS FOR INDUSTRY AND LOW POWER CHARGING INFRASTRUCTURE

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Abstract: In recent years, DC microgrids have gained increasing relevance across several application domains, including industrial environments, DC data center infrastructure, and fast-charging systems. This paper provides an overview of the current state of the art in industrial DC grid technologies and low-power DC charging infrastructure, drawing on recent research activities at Silicon Austria Labs. The work highlights the key advantages of DC microgrids while addressing several associated challenges, particularly in the areas of protection, useable converter topologies, concepts, coordination, and system stability.

Keywords: DC microgrids, industrial power systems, solid-state circuit breakers (SSCB), low-power DC charging, copper sustainability, shared charging, power electronics.

1 State of the art

Several research projects - particularly the DC-Industry and DC-Industry 2 initiatives - have demonstrated key advantages of DC microgrids. These efforts resulted in a comprehensive system description presented in [1], showing that DC microgrids offer several benefits compared to conventional AC grids [2], including:

- Reduced copper cabling requirements and lower cable losses
- Decreased overall energy consumption and the ability to recover braking energy
- Direct and efficient integration of renewable energy systems
- Increased system availability due to fewer energy conversion stages and, consequently, fewer components that may fail
- Lower infeed power and reduced peak power demand through the integration of battery energy storage systems (BESS)

Despite their advantages, DC microgrids have several drawbacks. Protection and fault interruption are challenging due to the lack of natural current zero crossings, requiring advanced devices such as solid-state circuit breakers. Initial costs can be higher because of specialized converters and protection equipment. While standardization exists, it often needs adaptation for DC technology. Integration with AC systems can be complex, and the overall deployment of DC microgrids is limited by the relatively low experience of planners and companies, as well as the limited availability of DC-specific products.

2 DC microgrids for industry

An industrial microgrid is shown in Figure 1. Since most industrial loads consist of machinery and rotating equipment, braking energy can be fed directly back into the DC bus, avoiding the typically required AC–DC conversion stages. Furthermore, DC–DC conversion stages are considered to have a higher efficiency potential compared to AC–DC solutions. This advantage, combined with the ability to maintain the active infeed converter at more favorable operating points - facilitated by the connected BESS - can lead to an improvement in overall system performance.

The DC bus voltage is regulated collectively by all connected converters using droop control [1]. A further advantage of industrial DC microgrids is the seamless integration of storage systems for peak shaving, which significantly reduces peak power demand from the public grid. Because both the BESS and the microgrid operate natively on direct current, redundant conversion stages are eliminated, substantially increasing overall system efficiency [3]. A key challenge in DC microgrids is the protection and rapid interruption of short-circuit currents, as well as the detection of arcs. Unlike AC systems, where current naturally passes through zero, DC faults do not self-extinguish, making conventional protection methods ineffective. These issues can only be effectively managed using solid-state circuit breakers.

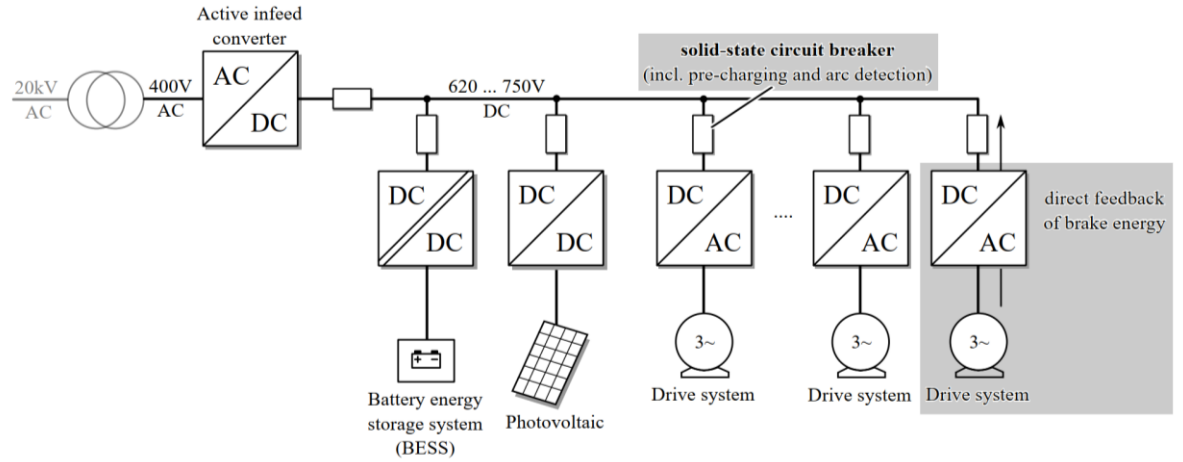


Figure 1: Example of an industrial DC microgrid with main infeed converters and loads.

2.1 Reduced copper cabling requirements and lower cable losses

A primary advantage of transitioning from a conventional three-phase AC system (400V line-to-line) to a DC architecture is the significant reduction in conductor requirements and associated losses. According to the ODCA guidelines published as VDE specifications in [1], a DC bus voltage of 620V to 750V can be maintained using only two conductors. This streamlined configuration allows for a direct comparison of transmission efficiency; the following investigation explores how this higher voltage, two-wire DC distribution minimizes power losses relative to standard AC systems. The difference in losses can be investigated as follows:

- copper losses of AC cables are: $P_{cable,ac} = \frac{3\cdot l}{\gamma\cdot A_{ac}} {I_{ac}}^2$
- copper losses of DC cables are: $P_{cable,dc} = \frac{2\cdot l}{\gamma\cdot A_{dc}} {I_{dc}}^2$

Whereby the variables are :P transferred power, $I_{ac} = \frac{P}{\sqrt{3}\cdot U_{LL}}$ three-phase rms current, $I_{dc} = \frac{P}{U_{dc}}$ DC current, l length of conductor, $\gamma = 59{,}6\frac{S}{m}$ specific conductivity of copper, A_{dc} cross section of each DC conductor, A_{ac} cross section of each AC conductor).

The efficiency of the proposed DC architecture is evaluated by comparing the ohmic losses and material requirements against a conventional 400 V three-phase AC system. As illustrated in Figure 2, the analysis considers installation condition B2 according to OVE E 8101 (international equivalent: IEC 60364) to determine the minimum required cross-sections for both 620 V and 750 V DC buses. The results indicate that the DC configurations significantly reduce the total conducting cross-sectional area - defined as $A_{tot,dc} = 2 \cdot A_{dc}$ compared to $A_{tot,ac} = 3 \cdot A_{ac}$ - while simultaneously decreasing transmission losses. This dual advantage leads to a measurable increase in overall system efficiency, particularly at higher DC voltage levels. As quantified in Figure 2f, the results demonstrate that the DC architectures significantly outperform the AC reference, achieving substantially lower power losses and a minimum copper saving of 55% across the investigated scenarios.

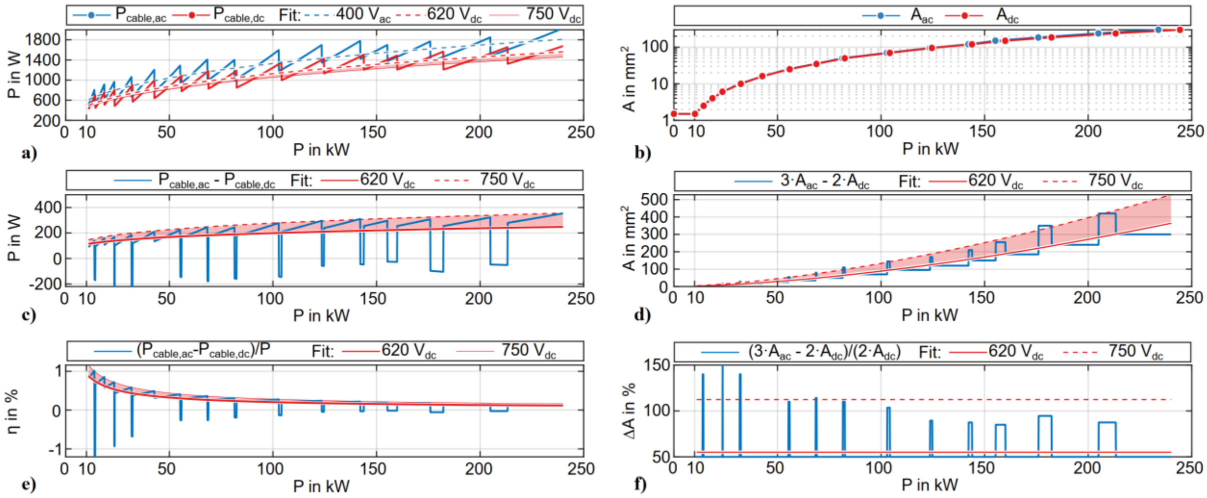


Figure 2: Comparison of ohmic losses and conductor cross-sections for AC (400 V) and DC (620 V - 750 V) systems (100 m). a) transmission losses; b) cross-sections per OVE E 8101 / IEC 60364 (B2); c) loss delta; d) total conducting area, e) efficiency impact and f) percentage variance.

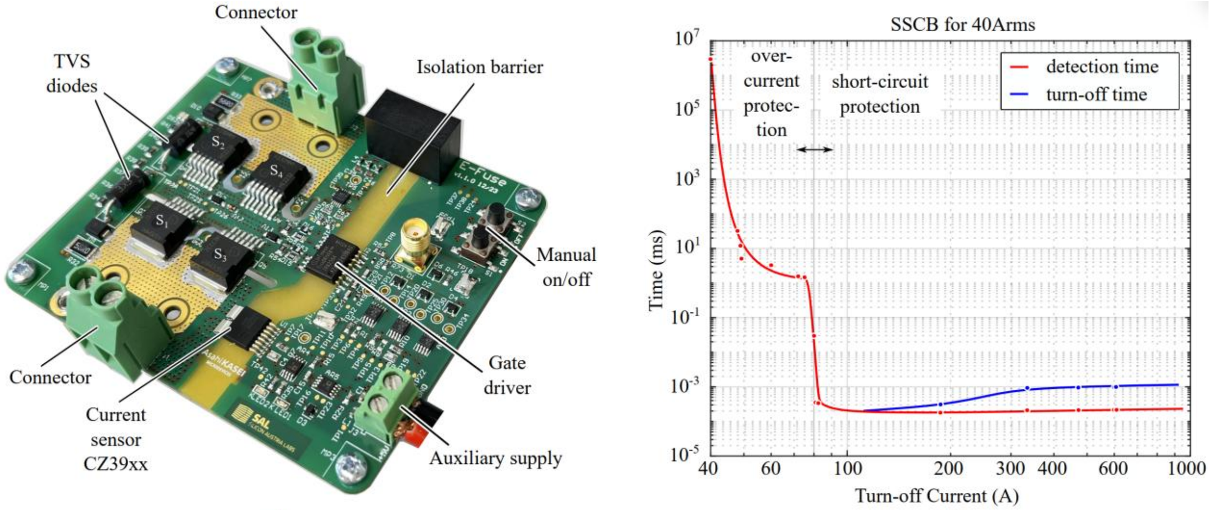
A further benefit of DC distribution systems is that they do not circulate reactive power. This results in lower current magnitudes compared to the equivalent RMS currents in AC systems, thereby significantly reducing ohmic losses [4].

A future driver for transitioning from AC to DC distribution is the significant reduction in conductor cross-sections, which leads to substantial copper savings. This transition is motivated by critical forecasts regarding the global availability and price volatility of copper; projections indicate a staggering supply deficit of 10 million metric tons (Mt) by 2040 [5]. By leveraging DC-native architecture, industries can mitigate the impact of these looming material shortages and rising commodity costs while achieving a more sustainable infrastructure design.

2.2 Short circuit protection

Short-circuit protection remains a primary technical challenge for the reliability of DC grids. The predominantly capacitive nature of DC microgrids results in extremely steep fault-current gradients (di/dt), leading to massive short-circuit currents that cannot be extinguished by a natural zero-crossing as in traditional AC systems. Consequently, protection technology is shifting from standard fuses via hybrid circuit breakers [6] - a combination of mechanical and semiconductor switches - toward fully semiconductor-based Solid-State Circuit Breakers (SSCBs).

A significant trend nowadays is the utilization of Wide-Bandgap (WBG) semiconductors, specifically Silicon Carbide (SiC), which allows for unprecedented reaction times. Recent demonstrations at Silicon Austria Labs have shown that SiC-based SSCBs can react to short-circuit events in as little as 200 ns [7], effectively isolating faults before they reach damaging peak levels highlighted in Figure 3. Within this field, SiC JFETs are emerging as a favored technology. Their "normally-on" characteristic provides a failsafe path for current during standard operation, while their exceptionally low on-resistance minimizes steady-state conduction losses [8]. This combination of speed and efficiency makes JFET-based SSCBs a critical enabler for the protection of sensitive DC-native infrastructure.



a) b)

Figure 3: Proof-of-concept of an automotive Solid-State Circuit Breaker (SSCB), commonly referred to as an E-Fuse [7]. a) Layout of the PCB and its primary components; b) Characterization of the system's reaction and turn-off times.

To mitigate high inrush currents from capacitive loads, DC microgrids currently rely on bulky precharging circuits with resistors and contactors typically integrated in the SSCBs. In future, by utilizing the precise control of power semiconductors, SSCBs can perform active current limiting or PWM-based precharging, significantly reducing system footprint and complexity while increasing reliability [9].

2.3 Grid interference, Conducted emissions and grounding

The grounding of DC microgrids can be implemented similarly to AC systems (DC-TN-S, DC-TT, or DC-IT), each presenting specific advantages and disadvantages as detailed in [1]. A critical differentiator is the behavior of Common-Mode (CM) emissions. A low-impedance grounding path facilitates higher current emissions, which may negatively affect the reliability of connected converters and sensitive electronics.

Furthermore, the choice between asymmetric (L+ or L- grounded) and symmetrical (midpoint) DC grounding significantly influences EMI performance. In asymmetric systems, high (dv/dt) transients induce significant currents in the ground conductor. In contrast, symmetrical grounding is recommended according to [1], as it utilizes cancellation effects and reduces voltage stress relative to earth, resulting in superior EMI behavior [4].

The interaction between parallel-connected input filters and line inductances can trigger system-wide resonances that correlate with the switching frequencies, potentially amplifying emissions. In such scenarios, high-impedance grounding can be a strategic solution to dampen these resonances, though it necessitates a careful evaluation of all associated protection implications.

Beyond EMI, grounding directly impacts long-term reliability and safety:

- **Corrosion**: Constant DC leakage currents can lead to significant electrolytic corrosion of metallic structures and earthing electrodes.
- **Arcs**: The grounding topology dictates the occurrence and detection of arc faults. While an isolated IT system can prevent a stable arc during a first line-to-ground fault, it requires sophisticated insulation monitoring. Conversely, in grounded systems, parallel arcs (line-to-ground) must be interrupted within microseconds by ultra-fast protection devices to prevent catastrophic failure.

2.4 DC Microgrid project

A current ongoing project at Silicon Austria Labs is the DC Microgrid project with eleven partner companies [10]. Research within this project focuses heavily on next-generation power electronics design and system integration. Specific areas of investigation include the development of modular and scalable converter systems, advanced integration concepts for Solid-State Transformer (SST) modules, and enhanced arc prevention techniques. Furthermore, significant effort is dedicated to improving selective fault protection mechanisms, implementing new control strategies and advanced energy management algorithms, and optimizing magnetic components through innovative materials and winding techniques. The ultimate goal is the implementation of cutting-edge integration technologies that enable volume-optimized, efficient system designs. Forthcoming conferences will serve as platforms to present the latest research findings and technological advancements resulting from this project.

3 DC microgrids for low power DC charging

Today, AC chargers rely on the onboard charger (OBC) integrated into electric vehicles, and the costs are typically borne by the vehicle owners. However, future vehicle designs may no longer require OBCs if a sufficiently dense low-power DC charging infrastructure becomes available, with the associated costs covered by the infrastructure owner. Such infrastructure could be deployed at supermarkets, commercial areas, or large parking facilities. An example of a DC charging infrastructure is shown in Figure 4. In the future, DC charging systems may become a viable alternative to the currently established AC charging infrastructure. To minimize hardware costs, one option is to implement power-sharing strategies, allowing the available charging power to be distributed among multiple vehicles when more than one car is connected to the charger.

A short comparison between low power AC and DC charging is listed in Table 1.

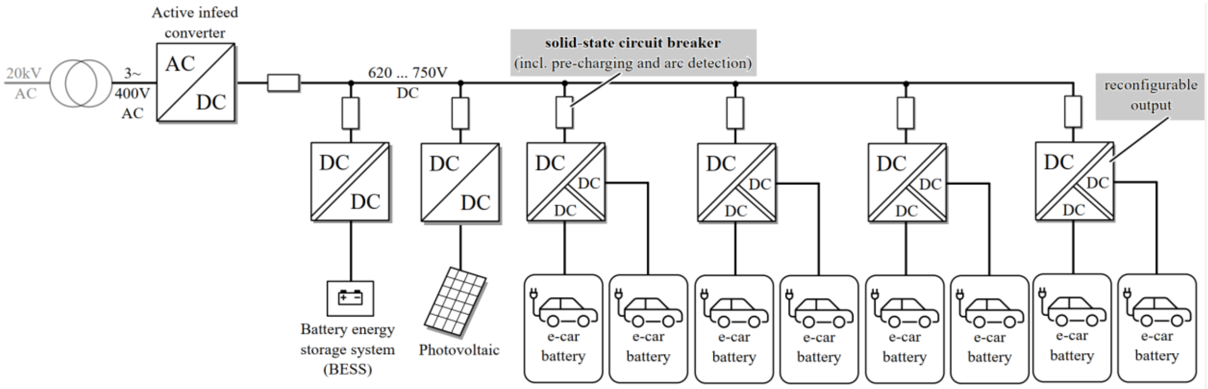


Figure 4: Example of a DC charging infrastructure for electric cars.

Table 1: Comparative comparison between low power AC and DC charging

	AC charging	**DC charging**
Standards	SAE J1772 AC-level 2 charging up to 19,2kW **IEC 61851 Model 3**	SAE J1772 DC-level 1 charging up to 80kW **IEC 61851 Mode 4**
Connector in Europe	Typ 2	Typ2 or CCS Combo 2
Typical power rating	3,7 to 22kW (Standard 7kW to 11kW in households)	Up to 400kW (CCS Combo 2) Up to 43kW (Typ 2)
Converter location	On-board Charger	Off-board Charger
Primary Use Case	Residential, workplace, and public slow charging	Industrial fleets, automated guided vehicles, and DC microgrids

3.1 Efficiency benefits of low power DC charging

Standard OBCs typically utilize a two-stage architecture: an initial stage to convert AC to DC, followed by a second stage providing galvanic isolation for the high-voltage battery. While research from 2014 recorded peak efficiencies of 90.60% for a full charging cycle [11], modern systems have achieved significantly higher performance of around 93,08% in 2022 [12]. Further, recent research projects at Silicon Austria Labs, such as the Tiny Power Box project [13,14], have demonstrated that achieving a high power density for OBCs while maintaining a peak efficiency of 98% is possible, leading to an overall increase in efficiency for the e-car charging cycle.

Despite these efficiency improvements, this architecture is not the optimal solution when considering the shifting of energy from photovoltaic (PV) generation to a BESS and then to connected e-cars. Both PV and BESS operate natively in DC [15]. In this scenario, using an OBC requires a redundant and inefficient conversion of DC power (from the BESS/PV) back to AC, only for the OBC to convert it back to DC again. Avoiding this unnecessary AC-DC conversion in the charging path saves these inherent conversion losses, highlighting the benefits of direct DC distribution systems in integrated energy environments.

3.2 Shift in ownership

Historically, vehicle owners pay for the OBC as a hidden part of the vehicle's purchase price. This hardware is often underutilized, sitting idle most of the day. With off-board DC charging, the expensive power electronics move from the vehicle to the station. This shifts the Capital Expenditure from the consumer to the site host (e.g., retailers, employers, or fleet operators).

- **Charging-as-a-Service:** Site hosts can now use "turnkey" models where a third party owns and maintains the DC equipment, and the host pays a predictable monthly fee.
- **Attractivity:** Retailers (supermarkets, malls) view DC charging to attract high-value customers.
- **Return of Investment:** For industrial fleet owners, the initial cost of DC charging stations is recouped through lower vehicle costs and better energy efficiency

3.3 Shared Charging Project

The 'Shared Charging' project, funded by the FFG, is being developed by a consortium including Silicon Austria Labs [16], which is designing a modular DC charging hardware that enables dynamic power allocation; the system can either distribute power to multiple vehicles simultaneously or provide full capacity to a single vehicle sequentially. Currently under development, the hardware demonstrator features a scalable architecture that leverages technical synergies with BESS converters, allowing for hardware synergies. This approach not only optimizes energy conversion efficiency within PV and BESS-integrated systems but also ensures significantly higher hardware utilization rates compared to traditional OBCs. While simultaneous charging may extend individual charging durations, the overall system throughput is substantially improved. The charging concept is outlined in Figure 5 which highlights the arrangement of the individual submodules for charging 400V and 800V battery e-cars.

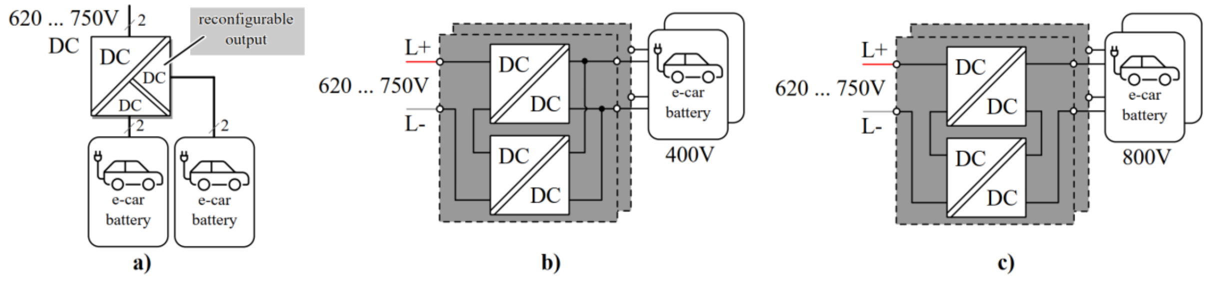


Figure 5: Off-board DC charging architecture featuring a switch matrix. a) Modular setup with four power units for parallel dual-vehicle charging. b) Configuration for 400V battery systems. c) Configuration for 800V battery systems.

An integrated switch matrix enables the dynamic coupling of all four modules to a single vehicle, significantly reducing charging times through increased power delivery. This modular architecture is inherently scalable; by incorporating additional modules, the system can support a larger number of vehicles per charging station, further enhancing the flexibility and throughput of the infrastructure.

4 Conclusion

DC microgrids are increasingly proving to be a viable solution for industrial applications, with several pilot plants already demonstrating their practical feasibility [17]. These systems offer clear advantages over traditional AC setups, including improved energy efficiency and reduced conversion losses. A primary driver for this transition is the potential for substantial copper savings of at least 55% and significant transmission loss reductions, directly addressing critical global copper supply challenges and price volatility forecasted for the coming decades. However, while pilot implementations confirm these benefits, the management of non-extinguishing arcs and rapid short-circuit interruption remain primary technical hurdles. To ensure long-term reliability, the implementation of symmetrical midpoint grounding is vital to optimize EMI performance and mitigate electrolytic corrosion. Although effective solutions like SiC-based protection exist, further optimization and practical testing with upcoming newest semiconductor devices are necessary to fully integrate these technologies into robust industrial DC infrastructures.

The transition toward a low-power DC charging infrastructure marks a pivotal shift for electromobility till 2035+. Although modern OBCs have reached peak efficiencies of up to 98% through research like the Tiny Power Box, AC-based architectures remain less efficient when integrated with native DC sources like PV and BESS.

The move to off-board DC systems - as demonstrated in the Shared Charging project - eliminates redundant conversion losses and reallocates hardware costs from vehicle owners to infrastructure providers. By utilizing modular hardware and dynamic power-sharing, these systems achieve significantly higher utilization rates than underutilized OBCs. Ultimately, this DC-native approach enables lighter, more affordable vehicles while optimizing the direct use of renewable energy within a highly efficient, integrated ecosystem.

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