

Advantages and Applications of Bi-Directional Open-Chamber DC Contactors



TECHNICAL PAPER

Written by: Marc Rosenmayr, Martin Zierer, Pavel Tomashev

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DC Power Under Control

Advantages and Applications of Bi-Directional Open-Chamber DC Contactors

Introduction

Many applications are gaining traction in the space of new mobility by offering innovative and sustainable solutions to move people and goods. From a variety of manned and autonomous electric vehicles (EV) utilizing fast-charging stations to energy storage systems that improve grid stability, they all use some kind of high-voltage DC bus and powerful lithium-ion batteries.

This whitepaper shows what is important when selecting the right DC contactor using different applications as examples.

New e-mobility applications depend on main contactors being able to control high levels of current and to reliably switch off loads in extreme situations. Other than semiconductors, only contactors can ensure galvanic isolation between the energy source and the downstream system. In addition, full bidirectionality is

required, which means, the contactor is able to disconnect the load independently of the current direction. While opening the contacts, electrical arcs occur, which are safely extinguished by highly effective open-chamber contactors, avoiding the disadvantages of gas-encapsulated, sealed arcing chambers commonly available on the market.

This whitepaper shows what is important when selecting the right DC contactor using different applications as examples. Depending on the level of the switched power, an electrical arc forms when opening (breaking) the load contacts, which can damage the contactor. Since no zero crossing of the voltage occurs in DC applications (as in AC applications), quenching the arc is technically challenging. Crucial strategies for dealing with switching arcs in DC contactors will be explained within the scope of this whitepaper.

Furthermore, this whitepaper will elaborate on how ambient conditions influence the performance of DC contactors, and how the reliable operation range might be adjusted as they change. The final section will provide insight into how high-power conditions define the number of safe opening (breaking) cycles for specific DC contactor applications.



DC Contactors in the High-Voltage Battery Disconnect Unit (HV-BDU)

Electric drives in all vehicle classes are an important prerequisite for reducing emissions. To achieve sufficient range, electric vehicles (EV) rely on high-power battery systems with up to 1,000V DC. To ensure a safe operation under normal conditions, but even more importantly, during accidents or other unusual situations, the battery needs to be disconnected from all other electrical components in the vehicle. This critical task is done by the high-voltage battery disconnect unit (HV-BDU), which creates a galvanic isolation between the high-voltage battery and the rest of the electrical network.

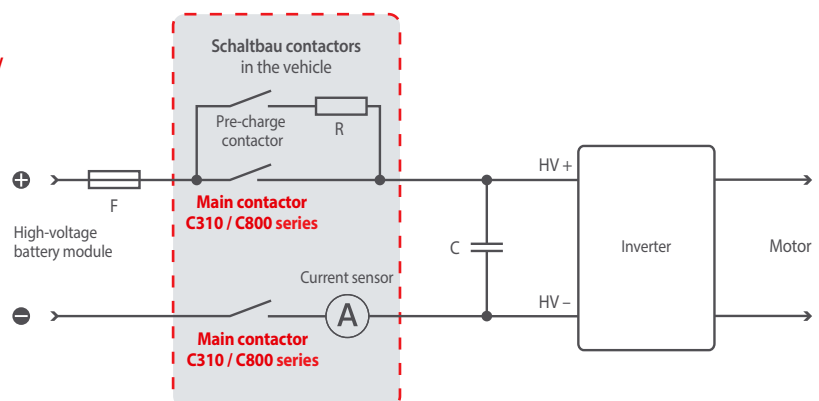
Main contactors are placed both in the positive and negative path of the battery. In this way, any potential faults are reliably kept under control and the electric powertrain network is safely disconnected from the battery. The bi-directional DC contactor has an important safety function: in the event of danger, the HV-BDU disconnects the battery from the high-voltage network and other conductive vehicle components.



Critical characteristics to ensure safety are:

- Full bi-directional switching capability
- Continuous currents of 500A and even higher breaking capacity
- High short-time current-carrying capacity up to 15,000A
- High rated insulation voltage up to 1,500V
- Low coil power consumptions
- High quality feedback signal from auxiliary contacts to monitor the state of the contactor

High-voltage battery disconnect unit/ battery junction box





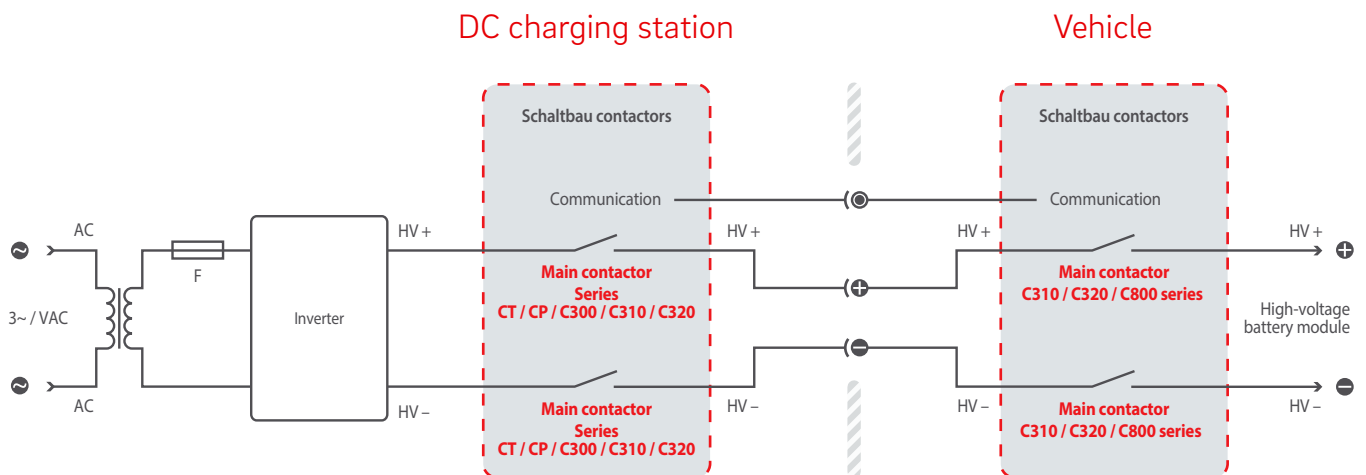
DC Contactors for Battery Charging

To reduce the charging time of electric vehicles, including buses and trucks, an increasing number of fast-charging stations are being installed. The charging takes place either via cable-based solutions or mast charging stations and takes just a few minutes. DC contactors in the positive and negative path form two independent switching elements in the power circuit.

They ensure safe galvanic isolation between the DC charging point and one vehicle as well as between multiple vehicles at a multiport DC charger. Further, to keep critical situations under control, they safely and reliably disconnect the high-voltage under full load in the event of a failure.

Critical characteristics to ensure safety are:

- Full bi-directional switching capability
- Continuous current up to 1,200A at 850V and temperatures up to 85°C is already in service, but even higher power levels are expected for future DC fast-charging standards
- Continuously low contact resistances
- Compact, robust design results in lowest probability of failure
- High quality feedback signal from auxiliary contacts to monitor the state of the contactor





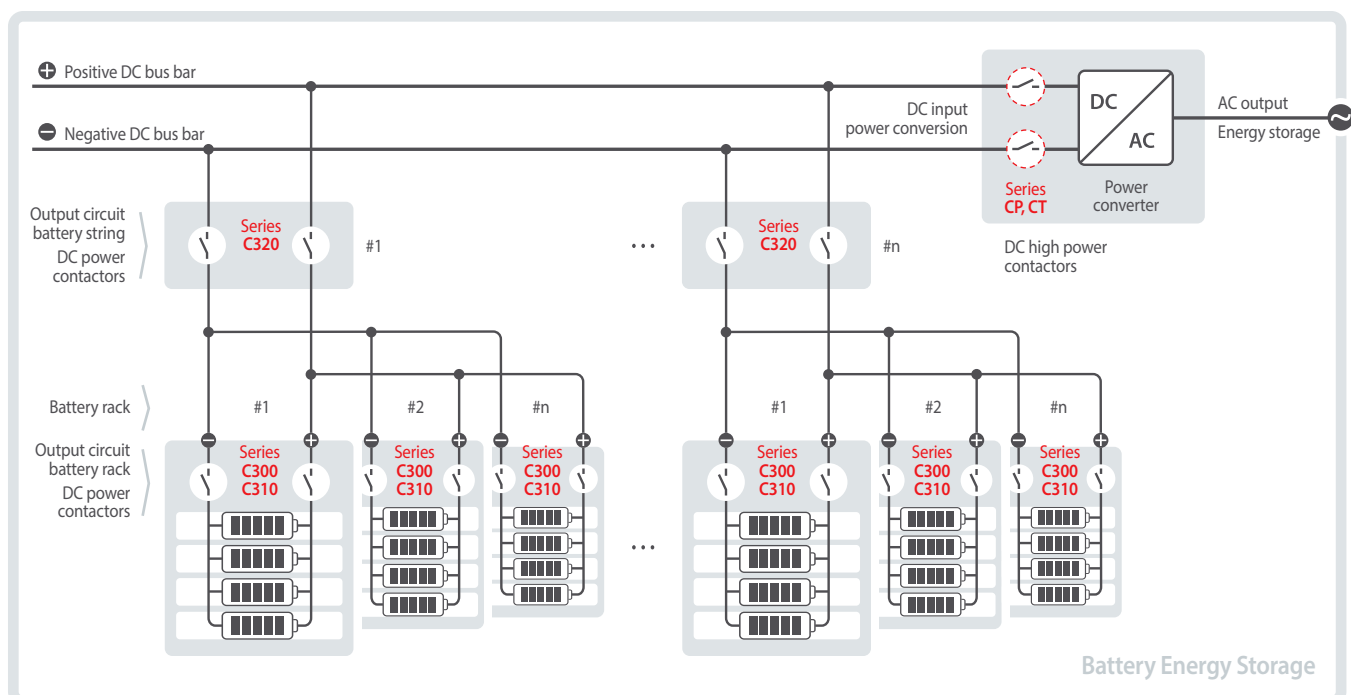
DC Contactors in Battery Energy Storage Systems

A battery energy storage system uses one or multiple battery banks to store electrical energy. Battery storage systems are the fastest responding source of power to support electric grids and stabilize critical load conditions as they can transition from standby to full power within milliseconds.

Together with pre-charging contactors, the high-power DC contactors in both the positive and negative path allow connecting and disconnecting the individual battery banks to the DC bus as needed and to ensure a reliable operation by isolating the different DC circuits under full load in the event of a failure.

Critical characteristics to ensure safety are:

- Full bi-directional switching capability
- Continuous thermal current up to 500A
- High short-time current-carrying capacity up to 3,000A
- Making capacity up to 2,500A
- High rated insulation voltage up to 1,500V



Switching Challenges of DC-Voltage

Contactors are used in applications where automated switching is required. Low currents and voltages can generally be switched without problems by means of simple mechanical switches as used in relays, since only small sparks result when opening or closing the contacts.

In case of a high voltage (above the break down voltage of air) during the switching process, combined with a high current density at the point of contact, the ionization threshold of air is exceeded and a plasma forms – a gas composed of ionized air molecules and free electrons – between the points of the contact. The formation of this switching plasma or electrical arc has two essential consequences. First, despite open contacts, the current continues to flow since plasma has a high level of electrical conductivity, and second, very high temperatures up to 20,000°C occur, which are easily capable of causing damage to the contacts of the contactor, as well as to the surrounding system components.

HIGH TEMPERATURES UP TO

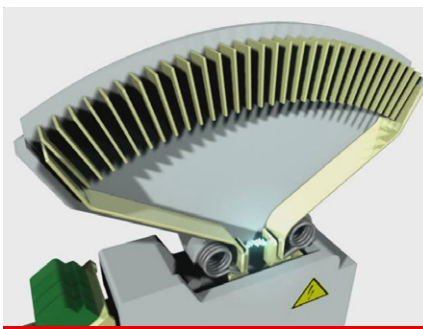
20,000°C

ARE EASILY CAPABLE OF CAUSING DAMAGE TO THE CONTACTS OF THE CONTACTOR, AS WELL AS TO THE SURROUNDING SYSTEM COMPONENTS.

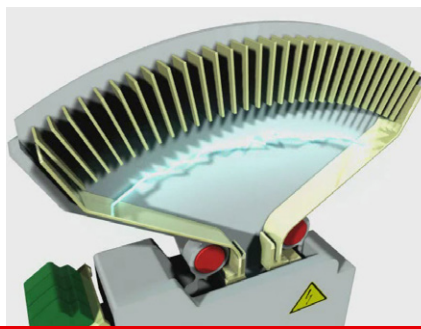
Switching arcs in AC systems are a very well examined phenomenon. Due to the zero crossing of the voltage, the arc automatically breaks down latest after 10ms at a frequency of 50Hz, or 8ms at 60Hz, respectively. Since a zero crossing of the voltage won't occur in DC systems, quenching an arc in a DC contactor is significantly more complex. Once it has formed, an electric arc can continue to burn indefinitely as long as the voltage between the load contacts remains unchanged after opening them. Consequently, additional measures have to be taken to extinguish the switching arc.

To avoid damaged load contacts, different strategies to quench electric arcs have been implemented in DC contactors. The main mechanisms are extending the electric arc column, constricting it, or cooling it. Depending on the contactor ratings, an individual mechanism or a combination of mechanisms is used. Based on the principal of the Lorentz force, a magnetic field, typically generated by permanent magnets, extends the electric arc and deflects it away from the contacts to avoid or limit their damage. This mechanism is also known as magnetic blowout.

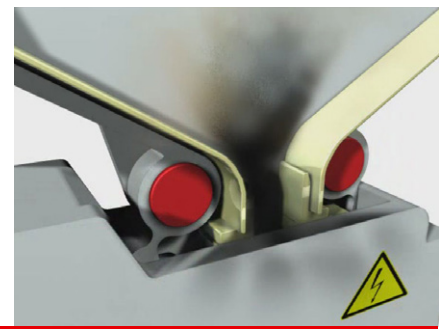
As a disadvantage of the conventional magnetic blowout using permanent magnets, only arcs formed by currents in one direction will move away from the contacts upwards into the arcing chamber, while arcs from currents flowing in the opposite direction will move down towards to the contacts resulting in their permanent damage.



Initial state of the arc at the bottom of the arcing chamber



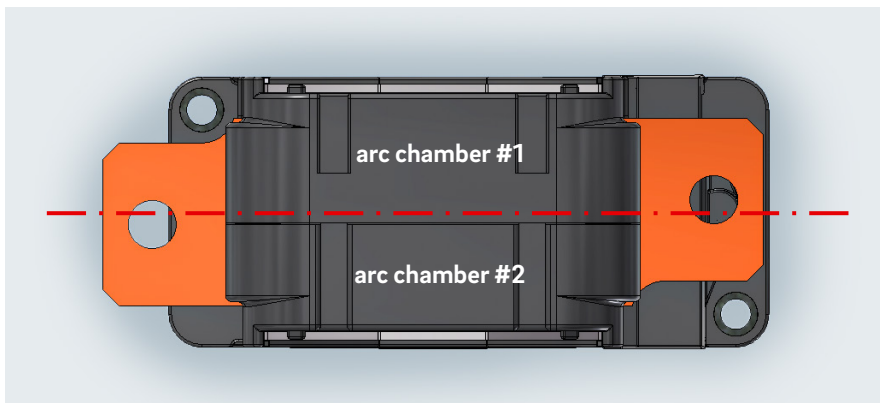
Arc formed by a positive current moves upwards into the arcing chamber and will be extinguished



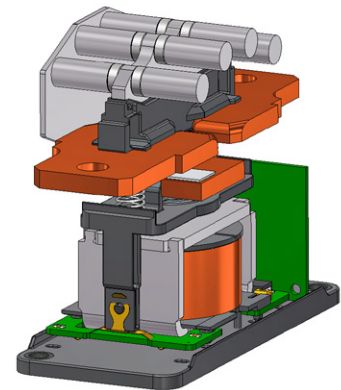
Arc from a negative current moves downwards to the contacts, permanently damaging them

Advantages of Open-Chamber Contactors over Sealed Contactors

To overcome this limitation, Schaltbau has developed a patented smart placement of the permanent magnets together with a geometric design of the arc chamber with two sections, guiding the arc always upwards and away from the contacts either into the left or right chamber, achieving full bi-directional switching capability. Elsewise the magnetic field can be generated by blow out coils, where the magnetic field changes its direction depending on the direction of the load current.



Outside view from top at the two sections of the arc chamber, one for each DC current direction



Inside view of the arc chamber with the permanent magnets to direct the arc into the left or right section

Another option is cooling the arc with special quenching gases. Unfortunately, this has a substantial disadvantage: the switching chamber must be encapsulated and gas-tight sealed. During production of the contactor, the arc chamber is filled with a mix of pressurized inert gases like hydrogen, nitrogen or sulphur hexafluoride. These gases have a higher dielectric strength than air and have higher thermal capacities, leading to better arc cooling. However, it is difficult to ensure long term impermeability of the chamber, in particular, for pressurized gases. Thermal alternating cycles of the chamber can lead to a gradual gas loss, and there is no possibility to detect such a leakage under normal working conditions until the contactor fails in an emergency situation. Even more severe: the contact chamber can rupture when extremely strong arcing, caused by high over-currents, generates excess gas pressure inside the chamber, resulting in a sudden and catastrophic failure of the contactor.

Due to these limitations of sealed contactors, open-chamber contactors are advantageous for currents of more than 200A, quenching an arc by constricting the electric arc between plates of insulating material, which also have a diffusive structure. In addition, by dividing the total arc into partial arcs, the anode and cathode drops can be used repeatedly to increase the electric column field strength. The short arcs are also cooled by the highly thermally conductive metallic sheets. This contactor design is well suited to repeatedly break currents around 500A, independent of their directions, as they occur during EV operation and charging.

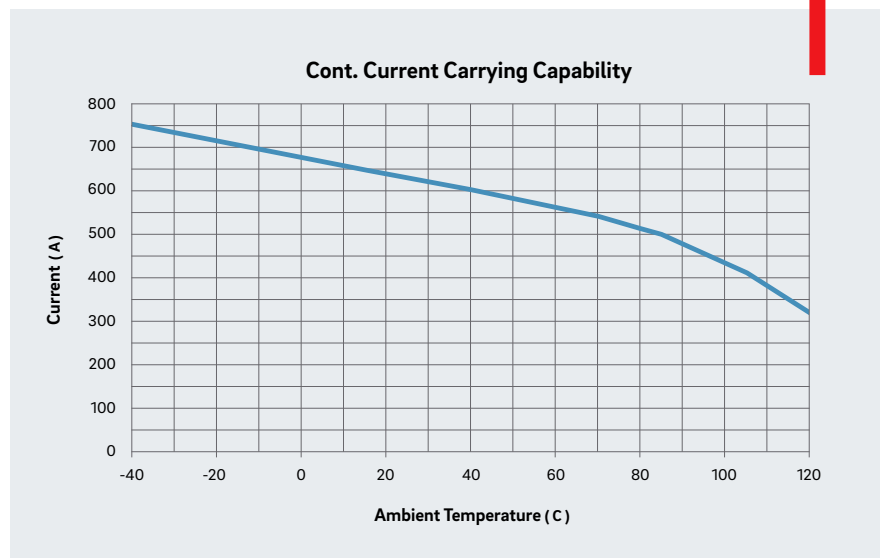
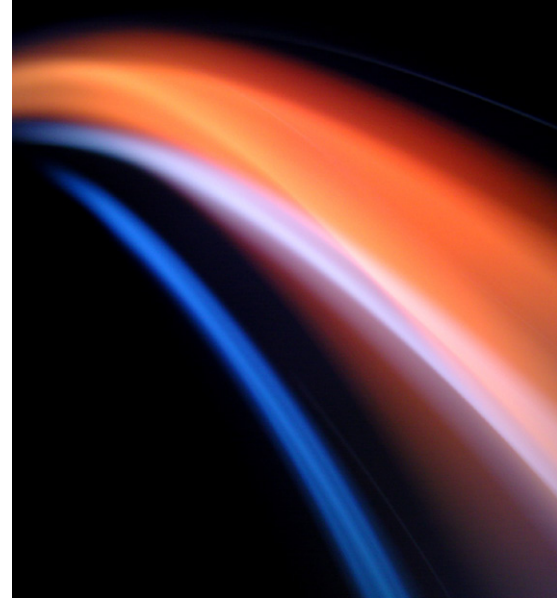
In addition, a Schaltbau DC contactor can switch off over-currents up to several 1,000A in the event of a fault situation.

Ambient Condition Limits of DC Contactors

DC contactors must be able to operate reliably under a number of challenging ambient conditions, like a wide temperature range from extreme cold to hot, or contamination caused by exposure to dust and other soiling.

The temperature range is defined by the material properties of the contactor components and easily fulfills the typical automotive requirements of -40°C to 85°C under no load condition. However, conducting high continuous currents of up to 500A results in significant losses inside the contactor, which increase the temperature of the load carrying parts. Due to the resistive nature of the load circuit, the losses grow with the square of the current: doubling the load current results in four times the losses. The thermal energy from the losses will dissipate into the ambient air and the connecting elements, like bus bars or cables and increase their temperature. The higher the temperature of the ambient air and conducting elements, the less thermal energy can dissipate and will remain inside the contactor.

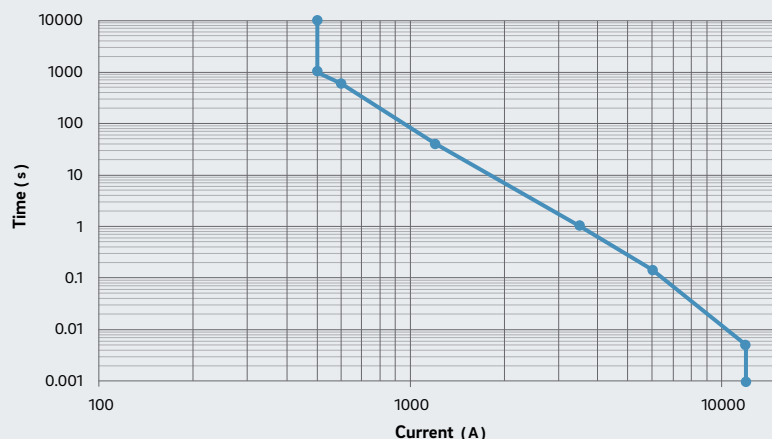
As a result of this, the maximum operating temperature depends on the load current while the maximum load current depends on the ambient air temperature, and both depend on how the contactor is connected within the high-power network.



Although high current peaks create high losses in the contactor, they won't cause immediate damage as long as the duration is short and the additional losses can be absorbed by the thermal capacity of the load circuit. As a result of this, the contactor can safely carry extremely high currents up to 12,000A, but for a few milliseconds only.

The table below lists typical short-term current values and the related safe operating time limits:

Current (A)	Time (s)
500	Cont.
600	600
1,200	40
3,500	1.0
6,000	0.15
12,000	<0.005



Designing the Right Enclosure for an Open Chamber Contactor

Another important factor is the contamination from ambient operation conditions. As outlined above, the open switching chamber design offers various benefits in regards of cooling, arc quenching and safe operating at high current peaks. At the same time, the contactor needs to be integrated in some kind of enclosure to prevent direct exposure to large amounts of water or dust contamination. This is not an issue for EV applications since the HV-BDU contains a number of other components like voltage and current sensors, fuses, and relays, which all require an enclosure for protection from the exterior environment or unintended contact with the high-voltage carrying contact elements and bus bars.

Although potentially required for other components, the HV-BDU enclosure does not have to be hermetically sealed for the contactors. Due to the open switching chamber design, the specification of an Ingress Protection (IP) rating can be less meaningful for an application inside a vehicle. Instead, the Pollution Degree (PD) rating according to IEC 60947-1 is used, a classification defining the amount of dry pollution and condensation present in the ambient environment. This classification is important since it affects creepage and clearance distances required to ensure the safe operation of the contactor.

PD	Description of Pollution Degree
1	No pollution or only dry, non-conductive pollution occurs (the pollution has no influence). Example for PD 1: Clean room environments, inside of sealed components
2	Normally, only non-conductive pollution occurs. Occasionally, however, a temporary conductivity caused by condensation may be expected. Example for PD 2: Office environment, laboratories, test stations
3	Conductive pollution occurs, or dry, non-conductive pollution occurs which becomes conductive due to condensation. Example for PD 3: Electrical equipment in industrial and farming areas
4	The pollution generates persistent conductivity, for instance, caused by conductive dust or by rain or snow. Example for PD 4: Electrical equipment for outdoor use

The expected pollution degree based on the ambient condition mainly impacts the rated operational and insulation voltage of the contactor, for example, 1,500V for PD2 versus 1,000V for PD3, which is considered worst-case for any application in some kind of vehicle enclosure.

Breaking High DC Currents without Breaking the Contactor

Think of the following situation: an EV is getting involved in an accident and the high-voltage cables, converters or other powertrain components of the EV are being damaged. Two things can happen now: conductive vehicle parts, like sheet metal, make contact with the lethal battery voltage, and the high amount of energy stored inside the battery pack can start sparks or even a fire.

To avoid these severe scenarios, the battery disconnect unit (BDU) needs to fully, galvanically separate the battery within milliseconds from the rest of the high-voltage network!



As mentioned, interrupting (breaking) high DC currents at high voltages is an extremely challenging task due to the unavoidable occurrence of arcing. Being able to disconnect a DC circuit reliably is a critical requirement for the DC contactor since the device is expected to create a safe system state in case of a critical condition or other failure mode. Schaltbau bi-directional DC contactors are not only

specified to reliably break the current rated for continuous operation, but also significantly higher currents as they can occur in overload situations.

While breaking the load contacts of a contactor, the number of contact points are getting reduced during this early opening phase with a few or even only one contact point left

that conducts the full current. As a result, the high current density and contact resistance drastically increase the thermal losses and hence the temperature at these remaining contact points, which potentially melt, creating a melting-bridge until the contacts fully separate and an electric arc forms along the ionized air.

Although a contactor is mechanically designed to make and break the load contact at least one million times, breaking a high current will reduce the number of operations due to the additional wear and tear caused by the melting and arcing at the contact surfaces. The maximal number of safe operations is the breaking capacity and depends on a combination of the load current, the voltage across the contacts after opening them, and the inductance of the load circuit.

Breaking Capacity Limits

The table below shows this relationship as an example, but the actual breaking capacity can vary widely from one contactor type to another.

Current (A)	Voltage (V)	Number of Operations
60	750	6,000
300	1,500	10
500	1,000	20
700	900	25
1,000	750	10
1,500	500	15

The number of operations shown in the table are the minimum number guaranteed for reliably opening the contact. It can be higher under real world conditions, but breaking the load contact repeatedly under very high voltage and/or current will eventually damage the contact points, resulting in a higher load contact resistance or contact points being melted together permanently.

As an additional important feature, the contactor offers auxiliary contacts (sometimes also called mirror contacts), which reflect the state of the load contact in the same or reversed logic. Connected to a diagnostic circuit, reading back the state of the auxiliary contact provides reliable information about the actual state of the load contact and allows detection of any unintended or unsafe condition like melted load contacts.

Conclusion

Innovative new mobility solutions are changing how we move people and goods in a sustainable way. Such applications include electric vehicles (EV), fast-charging stations and energy storage systems to stabilize the grid. They all comprise some kind of high-voltage DC bus and powerful lithium-ion batteries, which create very specific challenges to safely and reliably disconnect DC circuits carrying very high currents.

Although semiconductors are used to switch high power on and off, only electromechanical DC contactors have the capability to fully, galvanically separate the battery from the rest of the power network. While breaking high-voltage DC currents always results in a switching arc between the open contacts, very specific design features are required to quench the arc within extremely short time to avoid the contacts getting damaged.

The requirements for DC contactors can be very different, as showed by the various application examples. A variety of different criteria, which are not always apparent, must be considered when selecting the right contactor. The detailed application parameters need to be always taken into consideration in order to meet all the requirements in an optimum way. For example, different ambient conditions define the safe operating area of the DC contactors and the electrical switching parameters determine its lifetime.

Schaltbau's decades of experience in developing and manufacturing electromagnetic components for high-voltage, high-current industries like railway makes us a valuable partner in finding the best solution for new applications in the space of new energy and e-mobility.

Customers can take advantage of the help of Schaltbau's application engineers, who will provide support based on their many years of experience across industries and applications. The right solution may be an item from our product line, a special variant with minimal adaptation, or a completely unique design.

Schaltbau

DC Contactor Product Highlights

Schaltbau offers a large variety of bi-directional DC contactors for many high-power applications and continues its innovative approach to designing and developing contactors for future applications.

Full bi-directional capability is important for any system with a charging and discharging operating mode, such as in battery networks or electric vehicles. Other typical applications are the DC link in inverters, combiner boxes in photovoltaic systems or the management of battery banks in energy storage systems.

C310 | Generic single-pole bi-directional DC contactors up to 1,500V

C310 bi-directional DC contactors switch high powers in a small space. With a making capacity of up to 2,500A, the compact switchgear is suitable for applications with high inrush current or high capacities.

All versions can continuously conduct up to 500A. In the event of a short circuit, 3,000A, can even flow for one second without the contacts welding. The contactor therefore maintains its full function in order to disconnect high power ranges if necessary up to 500A and up to 1,500V – irrespective of the current direction.



READ MORE
www.schaltbau.com/en/products/contactors/c310/



C320 | High-power single-pole bi-directional DC contactors up to 1,800V

The bi-directional DC contactor C320 is capable to withstand very high insulation voltage of up to 1,800V. This switch can carry up to 1,000A continuously and up to 4,500A for 100ms without contact welding.

With a making capacity of up to 3,000A, the compact switch is suitable for applications with high inrush current or high capacities, and in case of a high-power failure situation, up to 2,200A or up to 800V can be safely and reliably disconnected in both current directions.



READ MORE
www.schaltbau.com/en/products/contactors/c320/



C300 | Super compact single-pole bi-directional DC contactors up to 1,500V

C300 bi-directional DC contactors switch high powers in a very compact formfactor. With a making capacity of up to 2,500A, the compact switchgear is suitable for applications with high inrush current or high capacities.

All versions can carry up to 500A continuously. In the event of a short circuit, 5,000A can even flow for 20ms without the contacts welding. The contactor therefore maintains its full function in order to disconnect high power ranges if necessary up to 500A and up to 1,500V – irrespective of the current direction.



READ MORE
www.schaltbau.com/en/products/contactors/c300/



C801 | Interlock contactor with patented contact technology

C801 bi-directional DC contactors are designed for automotive applications, specifically with interlocking contacts for extremely high shock resistance and a small packaging formfactor.

The current carrying capability of 250A continued in combination with the high insulation voltage of up to 1,000V supports a number of on-board vehicle applications like reconfiguring the battery in a way to allow an 800V vehicle to use either an 800V or 400V DC fast-charging station.



READ MORE
www.schaltbau.com/en/products/contactors/c801/



WE PRESENT

Our authors and experts



Martin Zierer

found his passion in direct current. As Head of Application Engineering Department at Schaltbau he ensures that direct current applications in both mobile and stationary systems are safe by using the suitable DC contactors.



Pavel Tomashev

is a passionate application engineer eager to explore new technologies. At Schaltbau he ensures that clients are selecting the right DC contactor for their application.



Marc Rosenmayr

Marc has more than 20 years' experience in building and leading global teams in the automotive industry with a strong focus on developing innovative products to meet the latest technology trends. He holds a Master's degree in Electrical Engineering and a Doctoral degree in Power Electronics and provides his expertise to Schaltbau as an independent technology advisor.

About Schaltbau

Founded in Munich in 1929 as a developer and manufacturer for the railway industry, today Schaltbau GmbH is a global innovation and growth company providing contactors and safety solutions for the energy, industry, mobility and rail sectors. The technology used in our products and tailor-made solutions is designed for direct current, an important part of the energy transition.

Schaltbau North America, Inc. became a wholly owned subsidiary of Schaltbau GmbH in 2001 to support the North American customer base for our products. A leading international supplier of safety-relevant electromechanical components, we develop and manufacture contactors, plugs, and switching systems with a focus on direct current (DC) technology. With our customized solutions, Schaltbau is an innovation driver for rapidly growing future markets such as new energy, new industry, and e-mobility.

One of the few specialists for smart direct current (DC) energy concepts, safety is top of mind in our development of products across battery management systems of high-voltage batteries, charging stations for e-mobility, battery test stands, DC circuits of inverters for photovoltaic systems, industry applications and rail vehicles.

CONTACT INFORMATION

Carolyn Sauer

Business Development Director
Schaltbau North America

carolyn.sauer@schaltbau-na.com

586-321-0589

IMPRINT

Schaltbau GmbH

Hollerithstr. 5
81829 Munich
Germany

marketing@schaltbau.de

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www.schaltbau.com