TECHNICAL APPLICATION PAPER

PROTECTION DEVICES FOR DIRECT CURRENT APPLICATIONS

ENGINEERED
TO OUTRUN

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1 Introduction – All-Electric Society

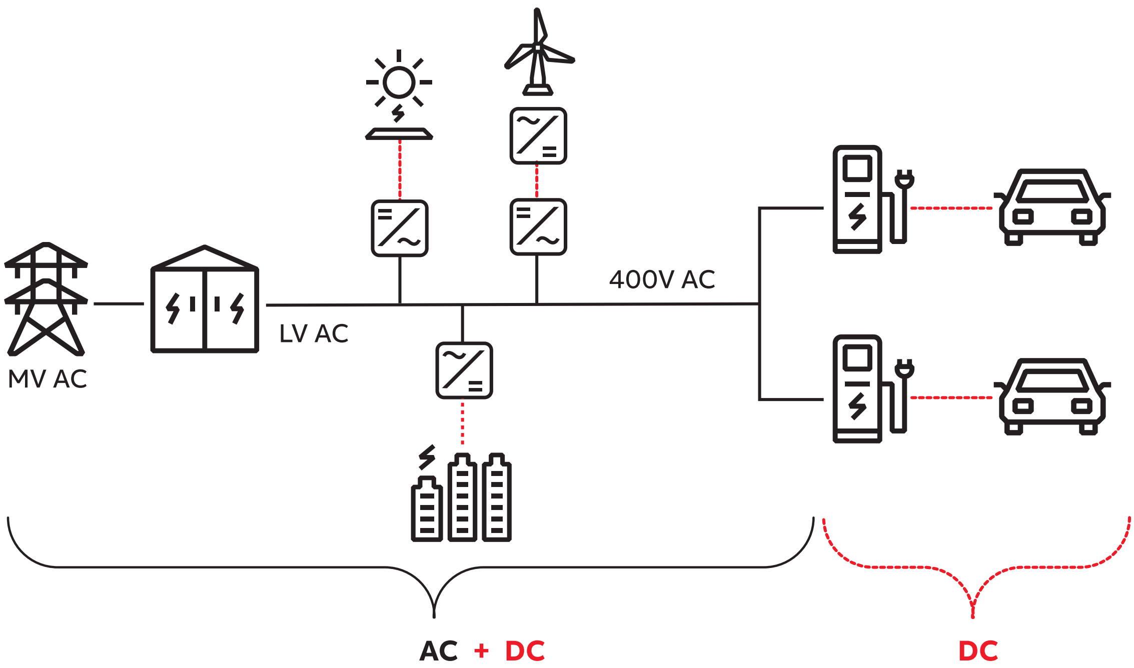
The “All-Electric Society” describes the vision of a future global society fully based on electricity. The initial idea was formulated already in the 1970s, and continuously further developed [1].

To meet the UN Sustainable Development Goals (SDGs), electricity was defined to be indispensable. It is seen as a “prerequisite” to mitigate global warming and thus limit the incidence of many future natural disasters [2].

The transition to an All-Electric Society relies upon the phasing out of fossil fuels (coal, oil and gas), which will need to be replaced by sustainable Renewable Energy Sources (RESs), such as hydropower, wind, marine energy (which includes wave, tidal and other water current converters), geothermal and solar power.

The intermittent nature of some RESs (wind and sun) will require expanding and improving the technology for energy storage.
Since both power generation as well as storage and more and more consumers are based on direct current (DC), DC technology will play a significant role in an All-Electric Society.
ABB has clear mission and purpose, which is to enable a more sustainable and resource-efficient future with our technology leadership in electrification and automation [3]. To deliver components for a reliable and safe DC grid, including protection is part of that mission.
When it comes to DC applications, it is already well-known how to integrate them in an existing Alternating Current (AC) system.
For example, connecting a Photovoltaic (PV) generation to the Low-Voltage (LV) AC grid through a

Figure 1 AC coupling of DC applications



string inverter or integrating a battery energy storage system, again to an AC network, is mainly a point-to-point power delivery, as shown in Figure 1. In such networks, some of the main challenges are frequency regulation and reactive power flow management. Considering the AC-side protection, the fault current is alternating and crosses zero, thus the well-known interruption technologies come in handy.
More details on DC-side protection instead, can be found in dedicated technical application papers, like in [4].

On the other hand, when several distributed generation resources and loads are connected as in Figure 2, the grid requires coordination and management (commonly done by droop control*) and fast protection. These networks, named active DC systems, are converter-dominated and behave rather differently in the case of a fault than the system in Figure 1. Hence, the protection requirements are peculiar and require particular attention.

Further classification of the DC grids can be made in passive and active, as in IEC TR 63282.

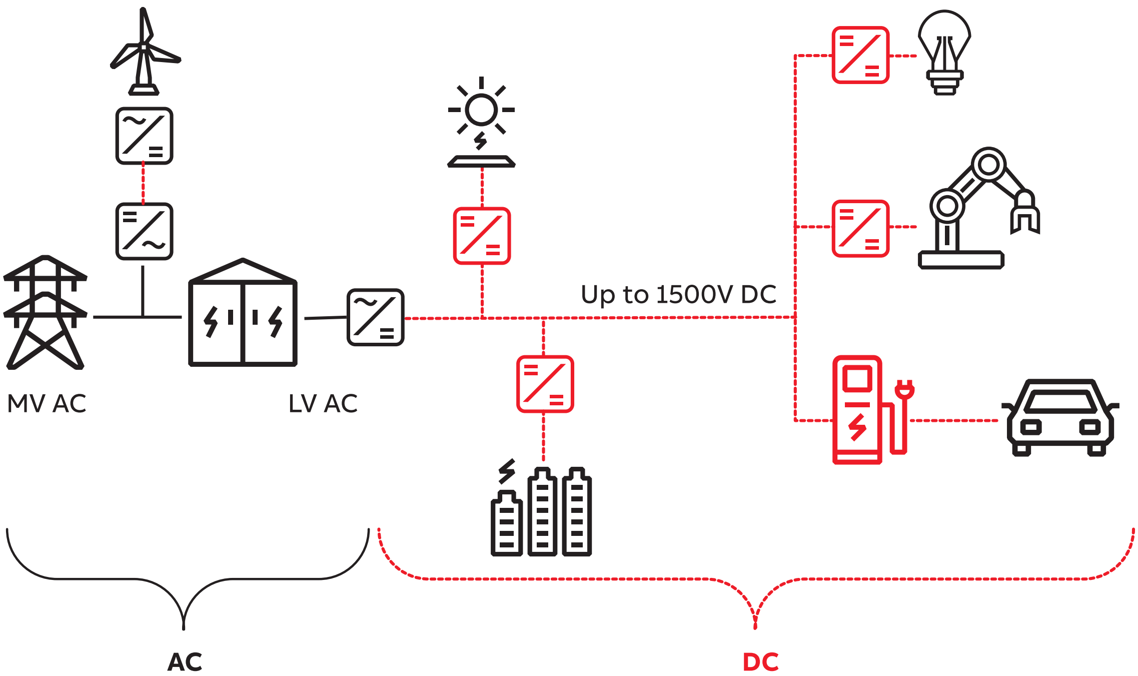
In passive DC systems, the integrated sources can be either voltage or current sources and they need control objectives defined from external controller. Usually, there is a central controller that sends command signals to all the converters and the power balance margin relies only on the voltage source capabilities. At normal operation, the system voltage can vary only in a narrow range [5].

An active DC system instead, is a distribution network where almost all sources and loads are connected to the DC bus by electronic devices that define and adjust the droop control curves. In this way, the energy balance is accomplished. The system voltage can fluctuate in a wider range, which is called nominal voltage band [5].

In this technical application paper, active DC networks will be described, strongly focusing on fault analysis. Consequently, all the protection devices and accessories that ABB offers for this type of networks will be presented, as well as some guidelines on how to choose the suitable protection device in some specific applications.

* Droop control is a strategy that regulates the output power of distributed energy resources based on the deviation of the system voltage to maintain voltage stability and power balance.

Figure 2 DC distribution grid

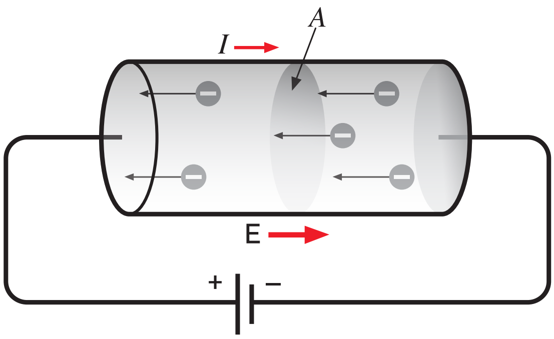


2 Direct current: generation and fault analysis

2.1 Notes on the DC current

Direct current refers to an electric current that flows always in the same direction. It can be constant (e.g., supplied from batteries) or time varying (e.g., provided by a rectifier), as we will explain later; however, the DC current can flow only in one direction [6]. During charging and discharging a battery or any other energy storage system, the current flows in opposite directions with respect to the battery terminals. However, this does not change the key characteristic of the DC current, i.e., it flows in only one direction at a time. An example of a DC current due to flow of electronic charge in a conductor is shown in Figure 3.

Figure 3 Electric current in a conductor



Direct current is typically provided by RESs such as photovoltaic, wind and also battery systems. Additionally, it is possible to convert alternating current into direct current through a process called rectification. However, when converting AC to DC current, periodic fluctuations can occur.

In a DC system, the direction of the current is crucial. Therefore, it is important to connect loads and sources according to the correct polarities. Wrong connections can lead to operational and safety issues. For instance, connecting a DC motor with reversed polarities would cause it to rotate in the opposite direction. Similarly, supplying electronic circuits with a mismatched polarity can result in irreversible damage.

Understanding the electrical characteristics of direct current and its differences from alternating current is essential for using DC effectively.

The effective value, i.e., the root-mean-square (rms) of a periodic current

$$I_{rms} = \sqrt{\frac{1}{T_p}\int_0^{T_p} i^2(\tau)d\tau}, \quad (2.1)$$

where T_p is one period, is the equivalent constant DC current that delivers the same average power to a resistor.

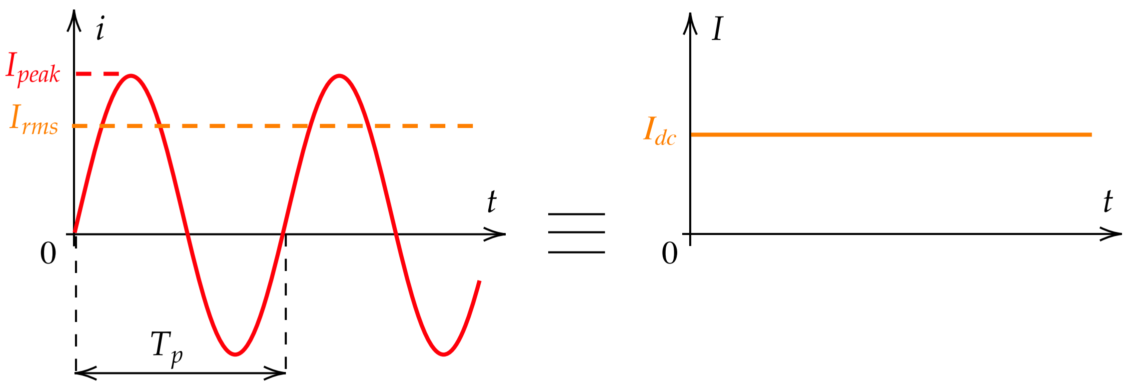
The rms value of an alternating current is the direct current value that causes the same thermal effects in the same time interval.

For example, a direct current of 100A in Figure 4 delivers the same power (and therefore, generates the same thermal effects) as a sinusoidal current with approximately 141A peak value. Another approach of interpreting the result is to have in mind that an AC current with I_{rms} effective value causes the same power losses as a DC current with the same value.

For pure sinusoidal current, the relationship between the peak and the rms value is:

$$I_{rms} = \frac{I_{peak}}{\sqrt{2}}. \quad (2.2)$$

Figure 4 AC and DC current parameters



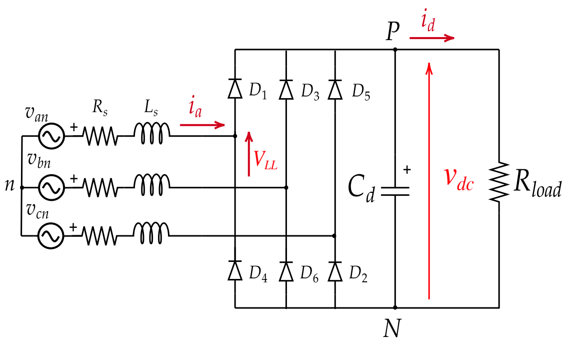
2.2 DC current generation

2.2.1 Generation from AC circuits

2.2.1.1 Diode-bridge rectifier

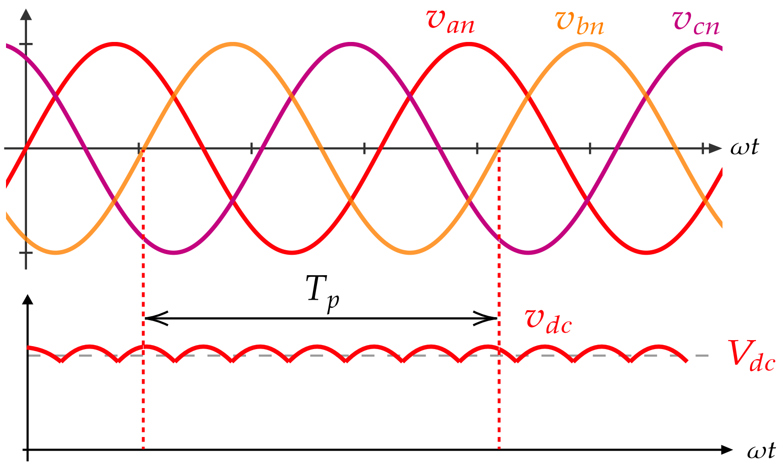
The simplest three-phase rectifier consists of six diodes, two for each phase of the AC input (Figure 5). It generates six pulses of output voltage during one period of the input voltage. The power flow is unidirectional only, from the AC to the DC side. The output voltage is a function of the input AC voltage, which is usually fixed; hence, the rectified voltage cannot be controlled further by the rectifier. To reduce the output voltage ripple, a suitably designed capacitor on the DC side is necessary.

Figure 5 Three-phase diode-bridge rectifier supplying resistive load [7]



The waveform of the output voltage v_{dc}, as shown in Figure 6, contains six pulses in one fundamental period T_p of the input voltage. To smooth the ripple in this waveform, an output capacitor C_d is needed.

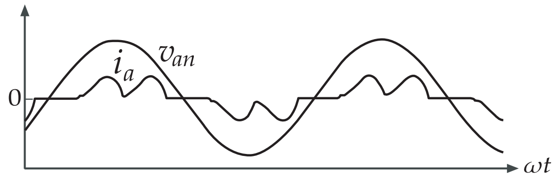
Figure 6 Three-phase AC supply voltages and rectified DC voltage waveform [7]



The line current i_a (Figure 7) consists of a fundamental component and superposed odd harmonics (h = 5, 7, 11, 13,...).

The amplitude of these current harmonics depends on the input line inductance L_s. To decrease the current ripple, an input filter is often required.

Figure 7 Phase voltage and line current in the case of three-phase diode-bridge rectifier [7]



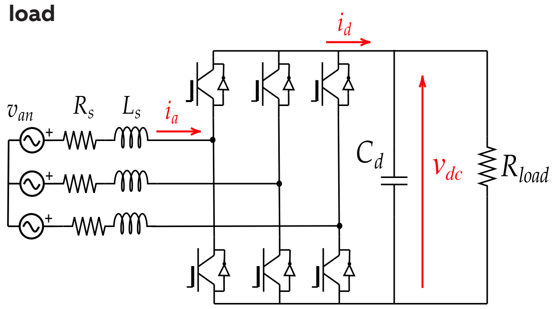
2.2.1.2 Six-switch voltage-source converter

The voltage-source converter, classified as active rectifier according to [8], consists of six controllable switches (Insulated Gate Bipolar Transistors IGBTs or similar power transistors) that are controlled in a way which provides the desired DC output voltage with fixed AC input. The structure is shown in the Figure 8. This converter allows bidirectional power flow and its main functions are to:

- Control the DC voltage at a desired level.
- Maintain the line current sinusoidal with limited current ripple.
- Guarantee the desired power factor on the AC input side.

Consequently, there is controlled active and reactive power exchange between the AC and the DC side.

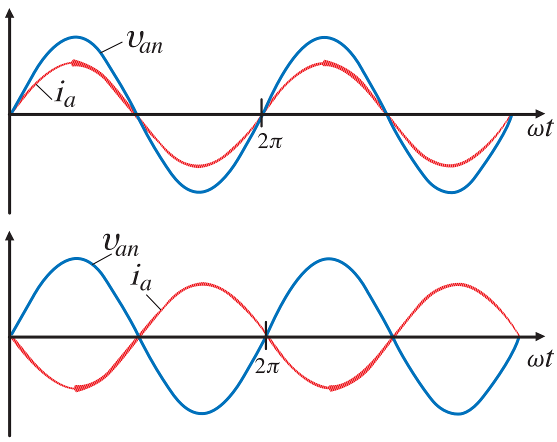
Figure 8 Six-switch converter supplying passive load



2 Direct current: generation and fault analysis

The waveforms of the AC-side voltage and line current in both power flow directions, as seen in Figure 9, contain very limited harmonic content.

Figure 9 Phase voltage and line current waveforms in six-switch converter in rectification mode (top) and generation mode (bottom) [9]



Main harmonics in the line currents are related to the modulation technique employed to control the converter switches. Hence, the high-frequency ripple is related to the switching frequency, which is commonly chosen from 2kHz to 20kHz in case of IGBTs.

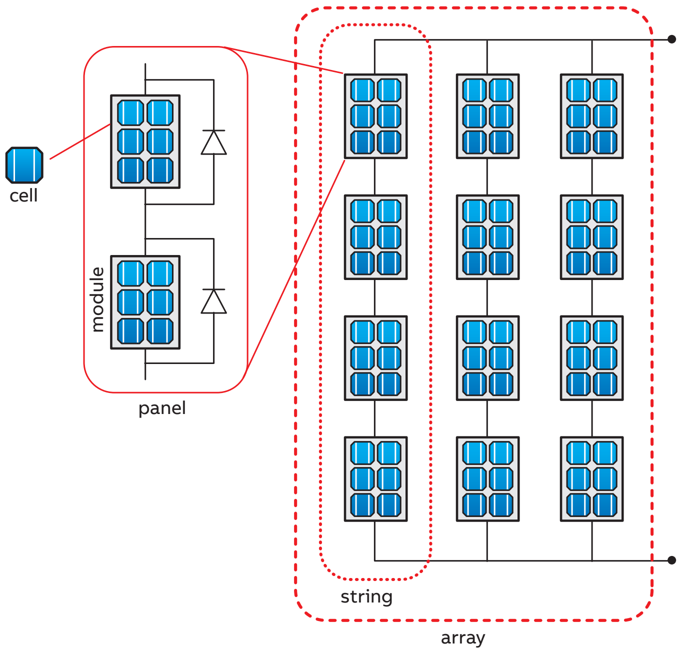
2.2.2 Generation from DC circuits

2.2.2.1 Photovoltaic (PV) generation

Photovoltaic (PV) systems are technology products that convert light into electricity. PV systems typically consist of solar arrays, which are made up of individual cells that generate electricity when exposed to light. PV systems are a clean and sustainable energy source, as they do not produce greenhouse gas emissions or air pollutants during operation. Moreover, PV systems are becoming increasingly popular as the costs of solar panels continue to decrease, and the technology becomes more efficient.

The photovoltaic cell is the most elementary photovoltaic device, according to the standard IEC 61836 [10]. A photovoltaic module is a group of interconnected and environmentally protected photovoltaic cells. Several modules, which are mechanically integrated, pre-assembled and electrically connected is called a PV panel.
The circuit of series-connected PV panels is called PV string. Mechanical and electrical assembly of modules, panels or sub-arrays and its support structure is called PV array. An assembly of arrays connected in parallel to obtain the required power is called a photovoltaic generator.

Figure 10 From a PV cell to a PV array

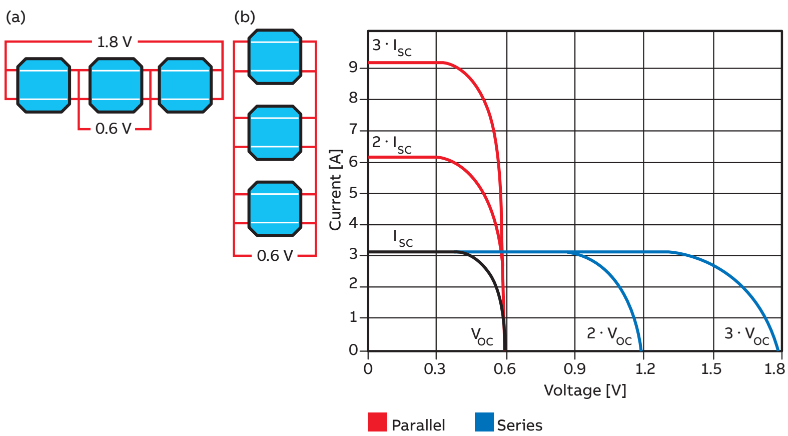


The details of the PV equivalent electrical circuit and formulae for computing the relevant currents can be found in [4]. Here we will highlight some aspects related to the operating curves and fault conditions.

In a series connection of cells / modules (Figure 11a), the system finds an equilibrium such that the same current flows through all the PV cells / modules, while the voltages add up.

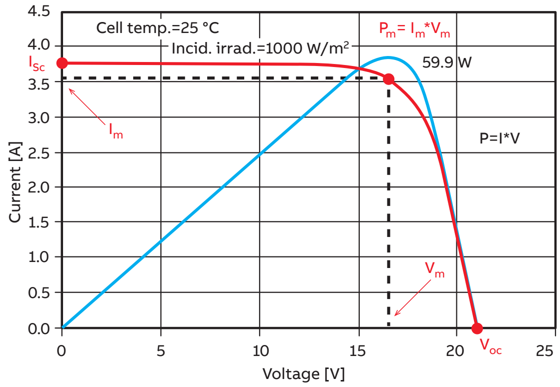
In a parallel connection of cells/modules (Figure 11b), the voltage across all PV cells/modules is the same, while the total output current is the sum of the currents generated individually by each PV cell / module.

Figure 11 I-U characteristics of series and parallel-connected PV cells



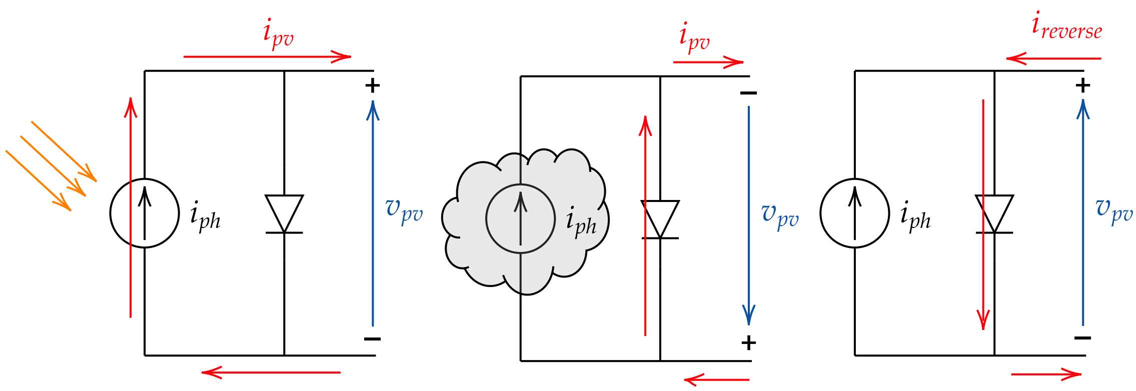
The operating characteristic of a PV generator at standard conditions (cell temperature 25°C, irradiation 1 kW/m²) has a maximum power point production P_m when the PV operates at a voltage V_m and current I_m (Figure 12).

Figure 12 I-U and P-U characteristic of a PV generator



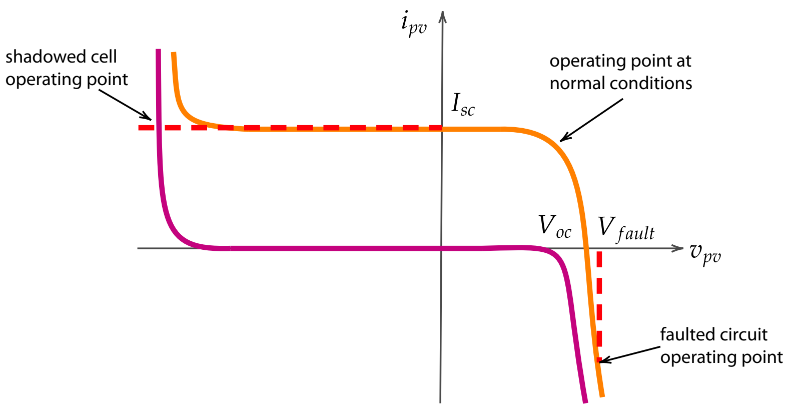
Taking into consideration the area occupied by the modules of a PV plant, part of them (one or more cells) may be shaded by trees, fallen leaves, chimneys, dumps, clouds or by PV modules installed nearby. In case of shading, the affected PV cell stops producing energy and becomes a passive load (Figure 13b). This cell behaves as a diode which blocks the current produced by the other cells connected in series and thus jeopardizes the whole production of the module. Besides, the diode is subject to the voltage of the other cells; this may cause perforation of the junction because of localized overheating (hot spot), and damage the module (II quadrant in Figure 14).

Figure 13 Equivalent electrical circuits of a PV generator in normal operation a), partial shadow b) and reversed operation c) [11]



2 Direct current: generation and fault analysis

Figure 14 I-U operating characteristic of PV generator in normal and faulted conditions



Due to shading or faults, a string could start behaving like a passive load. In this case, it absorbs and dissipates the power generated by the other strings connected in parallel. The current flows through such a string in the opposite direction with respect to the one in normal conditions, thus it is called reverse current. The voltage applied to the module V_{fault} exceeds the open-circuit voltage V_{oc} and the operating point is shifted to the IV quadrant (Figure 14).

To avoid shaded cells thwarting the whole string generation, some bypass diodes are installed at a module level (Figure 16). The bypass diode is blocked when all cells are illuminated and conducts when one or several cells are shadowed. To prevent from any reverse current flowing, each string is protected by a string (blocking) diode, which is carefully chosen. More details on the protection requirements for the DC side of a PV generator can be found in [4].

For example, in the case of N_s strings connected in parallel, when one module is short-circuited, the healthy N_s-1 strings feed the faulty one. The highest reverse current $I_{rev,max}$ that can flow through this module is

$$I_{(rev,max)} = (N_s-1) \cdot I_{sc}, \qquad (2.6)$$

where I_{sc} is the short-circuit current of each module. If $I_{rev,max} < I_{rev,module}$, $I_{rev,module}$ being the maximum reverse current that the PV modules allow as indicated in their datasheet, protection of strings against reverse current is not necessary. Otherwise, if $I_{rev,max} > I_{rev,module}$, strings protection against reverse current is strictly necessary in accordance with IEC 62548 clause 6.5.3. Further details on faults in PV systems can be found in many scientific papers, like [12] and [13].

Figure 15 Array, sub-array and string cable faults.

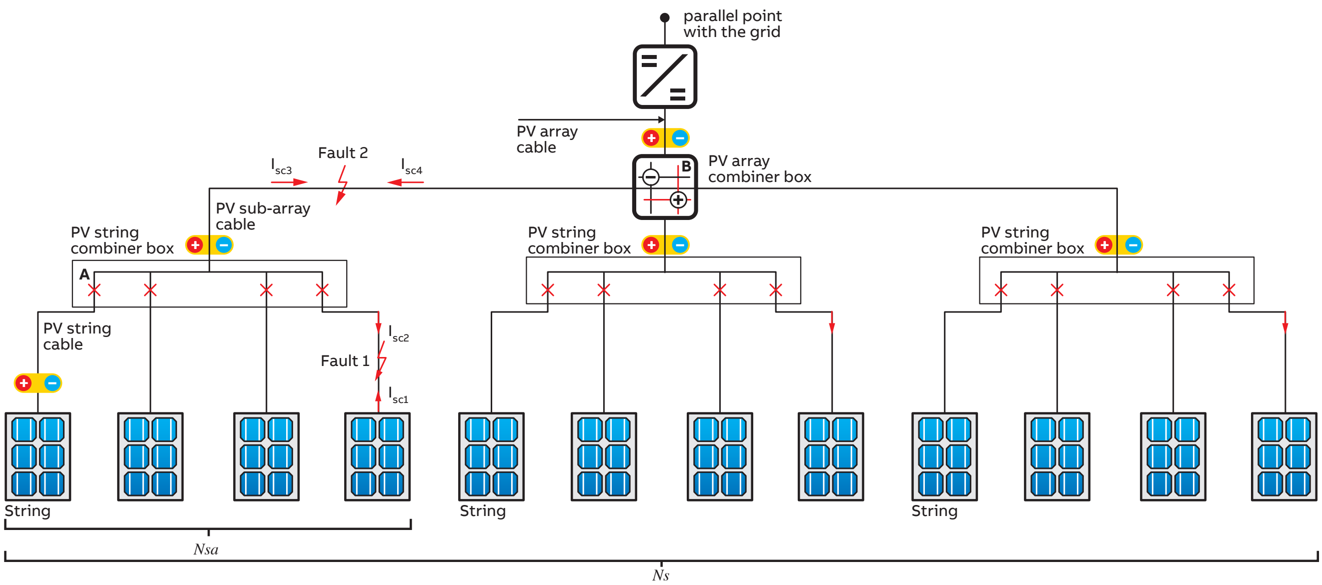
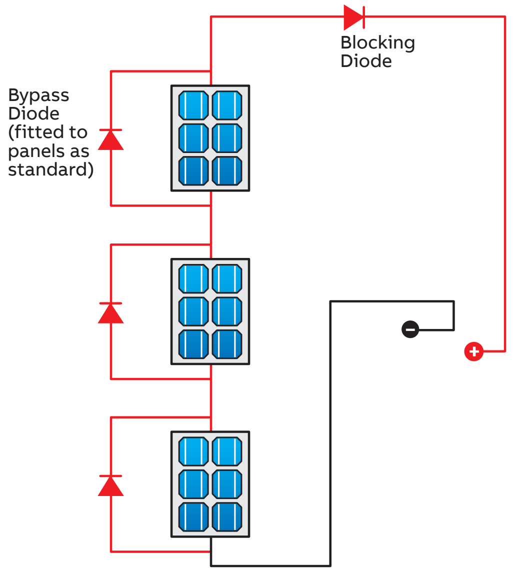


Figure 16 Bypass and string diodes illustration



A short-circuit overcurrent within a PV array can occur on the DC cables in the case of:

- Fault between the terminals of the PV system,
- Fault between a terminals and earth in earthed systems,
- Double fault between each terminal and earth in isolated systems.

PV modules are current-limited sources: their short-circuit current I_{sc} is slightly higher than the operating current I_m. Let us consider some fault cases through the system in Figure 15, where N_s and N_{sa} are the number of parallel-connected PV strings in the array and in the sub-array, respectively. A and B are protective devices installed in the PV string and array combiner boxes, respectively.

In case of a short-circuit affecting the string cables or connectors (fault 1 in Figure 15), the string cable is supplied by the string itself (I_{sc1} = 1.25 I_{sc}) and by all the other (N_s-1) strings (I_{sc2} = 1.25 (N_s-1) I_{sc}).

In the case of short-circuit affecting the cable between a PV string combiner box and the PV array combiner box (fault 2 in Figure 15), the cable is supplied by the PV sub-array string (I_{sc3}= 1.25 N_{sa} I_{sc}) and all the other (N_s-N_{sa}) strings (I_{sc4} = 1.25 (N_s-N_{sa}) I_{sc}).

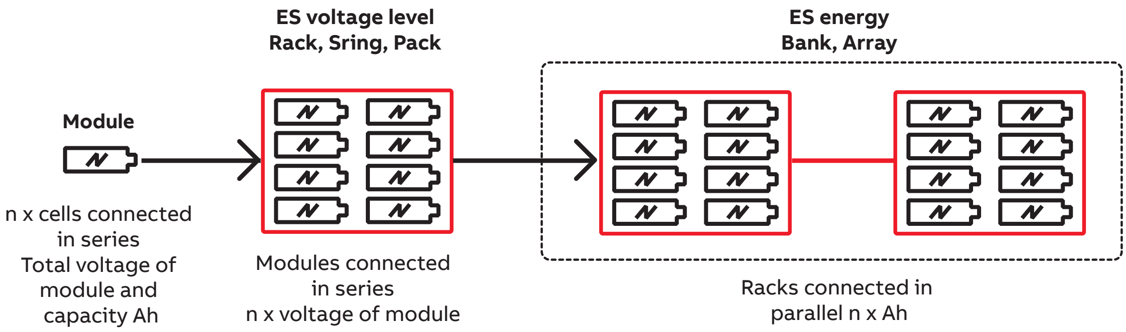
2.2.2.2 Battery energy storage system (BESS)

The basic role of energy storage is the same across all applications: to absorb energy generated at one time and to discharge it to supply power later. Introducing a BESS between the generation and the consumers allows the grid to balance electrical demand with the supply from the generators.

Batteries are devices that transform chemical energy directly into electrical energy through an electrochemical oxidation-reduction reaction. They have a high total energy storage capacity, but the rate at which the energy can flow out of batteries is low compared to supercapacitors. However, stress and high levels of heat generation can cause damage and limit the batteries' life cycle, a measure of how many times a battery can be charged and discharged before losing performance.

Batteries are usually used in a stack of connected individual cells to gain the desired voltage and capacity as shown in Figure 17.
This sets requirements for the system operating the stack because the cells need to be in balance with each other to avoid malfunctioning.

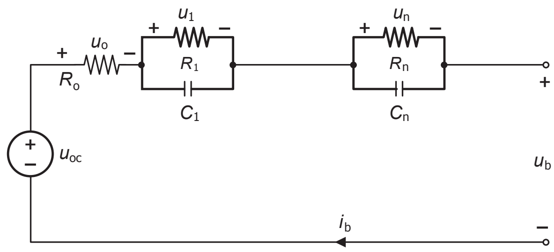
Figure 17 From a battery cell to a full energy storage device [14]



2 Direct current: generation and fault analysis

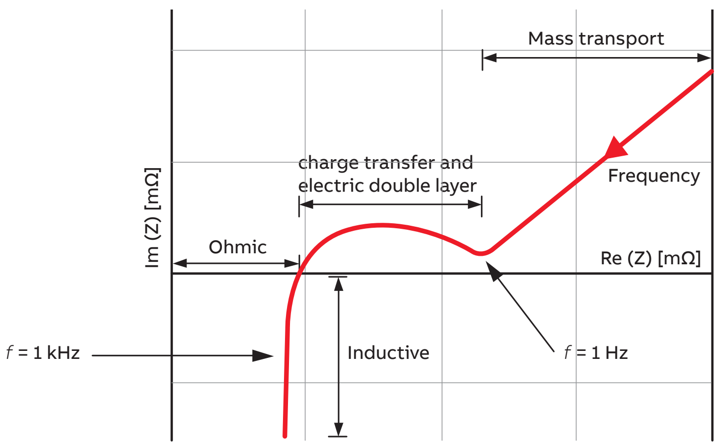
Additional information on battery types and their application in uninterrupted power supply (UPS) systems can be found in [15]. Regardless of the technology, batteries are typically modelled in the literature by a voltage source with a resistance in series, which describes the galvanic circuits in the battery. More accurate models include one or more resistance-capacitance pairs connected in series (Figure 18).
The component values of the R/C pairs are a function of several parameters such as temperature, state of charge, etc., and the number of these pairs depends on the desired dynamic accuracy.

Figure 18 Equivalent electrical model of a battery [14]



As an example, Figure 19 gives an idea of the battery's complex impedance over the frequency for a Li-ion battery. Note that the trace in the figure depends on the state of the battery. The short-circuit current peak is limited only by the ohmic resistance (and the leakage inductances) of the circuit, thus it can be very high.

Figure 19 Impedance characteristic of a Li-ion battery [14]

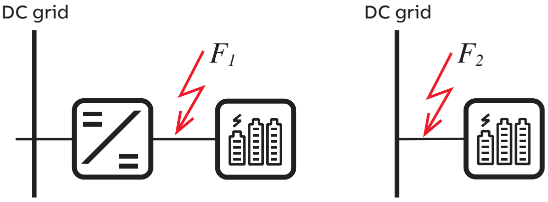


The BESS may be integrated in the power system in various configurations depending on the application. The following part describes integration to a DC grid.

- As shown in Figure 20, the battery is connected to a DC-bus through a DC/DC converter. Compared to the AC integration of batteries, DC provides a more efficient solution when the energy consumer is connected to the same DC-circuit. In this case, the DC-bus voltage is different from the battery voltage, hence the DC/DC converter. The converter matches the battery and the DC-bus voltage, controls the current for smoother operation and may come with built-in protection features like over- and under-voltage, overcurrent, etc.

- Otherwise, the battery can be connected directly to a DC-bus in the power system. In this case, it will define the voltage of the DC-bus. Consequently, all other equipment must be selected according to the voltage span of the battery (up to 25% variation). The main advantages of a converterless connection are energy efficiency and a smaller footprint as there is less hardware required. However, the disadvantage is less control over the power flow because the current flow is primarily determined by the load on the DC bus. This can lead to current fluctuations, which may be not acceptable for sensitive applications.

Figure 20 BESS integration in a DC grid



An example of the short-circuit current when a fault happens at the battery terminals (no converter involved, as the fault at location F_1 in the Figure 20) is shown in Figure 21. We can note that the fault current rises to a high value and reaches the peak in a relatively short time frame. This high current persists at steady state as well.

Figure 21 Short-circuit current in the case of three different batteries [16]

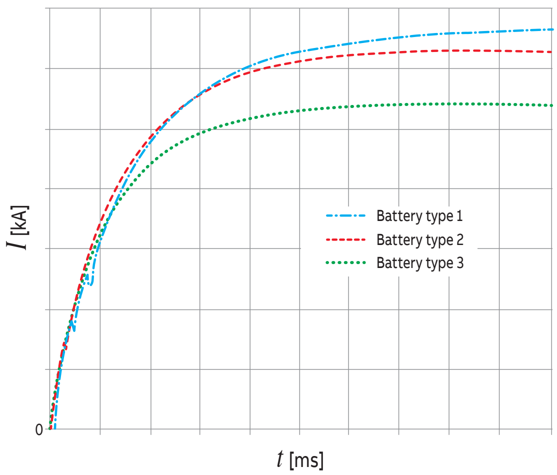
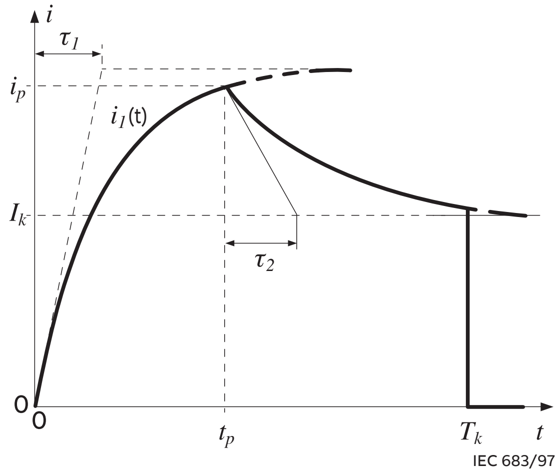


Figure 22 General approximated short-circuit current waveform [17]



2.3 Fault current in DC grids

Traditional AC systems are dominated by the inductance of all the synchronous generators, transformers and motors. On the contrary, LV DC systems nowadays include many power electronics converters, so the critical phenomenon to be considered in the case of faults is the behavior of these converters.

Initially, in this Section we will present how the short-circuit current is computed according to the existing IEC standards. Then we will analyze in depth a pole-to-pole and pole-to-earth fault in non-isolated front-end (AC/DC) converter. The last part will be dedicated to fault cases with DC/DC converters, where we will go through the buck/boost, buck-boost and dual-active bridge converters.

2.3.1 Short-circuit current calculations according to existing standards

The study of short-circuit currents is fundamental for correct design of the plant components. In fact, erroneous calculations could lead to selection of undersized protection devices at short-circuit conditions.

The evaluation of the short-circuit currents in DC installations is described in the IEC 61660-1 standard, entitled “short-circuit currents in DC auxiliary installations in power plants and substations”. Although this standard refers to auxiliary installations, it provides some insights applicable to DC grids in general.

According to IEC 61660-1, the short-circuit current from passive AC/DC rectifiers, stationary lead-acid batteries, smoothing capacitors and DC motors with independent excitation can be approximated by the function in Figure 22.

The relevant quantities in Figure 22 are:

I_k is the quasi steady-state short-circuit current (the value of the DC-side short-circuit current 1s after the fault occurrence)
i_p is the peak short-circuit current (maximum possible instantaneous value of the prospective short-circuit current)
T_k is the short-circuit duration (time between the short-circuit occurrence and the breaking of the DC short-circuit current)
t_p is the time to peak
τ_1 is the rise-time constant
τ_2 is the decay-time constant

The short-circuit current waveform in Figure 22 can be described mathematically by:

$$i(t) = \begin{cases} i_p \dfrac{1 - e^{-t/\tau_1}}{1 - e^{-t_p/\tau_1}}, 0 \le t \le t_p \\ i_p \left((1-p) e^{-(t-t_p)/\tau_2} + p \right), t_p \le t, p = I_k / i_p. \end{cases} \quad (2.7)$$

This approach gives rather conservative indications on how to compute the short-circuit current in the case of different sources. However, it does not address all the relevant aspects of active DC networks:

- Converter’s behavior in the case of a fault and their effect on the fault current.
- Distributed nature of the sources and the loads.
- Effect of all the capacitors interfacing the DC bus in the case of a fault.
- Active rectifier as an interlinking converter between the AC and the DC grid.
- Relevance of the earthing scheme and the type of fault.

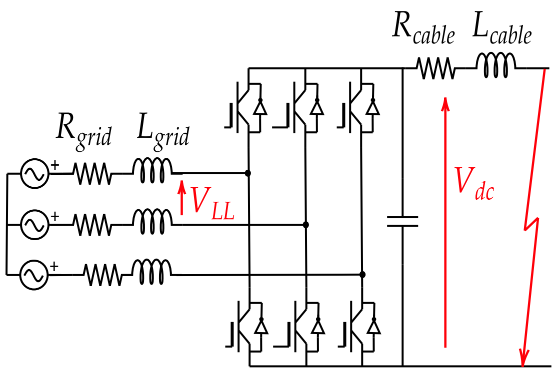
In the following, we will try to describe the short-circuit phenomenon in active DC networks, highlighting some peculiarities the designer must have in mind when choosing the suitable protection devices.

2 Direct current: generation and fault analysis

2.3.2 Pole-to-pole fault in non-isolated FEC

As an example, let us illustrate the short-circuit current waveform trend in an AC/DC Front-End Converter (FEC). For correct operation of this active non-isolated bidirectional front-end converter, V_{dc} must be larger than the peak value of the line-to-line AC voltage V_{LL} (Figure 23). In the case of a pole-to-pole fault, this condition is not met anymore.

Figure 23 Pole-to-pole fault in a non-isolated FEC



Note that R_{grid} and L_{grid} are the equivalent AC-grid parameters, while R_{cable} and L_{cable} represent the cable resistance and inductance between the converter terminals and the fault, respectively.

The fault current goes through three different stages after the fault has happened: capacitor discharge, diode freewheeling and steady state.

First stage: capacitor discharge

The first stage occurring immediately after the pole-to-pole fault is dominated by the DC filter capacitors discharge (Figure 24). It is characterized by very rapidly rising fault current and decreasing DC-bus voltage.
This stage lasts in a time range between µs and ms. As the capacitor discharges, the cable inductance, on the other hand, accumulates the released energy.

Figure 24 Fault current path during the first stage in the case of pole-to-pole fault in non-isolated FEC

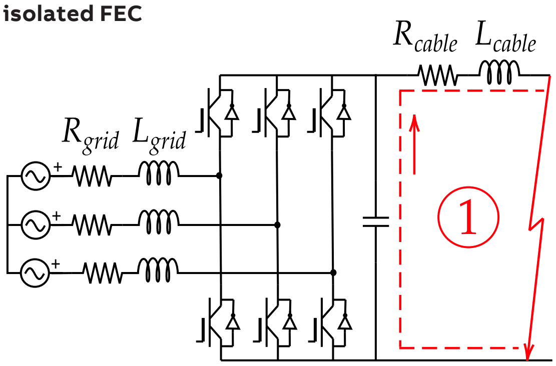
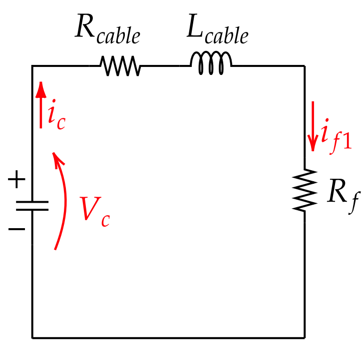


Figure 25 Equivalent circuit for the first stage in the case of pole-to-pole fault in non-isolated FEC



Depending on the application, the protection system may be required to detect, locate and clear the fault during this stage. In this way, grid stability and availability are ensured. A sudden DC-bus voltage drop to a very low value is likely to happen, hence there is a risk of the whole DC grid going out of service and a black start will be necessary. However, ensuring selectivity between the protection devices in such a short time interval is very challenging. Thus, the installation designer should evaluate and prioritize the requirements the protection system must meet at this fault stage. Typically, six-switch AC/DC converters have limited ability to withstand a fault current (IGBTs controllability, thermal ratings, etc.), usually 2-3

times the nominal current for a few tens of µs. This stage can be avoided if the converter manufacturer has already implemented a semiconductor-based protection on the DC side inside the converter.
The fault current in the time domain at this stage can be calculated from the equivalent circuit in Figure 25 and it is described as [18]:

$$i(t)=\frac{V_C(0)}{L_{cable}(s_2-s_1)}[e^{-s_1t}-e^{-s_2t}]+\frac{i_L(0)}{s_2-s_1}[-s_1e^{-s_1t}+s_2e^{-s_2t}], \quad (2.8)$$

where V_C (0) and i_L (0) are the capacitor voltage and cable current at the time instant the fault happens, respectively.
The roots of the characteristic equation are:

$$s_{1,2}=-\alpha\pm\sqrt{\alpha^2-\omega_0^2}, \quad (2.9)$$

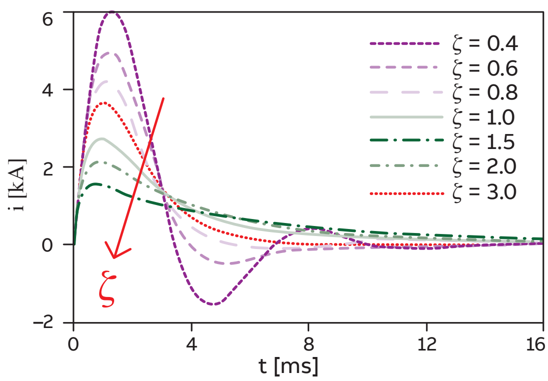
where the damping factor and the resonant frequency are:

$$\alpha=\frac{R}{2L_{cable}} \text{ and } \omega_0=\frac{1}{\sqrt{L_{cable}C_f}}, \quad (2.10)$$

where R is the total circuit resistance, including the cable, the capacitor series resistance as well as the fault resistance. Increased cable inductance means lower fault current peak value, but also reduced damping and slower transient evolution. This implies that a fault occurring closer to the converter terminals causes larger current peak with a very fast rate of rise.

Based on the relationship between the magnitudes of α^2 and ω_0^2, the fault current response can be overdamped ($\alpha^2>\omega_0^2$), critically damped ($\alpha^2=\omega_0^2$) or underdamped ($\alpha^2<\omega_0^2$), as in Figure 26.

Figure 26 Over- and underdamped fault current waveform in FEC



- Overdamped response $\alpha^2>\omega_0^2$ ($\zeta=\alpha^2/\omega_0^2>1$): the third fault stage follows directly after the first one.
- Underdamped response $\alpha^2<\omega_0^2$ ($\zeta<1$): both voltage and current have oscillating waveforms. The second stage, diode freewheeling, is unavoidable.

During the transition from stage 1 to stage 2, V_{dc} drops below the maximum AC voltage: alternation between capacitor discharge and diode conduction takes place.

Second stage: diode free-wheeling

The capacitor has discharged completely through the cable at the first stage. Its energy has been stored in the cable inductance, that starts discharging in the following time instants. There might be a significant inductive energy in the system and very low dissipative losses. The cable current commutates to the converter freewheeling diodes (Figure 27). If this stage lasts for a long time, the diodes are at high risk of damage. Therefore, it may be required to prevent from this stage by detecting and isolating the fault during the first stage.

Figure 27 Fault current path during the second stage in the case of pole-to-pole fault in non-isolated FEC

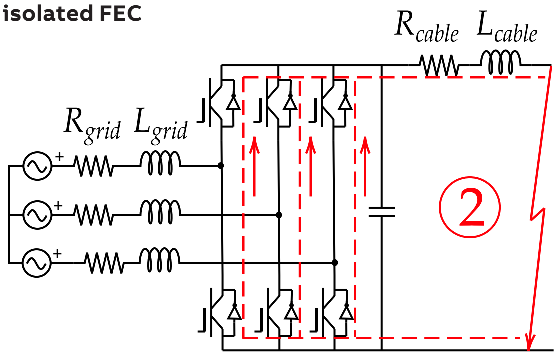
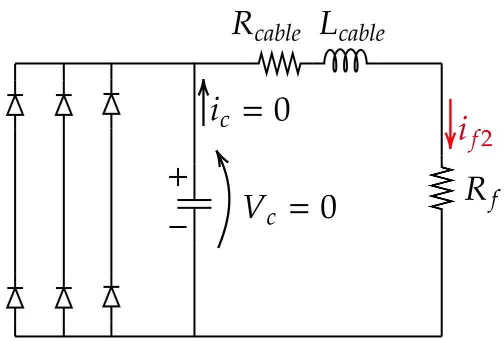


Figure 28 Equivalent circuit for the second stage in the case of pole-to-pole fault in non-isolated FEC



The fault current at this stage is computed from the equivalent circuit in Figure 28 [18]:

$$i_{cable}=I_0'e^{-(R/L_{cable})t}, \quad (2.11)$$

where I_0' is the value of the fault current at the end of stage one. The current through the converter diodes is:

$$i_{D1}=i_{cable}/3. \quad (2.12)$$

2 Direct current: generation and fault analysis

Third stage: grid-side current feeding

The final fault stage is known as grid-side current feeding, and it occurs when the fault has not been detected and cleared during the first stage.

The third stage depends on the converter topology as well: some converters, as we will see later, have the capability to limit the fault current and isolate the converter output from the input. On the other hand, some of them, like the six-switch AC/DC converter do not have this capability. This converter acts as an uncontrolled diode-bridge rectifier and the fault current is supplied by the AC grid through the freewheeling diodes (Figure 29).

The fault reaches its steady state, and the DC-bus voltage equals the product of the fault current and the fault resistance (typically low value). The equivalent fault circuit is first-order RL transient (Figure 30).

Figure 29 Fault current path during the third stage in the case of pole-to-pole fault in non-isolated FEC

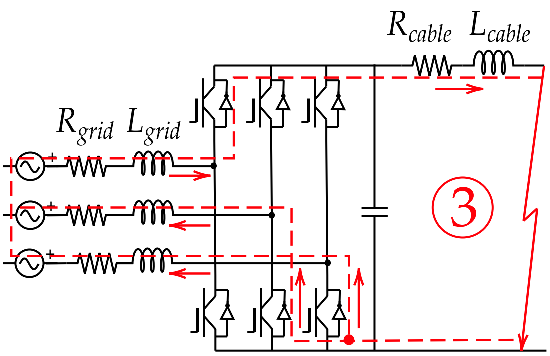
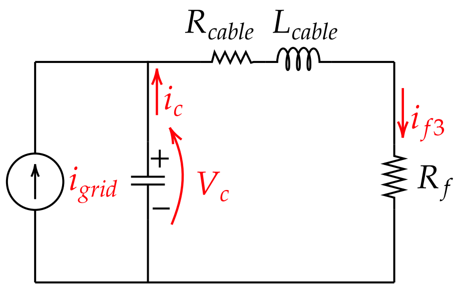


Figure 30 Fault current path during the third stage in the case of pole-to-pole fault in non-isolated FEC



The fault current in the time domain at this stage is described as [18]:

$$i_{VSC} = i_{D1} + i_{D2} + i_{D3} = i_{grid,a} + i_{grid,b} + i_{grid,c}, \quad (2.13)$$

where the positive value of the phase current passing through the diodes is [19]:

$$i_{grid,a} = I_g sin(\omega_s t + \alpha - \varphi) + I_{gn} e^{-t/\tau}, \quad (2.14)$$

where ω_s is the grid angular frequency, α is the grid voltage phase angle at the end of the previous stage. The phase angle and the time constant are:

$$\varphi = atan(\omega_s \tau) \text{ and } \tau = \frac{L_{grid} + L_{cable}}{R_{grid} + R_{cable} + R_f}, \quad (2.15)$$

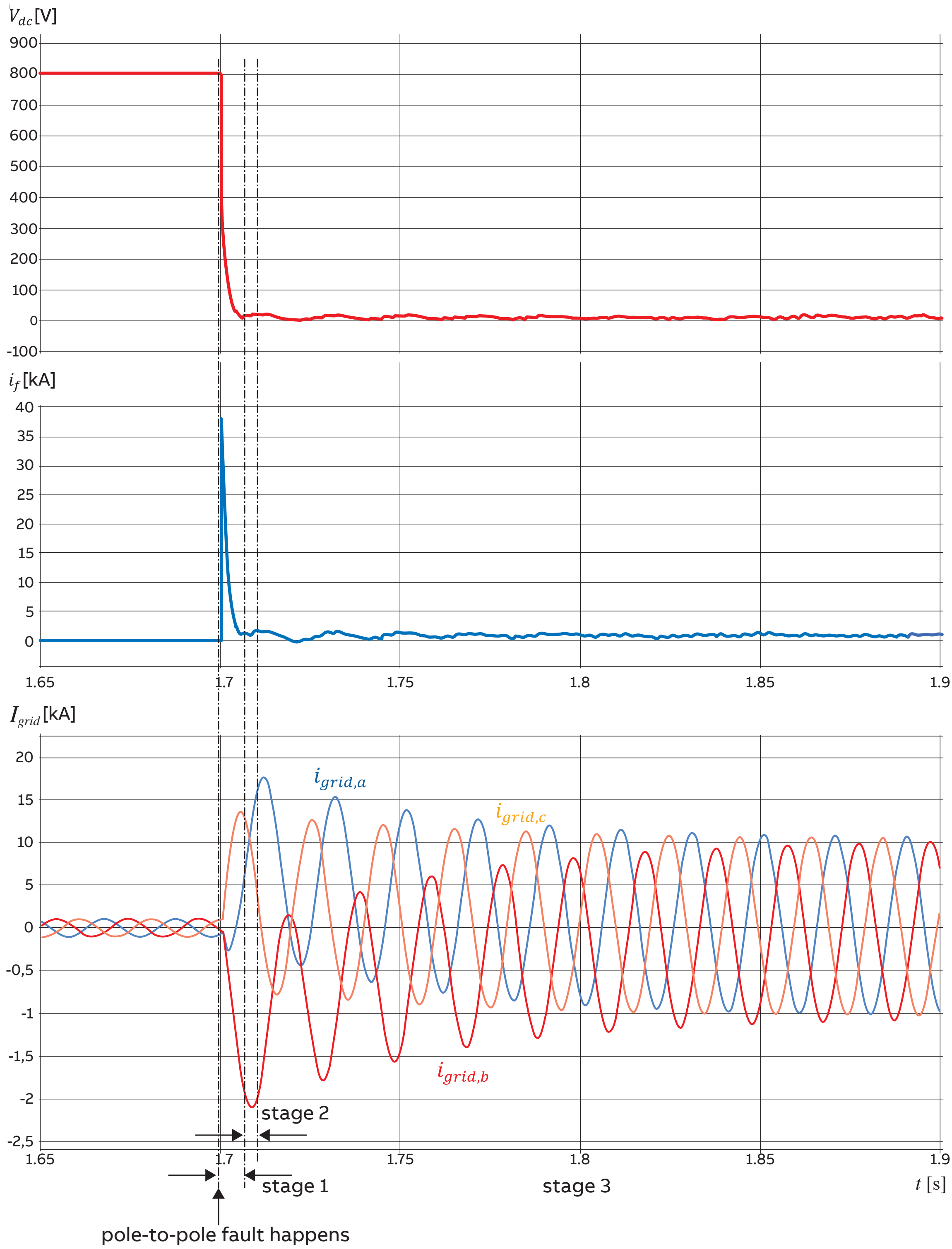
the grid current is:

$$I_{gn} = I_g(0) sin(\alpha - \varphi_0) - I_g sin(\alpha - \varphi), \quad (2.16)$$

where I_g (0) and φ_0 are the initial grid current amplitude and phase angle.

An example of the fault current , the DC-bus voltage and AC-side grid current waveforms is shown in Figure 31:

Figure 31 Current and voltage waveforms in the case of a pole-to-pole fault in FEC



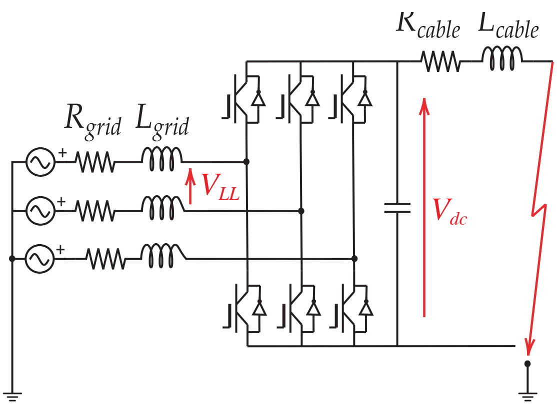
2 Direct current: generation and fault analysis

2.3.3 Pole-to-earth fault in non-isolated FEC

The fault analysis in the case of non-isolated front-end converter depends strongly on the type of earthing on both the AC and DC side of the system. More details on this topic are available in the Chapter 6.

Let us consider here an example of a pole-to-earth fault when the secondary of the AC-side transformer is connected to earth, as in the Figure 32.

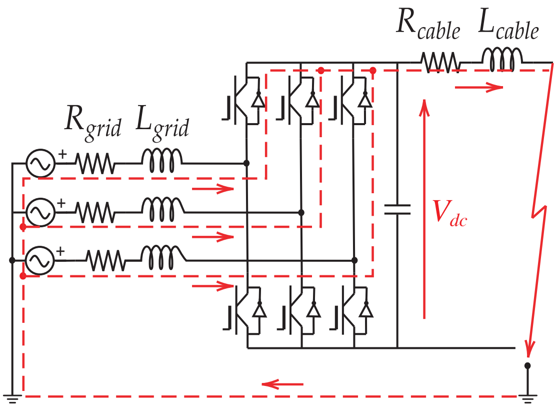
Figure 32 Pole-to-ground fault in a FEC with earthed AC-side transformer



The fault analysis methodology is the same as we showed for the case of a pole-to-pole fault. However, the fault current path is slightly different at steady state.

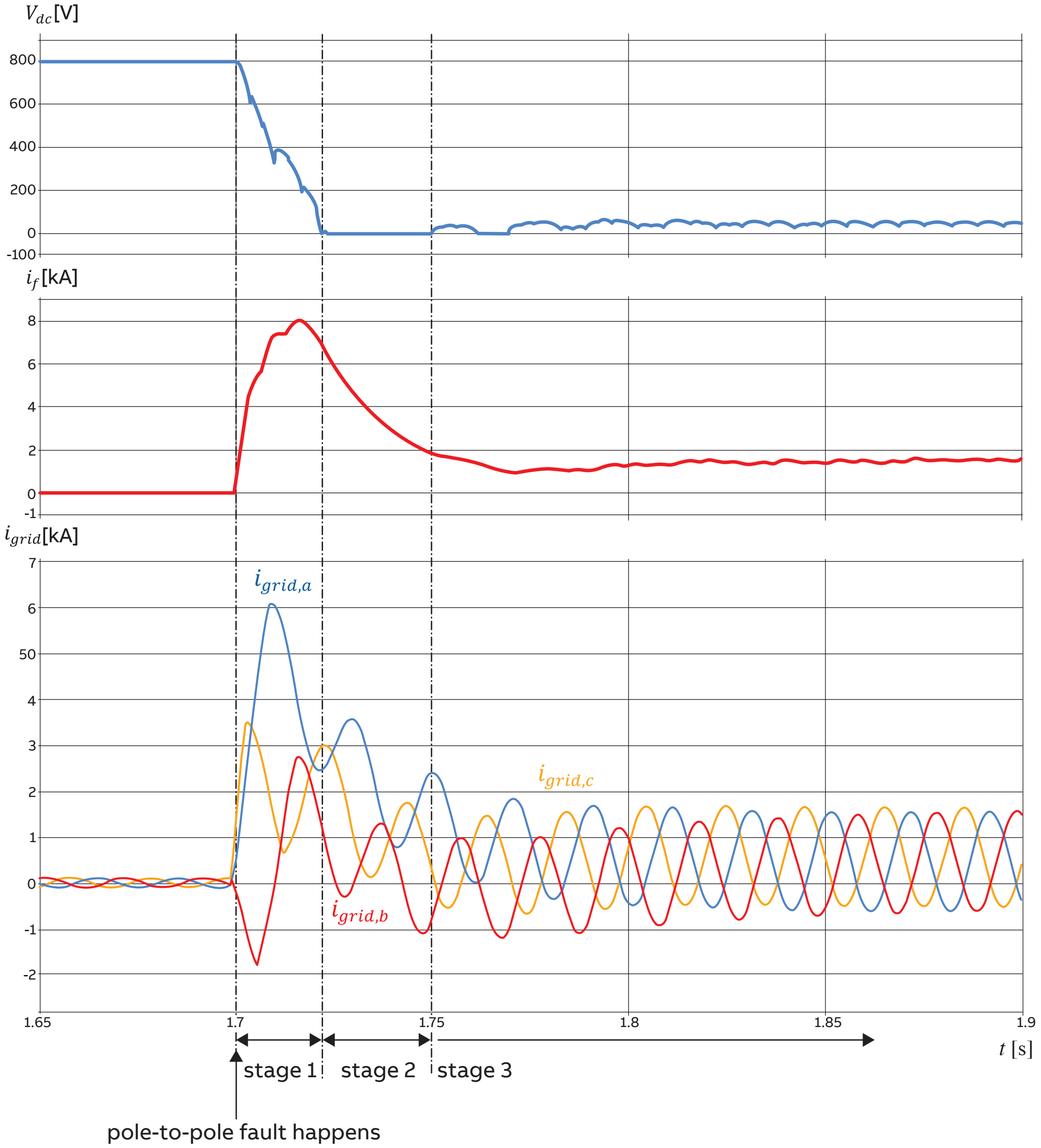
Based on whether the positive or the negative polarity conductor is faulted, different group of diodes will conduct during the third stage.
In our example, the fault at steady state affects only the diodes connected to the upper (cathodic) star, as we can see in the Figure 33.

Figure 33 Steady-state fault current with pole-to-earth fault in FEC



The waveforms of the DC-bus voltage, fault current and AC-grid currents are illustrated in the Figure 34. We can see that all the three stages described previously are present, and the diode-freewheeling lasts longer than in the case of a pole-to-pole fault.

Figure 34 Voltage and current waveforms in the case of a pole-to-earth fault in FEC



Compared to the pole-to-pole fault on the same converter topology (Figure 31 versus Figure 34), we can notice the peak fault current in the pole-to-earth case is much lower because of the higher impedance in the fault path.

The diode-freewheeling stage lasts longer; hence the DC-bus voltage remains zero during this interval as the fault current decreases, discharging the inductances.

In any case, an earth fault creates a loop with the grounding points and the converter will eventually operate as uncontrolled diode-bridge rectifier. The ground resistance cannot be ignored because it usually varies from less than 1Ω to hundreds of ohms.
Additional scenarios of faults in LVDC networks engaging a non-isolated FEC, with detailed simulation results, can be found in [20].

2 Direct current: generation and fault analysis

2.3.4 Pole-to-pole fault with a DC/DC converter

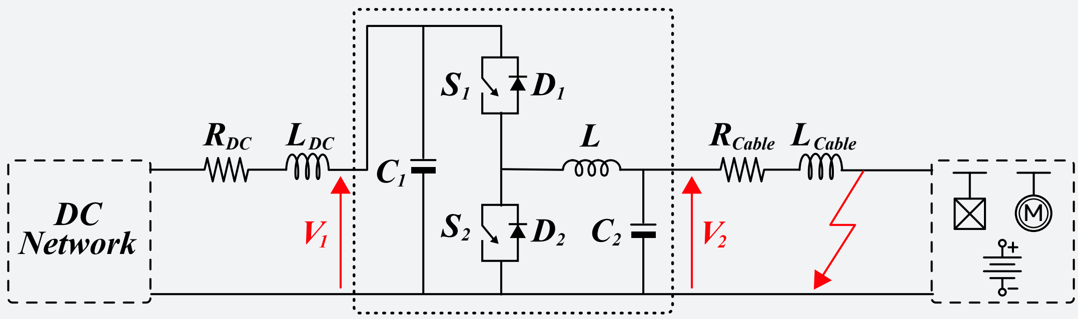
The behavior of DC/DC converters in the case of a fault depends mainly on the converter topology, but also on the capacitors employed, grid parameters, control strategy, etc. In this section, we will analyze some of the basic configurations to highlight their differences.
Let us first clarify the nomenclature related to the DC/DC converter topologies:

- Buck (step-down) converter reduces, i.e., steps down the input voltage to a lower output voltage.
- Boost (step-up) converter increases, i.e., steps up the input voltage to a higher output voltage.
- Buck/Boost converter can operate in either buck or boost mode, but not simultaneously in the same circuit. It is always the same converter side that has a higher voltage than the other converter side.
- Buck-Boost converter can simultaneously step up or step down the voltage. It inherently allows for both functionalities in one circuit design, producing output voltage that can be either higher or lower than the input voltage.

2.3.4.1 Buck/boost converter

Let us consider a buck/boost converter, as in Figure 35.
This converter consists of two controlled switches, so the power can flow in both directions. In any case, $V_1 > V_2$.

Figure 35 Buck/boost converter with a fault on the LV side



Assuming a fault occurs on the low-voltage side, the discharge of the capacitor C_2 is likely to happen in the few microseconds after the fault.
The energy accumulated in the capacitor is discharged to the cable inductance L_{cable}.
If the voltage falls below zero, the diode free-wheeling stage follows (stage 2) and the diode D_2 starts conducting the fault current.

In the second stage, the converter inductance L counteracts the reverse current buildup, thus the current flowing through the diode D_2 will be much lower than the initial fault current.
We can observe the different fault current path in the two stages in the Figure 36.

Immediately after the fault happens, it gets supplied by the DC network as well, for example through the switch S_1, as shown in the Figure 37.
Considering that this current is much higher than the nominal one, the control system of the converter will detect it as an overcurrent and act accordingly. It can continue supplying the fault with a limited current, e.g., two times the nominal one for a few milliseconds, so that the protection device downstream interrupts the fault current.
On the other hand, the control system can decide to turn off both switches S_1 and S_2, in a time interval of hundreds of nanoseconds to a few microseconds, so that the converter does not supply the fault any longer.

Figure 36 Fault current paths during stages 1 and 2 in a buck/boost converter

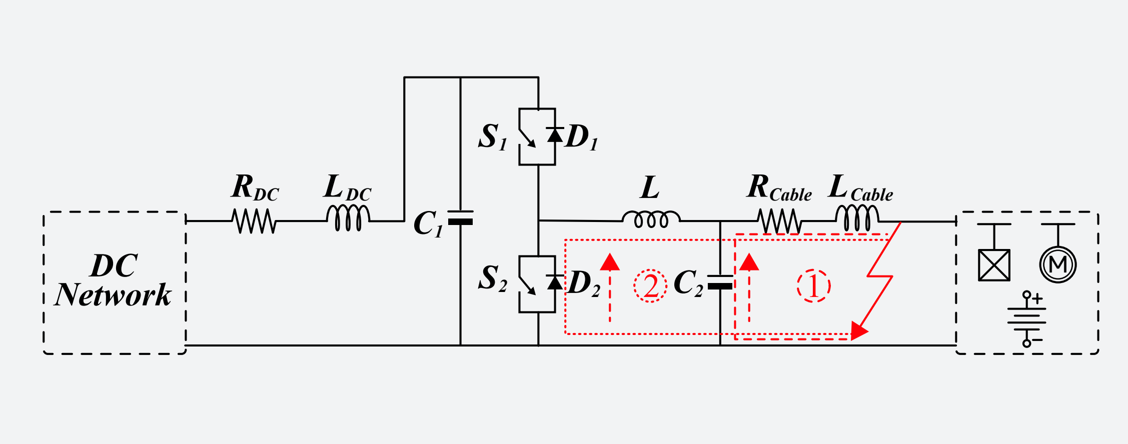
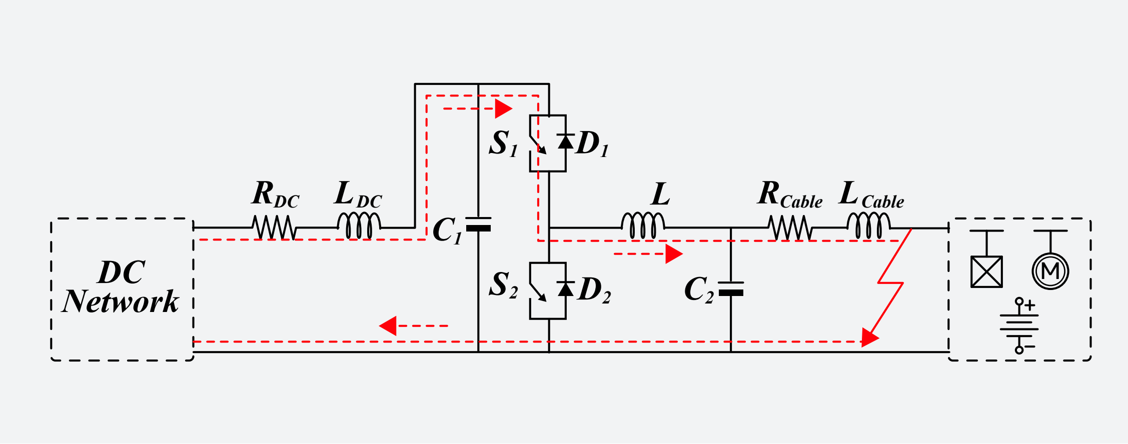


Figure 37 Fault current path when the DC grid supplies the LV-side fault in a buck/boost converter



2 Direct current: generation and fault analysis

Let us analyze the same converter when fault happens on the high-voltage side, as in the Figure 38.

In this case, the capacitor C_1 discharges at the first stage and, if the voltage falls below zero, both diodes D_1 and D_2 enter in conduction mode. The source will continuously supply the fault as well (stage 3) because even if the control system turns off both switches S_1 and S_2, the current will flow through the diode D_1.

We can distinguish the fault current path in the three stages as in the Figure 39.

In the Figure 40, we can observe the fault currents on either side of the converter. We have assumed rated power of 30kW, with 210V on the LV side and 700V on the HV side at rated conditions. When a fault occurs on the LV side (as in the Figure 35), after the capacitor discharge resulting in a high peak current, the converter control system limits successfully the fault current to $2I_n$ for 10ms (Figure 40a). When the converter stops operating after this time, the fault current decreases to zero.

On the other hand, when a fault occurs on the HV side (as in the Figure 38), even though the converter control system tries to limit the current to $2I_n$, we can see that this is not successful: the DC grid supplies a fault current of about 1kA at steady state (Figure 40b).

We understand now that the buck/boost converter can limit the fault current when it happens on the low-voltage side. If the fault occurs on the high-voltage side instead, the source will keep supplying it, as the converter cannot limit the fault current because of its configuration.

Figure 38 Buck/boost converter with a fault on the HV side

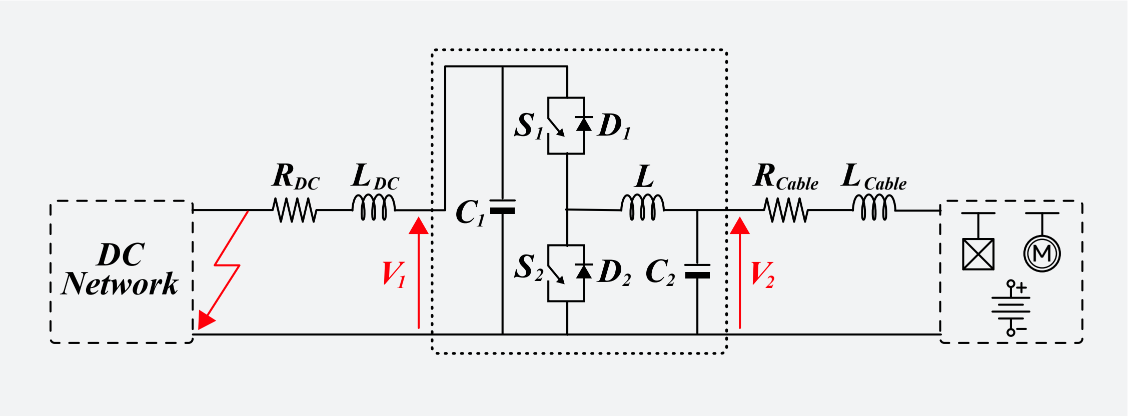


Figure 39 Fault current paths during stages 1, 2 and 3 in a buck/boost converter

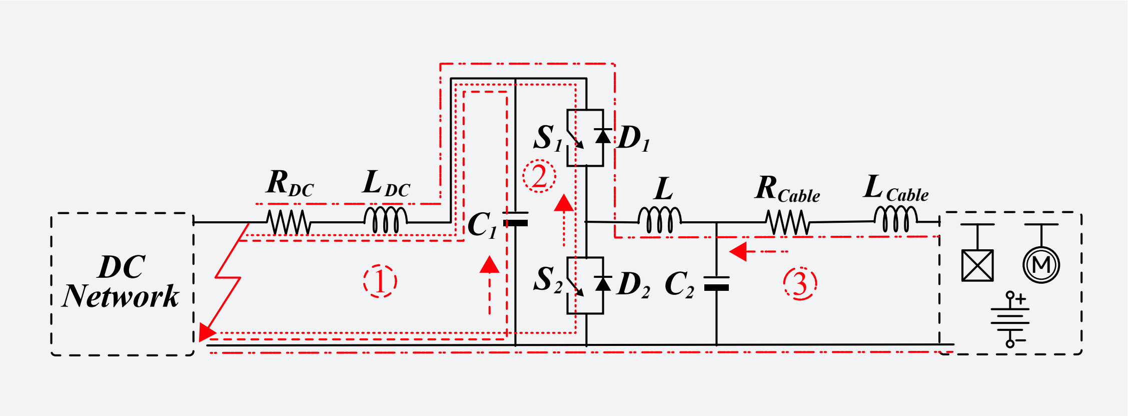
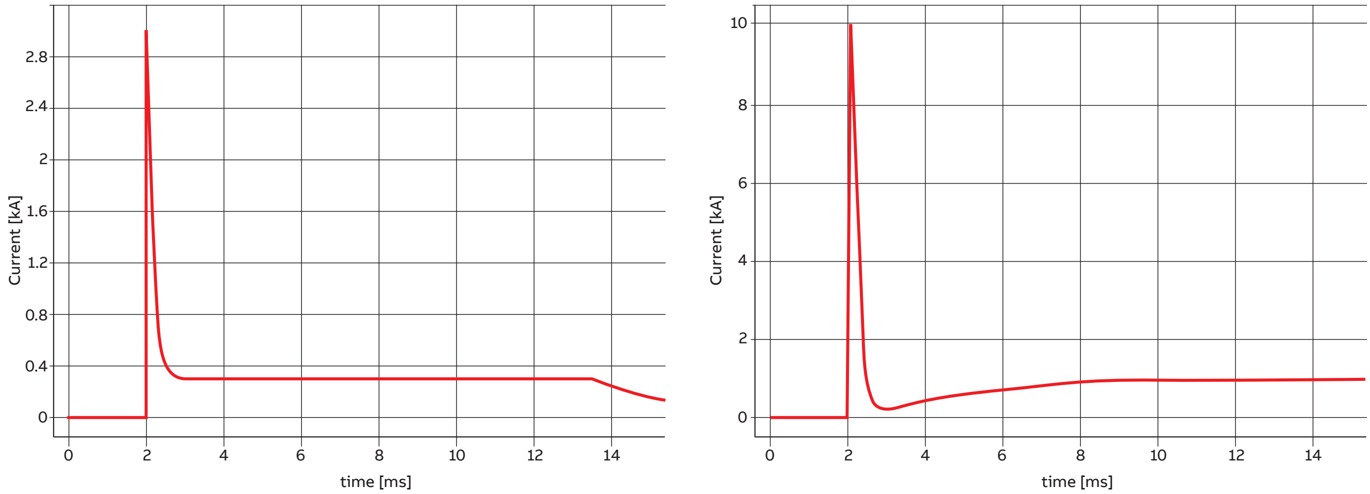


Figure 40 Fault currents in a buck/boost converter, when the fault happens on the LV side a) and HV side b)



2.3.4.2 Buck-boost converter

Another commonly used topology is the one shown in the Figure 41, i.e., a buck-boost converter. It means that this converter can operate as both step-up and step-down in both directions , i.e., the voltage V_1 can be higher or lower than the voltage V_2.

Note the difference with the buck/boost converter, where V_1 is always higher than V_2, regardless of the power flow direction. Let us consider a fault happening on the load side, as indicated in the Figure 41.

Initially, the capacitor C_2 discharges and if the voltage falls below zero, the diodes D_3 and D_4 start conducting (Figure 42).

The DC network initially supplies the fault, for example, through the switch S_1 and the diode D_3 as in the Figure 43. When the control system detects such a high overcurrent, it may decide to limit it to a few times the nominal current, or it may turn off all the switches. In both cases, this converter can limit the fault current inherently because of its topology.

Similar analysis can be done for a fault on the DC microgrid side.

The results will be the same because the converter is symmetrical: it can inherently limit a fault happening on both microgrid and source/load side.

Figure 41 Buck-boost converter with a fault on the load side

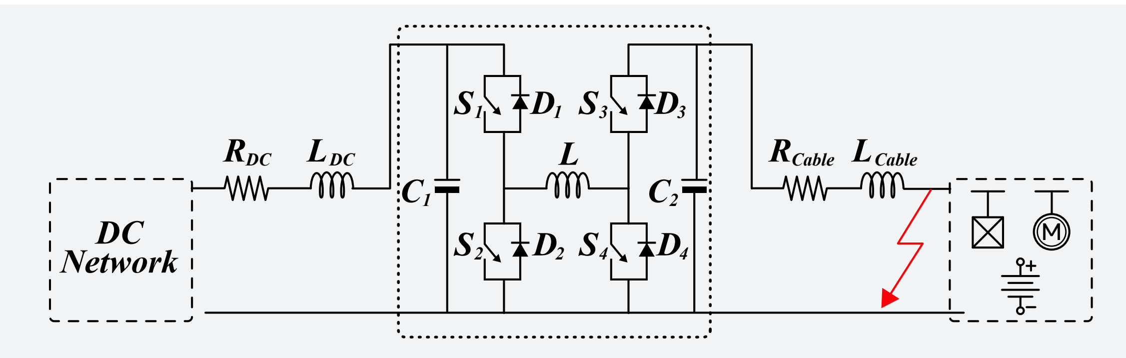
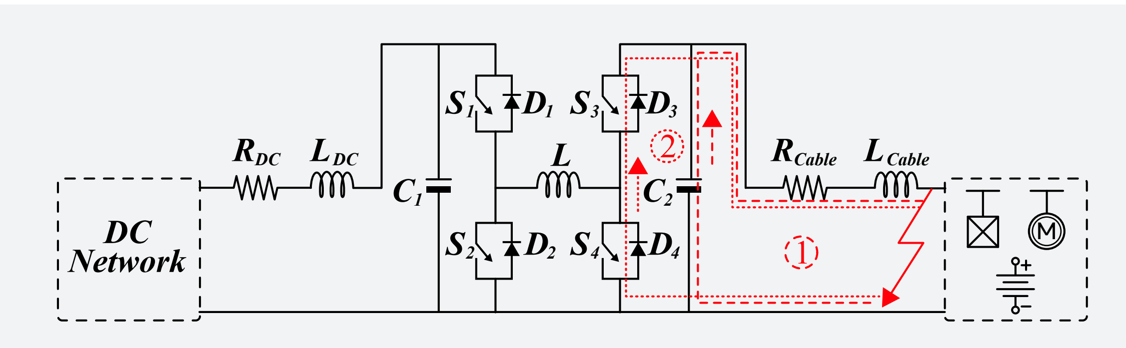
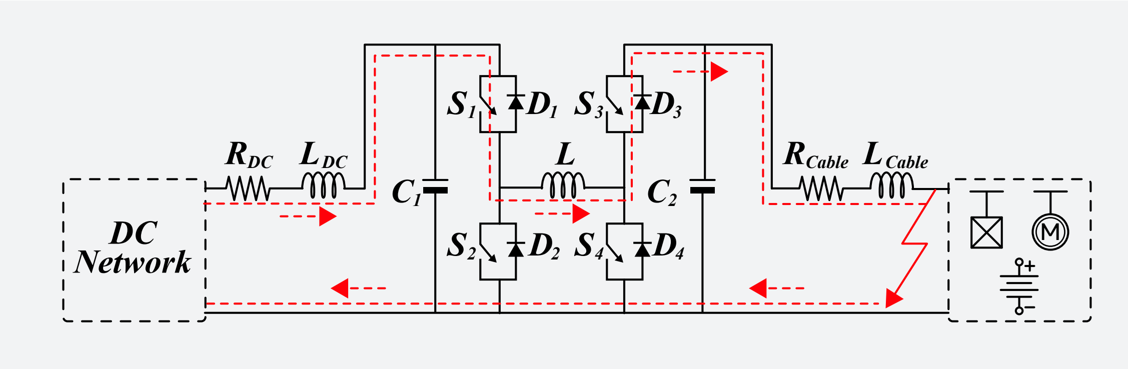


Figure 42 Fault current paths during stages 1 and 2 in a buck-boost converter



2 Direct current: generation and fault analysis

Figure 43 Fault current path when the DC grid supplies the load-side fault in a buck-boost converter



2.3.4.3 Dual-Active Bridge (DAB)

Let us now consider a dual-active bridge (Figure 44). Again, this is a symmetrical bidirectional converter, thus the side on which the fault happens is irrelevant for the analysis. The main difference with the buck-boost converter is that the DAB provides galvanic isolation between the input and the output.

The capacitor discharge and the diode free-wheeling stages are shown in the Figure 45. The former one concerns the capacitor C_2, the cable (R_{cable} and L_{cable}) and the load. In the latter one, the fault current flows through the diodes D_5 - D_8, and again through the cable and the load. In the same way as for the buck-boost converter, when an overcurrent flows through the semiconductors, the control system turns them off or continues operating at limited current value. Therefore, the DAB can inherently limit the fault current.

In conclusion, the DC/DC converter topology affects significantly the converter's behavior in the case of a fault. Simple buck and boost converters can limit fault currents only on the low-voltage side. Galvanically isolated topologies can limit fault currents on both sides.

To avoid output capacitor discharge, pseudo-buck stage, i.e., half-bridge not actively used, could be added in many converter-based systems, which can limit the fault current.

Converter components choice and system parameters are of paramount importance in fault scenarios. For example, if the capacitor discharging immediately after the fault has low accumulated energy, which is typically the case with small filter capacitors, the fault current peak is rather limited. Otherwise, if it is a DC-bus capacitor with significant energy accumulated, the peak current is very high.

Figure 44 Dual-active bridge converter with a fault on the load side

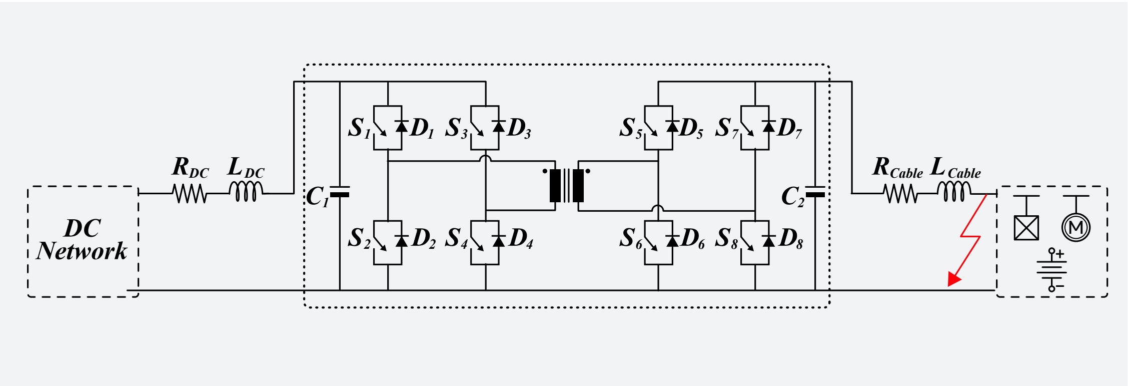
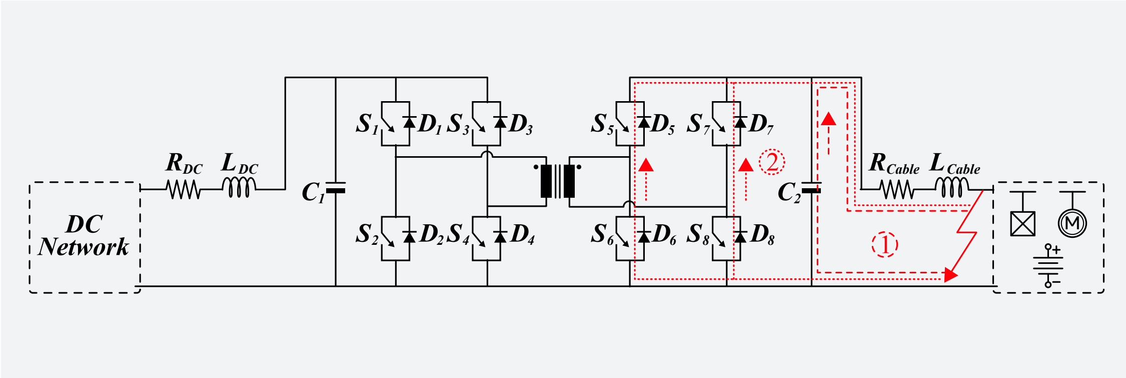


Figure 45 Fault current paths during stages 1 and 2 in a dual-active bridge converter



2.3.5 Characteristics of the fault current in DC networks

As we have seen in the previous Sections, the DC fault current has two distinguished characteristics compared to the AC fault current:

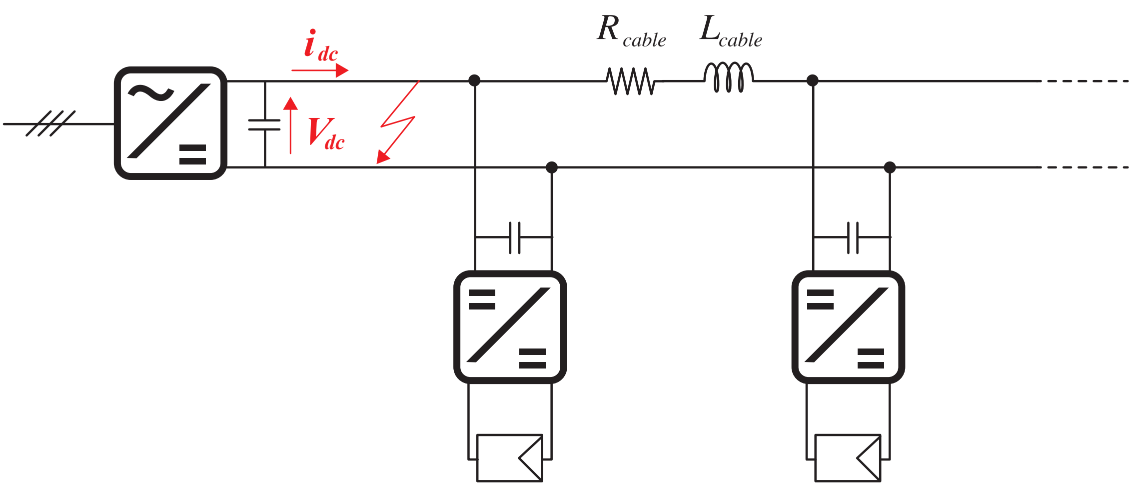
- There are no consistent 50Hz zero-crossings in DC fault currents, and
- The fault current rising slope is much faster than AC fault currents, especially due to DC capacitors and batteries present in the network.

The main challenges to protect an active DC grid are:

- **Low system energy**: faults in DC system are dominated by capacitor discharge, which can be very fast and results in high peak current with a very short duration (in order of µs). Nevertheless, the energy stored in the capacitor is limited and traditional circuit breakers or fuses may not be activated.
- **DC fault current rate rise**: because of the very little inductance in the DC system, the rate of rise *di/dt* of the fault current is very high. Consequently, the fault current reaches high peak value (could be tens of kA) in just a few µs.
- **Undervoltage**: the high fault current and the little energy stored in the capacitor cause fast drop of the DC-bus voltage. If the voltage drops below the system's minimum value, the grid goes out of stability and a blackout is likely to happen.
- **Bidirectional power flow**: given the decentralization of the sources and loads, identifying the flow of the fault current and all the sources that contribute is not straightforward. Therefore, bidirectional protection becomes a must.

All these aspects are illustrated through the example network in Figure 46.

Figure 46 An example of a DC grid consisting of several PV sources



2 Direct current: generation and fault analysis

As we can see in Figure 47, the fault current reaches 10kA in about 100µs. The DC-bus voltage drops down to zero and even decreases further to a few volts below zero. After about 350ms, the fault reaches a steady state, characterized by 4V on the DC bus and 750A fault current. Both these waveforms imply that the front-end converter has lost its controllability, i.e., its switches cannot be controlled anymore, and behaves like a diode -bridge rectifier.

For a fault occurring at short distance downstream a converter, the fault current is dominated by the discharge of the capacitors in that converter. As the fault inductance is very low, the current waveform exhibits a narrow peak, with rate of rise (di/dt) that can be in the order of tens A/µs and peak value up to hundreds of times the nominal current, whereas the voltage collapses in a time that can be as short as a few tens of µs.

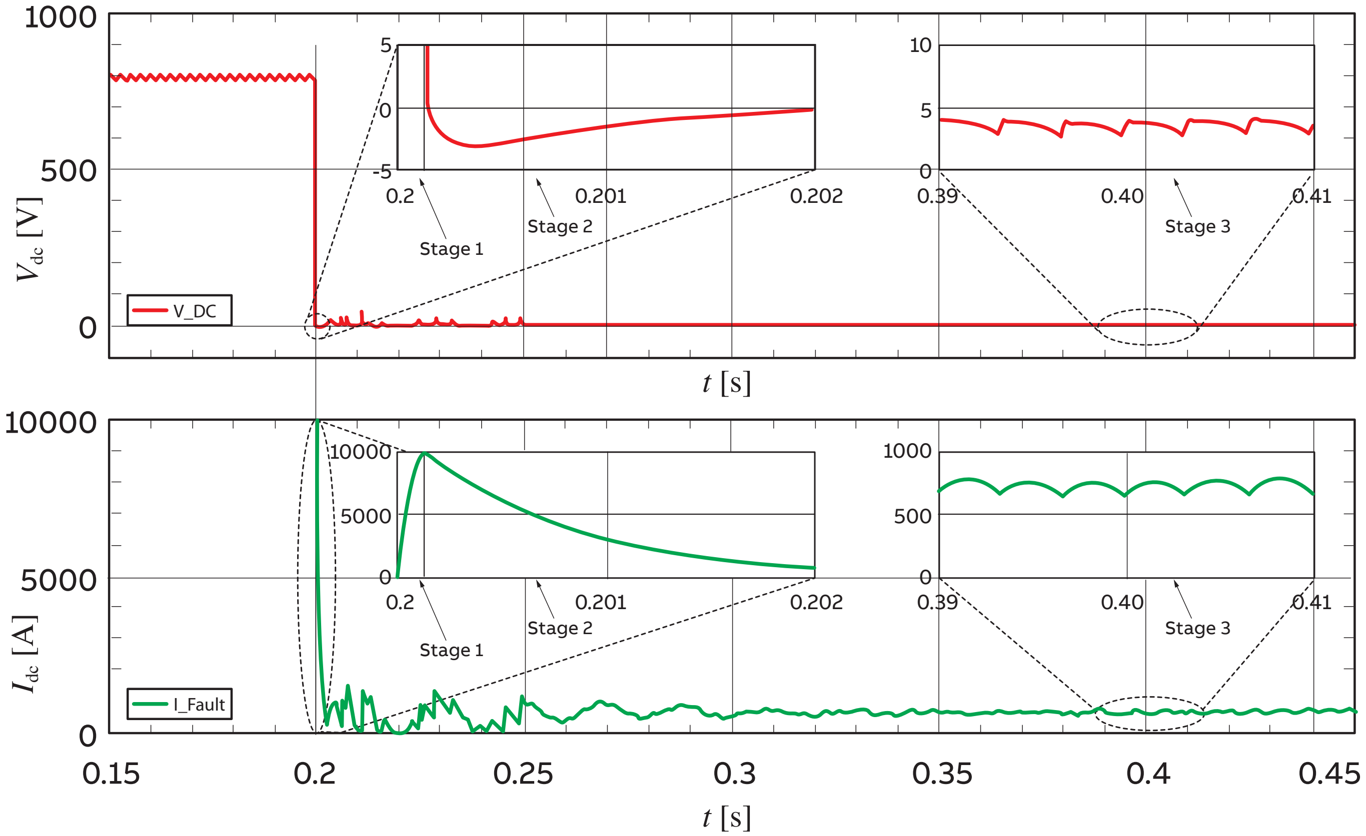
Therefore, the main requirements for active DC network protection are:

- Low fault energy threshold,
- Fast fault detection,
- Fast fault interruption
- Bidirectional fault protection.

The current derivative di/dt and the time to fault peak t_{peak} are crucial to define the required interruption time.
Some of the critical points in choosing suitable protection in DC systems are:

- Because of non-zero crossing in DC fault currents, traditional electromagnetic AC circuit breakers cannot be directly employed in DC systems.
- Converter-based networks have capacitive output filters whose fault energy must be accounted for in the protection design.
- Ensuring selectivity is challenging because of the different switching technologies available for protection, as we will explain in Chapter 6.

Figure 47 DC-bus voltage and current waveforms in the case of a fault downstream the FEC in Figure 46

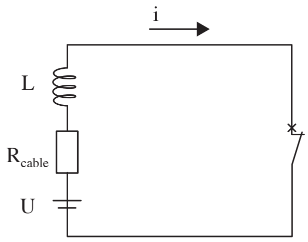


2.3.6 Direct current interruption methods

There are several methods that can be used for direct current interruption.
In the Table 2.1, we are showing a summary of the DC interruption methods and inviting the interested readers to check [21] for details.
In the following chapters of this document, we will explain in depth the conventional interruption and he semiconductor technology, as the most commonly used methods nowadays.

Table 2.1 Circuits for direct current interruption

<table>
<tr><th>Method for DC current interruption</th><th>Characteristics</th></tr>
<tr><td>Conventional interruption with direct suppression



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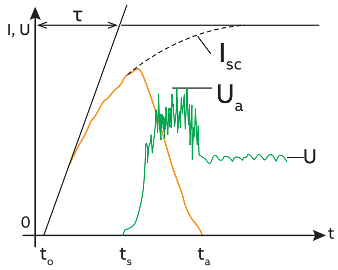
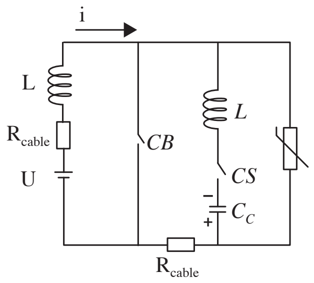
- When the circuit breaker opens, an arc is created at voltage U_a.
- The interruption is successful only if $U_a > U$ and if the circuit breaker can support energy W_a, which can be about 1.5 times higher than the initial energy.



t_0 – the fault happens
t_S – circuit breaker contacts start separating
t_a – the current is extinguished
τ = L/R – time constant
</td></tr>
<tr><td>Interruption with injected current



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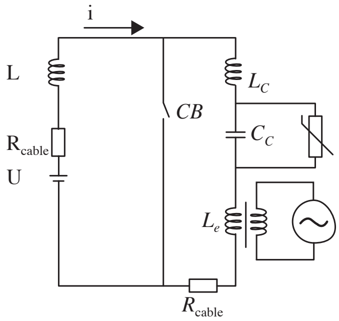
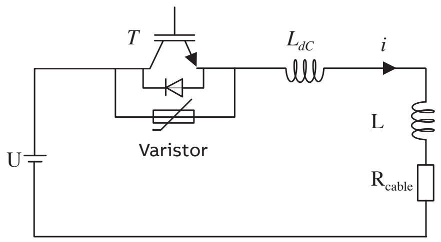
- An $L_c C_c$ circuit with a switch CS is conected in parallel to the main circuit breaker's contacts CB.
- The CS switch is operated at the $L_c C_c$ resonant frequency. This generates an AC current that is injected in the CB branch and superposed to the DC current.
- Now the current flowing through the main circuit breaker CB contains an AC component and it can be easily interrupted at its zero crossing.
</td></tr>
<tr><td>**Interruption with forced oscillation**



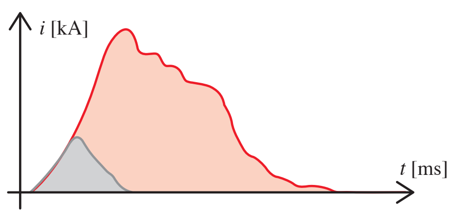
</td><td>

- Forced oscillations are generated by an external source.
- These oscillations overlap the DC current that needs to be interrupted, forcing it to cross the zero.
- The external voltage source amplitude should be high and the oscillation frequency relatively low.
</td></tr>
<tr><td>Interruption with semiconductor technology



</td><td>

- It interrupts the fault current without waiting / forcing it to cross the zero.
- The absence of mechanical parts makes it very fast
- A disconnector must be connected in series to ensure galvanic isolation.
- The let-through energy (gray area) is much lower than the case with traditional circuit breakers (red area).



</td></tr>
</table>

3 Earthing schemes

Important aspects when designing the protection system for a DC network are the type of distribution and the earthing scheme. We will discuss these topics in the following pages, assuming the DC side is galvanically isolated from the AC side and the front-end converter provides ideal constant voltage V_{dc}.

3.1 Unipolar vs bipolar distribution

Unipolar systems (Figure 49) have one line normally operating at DC positive or negative voltage in relation to earth. In this configuration, the mid-point conductor M is typically earthed (Figure 50) and only one voltage level, i.e., V_{dc}, is available.

Figure 49 Unipolar DC systems with positive polarity a) and negative polarity b) voltage

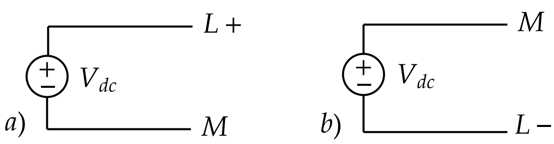
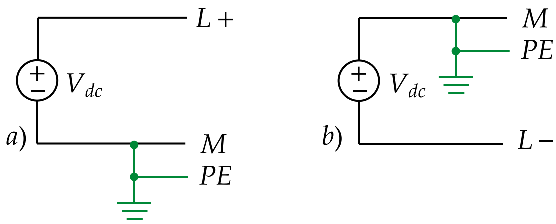


Figure 50 Earthing of unipolar DC systems with positive polarity a) and negative polarity b) voltage



Bipolar systems (Figure 51) have two lines normally operating at DC voltages of opposite polarity in relation to earth. In this configuration, the mid-point conductor M can be distributed along the network or not, and in each case, it can be connected to or isolated from earth (Figure 52).

Figure 51 Bipolar DC system without distributed mid-point a) and with distributed mid-point b)

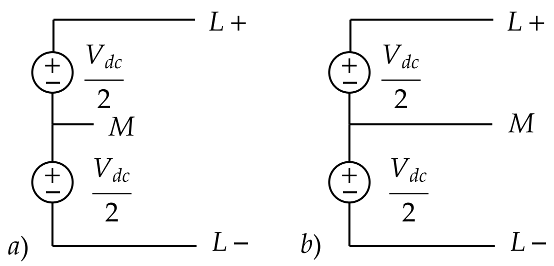
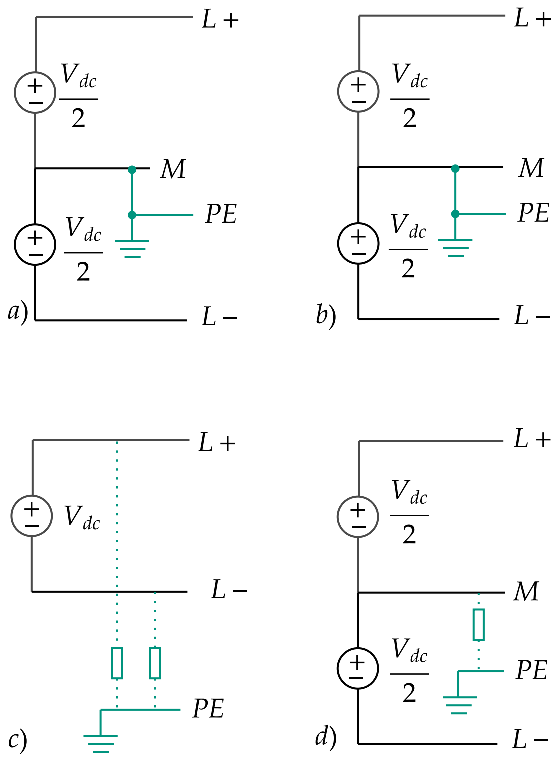


Figure 52 Bipolar DC system: mid-point earthed but not distributed a), mid-point earthed and distributed b), no mid-point c), mid-point not earthed but distributed d)



In principle, loads in bipolar systems can be connected either between the positive or the negative polarity and the mid-point if available (hence, at $V_{dc}/2$ voltage level) or between the two polarities (hence, at V_{dc} voltage level).

In any case, the implementation of bipolar distribution is more complex because the voltages between each polarity and the mid-point may not be always the same: in this case circulating currents will flow and a suitable balancing circuit is required.

In the following, we will describe the types of faults for each network topology and evaluate their severity. We will analyze both pole-to-pole and pole-to-earth faults.

3.2 DC grid with one polarity earthed

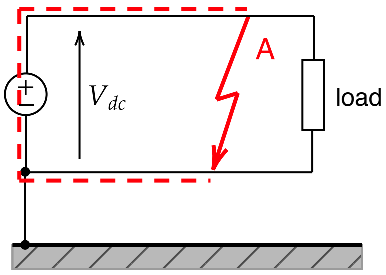
This topology is obtained by connecting one polarity to earth. Either the positive or the negative polarity can be earthed, and in both cases leakage currents will be introduced, which may result in corrosion issues.

This network allows static electricity overvoltages to be discharged to earth.

In the following examples, the negative polarity is earthed.

3.2.1 Pole-to-pole fault

Figure 53 Pole-to-pole fault in a DC grid with one earthed polarity

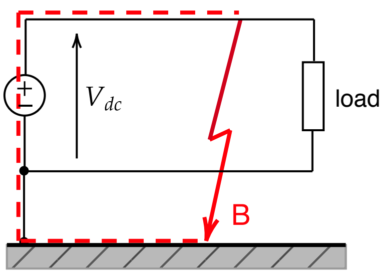


The fault between the two polarities , as for example in the Figure 53, is a short-circuit fed by the full voltage V_{dc}. In this network, the circuit breaker may be chosen to protect only the positive polarity or both polarities. In any case, the breaking capacity of each protected pole must be higher than the maximum short-circuit current at V_{dc}.

3.2.2 Pole-to-earth fault

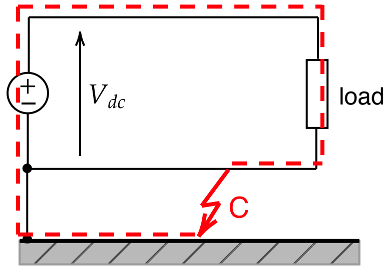
In the case of a pole-to-earth fault on the non--earthed polarity in this network, the fault current flows through the soil and its maximum occurs at the full DC-supply voltage V_{dc}. It is difficult to assess the fault current value because it depends on the soil impedance. Therefore, it is necessary to connect in series all the poles of the circuit breaker on the non--earthed polarity.

Figure 54 Fault between the non-earthed polarity and earth in a DC grid with one earthed polarity



A fault on the earthed polarity instead, as for example in the Figure 55, might seem harmless for the system at a first glance. However, it poses a fire risk and should be protected by a Residual Current Device (RCD). The value of the fault current depends on the soil impedance and, moreover, the supply voltage is almost zero. Additionally, there is a voltage drop on the connected loads, leading to extremely low value of the fault current.

Figure 55 Fault between the earthed polarity and earth in a DC grid with one earthed polarity



In a network with one polarity earthed, double fault is not possible if an RCD is present: the protection device trips on the first fault. Without an RCD, the first fault on the earthed polarity remains undetected until a double fault happens.

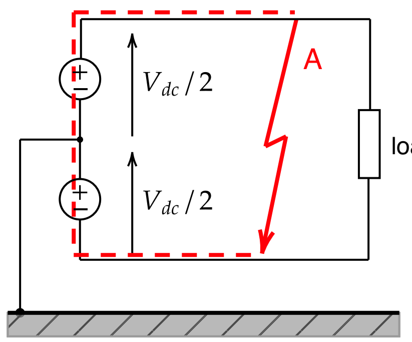
The worst-case scenario for this network type is fault A (pole-to-pole), which directly affects the circuit breaker choice and its poles connection. However, fault B (non-earthed pole-to-earth) must be considered as well.

3.3 DC grid with earthed mid-point

This network topology is created by connecting the mid-point of the DC supply to earth. The mid-point conductor can be distributed along the network or not: it does not affect the requirements on the protection device.
The main disadvantage of this connection type is that a fault between a polarity (regardless of whether it is the positive or the negative) and earth gives rise to a fault current at a voltage V_{dc}/2. This type of network reduces the static overvoltages, which could, for example, be present at full voltage in an isolated network.
Let us look at the possible faults in a network with earthed mid-point.

3.3.1 Pole-to-pole fault

Figure 56 Pole-to-pole fault in a DC grid with earthed mid-point



3 Earthing schemes

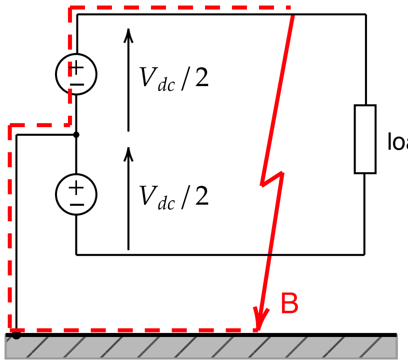
The pole-to-pole fault in this configuration is a short-circuit fed by the full voltage V_{dc}. Both polarities are affected by the fault. The breaking capacity of the circuit breaker should be chosen according to the relevant maximum short-circuit current I_{sc}. In any way, the circuit breaker must be inserted on both polarities and all the poles of the breaker must be able to withstand I_{sc} at the full supply voltage V_{dc}.

3.3.2 Pole-to-earth fault

The fault between a polarity and earth, like the one in the Figure 57, causes a short-circuit current fed by only half the DC voltage $V_{dc}/2$. It means this current has lower value than the pole-to-pole fault and it depends on the soil impedance only.

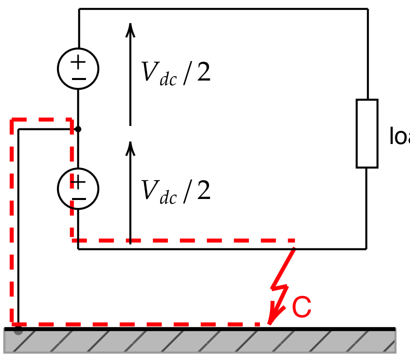
If the fault happens between the positive polarity and earth, only the positive polarity is concerned, and all the poles of the circuit breaker must withstand I_{sc} at $V_{dc}/2$.

Figure 57 Positive pole-to-earth fault in a DC grid with earthed mid-point



In a similar way, when a fault occurs between the negative polarity and earth as in the Figure 58, only the negative polarity is concerned. Again, the circuit breaker used on this polarity must withstand I_{sc} at $V_{dc}/2$.

Figure 58 Negative pole-to-earth fault in a DC grid with earthed mid-point



In any case, double fault in a mid-point earthed network is not possible because the breaker will trip on the first fault.

When the mid-point is earthed, the most dangerous situation is a pole-to-pole fault (A). However, also a pole-to earth fault will cause short-circuit current flowing through the network and must be accounted for.
The circuit breaker must be inserted on both polarities.

3.4 Isolated DC grid

When the DC system is isolated from earth, the installation is relatively easy and service continuity is guaranteed, as we will explain later.

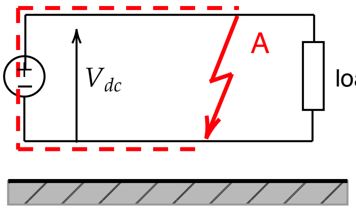
On the other hand, static electricity could cause dangerous overvoltages between the exposed conductive parts and earth. In this case, we can use overload dischargers to limit the hazards.

Let us go through the possible fault cases in isolated DC networks.

3.4.1 Pole-to-pole fault

A fault between the two polarities in an isolated network is fed by the full DC supply voltage V_{dc} and it affects both poles , as we can see in the Figure 59. The circuit breaker chosen must have breaking capacity higher than the maximum short-circuit current at V_{dc}.

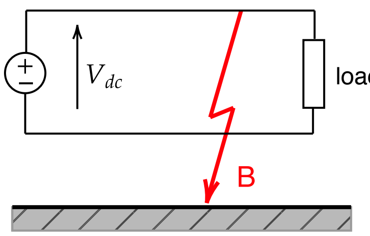
Figure 59 Pole-to-pole fault in an isolated DC grid



3.4.2 Pole-to-earth fault

A fault between one polarity (either the positive or the negative) and earth does not have a reclosing path for the fault current, as we can see in the Figure 60. However, it increases the voltage difference between one polarity and earth to the full voltage V_{dc}.

Figure 60 Pole-to-earth fault in an isolated DC grid

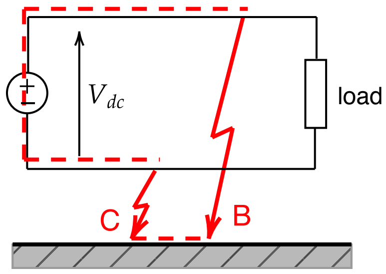


However, according to IEC/EN 60364, this fault must be indicated by a suitable insulation monitoring device (IMD) and cleared because otherwise a second fault may cause problems.

3.4.3 Double pole-to-earth fault

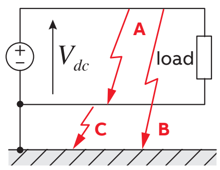
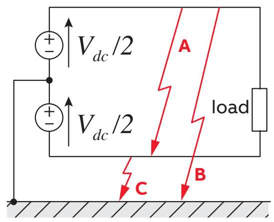
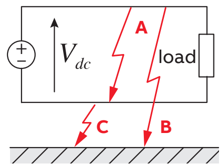
In the case of a double fault between a polarity and earth, there might be fault current supplied by V_{dc}, as shown in the Figure 61. To prevent this from happening, an IMD should be installed, which can detect a first earth fault as well as a decrease of the isolation between a polarity and the earth. Consequently, after the IMD has detected a fault, appropriate actions should be taken to clear the fault.
In isolated dc networks, the most critical fault is the one between the two polarities. Hence, the circuit breaker should be chosen accordingly, so its maximum breaking capacity I_{sc} is at V_{dc}.
At the same time, an insulation monitoring device is required, so that problems related to a second earth fault are prevented. In the case a second pole-to-earth fault occurs, the circuit breaker must interrupt the fault current with the full voltage applied to a single polarity.

Figure 61 Double pole-to-earth fault in an isolated DC grid



In Table 3.1, we will summarize the possible fault scenarios in the three network types presented and consider some characteristics of the protection device needed.

Table 3.1 Fault scenarios

Type of system	One polarity earthed	Earthed mid-point	Isolated
Fault cases			
Fault analysis (the resistance of the earth electrode is neglected)			
Pole-to-pole fault (fault A)	- Fed by V_{dc} - The CB must protect the non-earthed polarity or both polarities - Breaking capacity of each protected polarity ≥ max I_{sc} at V_{dc}	- Fed by V_{dc} - Both polarities are affected - The CB must protect both polarities - Breaking capacity of each protected polarity ≥ max I_{sc} at V_{dc}	- Fed by V_{dc} - Both polarities are affected - The CB must have breaking capacity ≥ max I_{sc} at V_{dc}
Pole-to-earth fault (fault B)	- Fed by V_{dc} - Fault current depends on the soil impedance - All the poles of the CB on the non-earthed polarity must be connected in series - Breaking capacity of each CB pole ≥ max I_{sc} at V_{dc}	- Fed by $V_{dc}/2$ - Fault current depends on the soil impedance - Only the positive polarity is affected - All the poles of the CB must withstand I_{sc} at $V_{dc}/2$	- Does not affect the system - Must be detected by a suitable insulation monitoring device (IMD) and cleared
Pole-to-earth fault (fault C)	- Does not affect the system	- Fed by $V_{dc}/2$ - Fault current depends on the soil impedance - Only the negative polarity is affected - All the poles of the CB must withstand I_{sc} at $V_{dc}/2$	- Does not affect the system Must be indicated by a suitable insulation monitoring device (IMD) and cleared
Double fault	Not possible (the breaker trips on the first fault)	Not possible (the breaker trips on the first fault)	- Fed by V_{dc} - The CB must interrupt the fault current with V_{dc} applied to a single polarity
Most severe case	Fault A (pole-to-pole). Fault B (non-earthed polarity to earth) must be considered as well.	Fault A (pole-to-pole). Fault B (pole-to-earth) must be considered as well.	Double fault.

4 Conditions in DC networks

In DC systems, in as similar way as in AC networks, four different conditions may occur. We will explain them briefly in this Chapter, exploiting the definitions from IEC 60364-4-43, which is the standard that specifies the protection against overcurrent in low-voltage electrical installations.
We will also clarify the nomenclature typically used for some of the crucial technical parameters of the circuit breakers in their catalogs.

4.1 Rated current levels and below

A circuit breaker is characterized by its rated current. The lifetime in terms of opening maneuvers holds for such rated current, as specified in applicable standards.

The circuit breakers are also tested at low DC load current levels according to IEC 60947-2. These so-called critical DC currents are chosen based on the rated current of the breaker.

4.2 Overload conditions

An overcurrent is the electric current whose value exceeds a specified limiting threshold. For conductors, this threshold is equal to their current-carrying capacity. An overcurrent is an overload current or a short-circuit current.
Overload is an operating condition in an electrically undamaged circuit, which causes an overcurrent. The overload may produce damage because of excessive heating if continued for too long time. It is characterized by slow overheating of the devices and leak of insulation characteristics in the cables.

Overload conditions are multiples of the nominal current levels. In the IEC 60898-2 standard they are called “reduced DC short-circuit currents”.
Ideally, the tested current levels represent a broad range from slightly higher than nominal current to low short-circuit levels. Note that in the present product standards this is not always given due to historic reasons (standards are based on an AC history and experience).

Beside the higher current level, also a slightly higher voltage level can represent an overload condition. In battery energy storage systems, for example, the voltage can vary between 0.8 and 1.15 times the nominal voltage depending on the actual state of charge (SOC).

4.3 Short-circuit conditions

Short circuit is an accidental or intentional conductive path between two or more conductive parts forcing the electrical potential differences between these conductive parts to be equal to or close to zero. In other words, the short circuit is a low-impedance path between conductive parts which by design are at different potentials. It results in very high current which causes strong electrodynamic forces, i.e., stress of the components.

For correct selection of a protection device, every circuit must be investigated for potential faults. It is crucial to be aware that only downstream faults can be cleared by a protection device.

Every fault that is upstream (in front of the protection device) cannot be cleared. Some faults, e.g., short-circuit to earth, may exclude protection devices or poles from the actual electrical network.

4.4 Endurance

The endurance, or lifetime, listed in the catalogs does only refer to the lifetime in nominal conditions at both rated voltage and nominal current level. The guaranteed lifetime in other conditions is always less than the one specified at rated conditions.

4.5 Definitions

To read correctly the technical specifications listed in the catalogues of various ABB products that will be presented in Chapter 5, some common ground on understanding the nomenclature is needed. Here is a list of the commonly used parameters, accompanied by a short description.

- **Rated operational voltage** U_e: the voltage assigned by the manufacturer to the circuit breaker (or other component) and to which operation and performance characteristics are referred.

- **Rated uninterrupted current** I_u: the value of the current which the equipment can carry for an indefinite time (uninterrupted duty). This parameter is used to define the size of the electromechanical circuit breaker.

- **Rated current** I_n: the value of current which characterizes the protection trip unit mounted on the circuit breaker and determines the protection characteristic according to the available trip unit settings. This current is often referred to as rated current of the load protected by the circuit breaker.

- **Rated ultimate short-circuit breaking capacity** I_{cu}: the maximum short-circuit current value which the circuit breaker can break twice (according to the sequence O – t – CO) at the corresponding rated operational voltage. After the opening and closing sequence the circuit-breaker is not required to carry its rated current.

- **Rated service short-circuit breaking capacity** I_{cs}: the maximum short-circuit current value which the circuit breaker can break three times according to a sequence of opening and closing operations (O - t - CO - t – CO) at a defined rated operational voltage (U_e) and at a defined time constant (for direct current). After this sequence, the circuit breaker is required to carry its rated current.

- **Rated short-time withstand current** I_{cw}: the current that the circuit breaker can carry in closed position during a specified short time at defined conditions of use and behavior. The circuit breaker shall be able to carry this current during the associated short time delay to ensure coordination between the circuit breakers in series.

- **Fault current rise rate** di/dt: the rate at which the fault current increases during a fault event.

- **Maximum switchable inductance** L_{max}: the maximum inductance that can be part of the electric circuit downstream the breaker. If the equivalent downstream circuit inductance L_{eq} is lower than L_{max}, the circuit breaker can guarantee correct operation.

5 Protection devices for DC networks

In this section, we will give an overview of the protection devices, certified according to the IEC standards, that ABB offers for DC networks protection.
Let us begin with a general overview of these device groups:

- miniature circuit breakers (MCBs);
- molded-case circuit breakers (MCCBs);
- air circuit breakers (ACBs);
- solid-state circuit breakers (SSCBs);
- switch-disconnectors;
- switch-fuses and fuse gear;
- contactors;
- surge protective devices (SPDs);
- accessories.

In the following tables, we will present the basic characteristic parameters of these devices. Details for each product can be found in the corresponding catalog.

Table 5.1 Miniature circuit breakers for DC networks

Product	Max rated voltage [V]	Rated current [A]	Short-circuit current I_{cu} [kA]
S200	125	100	10
S200M UC S200MT-UC	440	63	10
S200 MTR	440	63	10
S800 PV	1500	125	5
S800S-UC	1000 750	50 125	5
S800P	500	125	30
S800PV-SP	1500	125	5
S200 MTUC	440	63	10

Table 5.2 Molded-case circuit breakers and air circuit breakers for DC networks

Product	Max rated voltage [V]	Rated current [A]	Short-circuit current I_{cu} [kA]
Tmax	1000*	800	50
Tmax XT	500	250	100
	750 800	630 100	36
Emax DC	1000	5000	100

* 1500 V DC per T4N/PV-E

I_{cu} is the rated ultimate short-circuit breaking current.

Table 5.3 Solid-state circuit breakers

Product	Ratedvoltage [V]	Rated current [A]	Maximum di/dt [A/µs]
SACE Infinitus	1000	2500	No limit

Table 5.4 Switch-disconnectors for DC networks

Product	Max rated voltage [V]	Rated current [A]	Rated short-time withstand current I_{cw} [kA]
S800PV-M-H	1000	100	1.5
S800PV-SD	1500	125	1.5
Tmax XT switch-disconnectors	750	1250	20
Tmax T-PV switch-disconnectors	1500	1600	19.2
Emax DC switch-disconnectors	1000	6300	65
Emax 2 MS-1500V DC	1500	4000	100
OTDC switch-disconnectors 16A to 1kA	1500	1000	63
OT disconnectors 1.6kA to 4kA	1500	4000	100
Enclosed OTDCP switches	1000	32	0.8

Table 5.5 Switch-fuses and fuse gear for DC networks

Product	Max rated voltage [V]	Rated current [A]
Fuse bases OFAZ and OFAX	1000	1250
OS manual operated	1000	1250
Fuse switch disconnectors: EasyLine	440	630
Fuse switch disconnectors: SlimLine XRG	500	630
E90 32PV	1000	30
E90 32PV 1500e	1500	32
E9F PV	1000	30
E9F PV 1500	1500	32

Table 5.6 Contactors for DC networks

Product	Max voltage [V]	Rated current [A]
GF contactors	1500	1325
GAF contactors	1000	2050
AF contactors	850	2650
Installation contactors	220	100
Contactor relays for auxiliary circuit switching	600	1000

Table 5.7 Surge protective devices for DC networks

Product	Voltage [V]	Impulse current [A]
OVR PV T1-T2 QS	1000 1500	12.5 10
OVR PV T2 QS	1500	40

5.1 Miniature Circuit Breakers (MCBs)

5.1.1 S200M UC range

Miniature circuit breakers series S200M UC belongs to the most compact design class. They are designed for DIN rail mounting and comply with IEC 60947-2 standard.

They differ from AC-only versions and are marked with a “UC” extension, standing for “Universal Currents”, which means that they are applicable for both AC and DC networks. To achieve that, they are equipped with permanent magnetic elements on the internal arc extinction system.

The presence of these permanent magnetic elements determines the capability of the breaker to clear currents flowing in one direction. Accordingly, wiring must comply with the indications reported on the breaker. Multiple poles in series enables also polarity independent/bidirectional functionality.

Circuit breakers of series S200M UC are available with characteristics B, C, K and Z. Rated operational voltage is up to 440V DC and rated ultimate short-circuit breaking capacity I_{cu} = 10kA.

System voltage	Current rating
up to 440V DC	up to 63A

Global Product Catalogue 2024 - MCBs (abb.com)

5.1.2 S200MT-UC and S200MTR-DC

The miniature circuit breakers S200MT UC and S200MTR-DC are specially developed for traction applications, and validated according to the IEC standards.
Their operational voltage is up to 440V DC and breaking capacity is 10kA.

System voltage	Current rating
up to 440V DC	up to 63A

S200 MTR. Endurance and safety for rolling stock applications

5.1.3 S800S-UC and S8004U-UCZ

The S800S-UC and S8004U-UCS ranges are non--polarized high-performance DC MCB with breaking capacity of I_{cu} = 50kA and I_{cu} = 10kA, respectively. They are suitable in a wide range of DC applications.

For the circuit breakers series S800S UC the available characteristic curves are B and K: both have rated currents up to 125A.

System voltage	Current rating
up to 1000V DC	up to 125A

High performance circuit breakers

Global Product Catalogue 2024

5 Protection devices for DC networks

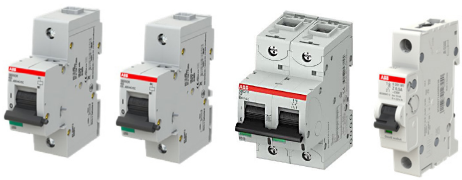
5.1.4 S800PV-SP

The S800PV-SP series are non-polarized high-performance DC MCBs with rated current up to 125A and breaking capacity of I_{cu} = 5kA, according to IEC 60947-2 Annex P.
This series is specially developed for photovoltaic system applications and offers reliable protection for PV modules and lines against reverse currents from defective strings.

System voltage	Current rating
up to 1500V DC	up to 125A

Global Product Catalogue 2024 - MCBs (abb.com)

5.1.5 Smissline TP



Smissline TP is a pluggable socket system that allows load-free devices and components to be plugged on and off under voltage with no need for additional personal protective equipment to guard against electrical hazards.
A specific MCBs range, named S400 M UC, is available for the Smissline TP system.

System voltage	Current rating
Up to 440V DC	MCCB up to 250A MCB up to 63A

SMISSLINE TP

5.2 Molded Case Circuit Breakers (MCCBs)

5.2.1 Tmax T

Tmax T is a range that provides protection performance in 1000V DC and 1500V DC systems, compliant with the standard IEC 60947-2 and equipped with thermal magnetic trip units. The Tmax T circuit breakers for DC applications have four poles, which are connected in series to provide rated ultimate short-circuit breaking capacity up to 50kA.
Their rated current is up to 800A and come only in fixed version.

System voltage	Current rating
Up to 1500V DC	up to 800A

CATALOG SACE Tmax for special applications

5.2.2 Tmax XT

Molded-case circuit breakers series SACE Tmax XT, complying with the IEC 60947-2 standard, and equipped with thermal magnetic trip units, are divided into six basic sizes, with rated uninterrupted current from 160A to 800A.

The Tmax XT trip units are designed to be used in a wide range of applications, providing a suitable solution for protection against both overloads and short-circuits. The new X version assures I_{cu} up to 100kA at 750V DC.

For the protection thresholds against short-circuits, correction values (Km) must be used, according to the type of distribution network and to the number of poles to be connected in series no impact on the thermal threshold.

System voltage	Current rating
500-750V DC	up to 800A

SACE Tmax XT IEC Low voltage molded case circuit breakers

5.3 Air Circuit Breakers (ACBs)

5.3.1 Emax DC

The SACE Emax range of low voltage circuit breakers is completed by the new SACE Emax DC series of circuit breakers for direct current applications complying with the IEC 60947-2 standard. Thanks to the exclusive technology applied to the new SACE PR123/DC and PR122/DC trip units, the SACE Emax DC range allows all installation requirements to be met and guarantees protection up to 1000V DC / 5000A. This series is a viable option not only for photovoltaic plants, but also for industrial, marine and data center applications.
The withdrawable circuit breakers must be associated with the fixed parts in a special version for applications at 750/1000V DC.

System voltage	Current rating
up to 1000V DC	800-5000A

ACE Emax DC Low voltage air circuit-breakers for direct current applications

5.4 DC high-speed circuit breaker

Gerapid is a single pole, DC high-speed circuit breaker designed for use in DC traction power substations. It provides high interruption capacity and has current limiting characteristics.

System voltage	Current rating
750 – 1500 – 3000V DC	up to 8000A

Gerapid - Circuit Breakers - Medium Voltage (Apparatus) | ABB

5.5 Solid-State Circuit Breakers (SSCBs)

Solid-State Circuit Breakers (SSCBs) use semiconductor devices, like Integrated Gate-Commutated Thyristors (IGCTs) and Insulated-Gate Bipolar Transistors (IGBTs) or MOSFETs, as switching mechanism. Unlike traditional circuit breakers, SSCBs eliminate arcs and offer much faster switching speed, typically less than 100µs, leading to reduced maximum fault currents.
These characteristics make SSCBs attractive for applications where the circuit breakers are located close to the protected equipment, such as in electric vehicle battery packs.

Main components of the SSCBs (as in Figure 62 and Figure 63) are:

- Low-loss semiconductor device (IGCTs or IGBTs), which can turn off in a few 100µs range.
- Voltage-clamping circuit (typically MOVs) to limit the overvoltage peak on the semiconductors and to dissipate the magnetic energy stored in the network, similarly to the arc in electromechanical circuit breakers.
- Mechanical contacts in series with the semiconductor device to provide the same isolation characteristic as electromechanical circuit breakers, according to the IEC 60947-2 standard.
- Cooling system, either liquid or air-based, often required to avoid overheating and ensure stability of the semiconductor devices.

5 Protection devices for DC networks

Figure 62 Components of the SACE Infinitus solid-state circuit breaker: external view

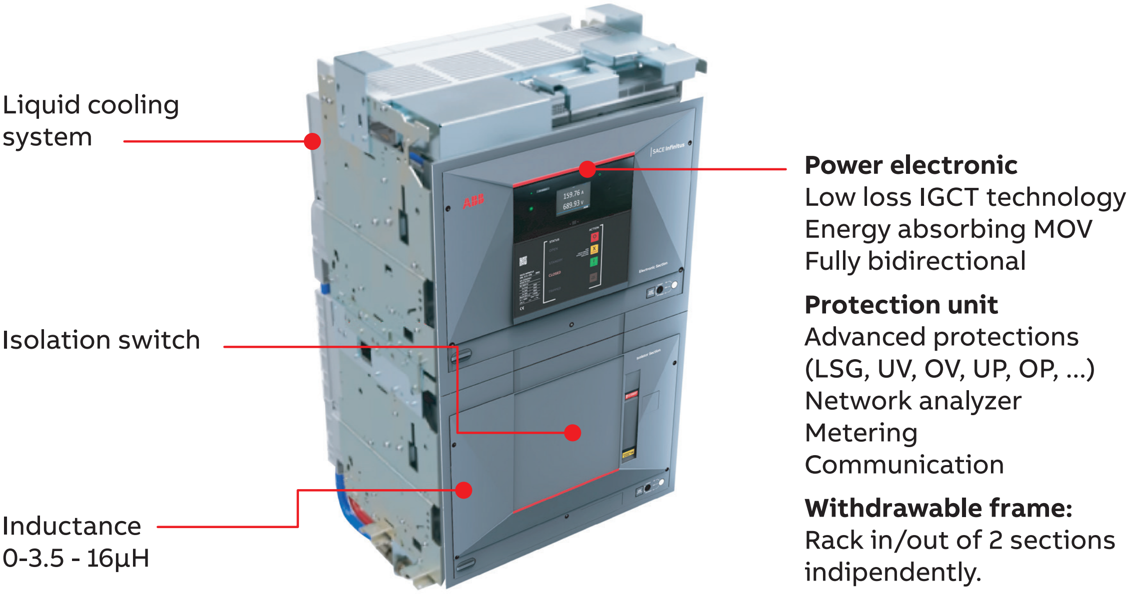
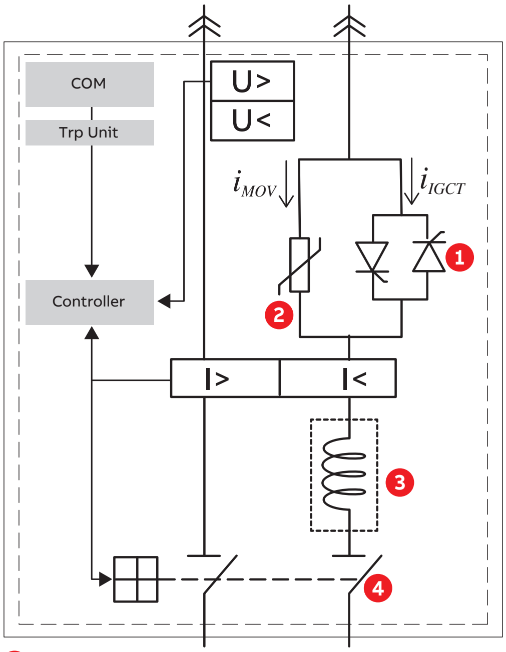


ABB launched on the market the first SSCB, SACE Infinitus, which is compliant with IEC 60947-2, the EC "Low voltage directive" (LVD) No 2014/35/EC, the EC Electromagnetic compatibility directive 2014/30/EC as well as DNV shipping register.

Figure 63 Components of the SACE Infinitus solid-state circuit breaker: internal view



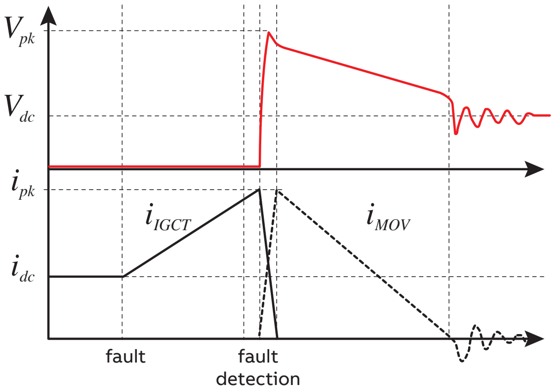
1 Semiconductor switches
2 Voltage-clamping circuit
3 Inductance
4 Mechnical contacts

The SSCB architecture has 1 protected pole and 2 isolated poles. The required fault current handling capabilities depend on the earthing. Considering the fault analysis of isolated systems presented in Chapter 3, the short-circuit current will always flow in both poles (or there is no current flow in case of single fault to earth). Therefore, the basic configuration of SACE Infinitus, having a semiconductor switch in one pole only, is adequate for fault handling in isolated systems.

On the other hand, galvanic isolation after current interruption, also in normal operation, must always be applied on both poles to ensure people's safety and provide adequate impulse withstand voltage protection of the disconnected circuit.

Typical voltage and current waveforms are shown in the Figure 64.

Figure 64 Voltage and current waveforms during fault current interruption with a solid-state circuit breaker



System voltage	Current rating
up to 1250V DC	2500A

ABB reinvents the circuit breaker - Circuit Breakers Low Voltage - ABB

5.6 Switch-disconnectors

Switch-disconnectors are mainly used as:
- general disconnection devices in sub-switch-boards
- switching and insulation devices for lines, busbars, or group of apparatus
- bus ties (connecting/disconnecting switch-board sections).

In the open position, the disconnector guarantees a sufficient insulation distance (between the contacts) to ensure safety and to guarantee overvoltage withstand.

The making capacity I_{cm} is highly important since a switch-disconnector must be able to withstand the dynamic, thermal and current stresses which can occur during closing operations without being destroyed, right up to short-circuit closing conditions.

Switch-disconnectors based on MCBs, MCCBs and ACBs range feature the same overall dimensions, versions and can usually be fitted with the same accessories.

5.6.1 S800PV-M-H

The S800PV-M-H, only available as 2-pole device, provides isolation protection up to 100A and 1000V DC with I_{cw}=1.5kA in accordance with IEC 60947-3. These disconnectors have a nominal current range up to 100A, covering a large range of applications. For example, it is used as a main switch for PV systems: the whole DC side can be safely isolated, either locally or remotely. S800PV-M-H guarantees safe switching under load and is suitable for international use.

System voltage	Current rating
up to 1000V DC	up to 100A

S800PV-M-H Polarized Disconnector

5.6.2 S800PV-SD

The S800PV-SD provides isolation protection up to 125A and 1500V DC with I_{cw}=1.5kA in accordance with IEC 60947-3 and Annex D. This series has compact design for installation on the DIN rail.

System voltage	Current rating
up to 1500V D	up to 125A

S800PV-SD Disconnector - High performance circuit breakers

5 Protection devices for DC networks

5.6.3 Tmax XT switch disconnectors

Tmax XT-based switch-disconnectors allow remote trip, remote operations and a full offer of accessories.
Tmax XT disconnectors comply with the utilization categories defined by IEC 60947-3 standard.

System voltage	Current rating
up to 750V DC	up to 1250A

SACE Tmax XT
Low voltage molded case circuit-breakers

5.6.4 Tmax T-PV

SACE Tmax PV is the range of switch-disconnectors for application up to 1500V DC and it is composed by a complete set of switch-disconnectors up to 1600A, suitable for photovoltaic applications.

System voltage	Current rating
up to 1500V DC	1600A

SACE Tmax for special applications

5.6.5 Emax DC switch-disconnectors

ABB SACE has developed the SACE Emax/E MS range of switch-disconnectors for direct current applications up to 1000V complying with the IEC 60947-3 standard. These circuit breakers are particularly suitable for use as bus-ties or main switch-disconnectors in direct current plants, such as electric traction applications.

System voltage	Current rating
up to 1000V DC	up to 6300A

Emax DC - Circuit Breakers Low Voltage - ABB

5.6.6 Emax 2 MS- 1500V DC

The SACE Emax 2 MS/DC-E IEC range has been developed for installations up to 1500V DC and 4000A, with short-time withstand current up to 100kA. The SACE Emax 2 MS/DC-E is compliant with DC-PV2, the most demanding utilization category according to IEC 60947-3 Annex D, since it requires the ability to connect and disconnect PV circuits where significant overcurrents may occur and where current flow can be in either direction; these are common characteristics of centralized PV systems.

System voltage	Current rating
up to 1500V DC	up to 4000A

SACE Emax 2 MS/DC-E. Air Switch-disconnectors at 1500V DC

5.6.7 OTDC Switch-disconnectors 16A to 1000A

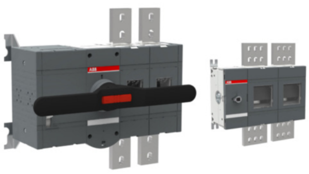
If operation under load is required, OTDC switch-disconnectors have a robust and high switching performance from 16A to 1000A, up to 1500V DC. The utilization categories covered are from DC-21B up to DC-22B and DC-PV2. OTDC switches allow multi-circuit switching with a small footprint. OTDC switches have a high I_{cw} up to 63kA and have been tested with fuses up to 100kA.
They are certified according to DNV* GL.

System voltage	Current rating
up to 1500V DC	16 - 1000A

DC switch-disconnectors - Switches | ABB

* DNV stands for Det Norske Veritas, an international accredited registrar and classification society that provides services for several industries like maritime, renewable energy, etc.

5.6.8 OT disconnectors 1.6kA to 4kA



OT disconnectors are suitable for applications in DC-20 category that do not require operation under load and where reliable isolation is needed. OT Disconnectors have a high I_{cw} up to 100kA and high maximum let-through peak currents. An electrical interlock enables safe operation for users.

System voltage	Current rating
up to 1500V DC	1600 - 4000A

DC switch-disconnectors - Switches | ABB requires the ability to c

5.6.9 Enclosed OTDC switches

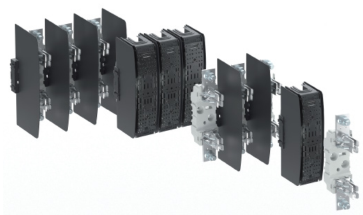
OTDCP from 16 to 32A (IEC 60947) offers DC voltage ratings up to 1000V DC and a control of up to two circuits within the same footprint area. Safety and protection are ensured with IP65 rating and the handle is pad-lockable.

System voltage	Current rating
up to 1000V DC	up to 32A

Enclosed DC switches OTDCP from 16 to 32 Amperes - DC switch-disconnectors (Switches) | ABB

5.7 Switch-fuses and fuse gear

5.7.1 Fuse bases OFAZ and OFAX



Fuse bases can be used in combination with NH fuse-links according to IEC 60269-2 and DIN VDE 0636-2 and solid links. Fuse bases offer a compact and simple solution for protection against short-circuit and overcurrents. Fuses as protective elements are characterized by galvanically silver-plated contacts providing reliable and high performing contact characteristics. OFAZ and OFAX fuse bases are available as open types or fully protected IP20 versions.

System voltage	Current rating
up to 1000V DC	up to 1250A

Fuse bases - ABB Low Voltage Fusegear

5 Protection devices for DC networks

5.7.2 OS manual operated

OS switch-fuses are suitable for marine applications. The OS range includes switch-fuses from 20 to 1250A, available for most common fuses: DIN, BS, NFC, CC, JJ and L types. OS switch-fuses are DNV GL marine certified and come with a wide range of different accessories such as interlocking and fuse monitoring devices.

System voltage	Current rating
up to 1000V DC 20	1250A

Manual operated switch-fuses - Switches | ABB

5.7.3 Fuse switch-disconnectors

EasyLine range of fuse switch-disconnectors ensures high protection and reliable operation from 160A to 630A. Variants up to 440V DC are available as 1- or 2-pole design.

System voltage	Current rating
up to 440V DC	160-630A

EasyLine - XLP - ABB Low Voltage Fusegear

The SlimLine XRG switch-disconnector fuse drives high energy efficiency, reducing temperature rise and enabling higher performance across the panel board. Variants with rated voltage 110V and 550V DC are available.

System voltage	Current rating
up to 500V DC	125-630A

SlimLine XR - ABB Low Voltage Fusegear

5.7.4 E90 PV fuse holders and fuses

E 90 PV fuse holders have been specifically designed for photovoltaic applications. Thanks to their rated voltage up to 1000V DC and 1500V DC, they are the ideal solution for protecting cells, inverters or surge arresters. In case of maintenance, they ensure isolation of circuits and strings up to 1500V in direct current, in total safety.

The 1000V DC E90 PV device has been tested in accordance with IEC 60947-3 (DC-20B), while the 1500V DC fuse holder has undergone testing compliant with IEC 60269-1 standard.

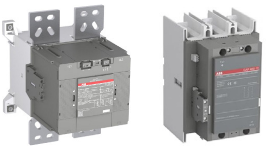
System voltage	Current rating
up to 1500V DC	up to 32A

E90 PV fuse holder 1500V DC for solar applications

E 90 range of fuse disconnectors and fuseholders. Uncompromising performance (abb.com)

5.8 Contactors

5.8.1 GF and GAF contactors

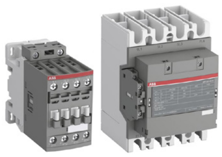


GF and GAF contactors are specifically designed for switching DC circuits up to 1500V. This product is suitable for applications such as PV, Electric Vehicle (EV) charging, UPS and energy storage systems.

System voltage	Current rating
GF: up to 1500V DC GAF: up to 1000V DC	875-1325A up to 2050A

Contactors for DC switching - Motor protection and control | ABB

5.8.2 AF contactor range



ABBs AF contactor range can also be used for switching circuits up to 850V DC.

System voltage	Current rating
< 72 – 850V DC	16 – 2650A

Motor protection and control | ABB

5.8.3 Installation contactors

ABB's hum-free installation contactor designs offer a wide range of ratings from 16A to 100A. They are widely used in buildings for switching and controlling lighting, heating, ventilation. With an innovative AC/DC design that eliminates hum, a selection of tool-free accessories as well as manual and automatic versions is available.

System voltage	Current rating
up to 220V DC	up to 100A

Installation contactors - Motor protection and control | ABB

5.8.4 Contactor relays for auxiliary circuit switching

ABB's contactor relays offer features a variety of products for different applications. NF contactor relays can be used in almost all network conditions. The mini contactor relays range offers various contact combinations and specific connection possibilities. The AS contactor relays allow users to optimize their equipment design applications.

System voltage	Current rating
up to 600V DC	up to 1000A

Contactor relays for auxiliary circuit switching - Motor protection and control | ABB

5 Protection devices for DC networks

5.9 Surge Protective Devices

5.9.1 OVR PV QS

Combined Type 1 and Type 2 SPDs can guarantee overvoltage reduction to protect end-equipment, whether the surge comes from a lightning strike or power grid perturbation.
This is due to its functions as Type 1 able to withstand 10/350µs waveform, as well as Type 2 for 8/20µs waveform, to limit the voltage rise.

This range aims at covering the main needs of large-scale PV power plants: keeping the solar production running, whatever the atmospheric discharge. This being from 600V DC up to 1500V DC.

OVR PV | ABB

5.10 Relays and control

5.10.1 Single-phase monitoring relays

For monitoring currents and voltages in single-phase AC/DC systems, ABB's CM-range contains a wide selection of powerful and compact devices, all in only 22.5mm wide housing. This product range includes current and voltage monitoring relays for over- and undercurrent and voltage protec-tion from 3mA to 15A, and from 3V to 600V DC.

System voltage*	Current rating*
up to 600V DC	0.003 to 15A

* Rated characteristics differ from model to model, please refer to the technical catalogue

Single phase monitoring relays

5.10.2 Thermal overload relays

Thermal overload relays are electromechanical protection devices for DC motors. In combination with contactors, they provide reliable protection against overloads and phase failures. They allow for setting up customized motor starting solutions according to individual needs. Thermal overload re-lays are rated as DC loads (e.g., for motors used in solar panel tracking systems).

System voltage*	Current rating*
up to 600V DC	0.1 to 200A

*Rated characteristics differ from model to model, please refer to the technical catalogue

Thermal overload relays

5.10.3 Power supplies

Reliable power supply units are vital components in energy management and automation technology.
They are available in four different ranges to cover different application requirements; the CP range, for example, offers maximum value from economic to high-end solutions.

Input voltage*	Output voltage*	Rated output power*
90-820V DC	5-24V DC	10-960W

*Rated characteristics differ from model to model, please refer to the technical catalogue

Power supplies

5.10.4 EPD24

EPD24 is a selective protection device for 24V DC load circuits: it is a 4-channel electronic circuit breaker with an overall width of only 25mm. Its rated currents are adjustable from 1A – 10A (entry) or 0.5A – 12A (advanced). It is used for switching on capacitive loads up to 40mF at rated current of 12A.

System voltage	Current rating
24V DC	0.5 to 12A

EPD24 - Selective protection of 24V DC load circuits

5.10.5 Manual motor starters

This is a broad range of manual motor starters, for protection and control in many situations including hazardous areas, protecting installations from short-circuits, overloads and phase failures while also controlling the current flow through a simple ON/OFF switch. These manual motor starters are suitable for use with DC-5 utilization category (DC-5 Series motors: starting, plugging, inching, dynamic breaking of DC motors) for loads like traction systems, cranes, and hoists.

System voltage*	Current rating*
250V DC	up to 80A

* Rated characteristics differ from model to model, please refer to the technical catalogue

Manual motor starters

5.10.6 Insulation monitoring relays

These CM-IWx insulation monitoring relays for IT systems provide continuous, reliable monitoring. The devices recognize insulation faults as they develop, tripping as soon as the value falls below minimum set thresholds.tors) for loads like traction systems, cranes, and hoists.

System voltage*
up to 1500V DC

* Rated characteristics differ from model to model, please refer to the technical catalogue

Insulation monitoring relays

5 Protection devices for DC networks

5.11 Accessories

5.11.1 Signal/Auxiliary contacts

These devices allow to choose between indication of the device's contacts position and fault signaling (overcurrent/short-circuit for MCBs and RCBOs, earth fault for RCCBs and RCBOs). They are suitable for MCBs S 200 series, SN 201 series, RCCBs F 200 series, RCBOs DS201, DS202C, DS 200 series.

S2C-S/H6R | SmartLinks | ABB

5.11.2 Shunt trip

The S 2C-A1 and S 2C-A2 shunt trips perform remote opening of the device when a voltage is applied. They are suitable for MCBs S200 series and RCBOs DS 200 series, up to 250V DC voltage.

S2C-A1 | SmartLinks | ABB

5.11.3 Undervoltage release

The S2C-UA 24 DC undervoltage release has the function to protect the load in case of a voltage drop included between 70% and 35% of its rated value. Positive safety (device tripping when the voltage is disconnected) emergency stop is achieved by means of a button. It is suitable for MCBs S200 series, RCCBs F200 series and RCBOs DS201, DS202C, DS200 series, in circuits with rated voltage 24V DC.

S2C-UA 24 DC | SmartLinks | ABB

5.11.4 Accessories for S800-HPMCBs

CMS

CMS Sensor

S800-AUX

Auxiliary Contact

S800-AUX-ALT

Auxiliary + Signal Contact

S800-NT

Disconnectable Neutral

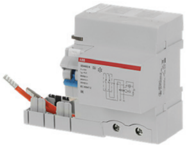
S800-RSU

Remote Switching Unit

S800-SOR

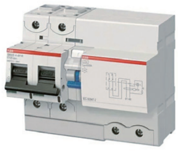
Shunt Opening Release

DDA 800



RCD Block

S800-RD



Factory Assembled RCBO

S800-UVR

Undervoltage Release

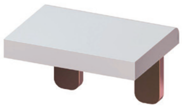
S800-RD

Rotary Drive

S800-BB

S800 Busbar System

S802-LINK

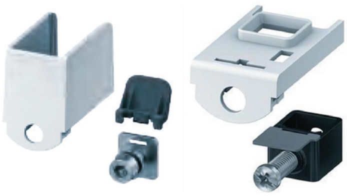


Pole Connector

S802-SCL-SR

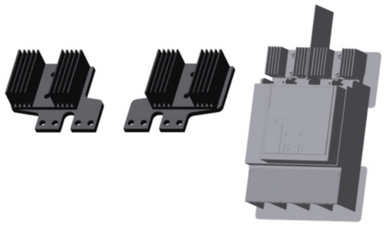
Self-resetting Short Circuit Limiter

S800-RT/CT



Interchangeable terminal adapter

5.11.5 Jumpers



In DC applications, the performance of switch-disconnectors and circuit breakers is strongly influenced by the wiring methods, especially when realizing the series of 2 side-by-side poles. To help the wiring, ABB supplies kits of jumpers shaped to fit suitably on the products.

The jumper's choice is based on the needs of the installation. It is possible to realize the connection of all poles on one single polarity (3 poles in series and 4 poles in series jumpers) or to divide the poles on both polarities with different wiring combinations possible. For example, two poles in series on the positive supply terminal and the other two poles in series on the negative supply polarity.

Some of the jumpers are realized with heat sink to assure the right heat dissipation when required. The performances declared in the DC switch-disconnectors and circuit breaker tables are tested with ABB original jumpers.

6 Guidelines for protection device selection

The most dominant parameter for the performance of the protection device is the voltage level. A breaker must be capable to withstand the (maximum) voltage that occurs in the considered application. The second parameter is the current level.
In DC grids with converter sources, the converter may limit the fault current to two or three times the nominal current, so the downstream circuit breaker must be able to trip reasonably fast at these low currents. If the nominal current of the selected circuit breaker is too high, then the breaker will not see this overcurrent as a fault. Too high rated current for the breaker requires suitable cables as well, which in case of low current loads will be oversized. Therefore, it is very important to match the rated circuit breaker current to the network current.
It is highly recommended to observe the individual applications for the different conditions listed in the Chapter 4.

6.1 Parameters relevant to selection

Different protection devices trip within a specific time in case of a fault. This time is the sum of two main intervals: fault detection and breaking time:

- fault detection can be done by various criteria and techniques; however, the time needed to complete this action is relatively constant, independently on the protection device chosen.
- breaking time significantly changes with respect to the protection technology used. In the following, we will address the main parameters that influence breaker's tripping time for each interruption technology.

6.1.1 Conventional Thermal-Magnetic Circuit Breakers

We can classify Miniature Circuit Breakers (MCBs), Molded-Case Circuit Breakers (MCCBs) and Air Circuit Breakers (ACBs) as electromechanical, i.e., thermal-magnetic protection devices. They use at least one pair of electrical contacts, one fixed and one moving contact, which provide a sufficiently wide isolation distance in open state.
By that, a secure galvanic separation is provided even under high voltage impulses. These breakers act via conventional electromagnetic actuators, partly in combination with a bimetal as a thermal release. The fault detection is done in a passive way: by designing an adequate balance of mechanical spring force and electromagnetic forces. In case of a fault, the current increases drastically and thereby the electromagnetic forces overcome the mechanical spring forces, which starts the contact separation and arc extinction process. The common isolation media is air.

A simplified DC circuit with thermal-magnetic circuit breaker, as the one in the Figure 65, is characterized by voltage and current waveforms like in the Figure 66. As soon as the contacts open (end of t_v), the limiting of the prospective short-circuit current starts.

Figure 65 Electrical circuit of a thermal-magnetic circuit breaker in DC grid

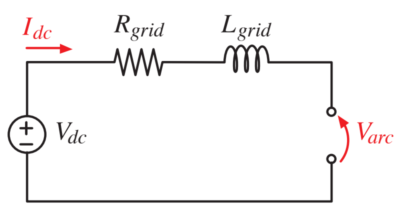
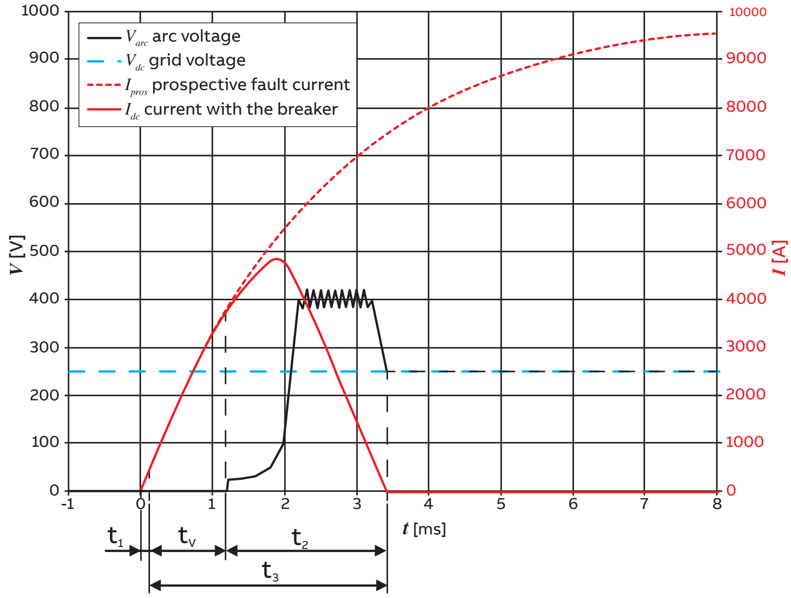
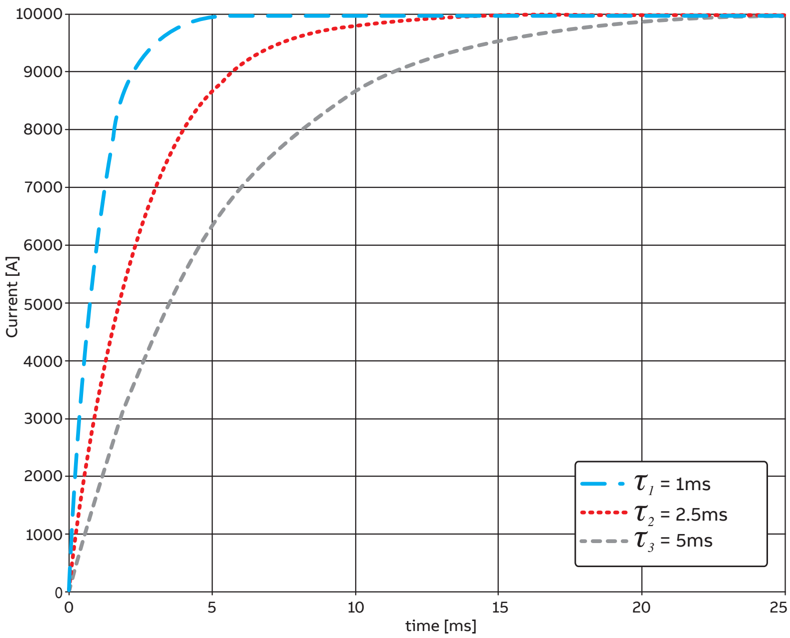


Figure 66 Arc interruption in electromechanical circuit breakers



The arc, which occurs between the two contacts, commutes to the arc chamber, which can be seen in a drastic voltage increase by measuring the arc voltage.

Figure 67 Current rise at different time constants τ



The current limitation is at its maximum when the arc voltage is higher than the driving network voltage V_{dc}. When the current is zero, the arc is extinguished, and the measured voltage over the breaker is equal to the driving network voltage.

In Figure 66, t_1 is the response time, t_2 the arc extinction time, t_3 is the clearing time and t_v is the mechanical opening time.

The clearing time of these circuit breakers is made of two major parts:

- mechanical opening time, which ranges from approximately 1ms for smaller MCBs to about 10ms or more for larger MCCBs and ACBs;
- arc extinction time, which can last from milliseconds to tens of milliseconds and depends on the fault voltage and on the inductive energy stored in the circuit.

In current limiting devices, the arc extinction process for AC and DC is very similar. In AC applications, some breaker designs do not limit the fault current by acting and influencing the arc, but simply withstand the current rise until the next zero crossing of the current. If the isolation distance is then high enough to prevent a re-ignition of the arc, the current stays zero, which means the current interruption process was successful. Devices which are awaiting the next zero crossing cannot be applied in DC networks.

According to the IEC 60947-2, each breaker is characterized by a rated short-circuit capacity I_{cu}, indicating the maximum prospective short-circuit current I_{pros} that the breaker can interrupt at a given time constant τ. The breaker is expected to interrupt any currents up to I_{cu}.

According to the product standard IEC 60947-2, the I_{cu} performance is evaluated with τ= 5 ms (for short-circuit conditions and I_{pros} <10 kA) The higher the prospective short-circuit current, the higher the τ. For short-circuit currents higher than 20kA, τ= 15 ms.

Figure 67 shows the rise of fault currents in different electrical circuits characterized by different time constants, but the same prospective short-circuit current of 10kA (assumption).

The time "0" represents the point in time when the short circuit is assumed to happen. The total fault clearing times are usually constant for a certain breaker type (e.g., 2ms).

Thereby, the figure illustrates that the fault current that needs to be handled by the breaker increases significantly when τ is lower. For example, at τ_1 = 1ms, the current is about 9kA, while in a circuit with τ_3 = 5ms, the current is about 3kA.

6 Guidelines for protection device selection

For the MCCBs and ACBs to trip effectively, it is necessary to determine a threshold current value I_{set}, which must be lower than I_{cu}, yet sufficiently larger than the maximum expected current in normal operating conditions to avoid unwanted trips. The circuit breaker works properly when the fault current is higher than I_{set} for a time longer than the time needed to detect the fault. Typically, this happens when:

- the short-circuit power of the system is quite large, i.e. the fault steady-state current value is larger than I_{set}, or
- the short-circuit current of the system is quite small (e.g., when the power converters limit the fault current to $2I_n$ with their control system, but the line inductance is large enough.

These electromechanical devices may not work properly when the short-circuit power of the system and the line inductance are small, as the capacitor discharge transient (stage one) might be too fast for fault detection, so the breaker cannot trip (particularly for large MCCBs and ACBs). If this is the case, the design of the protection system is quite challenging.

On the other hand, due to their relatively slow response with respect to solid-state circuit breakers, traditional circuit breakers typically interrupt the current after the capacitor discharge transient. Therefore, they do not necessarily need to have I_{cu} exceeding the peak value of the fault current.

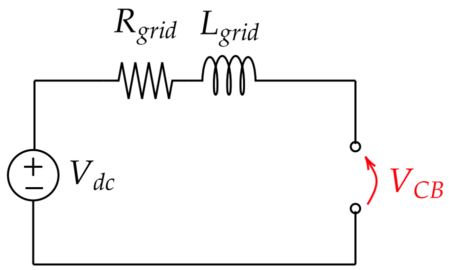
Despite these challenges, the use of electromechanical protection devices in active LVDC grids is possible with thermal-magnetic protection as the most suitable option.

However, as the steady-state fault current in DC grids can be quite low, typical Time-Current Curves (TCC) are not suitable because the tripping time would be too long. In this case, magnetic thresholds I_{set} can be set rather low, for example, 2-3 times the nominal current I_n. Such low magnetic ratings are not used in commercial AC thermal-magnetic circuit breakers, so special devices and designs are needed.

6.1.1.1 Arc extinction in thermal-magnetic circuit breakers

The Figure 68 represents a simplified electrical network with a DC source, a load and a protection device. The load includes(*) the equivalent grid and cable parameters upstream the protection device. Therefore, it is represented by a resistance R_{grid} and inductance L_{grid}. The protection device is represented by its two contact points and a voltage drop V_{CB}. Of course, also capacitive loads can be part of the network.

Figure 68 Electrical circuit using thermal-magnetic circuit breaker in DC grid



From the voltage equation of the circuit in Figure 68,

$$V_{dc} = R_{grid} \cdot I + V_{CB} + L_{grid} \frac{dI}{dt}, \tag{6.1}$$

we can express the current derivative:

$$\frac{dI}{dt} = \frac{1}{L_{grid}} \left(V_{dc} - R_{grid} \cdot I - V_{CB} \right). \tag{6.2}$$

To have the fault current crossing zero, its means that its derivative di/dt must be negative and decrease, so the current eventually reaches zero. According to the right-hand side of (6.2), V_{dc} - V_{CB} must be negative. We cannot rely on the $R_{grid} * I$ term because it might not be large enough to drive the current to zero.

Therefore, to limit and break a DC current, the circuit breaker must build up an arc voltage V_{CB} that exceeds the source voltage V_{dc}, i.e., $V_{CB} > V_{dc}$.

This is simple in low-voltage DC networks below 60V, but the higher the DC voltage, the more difficult the voltage build up is.

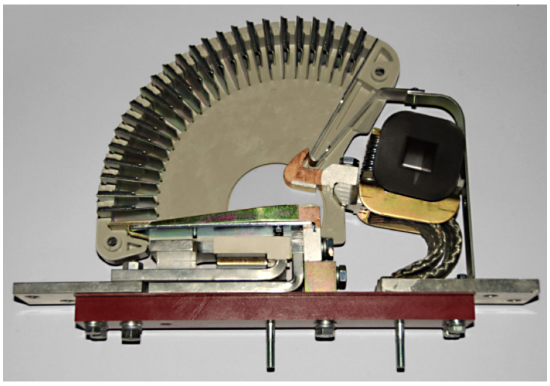
(*) We assume the source converter provides ideally constant voltage V_{dc}.

An example of such waveform is in the Figure 66: notice the arc voltage is higher than the DC supply voltage, so the current interruption takes place.

There are multiple ways of increasing the arc voltage V_{CB}. Following approaches are common:

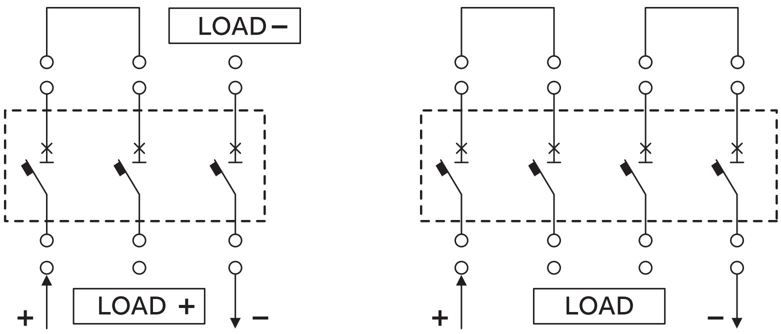
- Splitting the arc into multiple arcs. This is realized by an adequate arc chamber design, as it can be seen in Figure 69.

Figure 69 Arc chamber for splitting the arc



- Connecting several poles/MCBs in series.

Figure 70 Series pole connection of circuit breakers in DC applications



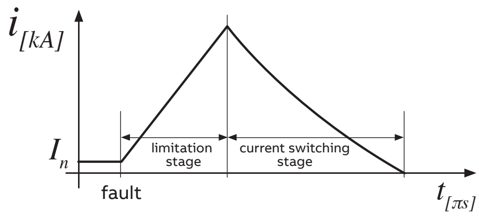
6.1.2 Solid-State Circuit Breaker

The typical SSCB response time is split into two stages (Figure 71):

- Limitation stage, i.e., the time interval between the onset of the short-circuit current and the moment when the limited peak current is reached. This interval is typically in order of microseconds, during which the SSCB detects the overcurrent and limits its flow by turning off the power semiconductor device . When compared to the thermal-magnetic breakers, the duration of this stage could be seen as an equivalent to the sum of t_v and t_l in Figure 66.

- Current switching stage, that is the time interval during which the current is commutated to a voltage clamping circuit (consisting of nonlinear passive elements, usually a metal oxide varistor and/or transient voltage suppressor diode), allowing the energy stored in the network's inductance to be discharged. This stage can take from a few microseconds up to a few hundreds of microseconds, depending on the value of the circuit equivalent inductance.

Figure 71: Current interruption with SSCB: generic waveform



Characterization according to the IEC 60947-2 standard, with short-circuit capacity I_{cu} evaluated by testing on RL circuits with a defined time constant τ, is not applicable to SSCBs. Considering that the interruption occurs very fast, the peak fault current is always precisely defined and therefore, the fault energy is limited, so the arc does not have the time to develop. The fault interruption performances of a solid-state circuit breaker are better characterized by the:

- Maximum current rise over time $(di/dt)_c$, determined so that during the limitation stage the fault current does not exceed the turn-off capability of the semiconductor device in the SSCB;

- Maximum energy the SSCB can dissipate during the current switching stage.

Independently of the prospective short-circuit current, if the maximum rate of rise of the fault current di/dt (assumed to occur at t = 0 s) is lower than the pre-defined $(di/dt)_c$, the circuit breaker will be able to interrupt the fault.

The maximum di/dt can be estimated by:

$$max\left(\frac{d}{dt}i_{dc}\right) = \lim_{\Delta t \to 0^+}\left(\frac{\Delta}{\Delta t}i_{dc}\right) = \frac{V_C}{L_{eq}}. \qquad (6.4)$$

By equation (6.4), the maximum di/dt occurs for faults with very low inductance value. This happens most often when the fault is very close to the converter capacitors, so that the maximum admissible current slope di/dt can be preliminary evaluated only if L_{eq} is known. In the case L_{eq} is too small, the rate of rise of the fault current is too large and, additional inductors are to be added to the circuit to limit the fault current derivative below $(di/dt)_c$.

When the limitation stage is concluded, the current switching stage starts. In this stage, the SSCB can switch in safe conditions if the energy stored in the equivalent circuit inductance, given by

$$E_{L_{dc}} = \frac{1}{2} \cdot L_{eq} \cdot I_{peak}^2 \qquad (6.5)$$

does not exceed the dissipation capacity of the voltage clamping device. For a given short-circuit current value, the maximum energy value occurs

6 Guidelines for protection device selection

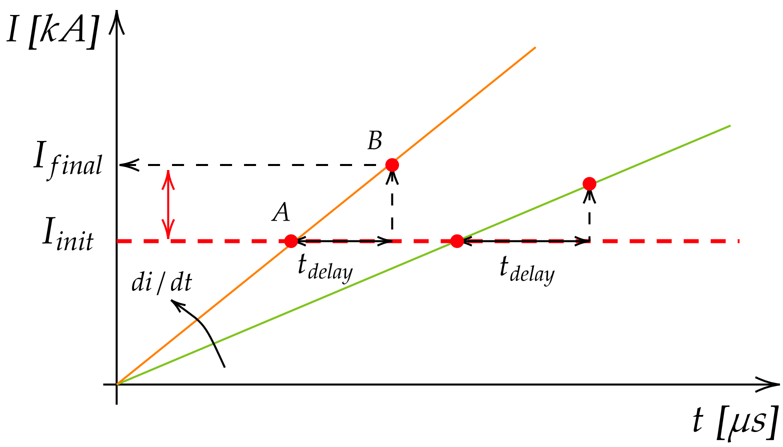
for faults with high equivalent inductance, i.e., occurring at a relatively long distance from the converter. Since the energy in the clamping circuit is independent from the fault resistance, the most critical parameter for SSCB safe switching is the circuit inductance. Therefore, a maximum switchable inductance L_{max} is defined, which represents another key indicator of the interruption performance for a SSCB.

There is always a certain delay between the fault detection and the time instant when semiconductor switches are turned off. This time delay consists of several elements:

- The protection device must ensure that a fault has occurred, and measured peaks are not just measurement noise.
- Calculation time, depending on the protection device used.
- Analog delay time.

During this total delay time (t_{delay}), the fault current keeps increasing, as shown in the Figure 72. Therefore, from the initial fault current value I_{init} at the time of fault occurrence (point A), the current rises to final value I_{final} (point B, when the semiconductor switches are turned off) because of the overall time delay T_{delay}.

Figure 72 Fault current increase from the fault occurrence till the semiconductors switch off



6.2 Selection procedure

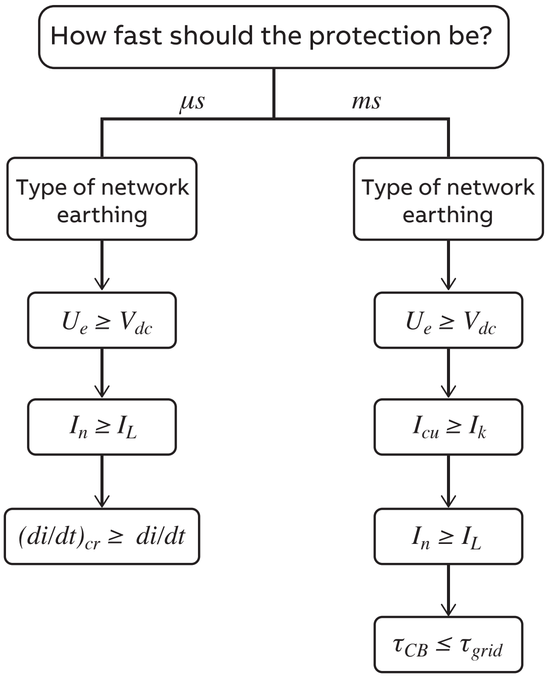
To choose the thermal-magnetic protection device suitable for a particular application, the following characteristics of the network should be known:

- **Fault current path**: it helps identifying the source of the short-circuit energy, the nearest protection device and the network components affected by the fault current.
- **Type of network**: (see Chapter 3) it helps you identify the worst type of fault in the network and the voltage level that the circuit breaker will be subject to. This information is later used to define the connection of the circuit breaker poles depending on the possible fault conditions.
- **Rated voltage of the plant V_{dc}**: to define the operational voltage U_e, based on the poles connection. The circuit breaker chosen must have rated operational voltage higher or equal to the plant voltage: $U_e \geq V_{dc}$. One should also have in mind that in DC systems with droop control, the normal operation voltage fluctuates in a so-called nominal voltage band, spanning around a rated value. Thus, the maximum expected voltage in normal conditions is higher than the rated value V_{dc} and this must be accounted for.
- **Short-circuit current at the breaker installation point I_k**: to define the circuit breaker version. The device chosen must be able to break the maximum short-circuit current at this point (according to the sequence O – t – CO), i.e., $I_{cu} \geq I_k$ must be satisfied.
- **Rated current absorbed by the load I_L** is used to define the rated current I_n of the thermal-magnetic trip unit of the DC electronic release (PR122-PR123/DC for Emax). Hence, $I_n \geq I_L$ must be satisfied.
- **Time constant τ_{grid}** of the network indicates how quickly the network responds to changes, while the time constant at which a circuit breaker is tested τ_{CB} tells us how quickly the breaker can respond to a fault. Thus, for a circuit breaker to be effective in protecting the network, it should respond faster than the network can stabilize, i.e., $\tau_{CB} < \tau_{grid}$.

On the other hand, for the choice of a suitable SSCB, except the voltage V_{dc} and the load current I_L, one must verify that the fault current rate of rise di/dt does not exceed the maximum rate of rise $(di/dt)_c$ the breaker can handle, i.e., $(di/dt)_c > di/dt$.

An essential parameter that determines the choice between a thermal-magnetic or a solid-state breaker is the required interruption speed and the designer should clarify whether it is in order of ms or µs. Faster clearing time means lower fault current, and consequently lower let-through energy and increased grid availability. However, it poses challenges related to selectivity and cost of the solution.

The following flowchart summarizes the steps to be followed for a correct selection of the circuit breaker, based on the plant characteristics and the designer requirements.



6.3 Examples

6.3.1 Example 1

Network characteristics:
- Type of network: one polarity earthed (the negative one).
- Network voltage: V_{dc}= 250V DC.
- Rated current absorbed by the loads I_L= 180A.
- Short-circuit current: I_k=40kA.
- Time constant of the network: L/R = 22ms.

In this network, the designer requires protection device operating in the ms range.

Referring to the indications given in Section 6.3, to proceed with the circuit breaker choice the following requirements must be met:

- $U_e \geq V_{dc}$
- $I_{cu} \geq I_k$
- $I_L \leq I_n$
- $\tau_{CB} < \tau_{gid}$

Let us consider the technical specifications of the Tmax XT circuit breakers family, given in Table A1.1 in the Appendix 1.

The first relevant parameter is the rated operational voltage of the breaker U_e. It must be higher than or equal to the plant rated voltage V_{dc}= 250V. In this case, it means breakers XT1, XT2 and XT3 can be considered further, since their operational voltage is U_e= 500V. Larger breakers like XT5 and XT6 could be accepted as well, but it will introduce unnecessary costs since XT5 and XT6 are designed for higher voltages and currents. Therefore, we will focus on XT1, XT2 and XT3.

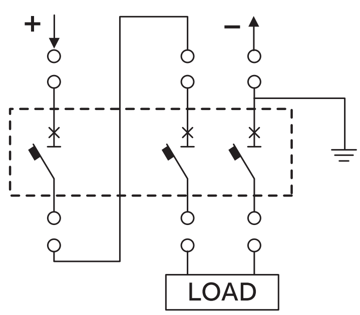
Now, the suitable version of the breaker should be chosen according to the relation $I_{cu} \geq I_k$.
In this example, since I_k= 40kA, version S can be used because its rated ultimate short-circuit breaking capacity is I_{cu}= 50kA. All the three possibilities (XT1, XT2 and XT3) have the version S available at 500V.
The load current I_L is the next parameter to be checked. The circuit breaker chosen must have uninterrupted rated current I_u higher than or equal to the load current I_L; in this case, it is only XT3 that satisfies this criterion, since its rated current I_u= 250A.

Last check point is the time constant suitability. Since the Tmax XT3 breakers are tested according to IEC 60947-2, their I_{cu} is guaranteed at a time constant τ_{CB} = 15ms. In this example, τ_{grid} = 22ms and therefore, $\tau_{CB} < \tau_{grid}$ is satisfied.

Finally, the circuit breaker type SACE Tmax XT3 with I_n= 250A can be used for this plant.

Within this choice, two possible schemes for the pole's connection can be identified in Table A1.2 in the Appendix 1. Assuming that also the earthed polarity is to be disconnected, the wiring diagram to be used is the as shown in the Figure 73.

Figure 73 Circuit breaker poles connection for example network 1



To summarize, a three-pole thermomagnetic circuit breaker XT3 250 TMD 200 shall be used connected as shown in the Figure 73, i.e., with two poles in series on the polarity isolated from earth and the other one connected on the earthed polarity.

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6.3.2 Example 2

Network characteristics:
- Type of network: isolated
- Network voltage: V_{dc} = 500V DC.
- Rated current absorbed by the loads I_L = 1800A.
- Short-circuit current: I_k=45kA.
- Time constant of the network: L/R = 26ms.

The chosen circuit breaker must satisfy the following requirements:
- $U_e \geq V_{dc}$
- $I_{cu} \geq I_k$
- $I_L \leq I_n$
- $\tau_{CB} < \tau_{gid}$

Regarding the type of network, the suitable table shall be identified in the Emax DC catalogue; in this case the table relevant to isolated network, provided again here in the Appendix 1, shall be chosen.

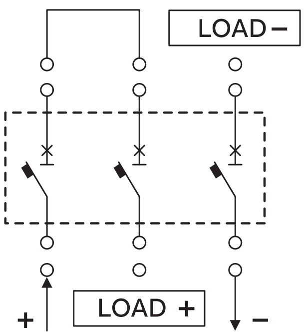
The column with performances referred to a network voltage V_{dc} ≤ 500V DC in the Table A1.3 is considered.
From this column, the circuit breaker version must guarantee an ultimate short-circuit breaking capacity higher than I_k = 45kA. Therefore, the suitable version is N. The immediate solution seems to be the circuit breaker E2N with I_{cu} = 50kA. Its rated current, as seen in the table, is I_n = 1600A.

However, since the current absorbed by the loads is I_L = 1800A, E2N cannot be chosen since the third relationship $I_L \leq I_n$ is not satisfied. Therefore, looking further in the same column, the next suitable option is version N with I_{cu} = 60kA and rated current I_n = 2000A, which leads to the choice of E3.

Let us check the time constants. The Emax DC circuit breakers are tested according to IEC 60947-2 in circuits with a time constant τ_{CB} = 15ms. In this example, since τ_{grid} = 26ms > τ_{CB}, the breaker is suitable for this network parameters.

Therefore, the suitable circuit breaker is a three-pole circuit-breaker type E3N 2000 with PR122-123/DC I_n = 2000A (the connection of the poles is carried out in the factory by ABB SACE).
The connection between three-pole circuit breaker, load and supply source is shown in the Figure 74.

Figure 74 Circuit breaker poles connection for example network 2



7 Applications

7.1 Marine systems

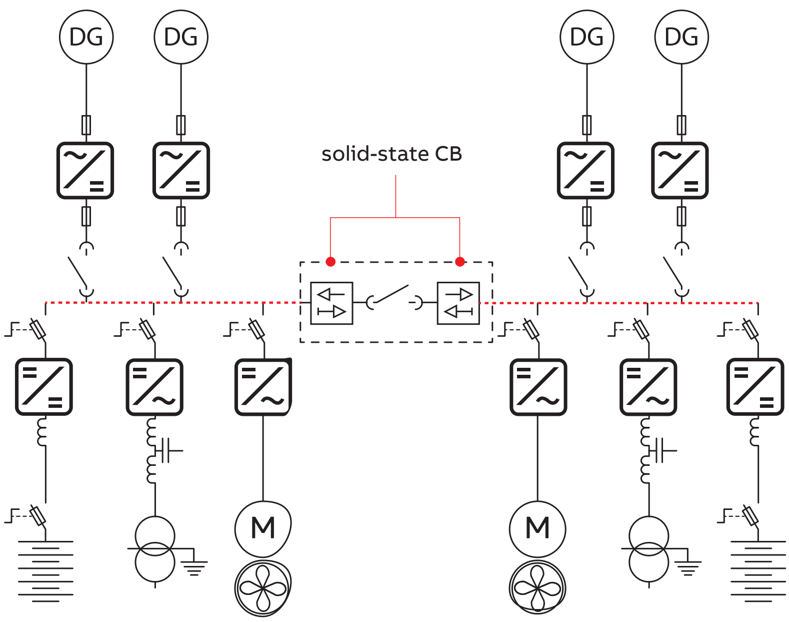
The development of power electronics technology has enabled wide use of Variable Speed Drives (VSDs) for the main propulsion and thrusters in shipboard installations. One of the main advantages of using VSDs is reduction of the fuel consumed by the vessel.

The shipboard DC power system encompasses generation, distribution, power conversion, and ship loads:

- The gen-sets and ship loads are linked to the shared LVDC bus via power converters.
- Electric generators, powered by gas turbines (GTs) or diesel engines (DEs), supply power to the bus.
- Larger vessels utilize multiple generators to meet high power demands as well as to ensure redundancy.
- An energy storage system (ESS) is integrated to offset fluctuations in the DC bus voltage resulting from load variations.
- Ship loads typically include propulsion, services, and pulsed power loads (PPLs).

To optimize the system's efficiency, multiple generator sets are linked to a common bus, supplying power to both propulsion and service loads.

Figure 75 Simplified architecture of a marine DC distribution system



In this way, the overall system efficiency increases by operating some prime movers at high output power levels and deactivating others during periods of low load demand.

Commonly used architecture is the radial bus configuration, as in Figure 75. It is cost-effective because it can deliver power to various loads through independent power lines. However, in the event of a fault, the ship's survivability is compromised. To address this vulnerability, additional energy sources can be installed for service loads, though this is challenging due to space limitations on ships.

In the shipboard DC distribution, isolated system type is favored due to its high survivability and reliability during line-to-earth fault occurrences. Additionally, it is a simple and cost-effective solution. The most critical faults in shipboard LVDC power systems are line-to-line faults.

The protection scheme for shipboard DC power systems often includes a solid-state circuit breaker, as in the Figure 75. It offers improved performance, reliability and safety over traditional mechanical circuit breakers. The main information to be known when choosing a suitable solid-state CB are:

- Operating voltage: the nominal voltage at which the SSCB is supposed to provide full functionality as well as the maximum voltage that the SSCB must withstand must be specified.
- Load profile: the power flow profile between segments in different operation modes is used to select SSCB current rating. For example, the load in the right segment in Figure 75 can be run from generators on the left in failure situation.
- Short-circuit current rate of rise di/dt: when the drive configuration and energy sources (e.g., battery) are known, it is possible to calculate or simulate the short-circuit current rise and resulting peak value that is cut off by SSCB.
- Galvanic isolation: for bus ties is usually required by ship classification societies and registers.

Note: The system integrator should verify the system stability (i.e., oscillations), cooling requirements and a pre-charging method.

7 Applications

7.2 Electric transportation systems

7.2.1 Railway applications

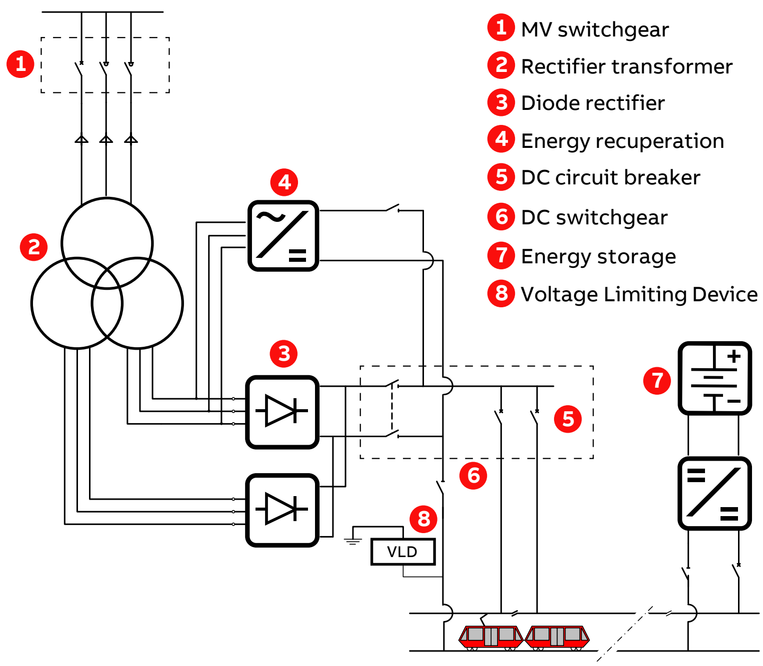
The torque-speed characteristic curve and the ease of speed regulation have led to wide use of DC motors in electric traction. Direct current supply also gives the great advantage of having the contact line consisting of a single conductor since the rails provide the return conductor.

Nowadays, direct current is used above all in urban transport, that is trolleybuses, trams, underground railways with a supply voltage of 600V or 750V, up to 3000V (according to EN50123-1).

An example architecture of a DC traction power supply is shown in Figure 76. It consists of:

- Medium voltage equipment like standard gas- or oil-insulated three-phase switchgear,
- Diode rectifiers or controlled bidirectional rectifiers that allow feeding back surplus energy into the MV grid,
- DC switchgear and voltage limiting devices as control and protection equipment and
- Energy storage systems used for peak shaving and voltage stabilization.

Figure 76 Simplified architecture of a rail electric system [22]



The use of direct current is not limited to vehicle traction only, but it represents a supply source for the auxiliary circuits on board vehicles. To this aim, batteries are installed on board, which constitute an auxiliary power supply source to be used if the external one fails. Additionally, climatic systems in modern trains operate at 110V, and many USB sockets for DC power supply are available for the passengers.

At typical voltage levels of 750V for urban metro and tram systems, and 1.5–3kV for interurban and regional systems, the distance between 1 to 10MW substations is between 3 and 20km, based on the operating voltages. The system is divided into sections using tie-breakers to contain faults within a limited area of impact. Generally, the zone of impact extends to approximately 8km for a 1.5kV DC substation with a current of 4kA [23].

The applications of circuit breakers in DC circuits for electric traction in general can be summarized as follows:

- protection and operation of both overhead and rail contact lines.
- protection of air compressors on board underground and train cars.
- protection of distribution plants for services and signaling systems.
- protection of DC supply sources (batteries).
- protection and operation of DC motors.

In DC railway networks, with large inductance due to the long lines, the fault current takes several milliseconds to reach its prospective value. This behaviour is characterized by the time constant $\tau = L/R$, with the fault current achieving 63% of the prospective value at $t = \tau$. Dedicated electromechanical circuit breakers that can take wide range of time constants and high fault currents are specially designed for these applications.

7.2.2 EV wired charging

Some of the main drivers regarding the future EV charging are:

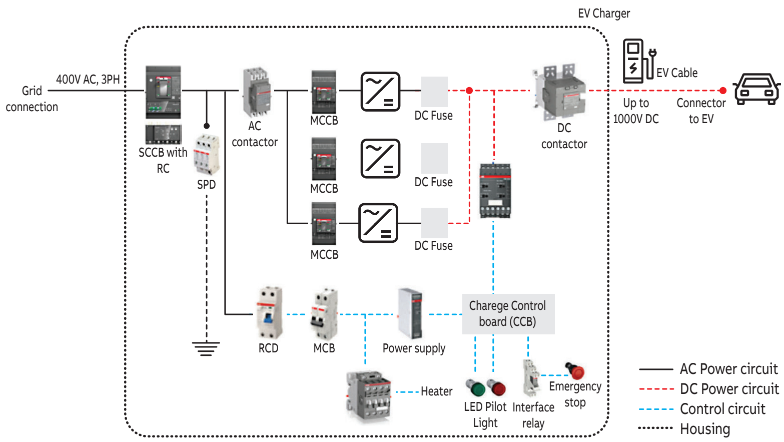
- High-powered and smart charging stations are being built to provide a faster charging time.
- Grid reliability upgrades will support more charger locations and provide local energy production and resources.

The general requirements for EV charging equipment for road vehicles are regulated in the IEC 61851-1 standard. Additionally, requirements for DC chargers with a DC input up to 1.5kV DC are given in the IEC 61851-23. According to these standards, four different charging modes exist, named from 1 to 4. While the modes 1-3 are AC charging, mode 4 means DC charging.

There are two categories of mode 4 DC charging:
- DC fast charging: up to 920V DC, up to 180kW, 60A, intended for public and workplace charging stations and charging time 15-60min.
- DC high power: up to 1200V DC, up to 360kW, 500A, intended for public and e-charging stations and charging time 5-15min.

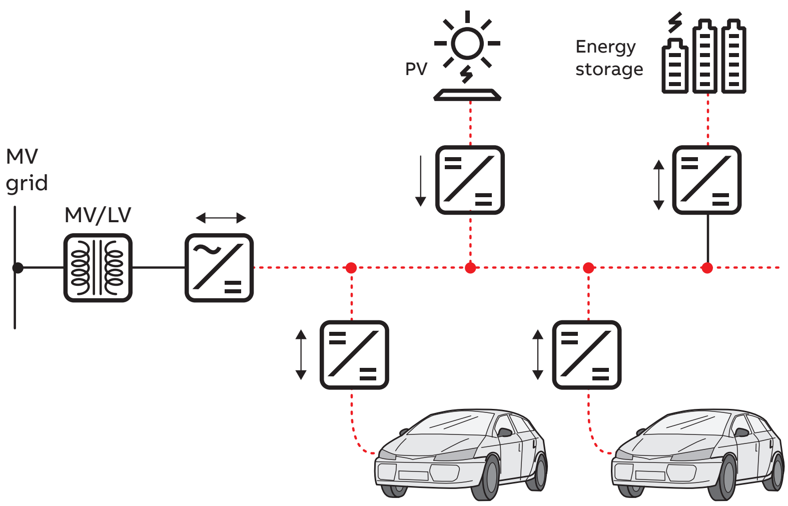
A possible architecture for Mode 4 DC fast charging is shown in Figure 77:

Figure 77 Simplified electrical diagram of mode 4 electric vehicle charging: including protection devices



The EV charging architecture in the Figure 77 is a traditional DC integration. The upgraded concept of active DC networks incorporates RESs like PV generation and battery storage in the system shown in Figure 78.

Figure 78 Electrical diagram of an EV charging station including RESs

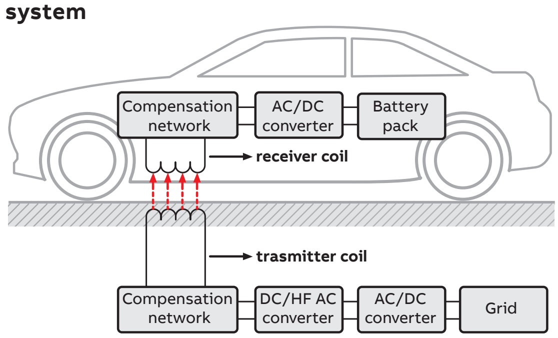


The protection requirements now are rather different: they must account for the worst-case scenario when the other sources are feeding the fault current, increasing the complexity of the protection device choice.

7.2.3 EV wireless charging

Wireless power transfer (WPT) is an innovative technology that enables EV charging without the need for physical cables and plugs. Instead of connecting the vehicle to a charging station using a traditional cable, WPT systems use electromagnetic fields to transfer energy from the charging infrastructure to the vehicle's battery.
A simplified example schematic of a WPT architecture, as in Figure 79, consists of:
- AC/DC converter, typically a diode-bridge rectifier, interfacing the main AC supply grid,
- High-frequency DC/AC converter (20kHz – 100kHz) that controls the output AC voltage in the range between 0.03p.u. and 0.97p.u. of the input DC voltage,
- Passive compensation components used to increase the overall power transfer efficiency,
- Primary and secondary coils, and
- AC/DC converter onboard which charges the vehicle’s battery.

Figure 79 Components of a wireless EV charging system



The transfer of power takes place between transmitting coils located beneath the road surface and receiving coils installed under the vehicle chassis. Each coil has the capacity to transmit power up to about 30kW, so the total power received by the vehicle will be determined by the number of receiving coils it is equipped with.

The wireless EV charging can be static or dynamic. When the transmitting coil or pad is embedded in the ground and the vehicle charges while it is parked over the pad, we have static charging. On the other hand, dynamic charging means the transmitting infrastructure is embedded in the road and the charging takes place while the vehicle moves along the road.

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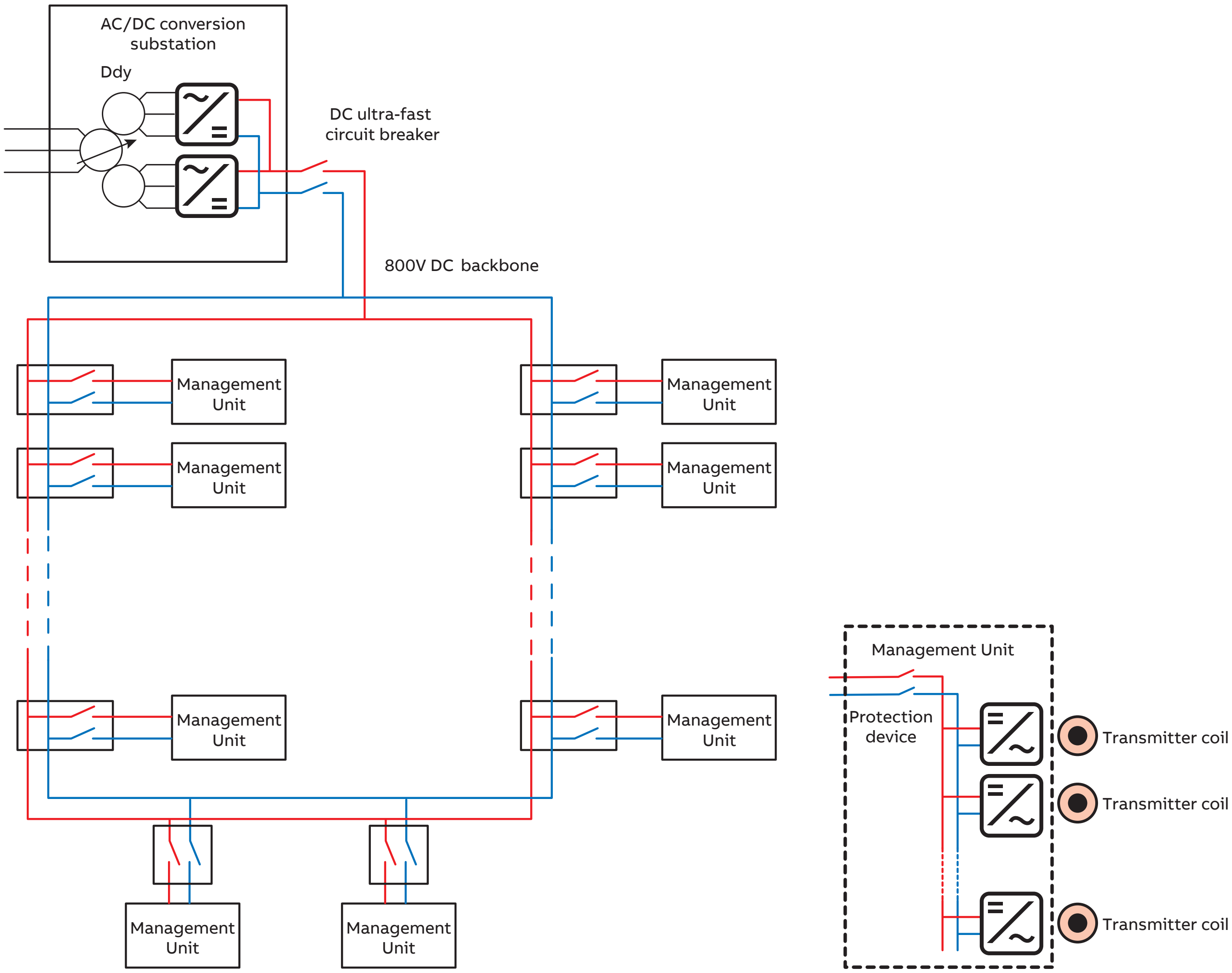
Let us consider an example of dynamic charging. The transmitting coils are activated exclusively when a vehicle equipped with a licensed receiver passes over them. At this juncture, the vehicle is charged by Management Units (MUs) positioned alongside the road, which facilitate the transfer of power from the grid to the transmitting coils (Figure 80).

Each MU incorporates:
- inverters designed to convert DC into high-frequency AC current
- protection devices
- communication systems with approaching vehicles.

ABB participated in the first pilot project in Italy of this kind, named Arena of the Future, which validates the concept of dynamic WPT charging system. It is a 1 km ring, with architecture as shown in Figure 80, supplied by 800V DC distribution, that allows for various testing scenarios [24].

Adopting DC for this application enhances the transmitted power, extends the connection distance from the public distribution grid, and improves overall efficiency due to more favorable cable sizing and the absence of rectifiers within each MU.

Figure 80 Simplified electrical diagram of the wireless charging distribution system [24]



7.3 H_2 generation

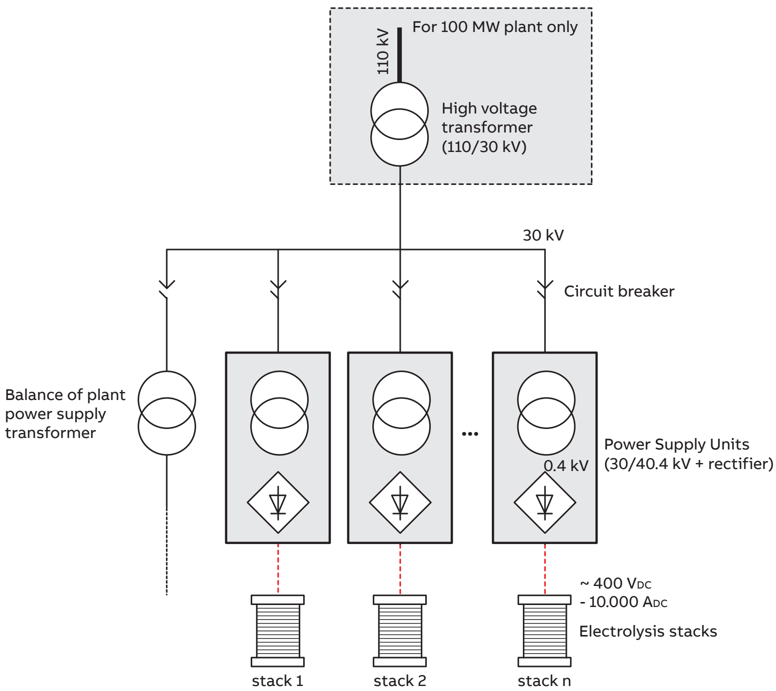
As a clean and efficient energy carrier, hydrogen (H_2) has become an increasingly important focus of research due to its potential to address environmental and energy challenges. There are several methods for H_2 generation, including steam reforming of natural gas, electrolysis of water, biomass gasification, and thermochemical processes.

'Green hydrogen' refers to H_2 obtained through electrolysis, employing electricity derived from renewable energy sources. To make 1kg of H_2 via electrolysis, normally 9kg of water are required and, depending on electrolyzer type, efficiency and lifetime, around 50kWh of electricity. The overall efficiency of a hydrogen-fueled power plant is about 35% [25].

The main elements of a H_2 generation chain are transformer and rectifier, electrolyzer, electrolyte system, gas holder, gas/water separator, deoxidizer, dryer, compressor, filters, pumps, motors, heating and refrigeration systems, oxygen storage tanks, etc.

An electrolyzer is a device that produces hydrogen through an electrochemical process, namely electrolysis. It consists of a conductive electrode stack supplied by DC voltage, and a membrane that separates the electrodes.

Figure 81 Simplified power supply system for H_2 generation with several electrolysis stacks [25]



Electrolysis plants with sizes below 100MW typically connect to the medium-voltage grid (20–30kV). To convert AC to DC, thyristor-based rectifiers (1) are often employed. These rectifiers operate at low input voltage (around 400V AC) and provide DC voltage levels of several hundred volts and sufficient current for the stacks. An example of this architecture is shown in Figure 81: this is simple DC integration.

Rectifiers are typically connected to the stack, which is a series of electrolysis cells commonly connected in series. The voltage and current vary depending on the number of cells in the stack design.

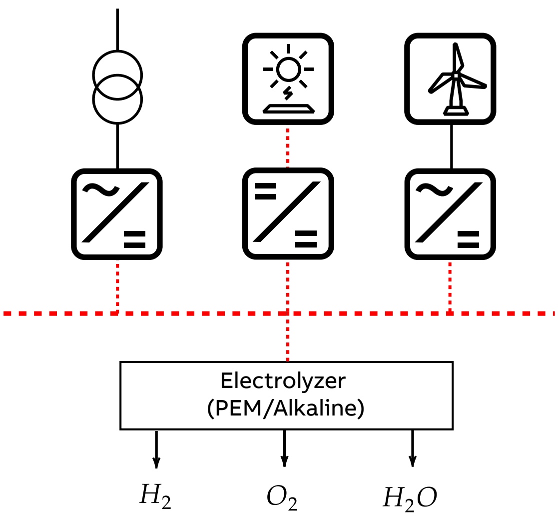
As an example, for a 973 MW total plant output power, about 423 stacks are used with 2.3MW each. The stack is composed by 258 cells connected in series, providing a stack voltage of 452V and stack current about 5kA.

Depending on the plant design and stack configuration, the rectifier may be designed for 400V DC and above, up to 1500V DC.

Protection for low voltage components is primarily needed in the rectifier (on both the AC and DC sides), the compressor, the cooling system, the heaters, and the water purification system.

Active DC network is created when RESs like solar and wind generation are integrated in the H_2 plant (Figure 82). The main driver for this solution is the strong push for decarbonization, and DC microgrids are an enabling technology. The voltage level in this case is about 1500V to 3000V because of the high power required.

Figure 82 RESs integration in a DC electrical system for H_2 generation



(1) Thyristor-based rectifiers have the same structure as diode-bridge rectifiers but they employ thyristors instead of diodes. The main difference is that thyristors need a control signal to be turned on and are turned off naturally when the current falls bellow a certain threshold.

7 Applications

7.4 Industrial application

Some of the main advantages of adopting DC distribution in industrial context are:

- Easy integration of energy storage and decentralized RESs.
- Less losses since DC/DC converters have a higher efficiency than AC/DC converters.
- No losses in additional rectifiers.
- Almost complete reuse of recuperative energy within the DC grid.
- Less copper needed for the distribution lines.

Typical voltage level is about 540V or 650V. Radial or ring architectures are often used and the rated power ranges from 100kW to 4MW. Some of the commonalities of DC industrial applications, as explained in detail in the ODCA documents, are [26]:

- The whole installation is divided in so-called DC sectors,
- Power management is designed by droop curves to ensure stability,
- Bidirectional energy flow in all or parts of the installation (e.g., for energy recovery or storage),
- Voltage ranges and defined timing within each range.

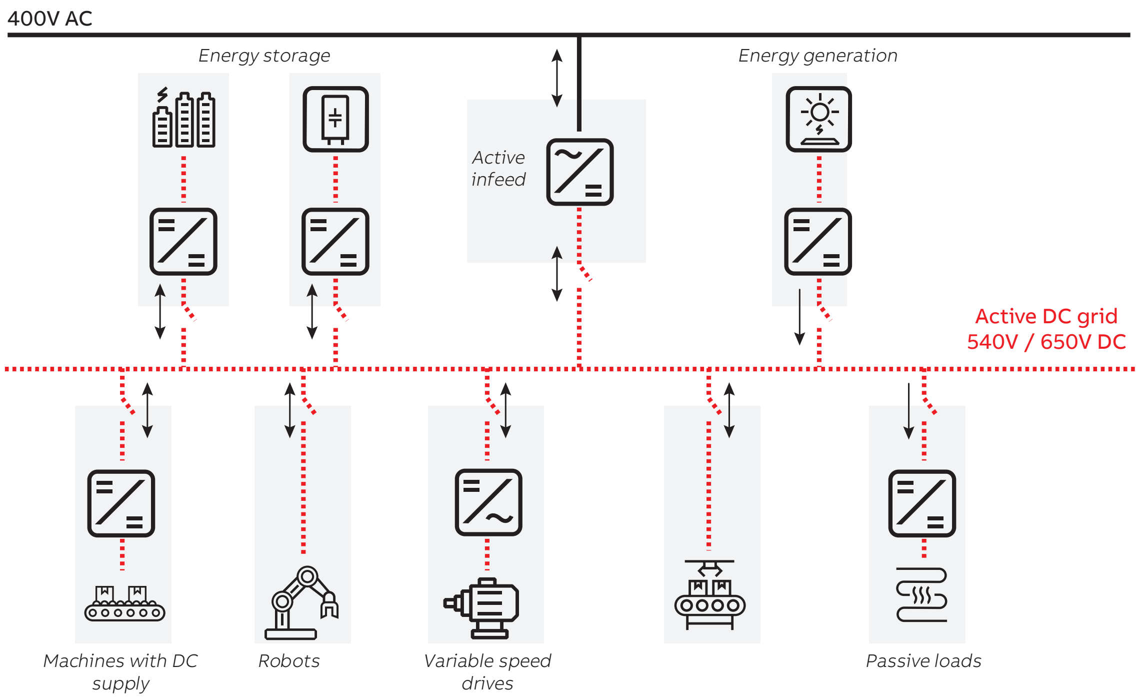
A DC sector is intended as a group of DC devices that are directly connected to one another in terms of power flow and together constitute a logical and functional unit. Each sector is connected to the DC grid via a so-called sector breaker that entirely cuts off the sector from the DC grid if a fault occurs within the sector. An example is shown in Figure 83, where each DC sector is highlighted in gray-shaded areas.

The sector breaker should provide protection in case of an overcurrent, short-circuit or earth fault. A DC sector breaker can be a single device or a combination of devices which provide adequate protection capabilities plus monitoring of the voltage and current levels.

Depending on the earthing scheme, high-speed protective devices should be used on one or both polarities. Typically the breaker includes current measurement to provide protection against overloads and short-circuits, as well as mechanical contacts for isolation to ensure reliable disconnection of the circuit if required.

Some of the common issues the designer must pay attention to are related to the electromagnetic compatibility of such installations, pre-charging steps and earthing choice.

Figure 83 Simplified electrical diagram of an active DC industrial grid



7.5 Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems can be divided into three categories, depending on their connection point to an AC grid. As illustrated in the Figure 84, this can be:

1. Residential Storage Systems (HSS)
    a. Residential and small commercial PV storage
2. Industrial Storage Systems (ISS)
    a. Commercial and industrial peak-shaving
    b. Stationary E-mobility for fast charging stations
3. Large scale storage systems (LSS)
    a. Renewable integration
    b. Frequency regulation
    c. Arbitrage – difference between peak and off-peak electricity cost

All systems have a similar fundamental layout: multiple battery modules are connected in series up to a certain system operation voltage. This setup is called a “battery bank”. Beside the application in residential PV storages, very often several racks are put in parallel to increase the overall capacity.

Commonly, BESS systems are built as IT systems, which are then equipped with an earth fault detection device. In case of an earth fault, the systems either shut down automatically to a safe mode or demand a service.

A Battery Management System (BMS), as the one in Figure 85, continuously monitors system parameters like voltage and temperature and communicates with the converter. In case a fault occurs, it trips the protection devices.

Figure 84 Overview on BESS systems (based on [27])

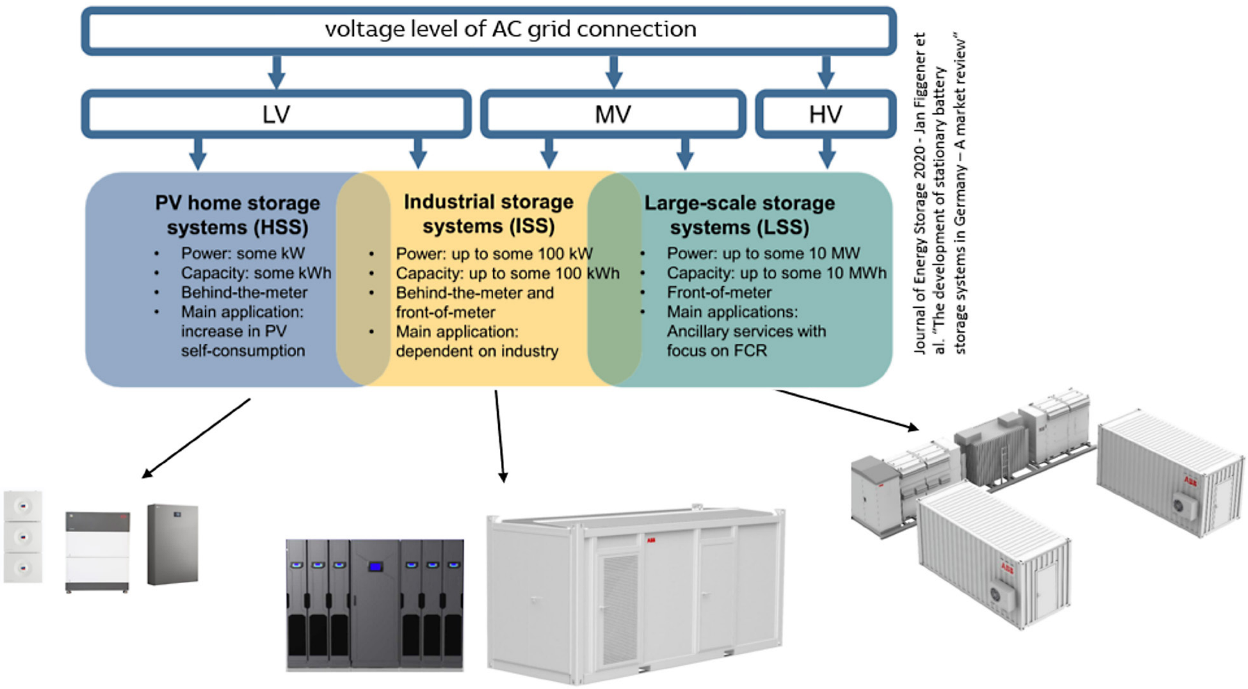
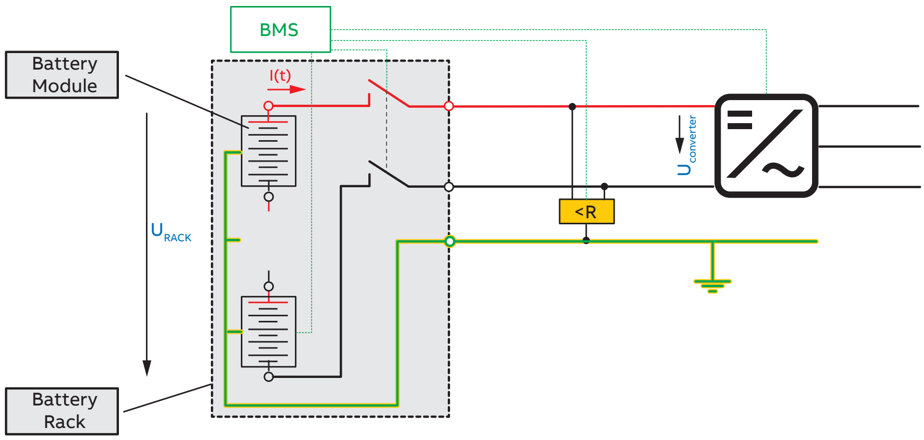


Figure 85 Layout of a standard BESS system



7 Applications

7.5.1 Residential Storage Systems

Home storage systems are very often connected with PV installations. Their standard voltage level is <600V DC and nominal current levels <63A. Most often they comprise a single battery rack. MCBs are suitable protection devices here.

7.5.2 Industrial Storage Systems

Beside protection devices, the offering of ABB comprises also industrial storage systems for different applications, as the ABB eStorage Flex. Their standard voltage level is 800 – 1500V DC and nominal current levels 90 - 256A. Most often they comprise several battery racks in parallel. MCCBs and fuses are suitable protection devices here.

Uninterruptable Power Supplies (UPS) are a further application and belong to the ABB portfolio, as the ABB Megaflex UPS. Here the standard voltage level is <800V DC and nominal current levels ~125A. Most often they comprise several battery racks in parallel. MCCBs and fuses are suitable protection devices here.

7.5.3 Large-Scale Storage Systems

Further offering of ABB comprises also large-scale storage systems for applications like frequency regulation. Their standard voltage level is 800 – 1500V DC. Most often they comprise multiple industrial storage systems in parallel (multiple racks and multiple converters). Again, MCCBs and fuses are suitable protection devices here.

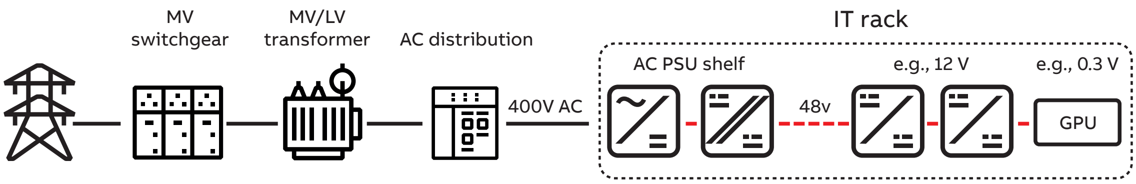
7.6 DC in Data Center

The rapid growth of cloud computing, artificial intelligence (AI), mobile communication and social media leads to the construction of numerous new data centers, which can consume megawatts of electric power.
An IT rack[1] for housing electronic chips used to be a small load, consuming only hundreds of watts in the past; nowadays these chips are moving to a few kilowatts range. It means that, shortly, an IT rack will require from 500kW to 1MW of power itself [28].

Data centers rely on advanced power distribution systems to ensure both reliability and power quality. Electric power is processed by power converters multiple times: typically, 2 to 3 power conversions occur, depending on the system architecture chosen.
This results in a high concentration of power electronics and consequently, the infrastructure supporting these data centers must be carefully designed to meet the increasing energy demands.

The IT racks with rated power between 10kW and 100kW use 48V DC internally [28]: an example architecture is shown in Figure 86, where PSU stands for power supply unit, and GPU for graphics processing unit. However, adopting such a low DC voltage level for a 1MW rack would require about 200kg of copper solely for the rack busbar [29], which is not feasible from both mechanical and economical perspective.
Similarly, the power infrastructure of the data centers is not designed for such high power levels. Therefore, both the IT rack and the data center infrastructure must be rethought.

Figure 86. Traditional power supply architecture for data centers.



[1] IT rack, also known as a server rack or equipment rack, is a standardized frame or enclosure used to house and organize multiple hardware components, like servers, networking equipment, etc. The racks are designed to optimize space, improve airflow for cooling, and facilitate easy access for maintenance and upgrades.

One of the possible solutions is to separate the single rack into a power rack (when disaggregated like this, also known as sidecar) and server rack, each optimized for its primary function. In this way, space can be optimized, power conversion efficiency increases, and this modular concept is easily scalable. The disaggregated power rack (sidecar) can be parallelized to meet various power requirements from 800kW to more than 1MW, while keeping the IT (server) rack the same.

An example of such architecture is the Mount Diablo project (Figure 87). It results from the collaboration between Meta, Microsoft and Google in the Open Compute Project (OCP), aiming at standardized specifications for electrical and mechanical interfaces for the future data centers [30]. Mount Diablo is an AC-DC sidecar power rack that disaggregates power components form the IT rack, allowing connection to existing AC supply infrastructure. It consists of a galvanically isolated AC-DC converter, and an AC overcurrent and short-circuit protection and cabled power distribution.

Multiple AC-DC converters can be used, where active current sharing can be adopted through voltage droop control. Supported AC input is 400V, 415V and 480V, with rated power ranging from 25kW to 30kW per rectifier [31]. The sidecar can also contain an energy storage block, i.e., a battery backup or a capacitor bank unit, to enhance computing availability.

The AC supply is converted to a ±400V DC system with a mid-point. According to the most recent specifications, the mid-point can either be solidly earthed or connected to earth through a high resistance, with both approaches having advantages and disadvantages [31]. In any way, suitable overcurrent protection and switching devices must be installed on the DC side of the power rack. There cannot be a leakage current exceeding 3.5mA (AC) and 10mA (DC).

The IT rack is connected to the sidecar by cables rated at 63A up to 125A [31]. Each output cable/connection to IT rack must have a Ground Fault Detection (GFD) for either solidly earthed mid-point or high-resistance mid-point earthing. In the latter case, a voltage balance detection circuit is necessary as well.

Figure 87. Power supply architecture for data centers: disaggregated approach.

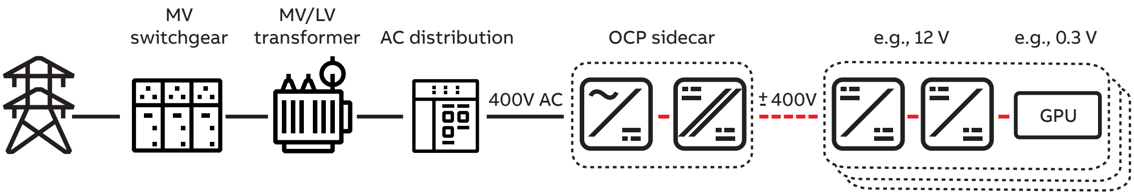
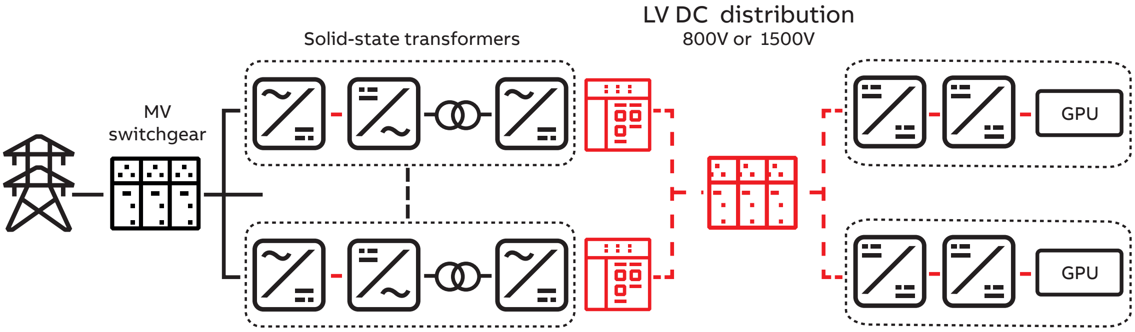


Figure 88. An example of data center power supply architecture using solid-state transformers.



[2] Solid-state transformer is a power converter that replaces traditional, low-frequency transformer. It consists of a rectifier and a galvanically isolated DC-DC converter. The later usually contains a high-frequency transformer.

7 Applications

These modifications of the data center and IT rack architectures are significant, but likely they are not enough to support the future needs of the AI industry. The next step is converting the AC power distribution to 800V DC distribution [29], which will be enabled by emerging solid-state transformer[2] (SST) .
The SSTs reduce the footprint of the connection to the MV grid and have high control capability [32].
When used together with DC distribution, the power delivery becomes very efficient, reaching up to 98.2% MV to load efficiency [33]. There are several different architectures employing SSTs that can be adopted for data center applications, like the example in Figure 88.

The protection of the LV DC system will need to evolve to contain potentially dangerous arc energy without compromising the power density and efficiency gains introduced by the higher voltages and new technologies.

The key design points for the protection equipment in DC data centers are likely to be:

- Operating speed to prevent arc energy build up
- Overvoltage coordination to protect sensitive IT equipment
- Schemes ensuring high IT equipment availability
- High power density of the components and resulting systems
- High electric efficiency supporting the driver to lower power utilization efficiency.

8 Conclusions

This technical application paper offered a comprehensive examination of the critical role of DC grids in the transition to an all-electric society. Let us summarize the key points highlighted in the document:

- **Unique characteristics of fault in DC circuits:**
  - DC fault currents do not have zero crossings.
  - DC fault currents can reach a significantly high peak within microseconds, creating challenges for traditional protection devices.
  - The DC bus voltage decreases consequently: it can collapse to zero or even small negative values.
- **Limitations of traditional protection devices:**
  - Conventional AC circuit breakers (miniature, molded-case and air circuit breakers) are not directly applicable in DC grids unless they meet specific criteria related to their short-circuit breaking capacity, arc voltage and grid time constant.
- **Fault scenarios:**
  - The paper discussed pole-to-pole and pole-to-earth faults in different network earthing types (one polarity earthed, earthed mid-point and isolated grids).
  - Each fault scenario has distinct implications for the selection of protection devices, according to the network earthing.
- **Converter topology:**
  - Different power electronic converter configurations exhibit varying fault behaviors.
  - Simple buck and boost converters can limit fault currents only on the low-voltage side. Galvanically isolated or input-output symmetrical topologies can limit fault currents on both sides.
  - A fault downstream of a converter is dominated by capacitor discharge, potentially reaching hundreds of times the nominal current.
- **Selection criteria for protection devices:**
  - Key parameters to consider for selecting a thermal-magnetic protection device include network type and fault current path, rated operational voltage, short-circuit current at the installation point, rated load current and grid time constant.
  - For a solid-state circuit breaker selection, key information are network type and fault current path, grid voltage, maximum switchable inductance and fault current rate of rise.
  - The critical question is how fast the protection should be, i.e., depending on the application, a fast (µs) or a slower (ms) protection may be required.
- **Bidirectional fault protection:**
  - In the case of decentralized DC grids, where multiple sources and loads complicate fault current flow, bidirectional protection may be needed.
- **Switching technologies:**
  - The paper compares the use of solid-state circuit breakers and thermal-magnetic circuit breakers in different applications.

In summary, this technical application paper aims to enhance the understanding of the complexities of DC systems and their protection requirements. As ABB continues to lead in electrification and automation, the insights provided will contribute to the development of safer and more efficient DC systems, aligning with the broader goal of creating a sustainable energy future.

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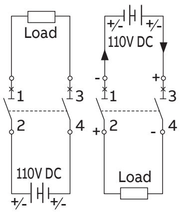
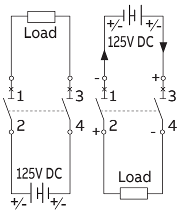
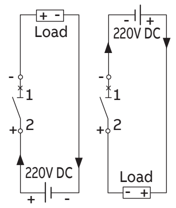
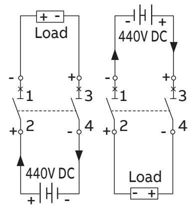
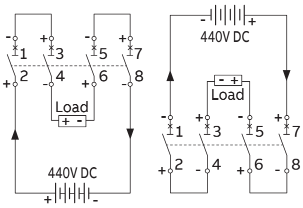
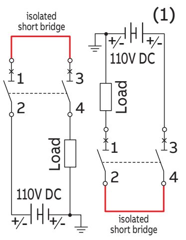
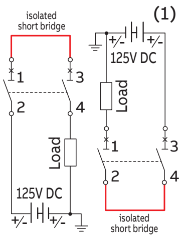
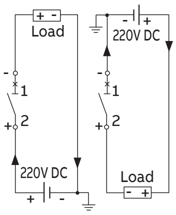
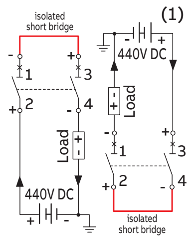
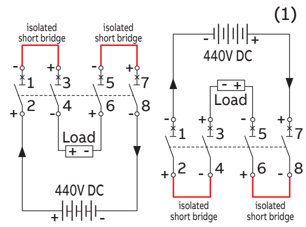
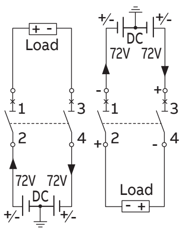
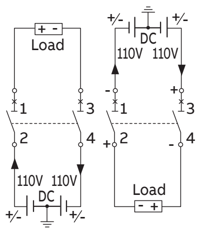
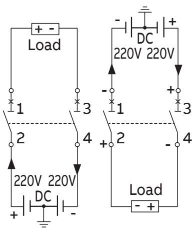
Appendix 1

In this appendix, we present the basic technical characteristics and wiring diagrams for miniature, molded-case and air circuit breakers.

Table A1.1 Miniature circuit-breakers characteristics and wiring diagrams

	S200 / S200 M(T) / S300P (AC)		S200 MUC / MTUC		
Voltage Un	72V DC	125V DC	≤ 220	≤ 440V DC	≤ 440V DC
Rated current	1-63A	1-63A	0.5-63A	0.5-63A	0.5-63A
Short-circuit current	6/ 10/ 25kA	6/ 10/ 25kA	6/ 10/ 25kA	6/ 10/ 25kA	6/ 10/ 25kA
Characteristic	B, C, D, K, Z	B, C, D, K, Z	B, C, K, Z	B, C, K, Z	B, C, K, Z
	bidirectional	bidirectional	polarity dependent	polarity dependent	polarity dependent
Insolated network Bipolar system					
Network with one polarity earthed Unipolar system					
Network with mid-point earthed Bipolar without distributed M Note: "Bipolar" =Two sources in series with each 1/2*Un					

(1) It must be ensured that the bridge between the 2 poles is as short as possible and isolated to avoid a ground fault at that point (isolated busbar recommended)

Appendix 1

Table A1.2 Tmax XT molded-case circuit breaker characteristics

Size		XT1					XT2					XT3	
Rated uninterrupted current	[A]	160					160					250	
Poles	No.]	3, 4					3, 4					3, 4	
Rated service voltage, Ue (DC)	[V]	500					500					500	
Rated insulation voltage, Ui (DC)	[V]	800					1000					800	
Rated impulse withstand voltage, Uimp	[kV]	8					8					8	
Versions		Fixed, Plug-in [2]					Fixed, Withdrawable, Plug-in					Fixed, Plug-in	
Breaking capacities according to IEC 60947-2		B	C	N	S	N	N	S	H	L	V	N	S
Rated ultimate short-circuit breaking capacity, Icu													
Icu @ 250V (DC) 2-pole in series	[kA]	18	25	36	50	70	36	50	70	85	100	36	50
Icu @ 500V (DC) 2-pole in serie	[kA]	–	–	–	–	–	–	–	–	–	–	–	–
Icu @ 500V (DC) 3-pole in serie [1]	[kA]	18	25	36	50	70	36	50	70	85	100	36	50
Icu @ 750V (DC) 3-pole in serie	[kA]	–	–	–	–	–	–	–	–	–	–	–	–
Rated service short-circuit breaking capacity, Ics													
Ics @ 250V (DC) 2-pole in series	[kA]	100%	100%	100%	100%	75%	100%	100%	100%	100%	100%	100%	75%
Ics @ 500V (DC) 2-pole in serie	[kA]	–	–	–	–	–	–	–	–	–	–	–	–
Ics @ 500V (DC) 3-pole in serie [1]	[kA]	100%	100%	100%	100%	75%	100%	100%	100%	100%	100%	100%	75%
Ics @ 750V (DC) 3-pole in serie	[kA]	–	–	–	–	–	–	–	–	–	–	–	–

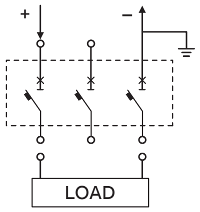
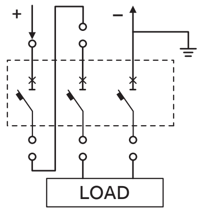
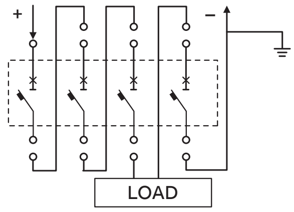
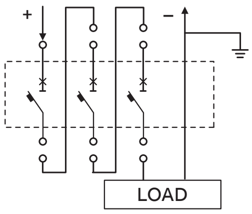
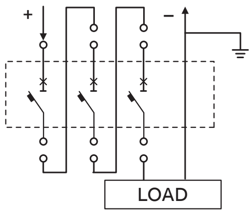
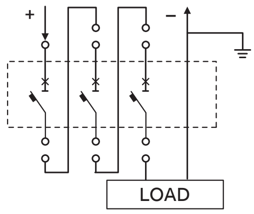
[1] XT1: a 4 poles in series connection is required to be used in 500V DC installations.

[2] XT1 plug-in In max=125A

Size		XT4						XT5						XT6		
Rated uninterrupted current	[A]	160/250						400/630								
Poles	No.]	3, 4						3, 4								
Rated service voltage, Ue (DC)	[V]	750						750								
Rated insulation voltage, Ui (DC)	[V]	1000						1000								
Rated impulse withstand voltage, Uimp	[kV]	8						8								
Versions		Fixed, Withdrawable, Plug-in						Fixed, Withdrawable, Plug-in						Fixed, Withdrawable		
Breaking capacities according to IEC 60947-2		N	S	H	L	V	X	N	S	H	L	V	X	N	S	H
Rated ultimate short-circuit breaking capacity, Icu																
Icu @ 250V (DC) 2-pole in series	[kA]	36	50	70	85	100	100	25	35	50	70	85	100	35	50	70
Icu @ 500V (DC) 2-pole in serie	[kA]	36	50	70	85	100	100	25	35	50	70	85	100	20	35	50
Icu @ 500V (DC) 3-pole in serie	[kA]	36	50	70	85	100	100	–	–	–	–	–	–	–	–	–
Icu @ 750V (DC) 3-pole in serie	[kA]	–	–	–	–	50	70	–	–	–	–	85 [1]	100 [1]	18	24	36
Rated service short-circuit breaking capacity, Ics																
Ics @ 250V (DC) 2-pole in series	[kA]	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	50%
Ics @ 500V (DC) 2-pole in serie	[kA]	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	50%
Ics @ 500V (DC) 3-pole in serie	[kA]	100%	100%	100%	100%	100%	100%	–	–	–	–	–	–	–	–	–
Ics @ 750V (DC) 3-pole in serie	[kA]	–	–	–	–	100%	100%	–	–	–	–	100%	100%	100%	100%	75%

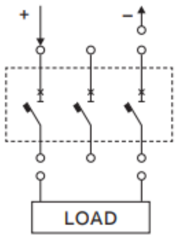
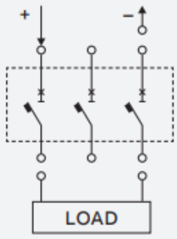
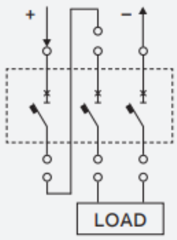
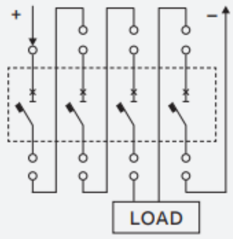
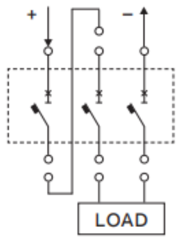
[1] Power supply only from the top

Table A1.3 Tmax XT circuit breaker connection diagrams of the poles in a network with one earthed polarity

Network with one earthed polarity						
Un	**≤ 250**		**≤ 500**			**≤ 750**
Protection + insulation function						
Protection function						
XT1		1.6				
XT2		1.5		1.5	1.5	
XT3		1.35		1.35	1.35	
XT4		1.5		1.5	1.5	1.5
XT5	1.1		1.1			1.1
CT6	1.1		1.1			1

Note: in the considered connections, the earthed polarity is the negative one.

Table A1.4 Tmax XT circuit breaker connection diagrams of the poles in an isolated network

Insulated network					
Un	**≤250**		**≤500**		**≤750**
Protection + insulation function					
XT1	1.6			1.6	
XT2	1.5		1.5		
XT3	1.35		1.35		
XT4	1.5	1.5			1.5
XT5	1.1	1.1			1.1
XT6	1.1	1.1			1

Appendix 1

Table A1.5 Tmax XT switch-disconnectors connection diagrams of the poles

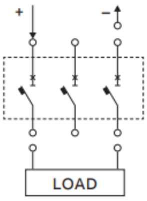
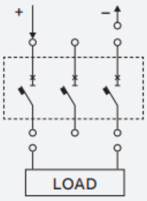
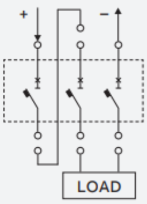
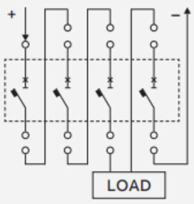
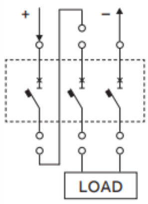
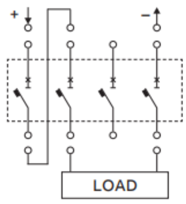
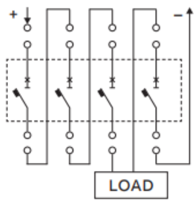
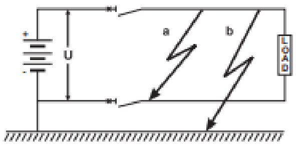
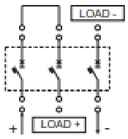
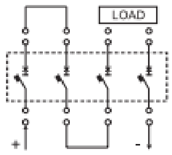
Un	≤250	≤500			≤750		
Protection + insulation function							
XT1	■			■			
XT3	■		■				
XT4	■		■				
XT5	■	■			■		
XT6	■	■			■		
XT7	■		■		■	■	■

Table A1.6 Emax DC circuit breakers wiring diagram in case of network with one earthed polarity

Network with earthed negative polarity (1)

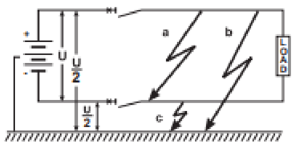
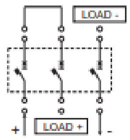
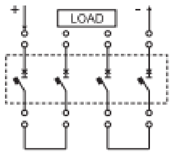
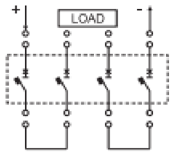
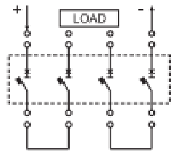
Rated voltage (Ue)			≤ 500(2)			
						
isolation			■		■	
protection			■		■	
PR122/DC			■		■	
PR123/DC			■		■	
type of fault (3)			a	b	a	b
poles in series affected by the fault			3	2	4	3
Icu(4)			[kA]		[kA]	
E2	**B**	**800**	**35**	**20**	**35**	**35**
		1000				
		1250				
		1600				
	N	**1600**	**50**	**25**	**50**	**50**
E3	**N**	**800**	**60**	**30**	**60**	**60**
		1000				
		1250				
		1600				
		2000				
		2500				
	H	**1600**	**65(5)**	**40**	**65(5)**	**65(5)**
		2000				
		2500				
E4	**S**	**1600**	**100**	**50**	**100**	**100**
		2000				
		2500				
		3200				
	H	**3200**	**100**	**65**	**100**	**100**
E6	**H**	**3200**	**100**	**65**	**100**	**100**
		4000				
		5000				

(1) for networks with positive earthed polarity, ask ABB.
(2) for higher voltages, ask ABB.
(3) for further information, see QT5: "ABB circuit-breakers for direct current applications".
(4) Icu with L/R = 15ms according to IEC 60946-2 Standard. For Icu with L/R = 5ms and L/R = 30ms, ask ABB.
(5) 85kA only if supplied from lower terminals and specifying the following extracode at the ordering stage: 1SDA067148R1. Ics=65kA.

Appendix 1

Table A1.7 Emax DC circuit breakers wiring diagram in case of network with earthed mid-point

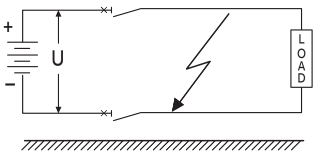
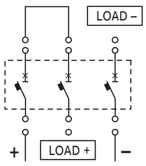
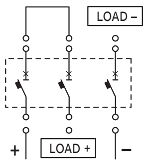
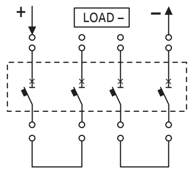
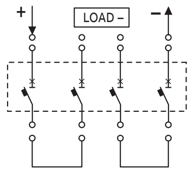
Network with the mid-point earthed

Rated voltage (Ue)			≤ 500			≤ 500			≤ 750			≤ 1000		
														
PR122/DC			-			-			-			-		
PR123/DC			■			■			■			■		
type of fault			a	b	c	a	b	c	a	b	c	a	b	c
poles in series affected by the fault			3	2 (U/2)	1 (U/2)	4	2 (U/2)	2 (U/2)	4	2 (U/2)	2 (U/2)	4	2 (U/2)	2 (U/2)
Icu[1]			[kA]			[kA]			[kA]			[kA]		
E2	**B**	**800 1000 1250 1600**	**35**	**35**	**18**	**35**	**35**	**35**	**25**	**25**	**25**	**25**	**25**	**25**
	N	**1600**	**50**	**50**	**25**	**50**	**50**	**50**	**40**	**40**	**40**	**25**	**25**	**25**
E3	**N**	**800 1000 1250 1600 2000 2500**	**60**	**60**	**30**	**60**	**60**	**60**	**50**	**50**	**50**	**35**	**35**	**35**
	H	**1600 2000 2500**	**65[2]**	**65**	**40**	**65[2]**	**65[2]**	**65[2]**	**50**	**50**	**50**	**40**	**40**	**40**
E4	**S**	**1600 2000 2500 3200**	**75**	**75**	**35**	**75**	**75**	**75**	**65**	**65**	**65**	**50**	**50**	**50**
	H	**3200**	**100**	**100**	**50**	**100**	**100**	**100**	**65**	**65**	**65**	**65**	**65**	**65**
E6	**H**	**3200 4000 5000**	**100**	**100**	**65**	**100**	**100**	**100**	**65**	**65**	**65**	**65**	**65**	**65**

[1] Icu with L/R = 15ms according to IEC 60946-2 Standard. For Icu with L/R = 5ms and L/R = 30ms, ask ABB.
[2] 85kA only if supplied from below and specifying the following extracode at the ordering stage: 1SDA067148R1. Ics=65kA.

Table A1.8 Emax DC circuit breakers wiring diagrams in the case of isolated network

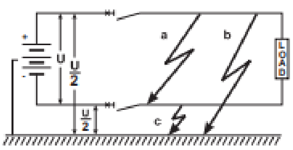
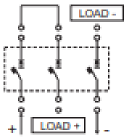
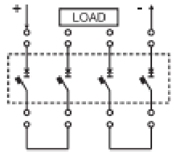
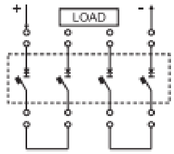
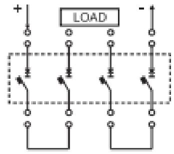
Isolated network [1]

Rated voltage (Ue)			≤ 500	≤ 750		≤ 1000
						
Insolation			■	■	■	■
protection			■	■	■	■
PR122/DC			■	■	■	■
PR123/DC			■	■	■	■
Icu [2]			[kA]	[kA]	[kA]	[kA]
E2	**B**	800 1000 1250 1600	35	25	25	25
	N	1600	50	25	40	25
E3	**N**	800 1000 1250 1600 2000 2500	60	40	50	35
	H	1600 2000 2500	65[2]	40	50	40
E4	**S**	1600 2000 2500 3200	75	65	65	50
	H	3200	100	65	65	65
E6	**H**	3200 4000 5000	100	65	65	65

[1] the possibility of a double earth fault is considered negligible with this type of pole connections. For further information, see QT5: "ABB circuit-breakers for direct current applications".
[2] Icu with L/R = 15ms according to IEC 60947-2 Standard. For Icu with L/R =30 ms, ask ABB
[3] 85kA only if supplied from lower terminals and specifyng the following extracode at the ordering stage: 1SDA067148R1. Ics=65kA.

Appendix 1

Table A1.9 Emax DC circuit breakers wiring diagram in case of network with earthed mid-point

Network with the mid-point earthed														
Rated voltage (Ue)			≤ 500			≤ 500			≤ 750			≤ 1000		
														
PR122/DC			-			-			-			-		
PR123/DC			■			■			■			■		
type of fault			a	b	c	a	b	c	a	b	c	a	b	c
poles in series affected by the fault			3	2 (U/2)	1 (U/2)	4	2 (U/2)	2 (U/2)	4	2 (U/2)	2 (U/2)	4	2 (U/2)	2 (U/2)
Icu[1]			[kA]			[kA]			[kA]			[kA]		
E2	B	800 1000 1250 1600	35	35	18	35	35	35	25	25	25	25	25	25
	N	1600	50	50	25	50	50	50	40	40	40	25	25	25
E3	N	800 1000 1250 1600 2000 2500	60	60	30	60	60	60	50	50	50	35	35	35
	H	1600 2000 2500	65[2]	65	40	65[2]	65[2]	65[2]	50	50	50	40	40	40
E4	S	1600 2000 2500 3200	75	75	35	75	75	75	65	65	65	50	50	50
	H	3200	100	100	50	100	100	100	65	65	65	65	65	65
E6	H	3200 4000 5000	100	100	65	100	100	100	65	65	65	65	65	65

[1] Icu with L/R = 15ms according to IEC 60946-2 Standard. For Icu with L/R = 5ms and L/R = 30ms, ask ABB.
[2] 85kA only if supplied from below and specifying the following extracode at the ordering stage: 1SDA067148R1. Ics=65kA.

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