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Necessary Considerations for Designing DC Architectures in Data Centers

White Paper 47

Version 1

Energy Management Research Center

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Executive summary

As global policies are calling for more sustainable development of data center infrastructures and energy efficiency, a maturing data center industry is looking to build on the successful infrastructure optimization of the past decade. Alternative power distribution architectures remain an important avenue for data center electrical designers looking to decrease costs and increase efficiency. Architectures using direct current (DC) distribution provide a prospective simplification of the AC/DC/AC conversion stage required in a traditional double conversion UPS and have gained some traction. However, when making this change, there are 5 areas that require additional focus including power converter design, UPS bypass, isolation and earthing, DC fault modeling and studies, and protection selection. Appropriately addressing these considerations in DC architectures is not trivial, however it allows for better data center designs and a better view of the implications of considering DC during the design planning stage.

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Introduction

Simplification is often at the root of efforts to make improvements in systems. In power architectures, minimizing power conversion stages is frequently associated with an increase in efficiency and a decrease in capital expense (CAPEX) and is often high-lighted by proponents as an advantage of the emerging direct current (DC)-based architectures in data centers. Given that IT loads in datacenters ultimately operate on DC and batteries used upstream of the loads to provide uninterruptable power are also DC, using DC power distribution (Figure 1) provides an apparent simplification. When deploying batteries using a centralized uninterruptable power supply (UPS), using a DC UPS instead of an AC UPS and distributing DC within the facility can maintain this simplification, when viewed at this level of abstraction.

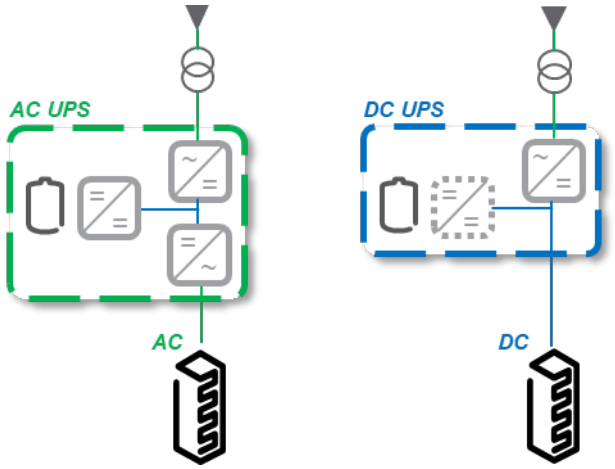


Figure 1

High level simplification of DC UPS and DC distribution compared to AC UPS and AC distribution

This paper will focus on the DC UPS concept and the resulting DC distribution[1], exploring the five necessary technical considerations beyond the apparent high-level simplification. The five considerations are:

- DC UPS power conversion topologies
- UPS bypass
- Isolation requirements and grounding constraints
- Fault simulation and calculation
- Protection device selection

These technical details should provide design input for DC data center architectures and serve as critical information in the design planning and consideration phase.

Overview of power conversion stages in data centers

Traditionally, power distribution in data centers has been done with alternating current (AC), consistent with available power from the greater electrical grid as well as with the dominant standards, equipment, and practices used throughout facilities of all kinds. Within the distribution path, between the grid connection and where the final load operates, multiple power conversion stages exist. They serve various functions including power quality stability, power outage back-up, voltage step-down and AC/DC rectification. Figure 2a illustrates a typical AC UPS data center powertrain, excluding a redundant pathway and maintenance bypass that would be typically present for a mission-critical facility.

[1] OCP-type systems have been the subject of other studies and utilize more traditional AC distribution

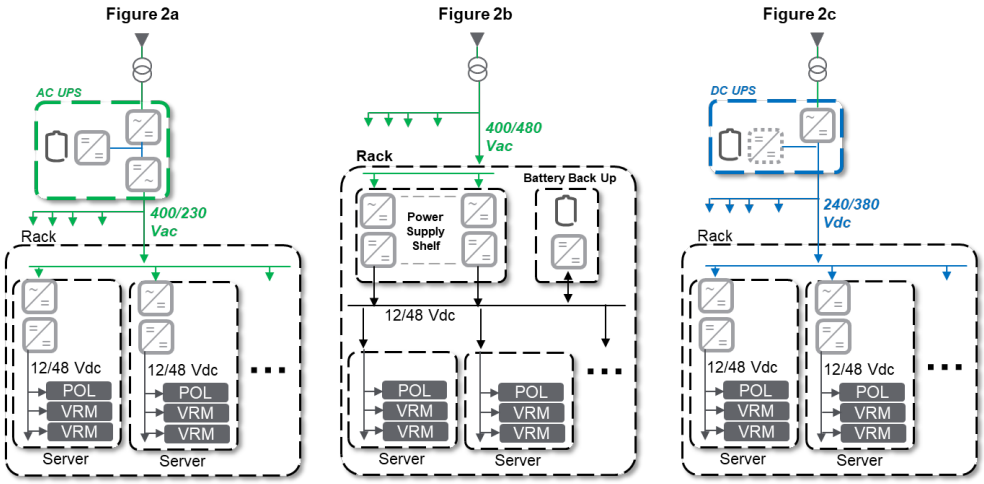


Figure 2

Power conversion stages in a standard IT powertrain: AC UPS, OCP, & DC UPS

Principal to data center power architecture and design is the support of critical loads which must be provided with uninterrupted and high-quality power, otherwise there is a high risk of a service outage. As a result, prominent in traditional architectures and shown in **Figure 2a** is an uninterruptable power supply (UPS). While many variations exist, UPSs generally use double conversion topologies with conversion from AC to DC and then conversion back to AC for distribution to the loads. Double conversion UPS systems provide two functions. First, through double conversion, the output is decoupled from the input power, providing pure sine wave output. Second, conversion through DC allows for the integration of DC energy storage which provides uninterrupted power to the loads in the event of loss of upstream power.

Energy storage in the UPS is generally, but not exclusively, used to cover gaps in input power during the transition to and from onsite generators. Also present in data center power architectures is power conversion at the server level providing 12V or 48V DC for server internal distribution and use. This is a change in voltage level from standard final distribution voltages (120V/208V, 400V/230V, etc.) as well as commonly a conversion from Vac to Vdc. IT Power Supply Units (PSUs) generally contain two stages of conversion as illustrated in the figures. Historically, UPS systems and IT power supplies have been separate products and sub-systems.

One evolving newer architecture which has gained traction, primarily in NAM, is the aggregation of IT power supply conversion to the IT rack level and distributing energy storage and historic UPS functionality within the rack. This is illustrated in **Figure 2b** and exemplified by open design standards such as the Open Compute Project (OCP). Energy efficiency is increased by a reduction of the number of power conversions in the prime power path (from utility to load) as well as from a reduction in the oversize ratio[2] enabled by aggregating PSUs and providing the potential for N+1 redundancy.

Another newer power architecture that has gained traction in China is the adoption of a DC UPS (primarily at the pod level) with DC distribution within the facility. At the time of this writing, it represents around a quarter of the China market for new data center builds. As shown in **Figure 2c**, it features a centralized conversion to 240 Vdc[3] with battery back-up directly connected at the DC main bus.

[2] The total nameplate capacity of the installed converters, vs the designed power draw of the IT

[3] Other DC voltages exist, such as 336Vdc / 380Vdc, however 240Vdc is dominant

The output voltage may float within a range of about 30%, bound by the connected battery strings' voltage through its discharge curve. The power distribution system must be sized to accommodate the lowest end of this voltage window. Some variants add a DC/DC converter between the batteries and the main bus, tightening the voltage regulation of the DC bus to +/- 1% and reducing the prospective short circuit contribution from the batteries. Other variants include the same DC UPS principle with the rectifying stages combined and re-designed together with the MV/LV input transformers (which can be multi-winding phase shifted to mitigate harmonics on the MV side) for each powertrain. This shift to direct current distribution does not just affect the design of the more centralized UPS, but also the downstream PSUs which must be compatible with direct current input.

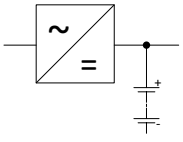
Following a qualitative review and digest of key drivers for direct current application, the technical complexities associated with DC distribution system design for data centers have to be highlighted. Significant level of technical trade-offs, detailed fault simulations, and product validations are pre-requisites for achieving an efficient, reliable, and safe DC architecture. **In this white paper, we highlight five necessary considerations that involve most of the design effort:**

- Conversion architectures
- UPS bypass
- Isolation requirements and ground constraints
- Fault simulation and calculation
- Protection device selection

Conversion architectures

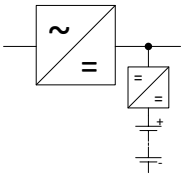
When abstracted and shown as a single functional block, a DC UPS seems much simpler than an AC UPS. However, a DC UPS cannot be designed by just eliminating the output DC/AC conversion stage, as the internal DC bus of a traditional three-phase AC UPS is usually in a range of 700Vdc to 900Vdc. A basic active front end rectifier used in a classic AC UPS cannot provide a DC voltage lower than the instantaneous voltage of the AC inputs, making 240Vdc output not feasible with a 400Vac input. Consequently, the input converter topology has to be specifically designed to step down the output voltage using voltage transforming topologies (e.g., buck/boost, resonant, dual active bridge (DAB), etc.) or additional conversion stages. Though the intention of this white paper is not to provide an overview of converter design, a wide range of conversion architectures do exist for DC UPSs and may yield completely different fault characteristics and system-level design requirements. Therefore, a basic understanding of the diverse conversion choices enabling DC is important.

First, there are several choices of connecting the energy storage/battery with the rectifier:

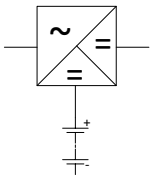


- Battery directly connected to output:
- Simple solution
- 1 full capacity converter (AC/DC)
- Large output voltage fluctuation (around 240Vdc (204Vdc - 270Vdc))
- High steady-state fault current due to battery characteristics
- Oversized cables due to higher current at low SoC

- Battery with a DC/DC interface:
- Stable output voltage
- 2 full capacity converters (AC/DC & DC/DC)
- Limited fault current from battery strings
- No need for oversizing of cables/ breaker
- Integrated control of battery management



- Integrated battery interface
- Stable output voltage
- Shared capacity AC/DC/DC converter
- Limited fault current from battery strings
- No need for oversizing of cables/ breaker
- Integrated control of battery management



Note that for large scale rectifier and batteries the impact of oversizing of the downstream LVDC power distribution can be significant (as much as a 30% difference in amperes).

In the meantime, there are 2 main categories of rectifying stages:

- Passive rectifier
- Active rectifier

The basic concept of passive rectifier is based on the use of only diodes and passive elements such as chokes or capacitors. The output variables (voltages, current) are not regulated or controlled. Such a concept requires a transformer with dedicated multi-winding phase shifted secondaries to arrive at an acceptable THD at the primary side of transformer. Note that relatively high distortions in the secondary windings would still generate additional losses/heat. Usually, a pulse number of at least 24 is needed to stay within the power quality requirement at the MV side. Load balance across the windings is of equal importance.

A major drawback of any passive rectifier is that the output voltage depends on both the mains voltage and load variations. Design requirement shall be based on the maximum allowed voltage at high mains voltage with no load. Consequently, the output voltage with nominal mains input at certain load conditions may result in lower voltage than the defined nominal voltage.

In contrast, the active rectifier concept shapes sinusoidal mains current and controls the DC output voltage. Under such a category, numerous conversion topologies can be used. Note that there are multiple ways of categorizing these topologies in terms of their power factor correction method, output voltage regulation range, etc. Among these methods, two are most relevant to this paper:

- Categorization based on conversion stages:
- Single stage, featuring usually best efficiencies
- Double stage, featuring usually lower DC output capacitance
- Categorization based on isolation:
- Non-isolated, usually with higher efficiency
- Isolated, usually with lower DC output capacitance

These categories are further referred to in later chapters in this white paper. For data center power systems designers trying to compare AC and DC architectures, an overview of the various conversion architects is a prerequisite.

UPS bypass

Power converters can require maintenance or experience failures over their life. In the case of a centralized UPS, these events have the potential to affect the uptime of many downstream servers. As a result, several methods have emerged to mitigate this risk.

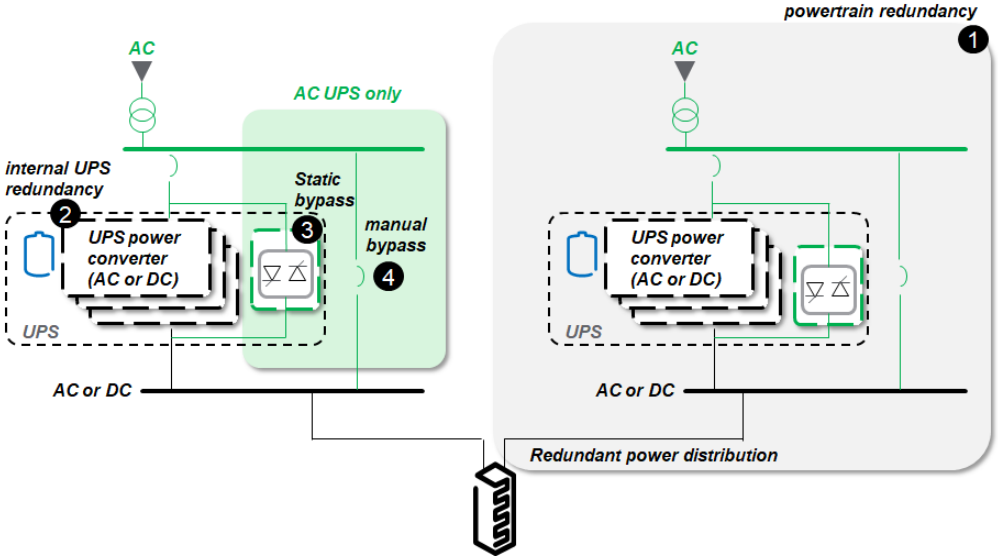


Figure 3

Static bypass, manual bypass, internal UPS redundancy, and powertrain/architecture redundancy (2N shown) are used to ensure uptime during failures and maintenance in critical facilities.

First, design redundancy can provide continuity of service during failure or maintenance. Note, the numbered items below correspond to the numbers above in Figure 3.

- Multiple powertrains and sets of electrical distribution (dual corded equipment) can be deployed with 2N or various N+1 (catcher, distributed redundant, etc.) designs. Powertrain and electrical distribution redundancy provide protection from a wide variety of power converter, energy storage, and electrical distribution failures.
- Modular designs of power converter systems and products can provide in-ternal redundancy of some critical sub-systems. For example, many UPSs allow for N+1 power modules or converter cabinets. While internal redundancy may maintain operation during a single power module failure, there are failure scenarios supported by powertrain redundancy that are not protected by internal redundancy.

Traditionally, with AC UPS, loads can be further protected from UPS downtime with UPS bypass. AC utility power can be routed around UPS systems to power loads, albeit without the support of the UPS functionality in that powertrain. An AC powertrain may have two types of bypass.

- A static bypass can provide instantaneous bypass of the UPS power modules during a sudden failure within a UPS.
- A breaker-based maintenance or manual bypass can route power entirely around the UPS.

The use of bypass can be very important in maintain availability or redundancy to prevent downtime in second failures or failures during maintenance periods.

When moving to a DC UPS design, with DC distribution, powertrain or UPS internal redundancy can be used to support loads during UPS failures and maintenance, but a bypass (static or manual) is not easily achieved, as the UPS input is AC and the output and power distribution is DC. Therefore, a DC design must rely on design redundancy to accommodate maintenance or any failures. This can impose additional cost on data center design, or leave load exposed to second failures or failures during maintenance. Unfortunately, DC designs commonly incorporate fuses (for other reasons discussed in this paper) which have a long time to repair/replace and therefore can exacerbate the lack of bypass. Overall, due to the lack of UPS bypass, DC UPS data center designs impose a greater dependency on powertrain level redundancy to maintain server uptime.

Isolation requirements and ground constraints

The galvanic isolation between MV and LV (AC or DC) part of the power train is usually made with grid frequency power transformers (setting aside the complexities of using solid-state transformers and isolated converter topologies). These transformers can be designed either centralized (at power train level) or decentralized (dedicated to rectifier unit). The difference is whether there is LVAC distribution in the power train to define (switchgear, earthing, protection) and to coordinate with the rectifier's upstream characteristics.

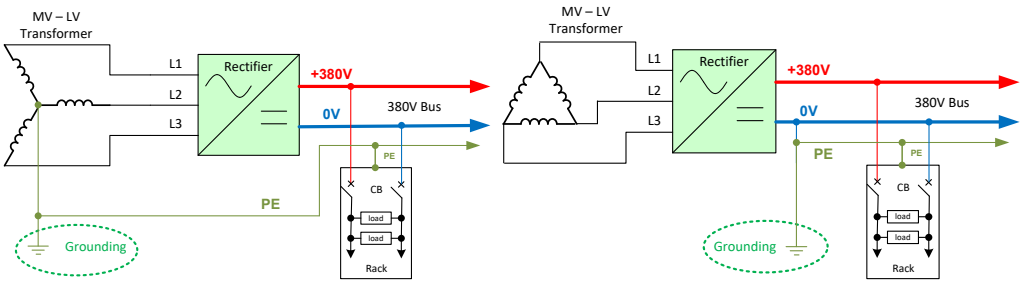
To target the best efficiency, capacity and cost, the rectifier converter shall preferably be single stage (active or passive buck). As such, the converter will not be galvanically isolated between the AC and DC side. Note this assumption results from converter design and naturally trades off with the upstream isolation choices, the selected output voltage, and the earthing philosophy introduced hereafter. This is regarded as a fundamental dilemma between system efficiency and complexity of earthing choices.

With TN earthing, the low voltage distribution shall be grounded with a single earth connection either at the AC input side or at the DC output side of the rectifier (Figure 4). Note that the magnitude of the output voltage (380V) is representative but not exclusive. However, the selection of such a voltage has to do with the upstream AC input voltage, the cabling and power losses in the downstream DC distribution system, the compatibility of PSUs and, hence, a performance trade-off is inevitable in all cases.

The input and output earthing system are identical when grounding is made upstream of the rectifier (i.e., left side of Figure 4). It does facilitate low impedance ground fault protection at both the AC side and DC side; however, it could be hard to achieve high impedance ground fault protection with proper sizing of the residual current sensor at the neutral connection due to converter behaviors. Note that AC distribution and DC distribution (breakers), in this case, exist at the same time.
In case of grounding downstream the converter (i.e., right side of Figure 4), The trans-former and the phase connections will not be referenced to ground and shall be protected in coordination with the output grounding. The converter itself together with the upstream part of the installation up to the closest galvanic isolation shall be considered as an integral part. The protection upstream the grounding is specific and shall be integral to the rectifier.

Figure 4

Earthing approaches around the DC UPS – TN earthing



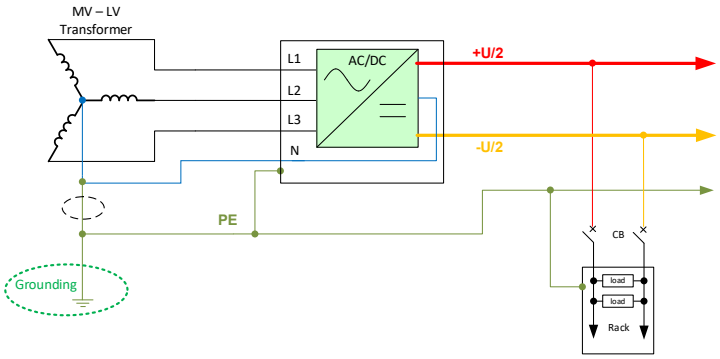
As an example, in the passive rectifier case where grounding is made at the DC output side, the MV-LV transformer, the associated protection, and the rectifier are considered as one unit. This may require the (DC UPS) manufacturer to integrate all components into one unit with specific unit safety assessment and type tests to demonstrate it. Despite no AC distribution in this case, the earth fault protection of the transformer internal / secondary winding is not straightforward.

The fault level on the DC side can impose further constraints. The DC UPS size, the converter current limiting topology selection, as well as the assurance of any current limiting function whenever required complicate the determination of the DC side fault level, as well as the protection coordination further downstream the DC UPS output.

Another variant of the earthing arrangement is possible with a mid-point connection brought from the converters to the AC neutral, even though from a converter design point of view, a passive or a single stage topology is no longer possible (refer to **Figure 5**). Such a scheme does facilitate impedance earth fault protection at the DC side, due to good controllability on both the positive and negative poles. However, the mid-point connection reduces the converter optimization freedom.

Figure 5

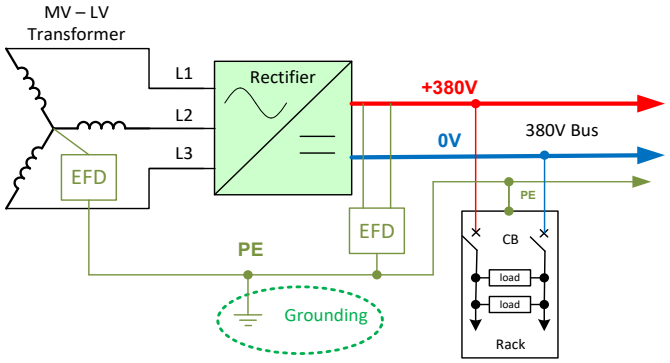
Earthing approach around the DC UPS – TN earthing with a converter mid-point connection



Alternatively, as illustrated in **Figure 6**, with IT configuration the low voltage distribution shall be ungrounded. None of the Transformer, N, L1, L2, L3 lines, the positive nor the negative output connection will be referenced to ground and the downstream protection shall be selected in accordance.

Figure 6

Earthing approach around the DC UPS – IT



According to IEC 60364-4-41, In cases where an IT system is used for reasons of continuity of supply, an insulation monitoring device (Earth fault detector (EFD) in Figure 6) shall be provided to indicate the occurrence of a first fault from a live part to exposed conductive parts or to earth. With a non-isolated converter, the sensitivity of insulation monitoring on both AC and DC side of the converter can be difficult to set. For relatively confined systems (e.g., pod level) with dual-corded racks, locating faults may be manageable within a limited time interval.

The above conversion architectures are in principle dealing with single power source to the direct current main distribution, resembling typical data center power distribution. As mentioned in the previous chapter, scenarios with DC coupling of multiple sources may be regarded as an important driver for direct current application in data centers. In this case, the exposure to risks of electrical faults is enlarged and protection becomes more complicated. Leakage current can be a concern when a DC microgrid scenario (coupling with geographically distributed PV, storage, and other sources) is considered, due to the difficulties to guarantee leakage flow in the metallic continuous path, where more remote and distributed source connections exist.

Corrosion occurs wherever the leakage currents leave the metal and enter an electrolyte or moist earth. This may be of less concern in a well bonded/prepared building but can be overlooked when multiple connections leading to outside the confined building area are made. Proper isolation then has a higher priority to system efficiency. DC leakage currents can cause up to one hundred times the amount of damage as AC leakage currents do for the same level. The design of the earthing of a DC installation should pay special attention to possible corrosion of the materials involved. DC leakage currents in concrete structures may cause electrochemical reactions that are destructive to the structure.

Fault simulation and calculation

Different fault behaviors – AC Vs. DC

As represented in Figure 7, an AC source is mainly transformer supplied and the equivalent circuit corresponds to a Thevenin voltage source with internal impedance (mainly inductive) from which the fault current can be clearly derived.

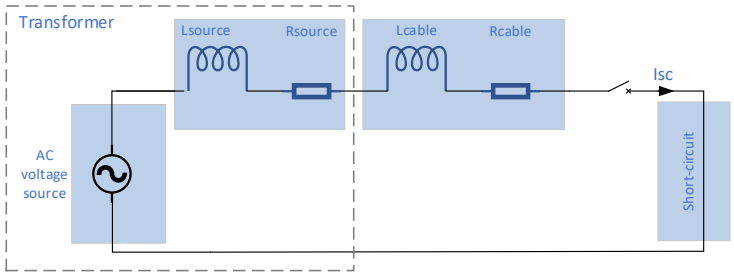


Figure 7

Typical equivalent model of a fault loop with AC source

A DC source, however, is mainly supplied from power converter(s). This includes battery sources supplied via DC/DC interface except in telecom architectures where batteries are directly connected in parallel at the power converter output. Therefore, regular AC short circuit calculation methods do not apply on DC fed systems. As mentioned in the previous section, various conversion topologies do exist and are categorized as either passive or active. This adds to the complexities of fault behavior modelling.

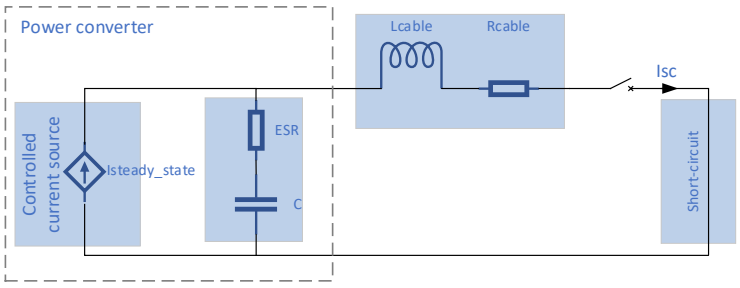


Figure 8

Typical equivalent model of a fault loop with DC source

As represented in Figure 8, typical equivalent model of a converter fed DC system consists of a controlled current source corresponding to the converter bridges and the inductance paralleled with a capacitance corresponding to the DC output link. However, note that it corresponds to a buck topology only, since a boost converter may not limit the current and, therefore, leads to a different fault behavior.

In normal operation, the current source is controlled to maintain the capacitor voltage. During a fault situation, the current source provides a maximum current, usually between 2 and 3 times the rated current, until it reaches its thermal limit. The short circuit output of such a converter has two modes or states:

- Transient state: the capacitor current is limited only by the internal resistance (ESR) and the impedance of the fault loop (including all cabling and busbar connections).
- Steady state: the fault current is constant at the maximum converter output current rating.

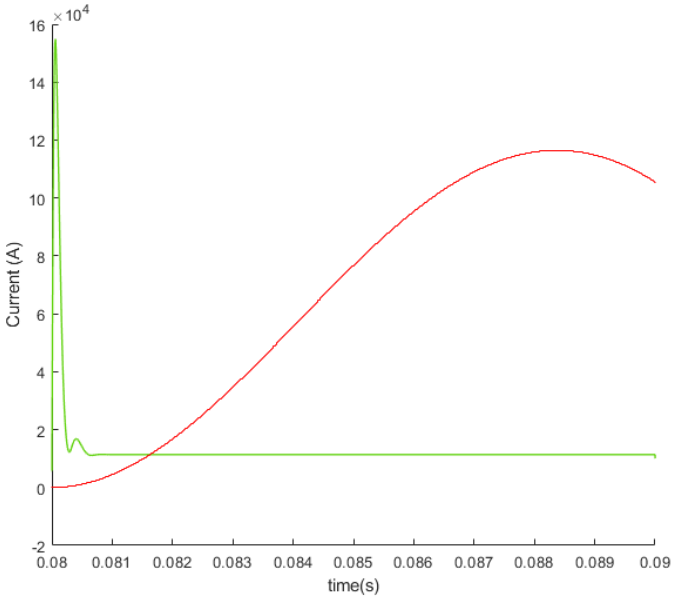


Figure 9

Illustration of typical AC and DC fault characteristic

Figure 9 illustrates typical AC and DC fault characteristics. The thermal limitation and steady-state fault current of an AC fault is much higher than DC. However, there is a high di/dt peak associated with a DC fault (fed by voltage source converters). In general, fault characteristics with presence of DC source (voltage source converters) differ from standard AC systems due to:

- a very high di/dt and peak current at the beginning of the short circuit with a limited steady state current.
- cable lengths being quite limited, sometimes with busways extensively used. This leads to a generally low fault impedance.

In a same manner as standard AC, protection coordination shall be performed based on fault calculations. Such fault characteristics are critical to the selection of breakers and the selectivity in between.

Quantification & Modeling Methods

IEC 61660 describes a method for calculating short-circuit currents in DC auxiliary systems in power plants and substations. The standard provides an analytical method generally applicable for calculating the fault current involving the following equipment, which may be present in a DC system, acting as fault-current sources:

- Rectifiers in three-phase AC bridges for 50Hz
- Stationary lead-acid batteries
- Smoothing capacitors
- DC motors with independent excitation

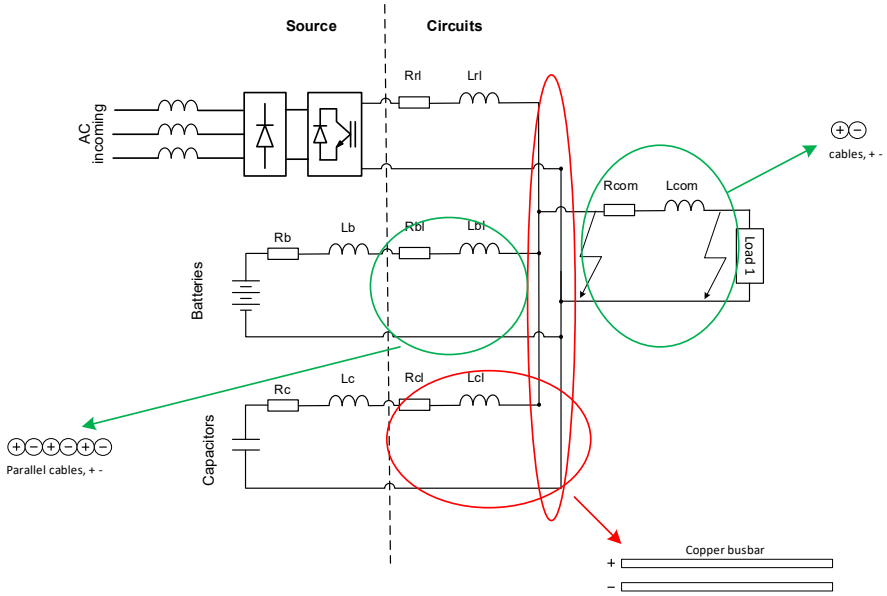


Figure 10

Decoupling of various sources – IEC 61660 method

Note that a complete short circuit calculation for such a DC feeding system shall be performed with a numerical simulation due to the time variations and non-linearities. However, the expense is quite high to manage the model and the parametric. A simpler way of evaluating the fault characteristic to a controllable level of confidence is always preferred when designing and comparing architectures. The result from the analytical calculation can then be compared with the result from numerical simulation possibly done with commercial design tools (e.g., ATP/EMTP/PSCAD/Matlab).

Decoupling the various sources and simplifying to characteristic quantities are key to the analytical calculation. If the equivalent circuit diagram contains several sources, the short-circuit current, in the case of a short-circuit location at a common coupling point, is calculated by adding the short-circuit currents of the different sources (refer to Figure 10). If the equivalent circuit diagram contains several sources and a common branch, the final fault current needs to consider correction factors based on the common branch impedance.

Standard approximation functions are used to capture the time variation of the fault currents:

$$i(t) = i_p \frac{1 - e^{-\frac{t}{\tau}}}{1 - e^{-\frac{t_p}{\tau_1}}} ; 0 \le t \le t_p$$

$$i(t) = i_p \left((1-p) e^{-\frac{t - t_p}{\tau_2}} \right) ; t_p \le t$$

Where…

i_p is the peak current;

r_1 and r_2 are the time constant during fault rise and decay;

p is the ratio of the steady state current to the peak current.

Despite the IEC 61600 method being easy to implement, it does not consider the power converter behavior (except for a passive rectifier), leading to an inaccurate estimation of the steady-state fault current, especially with longer cable lengths. Therefore, care shall be taken wherever a relatively large load side cable impedance is in consideration.

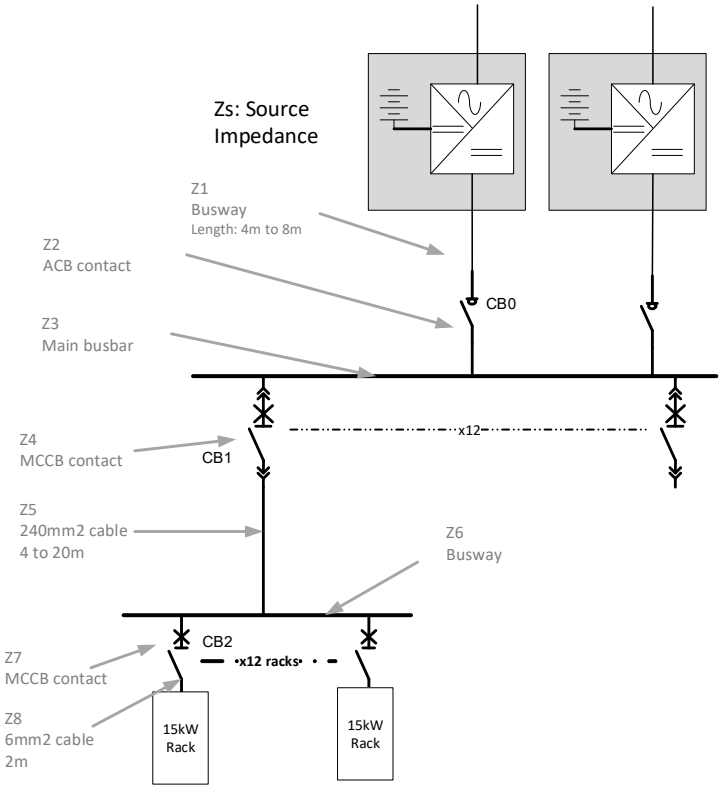


Figure 11

Fault impedances required for fault evaluation at different locations in a typical data center DC distribution

Numerical simulation is always preferred to characterize the time varying fault, especially when designing specific architectures with specific conversion topologies. The following components have to be properly modelled and defined:

- Power converter (including the source impedance): for both normal operation and fault condition, at least a behavioral model of the power converter is required. A detailed switching-controlled model is always good but may exhaust normal computational capacities. A suitable time-step needs to be defined to avoid unnecessarily heavy simulation. This model must be specific to the converter type chosen.

- Cables, busbars, and busways: for fault conditions, it is mandatory to consider all impedances seen by the fault current. For the most common data center DC distribution systems, refer to Figure 11. Note that such parameters may not be as easy to derive as they seem to be. A multi-physics simulation model aiding the derivation of parameters at frequency domain is helpful most of the time.
- Battery strings: for an architecture where battery strings are directly connected, the internal resistances, as well as the module connection impedances, need to be carefully determined.
- PSU input stage for validation of the dynamic performances

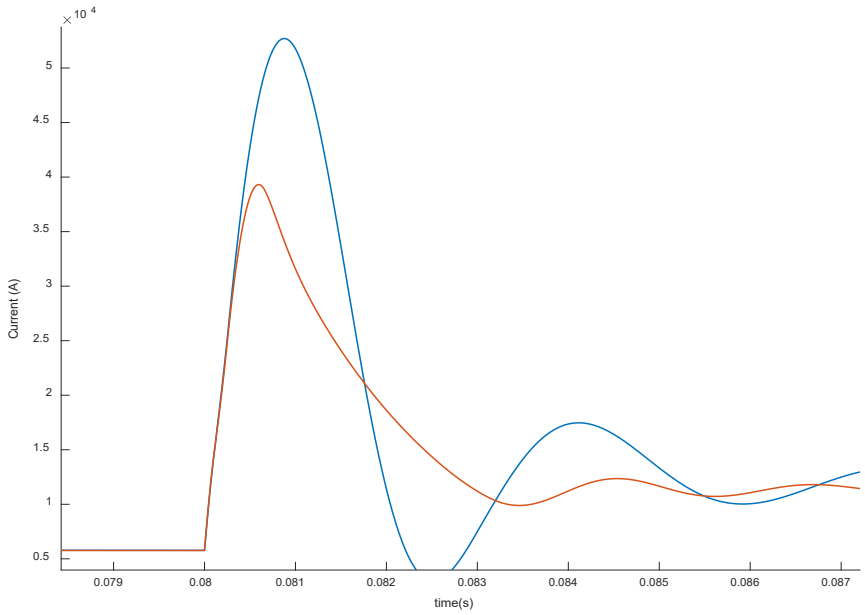


Figure 12

Fault behavior with different source impedances in a typical data center DC distribution system

Figure 12 demonstrates a difference in the fault characteristics with different (in blue and orange respectively) converter source impedances (in this simulation the battery is connected through a DC converter). The fault point is at CB2 input according to Figure 11. A common feature is a fast transient peak that can occur even within a millisecond. As discussed previously, different conversion topologies yield different output capacitances and source impedances and, as a result, different peak requirements, both in terms of its magnitude and its rise time to peak.

A straight-forward factor is the source capacity, or the DC power train size. This holds true for all architectures with or without the battery system directly connected. There-fore, there will be an architectural level trade-off between system-level redundancy, resilience, and CAPEX. Clearly, consideration on having a realistic peak current is vital to the selection of the protection devices.

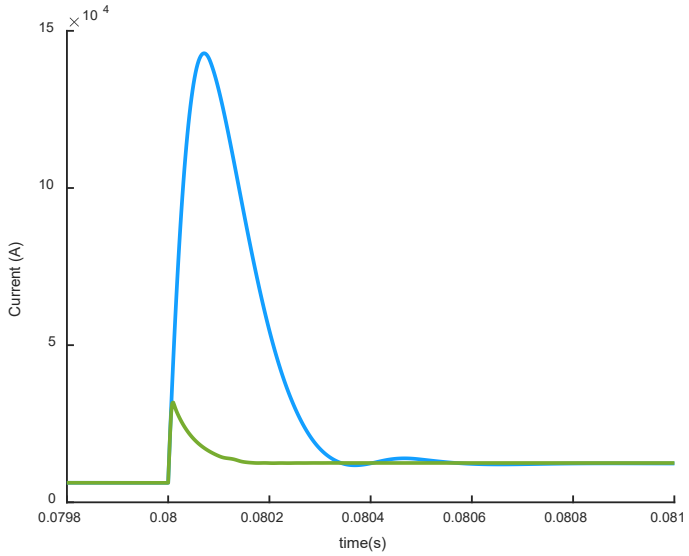


Figure 13

Example of fault current limitation in a typical DC distribution system to IT racks

In addition to system architecture-level considerations, another way to mitigate the peak discharge current is to apply fault current limiting either with dedicated components or with integrated circuits in the converters. Figure 13 shows an example of an effective fault current limitation in a typical DC distribution system to IT racks. It is regarded that such a mitigation may be critical for assurance of breaker capacities and selections, with specific DC architectures. However, additional losses and a higher complexity of converter design is inevitable.

Modelling Parametric

The fault behavior for DC differs fundamentally from AC. Further, and potentially more challenging, is the sensitivity of DC faults to fault loop impedances. The derivation of fault loop impedances can also be challenging due to the uncertainties associated with internal component selections, mechanical arrangements, and operating environments.

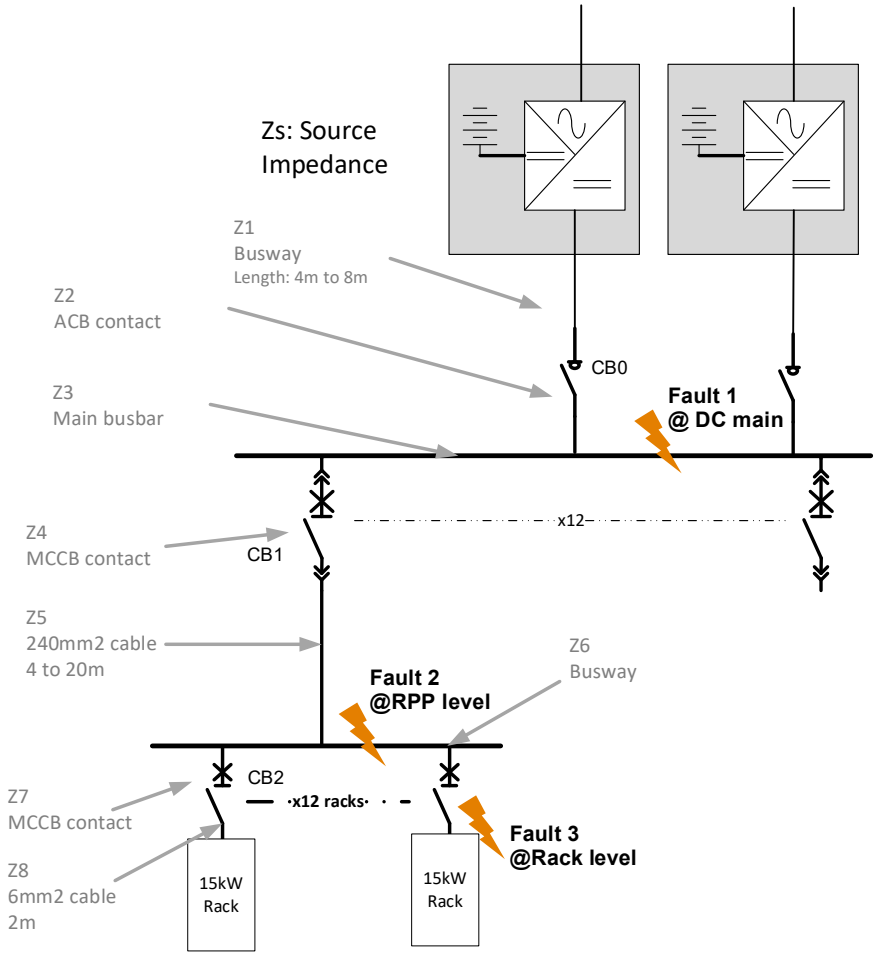


Figure 14

Fault level evaluation at different locations in a typical data center DC distribution system

For faults close to the converter output, the internal impedances of the power converters are the most critical ones. The resistance mainly comes from the capacitor series resistance and the internal converter switching devices. Any changes in these components can significantly change the values, and thus the conclusion of whether a specific architecture is suitable or not. Consequently, a sensitivity study must be rerun each time a power conversion topology is proposed. Converter output cable connections and branch busbar arrangement (inside the conversion/distribution cabinet) may also play an important role. Therefore, the structural design shall also be considered in the fault level evaluations.

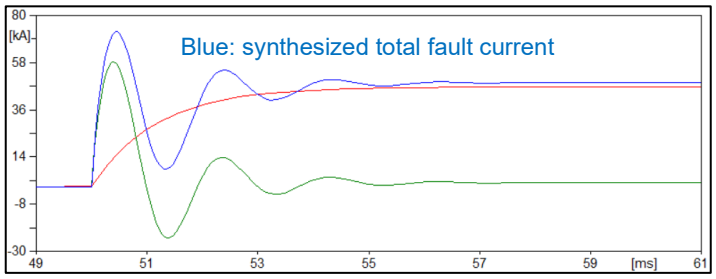
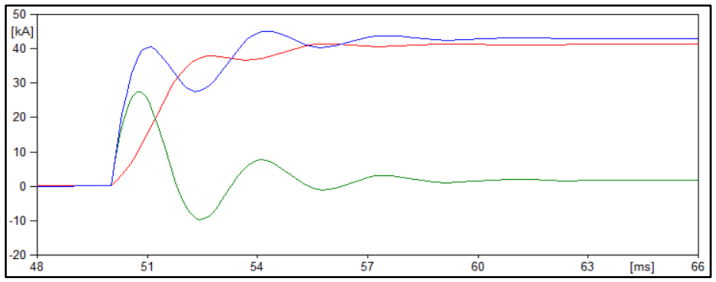
For faults at the remote power panel (RPP) level, the intermediate impedance is dominated by the physical distances between the DC main and the RPP in the IT room. The capacity of the RPP is closely related to its incoming cable impedance and would then impact the branch circuit breaker ratings of the RPP.

Table 1 and Table 2 summarize and compare the fault levels at different locations in a sample data center DC distribution system. Note that directly connected battery strings are considered in this example only (it can be exhaustive to present the fault behaviors with different conversion topologies, system architecture and DC main capacities). The only difference in this set-up is the DC main system capacity – Table 2 is with twice the capacity of that for Table 1.

Table 1

Example of fault level at different locations in a sample data center DC distribution

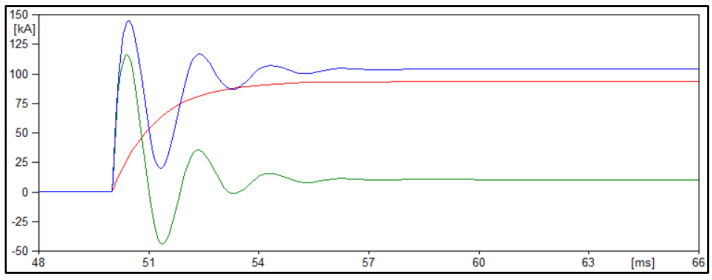
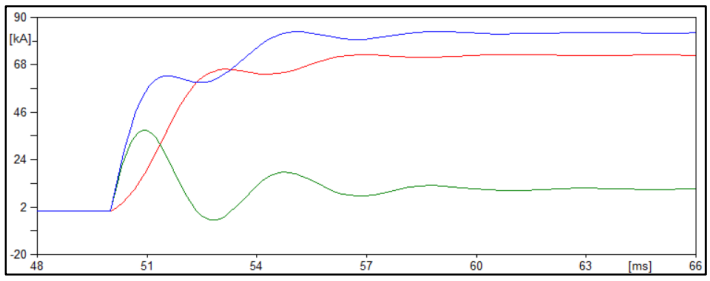
(DC main system capacity 1) system

Fault at DC Main (DC main system capacity 1)	
Fault at RPP level (DC main system capacity 1)	

It is obvious that the DC power train size directly impacts the fault level resulting in a critical evaluation of the RPPs. For systems with directly connected batteries, the slower permanent fault rise adds to the initial fast transient, defining the required capacity of the protection device for the branch circuits in the RPPs.

Table 2

Example of fault level at different locations in a typical data center DC distribution (DC main system capacity 2) system

Fault at DC Main (DC main system capacity 2)	
Fault at RPP level (DC main system capacity 2)	

It can also be seen that the fast transient fault peak is greatly dampened and slowed due to cable impedance in between the power train and the RPP. However, the rise time can easily be within a millisecond level. Sensitivity of the cable impedance is high to the resulted fault current rise time. **This is regarded as a critical uncertainty in the determination of fault level and the corresponding protection capacity, especially for architectures without the battery system directly connected.**

Protection device selection

DC circuit breaker characteristics

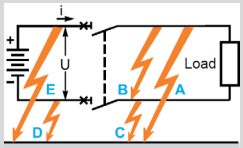
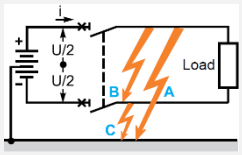
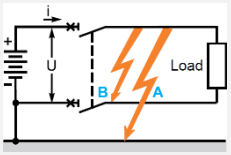
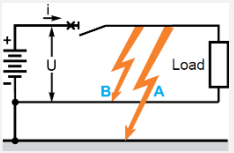
The selection of protection devices across the DC power distribution system is another key area of focus for defining DC architectures. As with AC systems, both the interrupting capability and selectivity have to be considered along with the specific characteristics of DC current breaking and the level of service continuity required in data center applications. The selection of DC circuit breaker depends essentially on the following characteristics:

- Rated operational voltage U_e
- Rated current I_n
- Ultimate breaking capacity I_{cu}
- Making capacity I_{cm}
- Earthing system

According to the earthing system, the requirements for the protection devices may be different as shown in Table 3.

Table 3

Requirement of circuit breakers in accordance with earthing system

Earthing system			
IT	**TN**		
Unearthed 2-pole protected	**Midpoint earthed 2-pole protected**	**+ or – Earthed 2-pole protected**	**+ or – Earthed 1-pole protected**
			
Single faut: Breaking the maximum short-circuit current Isc at U with both polarities	Single faut: Breaking the maximum short-circuit current Isc at U with both polarities	Single faut: Breaking the maximum short-circuit current Isc at U with only one polarity	Single faut: Breaking the maximum short-circuit current Isc at U with both polarities
IEC 60479-2 does not define any performance of the DC circuit breaker in case of a double ground fault. However, it is recommended to protect the installation against a double ground fault. In this case, the protection device needs to break the maximum short-circuit Isc at U with only one polarity		IEC 60364 Electrical Installation Rules (Chapter 42) can be applied to protect and break only the polarity that is not earthed in TN. However, both polarities conductors are "active" conductors, so it is recommended to disconnect both polarities. According to IEC 60479-1 upward current is twice as dangerous as downward current so for protection against electric shock it is recommended to earth the negative pole. In some DC applications the positive polarity can be earthed for galvanic corrosion reason.	

As shown in Figure 15, a DC circuit breaker can be arranged with several poles in parallel to decrease the current in each pole or several poles in series to decrease the voltage across the poles.

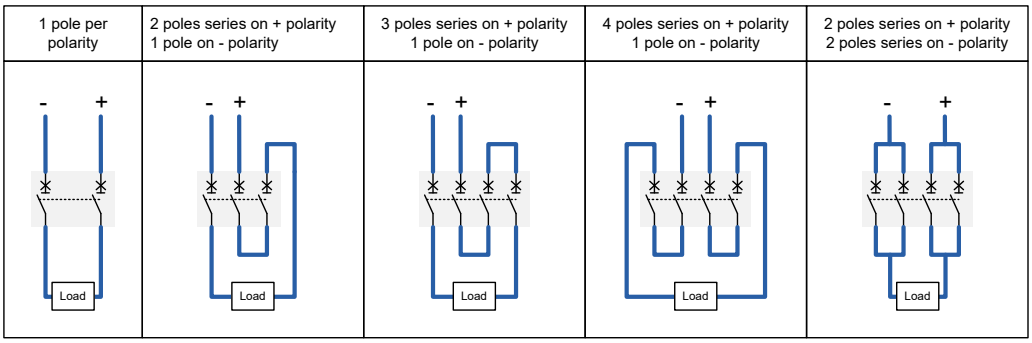


Figure 15

DC circuit breaker pole arrangement

Interrupting voltages, permanent fault level, and the transient fault characteristic together define the breaker type to be selected. Given the extensive number of final circuits, there is an important economic trade-off with DC power train sizing and conversion topology choices. In the meantime, protection selectivity shall ideally be achieved in data center down to the final distribution level.

Discrepancy with the fault characteristic used in LVCB standard

For data center application with a DC UPS, the source is typically UPS output DC/DC converter with short-circuit current limitation. In this case, the equivalent short-circuit model is a current source in parallel with the output capacitors of the UPS. As principally described in the previous chapter, typical fault characteristics of at DC UPS output with different architectures are illustrated in **Figure 16** and **Figure 17**.

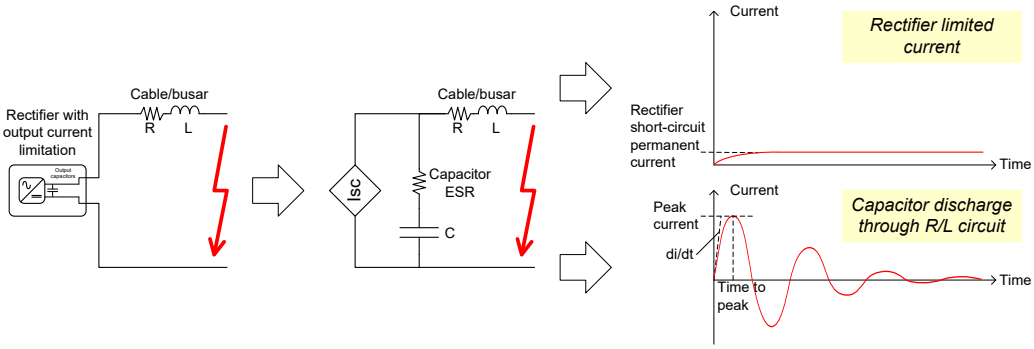


Figure 16

Electrical model of a DC UPS output short-circuit calculation (without battery)

Typically, the converter output short-circuit current limitation is quite low, between 1 and 3 times the rated current. However, the capacitors will give a high peak current with high di/dt. When the battery system is connected to a DC/DC converter, the short-circuit current contribution will be limited. If the battery system is directly connected to the UPS output bus, an additional source will be added and modeled as a voltage source with its internal impedance. Depending on the battery technology (VRLA or Li-ion type), the constant time can vary from 0.2ms to 1ms.

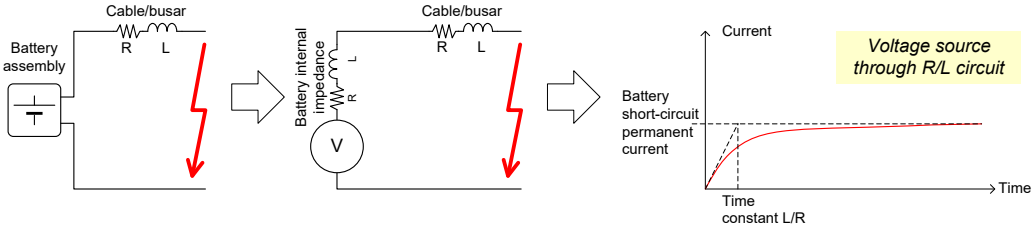


Figure 17

Electrical model of a battery circuit short-circuit calculation

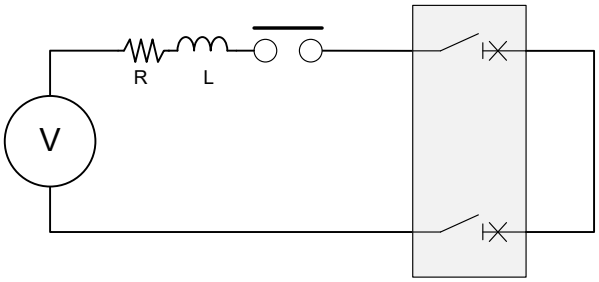
An important note is that for a typical DC UPS, the fault current waveform is significantly influenced by the capacitor discharge current with a rise time that can vary from 0.1ms to 1ms depending on the installation characteristics. When the battery is

directly connected, it adds a short-circuit current with a constant time between 0.2ms and 1ms.

DC circuit breakers are designed and tested according to the IEC 60947-2 standard. However, the specification of the short-circuit test for a DC circuit breaker only considers a voltage source through an RL circuit as shown in Figure 18.

Figure 18

Electrical test of DC circuit breaker in accordance with IEC 60947-2



IEC 60947-2 specifies a 15ms time constant (refer to Table 4) for DC current breaking and a lower value than that tends to facilitate the current interruption. However, this assumes an RL circuit with a fixed voltage source. Furthermore, very fast transient peaks may fall outside the usual way of defining DC breaking capability, since it turns to an RLC circuit in particular for architectures without the battery being connected. Both the permanent fault level (with battery contribution or with converter contribution, whichever is relevant) and the fault transient characteristic would impact the choice of the protection device.

Table 4

Required time constant of short-circuit test according to IEC 60947-2

Test current (kA)	IEC 60947-2 required time constant
Isc < 10 kA	5 ms
10 kA < Isc < 20 kA	10 ms
20 kA < Isc	15 ms

There is a significant discrepancy between the circuit breaker standard requirements and the applications with power converters mainly because the standard defines short-circuit current tests with large time constant compared to capacitors short-circuit currents.

Specific breaker tests are recommended to rule out uncertainties due to the discrepancy between the circuit breaker standard requirement and the DC UPS application requirements.

Challenge with high short-circuit peak current

Typically, the breaking capacity lowers as the time constant increases because the breaking phase is slower and the energy greater. For high peak current with short peak rise time, the breaker pole contacts are repulsed and will thus provide a current limiting effect. However, for short time constant below 1ms with very high di/dt, the breaking capacity may drop due to mechanical stress in the breaker poles. For high peak current with very short peak rising time, the breaker pole contacts are repulsed and will provide a current limiting effect as shown in Figure 19.

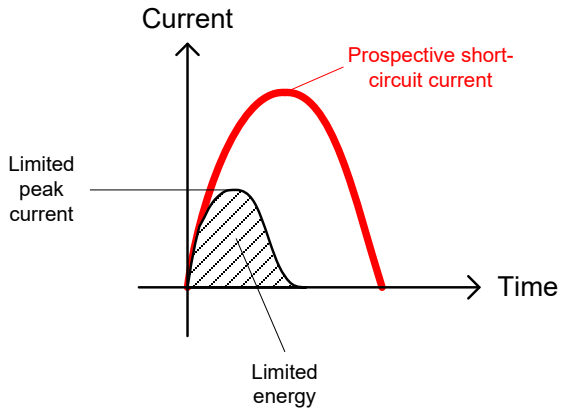


Figure 19

Illustration of breaker current limitation function

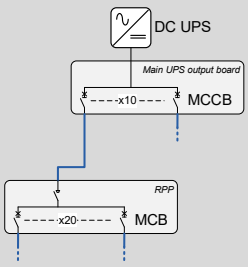
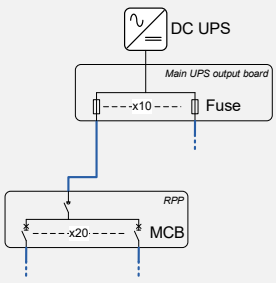
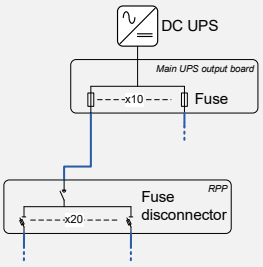
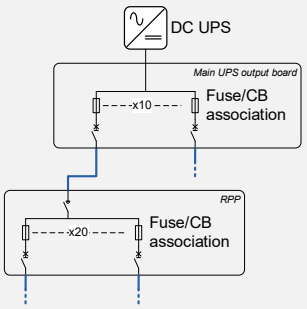
Depending on the circuit breaking technology, the behavior of the breaker with high di/dt can be quite different. Before selecting a protection device for such applications, simulations and tests may be done to validate the breaking capacity according to the specific installation characteristics. Usually, manufacturer simulation tools can model the behavior of breakers including the mechanical opening of the poles and the electrical arc. However, these models are typically valid for time constants of about a few milliseconds and must be reset and fine-tuned for short time constants.

In case the short circuit constraint is considered too high for any circuit breaker, fuse solutions can be applicable. Several possible solution combinations are summarized in Table 5:

- Mix of fuses and CBs, where fuses are used only at the location with possible constraints for CBs
- Only fuses but a few drawbacks (e.g., overload protection)
- Fuse/CB combination

Table 5

Protection device selection options for DC distribution

Circuit Breaker	Mixed CB and Fuse	Fuse	Fuse/CB association
			
The breaking capacity of each circuit breaker is manageable at every location. Selectivity must be checked with simulations and tested.	Fuses are used at the locations where fault currents are too high for CBs Fuse may also provide current limitation that allows the use of MCBs. However, selectivity may be partial.	Selectivity has to be checked with simulations and tested. Drawbacks inherent with fuses may not be acceptable (longer recovery time; no isolation)	The association of CB and fuse allows very high breaking capacity while keeping the advantages of CBs (fast recovery time; fine-tuned overload protection; isolation) The association must be checked with simulations and testing.

Conclusion

With the technical trade-offs, complexities, and uncertainties illustrated throughout the chapters, DC distribution in data center does not immediately represent 'a simplification of the data center powertrain', but rather requires solid technical justifications, careful design iterations, and significant design efforts.

This paper introduces 5 technical considerations which must be understood before deploying DC UPS architectures:

- A wide range of conversion architectures for DC may yield completely different fault characteristics and system design requirements. The source capacity, or the DC power train size may need to be carefully traded-off with protection device capacity.
- With AC input and DC output, DC UPS systems are incompatible with static and manual bypass. The implications to system availability and constraints on powertrain redundancy should be considered.
- Earthing and the dependency on converter design can be complex, with a dilemma between conversion system efficiency and complexity of earthing choices.
- DC faults are different than AC faults and it is more difficult to calculate fault levels and profiles in DC UPS systems. Detailed modelling, including converter behavior, the associated RLC parameters, and sensitivity studies should be completed.
- Specific breaker tests are recommended to be performed to rule out uncertainties about the interrupting capability and selectivity under specific fault characteristics.

While the use of DC in other applications is driven by fundamental improvements or necessity, in data center distribution the prospective value is more incremental. This prospective value should be weighed against the complexities of the discussed technical considerations.

About the authors

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Patrick Chambon is a microgrid and energy management senior architect. He is with Schneider Electric since 1999 and spent more than 15 years in the development of high-power UPS and BESS, as project design leader, control expert and architect. His research interest includes the conversion, protection and control technologies linked to Direct Current, and the new customer values that Direct Current can bring, with a special focus on data center applications. Patrick received a B.S degree in Electrical Engineering from Grenoble university, and a M.S. degree in Engineering from Grenoble INP- ENSERG engineering school.

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Xu Yuan is a power systems expert with the ELECTRA power systems competence center at Schneider Electric since 2019 and had since then been focusing on data center power distribution systems design, as well as architectural comparison for China and Global applications. Prior to that, he had 10 years of experience in large electrification projects featuring AC, DC and variable AC power transmission & distribution systems from the offshore & marine industry and the renewable energy industry. He holds a M.Sc. degree of Electric Power Engineering from the Royal Institute of Technology in Sweden.

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