



OPEN
Compute Project



DATA CENTER FACILITY — LOW VOLTAGE DIRECT CURRENT POWER DISTRIBUTION

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Executive Summary

The rapid escalation of AI-driven workloads is pushing data center power systems beyond the limits of traditional architectures. Rack power densities are increasing sharply, load profiles are becoming more dynamic, and efficiency, scalability, and grid interaction are now first-order design constraints. To address these challenges, the data center industry is increasingly exploring direct current (DC) power distribution as a complementary approach to conventional AC-based systems.

This white paper, developed within The Open Compute Project, a collaborative industry initiative focused on open, scalable, and efficient data center infrastructure, provides a high-level overview of DC power distribution architectures for data center facilities. It examines key design concepts, system boundaries, and tradeoffs across power conversion, grounding and earthing, protection, energy storage integration, and regulatory considerations.

Rather than promoting a single solution, the paper presents representative DC power distribution approaches observed or under evaluation across the industry. It is intended to support a shared understanding among data center operators, designers, equipment manufacturers, utilities, and Authorities Having Jurisdiction (AHJs), enabling informed discussion and consistent interpretation as DC architectures continue to evolve. This white paper represents an initial framework and identifies areas requiring further development.

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1. Introduction

As data center power systems evolve to support increasingly demanding compute environments, there is growing interest in alternative power distribution approaches that can accommodate higher power densities, dynamic load behavior, and expanding system scale. Among these approaches, direct current (DC) power distribution has emerged as an area of active evaluation and early deployment across the industry.

DC power architectures introduce different design considerations than traditional AC systems, particularly in areas such as power conversion boundaries, grounding and earthing, protection and fault behavior, integration of energy storage, and interaction with upstream utility infrastructure. These considerations span multiple layers of the data center, from facility-level power distribution to zone- and rack-level implementations, and involve close coordination between equipment design, system architecture, and regulatory requirements.

This paper focuses on describing these considerations at a conceptual and architectural level. It outlines commonly discussed DC power distribution configurations, identifies key system components and interfaces, and highlights technical tradeoffs that may influence design decisions. The intent is to establish a common technical framework rather than to recommend or mandate a specific topology. However, this white paper represents an initial framework. Areas requiring further development are identified within the document.

The content is written for a broad audience, including data center operators, designers, equipment manufacturers, utilities, and Authorities Having Jurisdiction (AHJs). All architectures discussed remain subject to applicable codes, standards, equipment certification, and AHJ approval. As data center power systems continue to evolve, multiple AC and DC distribution models are expected to coexist, shaped by site-specific requirements, regional practices, and ecosystem maturity.

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2. Compliance with Open Compute Project Tenets

This white paper aligns with the core tenets of [Open Compute Project](#) by promoting openness, efficiency, impact, scalability, and sustainability in the context of data center DC power distribution. As a conceptual and architectural document rather than a hardware or software contribution, its primary objective is to enable shared understanding, informed discussion, and ecosystem alignment across a diverse set of stakeholders.

2.1. Openness

This paper supports openness by presenting DC power distribution concepts, architectures, and design considerations in a vendor-neutral and non-proprietary manner. It avoids prescribing specific products or implementations and instead focuses on commonly discussed approaches, tradeoffs, and system-level implications. By establishing a shared technical vocabulary and framing considerations applicable across regions and deployment models, the document enables broad participation, review, and extension by the wider data center ecosystem.

2.2. Efficiency

Efficiency is addressed through a system-level examination of DC power distribution, including the potential reduction of power conversion stages, improved utilization of conductors, and closer integration of energy storage. The paper emphasizes architectural choices that can influence electrical efficiency, power density, and operational effectiveness, while recognizing that realized gains depend on site-specific design, load profiles, and implementation details.

2.3. Impact

The document aims to create industry impact by clarifying emerging DC power distribution concepts that are increasingly relevant to next-generation, high-density data centers. By providing a high-level, accessible reference for designers, operators, equipment manufacturers,

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utilities, and Authorities Having Jurisdiction (AHJs), the paper supports more consistent interpretation, reduces ambiguity, and facilitates informed evaluation of DC architectures across the ecosystem.

2.4. Scale

Scalability is addressed by considering DC power distribution across multiple layers of the data center, including facility, zone, and rack-level implementations. The paper highlights how different architectural approaches may support incremental deployment, modular growth, and adaptation to increasing power densities. This perspective aligns with OCP's emphasis on designs that can scale efficiently from smaller deployments to large, hyperscale environments.

2.5. Sustainability

Sustainability is reflected in the discussion of architectural options that may reduce energy losses, enable higher system efficiency, and support integration with energy storage and advanced grid interaction strategies. By focusing on long-term infrastructure adaptability and efficient power delivery, the paper contributes to broader sustainability goals without promoting specific technologies or solutions as universally optimal.

The OCP Data Center Facilities (DCF) Sustainability Project was formed to align the DCF project with the fifth OCP tenet - Sustainability. OCP has an IT focused Sustainability Project that focuses on the decarbonization of the IT infrastructure. This DCF-Sustainability Project is focused on decarbonizing the non-IT aspects of the data center. This project will engage industry partners to develop technology roadmaps, provide guidelines for the data center industry in support of achieving net zero carbon goals through innovation and collaboration in products and technologies. OCP's unique combination of hyperscaler influence, vendors and sub-projects such as the OCP Ready Program can be leveraged to accelerate the industry's sustainability goals.

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3. Background Context

3.1. Data Center Transition to Direct Current: Background and Needs

As AI models scale in complexity, significant architectural changes are envisioned to the IT rack to support higher compute density and speed up the overall compute cluster by minimizing network packet loss (through staying within the copper layer boundary and reducing reliance on optical interconnections). Low Voltage Direct Current (LVDC) Power Distribution (≤ 1500 VDC) will soon function as a critical link between the IT rack AI factory compute load and incoming data center facility power – whether from the utility service, local production, or both. To address this critical and rapidly developing area, The Open Compute Project (OCP) has organized a [Power Distribution](#) sub-project within the Data Center Facility project.

Initial adoption of the [Mt. Diablo](#) Power Rack (side car) enables the ORv3 HPR IT Rack to increase from AC-supplied [HPR v1 33kW](#) or [HPR v2 72kW](#) power shelves to DC-supplied [HPR v4 100kW](#) power shelves within the same 1 OU space footprint – itself a 39% increase in power density per power shelf, made possible in part by removal of the AC-DC conversion stage. Additionally, moving in-rack energy storage (in-rack 2 OU BBU and optional CBUs) from the IT Rack to the Power Rack has the further advantage of freeing up approximately 12-16 OU space footprint within systems that use in-rack storage, yielding a further 27-36% increase in available 44 OU IT Rack space for further compute power.

Ultimately, achieving the roofline power potential of HPR v4 requires addressing the further bottleneck of existing 50 VDC vertical bus distribution within the IT rack (as even ORW racks with horizontal bus face power limitations beyond the 100's of kW). For this reason, higher voltage (e.g. 800 VDC) vertical bus represents the next progression for the IT rack, enabling it to realize the potential of its 1+ MW roof line (see [Figure 1](#)).

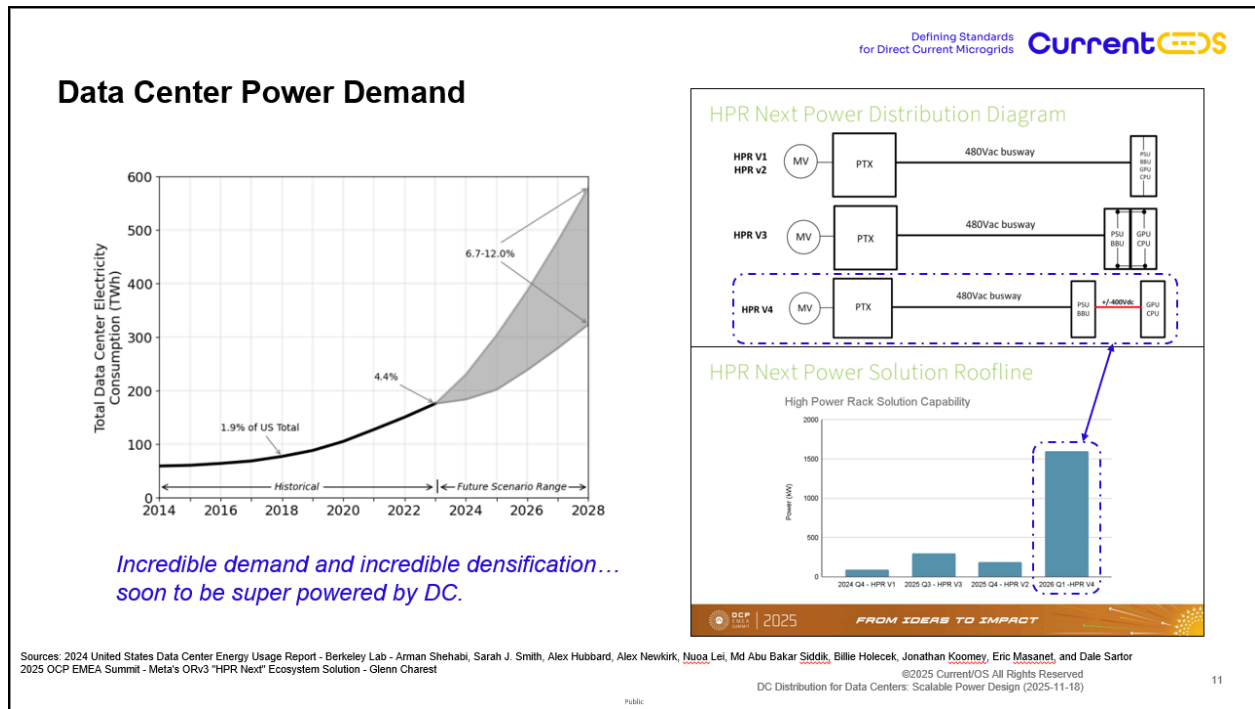


Figure 1. IT Rack Progression (Ref.: [Current/OS: DC Distribution for Data Centers](#))

This progression could be realized by shifting from utilizing DC power shelves with DC PSUs for conversion to 50 VDC vertical distribution (typically using Front-End Power DC-DC modules) to utilizing DC junction boxes (capable of interfacing the same higher input DC voltage for vertical distribution) (see [Figure 2](#) and [Figure 2B](#)).

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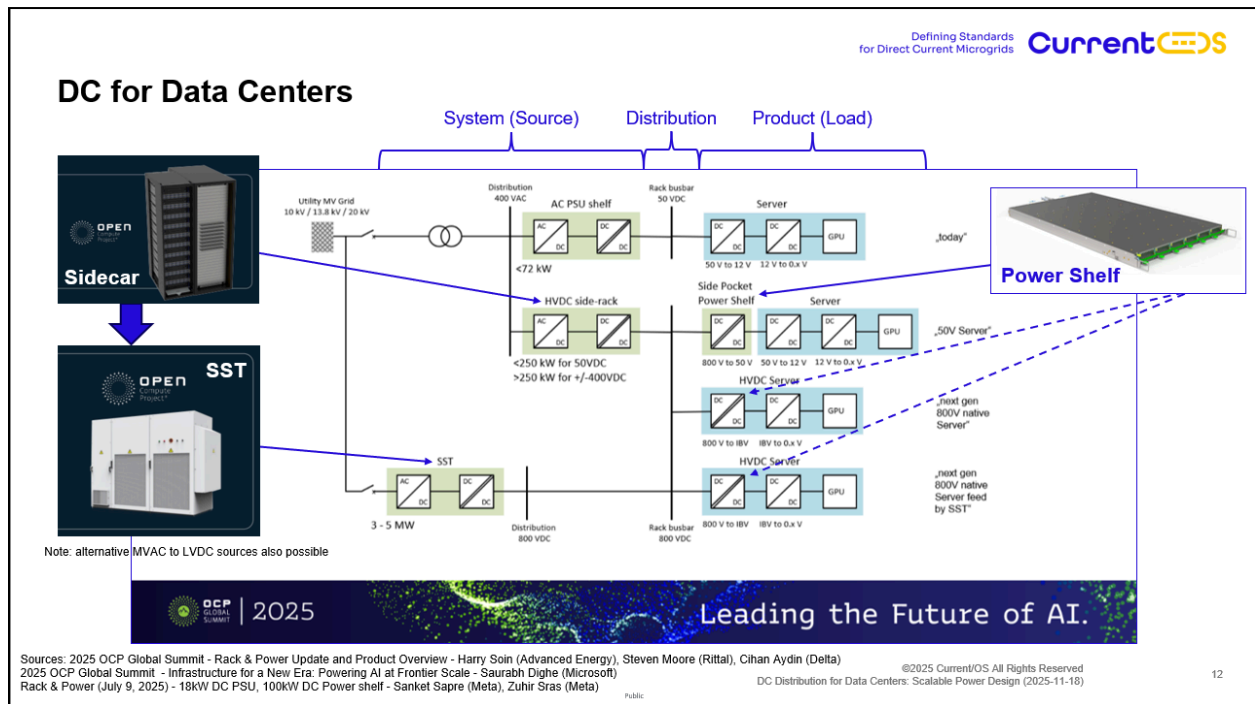


Figure 2. DC Distribution Progression (Ref.: [Current/OS: DC Distribution for Data Centers](#))

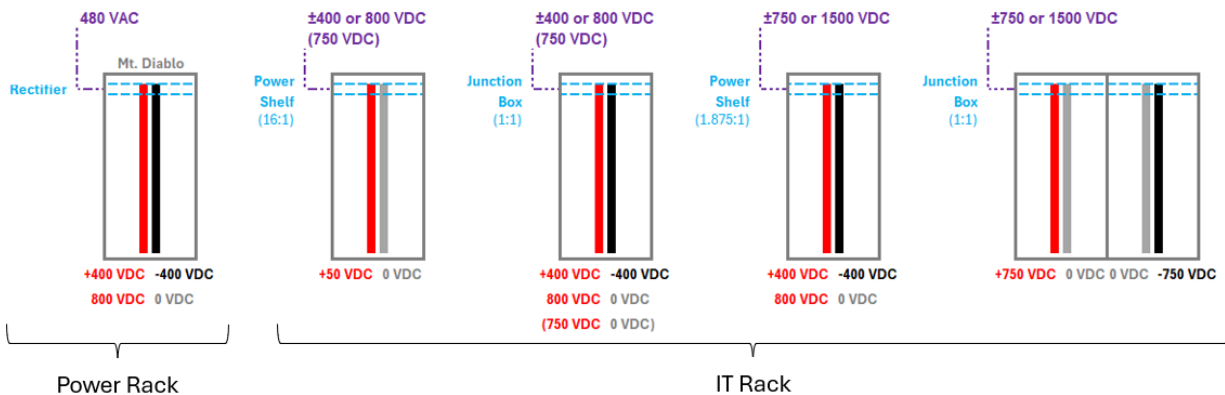


Figure 2B. Example Interfacing to Power Rack and IT Rack DC Vertical Bus

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3.2. Document Scope

This white paper is intended to address LVDC power distribution and its role as an interface between incoming Medium Voltage Alternating Current (MVAC) power (presently in the gray space) with IT rack compute in the white space. [Section 4](#) and [Section 8](#) of this white paper are intended to focus on the conversion of MVAC to LVDC, whether by Solid State Transformer (SST) or other conversion components. Future editions of this white paper may also consider other possible LVDC sources, their interconnection, and varying levels of available fault current. While energy storage is also included, direct connection is excluded (i.e. a converter interface is required).

At present, the scope is limited to 1500 VDC, thereby excluding what is commonly referred to as Medium Voltage Direct Current (MVDC) which finds usage in other applications such as 2000 VDC for solar PV renewable energy sources. Future editions of this white paper may also consider utilization of an MVDC underlay grid and SST conversion (or otherwise) from MVDC to LVDC.

Additionally, while Direct Current usage for industrial / commercial building microgrids is typically focused on loosely regulated droop control and interoperable component operation across a wide band of continuous voltage (reducing round trip losses for energy storage through the usable state-of-charge range), Direct Current usage in data centers is focused on tightly regulated operation in a narrow band of continuous voltage optimized for maximum power delivery at the limit of component voltage class capability.

These differences in application lead to a further consideration regarding the future trajectory of Direct Current usage in the data center facility for cooling, lighting, and other non-regenerative loads which have the potential to take advantage of efficiency from higher DC voltage distribution and reduced AC conversion losses. It is likely that such usage will reflect the higher voltage limits of IT rack compute loads rather than the traditional limits of DC microgrids.

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However, it may also introduce additional changes regarding bidirectional power flow considering energy storage, and is thus not included in the present scope.

Further, in the transition to DC-supplied IT racks, the power rack (sidecar) has been defined by the [Mt. Diablo](#) specification as developed by the OCP [Rack & Power](#) project. The scope of this white paper is limited to interface with DC-supplied IT racks including power shelves.

4. System Architecture Methodology

4.1. Grid Connection

This subsection describes, at a high level, the connection between loads and power distribution. In order to simplify the discussion we consider two topologies: a single “line-up” for an MV to LV power block to supply the AI load (e.g. 3 MW+), and a Direct Current power generation source feeding a similar AI load / Data Center room. Future papers will address full distribution systems as the focus of this paper is to be a foundational document to be built upon with further work.

4.1.1. From MV to LV distribution

MV gets distributed from substation into smaller power nodes that feed into the data hall's and mechanical hall's LV system. These power nodes consist typically in a MV switchgear setup that allows a redundant routing of the power, e.g. a loop feed, that ties in several nodes (connection points) together and is fed from two different sources. Each node will convert the power needed into LV power being used at a load nearby via a MV/LV transformer. These nodes are not placed in parallel, but can be interlaced on the LV side with a reserve bus topology (for N+1 to make N) or dynamic bus topology (2N) to provide redundancy. One node can have several feeds, with each feed having a dedicated breaker and protection setup.

The current standard topology consists in only AC type distribution, with eventual conversion from AC to DC in the rack to DC infrastructure located downstream from the LV AC switchgear, for each dedicated feed. Building on this topology, a first step into conversion into a DC network could be the addition of a DC network at the LV root of the power node (e.g. as described by the Mt. Diablo specification). One transformer would be feeding at the same time AC and DC networks. Transforming a data center's power supply is more than a technical upgrade—it is an adoption in a staged approach and a strategic step toward securing performance, efficiency, and reliability. The first principle driver is to support compute densification and congestion management.

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Such a transformation is seen to occur in adoption stages. This requires a structured, staged approach that brings clarity to complexity and stability to change—focusing on the first principle driver of the change, then moving to further optimizations as the supply chain matures to support size and scale.

Each phase provides valuable insights that help us optimize performance and enhance the system along the way. Based on this, we have structured the DC power transition into three distinct stages.

Stage 1:

- IT Racks (and optionally associated cooling) are supplied by direct current with other equipment powered by AC.
- Option 1a: with isolation on the DC/DC converters for the rack, i.e., where the step-down conversion from 800 V to below 50 V happens; see [Figure 3](#).

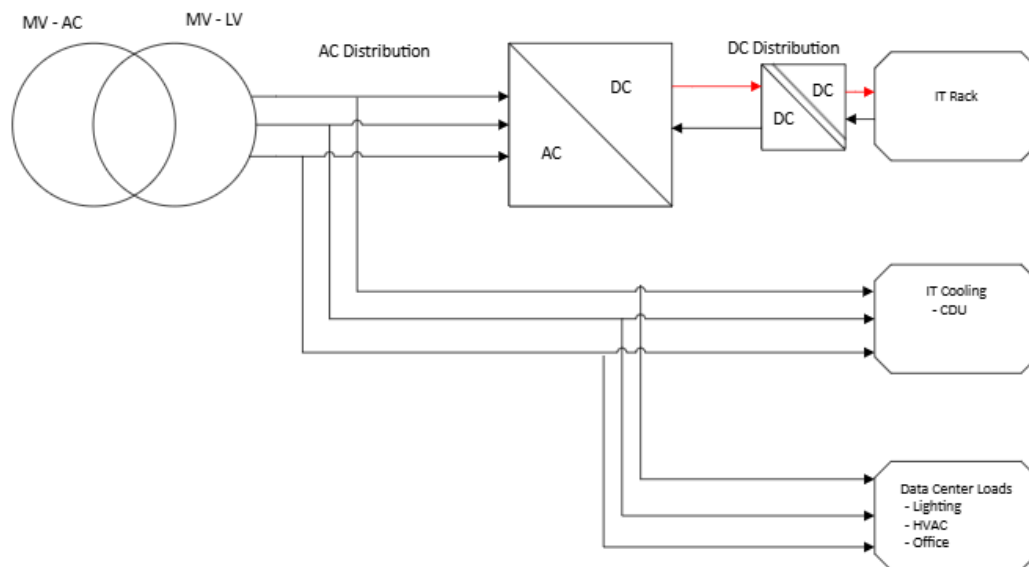


Figure 3. Isolation at the DC/DC converters for the rack

- Option 1b: Alternatives for the same stage with isolation at the central AC/DC converter is shown in [Figure 4. Isolation at the central AC/DC converter](#).

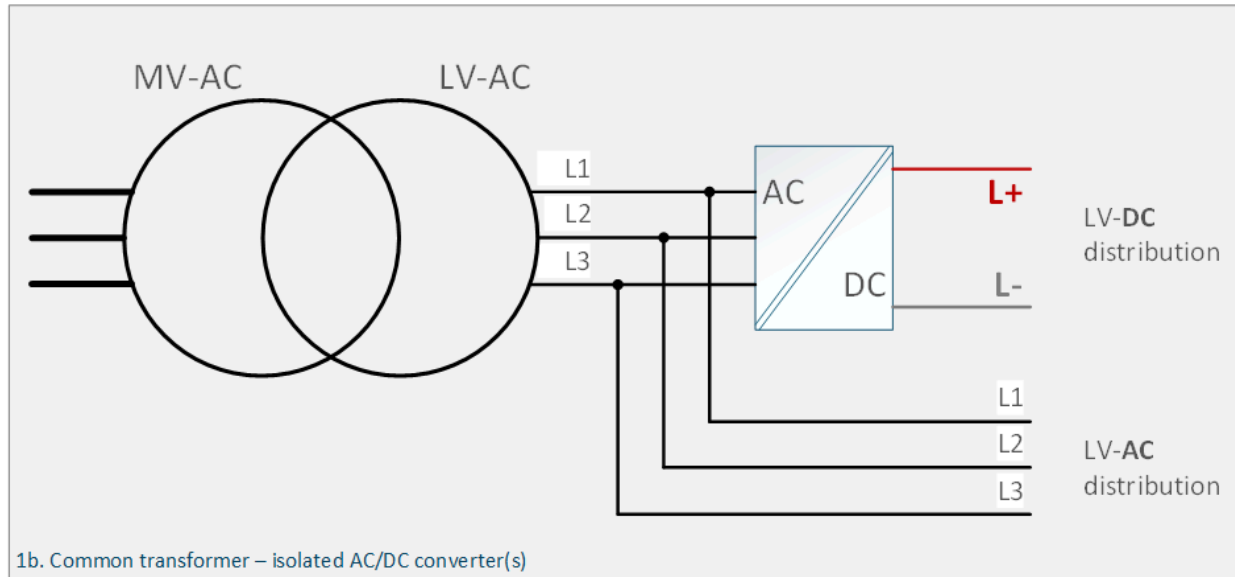


Figure 4. Isolation at the central AC/DC converter

- Option 1c: shown in [Figure 5 Separate transformers for DC and AC distribution](#) with separate transformers for the DC distribution and AC distribution, respectively.

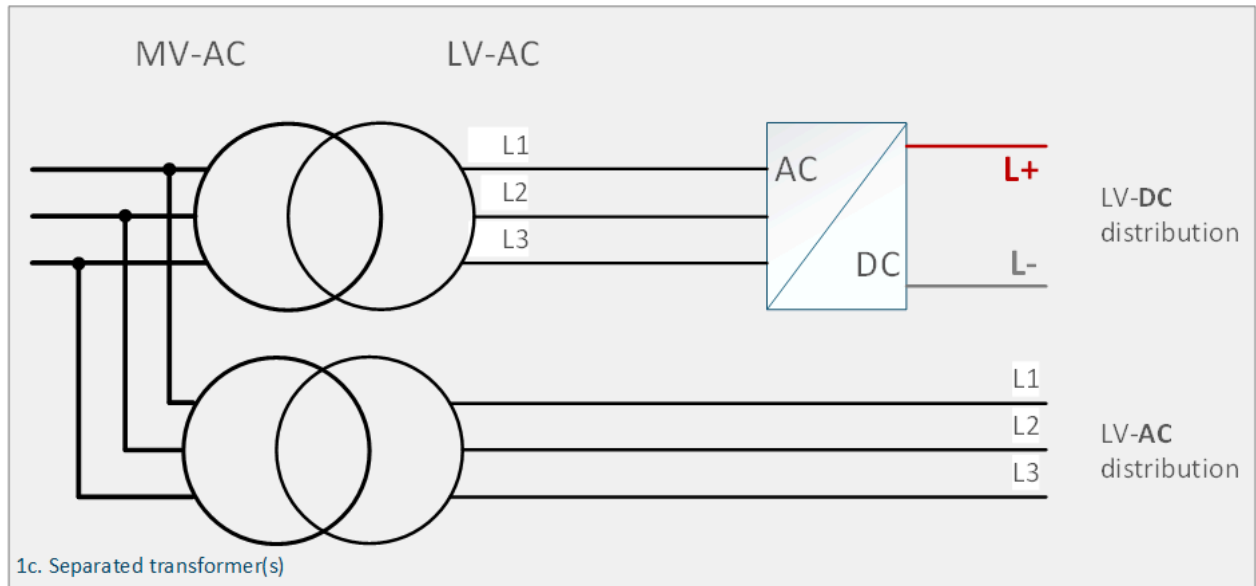


Figure 5. Separate transformers for DC and AC distribution

- Option 1d: shown in [Figure 6](#) with SST for the LV DC distribution part:

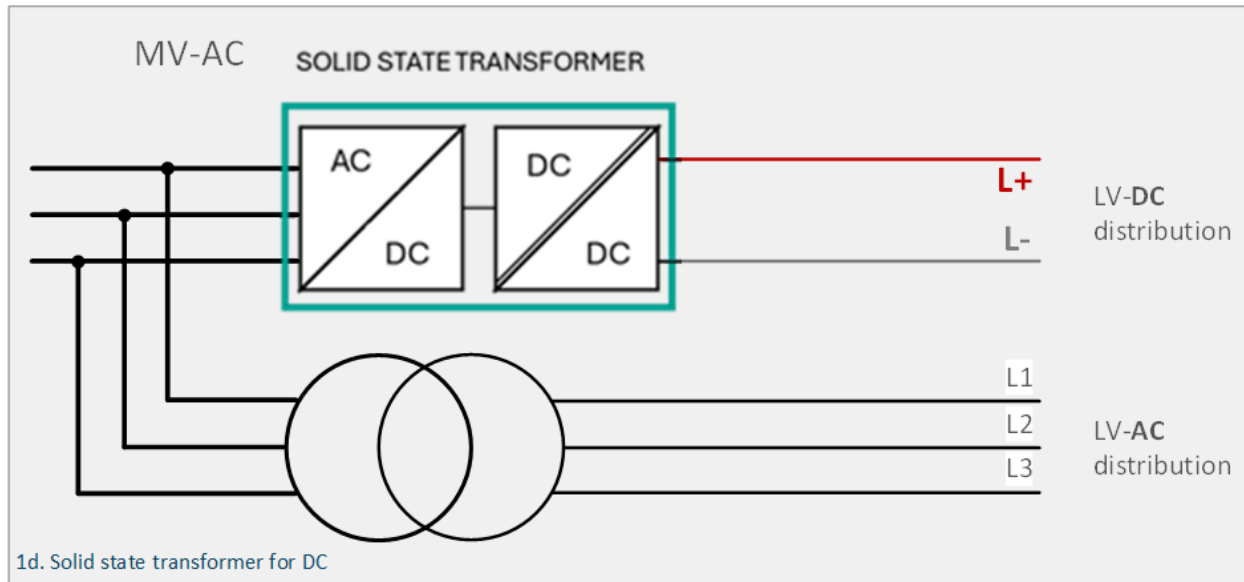


Figure 6. Solid-state transformer for DC distribution and transformer for AC distribution

Stage 2:

- Full Block 3 IT module (cooling distribution units CDU, Network, IT racks) on direct current is shown in [Figure 7 DC distribution for IT rack and the associated cooling devices](#), the building infrastructure still runs on AC.

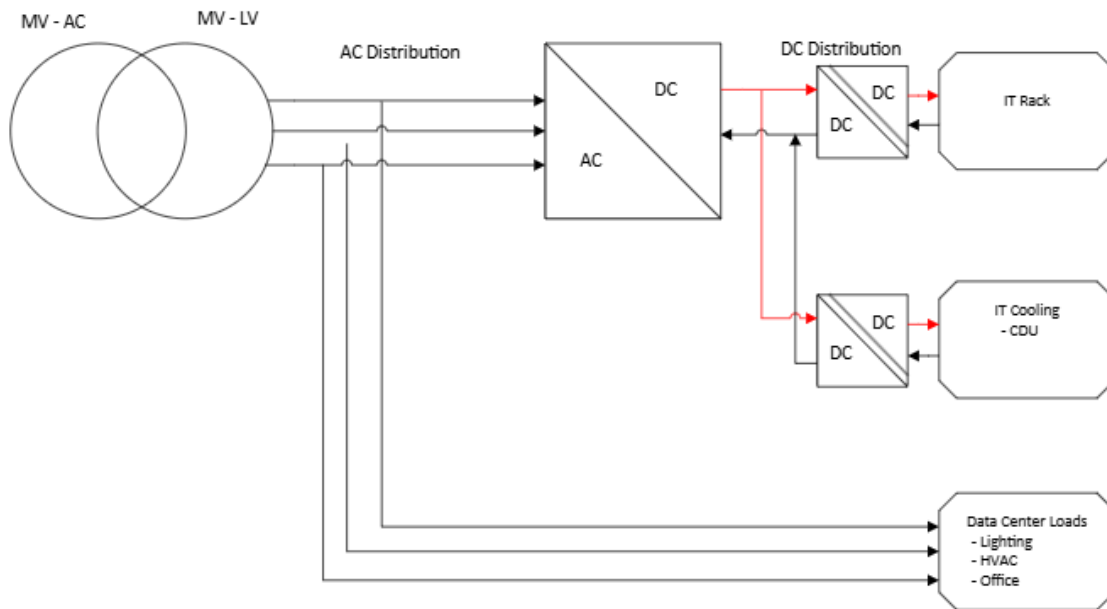


Figure 7. DC distribution for IT rack and the associated cooling devices

Stage 3:

- Full Direct current distribution between MV and all equipment in the Data Center.
 All Equipment is powered by DC only, as shown in Figure 8.

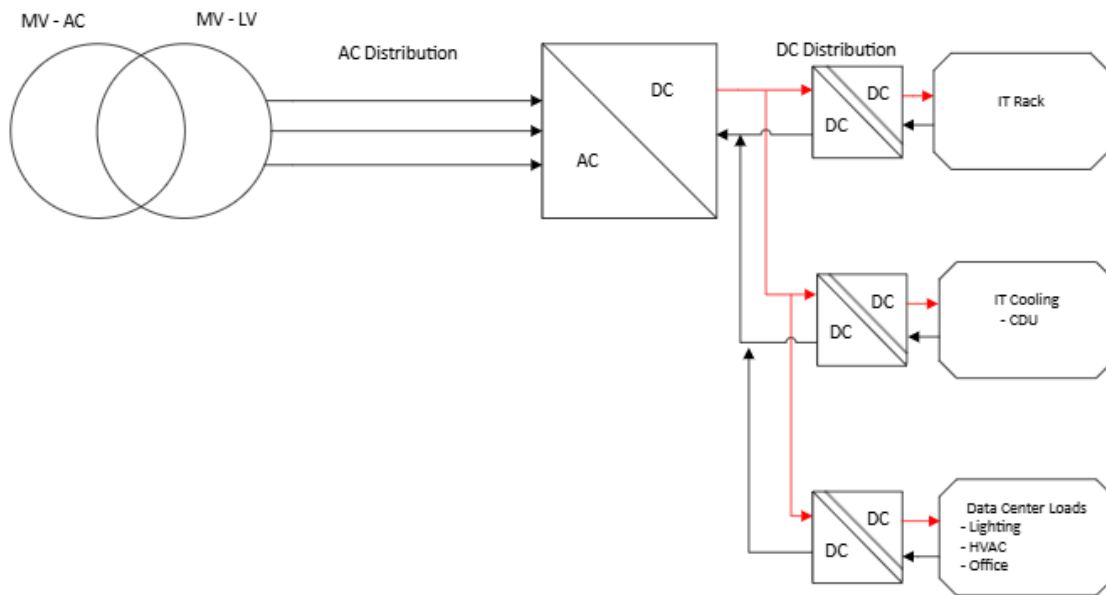


Figure 8. Full LVDC distribution for the datacenter

Instead of the SST it is also possible to install a MV/LV transformer in combination with an AC/DC converter (isolated or non-isolated). Please refer to the component section for more details.

4.2. Redundancy Levels

Currently, the targeted reliability level is 99.9% for training AI data centers and 99.999% for inference AI data centers.

Generally, power electronics are the components that have the highest failure rate in a data center (e.g., power shelves, UPS) and this has been managed by a few strategies such as N+1 power blocks, and maintenance bypass.

However, DC distribution does not allow for a maintenance bypass strategy of an uninterruptible power supply, so there needs to be redundancy at the power block level and potentially at the power distribution level as well.

If not, there needs to be some kind of upstream DC Static Transfer Switch.

Even for 99.9% availability level, there needs to be some kind of catcher system (type of uninterruptible power supply) to prevent single point of failure at the AC/DC conversion block.

To achieve 99.999%, if the AC/DC conversion block has a high failure rate, then there needs to be redundancy at the AC/DC conversion block level.

If there's modularity within the AC/DC conversion block, redundancy at that level may reduce the redundancy requirement at the AC/DC conversion block level

Other points of consideration:

- Failure rate scales with ambient temperature
- Useful life of the data center is ~10 years - so need to understand how the failure rate changes over that period of time; including on-site spare equipment for repairability
- For applicable equipment, need bypass test to detect fault that caused the failure of the power module

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- The migration to solid-state solutions may require a new, strategic approach to comprehensive coordination studies. Include higher levels of hierarchy as this allows for more flexibility in design.

As data centers migrate towards LVDC distribution, there's still the expectation that data centers continue to maintain similar levels of availability. For training AI data centers, 99.9% availability is the targeted level. For inference AI data centers, 99.999% availability is the targeted level. LVDC distribution introduces new technologies and architectures that require new ways to achieve this level of availability. Another example is that major building blocks (SST, UPS, BBU, PCS) are migrating towards solutions made up of even lower-level modular sub-blocks which must have live-swap capabilities ([Example](#)) A more in-depth look at strategies to achieve availability in LVDC data centers requires further investigation.

4.3. Verified Benefits of DC installations

LVDC installations have been installed and operating for years. This subsection gives some examples.

- **Schaltbau's NExT Factory** is a new, completely electrified building in operation since Sep.2023, [Schaltbau opens NExT Factory in Velden](#). It is a symmetrical, 2-wire DC-distribution with normal operating voltage band up to 750 V – installed following the DC-INDUSTRIE description, now available as VDE SPEC 90037. After about 2.5 years of operation, they reported these achievements, [Schaltbau's NExT Factory lessons from the world's first DC microgrid powered plant](#)
- **DC-powered datacenter**. In the year 2012 already, ABB and Green, an IT service provider, opened a datacenter, [World's most powerful DC data center online | News center | ABB](#). They conclude that "DC technology should preferably be used in new and large data centers". See also pages 16ff of ABB Review 4|2013, [ABB Review No. 4 2013](#)

- **Production cell of BMW.** The car manufacturer has converted a car body cell in their factory in Bavaria to DC supply. After almost two years of operation, **8.8% less energy is needed** to perform the same job as previously with AC supply, ['With direct current towards more sustainability in automobile production'](#).

5. Voltage Levels and Power Quality

This section reviews common definitions, introduces key concepts, and discusses critical considerations around voltage.

5.1. Voltage Classes

While many sub classifications of voltage exist, there are two primary classifications commonly recognized by codes and standards – low voltage and high voltage.

5.2. Low Voltage (LV), Including Sub-Classes (e.g. ELV, LES)

5.2.1. General Definition

In the context of power distribution, low voltage is defined by international product standards and regulations along with installation codes as operation at or below 1000 VAC or 1500 VDC. (The 1.5x multiplier from AC RMS to DC is based on comparable insulation stress considering AC peak as $\sqrt{2}$ factor above AC RMS voltage.)

- [NFPA 70®, the National Electrical Code® \(NEC®\)](#) - Article 100 Definitions -
High Voltage: *A potential difference over 1000 volts ac, 1500 volts dc, nominal.*
- [IEC 60050-195 International Electrotechnical Vocabulary \(IEV\) - Part 195 \(05-25\)](#) -
Low Voltage (LV): *voltage not exceeding a conventionally adopted limit*
 - *Note 1 to entry: For AC, the conventionally adopted limit is 1 000 V.*
 - *Note 2 to entry: For DC, the conventionally adopted limit is 1 500 V.*
- [IEC 60364-1 Low Voltage Electrical Installations - Part 1](#) - Section 11.2 -
IEC 60364-1 covers
 - a) circuits supplied at nominal voltages up to and including 1 000 V a.c. or 1 500 V d.c.;*
- [IEC TS 63527 Safe management and operation of electrical installations](#) -
Low Voltage (LV): *voltage normally not exceeding 1 000 V AC or 1 500 V DC*
High Voltage (HV): *voltage normally exceeding 1 kV AC or 1,5 kV DC*

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- [European Union \(EU\) Low Voltage Directive \(LVD\)](#) - Article 1 Subject matter and scope:
“This directive shall apply to electrical equipment designed for use with a voltage rating of between 50 and 1 000 V for alternating current and between 75V and 1 500 V for direct current, other than the equipment and phenomena listed in Annex II.”
- China GB/T 35727:
 3.6 本标准将3000(±1500)V~±50kV 划分为中压范围,将110V~1500(±750)V 划分为低压范围。
 3.6 This standard sets ±3,000 V (inclusive) to ±50 kV as the high-voltage DC distribution range and 110 V to 1,500 V (inclusive) or ±750 V as the low-voltage DC distribution range.

Even where the NEC has been updated to permit 2000 VDC for certain solar PV installations (see [Figure 11](#)), the dividing line between low and high voltage remains at 1500 VDC. This boundary is supported by established insulation coordination practices, equipment design constraints, and appropriately defined personnel protection requirements.

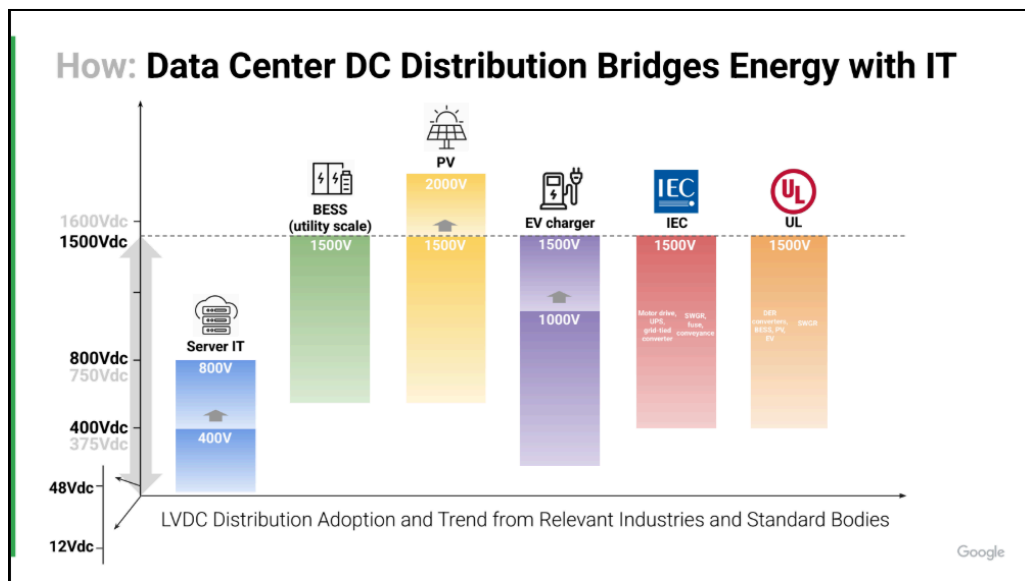


Figure 11. Low Voltage DC Limit (Ref.: [Intro of Data Center LVDC](#))

Despite general adherence to this limit, it is worth mentioning that there may be certain local exceptions or product standard scoping limitations which define lower voltages (for more info see [Section 11](#)). For example, in Japan, 600 VAC and 750 VDC are commonly defined in JIS standards.

Less commonly, there are also higher definitions applied by certain product standards such as [IEEE C37.14](#) which defines a 3200VDC limit for LVDC power breakers. However, these standards are still bound by local installation codes such as the NEC which adheres to the 1500 LVDC limit.

From a physics perspective, the possibility of corona discharge (whereby air surrounding energized electrical equipment becomes ionized and conductive) exists for certain conditions of sharp edges, defects, and low pressure environments with voltages as low as 300V. However, for voltages above 1000VAC or 1500VDC, additional design and testing measures become necessary, considering the large air gaps required and decrease in the dielectric strength of air with altitude.

5.2.2. Extra-Low Voltage (ELV)

Within the low voltage classification exists a sub-classification for extra-low voltage defined according to [IEC 61140](#) as ≤ 50 VAC or ≤ 120 VDC. Note that whereas LVDC generally applies a 1.5x multiplier between DC and AC rating, ELV applies a 2.4x multiplier in consideration of the electrical shock hazard as defined by [IEC 60479-1](#).

Additionally, basic protection against electric shock may be provided by ensuring touch voltage is limited to ≤ 25 VAC or ≤ 60 VDC in dry locations where large-area contact with live parts is not expected (≤ 6 VAC or ≤ 15 VDC otherwise) and supplying voltage from a battery, safety isolating transformer, or safety equivalent. The dependence of the exact voltage threshold for ELV on the conditions aligns with the more general definition below. Additional criteria specific to SELV (ungrounded) and PELV (grounded) systems are also identified.

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- [IEC 60050-195 International Electrotechnical Vocabulary \(IEV\) - Part 195 \(05-24\)](#) -
Extra-Low Voltage (ELV): *voltage not exceeding the maximum value of the prospective touch voltage that is acceptable to be maintained indefinitely under specified conditions of external influences*
- [IEC 60050-195 International Electrotechnical Vocabulary \(IEV\) - Part 195 \(06-28\)](#) -
SELV (safety extra-low voltage) system: *electric system in which the voltage cannot exceed the value of extra-low voltage:*
 - *under normal conditions and*
 - *under single fault conditions, including earth faults in other electric circuits*
- [IEC 60050-195 International Electrotechnical Vocabulary \(IEV\) - Part 195 \(06-29\)](#) -
PELV (protective extra-low voltage) system: *electric system in which the voltage cannot exceed the value of extra-low voltage:*
 - *under normal conditions and*
 - *under single fault conditions, except earth faults in other electric circuits*

Similar though different requirements exist in [NFPA 70E](#), where ≤ 50 V (AC or DC) is defined in Section 110.2(B) as part of general criteria for an electrically safe working condition. This is extended to ≤ 100 VDC when working on certain equipment under additional restrictions for fault current (e.g. 100VDC, 40 mA in Sections 320.3, 330.3, 340.4, 350.9). Note that OSHA also defines the 50V (AC or DC) threshold with certain exceptions in [29 CFR 1910.333\(a\)\(1\)](#).

5.2.3. Limited Energy Systems (LES)

The NEC additionally defines wiring classes 1 - 4, with classes 2 - 4 categorized as limited energy for mitigation of shock and fire hazards (see [Table 1](#)). Details of classes 2 and 3 voltage and power ratings are provided in NEC Chapter 9, Tables 11(A) and 11(B).

Table 1. Limited Energy System Wiring Classes in the NEC

	Common Applications	Typical Voltage	Power	Fire Risk	Shock Risk
Class 2	Power over Ethernet (PoE), alarms, automation	≤ 30 VAC, ≤ 60 VDC	≤ 100 VA	Low by design	Low by design
Class 3	medical, audio, industrial	up to 150 V	~ 150 VA	Mitigated by cabling rules	Low by design
Class 4	Fault Managed Power Systems (FMPS)	up to 450 V peak	100 W (L-E or L-L faults)	Low by reaction	Low by reaction

5.3. High Voltage (HV), Including Sub-Classes (e.g. MV, HV, EHV, UHV)

5.3.1. General Definition

In the context of power distribution, high voltage is defined in contrast to low voltage as greater than 1000 VAC or 1500 VDC. (The 1.5x multiplier from AC RMS to DC is based on comparable insulation stress considering AC peak as $\sqrt{2}$ factor above AC RMS voltage.)

5.3.2. Medium Voltage (MV)

The immediate voltage range above and adjacent to low voltage is medium voltage. The upper limit of medium voltage is variously defined at different levels, but typically not distinguished between AC and DC.

[ANSI C84.1](#) lists the upper limit of medium voltage as <100 kV. In an informative note for the definition of high voltage, the NEC identifies that circuits and equipment rated for up to 52 kV are commonly referred to as medium voltage. It specifically defines Type MV cable for ≥ 2001 V and ≤ 35 kV as well as other cable types in Table 690.31(A)(3)(1) for ≤ 2000 V. This corresponds with a typical application of medium voltage in many utility distribution systems.

With continuing advancements in renewable energy generation, additional market demand is bringing additional focus on the development of specific standards for MVDC (particularly up to 2kV and 3kV DC levels) and a recent report has been published by the IEC exploring [MVDC grids for an all-electric society](#).

5.3.3. High Voltage (HV), Extra High Voltage (EHV), Ultra High Voltage (UHV)

Voltages beyond medium voltage are typically the domain of utility transmission systems. [ANSI C84.1](#) defines:

- High Voltage (HV): ≥ 100 kV and ≤ 230 kV
- Extra High Voltage (EHV): > 230 kV and < 1000 kV
- Ultra High Voltage (UHV): ≥ 1000 kV

5.4. Nominal Voltage

Nominal voltage identification serves an important purpose to uniquely label an AC or DC system. It also defines both an installation rating class for facility wiring and a product rating class for sources, loads, and prosumers (devices which may be either producers or consumers). Several key definitions are provided as follows (refer to [Section 5.6](#) for further information on voltage bands and levels):

- [NFPA 70®, the National Electrical Code® \(NEC®\)](#) - Article 100 Definitions -

Nominal Voltage: *A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (e.g., 120/240 volts, 480/277 volts, 600 volts).*

- *Informational Note No. 1: The actual voltage at which a circuit operates can vary from the nominal within a range that permits satisfactory operation of equipment.*
- *Informational Note No. 2: See ANSI C84.1-2011, Voltage Ratings for Electric Power Systems and Equipment (60 Hz).*

- [IEC 60050-601 International Electrotechnical Vocabulary \(IEV\) - Part 601 \(01-21\)](#) -
 Nominal Voltage of a system: *a suitable approximate value of voltage used to designate or identify a system*
- [IEC 60050-826 International Electrotechnical Vocabulary \(IEV\) - Part 826 \(11-01\)](#) -
 Nominal Voltage <of an electrical installation>: *value of the voltage by which the electrical installation or part of the electrical installation is designated and identified*
- [IEC TR 63282 - LVDC systems - Assessment of std voltages & power quality reqs](#) -
 DC system nominal voltage: U_n , *value of the voltage by which the electrical installation or part of the electrical installation is designated and identified*
 - Note 1 to entry: The DC system nominal voltage U_n is within the nominal band $[U_2; U_3]$ but not always half-way between U_2 and U_3 . In all cases $U_2 \leq U_n \leq U_3$
 - Note 2 to entry: For a bipolar system, it is recommended to use a dual notation, for example, " $\pm U_{L-M}$ " or " U_{L-M} / U_{L-L} ".

IEC 60038 lists the standard nominal voltage values for AC and DC. At the time of writing it is being amended for LVDC with IEC 60038/AMD2/FRAG1 ED7 CDV, where 175/350V, 350V, 350/700V, 700V, 700/1400V and 1400V are the standard voltages for LVDC from 120V to 1500V. These voltages are consistently scalable with a factor of 2 in this range. Also Current/OS and ODCA (recently) use 700V as the nominal voltage. Therefore 350V, 700V and 1400V are used as the nominal voltage of the DC grids. (400V and 800V would scale to 1600V which is above the low voltage limit of 1500V.)

5.5. Rated Voltage vs. Operating Voltage

The rated voltage of a device (source, load, or prosumer) is visible on the nameplate and used to determine the various voltages applied during qualification testing to applicable standards. It is important to note that this may be more than one value or may be a range of values.

- [IEC 60050-151 International Electrotechnical Vocabulary \(IEV\) - Part 151 \(16-49\)](#) -
Rated voltage range: *voltage range as declared by the manufacturer expressed by its lower and upper rated voltages [SOURCE: IEC 62368-1:2010, 3.3.10.5]*
- [IEC 60050-614 International Electrotechnical Vocabulary \(IEV\) - Part 614 \(03-09\)](#) -
Rated voltage <of equipment>: *voltage value assigned by a manufacturer or other entity for a specified operating condition of a component, device or equipment*
 - Note 1 to entry: *The value for the rated voltage of high voltage equipment is generally assigned from the list of highest voltages for equipment in Tables 3, 4 and 5 of IEC 60038:2009.*
 - Note 2 to entry: *The value for the rated voltage of low voltage equipment is generally assigned from the list of nominal voltages in Tables 1 and 6 of IEC 60038:2009.*
 - Note 3 to entry: *Equipment may have more than one rated voltage value or may have a rated voltage range.*

The operating voltage is closely related to the rated voltage, but differs in important ways. Here below is the official definition of operating voltage according to the IEC:

- [IEC 60050-601 International Electrotechnical Vocabulary \(IEV\) - Part 601 \(01-22\)](#) -
Operating voltage (in a system): *the value of the voltage under normal conditions, at a given instant and a given point of the system*
 - Note – *This value may be expected, estimated or measured.*

Importantly for Direct Current within [IEC TR 63282](#), both a continuous and a temporary operating voltage range are defined with corresponding voltage bands, see [Section 5.6 \(Voltage Bands\)](#). This has the potential to be broadly adopted and is already being incorporated into IEC product standards, especially with the pending update and release of [IEC 60038](#). It is important that the operating rating considers the highest applicable sustained voltage for the product function.

The operating voltage is tightly coupled to the applicable product standard and not necessarily consistent across products. A familiar example is the AC/DC power adapter typically supplied with a laptop computer. Recently [IEC 60950-1](#) has been obsoleted and replaced by [IEC 62368-1](#), but for this example of [Table 1B](#) and [Figure 11B](#), a default tolerance for the operating

voltage of 90 - 254 VAC applies to the rated 100 - 240 VAC (as no tolerance is indicated on the rating nameplate).

Table 1B. Example Operating Voltage for Rated Voltage

Rated Voltage	Operating Range (Default Tolerance)	
	IEC 60950-1	IEC 62368-1
	AC: $\pm 10\%$ for 230/400 VAC, -10/+6% otherwise DC: -15/+20%	AC: $\pm 10\%$ DC: -15/+20%
100 - 240 VAC	90 - 254 VAC	90 - 264 VAC



Figure 11B. Rated Voltage Example (Ref.: [Current/OS: DC Distribution for Data Centers](#))

5.5.1. Slash Ratings, Neutral, and Midpoint

For AC, it is common to find 3-phase or 1-phase products with a slash rating where the larger number represents the line-line voltage and the smaller number represents the line-neutral voltage. Usage of slash rated overcurrent protection devices (OCPDs) is limited to solidly

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grounded systems according to NEC Section 240.85. Additionally, corner grounded delta systems require fully rated (line-neutral = line-line) OCPDs.

For DC, it is possible to encounter slash rating for 3-wire products where the larger number represents the line-line voltage and the smaller number represents the line-midpoint (or equivalently line-neutral) voltage (see Figure 11C). NEC Section 240.85 applies here as well. Note that slash ratings are also possible for DC chargers, e.g. 250/260 VDC but this represents nominal / float voltage.

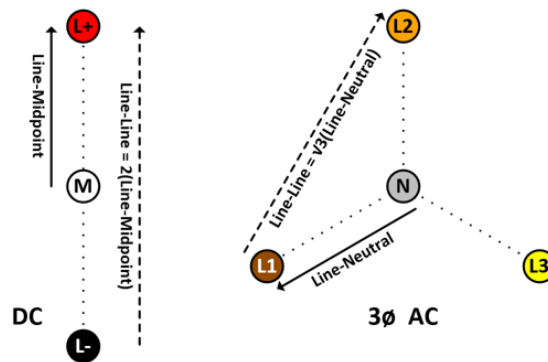


Figure 11C. DC Midpoint and AC Neutral (Ref.: [Current/OS: DC Distribution for Data Centers](#))

A set of example ratings is supplied in [Table 1C](#) for AC 1-phase (e.g. 120/240 VAC) and 3-phase (e.g. 480Y/277 VAC) as well as DC 3-wire (e.g. 125/250 VDC and 400/800 VDC) voltages.

Table 1C. Example Slash Voltage Ratings

Rating	Line-Neutral (Line-Midpoint)	Line-Line	NEC Grounding Type Compatibility		
			Solid (TN-S)	Functional (IT)	Ungrounded (IT)
480Y/277 VAC	277 VAC	480 VAC	Yes	No	No
480 VAC	480 VAC	480 VAC	Yes	Yes	Yes

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120/240 VAC	120 VAC	240 VAC	Yes	No	No
240 VAC	240 VAC	240 VAC	Yes	Yes	Yes
125/250 VDC	125 VDC	250 VDC	Yes	No	No
250 VDC	250 VDC	250 VDC	Yes	Yes	Yes
350/700 VDC	350 VDC	700 VDC	Yes	No	No
700 VDC	700 VDC	700 VDC	Yes	Yes	Yes
400/800 VDC	400 VDC	800 VDC	Yes	No	No
800 VDC	800 VDC	800 VDC	Yes	Yes	Yes

It is important to note that ± 400 VDC implies bipolar symmetrical distribution about the midpoint (neutral). While it is not equivalent to 400/800 VDC, devices which take advantage of the symmetry and lower line-neutral voltage in product testing would be rated as 400/800 VDC as opposed to the full 800 VDC. As such, they would be restricted by the NEC to usage in solid grounding systems.

5.5.2. Voltage Insulation and Isolation

Looking beyond the topic of slash ratings and design for bipolar symmetry, a closer look at the comparative creepage and clearance requirements for unipolar asymmetry in conjunction with either solid grounding (TN-S) or impedance grounding (IT) is provided in [Section 6.3](#). Additional guidance is also provided in this section for the important additional input factors of Over Voltage level and Pollution Degree.

When transitioning between classifications of MVAC, LVDC, and ELV through conversion, it is critical to consider the need for isolation to avoid the need to carry over higher rated insulation to the new voltage class. In addition, for each separately derived system produced by isolated conversion, it is important to state on the applicable equipment nameplate the grounding system compatibility.

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Furthermore, the ground fault detection and/or protection requirements of each system in consideration of the chosen grounding scheme require consideration according to [Section 7](#).

5.6. Voltage Bands in Active DC Microgrids

Passive DC microgrids include simple loads which operate independently, based on the presence or absence of source power within a defined tolerance. Active DC microgrids are capable of coordinating multiple sources, loads, and prosumers, and typically employ voltage droop control of current / power. Droop controlled devices are designed to operate within voltage bands and may also be combined with simple loads, provided the impact to system behavior is limited (as further described in [IEC TR 63282](#) and [NPR 9090](#)).

Active DC microgrid voltage bands typically provide greater nominal voltage flexibility than is possible in AC, where frequency, voltage, and phase must remain synchronized with the utility for rotating production sources (acc. to [UL 6200](#)) and inverters (acc. to [UL 1741](#)). Voltage change over time mirrors the power balance in the active DC microgrid, i.e., if more power is needed than available, voltage declines and vice-versa. This property can be used for power management, using so-called “droop curves” whereby active components (e.g., converters) adjust their power output according to the voltage measured at their terminals.

In addition to the voltage band descriptions found in [IEC TR 63282](#), droop curve descriptions and examples are also available in the system description documents of [ODCA](#) and [Current/OS](#) based on LVDC commercial and industrial installations.

5.6.1. Voltage Band Definitions

A summary of basic definitions for voltage bands and associated voltage levels is provided in [Table 1D](#) as defined by [IEC TR 63282](#). Continuous operation with full functionality is provided within “nominal” voltage band B3.

Temporary overvoltage operation is provided within band B4 (in Current/OS this is presently limited to 10 minutes and in ODCA devices may choose whether to disconnect). Temporary

undervoltage operation is provided in band B2 (in Current/OS this is limited to critical loads and in ODCA critical loads may operate together with derated non-critical loads).

Above the overvoltage band B4 and below the undervoltage band B2, the system operates for a very limited time. Examples are short voltage spikes (e.g. from switching operations) or short voltage dips (e.g. for ride-through capability or prior to selective interruption of a fault condition). It's helpful to consider the distinction between the operating voltage range for overvoltage protection devices (e.g. surge protection devices) as voltage band B6 from the operating voltage range for overvoltage and overcurrent protection devices (e.g. solid state circuit breaker SSCB) as B2 through B5 in Current/OS and B2 through B4 in ODCA.

Table 1D. Voltage Band and Level Definitions as defined by IEC TR 63282

Band	Short Description	Level	Short Description
B7	Prohibited band ($U_6 \dots \infty$)		
		U_6	Maximum voltage that equipment overvoltage protection devices clamp
B6	Overvoltage protection devices operation band ($U_5 \dots U_6$)	U_5	Overvoltage disconnecting voltage
B5	Overvoltage protection devices non-operating band ($U_4 \dots U_5$)	U_4	Maximum temporary operating voltage
B4	Switching, commutation and protection devices operation band ($U_3 \dots U_4$)	U_3	Maximum continuous operating voltage
B3	Nominal band ($U_2 \dots U_3$)	U_2	Minimum voltage for continuous operation with full functionality
B2	Critical band ($U_1 \dots U_2$)	U_1	Undervoltage disconnecting voltage
B1	Blackout band ($0 \dots U_1$)		

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5.6.2. Existing Voltage Bands

An overview of existing voltage band thresholds is provided in [Figure 11D](#) for DC microgrids (as defined by Current/OS, ODCA, CABEE, and EMerge Alliance) along with data centers (as defined by ETSI and OCP). Note that OCP values are identified based on [Mt. Diablo](#) and [HPR v4 100kW](#) power shelf specifications as shown in [Figure 11E](#).

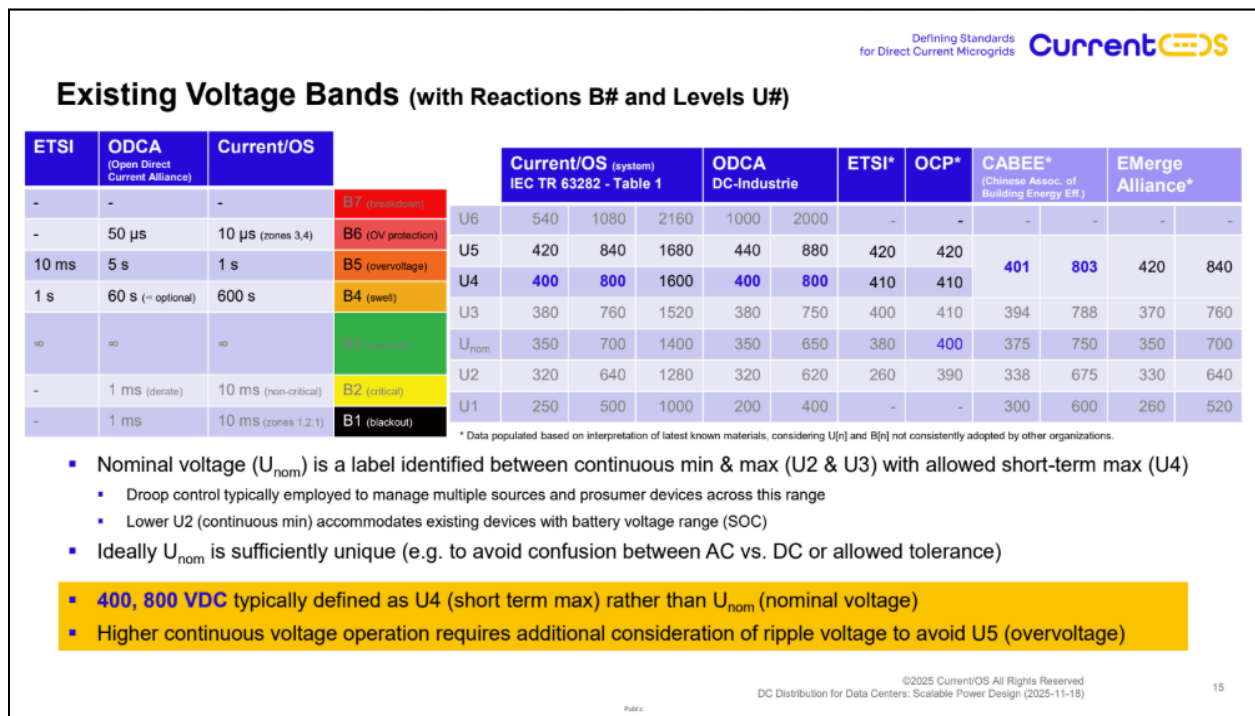


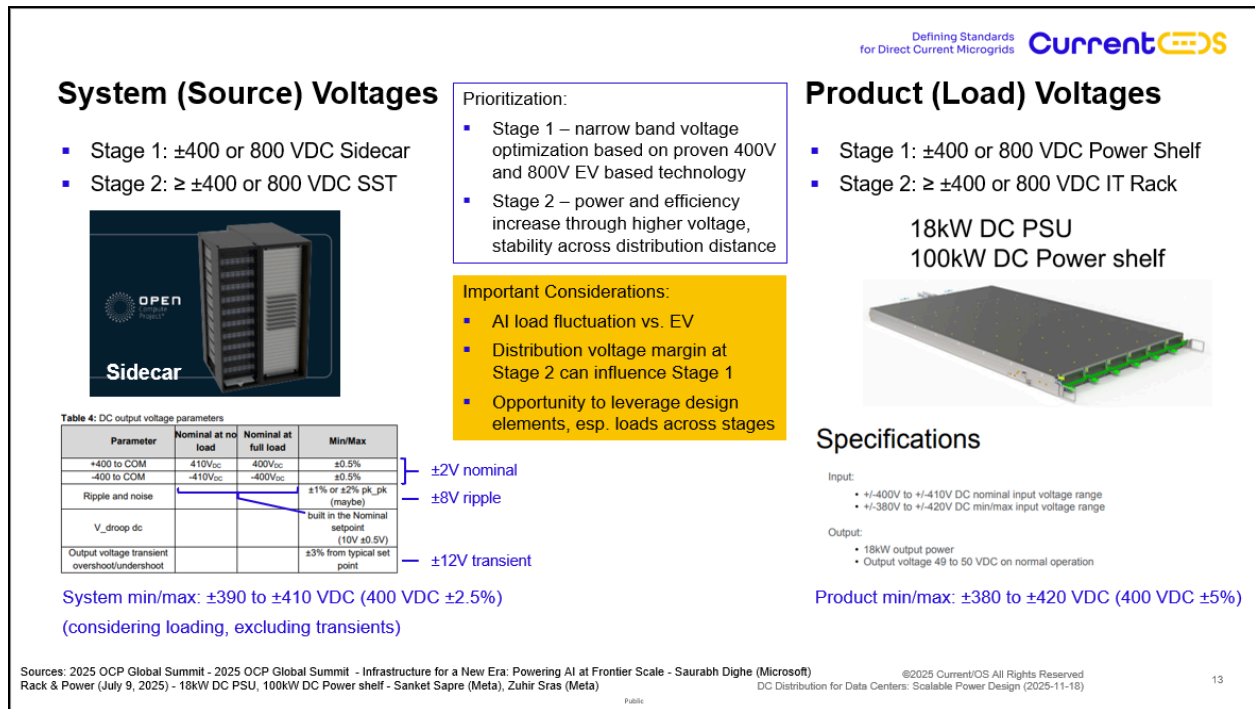
Figure 11D. Existing Voltage Bands (Ref.: [Current/OS: DC Distribution for Data Centers](#))

Note that Current/OS, EMerge Alliance, and ODCA (recent update from 650V shown in [Figure 11D](#)) have all adopted the 700V and 350V nominal voltages (with 1400V additionally defined by Current/OS). This aligns with the commonly used nominal voltages defined in [IEC TR 63282](#) and soon to be published in an updated version of [IEC 60038](#).

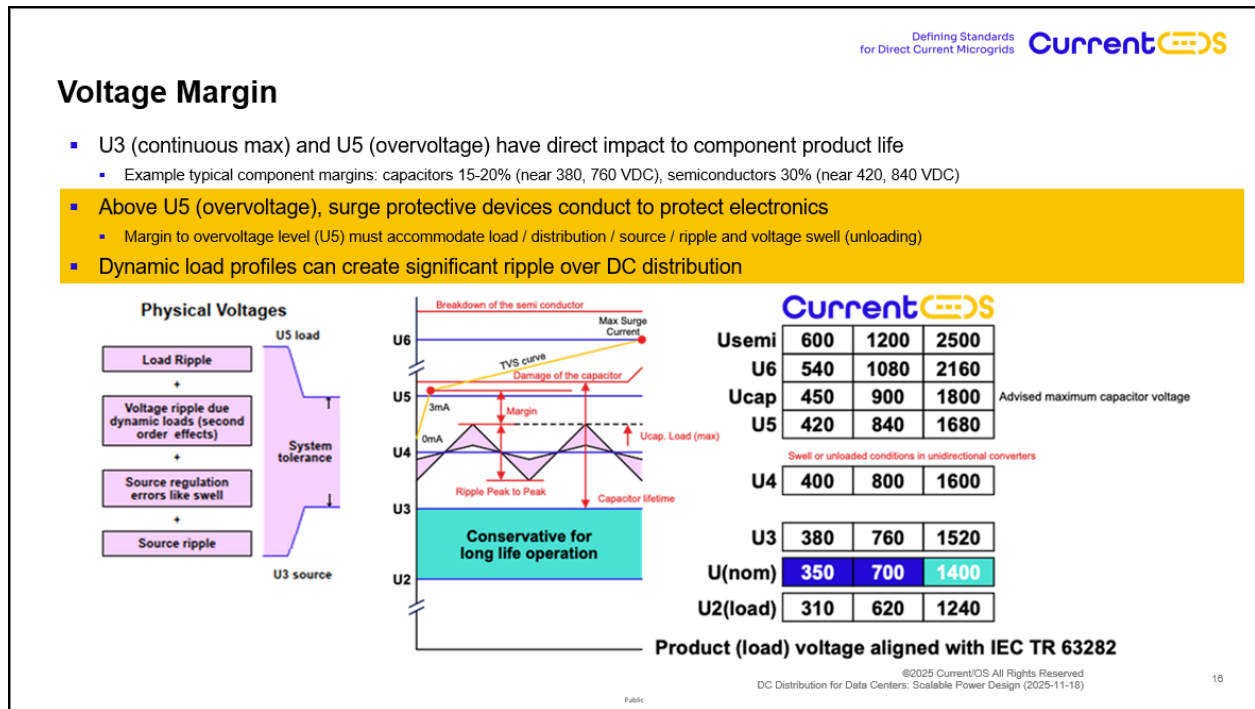
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 Figure 11E. Basis for OCP Voltage Bands (Ref.: [Current/OS: DC Distribution for Data Centers](#))

It is important to observe that historically for DC microgrids, operation up to 800 VDC has been limited to temporary overvoltage band B4 (U4 level) with margin above in voltage band B5 (U5 level) to avoid conduction by surge protective devices (e.g. TVSs) as shown by the yellow curve in [Figure 11F](#).


 Figure 11F. Surge Protective Device Margin (Ref.: [Current/OS: DC Distribution for Data Centers](#))

5.6.3. Narrow vs. Wide Voltage Bands

Traditionally, DC microgrid design has embraced wide voltage bands with ample overvoltage margin in band B5 as a means of facilitating “pre-designed” DC systems constructed from interoperable “off-the-shelf” components to provide interoperability among manufacturers, optimize equipment usable life, and minimize custom engineering.

A wide operation range of voltage bands B3 to B4 for normal devices and including B2 for critical loads, has the additional application benefit of minimizing round-trip energy storage losses by aligning with a typical state-of-charge range. Additionally, provisioning voltage band B5 accommodates voltage swell associated with unloading of simple loads and regenerative energy recuperation from motor drives.

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In data center applications, direct connection to energy storage is unlikely and chilling loads offer natural motor braking due to pump losses associated with circulating coolant. Fan operation is also possible but deceleration would require appropriate control measures to avoid regeneration during deceleration.

Furthermore, data center applications intend to take advantage of the economies of scale associated with converter designs and semiconductors utilized in electric vehicles where 400V and more recently 800V batteries have become common. However, it is important to note the significant load stability differences between AI compute and EV applications.

Given the focus on optimizing power delivery for compute loads in the compact footprint of the IT rack, ± 400 VDC or 800 VDC has become the design point for next generation DC input power shelves receiving power from Mt. Diablo power racks with ± 750 VDC or 1500 VDC as a logical progression for fully utilizing the maximum performance possible in LVDC.

Recognizing this need and objective, significant effort has gone into identifying and comparing the power capabilities of DC power shelves to define a framework for DC system interoperability between data centers and DC microgrids. This begins by taking a closer look at the Power Limiting Converters commonly utilized by DC microgrids which feature a built-in capability for derating at lower voltages as shown in [Figure 11G](#). Here also by slightly increasing the current limit (e.g. increasing from 131.6A to 140.3A), full power for 750 VDC $\pm 5\%$ is possible.

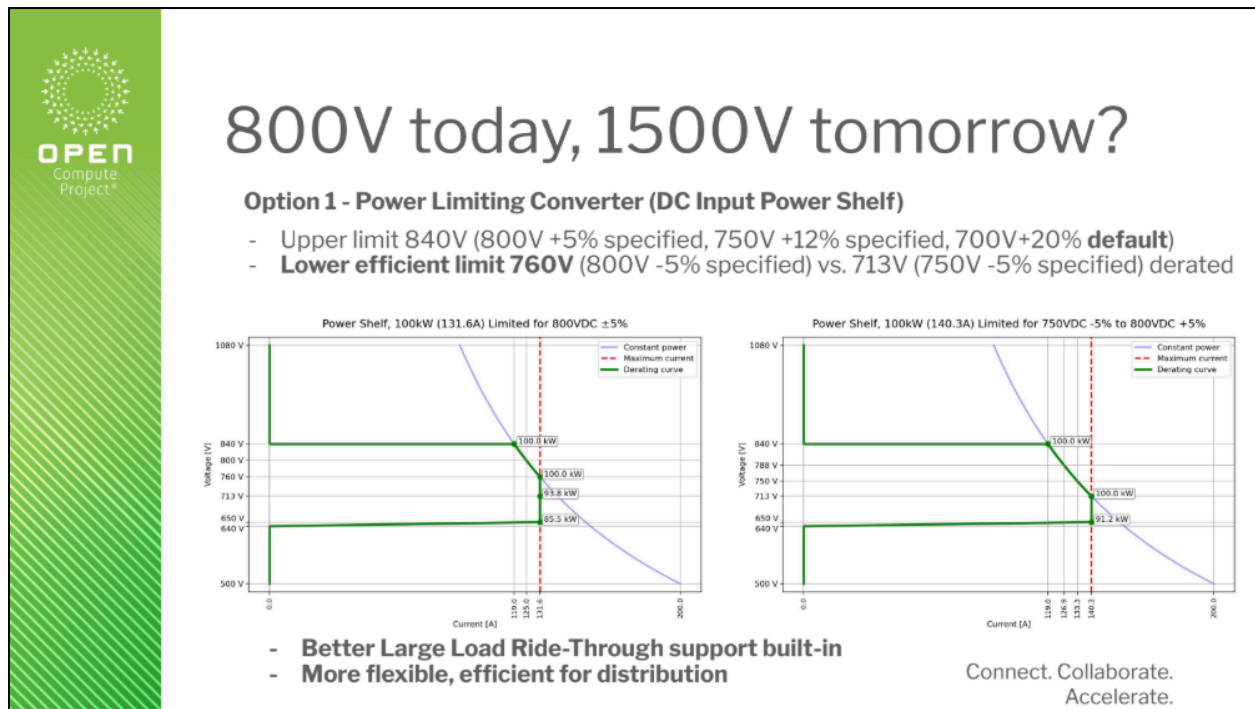


Figure 11G. Power Limiting Converter (Ref.: [OCP: DCF PD Voltage & Power Quality](#))

By contrast, another popular converter design being incorporated into data center power shelves is that of the Fixed Ratio with Point-of-Load Limiting Converter. This type of converter does not have the capability to enforce a fixed current limit, and as voltage decreases, it draws more current and employs protection to limit the duration of undervoltage operation as shown in [Figure 11H](#). Note that operation at lower voltage range is possible, but requires firmware modification with corresponding impact of derated performance across the entire curve.

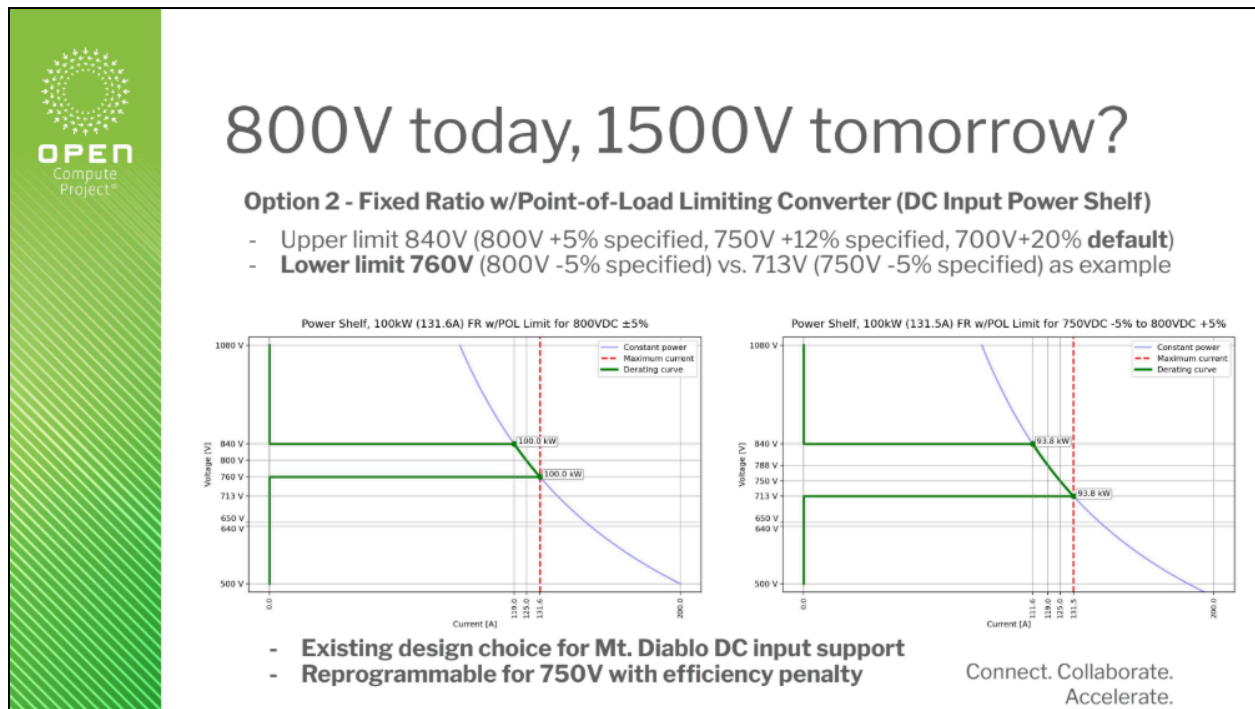


Figure 11H. Power Limiting Converter (Ref.: [OCP: DCF PD Voltage & Power Quality](#))

Ultimately the advantages of both narrowband DC for compute load space optimization and wideband DC for power distribution margin flexibility are possible to be jointly realized by means of pairing 1500 or ± 750 VDC wideband power distribution with 800 VDC narrow band rack utilization (Scalability for Option 1, [Figure 11J](#)). Alternatively, when optimizing for efficiency, usage ± 750 VDC within the rack directly is also possible (Scalability for Option 2, [Figure 11J](#)).

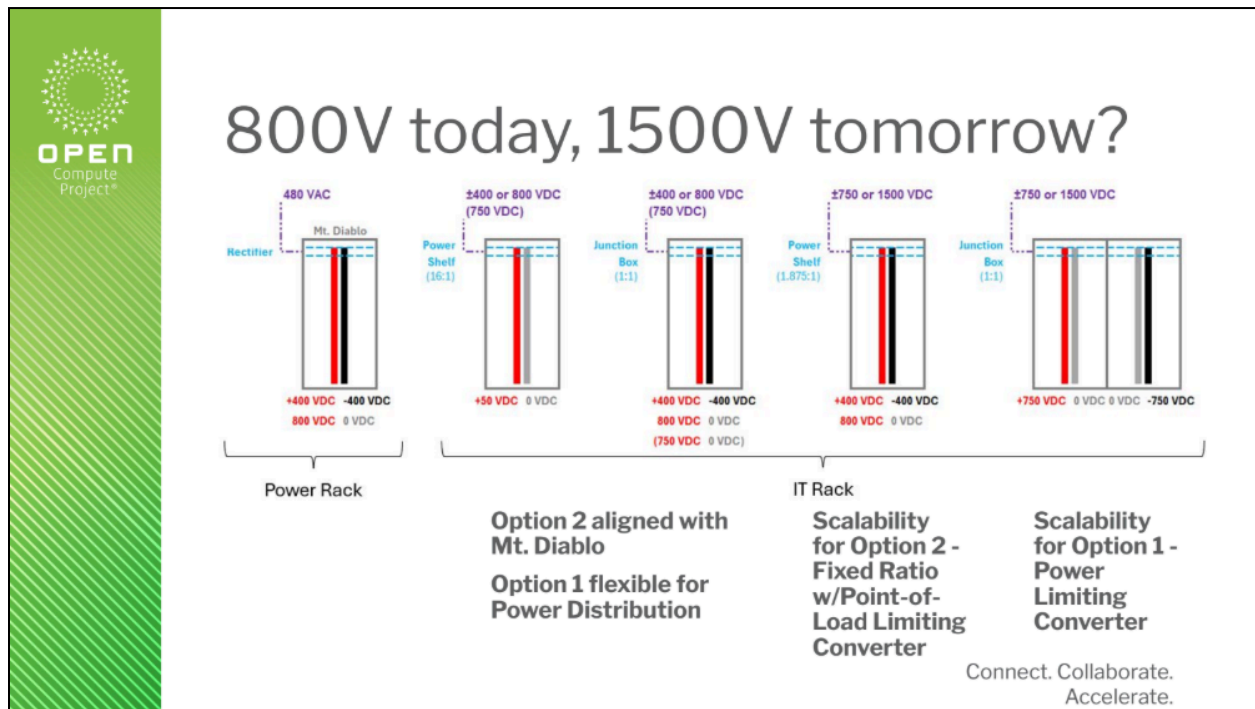


Figure 11J. Scalability Paths (Ref.: [OCP: DCF PD Voltage & Power Quality](#))

5.7. Interoperable Voltage Band Proposal

The challenge of delivering DC power to IT racks begins with the Mt. Diablo side car concept where interconnect cables may be only 1 meter long to supply the IT rack. DC power distribution delivery from the gray space to the white space is a next level challenge as factors like line inductance for 10's or even 100's of meters become important design considerations factoring in the cyclic load variability of AI compute.

In the interest of building on over a decade of DC power distribution design experience captured in specifications developed by Current/OS and ODCA as well as advancing an ecosystem where economies of scale can be leveraged across data centers and DC microgrids, the following are a set of principles for harmonization of critical design aspects considering present and future data center needs.

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The first principle is to consider the distinction between firmware adjustable values and hardware anchor points of ecosystem design. Toward this end, we consider the U2 and U5 levels as the initial boundaries constraining operation in voltage bands B3 to B5. Considering further that droop curves can be used to configure higher voltage limits than U2 without detrimental effect (lower startup voltage than U2 would require design changes to existing equipment to handle higher inrush currents), we are left with the key interoperability hinge point of U5 (840 VDC) as shown in [Figure 11K](#).

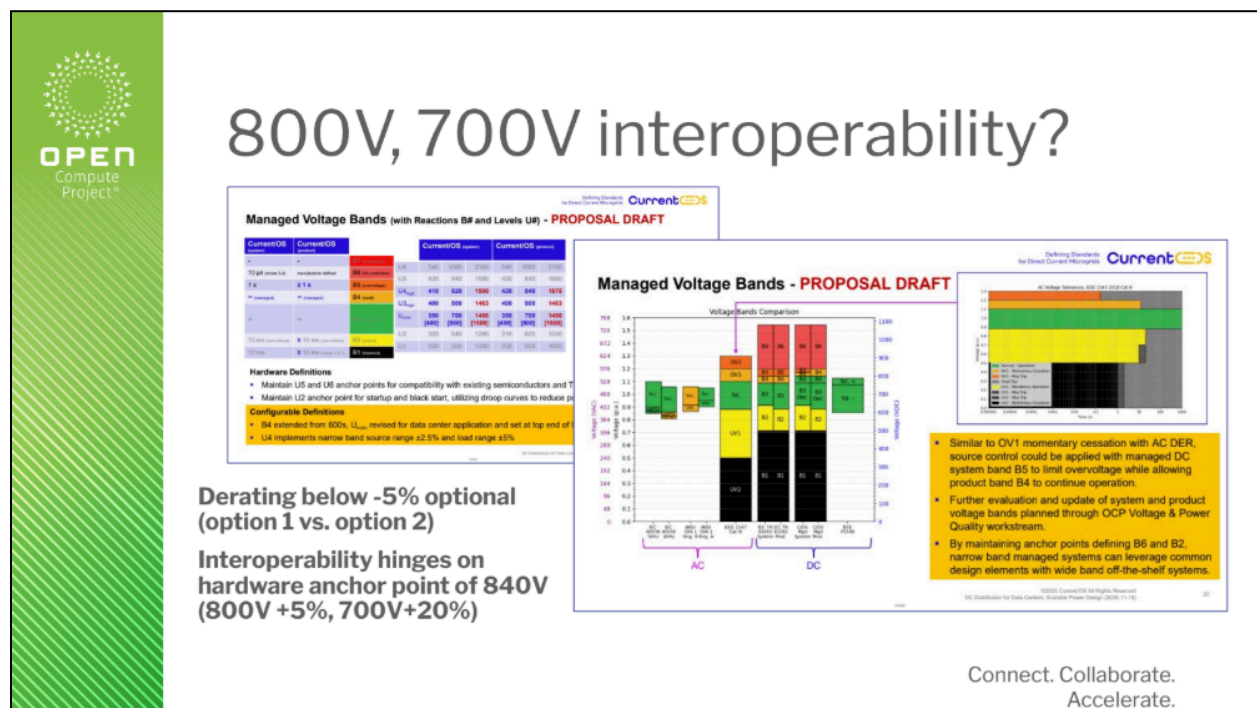


Figure 11K. Scalability Paths (Ref.: [OCP: DCF PD Voltage & Power Quality](#))

The second principle additional to this is that we can consider a portion of the B3 band below 800VDC -5% (760 VDC) as optional, thereby accommodating Option 2 Fixed Ratio with Power Limiting converters.

Ultimately, this leads to consideration of the specifics regarding implementation of a narrow band voltage curve. Here it is important to recognize that there is prior art which can be

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referenced from the 2011 timeframe when 380 VDC was being proposed by EPRI, EMerge Alliance, ETSI, and others as shown in [Figure 11L](#). Since that time, voltage ride through requirements for large loads have become an additional consideration, driving a closer look at the undervoltage portion of the DC equivalent to the AC ITIC curve (Information Technology Industry Council).

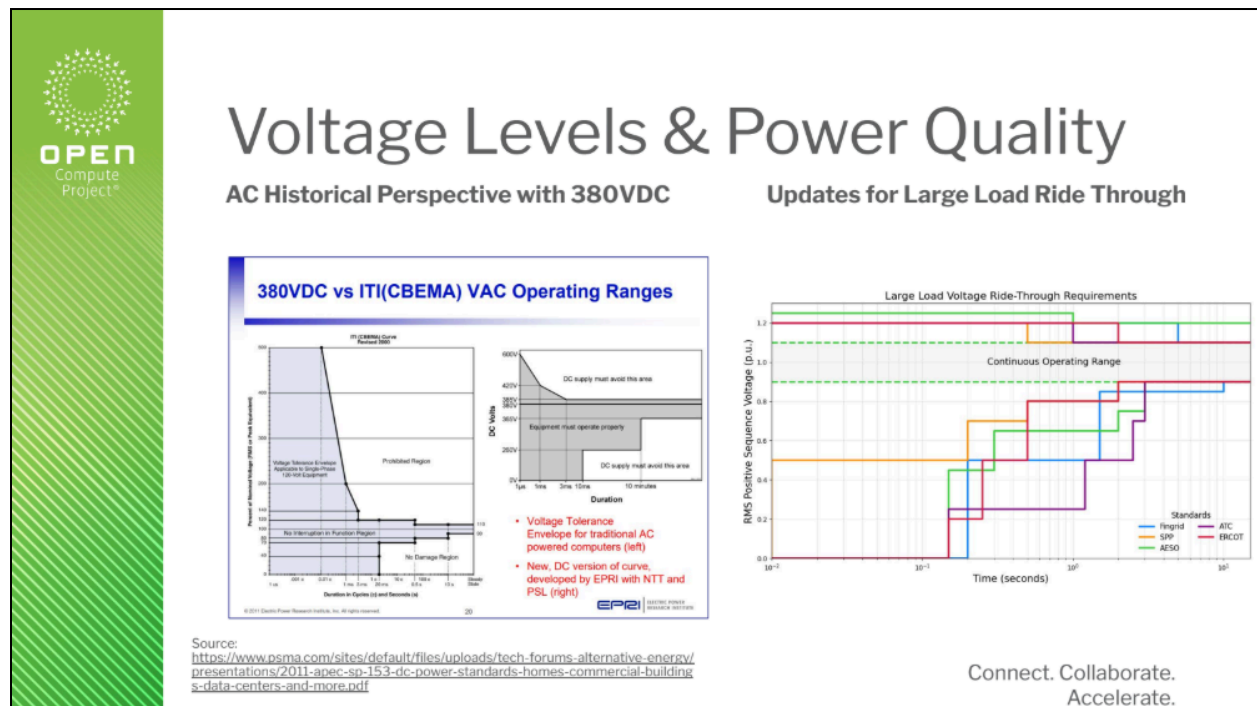


Figure 11L. 380 VDC Reference (Ref.: [OCP: DCF PD Voltage & Power Quality](#))

This undervoltage portion of the DC voltage bands definition is particularly relevant to load converter (power shelf) hold-up capability as additional energy storage may be required to ensure continued operation (see [Figure 11M](#)). Meanwhile, the overvoltage portion of the DC voltage bands definition is particularly relevant to protection and here, as mentioned previously in [Section 5.6.1](#), U5 (840 VDC) serves as the highest designed protection value according to Current/OS (see [Figure 11M](#)). For this reason, it is imperative that sources are constrained to not produce 800 VDC +10% for example. Additionally, there is a pending interpretive guidance

from IEC TC108 requested to clarify existing 600V scope as permitting 850 VDC. This could come significantly sooner than a proposed modification in scope to permit 1000 VAC / 1500 VDC.

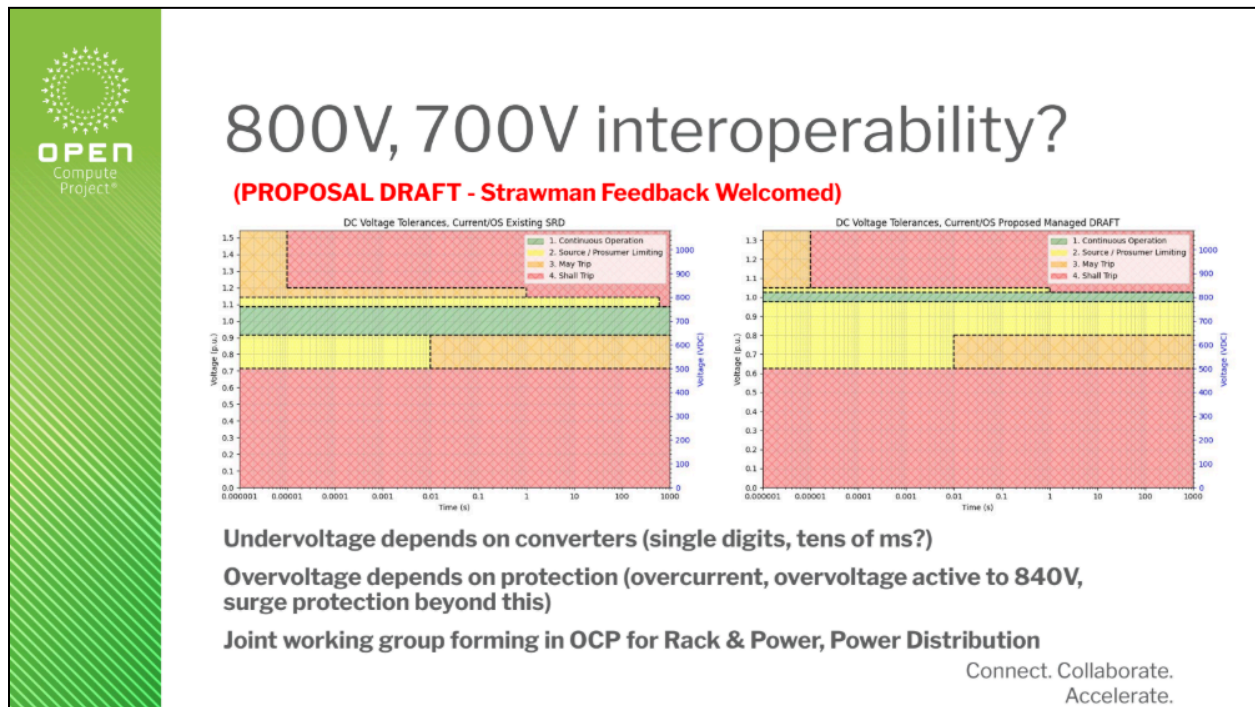


Figure 11M. Proposal Draft (Ref.: [OCP: DCF PD Voltage & Power Quality](#))

Additional refinement to the proposal shown in [Figure 11M](#) is an intended focus of the next edition of this white paper and a joint working group is being organized between Rack & Power and DCF Power Distribution for this.

5.7.1. Low Voltage Limit Considerations

As can be seen in the definitions provided in [Section 5.2](#), the limit for low voltage is 1500 VDC. However, an important nuance is that IEC TS 63527 defines this limit in reference to the average voltage whereas the other definitions provided define in the context of nominal voltage which does not have to be the same as the average voltage.

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A further consideration is that while ANSI C84.1 does not define an analogous nominal voltage of 1000 VAC, the 5.08% tolerance it commonly applies to other nominal voltages such as 600V results in a value of 1058 VAC which aligns to the maximum voltage defined in ANSI C37.50 for power breakers.

Considering further on this, it is not uncommon to utilize equipment rated to 1000 VAC in a lower voltage, e.g. 600 VAC system. The issue of name plate labels should then be differentiated for systems / sources as compared with products / loads. An interesting consideration in regard to sources is that whereas Distributed Energy Resources are required to accommodate continuous 110% overvoltage, they are typically utility grid following and thus synchronize with the supply of the utility rather than defining their own voltage level. However, notably this same 110% continuous overvoltage level is carried forward to grid forming operation when islanded for DER systems according to UL 3001.

ANSI C84.1 incorporates a factor of 5% for line losses and utilization voltage. Considering that the same line losses exist between a DER source point of connection (inverter terminals) and the point of common coupling with utility (at the meter), it is reasonable to consider that a source tolerance of at least 5% is generally possible – so the question comes down to what to do at the limit.

Ultimately, three likely sufficient but not necessary rules are as follows:

- 1) Avoid setpoints above 1500 VDC. Note that this has an important bearing on series usage of 800V sources. Due to the possibility of 1600V operation, max voltage limit setpoint restriction will be necessary, e.g. at 750V or 1500V. There is analogous max current limit setpoint restriction defined in context of conductor / busbar overload control via Power Control Systems compliant with UL 3141 Section 6.16 and NEC Article 130 Part II.
- 2) Avoid average above 1500 VDC (as per IEC TS 63527). This may come with a caveat to be clarified regarding open terminal floating voltage as opposed to loaded condition.
- 3) Avoid extended excursions above 1500 VDC. Additional work is needed to define a proposal here on the basis of transient and swell definitions.

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In addition to the line-line voltage constraint of 1000 VAC / 1500 VDC, an additional corollary may apply in certain locations. For example, in Britain (e.g. BS 7671) there is an additional requirement from BS 7671 for line-earth voltage being constrained to 600 VAC / 900 VDC.

5.7.2. Continuous Voltage Example

An example of the impact of line losses will be explored further in the next edition of this white paper.

5.8. Power Quality

DC data centers need to balance power demand with power supply within constraints of voltage bands, while also ensuring efficient and economic energy supply.

Further details on this section will be elaborated in the next edition of the white paper.

6. Polarities & System Earthing

This chapter defines and evaluates polarity configurations and earthing schemes used in direct current (DC) data center power systems. Its purpose is to clarify possible design options, identify technical tradeoffs, and support consistent implementation and commonalities across different system architectures.

The chapter reviews unipolar and bipolar systems, including variants with fully distributed, partially distributed, or non-distributed midpoints (M). These configurations are further reviewed in conjunction with earthing approaches such as TN-S and IT, including the use of single and multiple grounding points. Combinations of polarity, earthing scheme, and isolation of the AC/DC interlink are assessed to highlight practical implications, including stray currents and corrosion risks resulting from earthing choices and system topology. Additionally, the interaction between polarity, earthing, and isolation of the AC/DC interlink is analyzed with respect to fault behavior, protection requirements, electrical spacing, personal safety, maintenance and operational considerations.

6.1. Polarities

DC grids can be configured as either bipolar or unipolar. In general, bipolar has two poles, of opposite polarity, that significantly differ from ground while unipolar has one pole that significantly differs with respect to ground. These polarities have different characteristics and can affect the requirements for the technology or connected equipment used in the system.

Table 3. Definitions for designations of conductors in a DC grid

Symbol	Definition
L+	Positive Line
M (or N)	Midpoint Conductor (close to ground). Labeled N in NEC
L-	Negative Line

There are different variations of bipolar and unipolar systems that differ based on the presence of the three possible conductors (L+, M and L-) in the whole electrical system or in part of it as shown in the table below:

Table 4: Polarities and use of conductors

Variations of Polarities	L+	M (or N)	L-
Bipolar with distributed M	x	x	x
Bipolar with partially distributed M	x	(x)	x
Bipolar without distributed M	x		x
Unipolar (positive)	x	x	
Unipolar (negative)		x	x

The following sections will describe these variants and their main characteristics as they can affect the requirements for the technology or connected equipment used in the system.

6.1.1. Bipolar

A bipolar system, by definition, has two different polarities towards ground. It consists of at least two distributed conductors, L+ and L-, with opposite polarities relative to a ground. Optionally, a midpoint conductor M, can be included. The M may be connected directly to earth, or tied to earth through an impedance.

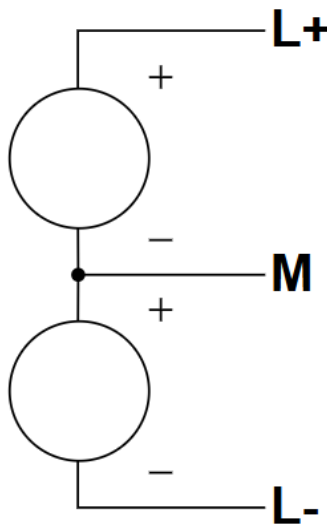


Figure 12. Bipolar DC grid circuit model where M connection is optional

Main Characteristics:

- Lower potential difference to earth than unipolar systems, leading to smaller isolation distance and device size.
- Higher power transfer capability compared to unipolar equivalent for a given voltage-to-ground potential
- More complex protection devices and requirements (2 protected poles)
- Different insulation stress pole-to-ground vs pole-to-pole
- Could be compatible with non-isolated AC/DC interlink implementation if grounded on the AC side

There are multiple M conductor distribution options in a bipolar system that are described in the following sections.

6.1.1.1. Bipolar with Distributed M

This configuration uses a full 3 conductor (plus PE) distribution. It requires all 3 conductors (L+, M, and L-) to be distributed throughout the system and it provides full flexibility to use sources and loads connected in four different configurations:

- L+ and L-
- L+, M and L-
- L+ and M
- M and L-

However, a bipolar system that has sources or loads connected to only one pole (L+ to M, or M to L-), has the potential to become imbalanced if the loading is not well matched. The M conductor could be rated for lower current, and using thinner cross-section, but only if it is ensured that the maximum unbalance is limited or M is appropriately protected against over current. This limits the ability of the system to continue operation on one pole (in the event of a fault in the other pole) to the maximum current rating of the M conductor. The requirement that both poles are required to trip in a M grounded conductor system (as is currently required in NEC standards) can be configured in some protection devices for Bipolar DC grids.

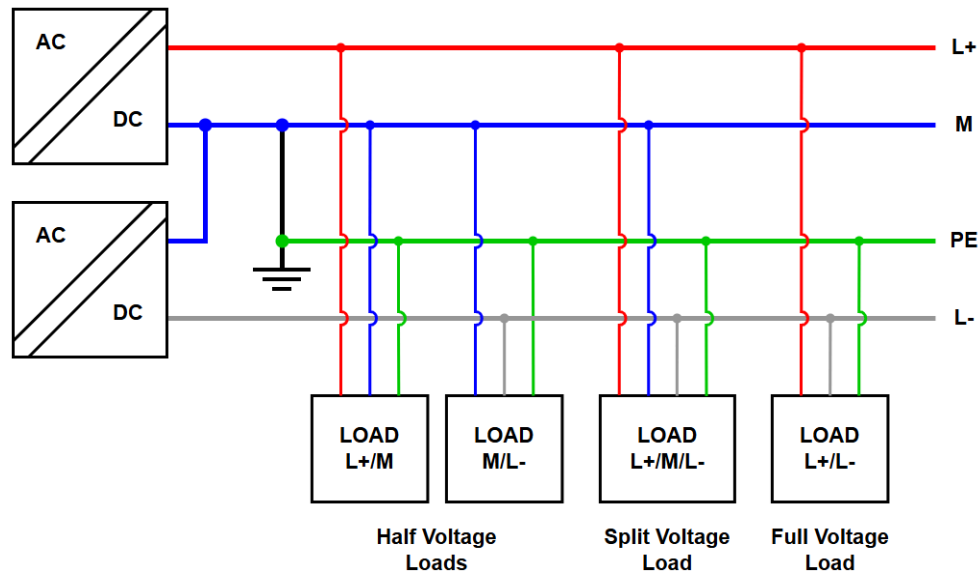


Figure 13. Bipolar TN-S grounding with one solid grounding point

Main Characteristics:

- Two voltage levels available at any connection point
 - Enables options for 2-level power topologies using 600V or 650V silicon or GaN devices operating on a 350V while the full 700V range may be more suitable for higher power units utilizing SiC devices or multi-level topologies with GaN.
- Unbalanced situations might require additional balancing equipment depending on design and control (if sources feed only L+ and L-)
- Could be designed to continue operation at reduced capacity, if one pole is lost, to enhance availability (provided that sources can handle fully unbalanced load).
- Presence of M conductor throughout the system allows multiple distributed grounding points throughout the system which permits localized ground fault return paths in the system, thereby increasing the systems protective selectivity.

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6.1.1.2. Bipolar with Partially Distributed M

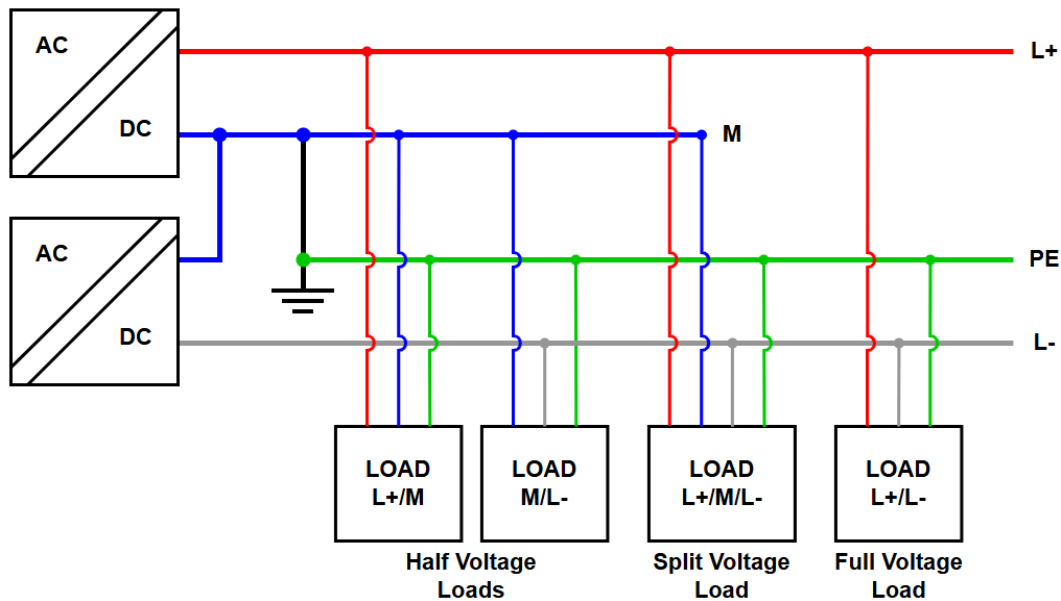


Figure 14. Bipolar TN-S grounding with partially distributed M

This option is a system where the M conductor is partially distributed. This allows loads, in some areas of the system, to utilize the M conductor while saving cost by not distributing M to other areas where only full-voltage loads are utilized. (Comparable to 3 phase AC with N for single phase loads and without N for large loads).

Main Characteristics:

- Maintains most characteristics of distributed M
- M conductors can be eliminated and copper saved in circuits that only distribute balanced power.
 - This can apply for circuits that only power large loads connected at L-L voltages
 - This can potentially also be done for longer cables as long as adequate balancing power is available on both ends.

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6.1.1.3. Bipolar without Distributed M

This symmetrical system uses two current-carrying active lines only, no midpoint is used. This system provides only one voltage. Note that although the M node is tied to PE at the source, the PE line shall not be used as a return path from loads to M. The PE line is only for protection.

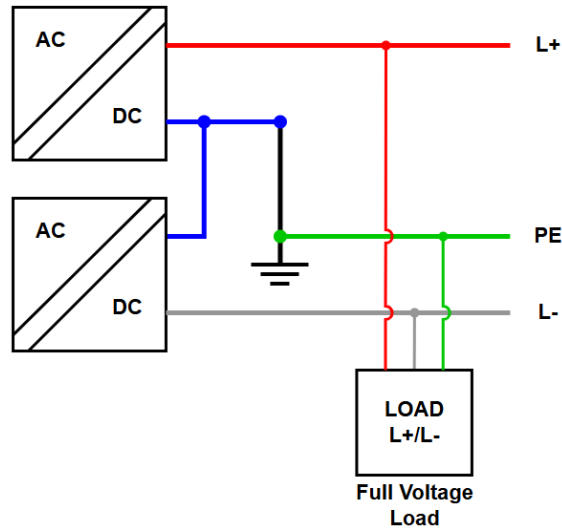


Figure 15. Bipolar DC system without distributed M

Main Characteristics:

- Only two active wires and one available voltage level
- No power balancing needed
- No active wire close to ground - lower electrolytic corrosion risk
- Can have lower power loss than with M

6.1.2. Unipolar

A unipolar system consists of one pole and a return conductor, either L+ and M, or M and L-. Same as the bipolar without M, these systems only provide a single voltage level. The M terminal is the ground referenced conductor. A positive system (L+ and M) is generally preferred in a unipolar configuration.

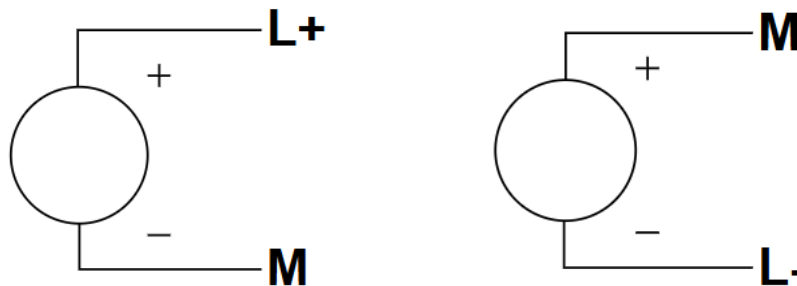


Figure 16. A positive unipolar system (Left) and a negative unipolar system (Right)

Since a unipolar system only has 2 active conductors, the distribution network requires the M conductor to be fully routed.

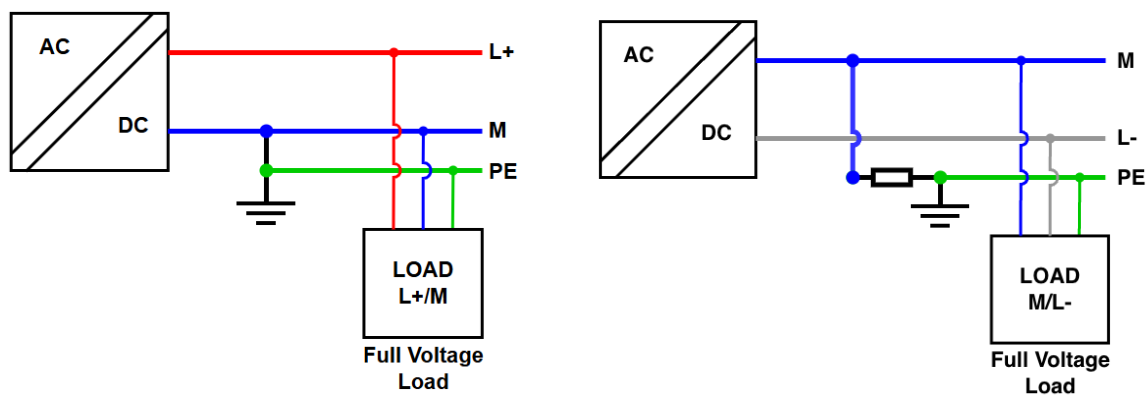


Figure 17. TN-S grounded unipolar positive system with L+ and M (Left) and a IT grounded unipolar negative system with M and L- (Right)

Main Characteristics:

- Single active conductor relative to a return path
- Only one voltage level available
- Simple protection devices (1 pole protected)
- Reduced power transfer capability relative to a bipolar configuration for a given voltage-to-earth potential.
- Isolation is required if fed from an AC supply. See [Figure 20](#) in the isolation section.

6.2. System Earthing

This section begins with two tables intended to clarify some grounding/earthing terminology (and semantic equivalents) taken from NEC and IEC standards. A third table contains a breakdown of IEC nomenclature used in grounding schemes. The following references used in the tables are listed below:

- NFPA 70 – National Electrical Code (NEC)
 - NEC Article 100 + Article 250
- IEC 60050-195 – International Electrotechnical Vocabulary
- IEC 60364 series – Low voltage electrical installations

Table 5. Terminology equivalents between UL/NEC and IEC standards

Concept	UL/NEC (North America)	IEC (International)
General Term	Grounding	Earthing
Resistance or impedance based grounding	High resistance grounding (HRG)/ Low resistance Grounding (LRG)	Impedance earthed
Faults	Ground Fault	Earth Fault
Electrode	Grounding Electrode System	Earth Electrode
Equipment grounding	Equipment grounding conductor (EGC)	Protective conductor (PE)

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Table 6. Grounding specific terminology equivalents between UL/NEC and IEC standards

NEC/UL Description	IEC System Type	Explanation / Note
Solidly grounded wye system (AC) or Grounded DC System (DC)	TN-S	Neutral solidly earthed, PE separate
Solidly grounded with combined N/PE	TN-C	Not allowed by NEC in most cases
Ungrounded System	IT System	System isolated from earth or via impedance
Corner-grounded delta	No direct IEC equivalent	North American specific practice
High-resistance grounded	IT or impedance-earthed TN	Depends on implementation

Additionally, [Table 7](#) explains these letters and their meanings (IEC 60364-1, ch. 1.9.1).

Table 7. Earthing Nomenclature: Nomenclature of earthing systems

First letter	Indicates how live parts of the electric system are related to earth:
T	One live conductor is directly connected to earth (terra)
I	All live conductors are isolated from earth
Second letter	Indicates how exposed conductive parts are earthed
N	Exposed conductive parts are connected to the same point where the live parts are connected to earth
T	Exposed conductive parts are connected to an earthing system which is independent of the electrical system
More letters (if any)	Separated by a dash from the first two. Indicates how live parts and earthing conductors are arranged
S	Separate conductors for neutral (midpoint) and protective earth (PE) conductors
C	Combined conductors for midpoint and PE, e.g., PEM or PEL

Additionally, in DC systems, only TN-S or IT systems shall be used. Other earthing schemes such as, TT systems and TN-C systems, are not used because of the risk of corrosion of grounding electrodes or ground-buried metal structures which are significantly higher because earth-fault currents, by design, path through metal (grounding electrode) to electrolyte (earth) interfaces. On the anodic side, the metal corrodes if the potential drop surpasses a (small) voltage threshold.

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6.2.1. Isolation of Electrical Systems

Isolation is typically used when transitioning between systems with different voltage levels, safety classes, or grounding requirements. When it comes to grounding, isolation creates two separate systems which can have separate grounding configurations (in the NEC, the new system created by isolation is defined as a separately derived system). On the contrary, no isolation means that you can have a single system with a single grounding configuration. As an example, if a non-isolated interlink (AC/DC) is used, it means that the AC side grounding point could be used as the DC side grounding. This configuration can be seen in [Figure 19. TN-S-AC](#).

6.2.1.1. Medium Voltage (MV) to Low Voltage (LV)

Isolation is needed when connecting MVAC or MVDC to LVDC distribution via a SST or dedicated AC transformer. With a dedicated transformer from medium voltage to low voltage, no isolation for the converter is needed (since the transformer does the isolation).

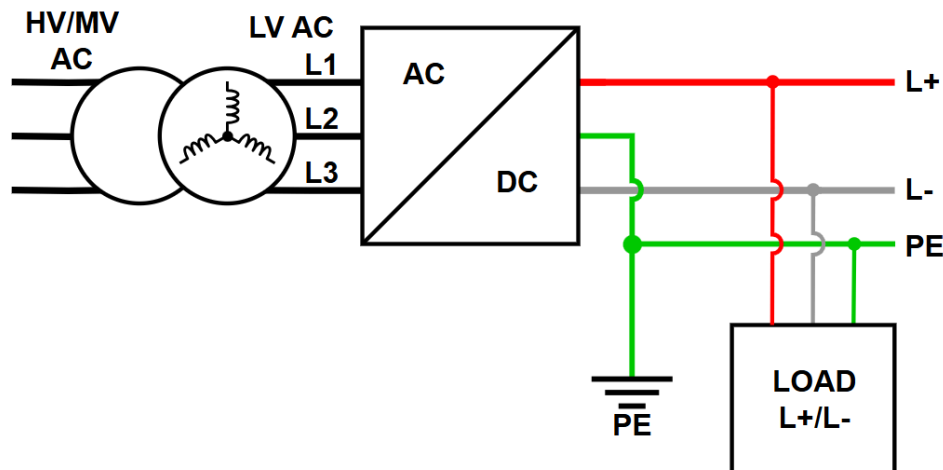


Figure 18. Symmetrical power distribution with non-isolated AC/DC converter **with DC side ground**

6.2.1.2. Low Voltage (LV) to Extra Low Voltage (ELV)

Isolation is needed in ELV applications, for example, in a server or for user-accessible equipment in data centers when a large voltage step is present from LV distribution. This is typically a large voltage step-down where isolated converters are more economically viable, anyways.

6.2.1.3. Grounded AC side Low Voltage AC (LVAC) to Low Voltage DC (LVDC)

In this scenario, an AC/DC interlink is required to connect to LVDC and it may be either isolated or non-isolated. The following list describes various considerations for isolation and grounding in this case:

- For isolated applications, any of the following polarity and grounding options can be utilized for the LVDC side: unipolar, bipolar, TN-S, IT, etc.
- The AC side hard grounding point can be utilized also as the grounding for a DC grid if a non-isolated interlink is used to interface the two systems. However, if no other AC loads are connected and the LVAC network serves only as an intermediate link, grounding on the AC side provides limited benefit. In such cases, it is preferable to ground the DC side instead.
- For a non-isolated application operating at low-voltage AC, if the AC side is grounded, the DC side must be implemented as a bipolar DC system. A unipolar DC configuration is not suitable because the DC voltage must exceed the peak value of the AC voltage (both positively and negatively) to avoid uncontrolled rectification through the converter.
- Advantages to non-isolated interlink: simpler, lower cost, less bulky, higher efficiency.
- Limitations for non-isolated interlink: Common mode currents (3rd harmonic) → AC side grounding requires consideration of harmonic effects and DC common mode current restrictions apply as well.

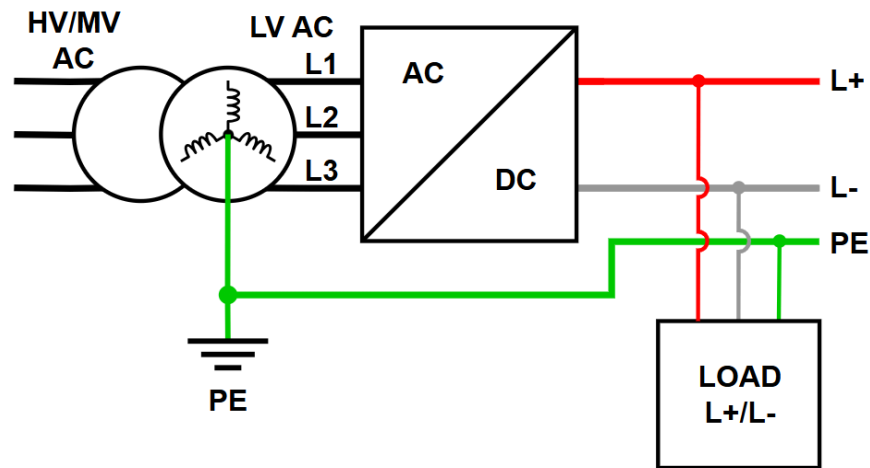


Figure 19. Non-isolated-AC-grounded: symmetrical power distribution with non-isolated AC/DC converter with **ground on the AC side**

6.2.2. TN-S (Solidly Grounded System)

These systems are characterized by a grounding connection at the source and separate paths for a neutral, current-carrying conductor (if applicable - midpoint M in a DC system) and the protective earthing conductor (PE) that connects all exposed conductive parts bodies in the application with ground. A single solid grounding point in a TN-S system can reduce the potential for DC ground currents and corrosion.

Grounding and connection to the supply grid for a TN-S system with DC-side grounding is shown in [Figure 20](#). The AC/DC converter provides a midpoint on the DC side which is grounded.

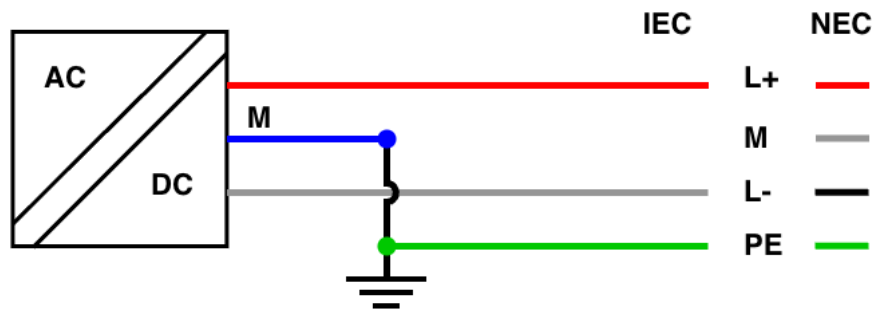


Figure 20. TN-S-DC: TN-S system with **ground on the DC side**

Similarly, the AC-side grounded TN-S system is depicted in [Figure 19](#). The connection to ground is most favorably made at the star-point of the AC transformer. A more detailed representation of this is shown in [Figure 19](#) above in Section 6.2.1.3.

6.2.2.1. Direct Touch Protection (with RCD)

Additionally, residual current monitoring (RCM) and residual current detection (RCD) can be implemented in a TN-S grounded system. The RCD can provide selective protection in the case of a bipolar DC grid, breaking a ground fault path on the faulty pole while the other pole remains functional. More information can be found in [Section 7.3](#).

6.2.2.2. Multiple References to Earth

For DC, multiple solid earthing points or system referencing conductors (SRCs) should be avoided because of the risk of DC currents through earth or other conductive structures that can cause corrosion. On the other hand, multiple *references* to earth can be beneficial for selective protection of the DC grid and can increase resilience and continued partial operation after faults if multiple supplies/sources exist. This can allow for new architectures to emerge which could optimize redundancy in data centers. Additionally, for DC, these additional references to earth

can be realized with System Referencing Devices (SRD) that block DC but conduct fault transients for fault protection. (Also commonly named: Capacitive Grounding, PCR (Polarized Cell Replacement), and Capacitor-Diode grounding). SRDs have to be rated for the expected maximum fault current. When using current limiting protection devices, such as semiconductor breakers, this maximum fault current is lower and can make this option more attractive. Typically, they include capacitive behavior in addition to a clamping mechanism to limit the voltage to PE. One last consideration for multiple earth references is for islanding and de-islanding a grid. If multiple SRDs are used throughout the system, the grid can be islanded in multiple configurations as long as an SRD is present. If there are not multiple references to earth, then a Switching Device for Islanding (SDFI) or similar technology could be used to establish an earthing reference for an islanded grid. Otherwise, the electrical system changes to IT and insulation monitoring is required. More information can be found in IEC 60364-8-82 as well as in this standard's current draft proposals and pending amendments.

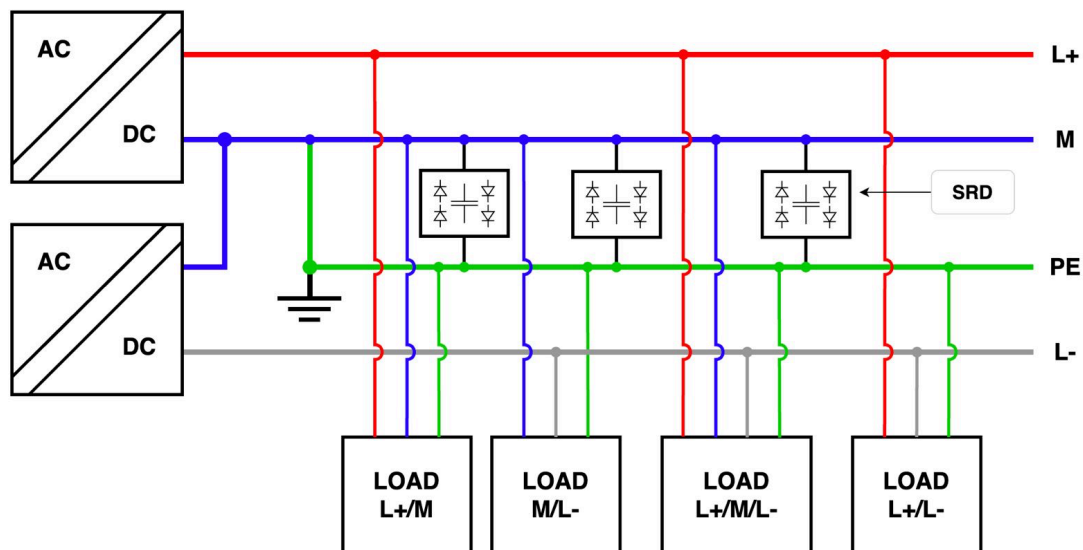


Figure 21. Bipolar TN-S with multiple distributed System Referencing Devices (SRDs) added

6.2.3. IT (Ungrounded System or High Impedance Grounded)

IT systems are often described as floating systems (ungrounded in the NEC, with no intentional connection to ground) or high impedance grounded systems. In either case, impedance is typically kept higher than 100 Ohm/V for DC or 500 Ohm/V where non-isolated from AC (per UNECE R100, ISO 5474 series, and ISO 6469 series). IT systems are able to continue operation for a certain time after a first ground fault. This enables the operator to continue services while looking for the cause of the fault, repair it, and then resume normal operation. Such a system needs components that are designed for the full line-to-line voltage because that voltage appears when one of the active, potential-carrying conductors has that fault-causing connection to ground. Specifically, clearance distances (air gaps) need to be larger than in a grounded TN system, and protection devices could be required in the future to clear a fault, with one pole only, against the full voltage (currently installation standards require overcurrent protection on all poles, but this is not needed, theoretically). [Figure 22](#) shows an IT system that has no direct connection to ground on the source (in this case, the AC/DC converter) and it shows isolation monitoring and symmetrization.

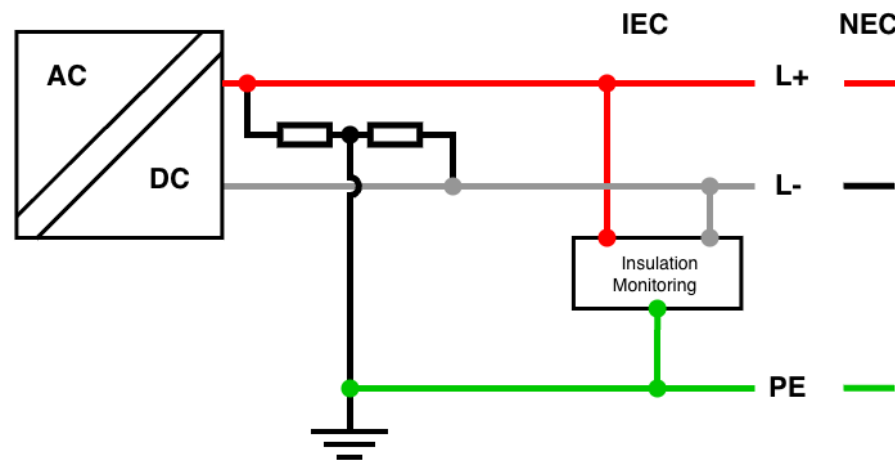


Figure 22. IT System ground reference with symmetrization and insulation monitoring

6.2.3.1. Direct Touch Protection (with IMD)

IT systems require a monitoring device to detect when a first fault to ground happens. An Insulation Monitoring Device (IMD), is a device commonly used to do this function. Fault locator devices are not mandatory but can be useful to locate the faulty feeder or branch. While it is possible to continue operation under a first fault, it is not recommended to keep this situation for a long period of time, especially in the case of single pole protection, as it increases the risk of a second fault and poses a serious threat for touch safety.

6.2.3.2. Safety (Y) Capacitor Limitations

Y capacitors are used for electromagnetic interference filtering and are designed to meet IEC safety standards for touch safety. In smaller or low-power systems, the leakage current and stored energy are typically low enough that the equipment remains safe to touch. However, in larger systems with higher capacitance values, Y capacitors can store significant charge, and during discharge this may create a hazardous touch voltage, posing a potential safety risk if not properly limited or controlled.

6.2.4. Corrosion

Electrochemical corrosion is caused by currents at the point where they pass from a metal into an electrolytic medium, e.g., concrete or soil. Electro-chemically, this process is known as a partial anodic reaction. For DC current to cause corrosion, a material-specific minimum potential difference at that metal-electrolyte interface must be exceeded. EN 50162 specifies a threshold of 200 mV for steel-reinforced concrete [DIN EN 50162:2005-05 “Protection against corrosion by stray current from direct current systems”]. Using Faraday’s law, it can be calculated that exposing an electrolyte to a current of 1 A for one year will cause the loss of 9.13 kg of an iron electrode (often used for providing the earth reference).

This type of corrosion can occur in DC installations when currents in the grounding system (PE) unintentionally – but sometimes unavoidably – leave the intended metallic PE conductor. One

example is fastening (grounded) metallic housing to the foundation and the mounting screws coming into contact with the reinforcement steel of the foundation. An effective mitigation method against electrochemical corrosion is to ensure that the potential drop between any metallic housing and the central earthing point stays below the 200 mV threshold mentioned above.

6.3. Combinations of Polarities, System Earthing and Voltages

Low voltage DC grids in data centers will use combinations of the various concepts introduced earlier in this chapter. In the following table, many relevant aspects for system choices and their impact on parameters and device compatibility are compared. Some of the aspects can be representative examples for other parameters that, although not shown, change similarly amongst the columns. In general, a power system or DC installation perspective is adopted for the parameters on the table rather than a power supply specification when considering the typical LVDC distribution in the data center. The Nominal Voltage is chosen from the 350V, 700V and 1400V, in order to scale consistently and indicate compatibility between scaling levels. This is also inline with international standardization for LVDC in Current/OS, ODCA and IEC. 380V, 400V, 750V, 800V and 1500V that have so far been used in the DC data center context fall into these classes. These equivalents are marked under the nominal table title row for ease of reference.

A more detailed explanation and interpretation for the table is provided afterwards. The grey columns are deemed less likely to be used in data centers.

Table 8. Combinations of voltages, polarities and system earthing and their impact on selected characteristics and device compatibility.

Nominal Voltage (equivalent) (V)	350/700 (400/800)				700 (800)		700/1400 (750/1500)				1400 (1500)	
Polarities	Bipolar				Unipolar		Bipolar				Unipolar	
M conductor	yes ^g	no	yes ^g	no	yes		yes ^g	no	yes ^g	no	yes	
Earthing	TN-S		IT		TN-S	IT	TN-S		IT		TN-S	IT
Impulse Withstand Voltage, OVC II (kV) ^a	2.5	2.5	4	4	4	4	4	4	6	6	6	6
Impulse Withstand Voltage, OVC III (kV) ^a	4	4	6	6	6	6	6	6	8	8	8	8
Clearance to PE, OVC II (mm) ^b	1.5	1.5	3	3	3	3	3	3	5.5	5.5	5.5	5.5
Clearance to PE, OVC III (mm) ^b	3	3	5.5	5.5	5.5	5.5	5.5	5.5	8	8	8	8
Clearance to PE, OVC IV (mm) ^b	5.5	5.5	8	8	8	8	8	8	14	14	14	14
Creepage to PE, PD2, for Mat Grp 1 (mm) ^c	2.5	2.5	5	5	5	5	5	5	8	8	8	8
Creepage to PE, PD2, Mat Grp 3 (mm) ^c	5	5	10	10	10	10	10	10	16	16	16	16
Creepage to PE, PD3, Mat Grp 3 (mm) ^c	8	8	16	16	16	16	16	16	25	25	25	25
Creepage for L-M, PD2, Mat Grp 1 (mm) ^c	2.5	-	2.5	-	5	5	5	-	5	-	8	8
Creepage for L-M, PD2, Mat Grp 3 (mm) ^c	5	-	5	-	10	10	10	-	10	-	16	16
Creepage for L-M, PD3, Mat Grp 3 (mm) ^c	8	-	8	-	16	16	16	-	16	-	25	25
Creepage for L-L, PD2, Mat Grp 1 (mm) ^c	5	5	5	5	-	-	8	8	8	8	-	-

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Nominal Voltage (equivalent) (V)	350/700 (400/800)				700 (800)		700/1400 (750/1500)				1400 (1500)	
Polarities	Bipolar				Unipolar		Bipolar				Unipolar	
M conductor	yes ^g	no	yes ^g	no	yes		yes ^g	no	yes ^g	no	yes	
Earthing	TN-S		IT		TN-S	IT	TN-S		IT		TN-S	IT
Creepage for L-L, PD2, Mat Grp 3 (mm) ^c	10	10	10	10	-	-	16	16	16	16	-	-
Creepage for L-L, PD3, Mat Grp 3 (mm) ^c	16	16	16	16	-	-	25	25	25	25	-	-
SST transformer iso. <i>recommendations</i> for MVDC/LVDC ^d	BI	BI	RI	RI	BI	RI	BI	BI	RI	RI	BI	RI
AC/DC isolation required if connecting to LV AC TN-S	no	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes
350V (or 400V) device compatible	(x) ^e	-	(x) ^{e,f}	-	-	-	-	-	-	-	-	-
700V (or 800V) device compatible	x	x	(x) ^e	(x) ^e	(x) ^e	(x) ^e	(x) ^e	-	(x) ^{e,f}	-	-	-
1400V (or 1500V) device compatible	-	-	-	-	-	-	x	x	(x) ^e	(x) ^e	(x) ^e	(x) ^e
Active Wires	2-3	2	2-3	2	2	2	2-3	2	2-3	2	2	2
Relative Active Wire Material	2-3	2	2-3	2	2	2	1-1.5	1	1-1.5	1	1	1
Relative Cable Losses	1-2	1	1-2	1	1	1	0.5-1	0.5	0.5-1	0.5	0.5	0.5
Relative Current for same balanced Power	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5
Min. # of Overcurrent Protected Poles	2	2	3 ^h	2 ^h	1	2 ^h	2	2	3 ^h	2 ^h	1	2 ^h

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Nominal Voltage (equivalent) (V)	350/700 (400/800)				700 (800)		700/1400 (750/1500)				1400 (1500)	
Polarities	Bipolar				Unipolar		Bipolar				Unipolar	
M conductor	yes ^g	no	yes ^g	no	yes		yes ^g	no	yes ^g	no	yes	
Earthing	TN-S		IT		TN-S	IT	TN-S		IT		TN-S	IT
Relative voltage Semiconductor Circuit Breaker ⁱ	0.5	1	1	1	1	1	1	2	2	2	2	2
Semiconductor Circuit Breaker FoM ^j	1	2	3	2	1	2	1	2	3	2	1	2

- a) Impulse Withstand Voltage(Uw, Uimp): IEC 60364-4-44, currently under revision and a new table with DC values is proposed. The DC voltages are proposed as 1.5 times the AC rms voltage.
- b) Clearance: IEC 60664-1, Table F.2, Case A inhomogeneous field. Values are for Basic Insulation (BI). OVC IV included for SST applications. Tables that define clearance distances in IEC 62368-1 also make reference to IEC 60664-1.
- c) Creepage: IEC 60664-1, Table F.5, values for pollution degree 2 and 3 are shown (Note: use of ribs can reduce PD3 requirement), Material Group (Mat Grp) 1 for PCB design, Material Group 3 for Assembly. Values based on Vrms at 500V, 1000V, 1600V for 350V, 700V and 1400V, respectively. Values are for Basic Insulation (BI). Tables that define creepage distances in IEC 62368-1 also make reference to IEC 60664-1.
- d) Recommendations for insulation coordination based on IEC 62477-1,-2, for HF TX between primary and secondary. (RI) Reinforced Insulation, (BI) Basic Insulation. In general, if it is accessible to humans it must be RI, if a human cannot access - it could be BI and if it can be tripped fast (RCD) - it could be BI. For a TN-S DC grid and there is SSCB, you could define this as BI with or without human accessibility. Topic is still under discussion and SST application based standards are still under development for this topic.
- e) Requires 1x the rated voltage and corresponding electrical spacing of the device from earth. See section below ([Combination Table Analysis: Device Compatibility](#)) for detailed description and legend, see [Table 11](#) for breakdown of x and (x).
- f) Requires 2x the rated voltage and corresponding electrical spacing of the device from earth. See [Table 11](#) for breakdown of x and (x).
- g) With (partially) distributed M. For some characteristics this results in a range from having M distributed everywhere, to only having it in some circuits, and to no distribution of M but just usage in protection cabinets.
- h) NEC 240.15(A) requires all ungrounded poles (regardless of TN-S or IT system type) to be protected, this is similar for IT requirements in references such as the IEC 60364-4-43 and NEN 1010.
- i) Semiconductor voltage example reference: 0.5=600V, 1=1200V, 2=2400V). Semiconductor selection (in a protection device) may vary by design. See section below titled [Combination Table Analysis: Impact on Protection Devices](#) for more information.

Nominal Voltage (equivalent) (V)	350/700 (400/800)				700 (800)	700/1400 (750/1500)				1400 (1500)	
Polarities	Bipolar				Unipolar	Bipolar				Unipolar	
M conductor	yes ^g	no	yes ^g	no	yes	yes ^g	no	yes ^g	no	yes	
Earthing	TN-S		IT		TN-S	IT	TN-S		IT	TN-S	IT
j) This Figure of Merit (FoM) quantifies the total semiconductor "effort" or cost required to protect a system. It is calculated by the multiplication of relative Semiconductor Circuit Breaker Voltage, Relative Current for same Power and Number of Protected Poles. For the current, the balanced case is considered in Bipolar systems with M. It is assumed that unbalance typically only occurs under lower load conditions.											

6.3.1. Combination Table Analysis: Overvoltage Category (OVC), Impulse Withstand Voltage (U_w, U_{imp}), Clearance, and Creepage

Overvoltage Category (OVC), isolation type, and the maximum Working Voltage determine the Impulse Withstand Voltage (U_w, U_{imp}) which is the transient surge voltage, which will impact Clearance. Various clearance values as well as impulse withstand voltages are shown for various OVCs in the combinations table. The following tables show when different OVCs and Pollution degrees (PD) may be chosen in data center applications.

Table 9. Overvoltage Category Application (IEC 60664, IEC 60947, IEC 62368)

OVC	Applications (likely data center applications in grey)
II	Plugged equipment, semiconductor circuit breakers (trending to lower OVCs), busway, Data center room
III	Normally fixed installation, semiconductor circuit breakers, busway, Power room
IV	Utility, LVDC to MVDC via SST

Table 10. Pollution Degree (PD) Applications (IEC 60664, IEC 62368, UL 840, UL 508A)

PD	Applications (likely data center applications in grey)
1	Within fully sealed (encapsulated) equipment, components, and subassemblies. No pollution, or only dry, non-conductive pollution.
2	Default for IT equipment racks, servers, and power distribution units. Heaters within enclosures help to achieve PD2. Normally, only non-conductive pollution is present. Some condensation possible.
3	Ancillary facility zones (mechanical rooms, loading bays in DCF etc.). Conductive pollution or dry, non-conductive pollution that becomes conductive due to condensation.

The maximum working voltage, presence of potting or conformal coatings, isolation type, and Pollution Degree (describes how conductive contaminants in the environment affect insulation) impact the Creepage. Additionally, for the given applications (PCB design and assembly), the Material Group, a classification based on comparative tracking index (CTI), is defined. For PCB design, this may qualify as Material Group 1 assuming high CTI laminates or conformal coatings are used on the PCBs. It should be noted that certification bodies may require additional testing to claim this designation which may result in additional cost. As a result, Material Group 3 would likely be used which is typical for standard PCB FR4 (no coatings). A conservative approach is assumed for assemblies in DCF applications, providing a higher safety margin over the lifetime of the system. For this reason, Material Group 3 is taken as the spec for the assembly (such as busbars, terminal blocks, switchgear) level. Lastly, for industrial applications, an assembly could be taken to have lower Material Group 1 classification if proper material quality, laminates, insulation between parts, and overall CTI requirements are achieved and validated by testing. It is important to note that the creepage spacing cannot be less than the clearance spacing requirement for a given application. Therefore, the minimum creepage for a given system must be greater than or equal to the clearance.

- Note 1: One clear trend that can be seen is that for bipolar TN-S systems, the clearance and creepage with respect to earth can be half of the value compared to a bipolar IT system. This is also half of the spacing required for the unipolar case to achieve the

same voltage. Therefore, systems and devices can be reduced in size when using bipolar TN-S if they are designed properly with respect to earth and the other lines.

- Note 2: Isolation Type (Basic, Functional, Supplementary, Reinforced) determines how much protection is needed and affects all related insulation test and design voltages (such as impulse withstand voltage). For example, reinforced insulation (RI) typically doubles clearance and creepage required under normal conditions (Basic). Throughout a product or system, the isolation requirements can vary. All of this can be determined in application specific standards in IEC such as where to apply higher isolation requirements.
- Note 3: In applications for busways such as those referred to in IEC 61439 and UL 857, the values of clearance and creepage do not depend on the polarity and system earthing but rather the electromagnetic displacement and mechanical deformation effects caused by high currents on the busbars. For example, this can be the case in applications with high incident fault energy, or when using fuses, mechanical circuit breakers, or protection devices with slower reaction times.
- Note 4: Line to line (L-L) clearance is not explicitly defined in the table because the values of L-L clearance do not depend on the polarity and system earthing. One possible interpretation is that this L-L clearance can be based on minimum required clearance based on the working voltage e.g 800Vdc. The other interpretation is that a full non-direct impulse could still appear between the lines, thus you would need to define the impulse withstand voltage based on double the value of working voltage used for clearance for L-M. Effectively, in this case, there is roughly double the value of L-M clearance for L-L clearance.

6.3.2. Combination Table Analysis: Device Compatibility (350V or 400V device compatible, 700V or 800V device compatible, 1400V or 1500V compatible)

The purpose of these rows is to provide multiple perspectives on device compatibility in various system configurations for various device voltage ratings. These rows can be interpreted from

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two different perspectives; a product designer / manufacturer perspective and a system integrator, architect, or data center operator perspective.

- From a product designer / manufacturer perspective, engineering a device to meet the 700V compatibility range ensures it can be deployed across all indicated (see [Table 8](#)) system configurations. This provides designers with a clear roadmap of compatible environments for their hardware. In addition, it shows that by simply increasing the internal electrical spacing, a device can meet the requirements for a broader group of systems, maximizing its market versatility.
- From a system integrator, architect, or data center operator perspective, the selection of a specific voltage, polarity, and earthing configuration establishes the technical boundaries for the facility. These choices define the group of compatible, voltage-rated products available for use, thereby providing a structured framework for long-term strategic planning and infrastructure design.

Table 11: Legend for the following rows in [Table 8](#): 350V or 400V device compatible, 700V or 800V device compatible, 1400V or 1500V compatible. Referenced in Footnote (e) in [Table 8](#).

Indicator	Description
x	Any product designed with the electrical spacing (clearance and creepage) for the indicated voltages will be a compatible device in the system for a given polarity and system earthing configuration
(x)	Special considerations have to be taken into account for cross-compatibility. Specifically, the full voltage to ground has to be considered in the design for spacing clearance and impulse voltages etc. For example, devices only designed for bipolar 350/700V might not be usable for unipolar 700V if not designed with sufficient (larger) clearances towards earth. The (x) label indicates additional caution should be taken to properly design products such that they can be used over a wider range of possible distribution system configurations.
-	Voltage is not available in the system for device to be used

6.3.3. Combination Table Analysis: Wiring (Active Wires, Active Wire Material, Relative Cable Losses, Relative Current for same balanced Power)

These rows show that for a given power, how the active wires, relative active wire material, cable losses and current rating compare under various configurations. These rows show that transitioning from 350/700V to 700/1400V with 0.5 scaling of active wire material still allows for the relative cable losses and relative current rating to both be halved, while maintaining a constant delivered power in all cases.

An additional consideration is also shown for active wires where a higher number of active wires, in some cases, can have positive efficiency impacts (e.g. 700V unipolar TN-S vs. 700/1400V bipolar with M TN-S). In a bipolar setup, the third wire (known as the middle/midpoint conductor (M) or neutral conductor) only handles the leftover "imbalance" between the two poles; if the loads are equal, almost no current flows through the M wire. This drastically reduces overall losses for the same power, compared to the unipolar case.

6.3.4. Combination Table Analysis: Impact on Protection Devices

The minimum number of protected poles from overcurrents (incl. overload and short circuit) (Row label in [Table 8](#): Min. # of Overcurrent Protected Poles) is a protection device related consideration, where a higher number signifies that additional overcurrent/overvoltage coordination may be required. It does not necessarily mean that more protection devices are required. As an example, semiconductor circuit breakers can be designed to connect on a single line (pole) or as standalone devices that connect over multiple lines. Moreover, bipolar systems with M might require more protected poles but, in unipolar systems, double the number of breakers would be required to connect the same number of circuits/loads if devices rated for two different voltage levels are required in a single system. Additional points on protection related analysis for [Table 8](#) are shown below:

- The Relative Voltage Semiconductor Circuit Breaker row in [Table 8](#) (SSCBs - solid-state circuit breakers) is a SSCB consideration (see footnote (i)). It specifies the relative voltage rating for SiC and GaN semiconductors required in various configurations. It shows that some semiconductor breaker designs require double the voltage for a given

application. Typically, the lower the voltage rating, the lower the cost for a given semiconductor.

- The Semiconductor Circuit Breaker Figure of Merit row is explained in footnote (j) and quantifies the total semiconductor "effort" or cost required to protect a system. It should be noted that this FoM is specifically impactful for SSCBs because a conventional electromechanical breaker does not have high cost scaling based on voltage for the LVDC level of voltage rating devices. Therefore, the cost for protection devices for electromechanical breakers and fuses only scales with the number of devices, while an SSCB also scales with voltage rating.
- The current rating (Relative Current for same Power row) from a circuit breaker perspective, means that if more current is required for the same power, larger current rated circuit breakers are required, which is a cost and system sizing impact.

More information on protection devices can be seen in [Section 7](#), Protection and Safety.

6.4. Conclusion

In this chapter, the polarities of DC grids were introduced. Unipolar and bipolar configurations, with and without (partially) distributed M conductor, have been described and characterized. In the system earthing section, firstly, electrical system boundaries created by isolation have been addressed. Then, the earthing options, such as TN-S and IT, and their implications have been discussed for these electrical systems. Lastly, the various combinations of polarities, system earthing and nominal system voltages have been compared and analyzed based on the impacts on various components.

The result of the analysis is that some combinations of these system options are more likely than others to be implemented in data centers. It should be noted that this could also change over time as power increases and new devices and components become available. In addition, the analysis shows that both data center architects and product manufacturers should account

for synergies between possible data center architectures and the interoperability / cross-compatibility of devices being developed for future data center applications.

The authors identified some options as likely to be used in data centers and others as less likely. In the following they are listed with some (non-exhaustive) considerations.

6.4.1. Likely to be used Combinations

The following options are considered likely to be used in data centers (not listed in any specific order). All likely combinations can supply 700V and 800V devices (if designed for full voltage to earth).

1. 350/700V Bipolar TN-S with (partially) distributed M (400/800V)

- Here also 350V and 400V devices can be supported.
- Has reduced voltage to earth compared to unipolar 700V for enhanced safety and can also connect without isolation to LVAC.
- This system is described in the OCP Mt Diablo Specification.

2. 350/700V Bipolar TN-S without distributed M (800V)

- Has reduced voltage to earth compared to unipolar for enhanced safety and can also connect without isolation to LVAC.
- Only two active wires needed, no M conductor.

3. 350/700V Bipolar IT without distributed M (800V)

- Reduced and more balanced leakage currents compared to the Unipolar IT system.
- Option in the NVIDIA 800 VDC Architecture design document.

4. 700V Unipolar TN-S (800V)

- Only one active pole has to be protected
- Higher clearances required than 350/700V Bipolar TN-S.
- Option in the NVIDIA 800 VDC Architecture design document.

5. 700V Unipolar IT (800V)

- Bipolar IT without distributed M is very similar and reduces leakage currents.

6. 700/1400V Bipolar TN-S with (partially) distributed M (750/1500V)

- In this case, the full LVDC range up to 1500V is used.
- Both 700V or 800V and 1400V or 1500V devices could be supported.
- The voltage to earth is the same as in unipolar 700V so the same devices could be used in both configurations.
- Sources will need to ensure that steady state voltage stays below the 1500V low voltage DC limit, e.g. by limiting voltage to 750V per pole.
- 800V devices can only be used if they can operate under 750V. This means 800V with only +-5% operation range can NOT be used.

6.4.2. Less likely to be used Combinations

The following options are considered less likely to be used in data centers mostly because of better alternatives that are very similar mentioned above. Some reasons are provided per system (not exhaustive).

1. 350/700V Bipolar IT with (partially) distributed M

- 350V devices would experience 700V to ground in case of first fault.

2. 700/1400V Bipolar TN-S without distributed M

- Can not support 700V devices that are expected to be available.

3. 700/1400V Bipolar IT with (partially) distributed M

- 700V devices would experience 1400V to ground in case of first fault.

4. 700/1400V Bipolar IT without distributed M

- Can not support 700V devices that are expected to be available.

5. 1400V Unipolar TN-S

- Can not support 700V devices that are expected to be available.
- Bipolar TN-S offers lower clearances and creepage to enclosure.
- In some countries LVDC has an additional limit of 900V to earth.

6. 1400V Unipolar IT

- Can not support 700V devices that are expected to be available.
- Bipolar IT without distributed M is very similar and reduces leakage currents.
- In some countries LVDC has an additional limit of 900V to earth.

7. Protection and Safety

7.1. Introduction

Protection of electrical installations -including data centers- from faults, such as short circuits, arcing, insulation or ground faults, is essential for ensuring safety and reliability. Without protective measures, faults can lead to severe consequences for people, equipment and property.

When designing protection for a data center many aspects must be taken into account, including:

- protecting against excess currents, that could overheat conductors and damage electronic equipment;
- protecting humans from electric shock, electrocution and arc flashes, that could reach extreme temperature and cause severe burns or blindness;
- preventing electrical faults, including overcurrent and arc faults, that can evolve into fires;
- protecting sensitive electronic equipment from high-voltage disturbances such as transient voltage surges;
- ensuring continuity of service of the data center in case of a fault, by quickly isolating the faulted circuit and ensuring that operation in the rest of the installation remains unaffected (selectivity);
- meeting requirements of applicable codes and standards, including the National Electrical Code (NFPA 70) or wiring codes based on IEC 60364 standards.

Unlike AC power systems and other DC systems, such as those in railways, DC power distribution systems for AI data centers are characterized by relatively low inductance and dominated by power-electronic sources and loads, e.g. AC/DC and DC/DC power converters or MV solid-state transformers (MV-SSTs). This changes the dynamic behavior and evolution of the faults and, consequently, the requirements on circuit protection. The low inductance of DC

circuits and the contribution of DC bus capacitors discharging into the fault demand specific protection strategies that act within microseconds to milliseconds. Yet these challenges are well understood and have been effectively addressed through proven engineering solutions.

In addition to traditional protection devices, fuses and electromechanical circuit breakers, new protection technologies - such as fast-acting, semiconductor (solid-state) circuit breakers and power converters with overcurrent blocking capability solid-state protection devices - have been introduced and have matured tremendously over the years.

This section provides a comprehensive yet practical overview of protection and safety in DC power distribution systems, based on best practices, real-world experience, and standards, aimed to prove that DC power systems to feed power hungry AI factories are safe and reliable and no longer a future aspiration, and to serve as a reference for protection design blueprints.

7.2. Protection against overcurrent

Overcurrent faults considered in the scope of this document are: pole-to-pole, pole-to-midpoint and pole-to-ground, short-circuit and high-impedance faults, including parallel arcs.

Protection from overcurrent in power systems is addressed in IEC 60364-4-43 and in Sections 110 and 240 of NFPA 70. As described below, power converters play an important role in fault protection, further investigations are needed if this is properly considered in current codes and standards.

7.2.1. Overcurrent faults in active DC systems

It is assumed that in DC power distribution systems for data centers, sources and loads are interfaced to the DC bus through power converters that regulate the voltage and maintain it in the required control band. These DC installations are characterized by capacitive sources connected at a short distance (hence low inductivity) to the loads, in the event of a short circuit the fault current increases very rapidly; an increase in the order of several tens of A/ μ s has been experienced.

Currently, no standards or recognized practices exist providing methods for assessing the short circuit current of this kind of DC power systems; IEC TC73 has recently started a new project aimed at filling this gap.

Considering a simple system with only one converter, the short-circuit current exhibits an initial peak resulting from the discharge of the capacitors followed by the steady-state contribution from power conversion, which depends on the type of the converter. Fault-limiting converters [Ca] (see [Section 8.3](#)) are able to limit the steady-state stage of the fault current to zero or low values in the range of the nominal current, not sufficient to sustain the voltage on the DC bus. If the fault is not cleared in time, the voltage decays to values lower than the minimum operating voltage of the system; the time to reach this level depends on the capacitors and on the fault-loop inductance and can be as low as a few 100s microseconds. Fast-acting overcurrent protection devices are therefore required to limit the DC voltage drop and ensure unaffected parts of the system continue operation. On the other hand, fault-feeding converters (see [Section 8.3](#)) can contribute to sustain the DC voltage, but they require an overcurrent protection device fast enough to avoid that excess current results in permanent internal damage or fires.

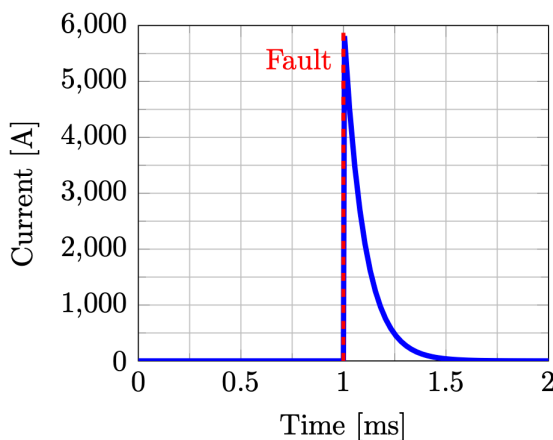


Figure 23. Fault current for a fault-limiting converter

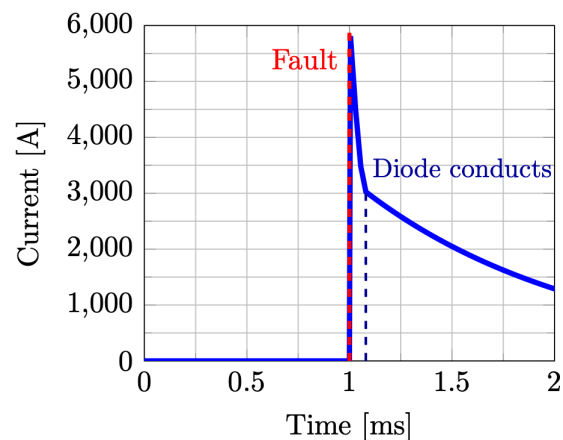


Figure 24. Fault current for a fault-feeding converter

In more complex systems with many converters, the fault current is the sum of the contributions of each converter connected to the DC bus. Also load converters, not intended to inject current in the DC bus, contribute to the fault current through the discharge of their capacitors.

7.2.2. Selectivity

As mentioned above, protection is a key aspect not only to avoid injury to personnel and damage to the installation but also to achieve the high system availability required for data centers. In case of a fault, the healthy (fault-free) part of the system must, as far as possible, continue operation.

Protection selectivity (or discrimination) is a system's ability to have the circuit protection device closest to the fault interrupt and therefore isolate only the directly affected part of a system in the event of a fault, while ensuring continued operation of the fault-free components and sections as far as possible.

Over the years, several methods have been developed to achieve selectivity in AC distribution systems, but Time-Current Selectivity remains the most widespread. This consists of setting protection devices to trip at different time delays for the same level of overcurrent, with the device closer to the load set to trip faster and the upstream device waiting longer. If the downstream breaker clears the fault in time, the upstream device does not trip. The high inertia of AC systems makes this relatively easy but can result in delays of up to 100-200 ms and, consequently, in case of arc flash, long arcing time and high energy release.

In a DC system, due to the fast fault evolution, in case of a short circuit the voltage can drop quickly. The fault should be cleared before the voltage drops below the minimum operating voltage of the converter and the system ceases to function, unless alternative strategies are implemented, as detailed below.

Additionally, with many energy storage devices connected in parallel, ensuring selectivity is more challenging than in a conventional linear configuration with a central power source, since in the event of a fault all energy storage devices may discharge into the fault location.

For selectivity, it must therefore be ensured that the protection devices in unaffected parts of the system will not trip when energy storage devices, such as capacitors, feed current into a fault via the DC grid. This can be achieved, for example, by detecting the direction of current flow in the DC breaker. Some possible alternative methods that require further investigation include:

- use fast protection devices, e.g. fast semiconductor circuit breakers (see below) to avoid the voltage drops below the minimum voltage. This is the simplest solution, but semiconductor circuit breakers are just arriving in the market now and the product portfolio may not cover all needs in the shortest terms.
- Add capacitors to store enough energy to meet the Voltage hold-up time requirements with the breaking time of the existing protection devices. This solution is based on mature protection technology, but the amount of stored energy needed must be carefully evaluated to avoid safety and reliability issues.
- Redundant-feeders architecture, in which each rack is supplied by at least two independent DC buses, arranged in a way that a fault in a bus does not propagate to the others, which can continue feeding the rack. This solution is simpler in terms of protection, but it introduces some design constraints that can reduce flexibility.

In any case, if no intentional tripping delay is used, the arcing time in case of arc-flash may be limited to the time necessary for the protection devices to interrupt instantaneously, and consequently lower energy release can be expected.

7.2.3. Branch vs supplementary protection

NFPA 70 distinguishes between overcurrent protective devices based on many factors including design, ratings and application. Supplementary overcurrent protection devices are considered to provide limited overcurrent protection within equipment, and is only supplementary to protection provided by an overcurrent protective device in the distribution system. Overcurrent protective devices such as fuses and molded-case circuit breakers (also referred to as branch circuit overcurrent protective devices), are considered to provide protection to the distribution

system, which includes branch, feeder and service conductors and equipment. Such distinction does not exist in IEC standards.

An example of supplementary protection protective devices are gR semiconductor fuses according to UL 248-13, intended for protection of power electronic equipment, which are not suitable for branch protection. Another example may be a hotswap controller located at the server shelf input. It protects the input connector from inrush current and arcing damage during hot-swap events, and it can also function as an electronic fuse to interrupt the current path during severe overcurrent or short-circuit conditions.

Requirements for branch circuit overcurrent protection devices are typically more stringent than for supplementary protection devices, e.g. they have higher minimum short circuit interrupting ratings, larger clearance and creepage distances, and more robust performance criteria. NFPA 70 specifies branch overcurrent protection devices to be readily accessible, whereas supplementary protection devices can be embedded in the equipment, e.g. in cabinets.

An example of a branch circuit overcurrent protection device is a circuit breaker located at a DC PDU output in the power rack or sidecar, or at the input of a DC bus. It shall be easily accessible, provide a clear visual indication of disconnection, and support lockout/tagout (LOTO) for maintenance activities.

7.2.4. Overcurrent protection devices

Many different overcurrent protection devices have been developed for DC, ranging from traditional fuses and electromechanical circuit breakers, that operate by creating an arc in the conductive path that develops an arc voltage larger than the system voltage, to new equipment based on power semiconductor devices.

Every overcurrent protection device rated for the appropriate voltage and current levels is able to clear overcurrent faults, regardless of technology, thus ensuring safety.

According to NFPA 70 Section 110.10, overcurrent protection devices shall be coordinated with the available fault current. However, there is currently no standard and no recognized practice

providing guidance about such coordination for the DC faults described above, in particular about how to consider the capacitor-discharge peak described above.

7.2.4.1 Fuses

Fuses need a minimum energy to melt and interrupt the current. In datasheets, this is typically stated in terms of the Joule integral (I^2t) of the current required for melting the fuse: I^2t_{melt} . In case the I^2t of the fault (I^2t_{fault}) is lower than I^2t_{melt} , then the fuse will not melt. In case of fault limiting converters, where the available fault energy is stored in the capacitors, such capacitors shall be large enough to meet such criterion mentioned [Rav]. As I^2t_{fault} in DC can depend on the shape of the fault current, the trip time -and consequently the let-through current- of a fuse can vary significantly.

In short-circuit, fuses have an interruption time ranging from less than 1 ms, for fast fuses intended for semiconductor protection (IEC 60269-4, UL 248-13), to several ms.

Low-Voltage fuses are covered by IEC 60269 and UL 248 standards. UL standards for fuses suitable for branch circuit overcurrent protection are currently limited to 600V.

7.2.4.2 Electromechanical Circuit breakers

Electromechanical circuit breakers according to IEC 60947-2, UL 489 or UL 1066 are also suitable for DC. Most DC circuit breakers in the market have a thermal-magnetic trip unit and poles arranged in series to build up a large enough arc voltage. Breaking time in short circuit ranges from about 1 ms, for small miniature circuit breakers (MCBs), to a few tens of milliseconds, for power circuit breakers. In active DC systems, breaking time is dominated by mechanical inertia, as short arcing time can be expected.

In case of active DC systems fed by fault limiting converters, the thermal-magnetic trip unit may not fit very well with the fault behavior, as the capacitor-discharge peak can be too narrow to trigger the magnetic protection, and the low fault energy can result in very long tripping time or no trip at all. Electronic trip units would fit much better for this application, but very few products

are available in the market. Electronic trip units can also implement additional protections, e.g. Ground-fault protection of equipment (GFPE).

7.2.4.3 Solid state CBs (SSCBs), Semiconductor Hybrid CBs (SCHCBs) and e-fuses

Solid state, or semiconductor, circuit breakers (SSCBs or SCCBs), according to the new UL 489I or to IEC 60947-10, to be published soon, use semiconductor switching devices, e.g. IGBTs, IGCTs or MOSFETs, in the main current path, to interrupt current, instead of an arc. They include mechanical contacts to ensure galvanic isolation, as required for safe maintenance, and typically have an electronic trip unit.

In a short circuit condition, these devices have breaking time in the order of microseconds. By clearing the fault in the early phase of the capacitor discharge, they limit the voltage drop even in installations with limited capacitance. Due to such ultrafast interruption, SSCBs are also able to break very high prospective short-circuit currents. As such, the key performance indicator is not the breaking capacity (I_{cs} / I_{cu} in IEC 60947-2, or $kAIC$ in UL 489), but the maximum rate of rise of the fault current (di/dt) that the circuit breaker can interrupt safely. Depending on the design, SSCBs can break currents up to several hundreds A/ μ s.

However, one drawback is that these devices have larger power loss compared to electromechanical circuit breakers and may require forced-air or even liquid cooling, for the larger current ratings, which could make integration in electrical panels more complex.

Semiconductor hybrid circuit breakers (SCHCBs), also covered by IEC 60947-10 and UL 489I, are similar to SSCBs but, in addition to the isolation contacts, they have mechanical by-pass contacts in parallel to the semiconductor switching device, intended for conducting the current in normal operation and therefore reducing power loss. SCHCBs have power losses similar to electromechanical circuit breakers but, due to the inertia of the by-pass contacts, they are much slower than SSCBs; their typical breaking time is in the order of a few hundreds μ s, making them suitable for currents with a rate of rise up to some A/ μ s.

Also similar to SSCBs, but without integral isolation contacts, are solid-state overcurrent protectors, also called e-Fuses in the industry. They have breaking time in the same order as

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SSCB and, unlike conventional fuses, are resettable. Presently, such devices are considered only to provide supplementary overcurrent protection in accordance with NFPA 70.

Solid-state overcurrent protectors in the form of integrated circuits (IC), intended to be mounted on a printed wiring board, are covered by UL 2367 and by subclause G.9 of IEC 62368-1, being limited to a rating of 5 A (removal of such limitation in the new edition of UL 2367 is under discussion) and 250 VA. While there are no explicit restrictions on voltage, UL 2367 does not address requirements for devices rated above 60V.

Devices according to UL 2367 can be used for providing supplementary protection of electronic equipment, e.g. power supplies, in accordance with UL/IEC 62368-1 and UL/IEC UL 60950-1, and for ensuring selectivity. They can also provide protection for Class 2 circuits as defined in Article 725 of NFPA 70. Application for higher power distribution is currently not addressed.

Properties of different protection devices for overcurrent protection are shown in the table below.

Table 12. Properties of different protection devices for overcurrent protection

	SSCB	SCHCB (hybrid breaker)	EM CB TM	EM CB ETU	Fuse (power distribution)	Fuse (semicondu ctor protection)	e-fuse
Reference standard	IEC 60947-10, UL 489I	IEC 60947-10, UL 489I	IEC 60947-2, UL 489	IEC 60947-2, UL 489	UL 248	UL 248-13	UL 2367
Suitable for branch protection	Yes	Yes	Yes	Yes	Yes	Only suppl. protection	Only suppl. protection
Ground fault protection of equipment	Possible	Possible	Not possible	Possible	Not possible	Not possible	Not possible
Tripping Method	I threshold (dl/dt)	I threshold (dl/dt)	I threshold (M), I-t curve (T)	I threshold (dl/dt)	Energy	Energy	I threshold (de-sat)
low let-through current	++	+	-/-	-	-	+	++
Interruption speed	1-100s μ s	0.1-1 ms	1-10s ms	1-10s ms	1-10s ms	0.1-1 ms	1-100s μ s
Interruption capacity	unlimited	very high	very high	very high	very high	very high	unlimited
Resettable	Yes	Yes	Yes	Yes	No	No	possible
Galvanic Isolation	Yes	Yes	Yes	Yes	With switch-disco nnecter	With switch-disco nnecter	No
Adjustable trip settings	Yes	Yes	Yes	Yes	No	No	No
Remote control (open)	Yes	Yes	Yes	Yes	No	No	(Yes)
Market availability	First products entering the market	First products entering the market	off-the -shelf	TV	off-the -shelf	off-the -shelf	Only low currents

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7.3. Protection against electric shock

Requirements regarding protection against electric shock in electrical installations are provided by IEC 60364-4-41.

Subclause 411.3.2 specifies requirements for automatic disconnection in case of fault, applicable also in DC. Requirements depend on the grounding system and the type of interlink converter. In TN-S systems with isolated interlink converters, a protective device shall automatically disconnect and isolate all the supplies to the line conductor in the event of a low-impedance fault between the line conductor and an exposed conductive-part or a protective conductor in the circuit or equipment. According to Table 41.1 of IEC 60364-4-41, for voltage higher than 400 VDC, the disconnection time shall not exceed:

- 0.1 s, for final (branch) circuits with rated current up to 63 A, if including one or more socket-outlets, and up to 32 A if supplying only fixed connected equipment;
- 5 s, for distribution circuits (feeders) and for final circuits other than those mentioned above.

The same requirement applies to systems with non-isolated interlink converters, with grounded AC neutral and DC active parts ungrounded (see [Section 6.2.1.3](#)). For IT systems, including both ungrounded and impedance-grounded systems, IEC 60364-4-41 does not mandate automatic disconnection on the occurrence of a first fault, provided a residual current monitor (RCM) or an insulation monitoring device (IMD) is used to signal the occurrence of such first fault with an audible and/or visual signal (IEC 60364-4-41, 411.6.3.1). On the other hand, NFPA 70 does require capability to detect a first fault if the IT system is ungrounded (no intentional connection to ground through high impedance) in Section 250.167(A).

For grounding systems different from IT, subclause 411.3.3 of IEC 60364-4-41 also mandates use of a residual current protective device (RCD) with residual current of 30 mA to provide additional protection of AC sockets (receptacles) with rated current up to 32 A used by ordinary persons, for applications requiring special attention, e.g. in kitchen and bathrooms, lighting systems, outdoor installations and eV-charging. Additional protection for DC systems is under consideration.

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Similarly, Section 210.8 of NFPA 70 identifies requirements for Ground-Fault Circuit Interrupter (GFCI) according to UL 943 (where applicable, other portions of the NEC like Section 422.5 may also identify further requirements), with tripping threshold not exceeding 6 mA, for the protection of receptacles supplied in AC in certain locations or supplying specific appliances. GFCI requirements in NEC Section 210.8 also apply to receptacles required by NEC Section 210.63 for equipment requiring servicing, with rated voltage up to 150 VAC, in locations other than dwelling units. Additionally, NEC Section 215.9 permits the installation of GFCI in the feeder instead of the branch circuit. Further updates to the NEC and UL 943 will be needed to extend traditional AC GFCI (Class A according to NEC and UL 943) requirements to more fully address DC GFCI.

Use of RCDs for DC power systems in data centers should be considered, especially in case of TN-S supply to racks with 800 VDC internal vertical bus. Current/OS and UL are developing technical specifications for DC RCDs. Application in data centers requires special attention to avoid unwanted tripping that could impact system availability.

Additional considerations apply in case of maintenance, due to the presence of capacitors facing the DC bus: disconnecting the sources is not enough to ensure electrically safe working conditions, but also the capacitors must be discharged to a safe voltage level.

Safety requirements are stated in Article 360 of NFPA 70E. In case the voltage is 400 V or higher and stored energy exceeds the hazard threshold of 0.25 J, which is very likely in a DC power distribution system of a data center, a written procedure shall be developed stating all the required steps to discharge the capacitors and place the equipment into an electrically safe working condition. The safe voltage level is stated in NFPA 70E Section 360.3 and is 100 V for 100 J stored energy. Additional prescriptions and recommendations are provided in other sections of NFPA 70E Article 360 and Informative Annex R and in NEC Article 460, although not directly applicable to the case of capacitors included as components in equipment. NEC Section 460.6 requires the residual voltage on a capacitor to be reduced to 50 V or less within 60 s after it is disconnected from the source.

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Similarly, subclause 4.4.9 of IEC 61800-5-1 requires capacitors to be discharged to a voltage less than 60 V within 5 s after disconnection. If this requirement cannot be met, warning labels reporting the discharging time shall be applied.

Country-specific workplace safety regulations may set additional requirements.

7.4. Protection against thermal effects and fires

Insulation failures, ground faults and series-arc faults in power distribution systems, may evolve into large parallel arcs, resulting in electrical fires and arc-flash hazard. These risks need to be considered and further evaluated.

IEC 60364-4-42 sets out protective measures for locations where consequences of fire are severe, which include locations where people sleep (e.g. in dwellings or hotels), or intended for groups of persons, or museums, or others. Such measures are the same for AC and DC systems and include:

- for TN-S and IT grounding: installing an RCD (or GFPE) with a rated residual operating current not exceeding 300 mA (for non resistive loads);
- for IT grounding and isolated interlink converter: installing an insulation monitoring device (IMD) monitoring the whole installation, and providing measures to eliminate a first earth fault with the shortest practicable delay

While not mandatory, these measures should be considered for data centers due to the high economic value of these.

For power distribution to industrial and data center loads, NFPA 70 indirectly addresses a specific type of ground and parallel-arc faults, where those faults have low impedance to ground. This is done for AC through the requirements of several sections, including Section 210.13(A), and has recently been extended to DC through Section 210.13(B) and correlating updates to other sections as well, requiring branch-protection disconnecting means rated 1000A or more, installed in solidly grounded DC systems at voltage up to 1500 VDC, to provide ground-fault protection of equipment (GFPE). For AC, this is supported by the UL 1053 listing and for DC this is under investigation by UL.

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Section 250.167 of NFPA 70 states that ground-fault detection is mandatory in ungrounded DC systems and permitted in grounded DC systems. Further investigations are needed about this requirement.

About series-arc faults, NFPA 70, Section 210.12(B) requires arc-fault protection by means of Arc-Fault Circuit Interrupters (AFCIs) in 120-volt, single-phase AC, 15- and 20-ampere branch circuits in dwelling units and similar locations, e.g. dormitories or guest-rooms in hotels. No similar requirement applies for commercial and industrial applications, neither in AC nor in DC. A special case is that of DC Photovoltaic systems, due to the harsh environmental conditions. In case of installation in or on buildings, Section 690.11 of NFPA 70 mandates arc-fault protection for voltage above 80 VDC; outline of Investigation UL 1699B specifies requirements for PV DC AFCIs up to 1500V DC.

In DC data centers, arc-fault detection could be considered for circuits supplying racks with 800V vertical-bus, in order to mitigate risks of arcs from hot swapping of modules, unless alternative measures are implemented to avoid swapping in case power supply in the module is active, or to switch off power automatically before swapping (semi-hot swapping).

7.5. Protection against voltage disturbances

Protection against voltage disturbances is addressed in Article 242 of NFPA 70 and IEC 60364-4-44.

In addition to voltage surges transmitted by the supply distribution grid, e.g. those of atmospheric origin, in DC systems special attention shall be paid to voltage surges generated by switching and breaking events, which can have significant magnitude.

All DC overcurrent protection devices, e.g. fuses, electromechanical circuit breakers, solid-state and hybrid circuit breakers, generate switching overvoltages which magnitude, duration and energy depend on the design of the device, the amplitude of the switched current, and the characteristics of the circuit. Protection devices based on semiconductors (SSCBs, SCHCBs and e-fuses) typically include surge protection devices (SPDs) to limit switching overvoltage. IEC 60947-10 for SSCBs and SCHCBs, and IEC 60269-3 for semiconductor fuses require the

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manufacturer to declare in the product documentation the maximum switching overvoltage generated by the device.

Due to the low inductance and the relatively large capacitors on the DC bus, DC power systems in data centers are supposed to be relatively robust with regards to transient overvoltages. However, in designing the protection system, attention shall be paid to overvoltage coordination to ensure that overvoltage surges do not damage other electronic equipment in the system.

7.6. Protection against arc-flash

There is the perception that the trend towards higher power densities in AI factories results in a significant increase of fire and arc-flash risks.

A single arc-flash incident can cause injury or death to personnel and destroy entire rows of expensive servers and other equipment, costing millions dollars .

Whenever possible, no work should be done on energized equipment. However, in data centers, typically operating on a 24/7/365 basis with strict uptime guarantees, turning off the power in a room or in a line of racks is impractical. As such, technicians may be required to perform maintenance and upgrade works on equipment while it is still energized.

For this reason, assessing and mitigating arc flash risks is crucial, in particular the adoption of adequate personal protection equipment (PPE), as described in NFPA 70E, protecting the workers thermal injuries resulting from the energy release or electric arcs (arc flash). This requires the Incident energy (IE_m) of the arc to be calculated.

New Section 110.16 of NFPA 70 2026 also requires permanent arc-flash hazard labels on distribution equipment likely to require servicing, or maintenance while energized. Additionally, Sections 240.67 and 240.87 of NFPA 70 require mitigation strategies be employed for circuits with overcurrent protective devices rated 1200 amperes or higher.

As of today, there is no standard for calculation of IE_m in DC systems, equivalent to IEEE 1584 for AC. However, NFPA 70E Annex D.5 provides recognized methods based on different studies, one of which is the “Maximum Power Method” [D.5.1], known to give conservative IE_m values. The calculation formula for this method are given below:

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$$I_{arc} = 0.5 \times I_{bf}$$

$$IE_m = 0.01 \times V_{sys} \times I_{arc} \times T_{arc} / D^2$$

where:

I_{arc} = arcing current, amperes

I_{bf} = system bolted fault current, amperes

IE_m = estimated dc arc flash incident energy at the maximum power point, cal/cm²

V_{sys} = system voltage, volts

T_{arc} = arcing time, sec

D = working distance, cm

Figure 25. Arc Current Calculation

Where the arc is in a box or enclosure, the incident energy should be prudently multiplied by a safety factor, a reasonable value of which is 3.

A problem of this method is that the real behaviour of the fault current is not considered and a steady-state current I_{arc} is assumed for the total duration of the arc. Furthermore, it is necessary to clarify whether the value of the prospective short circuit-current I_{bf} to be considered is the peak value of the capacitor discharge, the steady-state fault current or a combination of those. Even applying such conservative method, for a fault with short circuit-current $I_{bf} = 100$ kA, at 800 VDC, protected by means of a SSCB clearing the fault in 50 μ s, the incident energy IE_m at 18 inch (45.7 cm) working distance is as low as 0.02 cal/cm² in “open air” (0.012 cal/cm² inside an enclosure).

In general, the graph in [Figure 26](#), representing the IE_m calculated with the Maximum Power Method for different bolted fault current I_{bf} , in “open air” and “inside an enclosure” configuration, shows that the protection technologies described in 7.2.4 and the selectivity strategies in 7.2.2 are sufficient to limit the arc duration so that the Incident energy remains below the threshold of 1.2 Cal/cm² that triggers the Arc Flash boundary for Personal Protection Equipment (PPE).

The results of simple calculations and simulations [Mar] confirm that relatively low levels of the available fault energy in the type of DC system used for data centers.

More research is needed in the field of arc flash behavior in DC power systems, to confirm such considerations and develop industry-accepted methods for calculating incident energy and arc-flash boundaries.

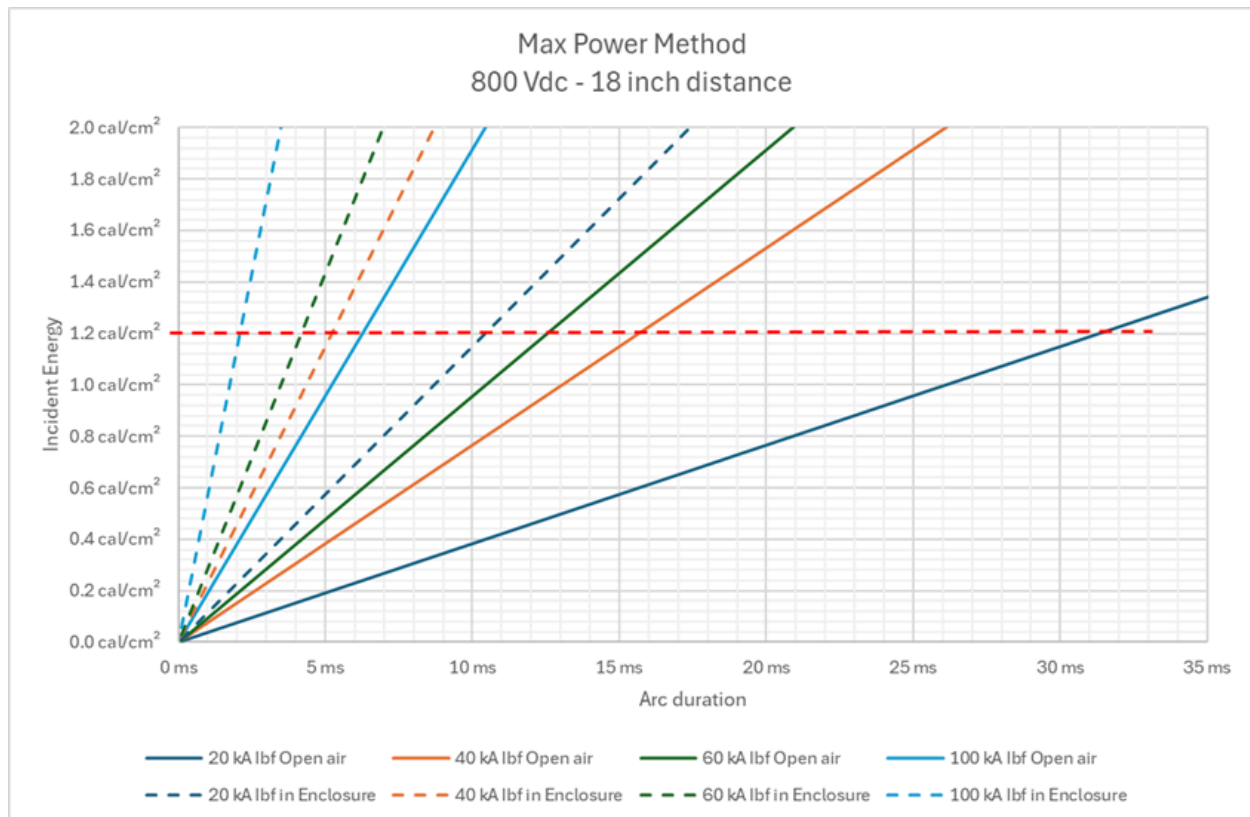


Figure 26. Incident Energy vs. Arc Duration

Worth noticing that the Incident Energy is one hazard among others which results from an arc-flash event. In presence of capacitors, Article 360 of NFPA 70E defines additional safety measures related to the ‘arc blast’ hazard: hearing protection is required where the energy stored in capacitors exceeds 100 J, which is quite likely to occur in data centers as energy storage is brought into the white space (with AC or DC power distribution). Whereas, the 122 kJ threshold, triggering the lung-protection boundary, is not likely to be exceeded.

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8. System Main Components

The “System Main Components” aims to list the principal power train components required to feed the AI Racks using DC power. For each component, relevant technology will be mentioned, and advantages and drawbacks will be discussed related to this specific application.

All the information shared in this part will remain high level unless it is deemed to be necessary to enter in more detail for clarification purposes.

Proposed Simplified Single Line Diagram:

The proposed single line diagram here is highly simplified, the only purpose is to facilitate the location of the different Main Components in the circuit.

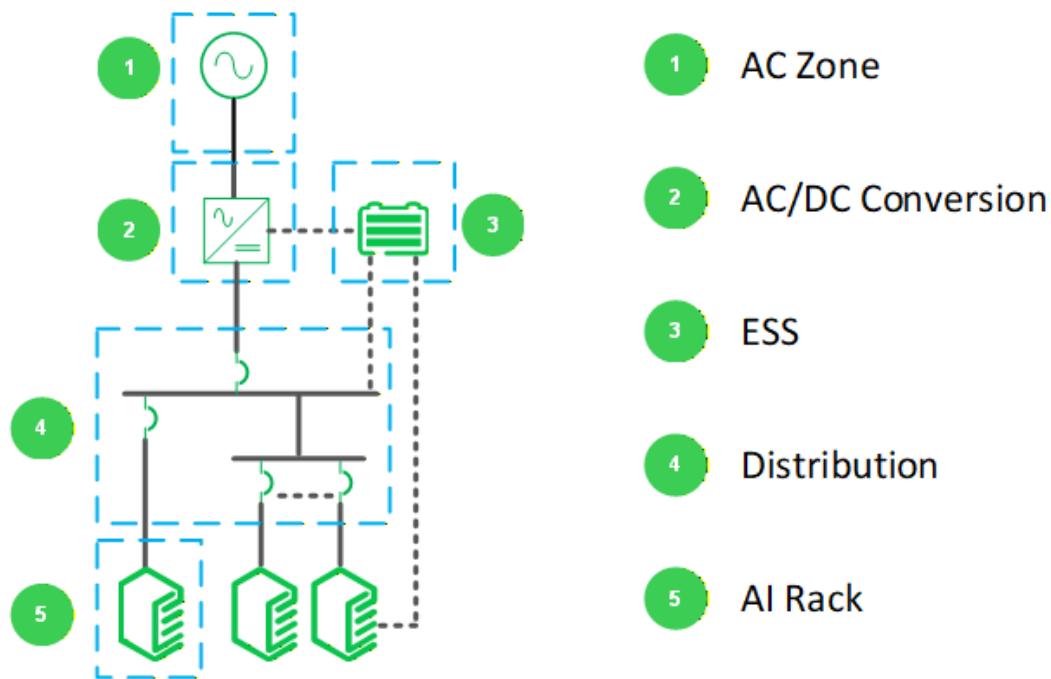


Figure 27. Simplified single line diagram for DC Power Distribution in Datacenter

The Main Components will be divided in several sections:**1. AC Zone**

The AC zone covers the requirements of the equipment upstream of the DC distribution side, such as connection to the grid, on-site generation, or even back-up generation.

2. AC/DC Conversion

This section presents the different technologies available to convert AC into DC.

3. ESS

This section highlights the different ESS technologies and where/how they can be used in the system.

4. Distribution

This section covers the equipment required to distribute the power from the AC/DC conversion to the AI Rack. The protection equipment is not covered in this document as it has its own chapter.

5. AI Rack

OCP has a dedicated Rack&Power work group, the information shared in this section are the ones which have been deemed impacting the DC power distribution requirements.

6. Miscellaneous

In this section will be listed equipment which will play an important role in the overall architecture but have not been covered yet in the other section.

8.1. Grid

For most data centers, the grid is their main source of power that is used to run the facility. Historically, data center load growth was relatively predictable and their impact on grid stability was minimal, grid operators were not concerned about data centers impacting the grid. However, as data center sizes continue to grow rapidly, driven by the accelerated development and deployment of AI workloads and reaching gigawatt scale, their impact on the grid reliability has become significant. Grid disturbances involving data centers have occurred across North

America and Europe have prompted grid operators and transmission operators to institute requirements in their grid codes for data centers connecting to the grid. If these requirements are not met the data center will not be allowed to connect to the grid and energize. The sudden loss of load from a data center can cause high voltages and frequencies that can trigger grid protection systems worsening a disturbance. Therefore, data centers must be designed to meet grid requirements to contribute to the overall reliability of the grid. These grid requirements include:

1. Voltage and Frequency Ride Through - The data center must be able to withstand temporary voltage and frequency excursions for normally cleared faults by staying connected.

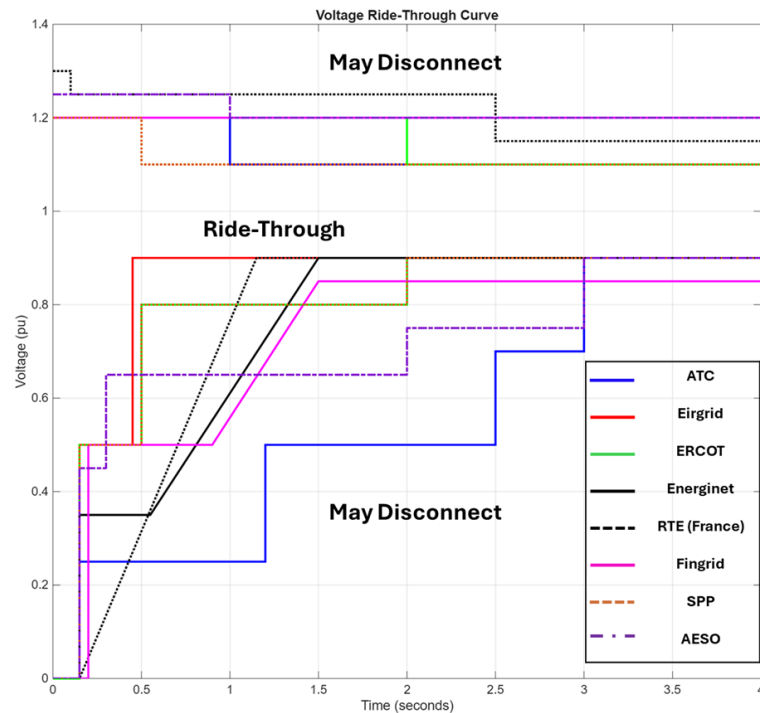


Figure 28. Voltage Ride-Through Curve

2. Post Fault Active Power Recovery - The data center must be able to expeditiously reconnect to the grid after the disturbance is cleared. For example some grid operators

are requiring that data centers reconnect and return to roughly 90-100% of pre-fault power consumption within one second. Therefore data centers must be able to program settings on how quickly the data center reconnects to the grid and returns to a specified pre-fault power consumption level in the event of a fault.

3. Protection System Coordination - The data center protection systems logic must consider timing needs for high speed reclosing and transmission breaker operations and coordinate with the grid protection to minimize misoperations. Any other control logic that is impacted by grid disturbance should also be coordinated to minimize misoperations.
4. Ramp Management - On the grid, demand and generation must remain balanced at all times. If demand or generation rises or falls too quickly then the grid may exhaust its power reserves and be unable to manage frequency threatening grid reliability. To avoid contributing to this issue, data centers must manage their active power consumption ramp rates by controlling how quickly the data center load ramps up and down. Ramp control may be executed by means of local generation or storage systems, creating a buffer between the DC power requirements and the load taken from the utility
5. Oscillation Management - Repeated power oscillations from a data center can be a source for forced oscillations on the grid which can damage generators. Data centers focusing on AI training have a higher oscillation potential including sub-synchronous oscillations than previous data center designs. Data centers must manage and avoid repeated power fluctuations to manage the potential for oscillations.
6. Power Quality - Data centers must meet power quality requirements to avoid impacting other customers and causing reliability problems.
7. Monitoring Methods - Data centers must be able to monitor the performance of the data center as a facility
8. Reactive Power and Voltage control - Connecting large data centers to the grid can have a significant impact on voltage and reactive power flows. It is expected that the data center actively participates in voltage management by providing reactive power within a

predefined range (typically ± 0.95 power factor) and can be coordinated with the setpoint from the connecting Transmission System Operator.

9. Validated Grid Models - Grid planning engineers rely on accurate electrical models that simulate data center behavior. Data center owners must develop and provide high-fidelity dynamic models in the positive-sequence (e.g., PSS/E) and EMT (e.g., PSCAD) domains that accurately reflect the facility dynamic responses.

8.2. On-Site Generation

As AI-driven applications scale, technology companies have traditionally relied on the local grid to power their data centers. But with soaring demand, the grid is struggling to keep up, facing capacity and transmission constraints. As a result, data center developers—who typically focus on facility design and optimization—are increasingly looking for alternative power solutions that are reliable and scalable.

On-site generation can function as behind-the-meter, island microgrid solutions, enabling data centers to operate independently where grid infrastructure is insufficient or unavailable.

In locations where grid operators require onsite power to contribute to the electricity market, these technologies can also run in parallel with the grid as dispatchable resources, providing additional flexibility.

In the case of on-site power generation, the applicable requirements for grid interconnection when grid is the source of power, and described in the previous chapter, are no longer needed .

However additional challenges apply, especially resulting from the following:

- A direct influence of AC/DC conversion harmonics onto the microgrid power quality: higher reactive power, losses, frequency and voltage stability;
- The reduced ability of the on-site generation to immediately react to the AI workload oscillations, given the more limited generation capacity compared to having the whole grid as a source.

8.3. AC/DC Conversion

With higher power densities and a DC distribution system, facility level AC/DC conversion is needed to supply the DC distribution system. By using a centralized conversion system, flexible DC and bidirectional power flow capabilities are enabled allowing for point-to-point power routing, improved fault handling, and seamless integration with battery energy storage systems. Several systems can be used for AC/DC conversion including uncontrolled rectifier “x” pulses, LV Interlink Converters, MV Interlink Converters, and Solid State Transformers.

The purpose of this section is to present a technical evaluation of different features and technologies available to convert AC into DC with high level pros and cons. Future versions of this section will include more analysis around maintenance, cost, integration or efficiency.

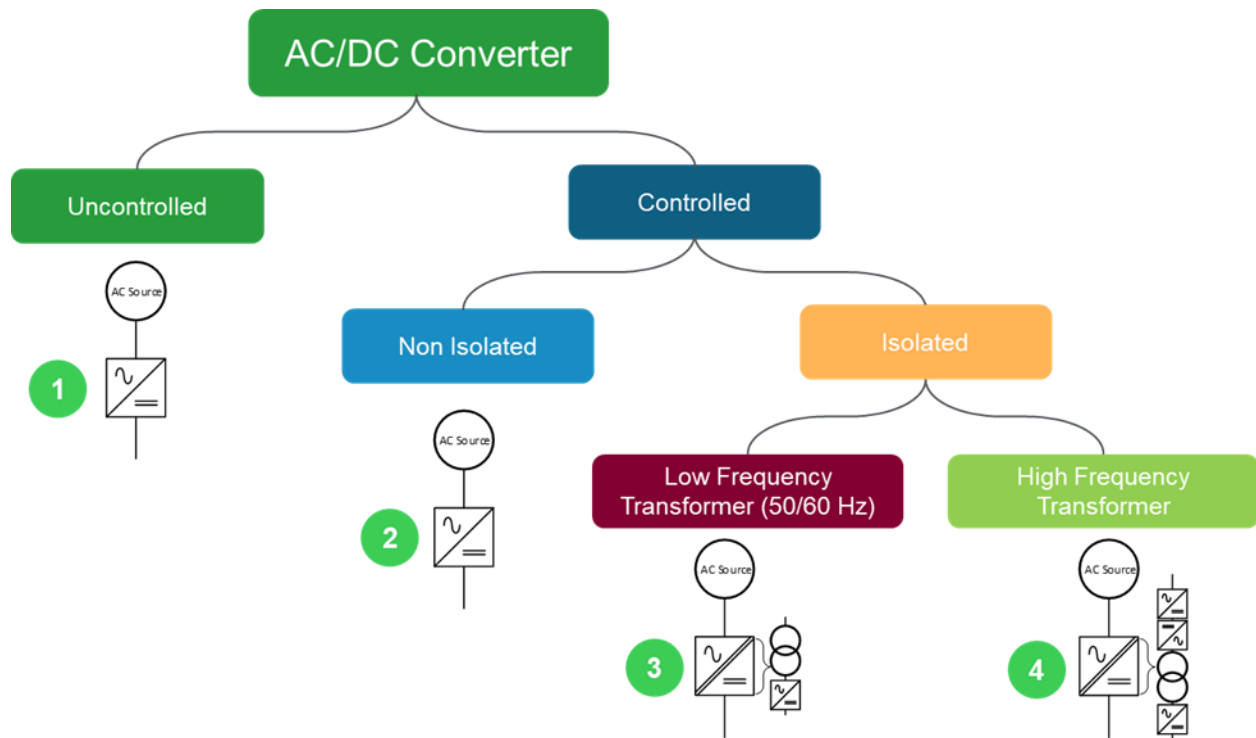


Figure 29. AC/DC Converter Block Diagram

Uncontrolled

- Vdc output is dependent of Vac input, any fluctuation on Vac will impact Vdc
- Vdc is always $>V_{ac}$
- Unidirectional only

Controlled

- Vdc output is independent of Vac input (to the limit of the converter topology)
- Vdc is always $>V_{ac}$ for “boost type”
- Vdc is always $<V_{ac}$ for “buck type”
- Vdc can be $>$ or $<V_{ac}$ for “boost/buck type”
- Unidirectional or bidirectional

Non Isolated

- No galvanic isolation between AC and DC side
- Grounding configurations between AC and DC are dependent

Isolated

- Galvanic isolation between AC and DC side
- Grounding configurations between AC and DC are independent

**Low Frequency
Transformer (50/60 Hz)**

- Galvanic isolation is provided by a low frequency transformer (50/60 Hz)

**High Frequency
Transformer**

- Galvanic isolation is provided by a high frequency transformer

1

“x” pulses Rectifier type (6,12,24,36...) using semiconductors such as diodes.

- Pros
 - Mature and reliable technology
 - Relatively less sensitive to fault current
- Cons
 - Energy control not possible (e.g droop)
 - May required harmonics mitigation devices
 - Unidirectional Only

While potentially a valuable solution for DC Datacenter (similar technology has been used in the previous project in the world), the lack of output voltage regulation will affect the stability and power quality of the system for AI type of load profile, which makes this solution hard to implement (it would require high complexity of controls).

2

“boost” type using semiconductor such as IGBT, Mosfet. Sometimes called “Active Front End” (AFE) or Interlink Converter.

- Pros
 - LVAC input only to provide LVDC output
 - Mature and reliable technology
 - Very efficient (reduced semiconductor switched device)
- Cons
 - Grounding configuration must be engineered to avoid incompatibility between AC and DC side
 - Sensitive to fault current, fast tripping time required to protect power electronic components

3

Similar to number 2 adding a low frequency transformer at its input

- Pros (in addition of number 2)
 - Provide galvanic isolation
 - Can take LVAC or MVAC as input
- Cons (in addition of number 2)
 - Solution can be bulky for very high power due to the LF transformer

These types of converter (2 and 3) are widely used in the industry today (Solar, BESS, Drive e.g). This solution is a good fit to provide stable and quality power to the AI rack until the integration (footprint, weight, transportation) becomes a constraint which can lead to the use of converter type number 4.

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4

Several topologies exist, using LVAC as input (e.g LV rectifier+dual active bridge) or using MVAC as input also known as Solid State Transformer (SST*)

- Pros
 - Provide galvanic isolation
 - Can take LVAC or MVAC as input
 - Reduce size (footprint and weight gain)
 - Some topologies allow control of the current during fault condition hence the use of slower protection devices.
- Cons (in addition of number 2)
 - “young” technology compared to the other ones
 - Reliability at scale to be proven (high number of switching devices)
 - Efficiency at scale to be proven

*A Solid-State Transformer (SST) is defined as a megawatt-scale power electronic converter designed to replace conventional 50/60Hz line-frequency transformer and rectifier units (isolated or non-isolated). The distinguishing features of SST include medium-to-high-frequency magnetic components/transformers (MFT/HFT), enabled by Wide-Bandgap (WBG) semiconductors such as Silicon Carbide (SiC) or emerging Gallium Nitride (GaN).

Adding an ESS+Control system on the output of the AC/DC converter and packaging it together makes a single equipment which can be called DC UPS.

There is no standardized “fault current behavior” today, in addition to being physically linked to the converter topology, controls (manufacturer based) also play a role.

Fault current behavior can be split into 2 categories:

1. Fault feeding (converter type 1,2 and 3)

In this category, the fault current from the AC source to the DC distribution cannot be limited. Converter type 1 can usually withstand fault current for a short duration, however, converter type 2 and 3, because of the semiconductor switches, cannot withstand fault current coming from the AC source. These types of converter usually have self fast protection (e.g fast fuse or semiconductor switch) embedded which will limit the fault current in duration and or in peak value.

2. Fault Limiting (converter type 4)

These types of converter, thanks to the inherent topology, can control and limit the fault current from the AC source to the DC distribution. It can limit the value to a small multiple of the nominal current (e.g 1.5x, 2x) and limit in duration (e.g 100ms, 200ms).

It is worth noticing that in any case, there could be a short surge current when the fault happens because of the exposed capacitor of the converter on the DC side.

Principal Standards which covers AC/DC Conversion technologies:

- UL 1741 → Standard covering Converters
- UL 2877 → Outline of Investigation which covers SST
- IEC 62477-1 and 2 → Standard covering Converters
- IEEE 1547 → Standard for grid interconnection

Refer to the [Codes & Standards](#) chapter for more details.

8.4. ESS

Energy storage systems (ESS) are becoming critical components of modern data center infrastructure. They go beyond the traditional role of an Uninterruptible Power Supply (UPS) by offering fast stabilization for AI-driven load swings, reliable ride-through during grid disturbances, cost optimization, renewable integration, and grid services.

The figure here under represents applications by the time frame the storage is expected to be active: milliseconds for local power quality, seconds for rapid stabilization and ride-through, minutes for UPS bridging and peak shaving, and hours for energy arbitrage, renewable shifting, and extended backup:

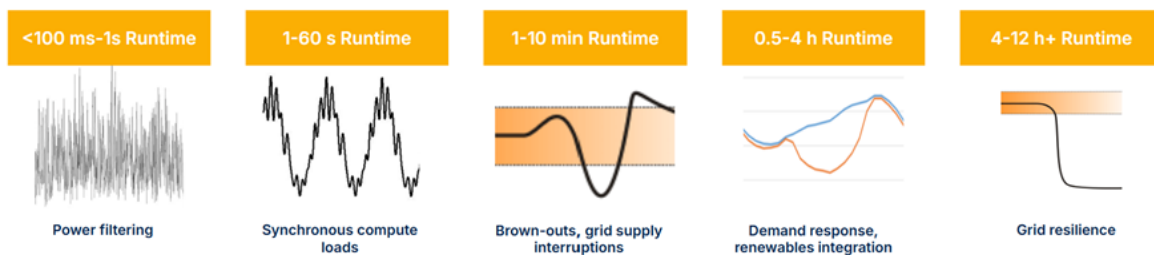


Figure 30. Power Equipment Applications

The key functions of ESS in a data center:

1. Smoothing power swings (milliseconds to seconds)

AI workloads present high power fluctuation, ramping power from 30% to 100% in milliseconds [Choukse et al. 2025]. These ramps and spikes are characterized by different dynamic elements occurring at different timescales (milliseconds, seconds, minutes), thus stressing equipment and degrading overall power quality. Without mitigation, the result can be voltage sags, oscillations, threaten broader grid stability, and risk tripping or damaging nearby generation and other upstream equipment. Energy storage systems address these dynamics by rapidly absorbing or injecting power across the relevant timescales, smoothing ramps and spikes, damping oscillations, and maintaining stable voltage and frequency through coordinated controls.

2. Providing backup power during grid disturbance (seconds to minutes)

This is the most fundamental function. Data centers require uninterrupted power for their mission-critical servers and other systems.

Traditionally, backup of the facility is by UPS, and battery backup units (BBUs) are also deployed in or close to IT racks. They ensure that the data center remains operational during grid failures or until backup generators can be brought online. The timescales required for these types of operations are generally considered to be minutes. Alternative solutions could be used, for example, ESS with extended runtime to even replace generators entirely in some cases. By using batteries (for example) instead of diesel generators for backup, data centers can achieve a zero-emission backup solution, supporting sustainability goals. The size and cost of the battery will be directly proportional to the amount of time that a given power level is desired to be provided.

Moreover, during Post-fault active power recovery the data center must be able to quickly reconnect to the grid after a disturbance is cleared. Some grid operators require large loads to return to roughly 90–100% of pre-fault power consumption within about one second. ESS enables this by “mimicking” the load for the grid, absorbing power during the reconnection ramp to keep the facility’s net import near its pre-fault level until the grid stabilizes.

3. Grid Services and Energy Optimization (minutes to hours)

In many regions there is a paid market for grid services (e.g., frequency regulation and reserves), while in others the emphasis is on strict grid-code compliance; ESS can support both, optimizing economics where markets exist and ensuring reliable, compliant operation everywhere.

- Energy arbitrage: store low-cost electricity and discharge when prices are high to optimize energy costs.
- Distribution efficiency: smooth power profiles to keep electrical and computing systems in efficient operating regions and reduce losses.

- Peak shaving and capacity reduction: rapidly discharge during demand spikes to power demand charges and, by limiting instantaneous draw, reduce maximum contracted capacity and ease interconnection.
- Grid stabilization and ramp compliance: inject or absorb power to stabilize frequency, participate in load shaving, and meet ramp-rate requirements set by grid operators.
- Integration with renewable energy: pair with on-site solar or wind to store excess clean generation and use it later, maximizing renewable utilization and supporting decarbonization targets.
- Reactive power and voltage control: provide reactive power and voltage support when required by the grid.

8.4.1 Technology

The landscape of energy storage for data centers is rapidly evolving beyond the traditional UPS, with different technologies offering distinct trade-offs in terms of duration, power density, safety, typical connection point and cost.

Proximity is relevant to how those needs and characteristics are provided for. Figure below illustrates commonly considered connection points in the data center architecture where they may be integrated. ESS that is located closer to the IT rack will be tasked with the highest response rate, high cycle count, shorter duration dynamics. While ESS that is located further upstream or at the utility interconnect will deal with applications required for grid compliance or energy management. The utility-scale BESS generally applied for the slower dynamics and longer duration, whereas E-STATCOM for the fast dynamics and short duration, such as load swings and low-voltage fault ride through. The configurations and voltage ratings that are feasible for a given ESS technology must be suitable for the voltage level at the point of connection for that ESS within the power distribution system - and/or make use of a DC-DC converter. The core challenge is how to solve the different load dynamic challenges at different levels of the power distribution system with a coordinated and optimized set of ESS technologies. [Table 13](#) is provided to give a summary of the nominal capabilities and strengths

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of different energy storage technologies to provide context for how they may be utilized or combined to provide for the overall load dynamic requirements.

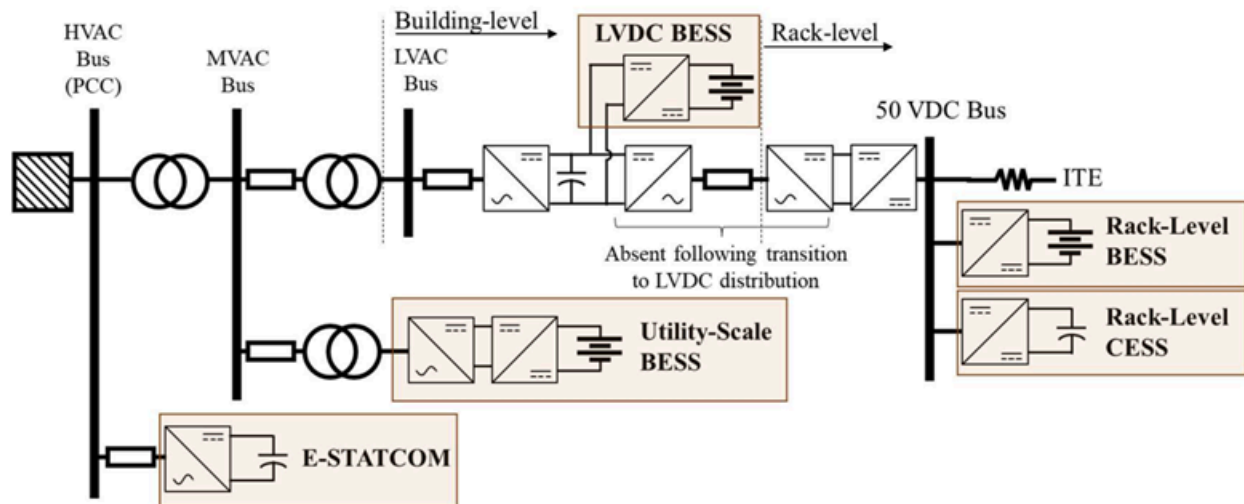


Figure 31. [Electromagnetic Transient Modeling of Large Data Centers for Grid-Level Studies](#)

Here is a breakdown of the primary energy storage technologies to be considered in data centers:

1. Electrochemical energy storage

The conversion and storage of energy are through electrochemical reactions. It includes lead-acid battery, lithium-ion battery, metal air battery, flow battery, sodium-ion battery and so on. The ESS based on batteries typically includes battery modules, thermal management system, and battery management system.

2. Mechanical energy storage

Mechanical energy storage systems store energy in the form of potential or kinetic energy. Unlike electrochemical energy storage, these systems use physical forces and

motion to capture and release energy. It includes flywheels, compressed air energy storage, and so on.

3. Electrical and magnetical energy storage

Electrical magnetic energy storage primarily refers to Superconducting Magnetic Energy Storage (SMES), they store energy directly in a magnetic field created by the flow of direct current (DC) in a superconducting coil. Conventional capacitors fall into electrostatic energy storage, they store energy directly in an electric field created by the separation of static electric charges. Supercapacitors function via a hybrid mechanism, by using an electrolyte and store charge in an Electric Double Layer (EDLC) formed at the interface between the electrolyte and the electrode (usually porous carbon).

Table 13: Main energy storage technologies considered for data center

Feature	Ceramic Caps (MLCC)	Electrolytic Caps (Al, incl. polymer/hybrid)	Film Caps (PP/PET DC-link)	Supercaps (EDLC / hybrid)	Battery Cap	Li-ion – LTO XNO NTO	Na-ion – NVPF	Na-ion – Prussian White	Li-ion – NMC 811	Li-ion – LFP	Lead-Acid Batteries (VRLA/ Flooded)	Al-Air Batteries
Primary Role	Point-of-load HF decoup, edge suppress	Bulk decoup, hold-up energy	DC-link ripple handling, damping	Bridge power, pulse buffering, power quality	High-power buffer/ ride-through, fast charge/ discharge buffering, pulse peak shaving, SD-ESS	UPS, SD-ESS, fast charge/ discharge buffering	High-power buffer / ride through	BESS	BESS, automotive	BESS, automotive	UPS ride-through + backup energy	BESS
Storage Mechanism	Dielectric (ceramic)	Dielectric (electrostatic)	Dielectric (polymer film)	Electrochem Cap	Capacitive & Faradaic	Electrochem	Electrochem	Electrochem	Electrochem	Electrochem	Electrochem	Electrochem
Typical Runtime	ns → ms	ns → ~100 ms	µs → 10s ms	Sub-s → s	Sub-s → mins	s → mins	s → mins	mins → hrs	mins → hrs	mins → hrs	mins → hrs	hrs → days
Energy Density	Very Low	Low	Very Low	Very Low	Medium	Low–medium	Low	Medium	Very High	Medium	Low	High
Power Density	Extremely High	High	Very High	Very High	Very High	Very High	Very High	Medium-high	High	Medium	Medium	Medium
Cycle Life	Extremely High	High (if lightly stressed)	Very High	Extremely High (100k–1M+)	Extremely High (100k–1M+)	Very High (10k–20k+)	High-Very High	Medium-high	Medium–high (thousands)	High (1ks to 10k+)	Low (100s)	N/A
Lifespan	Long (but can crack)	Medium	Long (often 15–25+ yrs)	Long (10–20+ yrs)	Long	Long (10–20 yrs)	Long	Long	Medium–long (8–15 yrs)	Long (10–20 yrs)	Short (3–6 yrs)	Long (10–20 yrs)
Thermal / Safety Risk	Very Low	Low	Very Low	Low	Low	Low	Medium	Medium	Medium–high	Low–medium	Low	Low
Maintenance	Very Low	Low (but planned replacement)	Very Low	Low (monitor balancing/ health)	Low-medium	Low-medium	Low-medium	Low-medium	Low-medium	Low-medium	Medium	Low
Response Time Band	sub-ns → ms	ns → 100 ms	10s of ns → ~10s of ms	µs → s	µs → s	sub-ms → s	ms → s	ms → s	ms → s	ms → s	ms → s	ms → s
Voltage Rating Practicality (ie for 800 V bus)	Low	Medium-low	Medium-high	Low-medium	High	High	High	High	High	High	High	High

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8.4.2 ESS Safety

ESS safety is a complex subject. The intent here is to provide a high level guide to ensure awareness of the most critical aspects and some understanding of why they should be considered. Most any ESS technology or medium poses at least some kind of thermal risk. Any ESS that utilizes an electrolyte consisting of an organic carbonate solvent will, in a failure scenario, produce an offgas that poses a risk for flammability and/or explosion. This summary will discuss primarily in the context of lithium-ion batteries, most electrochemical storage technologies (particularly those using organic carbonate solvent electrolytes) will be more similar than different. However, it is important to note that some lithium-ion batteries decrease or completely mitigate some of these risks through the use of different materials (aqueous electrolytes, ceramic separators, oxide-based anodes), making them safer and more suitable for high-risk or mission critical applications. Capacitors typically present lower or no fire risk (ie ceramic), but technologies using electrolytes (electrolytic, supercapacitors) do constitute thermal risk. In most cases, thermal events are characterized by very low likelihood of occurrence, but the impacts of an event can be so severe that the overall risk profile demands attention. The risks and results of thermal events can be managed and mitigated with existing engineering tools and technologies. But variations exist between different technologies and form factors such that the mitigating solutions must be fit for purpose. This poses a challenge for ongoing efforts towards standardization and for early stage project scoping. In addition, human error is often found to be the failure mode behind many historical ESS safety events.

Standards and best practices for large outdoor ESS installations do exist with years of history. However, the prospect of a significant amount of energy storage capacity distributed throughout an indoor space poses new and different challenges. The following summaries discuss general aspects of ESS safety for consideration, but primarily in the context of challenges and needs for those indoor installations.

1. **Thermal runaway:** A self-accelerating thermal event that is characterized by exothermic processes. Any medium or technology that stores chemical energy is capable of and at

risk of some degree of a thermal event. However, the amount of thermal energy released and the extent of abuse that is required before forcing a cell into thermal runaway certainly varies in different chemistries. However, suggestions that some battery technologies are completely incapable of a thermal event should be considered with skepticism. Some technologies may produce benign responses to certain failure modes, but still be at risk of significant thermal events in response to other failure modes. Objective testing and valid data is critical for assessment of the true risks, capabilities and requirements. Generally, a single thermal event (i.e. in a single cell) is of relatively mild consequence to the overall facility. The primary threat and challenge is the likely scenario that this single cell event will propagate to other cells, and thus spread exponentially. This is a critical aspect of ESS system design and the requirements are particular to the chemistry and module/system design and form factor. Evaluating thermal and propagation behaviors is a core component of UL 9540a testing.

2. **Electrical:** a great deal of consideration is given to thermal aspects of ESS safety. However, practically speaking, the vast majority of risk and real incidences are related to electrical shock and arc flash. Batteries present voltages often over 1,000 VDC and, critically, are always live. Proper precaution, processes and equipment for aspects such as disconnect and isolation, particularly during installation and service, are critical to ensuring safety.
3. **Ventilation:** In the case of a thermal event, offgas will be released that is both flammable and explosive. Managing and ducting this gas to avoid an explosion is a key challenge - particularly for indoor installations. There are many different approaches that can be considered for mitigating risks - appropriateness depends on the technology, form factor, and the space within which it is installed. Ventilation poses one of the most substantial challenges with regard to infrastructure and available space, and is one of the required safety systems that is often forgotten until the end.
4. **Fire suppression:** Generally speaking, putting out a lithium ion battery fire is difficult and access directly to the cell in thermal runaway is typically not possible. Thus,

‘extinguishing the fire’ is not a typical objective. A key objective is to limit propagation, as described earlier; and for this, removal of heat is critical. Many different fire suppression mediums exist, and each excels in certain areas and may underperform in others. Gaseous mediums excel at extinguishing flames, but not at removing heat and must take into account interactions with ventilation. Water is ideal for removing heat but produces short circuit risks. Many others face challenges of physical installation feasibility. The system should be selected and engineered appropriately for the ESS technology and form factor that is being installed.

5. **Codes and Standards:** ESS codes and standards are continually evolving. The differences between technologies and formulations makes it particularly difficult for ‘one size fits all’ safety requirements. For commercial installations in the US, the most relevant standards which will govern ESS installation are UL 1973, UL 9540, UL 9540a and NFPA 855. UL 1973 has been the longest standing ESS fire safety standard. UL 9540 addresses requirements for the ESS product. UL 9540a presents a testing regime which elicits the behaviors of what happens when a given ESS fails. NFPA 855 governs site requirements for the installation of an ESS at a location, such as sizing, proximity, spacing. Given the evolving nature of the ESS standards landscape, in all cases the Authority Having Jurisdiction (AHJ) will be a driving force for what is required.

8.5. Distribution

Depending on the architecture, layout, and power density, there might be different means to safely and efficiently transfer power between the point of AC/DC conversion to the AI Rack.

This section introduces some of these elements:

- LVDC equipment such as Switchboard or Panelboard
- Conductors such as cables, busway
- Connectors which connect each element to each other

Each of these equipment must be certified/listed for DC use.

As in the previous chapter, this section includes high level information on the different available technologies, and highlights the challenge and benefits which each raises in a high power DC distribution system.

As a reminder, circuit protection which would fall under this section, is covered in Section 7.

- LVDC Equipment

LVDC equipment includes Switchboard and Panelboard (including RPP, Remote Power Panel). There are no specific requirements beside the fact that it must be designed according to the selected architecture, 2 or 3 wires, the rated voltage and current, and the protection device installed must open all ungrounded polarities (refer to chapter on polarity and earthing as well as protection device).

The principal applicable standards are:

UL 891 → for Switchboard

UL 67 → for Panelboard

IEC 61439-2 → for Switchboard and Panelboard

Nota:

As of when this whitepaper will be published, UL 891 and 67 does not allow rated voltage > 1000 Vdc.

- Conductors

Conductors can be divided into different groups and technology.

“Traditional” Cable or Busway are a natural choice in the industry to transfer power to the load, in this case, the AI Rack.

While a valuable option for the DC distribution part for low to medium power (tens to hundred Watts, or low megawatts), this solution may introduce challenges when it comes to very high power (few megawatts). Especially around the infrastructure which would need to support the space and weight of multi conductors or large busbar.

For very high power distribution, another solution possible is the use of superconductor technology. Superconductors are unique materials that exhibit zero electrical resistance when

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cooled below a defined operating temperature. The amount of current they can carry depends on both temperature and the surrounding magnetic field.

The figure here-under shows an example of a cable and busbar configuration.



Figure 32. Superconductors Cable Cross-Section

(source OCP: [Advanced Datacenter AC/DC Distribution and Conversion Power Architecture](#))

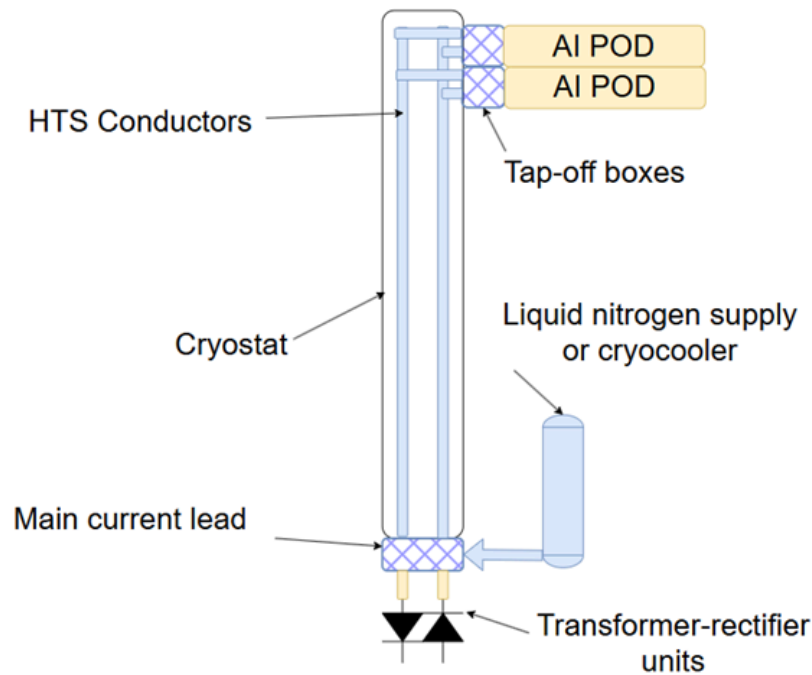


Figure 33. Cooling Heat Exchange Loop

Superconductor conductors enable significantly smaller, lighter, and more compact power delivery to the data hall whitespace compared with conventional cables and busway systems. These reductions translate directly to improved overhead congestion management, increased layout flexibility, and support for higher-density compute deployments.

The zero electrical resistance of the superconductors enhances the overall efficiency of the system and reduces heat generation inside the building, hence less stress on the HVAC system. However, it requires a specific dedicated cooling system to cool down the conductor at very low temperatures, which means that this solution would be only economically valuable for very high power and long run of conductors.

Superconductors have not yet been deployed in data centers, but the technology is under active development. The individual components required have already been designed and tested,

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although not specifically for data center applications. The ongoing trend toward higher rack power densities and DC power architecture strongly favors superconducting solutions. As these trends continue and MW+ racks are built, the deployment of the first superconducting data-center systems will become more and more economical.

Another promising solution, especially for the connection to the Rack itself would be the use of liquid cooled cable similar to the one used in the EV industry for MCS type of application (Megawatt Charging System). More of this type of cable is presented in the Connectors sections.

The principal applicable standards are:

- UL857 → Busway
- IEC 61439-6 → Busway
- There are standards which cover traditional cables.
- Standards cover superconducting cables:
- IEC 63075 - Superconducting AC power cables and their accessories for rated voltages from 6 kV to 500 kV: test methods and requirements.

- Connectors



Figure 34. Example of an IEC 60309 connector

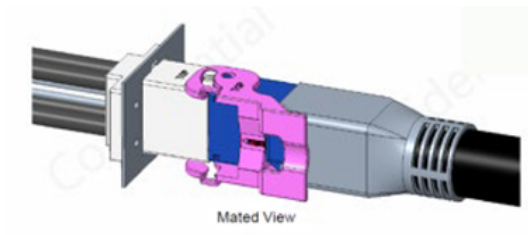


Figure 35. Example of a DC-Crosslink connector (Mt. Diablo)

Currently there is no applicable standard for separable connectors in the range up to 1500 VDC and currents in the 1 kADC range for data center applications. Products may be designed and released following e.g. IEC 60309 / UL 1682, IEC 61984, or UL 1977 (probably in conjunction) with UL 4128 – or other applicable standards – supplemented by application specific risk analyses in order to cover the extended operating range [REF TO CODES AND STANDARDS].

However, such connectors exist in other industries as mentioned above in the conductors section. UL 2278 covers cable and connectors for MCS for the EV industry with rating up to 1500 Vdc and 3000 A, which makes this solution a good candidate to be applied inside an AI Datacenter. EV Charging and AI Datacenter are 2 different applications, which means that to be able to use this type of technology, the industry must ensure the requirements written today for the EV charging application cover those of AI Datacenter.



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Figure 36. Example MCS Connector

Conditions for Normal Operation and under Failure conditions must be defined. One important Normal Operation Condition to be defined is ability or non-ability for disconnect under load. While disconnect under load is technically feasible via hybrid electronic switching or other means, the economy of such a feature should be challenged because of the resulting size and cost. For disconnect under no-load conditions pilot contacts should be incorporated to support interlock means on the load side (rack) or on the DC grid side (circuit breakers) linked with pilot or control pins or microswitches. This way circuit breakers can shut down strains to ensure safe disconnecting. Also the type of operator should be considered. If there are skilled operators, interlocking mechanisms preventing unwanted disconnection under load might be suitable. If there are unskilled operators, more sophisticated solutions to ensure safe disconnecting under load should be implemented.

For breaking capacity under load it should also be considered if full operational current and voltage need to be disconnected. Often devices can be shut down to idle modes before disconnecting. Therefore a connector rated for example 800V and 125A might only need a breaking capacity of 800V but only 2 to 5A, which is in a range that can be handled using different protection methods.

Important parameters for Operation under Failure Conditions are overload and short circuit conditions, which are imposed on the connector from the embedding system, i.e. the DC grid and the load (racks). The Joule Integral I^2t and I_{peak} which the connector must sustain under short circuit conditions must be determined on system level and covered by constructive means (conductor cross sections, magnetic force capability, etc.).

Consideration for handling capability (cable pulling weight and flexibility, overhead or blind mating, mechanical locking, etc.) should be considered.

Alternate termination means hard wiring with cable lugs, bolts, etc. Such methods, however, might require a certain training and certification level of the operator/installer while a connector typically can be operated with minimum training and allows for more speedy installation.

In data centers high capacitive loads are to be expected. Therefore connecting live parts result in high inrush currents. These peaks might harm contacts or can trigger protection devices like fuses or circuit breakers. When disconnecting and connecting under load is a general use case the effects of voltage peaks as a result of disconnecting and high inrush currents during connecting must be considered on system level.

8.6. AI Rack

Here is an example of a DC Power shelf which resides in the IT rack and powers compute load.

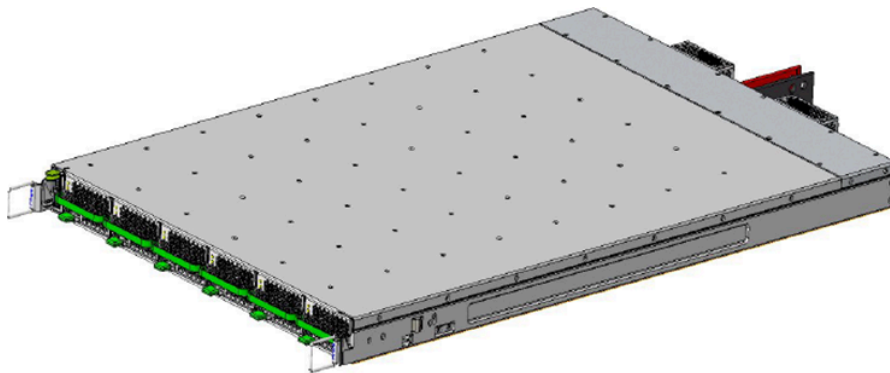


Figure 37. Example 100kW DC Power shelf

Here is an example of how power supplies are configured in the power shelf:

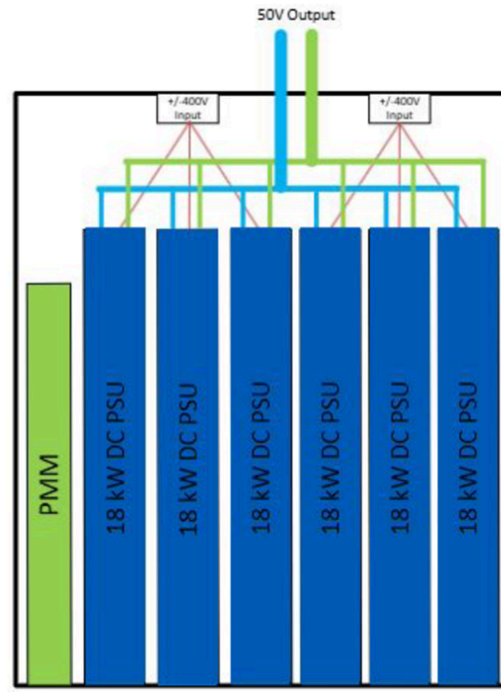


Figure 38. Power Shelf arrangement.

Table 14. Power Shelf parameters

	100kW Power Shelf
PSU Rating	18kW
Input Cable	2x HVDC 6 pin connectors: +400V, -400V, Return, Earth, Sense1 and Sense2
Shelf output connector	Bolted, BK2000
Shelf output connector temp monitoring	Yes, with thermistor
External busbar temp monitoring	Yes, with sensing circuit
Shelf (W x H x D)	537mm x 46mm x 867mm
PSU (W x H x D)	83.4mm x 40mm x 690mm
PMM (W x H x D)	15mm x 40.6mm x 350mm

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Key elements to manage power are:

- **PMM**

Power Management Module is an intelligent power management and distribution system. It monitors and controls power usage real time and embeds advanced communication protocols to enable interaction with other systems.

- **BBU — Battery Backup Unit**

Provides sustained backup energy to maintain the DC bus during upstream line interruptions, transfer events, or longer disturbances. Enable continuity through generator start and system transfer windows, and support graceful handling of power events at high rack power levels.

- **High-Level Requirements:**

- **Scale:** designed to be compatible with megawatt-class rack power delivery targets in Mount Diablo deployments.
 - **Ride-through:** seamless takeover on power line loss without destabilizing the DC bus; support ride-through durations appropriate for site transfer/generator start policies.
 - **Modularity & redundancy:** modular building blocks to support N, N+1 (and higher) redundancy configurations.
 - **Integration:** installable within the power sidecar rack; maintain “no compute-rack space” impact and support serviceability (e.g., hot-swap where applicable).
 - **Thermal:** air-cooled baseline with options for liquid-cooled integration in high-density power racks.

- **CBU — Capacitor Backup Unit**

Provide ultra-fast, high-peak-power support (milliseconds to short seconds) to stabilize the DC bus during rapid load transients and brief disturbances. Act as a “shock absorber” for sudden AI workload power steps, smoothing voltage/current excursions while rectifiers and/or BBUs respond.

- High-Level Requirements

- Response time: extremely fast response to load steps (sub-millisecond class behavior typical of capacitor systems).
- Peak power capability: deliver very high peak current/power for short durations to hold bus stability under AI load steps and switching events.
- Lifecycle: tolerate frequent charge/discharge cycles consistent with continuous transient mitigation.
- Coordination: operate in coordination with rectifiers and BBUs (CBU covers immediate transients; BBU covers sustained events).
- Integration & thermal: modular installation in the power sidecar rack with appropriate thermal management for high current handling.

Table 15. BBU vs CBU Quick Comparison

Attribute	CBU (Capacitor Backup Unit)	BBU (Battery Backup Unit)
Primary role	Instantaneous bus stabilization and transient ride-through	Sustained ride-through during longer disturbances
Typical time scale	Milliseconds to short seconds	Seconds to minutes (policy-dependent)
Power vs energy	Very high peak power, low energy	High energy, moderate peak power
Best for	AI load steps, switching events, short dips	Generator start window, longer outages

It should be noted that BBU and CBU no longer need to be mutually-exclusive pieces of HW, where there are newer solutions that combine this functionality in integrated solutions improving key metrics for space, density, performance, efficiency, sustainability, and TCO.

8.7. Miscellaneous

In this section are listed equipment which have not been listed as Main Component but play a significant role in the system.

1) Cooling

CDU (Cooling Distribution Unit) embeds equipment which could run on DC power. In some cases, feeding CDU in DC would result in better overall efficiency, for example when removing the rectifier stage of a Variation Frequency Drive.

2) Metering/Monitoring

As per traditional AC power system, metering and monitoring could be required at different areas (main DC output, feeder, branch). The requirements for such features will be discussed in a future version.

3) Operation/Maintenance

Equipment related to operation and maintenance (e.g continuous thermal monitoring) are not covered in this paper version. Readers can refer to NFPA70B for more information.

9. System Operation, Control and Monitoring

This chapter has not been developed in this white paper edition. Nevertheless, being recognized as an important topic, will need further work, to be included in future revisions of this paper. The main aspects to be developed are:

- Startup Sequence (Black Start, Precharging)
- Hot Connection/Disconnection (discharging)
- Energy Measurement

10. Electromagnetic Compatibility (EMC)

This chapter has not been developed in this white paper edition. Nevertheless, being recognized as an important topic, will need further work, to be included in future revisions of this paper. The main aspects to be developed are:

- Emissions and Immunity
- Ripple Voltage and Harmonics
- Cable Shielding and Filtering

11. Codes and Standards

As direct current (DC) system architectures and microgrids gain momentum, especially in AI data centers where efficiency and reliability are critical for high-density computing, the role of global codes and standards (e.g., UL, IEC, IEEE, etc.) becomes increasingly important.

These codes and standards, along with the testing and certification protocols and demonstration of compliance that they empower, help enable installers, integrators, and operators to design and deploy safe, efficient, and interoperable DC systems.

However, the rapid growth of DC technologies is outpacing the standardization landscape, creating notable challenges.

This section of the white paper outlines the current landscape as well as gaps in the installation codes and standards for DC products and systems, explains why they exist, and outlines where industry cooperation is urgently needed.

This first draft is an initial – and surely incomplete – accounting of the codes and standards that will support the transition to a higher voltage DC future. By identifying these challenges early, stakeholders can participate and accelerate safe innovation and help shape the next generation of DC codes and standards.

11.1. Why DC Codes & Standards Matter

- **Safety:** Clear regulations ensure that protection systems, fault management, and grounding schemes are consistently implemented.
- **Interoperability:** Harmonized standards allow components from different vendors to work seamlessly together.
- **Scalability & Future Expansion:** standardization simplifies system replication and modular growth, allowing capacity, voltage levels, or new loads to be added with minimal redesign, reduced risk, and lower costs over time.
- **Efficiency & Sustainability:** Proper DC design can reduce conversion losses.
- **Regulatory Compliance:** Standards enable local code and regulatory compliance, which helps streamline installation and commissioning.

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11.2. Key Challenges in DC Standardization

- 1) **Alternating Current (AC) has a 100-Year Head Start:** AC systems have benefited from decades of evolution, research, and global harmonization. In contrast, DC is still emerging at scale – particularly at power levels relevant to data centers.
- 2) **Demand for DC Is Growing Faster Than Standards Can Evolve:** Industries want DC solutions now to meet efficiency and sustainability goals. But many DC-related standards are incomplete, outdated, or not globally aligned.
- 3) **Slow Standard Development Cycles:** Creating or updating standards typically takes several years, involving expert committees, testing cycles, and multinational coordination. This timeline does not match the pace of DC innovation and requires urgent action from Standards Development Organizations (SDOs) to accelerate the pace of requirements.
- 4) **Alignment Between International Standard Development Organizations (SDOs):** Harmonization efforts between major bodies such as UL, IEC and IEEE are ongoing but slow. Misalignment leads to duplicated testing, engineering workarounds, and higher costs.
- 5) **Country-Specific Requirements:** Installation codes and regulations differ widely across regions, making global deployment complex. An installation compliant in Europe may require significant redesign to meet US or Chinese requirements.
- 6) **Cultural & Technical Inertia:** The industry is largely built around AC. Many professionals are reluctant to leave this comfort zone, creating skill gaps and hesitancy in adopting DC-based architectures. Training and education on DC systems will take time to implement and ensure workers are prepared.
- 7) **Utility Interface:** While the white paper primarily focuses on chip-to-grid power architecture, the point of common coupling (PCC) – where the data center meets the utility – presents significant integration hurdles. Data centers are not "static" loads; they are dynamic, high-density environments that strain traditional grid

management in three specific ways: load swings, inrush and surge management, and grid balancing and curtailment. Without harmonized standards for utility-specific study requirements and commissioning criteria, operators face longer approval queues and higher "soft costs" before a single server is even racked.

11.3. System-Level Standards

11.3.1. Existing system-level knowledge and applications

Multiple industries are already piloting, deploying, or operating DC microgrids at scale. These sectors provide valuable real-world experience that the data center ecosystem can leverage to accelerate adoption, reduce risk, and lower cost.

Industrial Applications: As outlined in previous sections of the white paper, factories, robotics, process automation, and traction increasingly use DC to improve efficiency, stabilize renewable integration, and simplify power conversion. These systems can offer insights into coordinated control, protection strategies, and energy flow management.

Renewables: Renewable energy sources like solar photovoltaics (PV) and fuel cells natively generate DC, and while wind turbines initially produce AC, their output is often rectified to DC for efficient control and storage. In modern applications, DC-coupled systems are emerging as the industry standard for co-located solar and battery storage.

Marine & Offshore: Ships and offshore platforms rely heavily on DC grids to optimize propulsion efficiency and manage distributed energy sources. Marine applications demonstrate mature approaches to system-level coordination and fault handling in compact, mission-critical environments.

EV Charging Infrastructure: In some regions, high-power EV fast chargers operate natively on DC, and large charging hubs use DC distribution for improved efficiency and simplified conversion. Their experience with high-current protection, conversion technologies, and the knowledge and learnings from AC/DC interfacing should be evaluated for transferability to data centers.

Although their end applications differ, the fundamental structure of DC grids across these industries is remarkably similar:

- Distributed converters feeding a common DC bus
- Coordinated control of power flow and voltage levels
- High-power protection requirements
- Interfaces to AC utility grids or backup systems

This similarity creates a major opportunity. Data centers can learn, copy, and align with proven architectures rather than reinventing DC system concepts from scratch.

11.3.2. Existing system-level standards

A diverse coalition of Standards Development Organizations (SDOs) and industry-led alliances is currently engaged to codify the future of DC power.

Legacy safety leaders – including UL Solutions, NFPA, ANSI, IEC, and IEEE – are working in tandem with specialized trade bodies like the Open Direct Current Alliance (ODCA) and Current/OS to bridge the gap between traditional electrical safety and the unique demands of high-density DC architectures.

More than 20 system-level standards were identified for 800V DC architecture through this white paper effort. Technical requirements are being reviewed for adaptation to data center applications, and several emerging technical reference documents are available to help planners, installers, and end users design and deploy DC systems.

Highlighted standards are below, and a full list of all identified system-level requirements applicable for 800V DC power distribution architecture can be found in the master reference file located at this [link](#).

- IEC 60364 Series (specifically 60364-8-82), IEEE 2030.10, IEEE 1547, UL 3001, UL 3001D, and Current/OS and ODCA system specifications – documents which define requirements of the DC system and related AC utility interconnection.
- IEEE P3710, UL 2755, and UL 2140 – defines requirements for testing and certification of Modular Data Centers and Prefabricated Power Assemblies.

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- UL 2941– provides a comprehensive framework for testing and certifying the cybersecurity of grid-interactive equipment (inverters, BESS, and EV chargers).
- NFPA 75 – the standard for the Fire Protection of IT Equipment, which outlines requirements for construction, equipment, and fire suppression in data center environments.
- ANSI/BICSI 002, ANSI/TIA-942C, IEC 22237, and Uptime Institute Tier Standard Topology – documents which define various classes for power redundancy and reliability applicable to electrical and associated cooling systems.
- IEEE has standards that apply to both AC and DC (IEEE C37.20), or some specifically for DC (IEEE 947); however, the industry expectation is that DC components must demonstrate performance parity with their AC counterparts in critical safety and resilience metrics, such as impulse withstand and short-circuit ratings. IEEE P3710.1 also has a document in development that will be a DC power system recommended practice for data centers from 300Vdc to 1500Vdc.

11.3.3. System-level gaps and standards in development

While the individual components for DC power distribution are maturing rapidly, the industry is navigating a governance gap regarding how these products function as a unified, resilient ecosystem. Rapid mobilization is required to address critical system-level blind spots that, if left unmanaged, could delay the scaling of AI-ready power distribution infrastructure. This effort focuses on moving beyond component safety to establish a holistic framework for architecture, control logic, and personnel protection. By codifying these emerging practices, the industry aims to replace custom, one-off engineering with repeatable, certified system designs.

- **System Design Principles:** There is no unified guidance on how to architect a complete DC system and ongoing strategies are in development optimal distribution topologies, fault management strategies, grounding concepts, and coordinated protection schemes.
- **System Control & Coordination:** Unlike AC systems, where frequency and voltage behavior are well defined, DC systems rely on control algorithms and coordinated

converter behavior. Standards describing how devices should interact, share loads, and react during faults are still emerging. However, existing large-scale, commercial installations show the functionality and benefits of Low Voltage DC (LVDC) installations.

- **Maintenance & Operational Procedures:** Operators lack standardized frameworks for inspection intervals, diagnostic procedures, and safe handling of energized DC equipment, especially considering unique DC hazards like sustained arcs.
- **AC/DC Interface Management:** The transition between AC and DC is critical but not yet fully regulated. Specifications for interoperability, protection coordination, and energy flow control at this interface vary widely across regions and applications.
- **DC Arc Flash & Worker Protections:** Implementing DC power systems with increased voltage levels introduces critical gaps in NFPA 70E safety protocols, primarily because current standards and empirical models (like IEEE 1584) were developed for application to AC systems and more work is needed to ensure DC system risks are covered. While decades of rigorous research have enabled widely adopted AC arc-flash equations, no equivalent, comprehensive, and validated methodology exists for DC systems.

11.3.4. Product-Level Standards: Existing & In-Development

Product-level standards are crucial in providing the foundational safety, interoperability and performance requirements needed for effective design and deployment of components, products and sub-systems across DC system architectures. These need to cover nearly every component of the full system architecture across a range of product categories from chip-to-grid:

- Source
- Distribution Equipment
- Power Supplies/Converters
- Switching/Control Devices
- Overcurrent/Protection Devices
- Grounding/Bonding Equipment

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- Connectors
- Cables/Cords
- Power Utilization
- Reference Standards

More than 70 product-level standards were identified for 800V DC architecture through this white paper effort. While a majority of these already address 800V DC requirements, a subset of gaps require standards to be updated, and in some cases, new standards need to be created.

A full list of all identified product-level standards applicable for 800V DC power distribution architecture can be found in the master reference file located at this [link](#).

11.3.4.1. Existing product-level standards

The majority of UL, IEC, and IEEE Standards across product categories for data center power have requirements that cover 800VDC, but the majority of products for these categories have not yet had products vetted or tested for 800V/1500V DC for data centers.

Some of these organizations are conducting gap analyses to determine required updates or revisions to address this issue. For example, all UL Standards with gaps not covering 800-1500VDC for data center use are in the process of being updated or created. To support the industry's need for speed and safety requirement adoptions, the UL Enterprise is working to expedite UL Standards updates with the following tools:

- **Certification Requirement Decisions (CRD)** - An official UL Solutions determination that establishes new or revised safety requirements for products, often facilitating the adoption of new technology before formal standards are updated. These decisions provide immediate compliance paths, often addressing specific technical, performance, or safety issues.
- **Outlines of Investigation (OOI)** - A non-consensus document, developed and owned by UL Solutions, containing specific requirements to certify products, components, or systems for which no published, formal standards currently exist. These documents are

used to evaluate, test, and apply safety certification marks to emerging technologies or specialized products.

- **Category Control Numbers (CCN)** - A four-letter code assigned by UL Solutions to classify products and components based on their specific safety standards and intended use. These codes can be used to find guide information in the UL Product iQ database and allow for quick verification of safety compliance by regulators and manufacturers.
- **Guide Information** - UL Guide Information provides essential details on product safety standards, usage limitations, and installation requirements for UL-certified products, primarily accessed through the UL Product iQ database. It defines the scope of certification, applicable standards, and the specific Mark required for compliance. These guides cover categories like electrical safety, fire resistance, and building materials.

11.3.4.2. Product-level standards in development

Many Standards Development Organizations (SDOs), including NFPA, IEEE, IEC, and UL Solutions are in a state of high mobilization to update their frameworks. The rapid shift toward DC systems has turned what were once slow review cycles into urgent, collaborative sprints.

As of early 2026, several key standards have either been updated or are in the final stages of revision to address high power DC systems. Again, an example of this exists where UL Solutions has engaged industry via meetings and working groups to address code updates, standards gap analyses, and exploration of emerging needs.

A brief selection of important standards in development are included here, and a more exhaustive list can be found in the master reference file located at this [link](#).

- IEEE SA P3105 – Recommended Practice for Design and Integration of Solid State Transformers in Electric Grid
- UL 2877 – OOI for Power Supplies, Medium Voltage that covers safety requirements for equipment with input/output ratings above 1000 V up to 38 kV
- UL/IEC/CSA 62368-1 – Technical Committee (TC) 108 is exploring how to refine safeguards for high-power DC delivery. An adhoc group created within the

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TC108/HBSDT working group is drafting a requirements proposal to expand IEC 62368 scope to 1000VAC/1500VDC; preliminary report expected Q2 2026.

11.3.5. Installation Codes: Existing & Gaps

DC power distribution in data centers is governed by a combination of regional- and/or country-level electrical safety codes, fire protection standards, and industry best practices. Applicable commissioning standards should be consulted and need to be met for each region/installation location.

For electrical installations and safety-related aspects, there are two main Standards Development Organizations: International Electrotechnical Commission (IEC) and Underwriters Laboratories (UL). Whereas UL standards target primarily the United States and Canada (North American markets), IEC standards target global markets, especially Europe and Asia. In addition to the difference in the geographical scope, IEC standards focus on minimum safety and performance requirements for electrical products, while UL Standards offer stricter, more detailed descriptions and rigorously focus on in-depth product testing, factory inspections, and follow-up audits.

This white paper provides a summary of global IEC-based installation requirements below, while the US is covered in more specific detail. Deeper work is required to provide a comprehensive global analysis on the current and emerging code and regulatory landscape. This will be covered in a future revision of this document.

11.3.6. Global Installation Requirements

As noted in the Voltage section above, in the context of power distribution, low voltage is defined by international product standards and regulations along with installation codes as operation at or below 1000 VAC or 1500 VDC.

Most countries outside the United States (US) use IEC 60364 as the base for installation rules with local translation and modifications.

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IEC Technical Committee 64 (IEC TC 64) is responsible for the IEC 60364 series, the international "gold standard" for low-voltage electrical installations. These rules provide a comprehensive framework for the design, erection, and verification of electrical systems to ensure the safety of persons, livestock, and property.

This applies to installations with nominal voltages up to 1000VAC or 1500VDC. The installation rules are organized into several key parts:

- **Part 1: Fundamental Principles** – Defines the scope, basic safety requirements, and general characteristics of an installation.
- **Part 4: Protection for Safety** – This is the "safety engine" of the rules, covering:
 - **Electric Shock:** Requirements for automatic disconnection of supply, insulation, and the use of Residual Current Devices (RCDs).
 - **Thermal Effects:** Rules to prevent fires caused by electrical equipment.
 - **Overcurrent:** Protection against short circuits and overloads.
 - **Voltage Disturbances:** Protection against surges and electromagnetic interference.
- **Part 5: Selection and Erection of Equipment** – Guidance on choosing and installing wiring systems, switchgear, and earthing arrangements.
- **Part 6: Verification** – Specifies mandatory initial inspections and periodic testing to confirm the installation remains safe over time.
- **Part 7: Special Installations** – Tailored rules for high-risk locations like bathrooms, swimming pools, medical facilities, and solar photovoltaic (PV) systems.
- **Part 8: Functional Aspects** – Modern additions focusing on energy efficiency and "prosumer" installations (where buildings both consume and produce energy).

11.3.7. United States Installation Requirements

In the US, DC systems must operate within a hierarchy of federal safety standards, construction codes promulgated by various levels of government including state and municipal agencies

responsible for building safety and industry-specific fire protection requirements that are developed and managed by **NFPA 70® (National Electrical Code®)**:

- Applies to AC and DC premises wiring systems connected to the load side of the utility service point. Current requirements are not voltage or system limited. Most current DC requirements are general in nature and data center specific infrastructure requirements do not currently exist. The next revision will be completed in the third quarter of 2028. There are task groups focused on Bi-Directional Power, Data Centers, and DC Systems, which are reviewing and identifying gaps for DC systems in general and AC & DC infrastructure specific to data centers.
- The National Electrical Code® developed by NFPA® is revised on a three-year schedule and is incorporated into statute or administrative rule by state and/or local governmental agencies in all 50 US states and several international jurisdictions. None of these agencies automatically update the NEC® when it is revised and the current landscape of editions in effect ranges from the 2008 to the 2023 editions. Like the code development process, there is a process by which these agencies to promulgate new construction and electrical safety codes and these processes often involve multiple steps of review and public comment which naturally delays implementation of the most recent electrical safety requirements. [Learn where the NEC is enforced](#).
- National Fire Protection Association (NFPA) standards, US Occupational Health & Safety Administration (OSHA), and the US Department of Energy (DOE). Current requirements focus primarily on AC systems, so specific sections of code and related standards are actively under evaluation to address the unique hazards of DC systems.
- **Existing Codes**
 - **NFPA 70® (National Electrical Code®-2026)**: Applies to AC and DC premises wiring systems connected to the load side of the utility service point. Current requirements are not voltage or system limited unless otherwise specified. Most current DC requirements are general in nature and data center specific

infrastructure requirements do not currently exist. The next revision will be completed in the third quarter of 2028 and there are task groups reviewing and identifying gaps for DC systems in general and DC infrastructure specific to data centers. www.nfpa.org/70

- **NFPA 70B (Standard for Electrical Equipment Maintenance-2026):** Requirements that detail the preventive maintenance of electrical, electronic, and communication systems. Covers AC and DC equipment, but more focus on AC infrastructure. Has synergy with NFPA 70 and NFPA 70E personnel safety requirements that contemplate electrical equipment being properly maintained. Voluntary compliance is primary use, not mandated like the NEC®. Next revision cycle is for 2029 edition. www.nfpa.org/70B
- **NFPA 70E® (Standard for Electrical Safety in the Workplace-2024):** Focuses on personnel safety, specifically shock and arc flash hazard protection. Applies to AC and DC systems rated over 50 volts. Is promulgated by US DOE and is used by the US Department of Labor, OSHA in general duty clause citations. More focus on AC systems. Currently near completion for the 2027 revision cycle. The next revision cycle for 2030 edition. www.nfpa.org/70E
- **NFPA 75 (Standard for the Fire Protection of Information Technology Equipment-2024):** Standard contains requirements for the protection of information technology equipment and information technology equipment areas from damage by fire or its associated effects-smoke, corrosion, heat, and water. Next revision cycle is for 2028 edition. www.nfpa.org/75
- **NFPA 855 (Standard for the Installation of Stationary Energy Storage Systems-2026):** Standard provides the minimum requirements for mitigating hazards associated with energy storage systems. Standard applies to utility and customer owned ESSs. Next revision cycle is for the 2029 edition. www.nfpa.org/855
- **NFPA 37 (Standard for the Installation and Use of Stationary Combustion**

Engines and Gas Turbines-2024): Standard establishes criteria for minimizing the fire hazards related to the installation and operation of stationary combustion engines and stationary gas turbines that are fueled by liquid or gaseous fuels and are used as the prime movers for emergency generators, fire pumps, and stand-by and peak power systems. Next revision cycle is for the 2027 edition.

www.nfpa.org/37

- **NFPA 1(Fire Code-2024):** Code advances fire and life safety for the public and first responders as well as property protection by providing a comprehensive, integrated approach to fire code regulation and hazard management. It addresses all facets of fire protection with extracts and references to over 130 NFPA codes and standards. Has many system and occupancy based chapters. There is a chapter on telecommunications facilities and information technology equipment but no chapter specific to data centers. Is promulgated in a number of US states and municipalities. Next revision cycle is for 2027 edition. www.nfpa.org/1
- **International Fire Code (IFC)** – This is a comprehensive model code published by the International Code Council (ICC) to establish minimum regulations for fire prevention, life safety, and property protection in new and existing buildings. It regulates hazardous materials, fire protection systems, and emergency responder access to minimize risks from fire, explosions, or hazardous material discharges. There is no specific chapter for data centers. The IFC is promulgated in a number of US states and municipalities. The current revision cycle is for the 2027 edition. <https://codes.iccsafe.org/content/IFC2024V2.0>

11.3.8. Emerging trends and recommendations

When all these elements come together, how will local authorities handle commissioning and approvals; DC vs. AC requires training and education.

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- **US & Canada** – State & Federal Jurisdiction: Large-scale data center power interconnections (often exceeding 20MW) are increasingly coming under the scrutiny of the Federal Energy Regulatory Commission (FERC) and state-level bodies (e.g., Texas SB-6) regarding grid reliability and cost allocation. **Energy Performance Standards:** Newer regulations, such as **California's A.B. 222**, may soon require data center operators to report energy consumption and adhere to efficiency performance standards.

11.4. Interim Guidance

DC technology is advancing faster than system- and product-level standards can adapt. While many product standards are available, and some system standards are emerging, guidelines for designing, controlling, maintaining, and integrating DC systems remain under development.

Where gaps in standards or regulation exist, OEMs can still prepare and mitigate risk by taking thoughtful steps to help assure the safety and performance of new technologies and end-use applications.

- **Evaluate Existing Standards** – Review standards, OOLs, or CRDs where a close alignment to the technology and risks can be demonstrated. For example, standards written for high-power DC systems in photovoltaic (PV) and electric vehicle (EV) applications can be evaluated for learnings, risks, and testing considerations.
- **Hazard-Based Risk Assessment** – Engage a certifying body and use a hazard based risk assessment approach to conduct pre-certification validation, interim testing, or field evaluation.
- **Modeling and Simulation** – Hardware-in-the-Loop (HIL): PHIL/CHIL, and EMT
- **Laboratory Testing** – high power laboratory testing for isolation, protection strategies, power quality performance
- **Pilot Projects** – potential benefits include faster pilot deployment/time to data, lower costs, faster validation of reliability, controls, and communications before advancing to higher voltage classes.
 - Bidirectional power flow control, performance under grid faults.
 - DC bus stabilization.

- Utility communications (and sometimes curtailability).
- Storage at different locations:
 - GPU serverboard
 - Rack DC bus (100's ms-sec) GPU load peaks/valleys, training power smoothing
 - Row/PDU/UPS - fault ride through
 - Online ESS/UPS - seconds-minutes
 - ESS/UPS - minutes/tens of minutes
 - Energy resilience/grid services - minutes to hours
 - DC-coupled storage/generation
 - AC-coupled storage/generation

12. The path forward - Key Takeaways for Stakeholders

The transition to high-density DC architectures in AI data centers is no longer a theoretical pursuit – it is a technical necessity. As this white paper has outlined, the efficiency, scalability, and reliability gains offered by DC systems are clear. However, the path to global adoption is currently constricted by a standardization landscape that was built for an AC world.

While AC systems benefited from a century of refinement, the DC ecosystem is being forced to mature in a fraction of that time. We are operating in a "standardization gap" where innovation is outstripping formal regulation. This has created a unique set of challenges, from the lack of unified guidance on system-level topologies to the urgent need for a validated DC arc flash methodology.

- **The Foundation Exists:** Despite gaps, existing product-level standards and proven architectures from the marine, industrial, and EV sectors can serve as a launching pad for DC design and deployment.
- **Collaboration is Non-Negotiable:** The "Known Unknowns" of DC technology, such as complex utility interfaces and high-power protection, cannot be solved in isolation. Success requires active participation and alignment between SDOs like UL, IEC, IEEE and NFPA.
- **Proactive Risk Mitigation:** Until formal installation codes like the 2029 NEC® are finalized, organizations must lean on interim guidance, utilizing Outlines of Investigation (OOI), conducting hazard-based risk assessments, and leveraging Hardware-in-the-Loop (HIL) simulations.
- **Voltage and Power Quality Alignment:** Key focus for further work to align the industry and further the discussion specifically on scaling. Sub workstream focus is needed for the next version of the paper.
- **DC Arcflash Rules:** Need work to be focused on and aligned as an industry as this analysis as it is the current bottleneck for the supply chain development and installation for the direct current infrastructure.

- **Power Distribution - Rack and Power Alignment:** A sub-workstream for the next version of the paper to fully understand the handoff to support collaboration and acceleration of the industry.

By closing the gap between the pace of innovation and the pace of regulation, we can ensure that the next generation data center power infrastructure is not only faster and more efficient but fundamentally safer. The frameworks under development today will serve as the bedrock for a decentralized, DC-powered future.

13. Conclusion

The shift towards AI-driven workloads is fundamentally reshaping the data center power landscape, demanding greater efficiency and scalability than traditional AC architectures can easily accommodate. This white paper, a collaborative effort within The Open Compute Project, establishes a foundational technical framework for understanding and evaluating Direct Current (DC) power distribution systems in data center facilities. We have systematically examined the architectural concepts, key design trade-offs – including voltage selection, polarity, system earthing, and protection schemes – and the critical interplay with main system components. The document purposely presents representative DC approaches observed across the industry, rather than mandating a singular solution, to foster an environment of open discussion and consistent interpretation among all stakeholders, including operators, designers, manufacturers, utilities, and AHJs. By aligning with the OCP tenets of openness, efficiency, impact, scale, and sustainability, this work aims to facilitate informed decision-making as DC architectures continue to evolve. While this paper provides a robust initial framework, it concurrently identifies specific areas for further collaborative development to ensure the path forward results in safe, efficient, and widely-adopted next-generation power solutions. The ongoing convergence of energy and IT infrastructure will continue to drive a multi-modal power environment where both AC and DC models must coexist and evolve.

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14. References

○ Papers

- [Ca] P. Cairoli, R. Rodrigues and H. Zheng, "Fault current limiting power converters for protection of DC microgrids," SoutheastCon 2017, Concord, NC, USA, 2017, pp. 1-7, doi: 10.1109/SECON.2017.7925392.
- [Mar] A. Marroquin, C. Carne, W. Brown and T. Landry, "Transient DC Arc-Flash Incident Energy Calculations for DC Distribution Systems," 2025 IEEE IAS Electrical Safety Workshop (ESW), Jacksonville, FL, USA, 2025, pp. 1-12, doi: 10.1109/ESW58401.2025.11159088.
- [Rav] S. Ravyts, G. V. d. Broeck, L. Hallemans, M. D. Vecchia and J. Driesen, "Fuse-Based Short-Circuit Protection of Converter Controlled Low-Voltage DC Grids," in IEEE Transactions on Power Electronics, vol. 35, no. 11, pp. 11694-11706, Nov. 2020, doi: 10.1109/TPEL.2020.2988087.
- [Sh] J. J. Shea, T. Landry and M. Liptak, "Short-Circuit Faults in DC Microgrids," 2024 IEEE Sixth International Conference on DC Microgrids (ICDCM), Columbia, SC, USA, 2024, pp. 1-6, doi: 10.1109/ICDCM60322.2024.10665093.

○ Web resources

- Choukse, Esha, et al. "Power stabilization for AI training datacenters." arXiv preprint arXiv:2508.14318 (2025).
- [1] S. Bartlett, et al. (Oct 2, 2024). Data Center Facility Sustainability Metrics. OCP White Paper. [Online]. Available:
<https://www.opencompute.org/documents/dcf-sustainability-metrics-final-r3-docx-pdf>.
- [2] A. Desimone, et al. (July 2025). Embodied Carbon Disclosure Base Specification v1. OCP Base Specification. [Online]. Available:
<https://www.opencompute.org/documents/carbon-disclosure-ocp-base-specification-20250730-pdf>.

- [3] M. Dansie, et al. (Dec 2024). Requirements for Energy Storage Systems used in Data Centers v1. OCP White Paper. [Online]. Available:
<https://docs.google.com/document/d/1lQfdPtMe-XVQzydZVKTO6mnoubHUkn1UjBAa70Cbx-Q/edit?tab=t.0>.
- G. Yang and M. Tu (Dec 2025). Protections for Data Centers Powered by Direct Current. [Online]. Available:
https://assets.new.siemens.com/siemens/assets/api/uuid:cacbc29b-5d0d-4b12-9053-696eb0b43e74/Protections-for-Data-Centers-Powered-by-Direct-Current-Technical-Paper_original.pdf.

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