Protections for Data Centers Powered by Direct Current

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1. Background

Future data centers for artificial intelligence (AI) are predicted to have unprecedented power densities. Nvidia has revealed the plan for a single rack with 1MW+ power consumption and a reference concept that utilizes direct current (DC) power distribution to deliver power to such racks, as shown in figure 1[1].

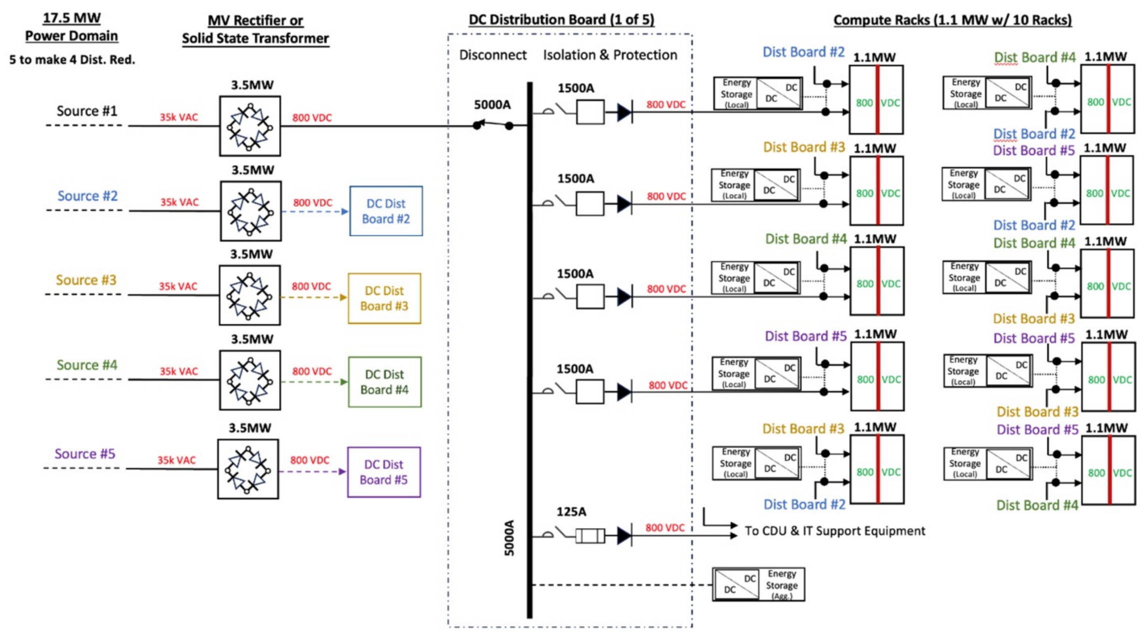

Figure 1. Reference DC power distribution concept from Nvidia [1]

Compared to traditional three-phase alternating current (AC) power distribution, DC distribution has the following advantages:

- Simplified construction. DC distribution has the potential to reduce conductor count and size, because of simpler conducting paths, less skin effects and less proximity effects.
- Improved conversion efficiency. When converting from AC power to DC power used in loads, an AC-to-DC conversion is often used, followed by a DC-to-DC conversion to the desired voltages. In a DC distribution, the AC-to-DC conversion is not needed.
- Greatly reduced reactive power. In AC distributions, the naturally varying current causes reactive power in transformers, loads and wirings because of their inductance. DC distribution, in contrast, delivers constant current instead of sinusoidal waveform with oscillation. Therefore, the system operates with an effective power factor near unity and improves overall power delivery efficiency

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- Flexibility and simple integration of backup power and other energy sources, such as battery storage systems and solar panels. With direct DC bus connection, devices, like automatic transfer switches, are no longer needed.

On the other hand, implementing DC power distribution also has its own unique challenges in various areas, such as power conversion and delivery, electromagnetic compatibilities, metering and so on. This paper focuses on protection and safety aspects of such a system. DC distribution is capacitive in nature, in which capacitors throughout the network are connected to DC voltage and store necessary operating energies. In case of faults, these capacitors will quickly release stored energy. Consequently, fault current is greatly increased, and DC voltage is disrupted, resulting in safety risks and system down time. Therefore, capacitors must be included in fault analysis, which makes quantitative analysis more complicated. Lastly, DC power doesn't have the natural current zero-crossing as in an AC system. Therefore, a forced zero-crossing must be created by switching and interrupting devices.

DC power distribution is not a new concept. Several industries, such as marine vessels[2], electrical vehicles charging[3], railroad[4] and industrial drives[5] have successfully implemented DC power, which provide valuable references to data center applications. From a protection point of view, active converters in the electric vehicle charging industry have long been considered as part of protection schemes with their capabilities to easily detect and turn off fault current. In marine applications, robust microgrid architectures with protection means at different interrupting speeds allow coordination, redundancy and backup energy integration[6]. Several industry-wide organizations, such as Current/OS[7] and ODCA[8], have been formed in recent years to standardize the best practices of DC power distributions.

At the same time, it is important to note the unique challenges in data center applications. The loads in data centers are largely electronics loads. Compared to other types of loads, electronics loads are more sensitive to voltage fluctuations. Furthermore, in order to maximize the space for computing, little energy storage is used inside racks, which results in very short ride-through. This is different from other industries. For example, the mechanical energies in marine, drive and railroad applications allow more time for systems to react during voltage fluctuations without losing performance. The energy stored in batteries in electrical vehicle charging also allows longer ride-though time. To solve the problem, external energy storage, such as capacitors and/or batteries, is needed. The sizing of such external energy is then directly proportional to the duration of expected voltage fluctuations. This creates a unique situation in data center applications, where speed of operation can be directly related to smaller and potentially more cost-effective systems.

In this paper, basics of protecting DC distribution for data centers are discussed, including wiring and grounding, protection devices, coordination, arc flash mitigation and ground fault protection. More details on each of these topics can be discussed in future papers.

2. 2-Wire DC Distribution

DC distributions can be 2-wire or 3-wire. In a 2-wire DC system, the loads are powered between the positive and the return. A mid-point may be used but does not carry current, in contrast to a 3-wire system where mid-point carries current. 2-wire systems are often considered easier to implement for the following reasons.

- Less current carrying conductors.
- Less protection considerations. Other than the increased number of protection devices, 3-wire distributions have some unique challenges that require more design efforts, such as reverse capacitor voltage in certain fault conditions.
- No concerns about balancing. In 3-wire distributions, mid-point normally carries current because of balancing. Sizing of the mid-point conductor needs careful consideration of all possible fault current levels.

These make 2-wire systems good starting point for data center applications. In the following discussions, a floating 2-wire system is assumed. 2-wire high resistance ground systems in general have similar behaviors. Similar analysis for 3-wire systems will be discussed in future studies.

Depending on the grounding method and DC source design, the potential difference between positive, return and ground can be different. Table 1 summarizes a few scenarios with different groundings for an 800VDC system. It should be noticed that regardless of the potential difference to ground, the highest fault voltage of a 2-wire system is the potential difference between positive and return. The protection device voltage rating can vary depending on the grounding scheme. In table 1, 400/800VDC devices have protection components in both positive and return conductors, and those components must work together to interrupt 800VDC faults.

Other than the scenario with a solid-grounded return, both positive and return need to be disconnected before servicing in case of a fault or normal maintenance. NEC 240.15[9] requires circuit breakers to open all ungrounded conductors. In case of fuses, although NEC doesn't require common trip fuses, a disconnect means is needed to open all ungrounded conductors. In the case of a solid-grounded return, only positive needs to be disconnected, which is an advantage from a number of protection devices' point of view. However, unlike floating systems and high resistance grounding systems, solid grounding systems need to manage the first ground fault, which requires fast reacting devices (see section 6 for further discussion). Floating systems and high resistance grounding have been more widely used in applications where more time is needed to react when a ground fault occurs or where the system needs to continue operation after the first ground fault. Another aspect is that solid grounding the return, while keeping safety isolation, loses functional isolation of isolated converters. This may require additional considerations for converter designs.

	Highest Fault Voltage	Protection Device Rating	Disconnect Needed on Both + and - ?	Groundd Fault Mitigation
+/-400V –High Resistance Ground	800VDC	800VDC or 400/800VDC	YES	1st ground fault: Inherently 2nd ground fault: Fast protection devices
+/-400V – Solid Ground	800VDC	800VDC or 400/800VDC	YES	Fast protection devices
800V – Floating/ High Resistance	800VDC	800VDC or 400/800VDC	YES	1st ground fault: Inherently 2nd ground fault: Fast protection devices
800V – Solid Ground	800VDC	800VDC	NO	Fast protection devices

Table 1. Grounding schemes for 800VDC 2-wire system.

3. Devices for Isolation, Overcurrent and Short-Circuit Protection

Overcurrent and short-circuit protections as well as a means to disconnect/isolate are needed at each branch and at main distribution bus.

3.1 Disconnect

For disconnect purposes, a physical airgap is needed. Therefore, contact-based mechanical switches are suitable choices, such as Siemens 3WA product family. In a system where return is not grounded, the disconnect shall be connected in such a way that both conductors are disconnected. The switching performance of disconnect switches is influenced by the level of current being switched, similar to mechanical breakers as described in section 3.2 below. As a result, when planning coordination, worst case arcing time should be considered.

3.2 Mechanical circuit breakers, relays and contactors

Mechanical interrupting devices, such as circuit breakers, relays and contactors, use contact systems to interrupt current. To extinguish arcs, arc quenching chambers with cooling and magnetic arrangements are often used. The effectiveness of arc quenching chambers in DC interruptions has a strong relationship to the current level, as shown in figure 2. With similar time constants, the arcing time increases as the current level reduces. This is due to the lower electromagnetic field that comes with lower current to interact with the arc chambers. Therefore, when planning protection coordination, both high and low fault currents need to be considered. Mechanical breakers' characteristics often follow trip current curves (TCC), which define the delay time at each current level before contacts open. Such TCCs are crucial for coordination purposes. It is also important to realize that in a short-circuit fault, fault current doesn't start to decrease at the moment of fault detection, and current continues to rise until the operating mechanism opens contacts and arc quenching chamber becomes effective. As a result, with mechanical interrupting devices, protection devices at different stages can see fault current and their reaction times must be coordinated.

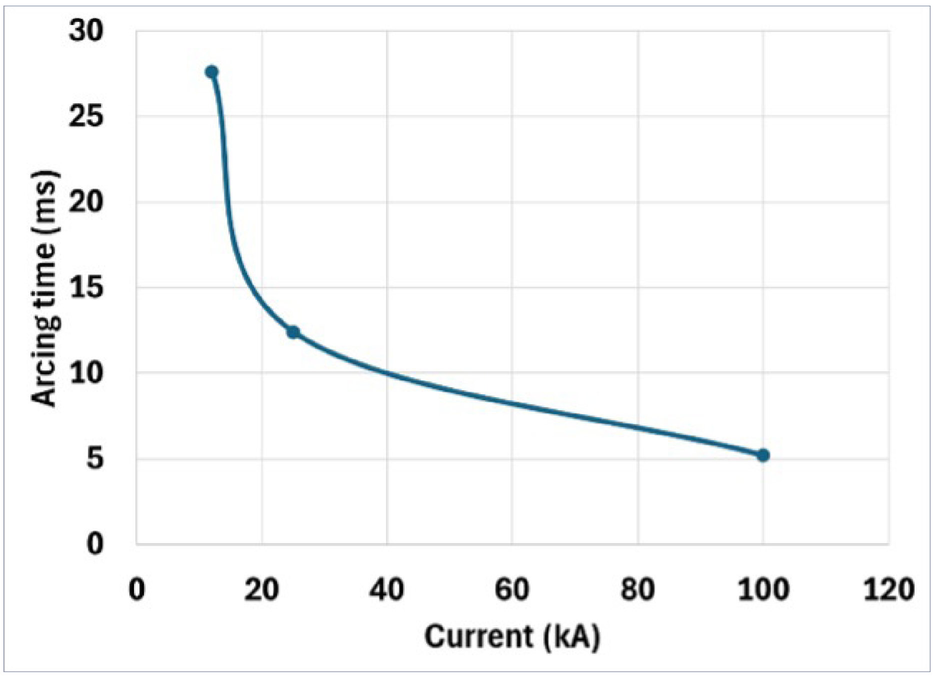


Figure 2. Arcing time of a 2000A mechanical circuit breaker

3.3 Fuses

Fuses are single use protection devices, which melt conducting paths if overcurrent happens. They are cost effective, and some fuses can have fast clearing times, which makes them attractive for data center applications. In short-circuit conditions, fault current continues to rise during the pre-melting phase, which presents coordination challenges similar to mechanical breakers, since protection devices at different stages can see fault current. Fuses also have TCCs to define the time needed before melting at different current levels. However, for fuses, such TCCs are completely passive without adjustment, which makes coordination more complicated. Another aspect of fuses is that they cannot ensure common trip, especially at low fault current levels. Tolerances on TCCs often make one fuse trip before another even if they see the same current. Disconnects that open all ungrounded conductors are needed when fuses are used. Also, like circuit breakers, the lower the fault current, the longer the arcing time. Therefore, both high and low fault currents need to be considered when planning coordination.

3.4 Solid-state circuit breakers (SSCBs)

SSCBs use power electronic components to conduct current and to interrupt in case of a fault, which makes interruption ultra-fast (<0.5ms). The interruption performance is not affected by fault current levels and trip current curves can be adjusted to fit the system they protect. Furthermore, fault current decreases almost immediately after power electronics are turned off and can be controlled closely, which greatly simplifies coordination efforts needed. Much research has been conducted in recent years, and the technology has become commercially available, such as the first UL-listed 120Vac SSCB introduced by Siemens [10]. Safety standards have also been developed as the technology becomes more mature. UL 489i [11]was recently published as the governing standard for SSCBs in North America, and IEC 60947-10 is published early 2026 in Europe.

SSCBs are particularly fit for capacitive distribution systems, as they can stop capacitor discharge quickly in case of fault. Such behavior is demonstrated in the simulation below. A 1MW floating 800VDC distribution network is simulated with one source converter and four identical parallel loads, as shown in figure 3. Each load is assumed to have a DC/DC converter to further adjust DC bus voltage to the applicable voltage inside the load. DC link capacitors, which are circled in figure 3, are sized only for operational purposes, not for storage purposes. A short-circuit fault is then created at the input side of the DC/DC converter in one of the loads. Two types of protection devices are compared, fuses and SSCBs. The fuse arcing time is not considered in this study. Therefore, as soon as the melting I2t is reached, the circuit is considered interrupted. In reality, the clearing time of fuses is longer with arcing time, and the effects discussed here are further scaled up. For SSCBs, a fixed tripping threshold of 2 times nominal current is used and 3us delay is added after the threshold is reached to simulate breaker hardware reaction time. As can be seen in figure 4(a), in case of fuse protection, the fuse reached melting I2t in ~1ms. The fault current rose significantly during this time. It is also noticeable that due to the common DC bus, the DC link capacitors of the three healthy loads all discharged into the fault, which contributed to the high fault current. As a consequence of DC link capacitor discharge, the voltage of the three healthy loads sees large fluctuations during the fault and needs additional time to recover after the fault is cleared.
The total recovery time was ~20ms. In case of SSCB protection, as shown in figure 4(b), due to the fast interruption, capacitor discharges were quickly stopped. Peak current was <800A, which doesn't trigger upstream protection to react, and the healthy loads see a voltage variation about 1V. This case study demonstrates the inherent advantages of SSCBs in maintaining DC network stability during fault conditions.

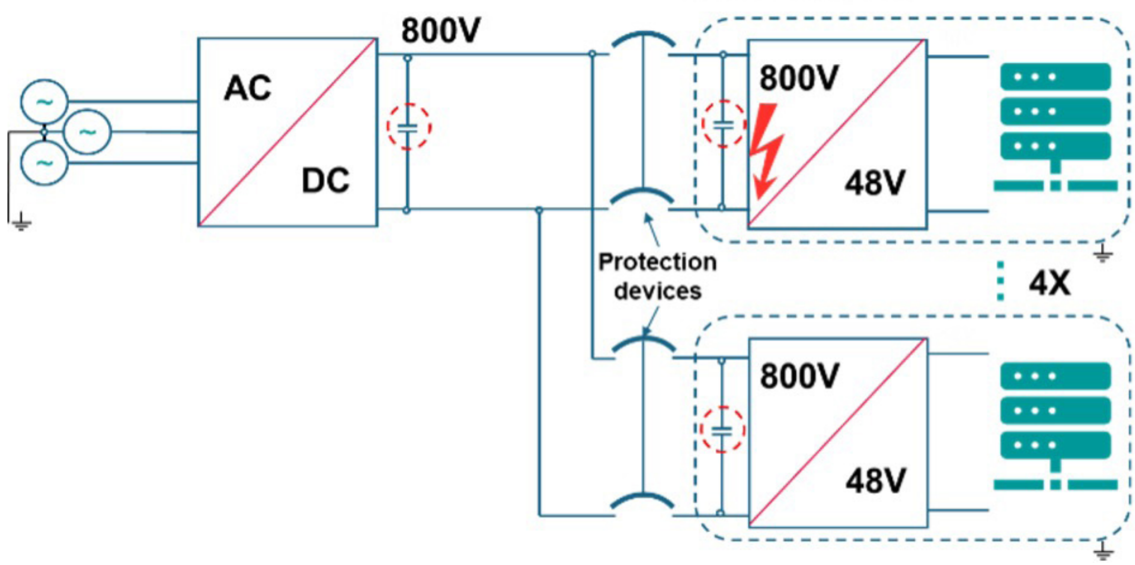
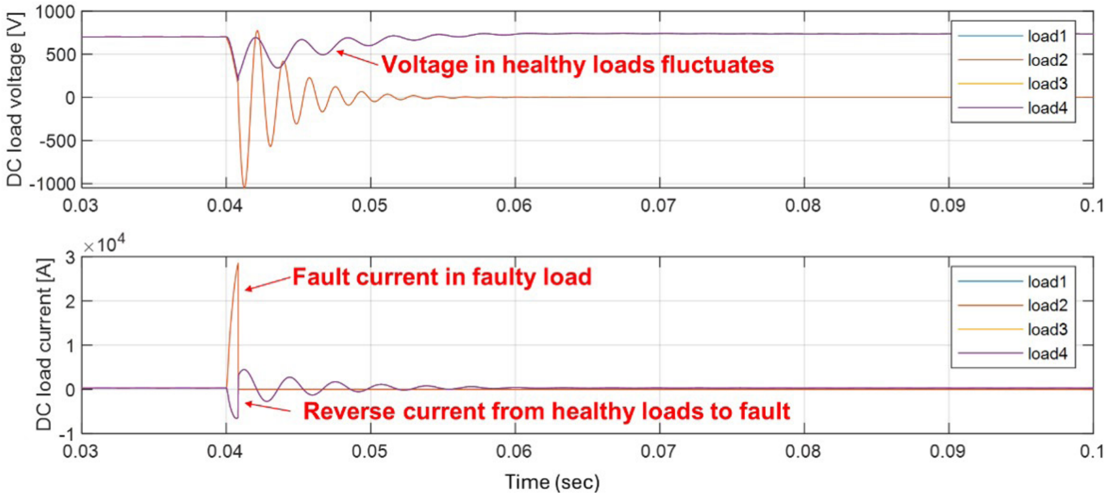
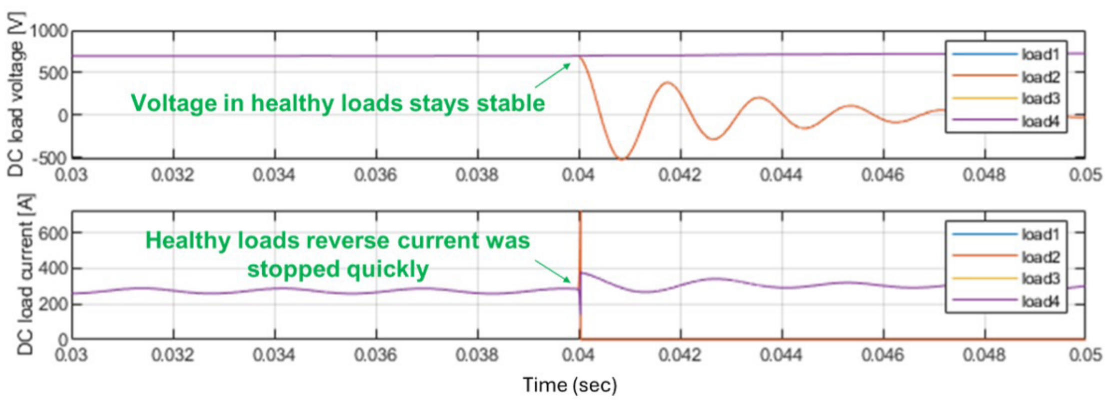


Figure 3. Simplified 1MW floating 800VDC block with one source and four loads



(a)



(b)

Figure 4. Loads voltage and current behaviors with different protection devices. (a) with fuses; (b) with SSCBs

One drawback of SSCBs is the heat generated in ON state, which has seen reduction from the latest semiconductor material development, such as SiC, and power electronics component development, such as JFETs[12].

3.5 Solid-state hybrid circuit breakers (SSHCBs)

SSHCBs implements a metal contact system for ON state conducting as in mechanical circuit breakers, and power electronics for interruption like SSCBs. A simple illustration is shown in figure 5. Mechanical contacts SW1 is placed in series to mechanical contacts SW2, which is in parallel with power electronic component Q1. In ON state, both SW1 and SW2 are closed to conduct current. This helps reduce heat generation. When a fault happens, Q1 is turned on and SW2 is open. The current then shifts to Q1. Q1 then turns off and the current further shifts to the energy absorbing component Z1 to complete interruption. SW1 is then opened separately to create isolation. SSHCBs' interruption time, 1-3ms, is usually shorter than fuses and mechanical breakers, but longer than SSCBs. This is because once Q1 receives current, it needs to wait until SW2 opens wide enough before turning off to avoid dielectric breakdown in SW2. The use of SSHCBs is possible in DC networks especially if di/dt limiters are implemented to slow down the fault current rise rate. Like SSCBs, SSHCBs are also governed by UL 489i, meaning some initial regulation hurdles have been cleared for its application.

Figure 6 compares the performance of the protection devices mentioned above in a short circuit condition. The capacitor discharge interruption with 200A/us current rise rate was only possible with SSCBs; other devices were not able to react fast enough. Capacitor discharge is inevitable in DC distribution as DC link capacitors or output filter capacitors are placed in almost all equipment. Depending on capacitor size and current path length, the current rise rate of discharge can be different. Figure 7 shows relationship between peak current, current rise rate (di/dt) and busway length with 10mF capacitor. As demonstrated, the longer the busway, the lower the di/dt and peak current. Therefore, with high di/dt protection capability, SSCBs reduce the minimum length requirement on busways.

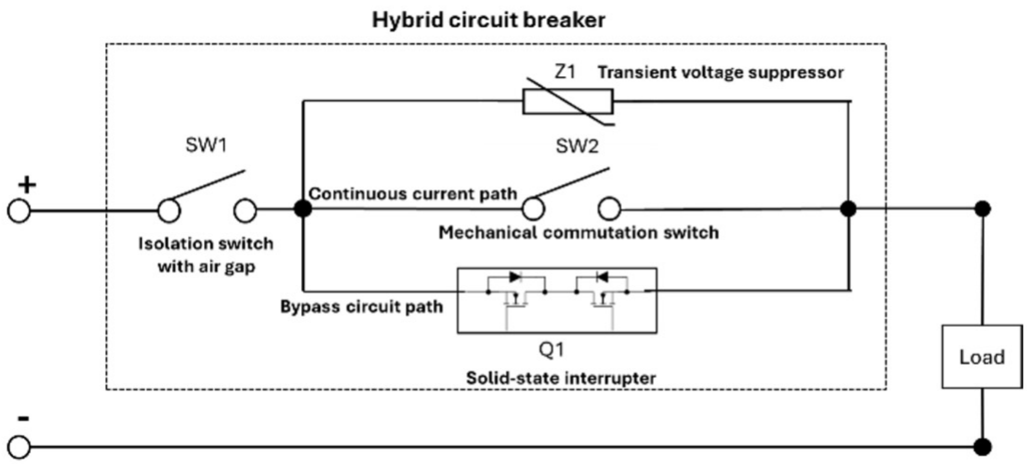


Figure 5. Common architecture of SSHCBs

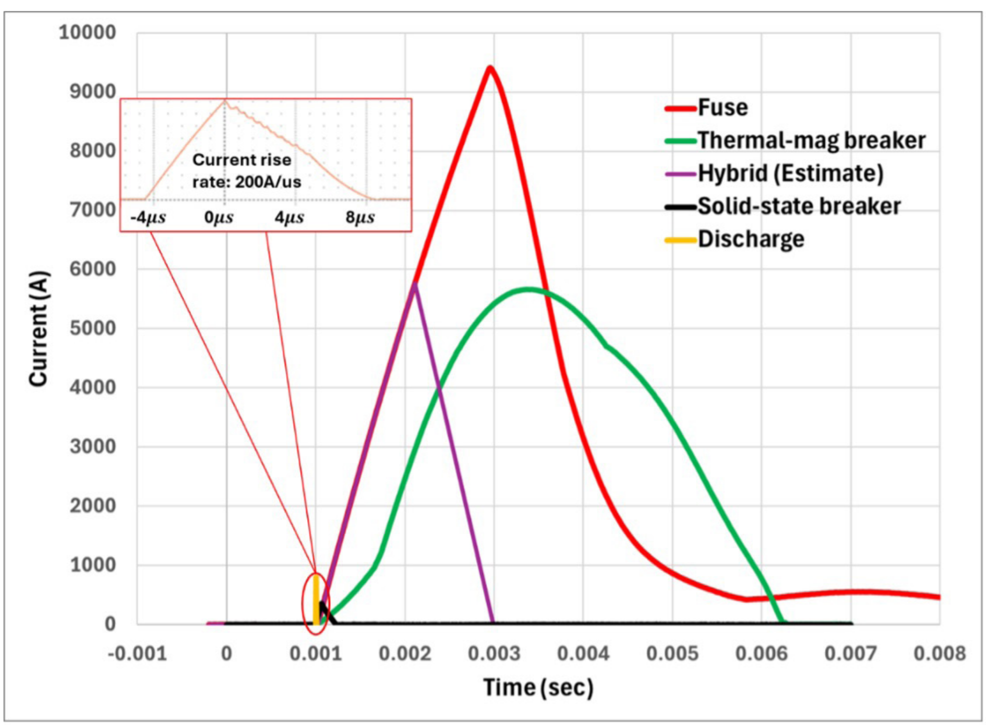


Figure 6. Short circuit performance with fuse, mechanical circuit breaker, SSHCB and SSCB

*Note: SSHCB performance is estimated, others are tested data

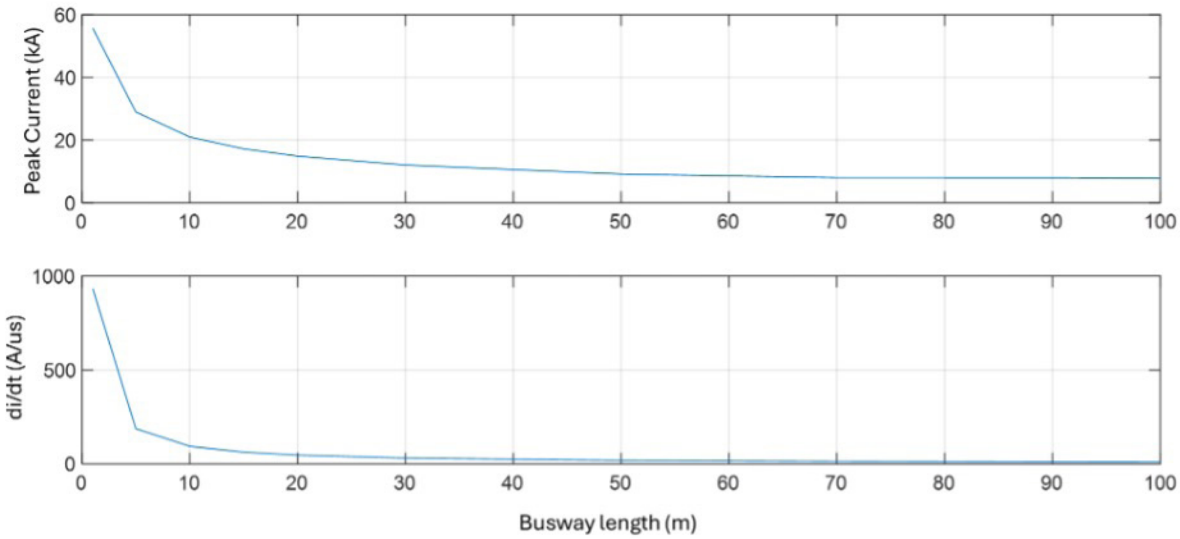


Figure 7. Capacitor discharge characteristics with 10mF capacitance

3.6 E-fuse (solid-state overcurrent protectors)

E-fuses are very similar to SSCBs, but without the integral airgap. As a result, e-fuses cannot be considered as branch circuit protection. They can only be considered as a means of supplementary protection as mentioned in UL 2367[13]. The main reason is lack of isolation. When power electronics are turned off, leakage current is always present, which can be as high as tens of milliamps depending on power level and design. High leakage current can allow downstream capacitors to remain charged even if the e-fuse is turned off. Such scenarios are addressed in SSCBs. As mentioned in UL 489i, if a DC SSCB is in standby state (equivalent to e-fuse off state), the SSCB shall either discharge capacitors or have markings warning of possibilities of charged capacitors. Also, as with other fuses, a disconnect is needed before servicing. In theory, a combination of an e-fuse and a shunt-trip disconnect can serve as branch and equipment protection. However, such combination is more cumbersome and costly than SSCBs for the same rating.

Another aspect of implementation of e-fuses is the lack of standards. UL 248-1[14] still defines fuses as in traditional filament format, and UL 2367 only covers e-fuses up to 60VDC, which corresponds to in-rack voltage level after conversion, not the distribution voltage.

3.7 Converters

In DC networks, converters are necessary. Almost all isolated converters, as well as some non-isolated converters, can provide basic protection in case of overcurrent faults by simply stopping switching. Therefore, they have been viewed as alternatives to traditional protection devices, such as circuit breakers and fuses. Other than simply stopping switching, more advanced converters often can perform one of the two functions below:

1. Current limiting mode. In case of fault, converters limit output current to a pre-defined level. Output voltage drops significantly.
2. Constant power mode. In case of overcurrent, voltage drops accordingly to maintain constant power output

The current limiting mode and the constant power mode provides flexibility when it comes to protection coordination. Whether converters themselves are sufficient as protection is tied to the system design, and some examples are discussed in the Appendix.

Some additional considerations are also needed when using converters as protection devices. First, unlike SSCBs and e-fuses, converters normally have isolated transformers, which provide isolation without airgaps. With this in mind, regulations need to clarify whether converters can be used for branch protection purposes. Second, converters commonly have output DC link capacitors or filter capacitors, which will discharge into faults regardless actions of converters.

3.8 Summary

A high-level qualitative comparison of the devices mentioned in this section is given in Table 2. It is important to note that protection device selections are highly dependent on system design and early collaborations between system designers and device manufacturers are essential.

Device Types	Branch Protection Capable	Additional Disconnect Needed	Fault Current Level	Clearing Time	Capacitor Discharge Protection	Controllability and Flexibility	Cooling Effort	Cost	Size
Disconnect	Red	Green	N/A	N/A	N/A	Yellow–red	Green	Green	Green
Mechanical Circuit Breakers	Green	Green	Red	Red	Red	Yellow–red	Green	Green	Green
Fuses	Green	Red	Yellow	Yellow	Red	Red	Green–yellow	Green	Green
SSCBs	Green	Green	Green	Green	Green	Green	Yellow–red	Red	Red
SSHCBs	Green	Green	Yellow	Yellow	Red	Green	Yellow	Yellow–red	Yellow
E-fuses	Red	Red	Green	Green	Green	Green	Yellow–red	Red	Red
Converters	Yellow–red	Red	Green–yellow	Green	Red	Green	Red	Red	Red

* Need regulatory clairification/updates

Table 2. Qualitative comparison of protection devices

4. Protection Coordination

In any power distribution systems, protection devices are deployed at different stages. In case of faults, it is important to have only the protection for the fault branch activated to reduce the impact of the faults. Two aspects make it more difficult for DC data center applications. First, fault current rises quickly in DC distributions, which triggers upstream protection devices to react. Second, in a DC system, an over current fault can come with voltage fluctuations, which are more impactful for data center applications if the duration is long. As a result, more considerations are needed for DC data centers than traditional AC systems based on coordination of TCCs of protection devices.

1. Current coordination. Ideally, fault current should be controlled to a level that only triggers branch protection, not upstream protection. This can be achieved with SSCBs. However, when converters are considered as part of protection scheme, the current limiting mode may provide more options for conventional protection devices.

2. Voltage coordination. Prolonged voltage fluctuations can trigger undervoltage or overvoltage protection. This is in particular important when the fault current level is low. The long delay times of conventional devices may cause long voltage dips. In this case, solutions like oversized power source and/or large backup energy sources can be considered. However, it is more efficient to simply reduce the duration of voltage dips.

3. Backup energy coordination. Backup energy sources are needed for DC data centers and are potentially distributed at different stages. Coordination of timing to deploy certain backup energy sources will become important to properly size the components. It is also critical to prevent backup energy sources from feeding energy to primary sources during fault conditions.

To better demonstrate coordination considerations, two case studies are given in the Appendix. It can be seen from the case studies that with SSCBs, coordination becomes inherently built in. With traditional protection devices, such as fuses, more involvement of the converters with active controls and communications are needed to set up proper coordination.

5. Arc Flash

Arc flash hazards present significant risks to the operation of data centers as power density increases, hence it is essential that this is addressed. A significant amount of studies have been performed on arc flash, tracing back to 1985 when Lee defined the curable skin burn level of 1.2cal/cm2 that is used today[16]. Several subsequent studies [17] [18] eventually led to the formation of IEEE 1584[19] that defines arc flash incident energies. It is important to note that these studies are heavily based on AC. DC studies have been conducted in more recent years and NFPA 70E[20] has provided some updated guidelines on DC arc flashes. However, the max power calculation has been viewed as overly conservative by many and further studies and standard updates are still needed.

In the fast-paced data center industry, some methods are worth considering to safely mitigate arc flash risks while the standards are developing. Regardless of the origin of the studies, arcing time and peak current are always the dominating factors when it comes to incident energy reduction. Actively reducing arcing time and peak current is the best method to reduce or even eliminate arc flash risks. NEC 240.87(B)[9] lists seven acceptable methods for arc energy reduction, and one of them is energy-reducing active arc flash mitigation system. Figure 8 shows the best-case scenario such systems can achieve in AC system presently. Once an arc was initiated, the mitigation system detected and shorted the arc to extinguish it in ~3ms and then the main circuit breaker reacted to the short circuit to clear the circuit afterwards.

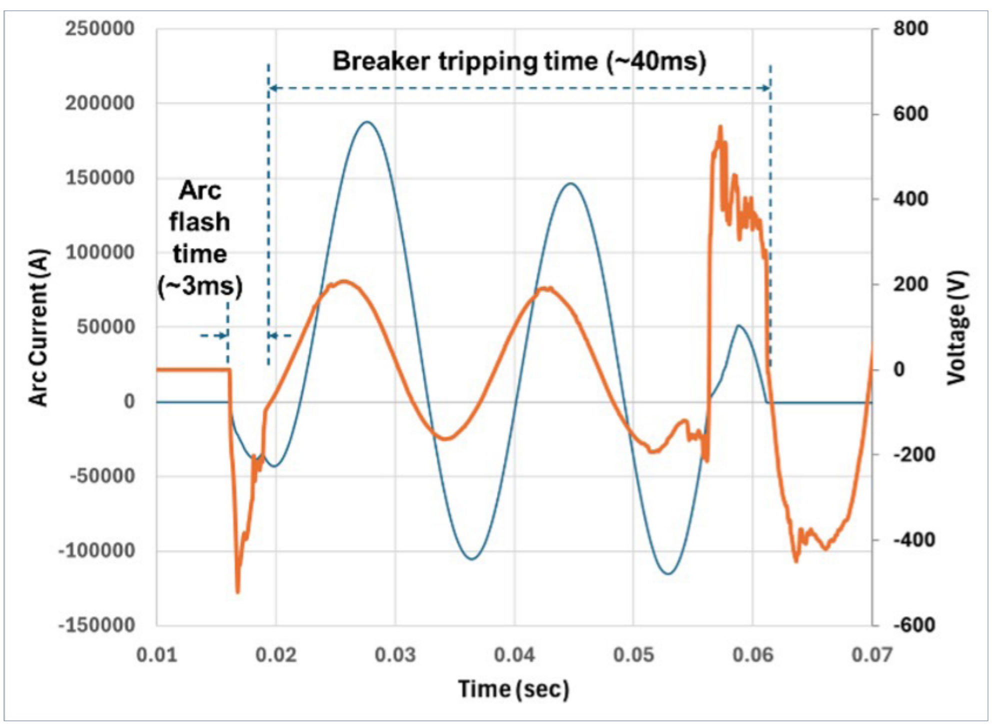


Figure 8. Example behavior of AC active arc flash quenching system

In a DC distribution network, devices like converters, SSCBs, SSHCBs are all capable of limiting arcing time and peak current beyond traditional means used in AC distributions, for example, less than 1ms. Previous studies have not fully studied the arc behaviors for such a short time frame. Arc physics research in other fields have provided some information, such as the one mentioned in [21]. For an arc plasma to form, several physical processes are needed, involving propagating electro-magnetic fields, heating up electrons, ionization, heating up heavy particles and initiating plasma flow. The ranges of time scales of these physical processes are provided in [21]. If the arcing time is less than 1ms, it interferes with the heavy particle heating and conducting process, and starts to limit the formation of arcs themselves. If the arcing time is less than 100us, it interferes with the ionization process, and if the arcing time is less than 1us, it starts to prevent electrons from heating up. As a result, arcs do not start. It is also important to recognize the propagation speed of arc plasmas. [17] and several other studies have early results on pressure and propagation, which in general match the observation in this paper, as shown in figure 9. In figure 9, a 3kA arc is observed with a high-speed camera at 6000fps. The exhaust channel was intentionally designed to allow the arc to vent rapidly. In this test, the arc exited the channel at approximately 300 m/s and maintained this velocity for roughly 350 μs after ignition. No noticeable expansion or constriction occurred, indicating that the flow was neither choked nor restricted. Even at this high exit speed, the arc traveled less than 200 mm within the first 1 ms.

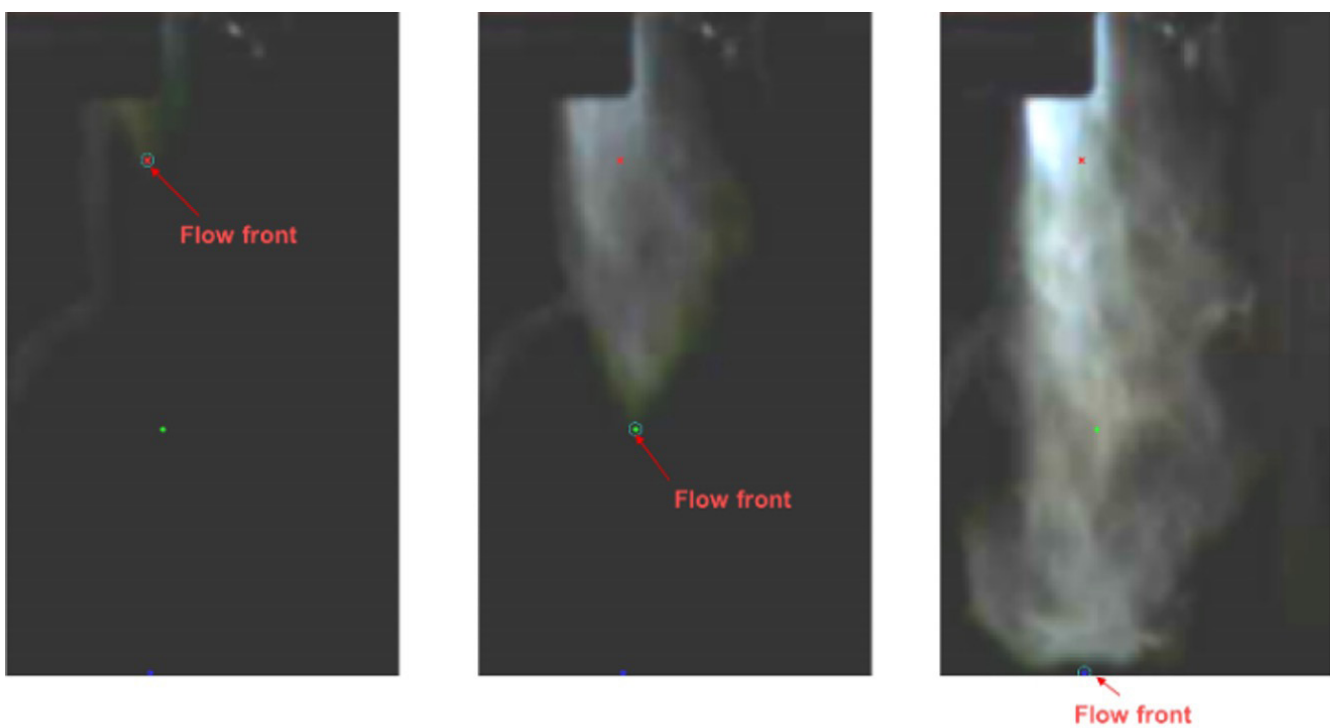


Figure 9. High speed video of arc exhaust

In summary, with the active components in DC distribution, arcing time can be limited to before arcs are formed and/or propagated, which will outperform any AC arc flash mitigation systems in the market currently.

6. Ground Fault for Personnel Protection

Traditional personnel ground fault protections have been focused on residential type applications covered by UL 943[22]. However, UL 943 doesn't have branch voltages higher than 150V in scope. Recent developments in the electric vehicle industry have started to push the boundary of such protection devices, and UL 943C[22] is published as an outline of investigation to cover voltages higher than 150V. In UL 943C, two additional classes are added to address situations where conductor to ground voltage is higher than 300V, Class D that requires oversized grounding conductors and Class E that requires fast reacting devices. To meet Class D, the grounding conductors shall have 60% and 23% resistance of ungrounded conductors at 400VDC and 800VDC, respectively. With tight space in server racks, placing such oversized grounding conductors is challenging. Furthermore, in a data center, when technicians work on server racks, they need to ground themselves with ESD straps. Depending on where the straps are connected, Class D may not apply as the oversized ground conductor can be in series to the body. To meet Class E requirements, a ground fault shall be interrupted within~850us and ~300us for 400VDC and 800VDC, respectively. Such short interruption times are not achievable with ground fault interrupters in the market. However, SSCBs or other power electronics based components provide possibilities to realize Class E protection.

It is worth noting that if floating system or high resistance grounding is used, the first ground fault is mitigated by system design. Although power still needs to be removed, the protection devices can have more time to interrupt considering it always takes some time before the second ground fault happens. Therefore, power electronics based ground fault protection is not necessary. Instead, ground resistance must be monitored continuously with insulation monitoring devices.

7. Conclusions

DC power distribution for data centers presents some unique challenges in terms of protection, such as capacitive networks, unstable voltage during faults, coordination at different stages and distributed energies contributing to faults. At the same time, it also shows possibilities to perform inherently better than an AC counterpart in areas like arc flash mitigation and achieving Class E ground fault protection.

This paper lists multiple possibilities for several aspects of safe operations, including different protection and coordination schemes with active and passive protection devices, different energy backup options, different grounding schemes for ground fault protection, and arc flash mitigations. It should be noted that SSCBs and converter based active protection solutions show many technical advantages with their short interruption times and precise fault current control. Continuous developments and innovation of such solutions will provide great benefits to the data center industry. On the other hand, traditional passive protection devices, if properly designed, can still perform, especially when requirements are not as stringent.

It is important for data center builders and operators and equipment manufacturers to co-design at early stages to achieve the optimal combinations. Active conversations at research and development level are needed, in which topics like grounding, 2-wire versus 3-wire, coordination and, etc. can be discussed.

It is also crucial for regulations to develop further to safeguard the rapid growing data center industry by recognizing unique aspects of data centers. Codes and standards still need to be developed and/or clarified in the areas of voltage bands and tolerances, wiring practices, grounding, over current protection device requirements, ground fault requirements, arc flash requirements, personal protection equipment, battery storage, and medium voltage power supplies.

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Appendix: Coordination Case Studies

This section uses two case studies to illustrate qualitative coordination analysis among protection devices in a data center. The analysis is based on one block in figure 1, where one DC source is used to feed multiple parallel loads. Basic assumptions are as follows:

- 2-wire floating 800VDC distribution is considered.
- AC/DC converters can be either isolated or non-isolated.
- Although each load is fed by two sources, only one source feeds current and the other one serves as backup.
- It is also assumed that the loads are highly dynamic with large fluctuations, and the current can go above nominal current momentarily under normal operations.

A.1 Case 1: Protection with advanced AC/DC converter and fuses or mechanical circuit breakers, figure 10.

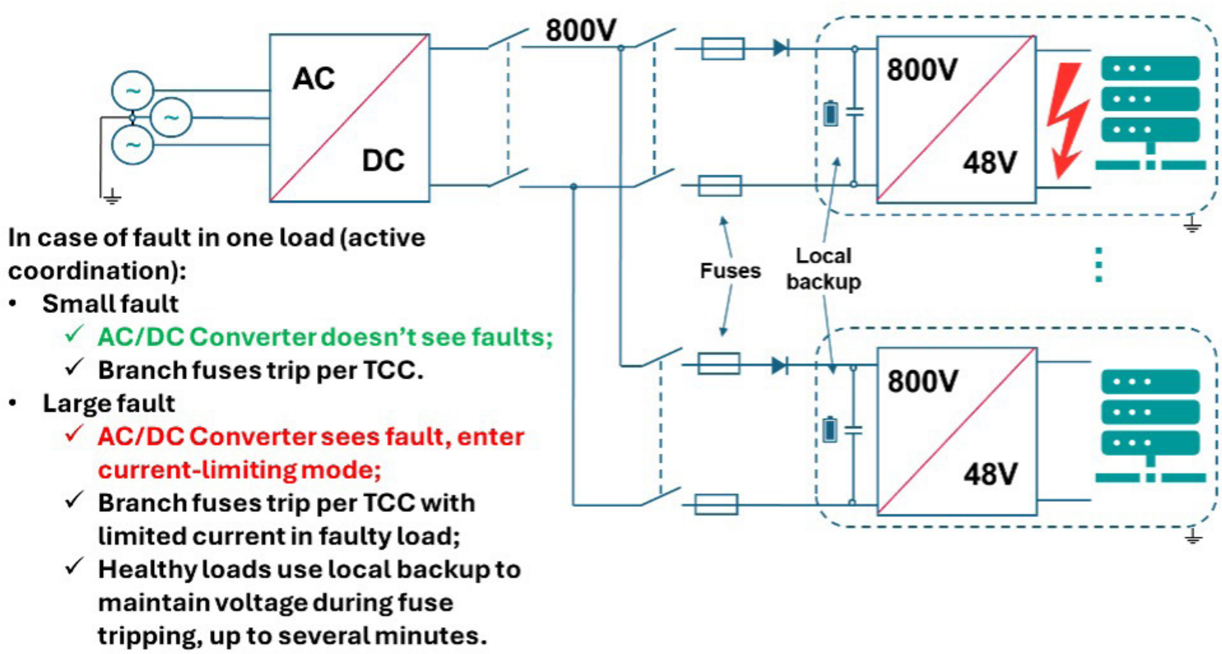


Figure 10. Converter and fuse based protection and coordination

In this case, it is assumed that the AC/DC converter can enter current-limiting mode and maintain a constant current at lower voltage in case of converter current reaching over a threshold, 1.3 times nominal current in this study. Before the current level reaches the threshold for current-limiting mode, the converter is sized such that operating voltage requirements can be met. The time needed to switch between normal operating mode and current-limiting mode is neglected for simplicity purposes. However, in real devices, such transition time needs to be considered.

A.1.1 Short-circuit faults in individual loads

The sequence of protection is as follows. Once threshold current is detected by AC/DC converter, it enters current-limiting mode and reduces main DC bus voltage. The fuse or mechanical breaker located in the faulty load then follows their trip current curves to interrupt the faulty branch. Once the fault is cleared, the AC/DC converter senses the reduced current level and goes back to normal operations. As mentioned previously, since neither current carrying conductors is grounded, common-trip circuit breakers or double-break disconnect switches in case of fuses are needed.

During the fault clearing time, it is important to keep other healthy loads operating by keeping the voltage within operating range. This is achieved by using reverse blocking diodes and local energy storage. Reverse blocking diodes prevent local stored energy from being released to the converter or to the fault. For local energy storage, the short interrupting time under short circuit conditions, <20ms, makes batteries questionable as they may not be able to ramp up to fully functional voltage levels fast enough. Therefore, capacitors are preferred for short-term energy storage. It should be naturally understood that the longer the total time for voltage to recover, the bigger the capacitors needed. As a simple example, assume that the total clearing time is 10ms and the load power is 1MW. To keep voltage within 10% of nominal voltage, ~80mF is needed. The longer the clearing time and the tighter the voltage range, the larger the capacitor needed. In real applications, the operating voltage range is likely tighter than 10%, also with ripple requirements and converters also need ramp up time when recovering from current-limiting mode. Therefore, the capacitor needed for backing up a 1MW load is likely higher than 80mF.

Also, energy backup at the main bus level is challenging in this scenario. This is because the energy backup needs to stay on during fault clearing time to supply the healthy loads, but will also contribute to the fault as a consequence.

A.1.2 Overcurrent faults in individual loads

Overcurrent faults are at lower levels than short-circuit faults, and when happening in individual loads, they may or may not trigger the AC/DC converter to enter current-limiting mode. For example, in figure 10, each converter feeds four loads. If the branch overcurrent is 2 times nominal current, the converter only sees 1.25 times nominal current and stays in normal operating mode. In this case, all the healthy loads are unaffected. The fault is cleared by the fuses or mechanical circuit breakers that protect the faulty load. In this case, it can take minutes to clear depending on TCCs. If the branch overcurrent is 3 times nominal current, the converter sees 1.5 times of nominal current and enters current-limiting mode to allow branch protection to trip. To clear fault current of 3 times nominal current, it may take branch protection tens of seconds to clear. This means that the healthy loads need to maintain their voltages for a long period of time. Therefore, capacitors may not be sufficient anymore, and supercapacitors or batteries will be needed at each load.

Another aspect of overcurrent protection in this case is that active communication may be needed between a faulty branch and the converter. As mentioned above in figure 2, arcing time of fuses and mechanical circuit breakers increase as fault current gets lower. During arcing time, branch voltage is expected to vary greatly. This is because protection devices need to bring the arc voltages higher than system voltage in order to interrupt. Depending on the design of the converter, it may react to the varying load voltage. Therefore, the branch may need to communicate with the converter to ensure it doesn’t interfere with interruption and doesn’t turn off.

A.1.3 Dynamic loads

It is anticipated that GPUs for AI computing will cause highly dynamic behavior. Last Open Compute (OCP) requirement spec published [15] uses load examples at frequency as high as 10kHz. Such high frequency fluctuations bring complications to power distribution. First, high power converters are unlikely to be able to supply such high frequency. Second, high frequency current amplifies skin effects of distribution busways and cables and can cause overheating. These effects also emphasize the importance of capacitors needed at each load, which can smooth out high fluctuating current. Figure 11 shows an example of the effects of capacitors at each load. In the example, the power of each load varies from 0.7MW to 1.3MW at 10kHz frequency and 50% duty cycle. 5m of busway is assumed between the converter and the first load, and the loads are 1m apart from each other. Up to three loads are studied with different phase shifts among the loads. Each load has a local capacitor, and the effect of the capacitance values is shown in figure 12. First, it is important to realize that the inductance on the busway already lowers the peak current level at the converter output. The increasing capacitor values clearly reduce the high frequency component in temporal domain, figure 12(a). In the frequency domain shown in figure 12(b), as the capacitor values increase, the 10kHz component reduces and lower frequency components become more dominant. At ~10mF, the high frequency component becomes negligible.

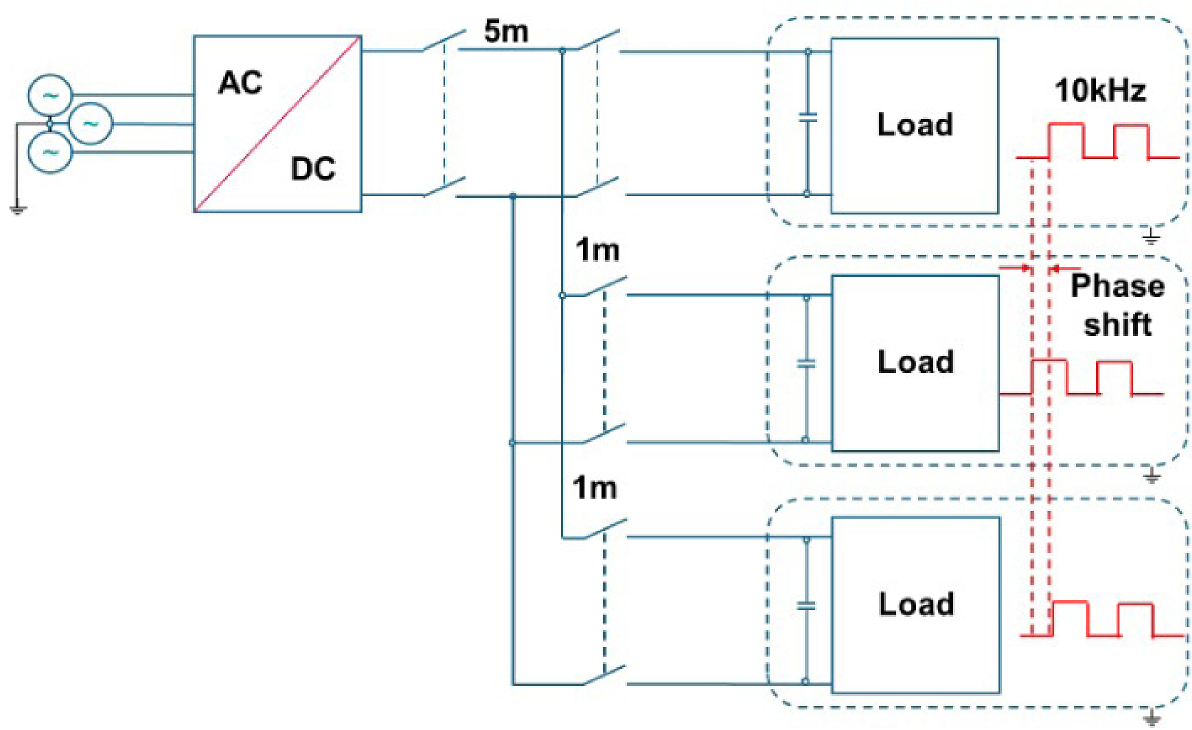
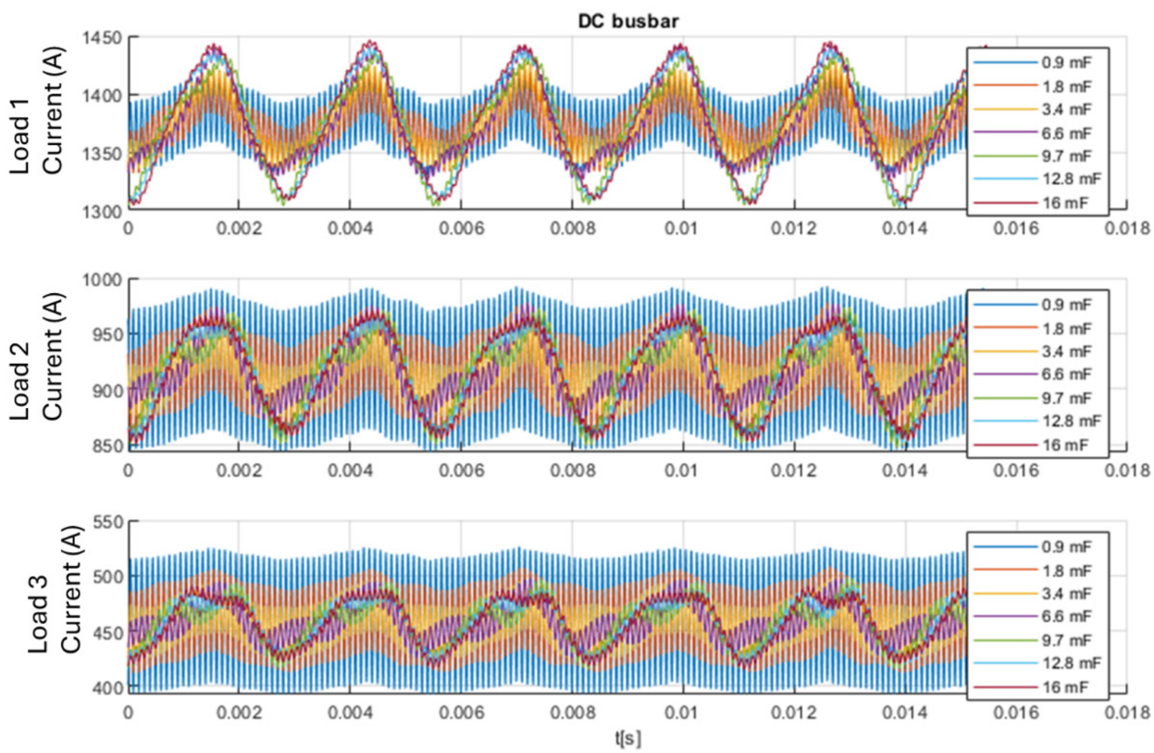
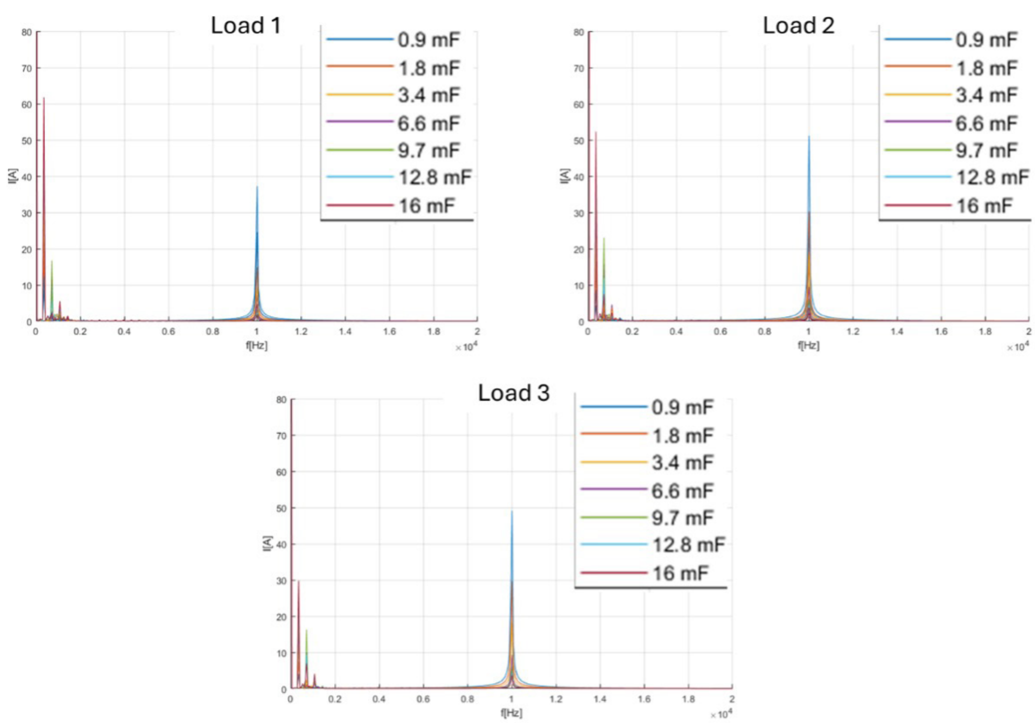


Figure 11. Dynamic load setup with three loads



(a)



(b)

Figure 12. Capacitor effect on dynamic load current. (a). Temporal domain; (b). Frequency domain

A.1.4 Case 1 summary

Local capacitors are needed at each load to remove high frequency components in current and to provide necessary back-up during the clearing time of local protection devices. The minimum capacitance is determined by the dynamic load profile, and the upper end of the capacitance value needed is determined by the backup time needed. It's worth mentioning that since minimum capacitance is needed, protection device clearing time doesn't need to be unnecessarily short. For example, with 10mF mentioned in the previous section to deal with dynamic loads, it can also provide ~0.5ms backup during fault. Therefore, interruption time faster than 0.5ms is not necessarily beneficial.

Reverse blocking diodes are critical in this coordination example. They prevent local capacitors from discharging during faults. In this case, converters and their functions are critical to overall protection and coordination.

A.2 Case 2: Protection with AC/DC converter and SSCBs, figure 13

In this case, SSCBs are used to protect each load branch. It is assumed that the AC/DC converter simply turns off in the case the converter current reaches over a threshold, 1.3 times nominal current in this study. Before the current level reaches the threshold, the converter is sized such that operating voltage requirements can be met. SSCBs trip immediately if the branch current reaches 1.3 times nominal current.

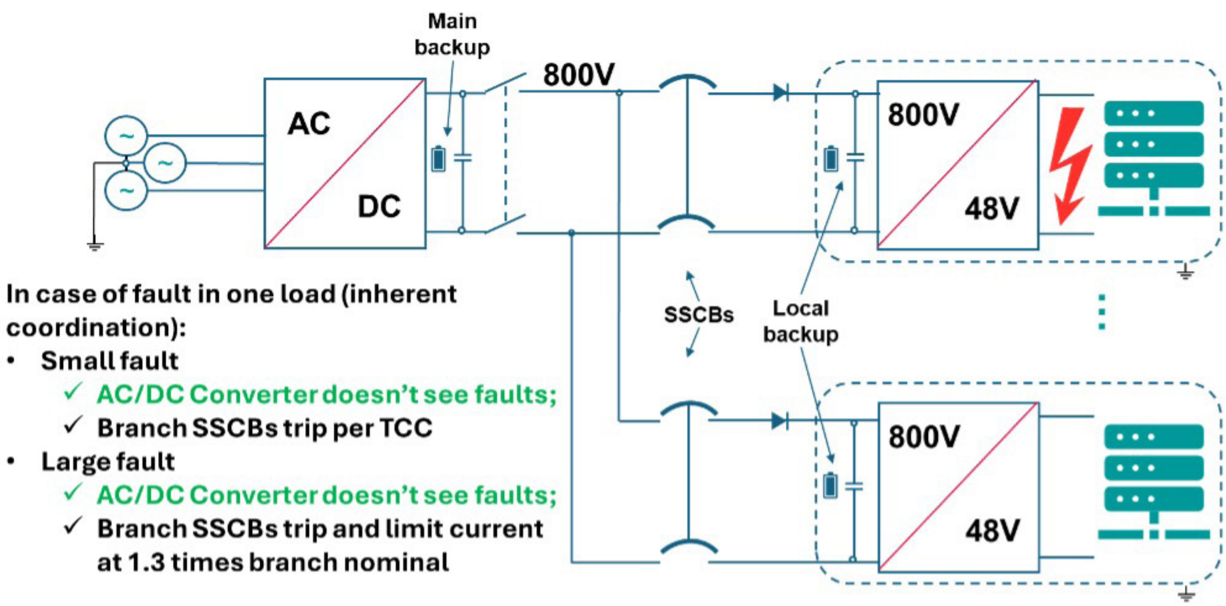


Figure 13. Converter and SSCB based protection and coordination

A.2.1 Short-circuit and overcurrent faults in individual loads

The protection coordination is significantly simplified with SSCBs. In case of short-circuit and overcurrent more than 1.3 times nominal current, branch SSCBs trip immediately and limit the fault current very close to the threshold. The converter doesn't see current high enough for a fault, and hence stays on as normal operations. For overcurrent less than 1.3 times nominal current, a trip current curve can be programmed in SSCBs as needed per application. The ability to limit fault current precisely has made SSCBs ideal for coordination.

With fast clearing times of SSCBs, load capacitors do not need to be sized for backup and only need to be sized for dynamic load smoothing.

Furthermore, with fast clearing time, SSCBs can prevent energy backup on the main bus from discharging to the fault, and hence main backup can be an option.

A.2.2 Case 2 summary

Considerations on coordination are greatly simplified with SSCBs, and load capacitors have the potential to be much smaller.

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