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Medium Voltage Direct Current (MVDC) Fault Detection, Localization, and Isolation

Norbert H. Doerry[1] (FL) and **John V. Amy Jr.**[2] (FL)
1. Naval Surface Warfare Center Carderock Division
2. Naval Surface Warfare Center Philadelphia Division

Medium Voltage Direct Current (MVDC) is an attractive power system option for commercial and naval ships. However, the lack of a comprehensive design strategy for MVDC circuit protection is a barrier to implementation. For a range of MVDC architectures, this paper explores the inter-relationships among the different functionalities that isolation devices can have, the technologies for implementing isolation devices, power quality requirements, protective relaying strategies, source design, load design, and energy storage. Because commercial products implementing the technologies do not currently exist for MVDC applications, their costs cannot be determined and therefore the optimal solution cannot yet be determined.

KEY WORDS:
Electrical system; medium voltage direct current; circuit breaker; fault protection; disconnect switch; switchgear

INTRODUCTION
The technologies employed in naval warfare are evolving quickly. To remain militarily relevant over their service life, naval warships will need to be able to support weapons and sensors that do not currently exist and that will present large, nonlinear, stochastic, and pulse loads to the power system. Adhering to established interface requirements with an AC distribution system, requires warship designs to incorporate considerable dedicated power conditioning and energy storage that will present affordability, size, weight, and reliability challenges. An alternate approach employing Medium Voltage Direct Current (MVDC) for power generation and primary power distribution promises to support future loads at lower cost and improved power density, and to reduce fuel consumption as compared to traditional Medium Voltage Alternating Current (MVAC) solutions. (Doerry 2015, 2016)

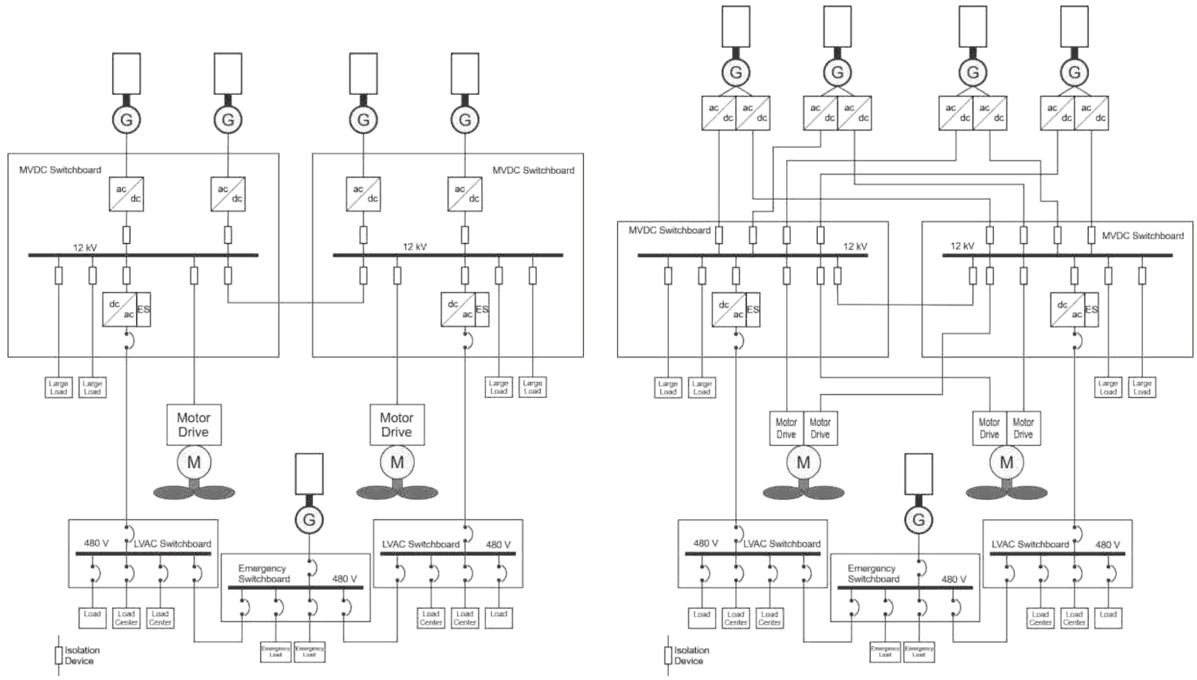
Commercial ships with a high-power demand may also benefit from MVDC. For these ships, the ability to employ variable speed diesel generator sets offers the opportunity for increased fuel economy. (Zahedi 2013) (Skjong 2017). Additionally, variable speed operation enables operating diesels at their rated power and rated speed rather than at a lower power corresponding to a lower speed (a sub-multiple of 3600 rpm) required for 60 Hz. operation. The power density of the diesel can thus be effectively greater for MVDC and can offset either partially or entirely the additional volume and weight required for the rectifier.

One barrier to the use of MVDC onboard ships is the lack of a comprehensive design strategy for fault detection, localization and isolation (DLI). This design strategy must account for the variability in MVDC system architectures, the MVDC interface standard, line-to-line faults, arc faults, line-to-ground faults, the expected dynamic behavior of loads and sources under normal operation and when the power system is faulted, cost, and the risk tolerance of the customer. This strategy must account not only for the capability to interrupt fault current, but also on the proper relaying methods to ensure proper coordination among the various fault interruption and fault isolation devices and energy storage design. Recognizing the many advances in MVDC technology over the past several years, this paper explores trade-offs among five isolation device strategies for designing MVDC fault protections systems.

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the U.S. Government.

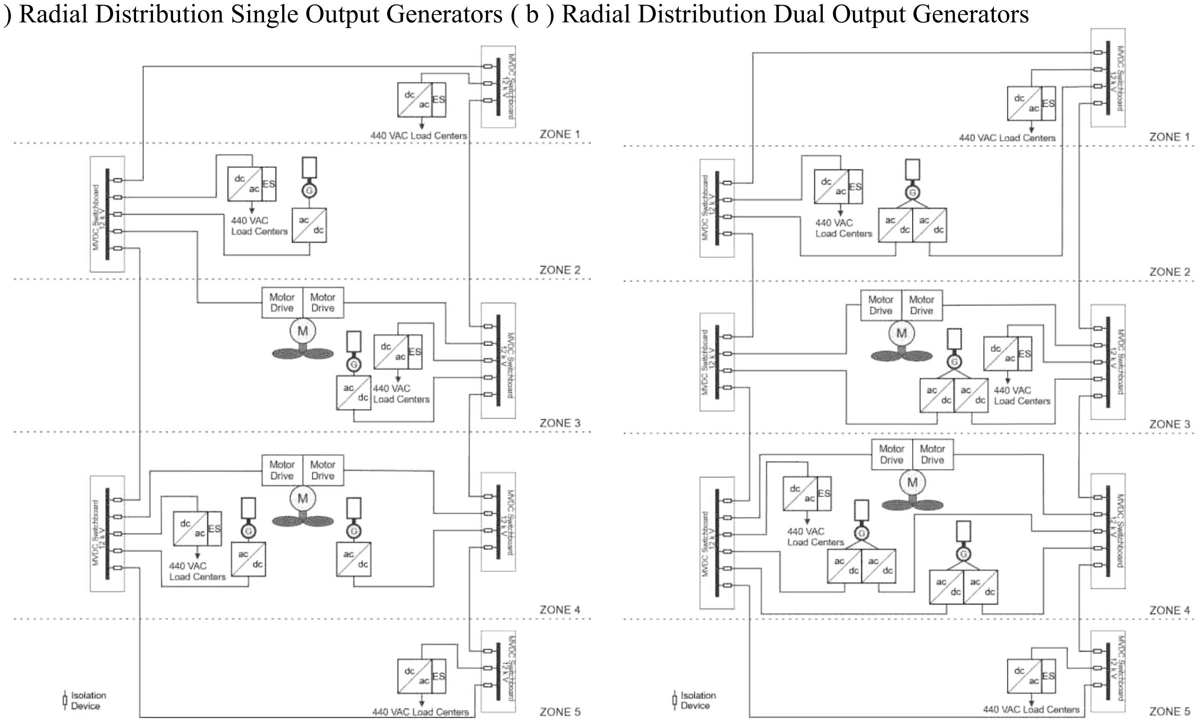
POWER SYSTEM ARCHITECTURES
The primary objective of the power system onboard a ship is to affordably provide electrical power of the appropriate power quality to loads with an acceptable Quality of Service (QOS) and survivability. QOS measures the ability of the power system to support the normal, undamaged operation of its loads. QOS is measured in terms of a Mean Time Between Service Interruption (MTBSI) where a service interruption is any interruption in the supply or deviations outside of power quality standards that prevent the load from performing its assigned function. Survivability measures the ability of the ship to continue to function during and following damage. (Doerry 2005a, 2005b)

The design of the fault DLI system must be consistent with the power system objective and be compatible with the power system architecture chosen. It is anticipated that the power system architecture will be either zonal or radial, and will either employ single output or dual output generators as depicted in Figs. 1-2. Most commercial ships and smaller naval ships are anticipated to use a radial architecture while larger naval vessels and some complex commercial ships are anticipated to use a zonal architecture. To enable continued operation with one line grounded, the MVDC system will likely be high resistance grounded; necessitating isolation devices on both conductors or poles of the power system.



(a) (b)

Fig. 1, (a) Radial Distribution Single Output Generators (b) Radial Distribution Dual Output Generators



(a) (b)

Fig. 2, (a) Zonal Distribution Single Output Generators (b) Zonal Distribution Dual Output Generators

FAULT PROTECTION APPROACH

Because of the lack of experience in designing and operating MVDC fault DLI systems, the fault DLI approach should be layered such that the failure of any one device does not result in a complete loss of power onboard the ship or result in extensive damage to equipment. Options to achieve this goal include:

- Dual output generator architectures
- Ability to control generator or rectifier output to not feed fault
- Solid State Circuit Breaker (SSCB) on output of sources
- Use of a.c. fuses (or circuit breakers) between generators and rectifiers
- Use of unidirectional isolation devices for sources and loads.
- Use of independent directional control bi-directional SSCBs for regenerative loads and energy storage.
- Use of protective relay as primary fault control method, and local overcurrent as backup
- Use of energy storage to power mission critical loads while the MVDC system isolates faults and reconfigures.
- Use of dual inputs on large MVDC loads to provide independent source of powers and continued operation while the MVDC system isolates faults and reconfigures.

The number of these options that are employed will depend on the risk tolerance of the customer as well as the customer's willingness to pay for additional incremental cost of implementing each option.

Dual output generators use generators with independent sets of windings (each normally rated for 50% of the overall generator set power ratting). Each independent set of winding has its own dedicated active rectifier. The two outputs normally connect to separately derived systems as defined in IEEE Std. 3003.1. The use of dual output generators helps simplify operations, can help ensure generator sets remain on line during and after a fault, and improves the robustness of the power system to protection device failures. (Doerry 2015, 2016). Dual output generators enable the fault protection systems of each bus to be completely independent of each other; the unfaulted bus remains operational. Control methods exist for generator sets to ensure power quality on an unfaulted bus remain acceptable during fault clearing on a faulted bus. (Doerry 2020b) Energy storage and/or alternate power supplies to mission critical loads ensure power continuity for all mission critical loads during fault clearing. However, since dual output generators are not practical in traditional a.c. systems, there is essentially no experience in operating electrical plants using generator sets with dual outputs.

Some active rectifier designs, such as the full bridge modular multi-level converter (MMC) can provide the functionality of a SSCB. These rectifiers can also limit the magnitude of fault current provided by the sources. If a rectifier is employed that does not have SSCB functionality, then an SSCB should be used as a generator breaker between the rectifier and the bus. Limiting the fault current to a steady value that the SSCBs can interrupt helps prevent differential protection from misdiagnosing a fault within a protection zone.

A.c. fuses or circuit breakers between the generator and rectifier protect the generator from a faulted rectifier or a failed generator breaker.

In d.c. systems, d.c. current flows in only one direction under normal operation for sources and loads. Reverse current flow, such as load input capacitance discharging into a faulted bus, or a fault in a rectifier being fed from the bus, can be prevented by using a uni-directional isolation device with the ability to block reverse current. Current can be interrupted in the normal direction and inherently blocked in the reverse direction.

Regenerative loads and energy storage are devices where the current can normally flow in either direction, but the direction of current flow is determined by controls. Protection devices which have the ability to independently control current in each direction can be useful for these power system elements.

Traditionally, the magnitude of overcurrent and time (I2t) has been employed to determine whether a circuit breaker should trip. With SSCBs, this strategy alone will likely not be reliable to properly coordinate breakers to ensure only the breakers nearest the fault will trip. SSCBs are limited in their ability to interrupt fault current and must trip quickly before fault current rises to a level they are no longer able to interrupt. As described by Doerry (2021) the amount of time available to interrupt the fault current is a function of the SSCB interrupting capability, the system inductance, and the system voltage. The required interruption time can range from microseconds to tens of microseconds. Increasing the system inductance will increase the required interruption time, but at the expense of limiting the ability to supply pulsed loads and high current ramp rate loads without power quality issues.

Advanced digital protection relays can detect and localize faults much quicker than traditional overcurrent methods. The existence of a fault can be detected by sensing an undervoltage in the system. The location of a line-to-line fault can be detected using a combination of directional and differential protection zones. Each cable segment and switchboard can be defined as a protection zone. For each conductor, the current is continuously monitored at every place where the conductor crosses the protection zone boundary and through any load within the protection zone boundary. In directional protection, if all of the current directions are of the same sign, then a fault has been detected within that zone. In differential protection, the current values are added; if the sum, which by Kirchhoff's current law should be zero, exceeds a threshold value, then a fault has been detected within that zone. During the early stages of certain faults, the fault impedance may still be high enough to preclude directional protection. If multiple faults occur at the same time, directional protection may have difficulty identifying a fault within a protection zone; current can flow from one faulted zone to another. Differential protection can detect faults within a protection zone reliably, but if the current measurements are not appropriately synchronized, and the fault current levels ramp too quickly, then differential protection may determine that an unfaulted protection zone is faulted. Establishing the threshold value of the current sum for the differential protection to declare a fault should be done with care and after an appropriate amount of analysis. Differential protection is less sensitive to multiple simultaneous faults. The digital protection relay should implement both differential and directional relaying. In either case, a fault within a protection zone should be detected and isolation activity initiated before the SSCB over-current trip activates. The over-current trip should be reserved as a back-up in case the differential or directional protection fails or is too slow.

Energy storage co-located with power converters between the MVDC and low voltage system can reduce or eliminate the impact of MVDC bus faults on the low voltage system until the bus fault is eliminated. The energy storage should have a power rating sufficient to at least power all online loads until the non-mission critical loads can be safely shed, and then all mission critical loads. The energy capacity should be at least on the order of seconds (Doerry 2011) to enable the bus voltage to recover following a fault, for clearing multiple near-simultaneous faults, and for allowing the fault protection system to implement backup-strategies if elements of the fault protection system do not operate as intended.

Providing large MVDC loads with multiple connections to different MVDC switchboards reduces the risk of these loads totally losing power should one of the switchboards become isolated due to a fault or misdiagnosis of a fault.

POWER QUALITY

The power quality requirements for the system impact the fault protection system because normal operation must not be interpreted as a fault. Similarly, if a fault is present, then system voltages and currents will likely be outside of normal limits. See Doerry (2020b) for a proposed MVDC interface standard. Some of the attributes from this standard that are important for fault protection include:

- In-rush current limit: If the current entering a load exceeds the in-rush current limit, then the load can be assumed to have a fault.
- Load abnormal service steady-state voltage range and load peak voltage ripple: If the line to line voltage is in the abnormal service steady-state voltage range by more than the load peak voltage ripple, then either a fault has occurred or there is a mismatch between load and the available online sources.
- Load maximum current pulse: If a current pulse exceeds the maximum value, then the system can be assumed to have a fault.
- Load maximum current rate of change: If the current rate of change exceeds the load maximum current rate of change, then the system can be assumed to have a fault.
- Load peak current ripple: If the current into a load is greater than the sum of its maximum steady-state load and the load peak current ripple, then the load can be assumed to have a fault.
- Neutral voltage: If the neutral voltage is outside acceptable limits, then a ground fault is present.

TYPES OF ISOLATION DEVICES

Traditional electromechanical circuit breakers used in MVAC systems are not appropriate for MVDC systems due to the lack of current zero crossings; current zero crossings are essential for extinguishing the arc in these breakers. For MVDC systems, isolation devices are generally categorized into fault-clearing and non-fault clearing devices. SSCBs are generally fault clearing while disconnect switches are generally non-fault clearing.

While a.c. circuit breakers are inherently bi-directional, d.c. circuit breaker need not be. When employing certain technologies, uni-directional breakers can be considerably smaller and less expensive than bi-directional breakers. Different locations within a system will have different needs for circuit breaker directional functionality. Fig. 3 depicts transistor based SSCBs for four different functionalities. Reverse blocking always prevents current from flowing in the direction opposite of the direction that can be interrupted. Without reverse blocking, current is not prevented from flowing in the direction opposite of the direction that can be interrupted.

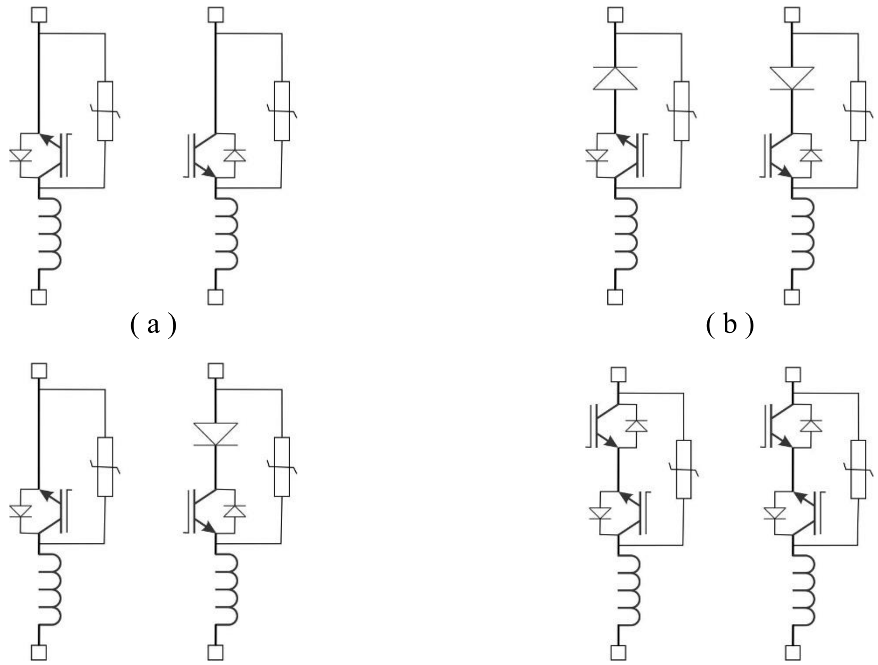


Fig. 3, SSCB directional functionality (a) unidirectional without reverse blocking (b) unidirectional with reverse blocking (c) unidirectional with one pole reverse blocking (d) bidirectional (with independent directional control).

If SSCBs are employed, non-regenerative loads are best served by uni-directional with reverse blocking SSCBs. In an unfaulted condition, current only flows in one direction for these power system elements; reverse blocking automatically prevents the load's input capacitors from discharging into a bus fault. Preventing this capacitor discharge reduces the fault current that must be interrupted.

For sources, it is best to have unidirectional with one pole reverse blocking to isolate faults within the source from the bus. Reverse blocking on only one of the poles avoids a fault condition where two sources can be placed in series, doubling the line-to-line voltage, due to a particular combination of ground faults (Doerry 2019)(Gudex 2021).

If SSCBs are employed, bus ties between switchboards can be served with uni-directional without reverse blocking or bi-directional SSCBs. If uni-directional SSCBs are employed, they should be able to prevent faults on the bus-tie from impacting the switchboard. Faults within the switchboard would be isolated by the SSCB in the other switchboard connected by the bus tie. Bi-directional SSCBs provide an extra layer of protection from faults within a switchboard.

If SSCBs are employed, energy storage and regenerative loads require bidirectional SSCBs. Some bidirectional SSCBs enable independent control in each direction (Fig. 3(d) for example). These SSCBs should be configured as uni-directional with one pole reverse blocking if acting as a source, and as unidirectional with reverse blocking if acting as a load.

ISOLATION DEVICE TECHNOLOGIES

Isolation device technologies fall into four broad technologies: Disconnect switches, Transistor-based SSCBs, Thyristor-based SSCBs, and Hybrid Circuit Breakers. Rodrigues (2017), Berg (2018), Pei (2016), and Hughes (2021) provide descriptions of a variety of SSCB configurations and devices suitable for MVDC application.

Disconnect Switches are electromechanical devices that provide an air (or vacuum) gap when in the off position. Disconnect switches can be specially designed for d.c. operation, or can be devices designed for a.c. operation, but in d.c. operation are only able to interrupt a fraction of the a.c. rated current. One option is to use vacuum interrupters from a.c. vacuum circuit breakers with high-speed Thomson coil actuators that can actuate within 1 millisecond (ms). (Peng 2016) A piezoelectric actuator based disconnect is also able to actuate in less than 1 ms. (Bosworth 2017) While fast operational speed is desirable, speed can be traded off for low cost, reliability, and reduced size and weight. Energy storage can compensate for a slower actuation time. The current interrupting capability of disconnect switches can range from essentially zero up to rated current. Most disconnect switches can interrupt only a small fraction of their rated current.

Because disconnect switches are mechanical, bidirectional operation is inherent. Unidirectional operation can be achieved by adding a set of diodes in series with the mechanical switch. To limit transient overvoltages, disconnect switches may require surge arrestors across them and to ground. Disconnect switches have much lower conduction losses as compared to transistor based and thyristor based SSCBs.

Transistor-based SSCBs typically use series and parallel combinations of insulated-gate bipolar transistors (IGBTs) or field effect transistors (FETs) to obtain the current rating and voltage rating needed. Transistor-based interrupters are generally unidirectional as depicted in Fig. 3(a-c). Two sets of devices as depicted in Fig. 3(d) are needed for bidirectional operation. Advantages of transistor-based SSCBs include very high speed actuation on the order of microseconds (Langston 2018)., and the ability to independently control operability in each direction. One concern with these SSCBs is that conduction losses can be in the tens of kilowatts for high current operation. Another concern is that interruption must occur quickly to prevent the fault current from exceeding the device ratings. Added system inductance may be required as described by Doerry (2021) but may limit the current ramp rates allowable from pulsed loads and stepped loads.

Thyristor-based SSCBs typically use a Silicon Controlled Rectifier (SCR). These SSCBs are turned on by providing a gate pulse to the SCR and are turned off by externally driving the current through the SSCB to below the SCR's minimum holding current. Turn off is often achieved through the use of energy stored in inductors and capacitors. Many different SSCB circuits exist that employ SCRs. These include the Z-Source Breaker (Maqsood 2015)(Corzine 2011, 2017)(Taft 2019), Y-Source Breaker (Al-Khafaf 2018), T-Source Breaker (Sapkota 2020), and H-Bridge (Cooke 2017). These SCR-based SSCBs are generally designed to automatically trip on a fault, which must be accounted for in the circuit breaker coordination method. Some circuits do not inherently have a method for a protective relay to trip the breaker, which either must be accommodated, or additional circuitry added to provide this capability. Other design features that must be accounted for are that some circuits are unidirectional, and others are designed for unipolar operation. Actuation times of SCR-based SSCBs can be on the order of tens of microseconds. Other devices, such as RB-IGCTs (Rodrigues 2021) and ETOs (Zhang 2018) have also been proposed for SSCBs.

Hybrid circuit breakers combine the low conduction losses of the disconnect switches with the interrupting capability of the transistor-based and thyristor-based SSCBs. Transistors, or thyristors, or both are used to commutate fault current from a normally closed mechanical switch so that it can open without an arc. Actuation times of Hybrid circuit breakers depends on the actuation time of the mechanical disconnect and can vary from under a millisecond to tens of milliseconds. The commutation circuitry determines whether a hybrid circuit breaker is unidirectional or bidirectional. Variations of hybrid circuit breakers are described by Alferov (2008), Venkata (2020), Wu (2017), Xu (2020), Xiao (2020), and Liu (2021).

STRATEGIES

Symbology for one-line diagrams does not currently exist to differentiate among the various MVDC isolation devices. Until standards define the appropriate symbology, the authors recommend the symbology depicted in Fig. 4. This set of symbols is easily extended to reflect new functionalities.

Fig. 5 depicts five isolation device strategies for the application of the different MVDC isolation devices to two switchboards of a shipboard system. Fig. 5(a-b) rely on SSCB for fault isolation. 5(a) employs bi-directional SSCBs between switchboards while 5(b) employs uni-directional SSCB between switchboards. The use of bi-directional SSCBs allows each switchboard to operate autonomously while the use of uni-directional SSCB between switchboards requires coordination between the two switchboards. Fig. 5(c-d) reflect disconnect based strategies. Fig. 5(c) relies upon tripping the SSCBs upon fault detection, isolating the fault by opening / closing disconnect switches, and then re-energizing the bus by closing the SSCBs. Fig. 5(d) operates essentially the same way, but the source converters and energy storage converters have the capability to turn off fault current, thereby enabling fault protection using only disconnect switches. Fig. 5(e) uses SSCBs to split the power system into multiple islands upon detection of a fault, one for each online generator set. The source converter for the generator set in the faulted island then turns off to enable the disconnect switches to isolate the fault. Once the fault is isolated, the source converter is turned on again and the bus ties closed to restore power. If a fault occurs on a bus tie, then the SSCBs can immediately isolate the fault without impacting sources.

Each of the strategies depicted in Fig. 5 is feasible. The strategy one implements will depend on the reliability, size, weight, and cost of protection devices available for the intended environment as well as the impact of derived requirements on the reliability, size, weight and cost of available source converters. All protection devices must be suitable for a marine environment. Protection devices for naval service must also be capable of normal operation in a high-impact shock environment. (See MIL-DTL-901 for example)

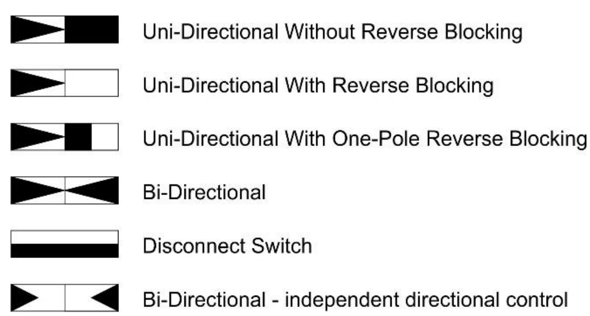


Fig. 4, Recommended symbols for different types of protection devices

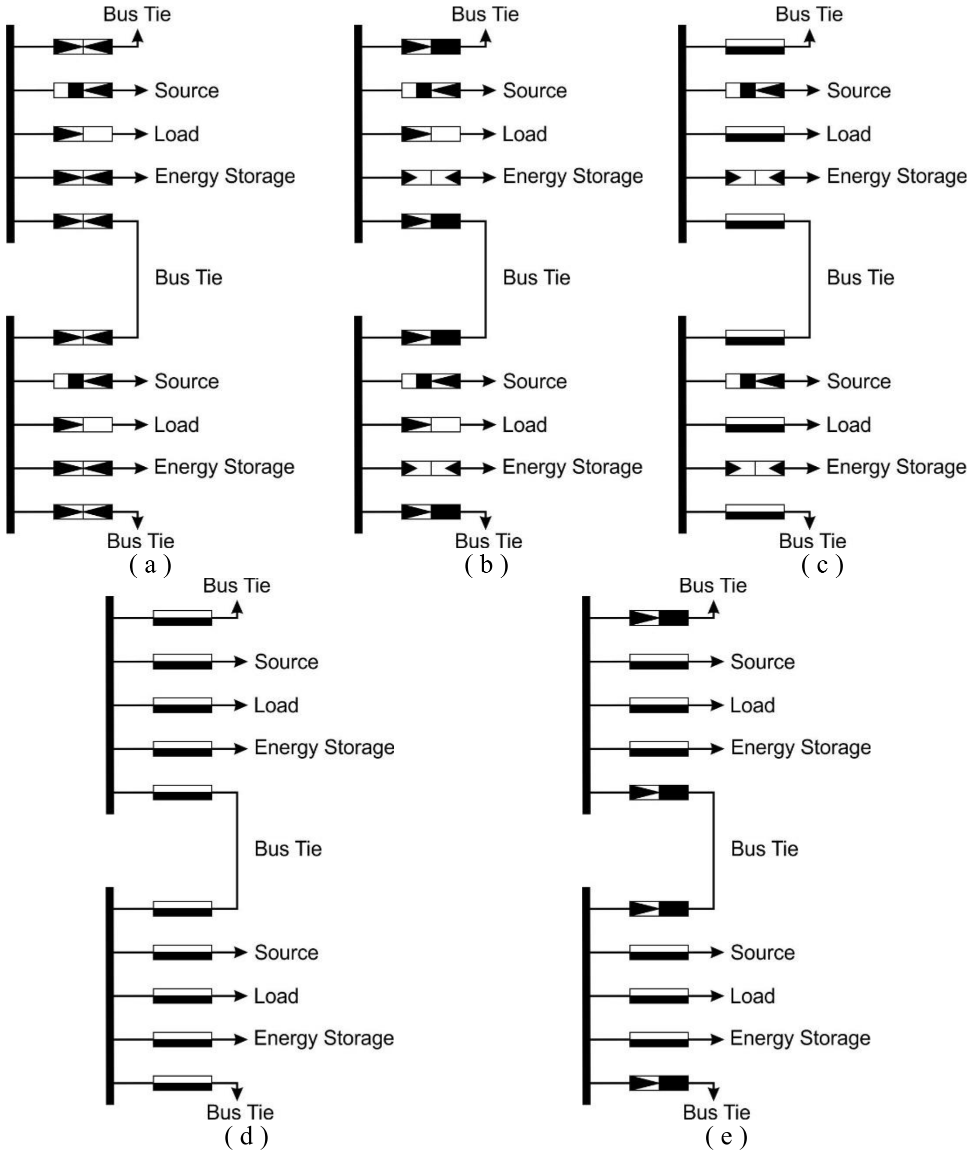


Fig. 5, Isolation device strategies for MVDC fault protection

QUALITY OF SERVICE (QoS)

As defined in IEEE Std. 45.3, Quality of Service (QoS) is a metric of power system reliability measured as a Mean Time Between Service Interruption (MTBSI). A service interruption occurs when power quality falls outside of normal bounds for a duration longer than a load can tolerate. This duration is compared to the length of power interruption due to system reconfiguration (t1 or reconfiguration time) and to the time it takes to start and bring online another generator set (t2 or generator start time). The choice of MVDC fault protection strategy and isolation device technology directly impact t1. An MVDC system t1 longer than a load can tolerate can be mitigated by energy storage integrated into power conversion equipment between the MVDC bus and the load. The magnitude of the load (kW) and the duration of the outage (milliseconds) will determine the amount of energy storage required.

FAULT DETECTION

The first indication of a line-to-line fault is usually that the line-to-line voltage drops below the normal range as defined in the MVDC interface standard. The fault current will ramp up at a rate inversely proportional to the system inductance and should normally be faster than the current ramp rate for pulsed loads or step loads. Thus, a current ramp rate greater than allowed by the MVDC interface standard is also an indication of a fault.

Arc faults are more difficult to detect because their impedances may not cause currents and voltages to fall outside of normal ranges. Arc faults can be detected by their current spectral signature. Fourier analysis or wavelet transformations can be employed to detect arc faults (e.g. Wang 2015).

Ground faults are detected by measuring the neutral to ground voltage which is the average of the positive conductor voltage to ground and the negative conductor voltage to ground. Under normal conditions, the neutral to ground voltage will be nearly zero. During a ground fault, the neutral to ground voltage magnitude will be approximately equal to half the line-to-line voltage magnitude. Additionally, the common-mode (CM) current, equal to the sum of the conductor currents in the same direction, will increase due to a ground fault. The differential-mode (DM) current, equal to half the difference of the conductor currents in the same direction, will not change significantly during a ground fault. The DM current is the normal, intended current of the power system. The CM current is generally unintended and is due to CM voltages interacting with parasitic impedances, filter impedances, and grounding system impedances to ground.

FAULT LOCALIZATION

Once a fault has been detected, determining the location of the fault is necessary to ensure the proper isolation devices are employed to isolate the fault while minimizing the impact on served loads.

Ground faults can be localized via variety of methods. A traditional way is to inject a current signal at the grounding resistor and use current sensors to trace this signal to the ground fault. Ground faults can also be located using only sensors through feature extraction (spectral or wavelet) of current waveforms. (Pan 2008) (Li 2014)

Arc faults can similarly be located through feature extraction of current waveforms. Additionally, arc faults in switchboards and other enclosed equipment can be detected through pressure and photo sensors. (Land 2002). High temperatures in cable and cable connections, an indicator of an arc fault, can be localized by embedding a fiber optic cable in the MVDC cable and using distributed optical fiber temperature sensing (Gan 2011)(NSRP 2018).

Ideally, line-to-line fault localization should take only microseconds before the fault current grows so large to prevent the SSCB from clearing the fault. Monadi (2015) describe a number of different methods for localizing line-to-line faults in d.c. systems. The most promising methods are not the same for all power system elements.

Line-to-line faults in loads or the feeder cables to the load can be localized by either overcurrent, or excessive current ramp rate. Loads should have the ability to detect internal faults and initiate isolation actions. For added protection, the load feeder cable can be considered a fault protection zone for differential protection; the fault can be isolated to the cable if for one or both conductors, the current magnitude of the cable at the switchboard or load center does not equal the current magnitude at the load.

If provided with a device that provides uni-polar reverse blocking, then an indication of a line-to-line fault in the source or on the source cable will be that the source ceases to provide power to the distribution system. If provided with a bidirectional disconnect, then a reverse current through the disconnect is an indication of a fault in the source or source cable. Sources should have the ability to detect internal faults and initiate isolation actions. For added protection, the source cable can be considered a fault protection zone for differential protection.

Each bus tie and each switchboard should be defined as a protection zone. Differential and directional protection should be used to localize faults to the bus tie or switchboard.

In a MVDC system, implementing differential protection can be challenging while the fault current is ramping; current measurements must be made near simultaneously to avoid concluding a fault exists in a protection zone that is not faulted. If the fault cannot be localized before SSCBs must clear the fault, then it may be necessary to remove all MVDC power from the bus and then inject a constant current into the bus to facilitate fault localization via differential protection. The use of a constant current eliminates the need for highly coordinated current measurements.

FAULT ISOLATION

Fault isolation consists of opening and closing isolation devices to reconfigure the power system to isolate faulted equipment and cable and preserve or restore power to the maximum number of loads. Ideally fault isolation actions occur after the fault has been localized, but this may not always be possible.

The reconfiguration time t1 is composed of the time to detect, localize, and isolate the fault and restore power to loads will take time. Power conversion equipment serving mission critical loads should have sufficient energy storage to serve its loads for three to six t1 time intervals to address multiple near simultaneous faults.

If disconnect switches are employed, the bus typically must be completely de-energized before the disconnect switches are configured to isolate the fault. Once the disconnect switches are configured, power can be re-applied. (Soto 2017) This may result in a t1 ranging from 20 to 100 milliseconds.

If SSCBs are employed, it may be necessary to trip all SSCBs experiencing an overcurrent, then once the fault has been localized, opening or closing the appropriate SSCBs to restore power to the maximum number of loads while isolating the fault. This may result in a t1 on the order of tens of microseconds up to 100 microseconds for transistor based SSCBs and up to ten milliseconds for thyristor based SSCBs.

In a high resistance grounded system, a ground fault can be tolerated for a short period of time. The ground fault should be cleared as soon as the operational situation permits to preclude a second ground fault on the other polarity conductor from occurring and resulting in a line-to-line fault.

For most ships, the MVDC power system will have relatively few elements and the reconfiguration algorithms to restore power to the maximum number of loads are straight forward. Neuwirt (2018) provides power restoration algorithms suitable for most MVDC applications.

INTEGRATING FAULT PROTECTION ACTIVITIES

Fault protection within an MVDC power system will require the integration of a number of activities, each with its own timeline. Fig. 6 illustrates one possible series of activities for accomplishing fault protection. Not every fault protection strategy may work through the same series progression. As discussed with respect to the five strategies proposed above,

Fig. 5(e) uses SSCBs to split the power system into multiple islands upon detection of a fault without waiting for localization to occur as shown in Fig. 6.

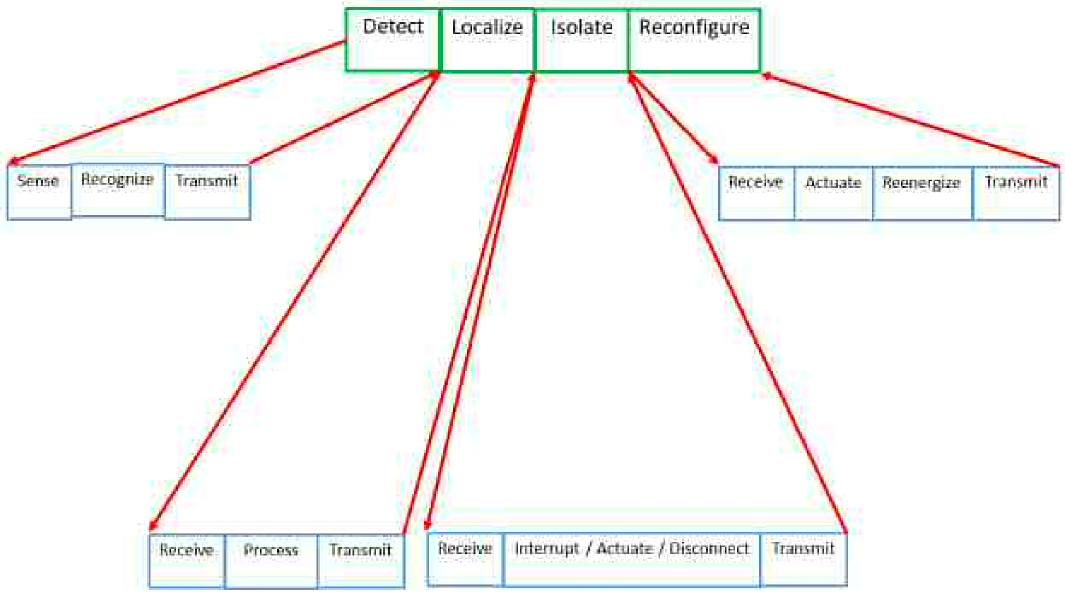


Fig. 6, Activities within MVDC fault protection timeline

The duration of each of the activities shown in Fig. 6 depends upon the details of the selected strategy and implementation. The duration of activities discussed in this paper are plotted on a logarithmic scale in Fig. 7 to provide insight into the importance of determining the dominant contributor to fault protection durations. In an MVDC power system, the t1 reconfiguration time is dominated by the time that the disconnect elements require to completely actuate.

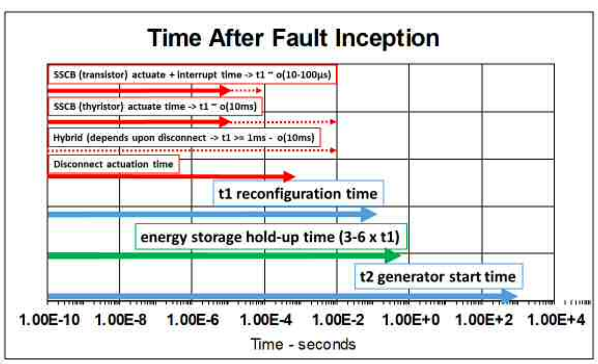


Fig. 7, MVDC fault protection duration times

Fig. 7 illustrates durations for only a few of the activities shown in Fig. 6. Durations for localization activities, such as processing inputs to determine fault location, are still in question. Durations for disconnect actuation times will be better known once MVDC disconnect switches are commercially available.

BEHAVIOR OF SOURCES AND LOADS

The system fault detection system will likely not be able to detect all faults within the boundaries of source or load equipment. The specifications for MVDC system connected equipment should require detection and corrective action for faults within the boundaries of the equipment other than those that would otherwise be detected by the system fault detection system (i.e. over-current, excessive current ramp rate, etc.) Detecting and taking corrective action due to arcing faults within equipment is one example of a type of fault best left to the equipment manufacturer.

A.c. fuses between the generator and rectifier of a generator set should be employed to protect the generator from a faulted rectifier or a failed generator breaker. These fuses should be designed so that they coordinate with the generator breaker; the generator breaker should be designed to always remove fault current from a down-stream system fault before the fuse blows. The fuses should only blow if there is a fault in the rectifier or the generator breaker. An a.c. circuit breaker may be used in place of the fuses, but the a.c. circuit breaker likely will be larger, heavier, and more expensive.

The rectifier and the isolation device connecting the rectifier to the MVDC bus must have the capability to interrupt the fault current from the generator set. Some rectifiers (such as the full bridge MMC) have the ability to current limit into a fault while other rectifier topologies do not. Those that have the ability to current limit into a fault are compatible with a disconnect switch while those that are not must employ a SSCB. Trade-off comparisons of different rectifier choices should include the impact of the choice on the selection of isolation device (Cuzner 2017).

Loads directly connected to the MVDC bus should be capable of tolerating power interruptions of duration t1. During a power interruption of duration t1, propulsion motor drives and thruster drives should have sufficient energy storage to keep control systems online, but should allow the propulsion motor or thruster to coast until the power interruption is over. Other loads should incorporate sufficient energy storage to ride through an interruption of duration t1 without a change in operating mode, or go into a low power consumption mode until power quality is restored.

Loads must also limit maximum steady-state current, current ripple, inrush current and current ramp rates to the values specified in the interface standard. This is critical to ensuring the fault protection system can successfully discriminate between normal operation and faulted operation.

Large MVDC loads such as propulsion motors should ideally draw roughly half their power from each of two MVDC inputs. These inputs should be connected to independent switchboards such that if one switchboard is faulted and isolated, continued operation, albeit at reduced power, is still possible. Other MVDC mission critical loads should be able to draw their entire power from each of two MVDC inputs connected to independent switchboards. MVDC to low voltage converters may have only one MVDC input if the low voltage mission critical loads are provided alternate sources of power from a different source. (Doerry 2015)

SIZE CONSIDERATIONS

Because MVDC isolation devices are not yet commercially available, definitive conclusions with respect to the relative size of different strategies cannot be made. However, with suitable assumptions that must be verified once commercial products are available, relative size trends can be made.

If we assume a notional switchgear “cabinet” to be roughly 1 meter deep by .8 meters wide by 1.8 meters high, then it will have a little less than 1.5 cubic meter of volume. This volume should be sufficient for housing and cooling one uni-directional SSCB or at least two disconnect switches. A bidirectional SSCB would require two cabinets.

If loads are required to ride through power interruptions, additional energy storage may be required. When using disconnect switches, t1 can be on the order of 100 ms. If we require the energy storage to have sufficient capacity to handle three near simultaneous fault clearing events, then the energy storage should have capacity to supply power for 300 ms.

A commercially available ultracapacitor (MAXWELL 2021) has a maximum stored energy capacity of 3 Wh and has bounding box dimensions of 60 mm x 60 mm x 166 mm. This translates into an energy density of 18 MJ/m^3. This value is considerably larger than can be realized in physical hardware. Voltage derating to improve service life, minimum operating voltage limits, packing factor to enable cooling, structure, control and protection hardware will likely result in a cabinet level energy density about 5% of the ultracapacitor rated energy density. With careful design, the cabinet level energy density could be higher. Hence at the cabinet level, one could expect to achieve at least 0.9 MJ/m^3. A 3 MW load operating for 300 ms would also require about 0.9 MJ, or about 1 m^3 of cabinet volume; about 2/3 the volume of a switchgear cabinet. This is a very rough estimate that should be accurate within an order of magnitude.

If a greater amount of energy storage is provided to serve loads for a longer time, perhaps to enable continuity of power while a generator set starts in support of reliable operation with a single generator set online (t2), then no additional energy storage is needed to support fault protection.

Since t1 for a SSCB-based system is on the order of 10 to 1000 times faster than for the disconnect-based system, the extra volume required for energy storage is considerably less. The capacitance of the input filters of the converters is likely sufficient to enable ride-through, or can be increased moderately to enable ride-through.

Tables 1 through 4 develop the comparison of the total number of cabinets required for each of the configurations depicted in Figs. 1-2. Table 1 provides the number of isolation devices for the different functions for each of the configurations. It differentiates between loads that are expected to ride through fault clearing without energy storage and those that are served by energy storage to ensure continuity of power while a fault is cleared. Table 2 identifies the type of isolation device for each function for each of the isolation device strategies depicted in Fig. 5. Table 3 displays the number of cabinets required for the types of isolation devices from Table 2. This analysis assumes the energy storage would employ a cabinet roughly the same size as the switchgear cabinet. Table 4 combines Tables 1 and 3 to present the total number of cabinets required for each configuration.

From Table 4, one can conclude that a SSCB only strategy (Fig. 5(a-b)) will likely require more cabinets and correspondingly more arrangeable area than strategies that employ disconnect switches (Fig. 5(c-e)). This conclusion assumes that appropriate SSCBs and disconnect switches become commercially available.

Table 1. Number of isolation devices by function for configures depicted in Figs. 1-2

Isolation Device For:	Configuration 1a	1b	2a	2b
Source	4	8	4	8
Bus Tie	2	2	12	14
Load without Energy Storage	6	8	4	4
Load with Energy Storage	2	2	5	5

Table 2. Type of isolation device by function for isolation device strategies depicted in Fig. 5

Isolation Device For:	Isolation Device Strategy 5a	5b	5c	5d	5e
Source	SSCB	SSCB	SSCB	Disconnect	Disconnect
Bus Tie	SSCB x 2	SSCB	Disconnect	Disconnect	SSCB
Load without Energy Storage	SSCB	SSCB	Disconnect	Disconnect	Disconnect
Load with Energy Storage	SSCB	SSCB	Disconnect	Disconnect	Disconnect
Additional Load Energy Storage	No	No	Yes	Yes	Yes
Source Converter limit fault current	No	No	No	Yes	Yes

Table 3. Number of cabinets required for each isolation device for strategies depicted in Fig. 5

Isolation Device For:	Isolation Device Strategy 5a	5b	5c	5d	5e
Source	1	1	1	0.5	0.5
Bus Tie	2	1	0.5	0.5	1
Load without Energy Storage	1	1	0.5	0.5	0.5
Load with Energy Storage	1	1	0.5	0.5	0.5
Load ESS	0	0	1	1	1

Table 4. Total number of cabinets required by configuration for isolation device strategies

Configuration	Isolation Device Strategy 5a	5b	5c	5d[1]	5e[1]
1a	16	14	11	9	10
1b	22	20	16	12	13
2a	37	25	20	18	24
2b	45	31	25	21	28

Note 1: 5d and 5e may require additional volume for source converters

EQUIPMENT MAINTENANCE CONSIDERATIONS

While SSCBs are effective at switching large MVDC currents on and off, in the off state they are not totally off. Both transistors and thyristors can exhibit a leakage current when turned off that can result in the SSCB being capable of supplying milliamps or more current to loads that are nominally off.

This leakage current can be useful in that it can be used to keep input filter capacitors of loads charged while equipment is off, reducing the time to "turn on" a load. However, this leakage current could be deadly to maintenance personnel.

When performing maintenance on MVDC equipment, a means for providing an "air gap" in the conduction path to the equipment should be provided. This can be done through the use of mechanical disconnect switches, or by being able to physically rack out SSCBs. If the latter approach is used, the SSCB and its associated switchgear should be designed such that the SSCB motions are controlled and that SSCB motion is constrained to prevent damage or injury due to ship motions.

MVDC equipment should also be provided with a means for safely isolating or discharging energy storage within the equipment. Consideration should also be given to providing the capability to temporarily and safely ground each MVDC input conductor as a secondary means of protection.

If power cable shield current is anticipated to exceed a few milliamps, provisions should be provided to safely interrupt this shield current before the cable is disconnected from or connected to equipment.

ISOLATION DEVICE DATA

Producers of MVDC isolation devices and associated switchgear should provide the following data to facilitate protection system design:

Isolation Devices

a. Isolation device mass and size properties
b. Voltage and current rating
c. Power quality interface standard employed
d. Maximum current interruption capability
e. Operation time (opening and closing)
f. Inductance per pole
g. Minimum system inductance required
h. Cooling interfaces
i. Heat produced as a function of current
j. Control power requirements
k. Leakage current
l. Available power quality measurements

Switchgear

a. Switchgear mass and size properties
b. Maintenance and shock excursion (if applicable) envelopes
c. Voltage and bus current rating
d. Power quality interface standard employed
e. Cooling interfaces
f. Control power requirements
g. Isolation device racking mechanism description
h. Protection relay functions and interfaces
i. Available power quality sensors and measurements
j. Control interfaces
k. Arc flash criteria

CONCLUSIONS

While MVDC is attractive for commercial and naval applications, circuit protection remains a barrier. Considerable research has developed the technology necessary to implement MVDC circuit protection, but this technology has not yet transitioned to commercially available isolation devices and switchgear.

This paper detailed the inter-relationships among the different functionalities that isolation devices can have, the technologies for implementing isolation devices, power quality requirements, protective relaying strategies, source design, load design, and energy storage. Once commercial isolation devices and switchgear become available, a trade-off analysis of feasible protection strategies will become possible.

Technology has been developed; it is time to transition to product development.

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