DYNAMIC POSITIONING CONFERENCE
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Leveraging Single-fault Tolerance to Support Business Objectives Session

Closed bus tie operation with Onboard DC Grid

By

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Introduction

To support the maritime industry in developing efficient and safe onboard power systems, classification societies and technical associations are introducing additional requirements to protect power plants with closed bus-ties. This article describes how ABB's Onboard DC Grid™ power system platform has been built around a versatile protection philosophy to deliver reliable and fault-tolerant DC systems that meet evolving requirements for redundancy and integrity.

Closed bus-tie arrangements have become a common feature across multiple vessel types in the maritime industry, often with the flexibility to open the bus during critical operations. However, their adoption in dynamic positioning (DP) vessels has been approached with caution, due to the heightened risks associated with failure propagation. Recently, advancements in system protection and the drive for greater operational efficiency have led to a broader acceptance of closed bus-ties across different ship types, unlocking both operational and environmental benefits.

Closed bus-ties allow electrical power transfer between different redundancy zones within a vessel's power system, enabling optimized power distribution. This configuration reduces the number of generators required to operate at the same time, leading to lower fuel consumption, lower emissions, decreased engine running hours, and reduced wear, tear, and maintenance needs. Furthermore, integrating closed bus-ties facilitates the effective use of battery energy storage systems, enhancing overall energy efficiency and supporting the industry's decarbonization goals.

Operating with closed bus-ties also presents challenges, primarily related to the risk of failures spreading throughout interconnected parts of the power systems. A fault in one section can quickly impact the entire system if not properly managed, raising concerns about system reliability and safety. Historically, these risks have led several operators to prefer open bus-tie configurations, isolating power system sections to prevent fault spread but at the cost of operational inefficiencies.

To ensure that vessels with closed bus-tie systems maintain high safety and reliability standards, classification societies and maritime technical associations are updating their guidelines and recommended practices. These updates aim to balance the benefits of closed bus-tie operations with the necessary safety measures to mitigate associated risks. One of the safety measures introduces enhanced requirements for the power system protection for closed bus-tie operation.

This article explores how ABB's Onboard DC Grid™ technology addresses the latest power plant protection requirements. We begin with an overview of the system's core principles and protection concepts before looking into advanced protection strategies and the design of closed bus-tie configurations that enhance redundancy and system integrity.

Abbreviations

Term	Description
AC	Alternating Current
AVR	Automatic Voltage Regulator
DC	Direct current
DP	Dynamic Positioning
EF	Earth fault
FMEA	Failure Mode and Effect Analysis
kA	Kilo Ampere

Short circuits in DC systems

Short circuits in DC system are inherently different for short circuit in AC systems. While in AC systems the short circuit currents originate from the generators, the fault current originates from the DC bus capacitors in a DC system.

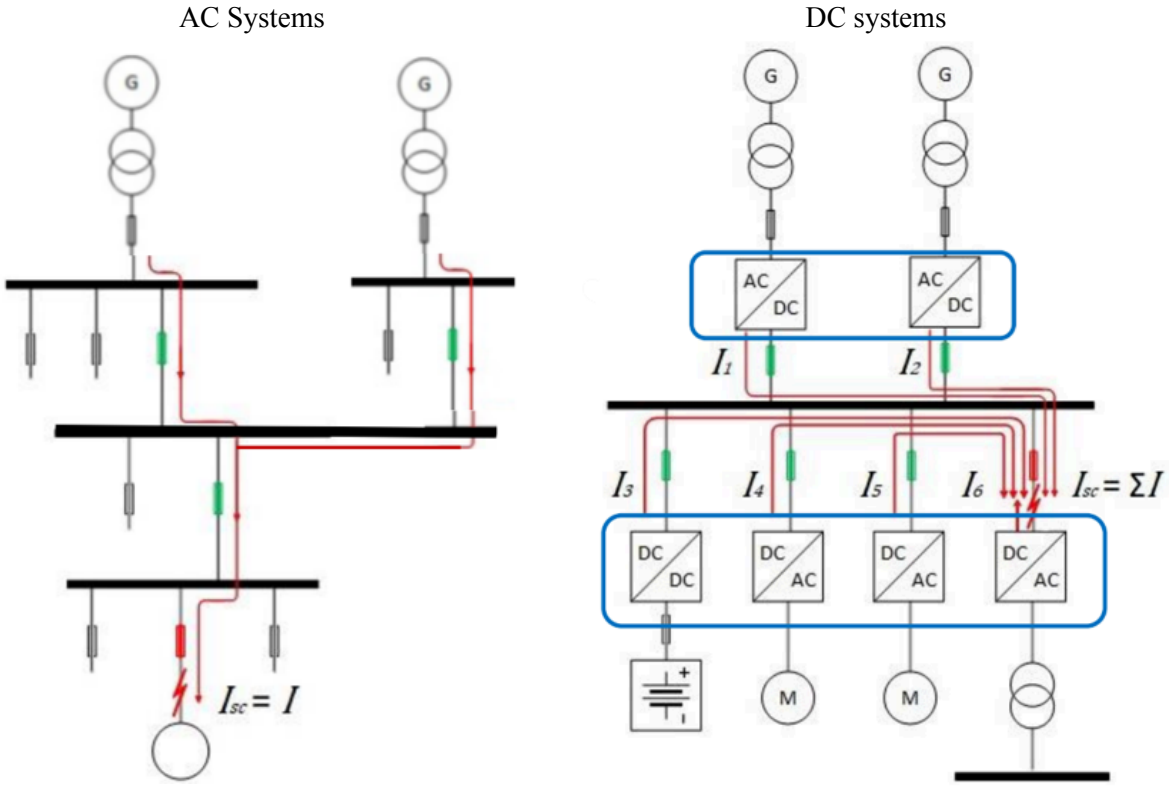


Figure 1: Fault currents AC vs DC

The difference between AC and DC type short circuits are notable also in their rise time, peak and duration. Short circuits originating from generators are limited by the impedance of the windings, cables and fault current paths. The DC bus is characterized by converters with integrated capacitor banks that support the DC voltage. The capacitive nature means that fault currents in this zone have very short time constants and reach high levels quickly, necessitating rapid fault clearance.

As a comparison, its possible to say a low voltage generator will have a fault current in tens of kA and a rise time of tens of milliseconds, while a DC current will have a fault current of up to a few hundred kA and a rise time of a few hundred microseconds. I.e. 10 times higher and 100 times faster. See Figure 2 for examples.

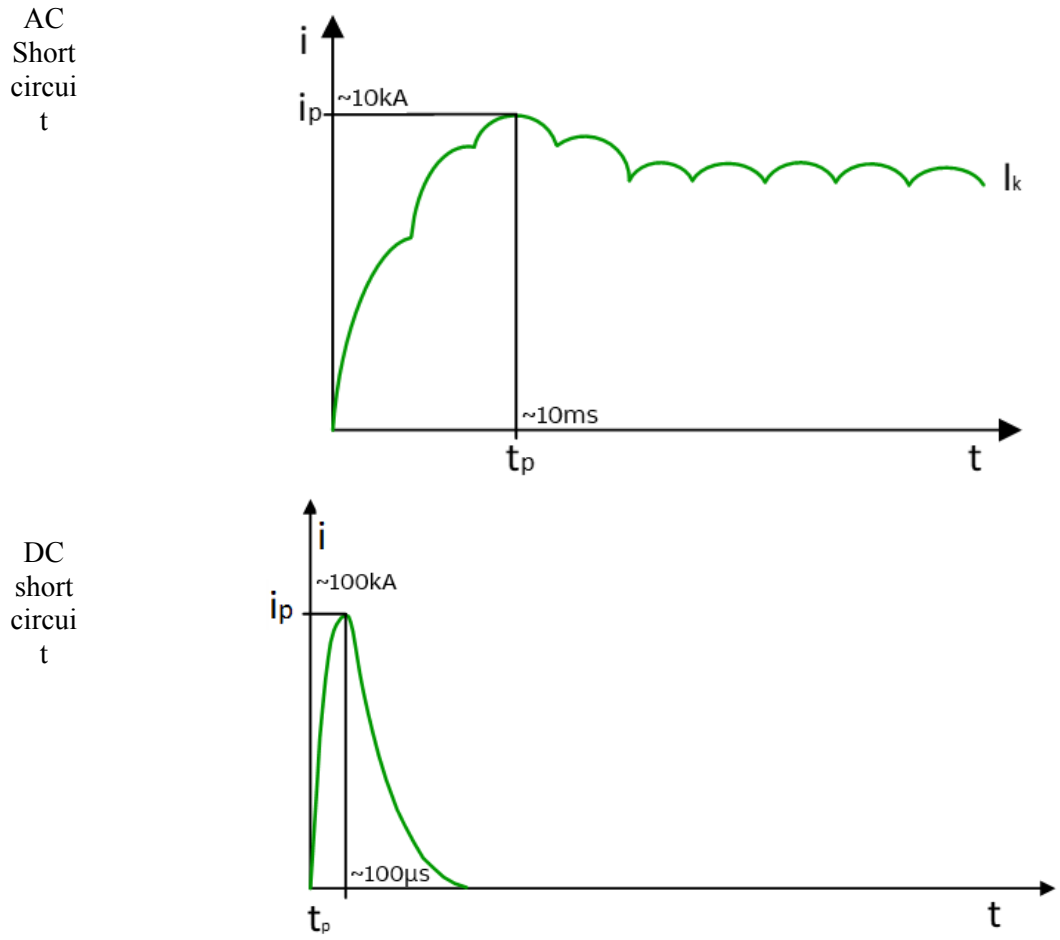


Figure 2: Example of short circuit currents to a DC bus

Due to the fast-rising currents normal air circuit breakers cannot be used to prevent short circuits in one bus from another. They must be complimented by solid state components to ensure that the fault is cleared fast enough. Solid state breakers utilise semiconductors to block the fault current and will typically block within 5-50us, depending on rise time and equipment performance.

The solid-state circuit breakers design and performance depends on the supplier. In the dotted box below is how a typical solid state circuit breaker will look like in an ABB single line diagram.

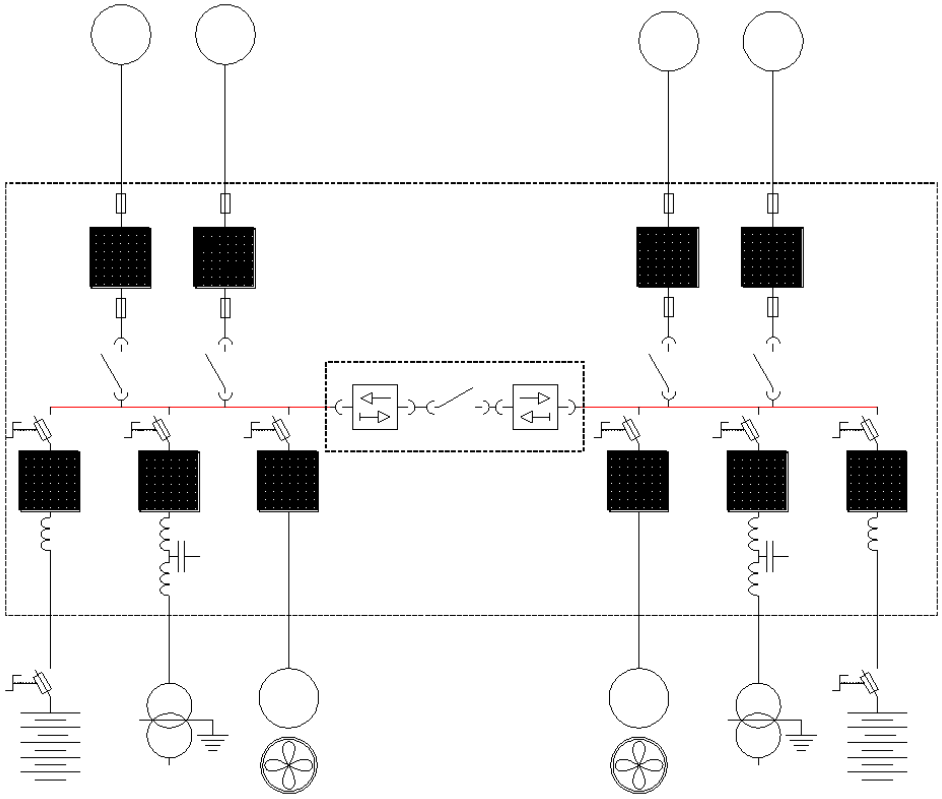


Figure 3: Solid state circuit breaker in a DC system

Onboard DC Grid™ short-circuit protection

Onboard DC Grid™ employs a patented protection scheme, in which ABB's input circuit (IC) plays an essential role. The IC is a solid-state current interrupting device complementing fuses, isolators, breakers, and converter control in clearing short-circuit currents and isolating faults. It segregates the system into two distinct protection zones:

- DC-grid (blue): this is the power distribution zone connecting DC switchboards together.
- DC-link (red): this is equivalent to the traditional DC-link of a multi-drive, containing the power sources and consumers.

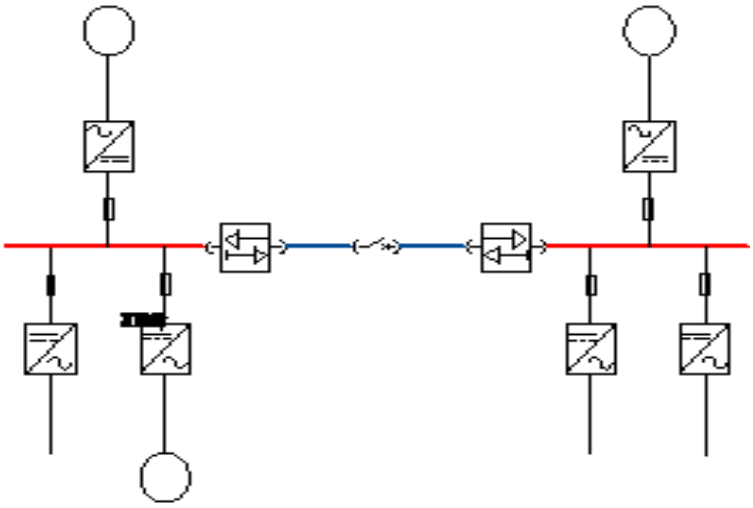


Figure 4: Example of a simple two-split Onboard DC Grid™ system.

The DC link zone is characterized with fast transients as described in the chapter above, but the DC-grid zone has fault currents with longer time constants, allowing for a slower-acting protection approach.

The IC is a unidirectional component forming the boundary between the link and grid zones. Each IC protects its respective DC link, allowing current to flow freely in both directions during normal operation. However, if a fault occurs outside the DC link, the IC rapidly blocks the current to prevent its healthy DC link from discharging into the fault.

To explain how the IC works in more detail, let us assume there is a short-circuit fault in the inverter module feeding the motor in Figure 2, with the system operating in a closed bus-tie configuration prior to the fault. IC1 protecting DC link 1 will not block, as its blocking functionality is from link towards grid side only. IC2, on the other hand, will block to protect the healthy DC link 2 from discharging towards the fault. The current through IC2 from link to grid will progress as shown and described below.

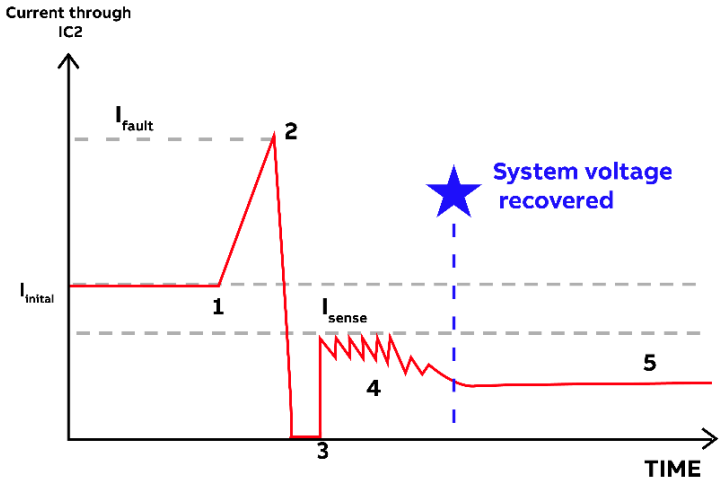


Figure 5: Current flowing through IC2 from link to grid during the fault.

1. The fault in the inverter occurs and the current through IC2 will rapidly rise from its initial value.
2. The current through IC2 reaches fault current levels, typically a few kiloamps. This is detected by two separate protection functions in the IC, one hardware-based and one software-based, at which point the input circuit takes preventive action and blocks. This happens within tens of microseconds after the fault occurrence.
3. IC2 outputs a controlled sensing/charging current, which is used for further localizing the fault and charging up neighboring DC links. If IC2 detects that the sensing/charging current re-establishes the voltage on the DC grid and DC link 1, it means the fault has been cleared.
4. Either way, the motor inverter feeder fuse F1 blows due to the DC link capacitors on DC link 1 discharging into the fault. This clears the fault, and the motor load trips, which typically happens within ~0.5–1 millisecond.
5. The controlled current from IC2 together with currents from any available sources on DC link 1 (e.g., generators and batteries) re-establishes the voltage on the DC grid and on DC link 1. This means the fault has been cleared and operation continues with remaining load after IC2 fully opens.

Let us now increase complexity and consider how the IC operates for a fault in a four-split system. The four DC links in Figure 4 are connected in a closed ring prior to the fault, and the fault occurring is a bolted short-circuit on the busbars on the grid (blue) side of IC1. As the fault cannot be cleared by a fuse, it requires DC link 1 to be segregated from the rest of the system, meaning opening CB11 and CB12.

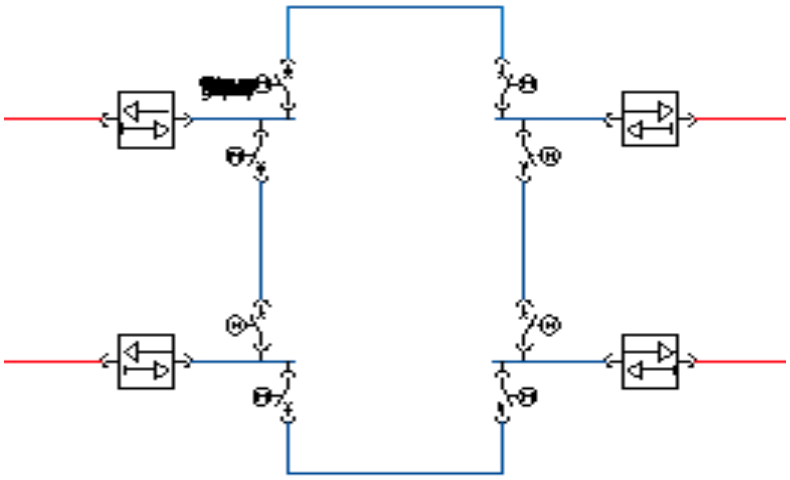


Figure 6: Example bus-tie configuration of a four-split Onboard DC Grid™ system.

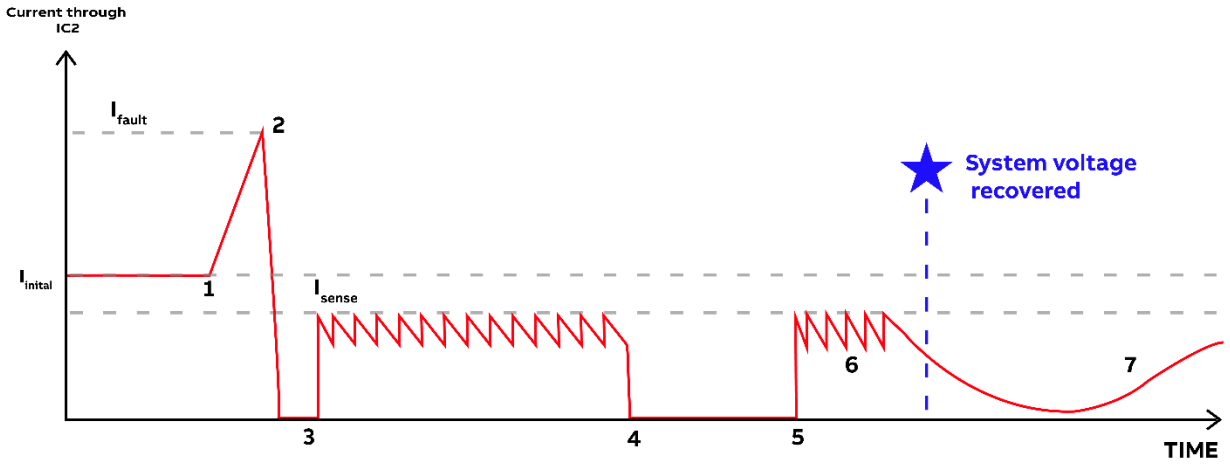


Figure 7: Current flowing through IC2 from link to grid during the fault.

Figure 5 shows the current passing through IC2, assuming that IC2 was feeding the closed ring prior to the fault. Points 1 and 2 recreate the path for current vs time shown in Figure 3. The behavior of the currents through IC3 and IC4 will be similar to that through IC2 throughout the fault scenario.

3. The input circuits output a controlled sensing/charging current. Based on the direction of current flow through the bus-tie breakers, the fault is localized. Through communication in the protection network, it is concluded that CB11 and CB12 must open to segregate the fault from the system. After a time-delay allowing fault clearance (which in this case does not happen), CB11 and CB12 open.
4. In some cases, the course of the current will go directly from point 4 to point 6, meaning the system will recharge and reestablish after the fault has been segregated. The blocking of current is required between point 4 and point 5 if there is a need to shed load somewhere in the system for the input circuit(s) to recharge the system voltage. The time between 4 and 5 allows for necessary load shedding to occur.
5. The input circuits will again output the controlled sensing/charging current.
6. The controlled current from the input circuits together with currents from available sources re-establishes the system voltage, allowing the input circuits to fully open.
7. DC link 1 is now separated from the closed ring. The system voltage recovers and the closed ring operation between the remaining three DC links continues.

Enhanced short-circuit protection for vessels with closed bus-tie operation

The Onboard DC Grid™ protection philosophy and the capabilities of the input circuit (IC) can be tailored to meet the specific requirements and needs of any vessel. The system also scales effectively from the simplest to the most advanced configurations, including closed bus-tie systems meeting the stringent requirements of DP2 and DP3 notations.

For all vessels operating with a closed bus-tie Onboard DC Grid™ system, it is important to consider scenarios where the IC unit fails to block fault currents. This may happen if a component within the unit has a malfunction. While this does not cause immediate problems, it can lead to additional damage if a second fault occurs. To avoid such situations, the IC is equipped with sophisticated diagnostic and monitoring functions that detect and identify potential failures. As previously mentioned, the IC is also equipped with two separate means of fault detection, one hardware-based and one software-based, to have a backup detection method should one of them fail.

Because of the extensive monitoring and the separate fault detection functions, some regulatory bodies permit hidden failures to be disregarded for the IC. Instead, the IC is considered to have redundancy built-in to its protective features.

However, to meet the most stringent class notations, protection mechanisms must have two separate and independent protective functions—primary and secondary—to effectively mitigate the impact of hidden failures. This has a significant influence on system design, as all protection layers must be fully redundant and free from interdependencies between redundant parts. For an Onboard DC Grid™ system, relying on a single IC to protect a DC link is therefore no longer sufficient. Additionally, redundancy must be built into the protection networks and protection logic.

Figure 6 shows the bus-tie configuration for a 4-split Onboard DC Grid™ adhering to the strictest closed-bus notations, incorporating double ICs and redundant protection functions.

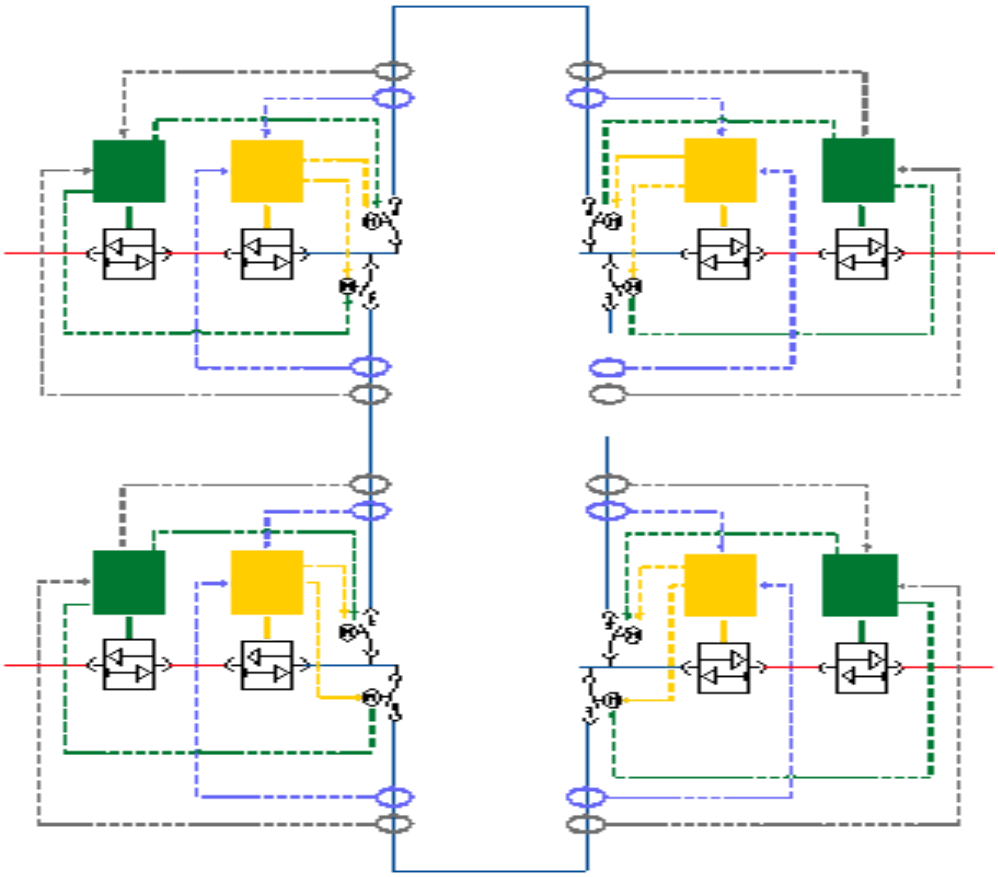


Figure 8: Enhanced protection setup for Onboard DC Grid™ with redundant ICs and protective functions.

The protection setup in Figure 6 features enhanced redundancy in short-circuit blocking by incorporating two ICs in series operating independently from one another. Each IC communicates with a dedicated protection relay, which can open both bus-tie breakers and has independent current sensing capabilities. Additionally, the protection relays are on different communication networks, identified as green and yellow. This configuration leads to independent fault clearance capability and optimal redundancy in the protection system.

The protection configuration is not merely a theoretical concept—it has also been tested and validated in practice. Its correct functionality has been demonstrated through fault simulations and live short-circuit testing at ABB Marine's facilities. Based on simulation of protection signals, the protection logic has been demonstrated to handle all major short-circuit locations in the system effectively. This includes accounting for hidden failures within the protection system and failure of the protection network. Additionally, live short-circuit testing at various locations has verified that the input circuits together with the protection relays can accurately identify the location of faults and selectively open the correct breakers. In short, the protection setup is proven to provide the necessary integrity and redundancy for safe closed bus-tie operation.

Onboard DC Grid™ voltage variations during in fault scenarios

Faults in a DC distribution system will cause voltage variations due to change in the power supply or consumption. The DC switchboards include a lot of capacitors that are parallel connected to the DC bus. If the energy input to the DC bus exceeds the energy output, the voltage rises and vice versa. In order to prevent that harmful voltages occur or blackouts, the voltage fluctuations must be properly managed.

The energy sources of a DP vessel are predominantly synchronous generators connected to by rectifiers. In case a large load trips, the generator will see a load rejection. Due to the energy stored in the windings and the excitation circuit and the response time of the automatic voltage regulator, there will be a temporary overvoltage on the generator output terminals. Since the rectifier will conduct if the peak AC voltage is higher than the DC voltage, the energy will flow into the DC bus. To manage the overvoltage, a few methods can be applied:

1. Include over voltage choppers or breaking resistors in the DC bus
   These devices will add load to the system, if the voltage rises above normal operating level. The added load will ensure that the overvoltage on the AC side is less and that the DC voltage stays within acceptable limits.
2. Converter controls
   Converter can help the overvoltage in a few different ways.
   i. If the rectifier is thyristor based, it may reduce the firing angle or block completely in case of overvoltage and this will limit the energy flowing into the bus.
   ii. If the converter is IGBT based it may normally be able to block the power flow in case of overvoltage.
   iii. Load converters may help the situation by providing reactive currents in i.e. motors to increase losses and thus add load to the system.
3. Overvoltage can be taken into consideration when selecting the nominal voltages. The generator voltage may be selected to be lower if the voltage variations are expected to be substantial.

Managing undervoltage is also important. In a scenario where there is an overload in the system, the DC voltage will drop. This can be due to start of heavy consumers, tripping of generators or tripping of bus ties if the power generation is not perfectly distributed. In either case, it is important that the power supply to essential consumers is secured and that the power plant will be back in normal operation as fast as possible. The voltage variation needs to be coordinated in voltage and time to ensure that the least essential system is shed first and that the load disturbance is minimal Figure [7] below illustrates such a coordination example:

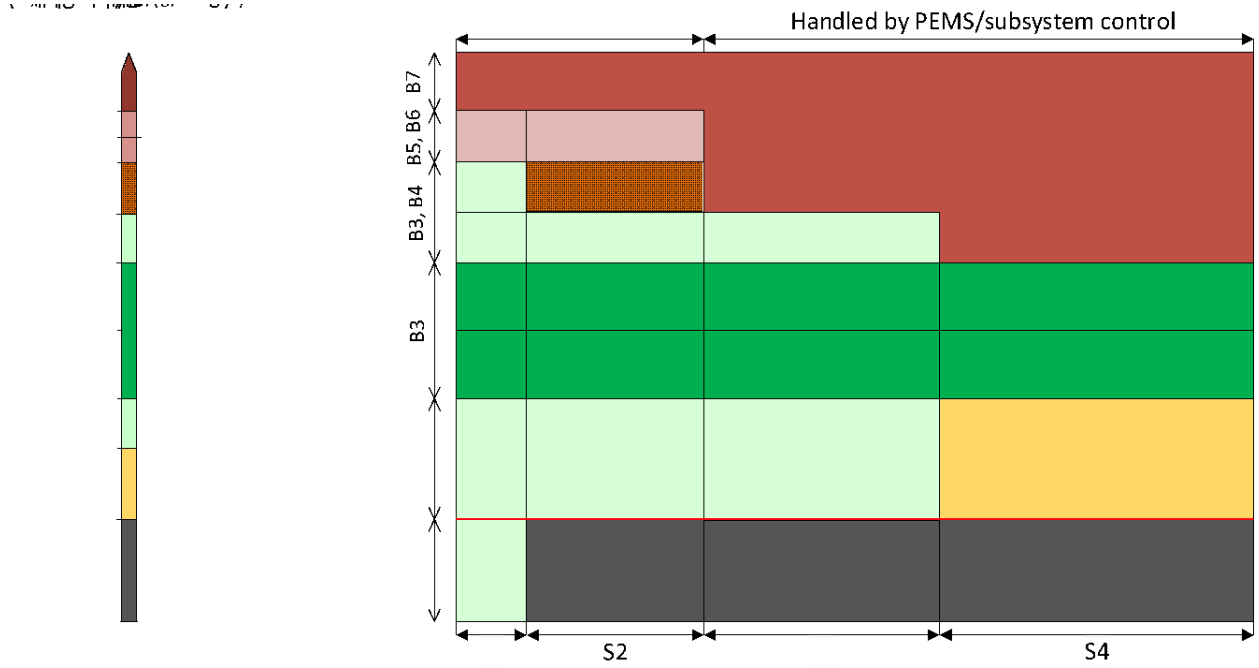


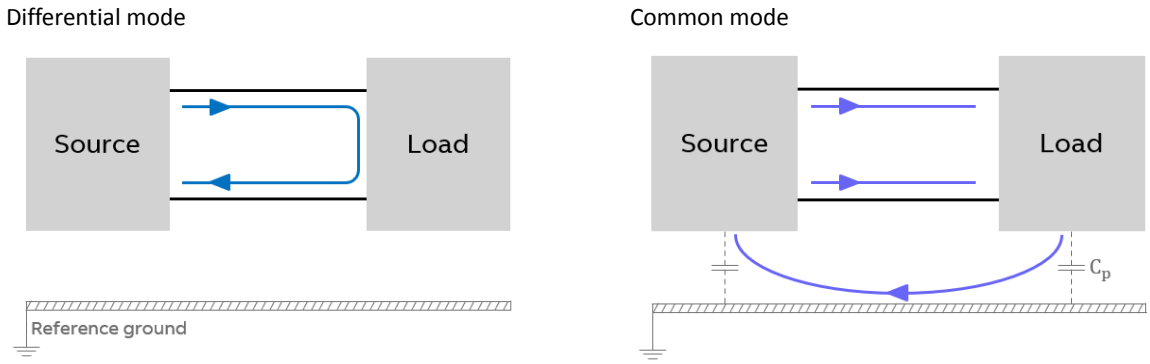
Figure 9: Voltage coordination example – based on IEC TR63282

Onboard DC Grid™ Earth fault handling

Each electrical system that operates isolated from other systems needs to have an active insulation monitoring system. There can only be one active insulation monitoring system in the same system. Due to this, one earth fault relay needs to be disconnected when a bus tie is closed.
In case of an earth fault, it is recommended to open the bus tie. This is because the bus tie has single pole protection, and two earth faults could bypass the protection devices. It is further recommended that the system is not operated for a long time with an active earth fault.

Onboard DC Grid™ Common mode handling

In all industrial converters there will normally be common mode current in addition to differential currents. The differential mode currents are defined as the currents that flow from the source to the load and back. The sum of phase currents of differential mode is zero. The common mode currents are defined as the average current flowing from the source to the load and does not return through the intended path, but through the ground.



Common mode current is not something new. It is present in most converter systems, and methods are in place to mitigate the effects. It should be noted that when there are several converters on the same DC bus, the common mode voltage and currents will be different from a single drives. The common mode voltage will be shared between the machines according to the ground capacitance. This means that a combination of machines of different sizes and long cables may lead to a need for higher machine insulation.
Batteries need to be evaluated for common mode performance to ensure a successful integration. A small battery is likely to see a lot of disturbance from the motors. A large battery is likely to push the common mode voltage to the machines. It is important that the machines are designed to withstand the voltage.

Closing the loop: safe and reliable bus-tie operations

The adoption of closed bus-tie configurations in vessel power systems is accelerating as operators seek greater efficiency and lower emissions. However, operating with a closed bus-tie introduces greater complexity in fault management, requiring advanced protection strategies to maintain system resilience and operational safety. In response, classification societies and maritime technical bodies have introduced stricter protection requirements to ensure vessels can fully capitalize on the advantages of closed bus-tie operation while upholding the highest safety standards.

For vessels with closed bus-tie operation it has been demonstrated that DC based systems can be built with suitable protection to effectively mitigate hidden failures and enhance system resilience. This ensures that vessels with closed bus-tie operation can meet the most stringent requirements set by maritime regulatory bodies and operate with similar integrity as with open bus-ties. This provides vessel operators with the confidence that their power systems are both safe and reliable, even in the most demanding conditions.