

HaloBus-ZBØSM: A Novel DP-3 Closed Bus Protection System Design

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Background

This paper presents HaloBus-ZBØSM, a novel DP-3 Closed Bus Tested (CBT) protection architecture. The ZBØ designation reflects the design's Zero Black-Out mission: to treat electrical-fault-induced Total Blackout as a preventable design outcome rather than an accepted residual risk. HaloBus-ZBØSM is based on two fully independent bus-directional protection zones that provide autonomous and redundant fault-isolation paths. HaloBus-ZBØSM uses established protection-relay technologies, conventional sensing methods, and mature communication interfaces to achieve protection redundancy through architectural independence rather than additional protection devices. The architecture combines a primary bus-directional protection zone utilizing IEC 61850 GOOSE communications with a secondary fully independent bus-directional protection zone utilizing dedicated Fiber Optic (FO) communication between relays installed outside the protected switchboard. This architectural independence provides autonomous and redundant fault-isolation paths while reducing common-mode vulnerabilities and implementation complexity.

The paper examines the electrical-fault characteristics of DP-3 MODU power systems and establishes a protection philosophy based on immediate Earth-Fault isolation, rapid Phase-Fault containment, and autonomous backup protection. To evaluate the robustness of the proposed architecture, a structured Hidden Failure framework is introduced and applied through an Electrical Fault Analysis that extends beyond the minimum DP-3 CB/CBT requirement. Rather than stopping after demonstrating compliance with the vessel's Worst Case Failure Design Intent (WCFDI), the analysis continues through complete fault isolation while progressively introducing additional simultaneous Hidden Failures, including the conservative assumption that one protection relay may be affected by a Blind Relay Hidden Failure and therefore be entirely unresponsive to the Active Failure.

The analytical results demonstrate that HaloBus-ZBØSM can maintain the vessel's WCFDI and subsequently complete fault isolation despite multiple cumulative Hidden Failure combinations. These findings were validated through full-scale live Earth-Fault and Short-Circuit testing performed on nine DP-3 MODUs, including tests that intentionally simulated primary protection failure. In all tested cases, the observed protection response matched the predicted fault-isolation sequence and maintained DP redundancy.

Fleet implementation demonstrated that HaloBus-ZBØSM can typically be deployed by replacing only the bus-tie protection layer while retaining suitable existing feeder and generator protection systems. The nine vessel upgrades were completed without dedicated out-of-service time and at approximately 10% of the cost of traditional retrofit solutions. The results demonstrate that a simplified and highly autonomous protection architecture can provide protection redundancy beyond minimum Class requirements while substantially reducing implementation complexity. Within the fault scenarios, operating configurations, and Hidden Failure combinations evaluated and tested in this paper, the findings support the conclusion that electrical-fault-induced Total Blackout should be regarded as a preventable event rather than an accepted residual risk of DP-3 Closed Bus operation.

DP-3 MODUs – Why upgrade to Closed Bus design specifications?

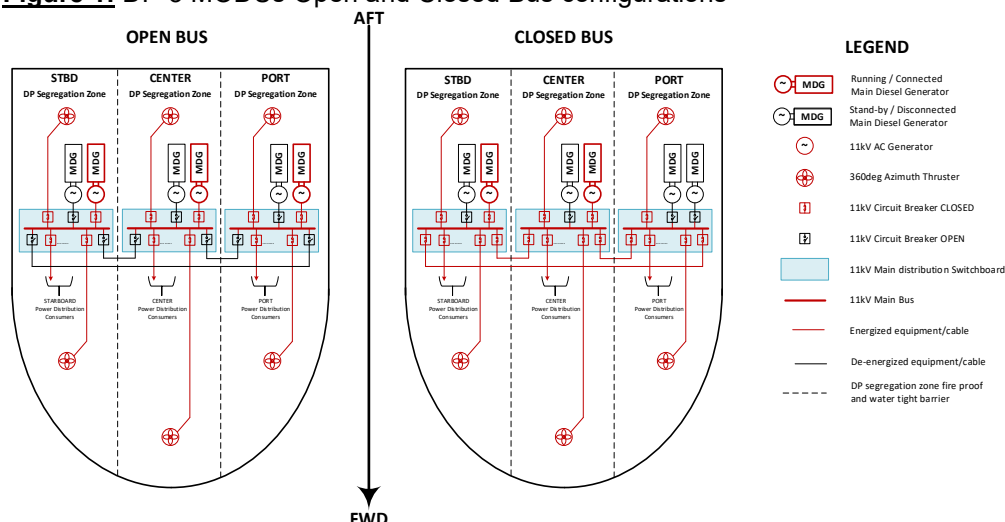
As shown in Figure 1, DP-3 MODUs can operate the main power plant in either **Open Bus** or **Closed Bus** configuration. In the Open Bus configuration, all bus-tie breakers remain open, electrically separating the three 11 kV switchboards and aligning the electrical system with the vessel's three DP segregation compartments. In the Closed Bus configuration, the bus-tie breakers remain closed, creating an interconnected power plant that allows generation capacity to be shared across all switchboards. While Open Bus operation inherently limits fault propagation between segregation zones, Closed Bus operation provides greater flexibility in generator loading, spinning-reserve management, and overall power-plant efficiency. Table 1 provides a summary of the pros and cons between the Open and Closed Bus operating configurations.

Open Bus operation is commonly regarded as the DP-3 safe-case configuration because electrical faults are inherently contained within an isolated bus section. However, Closed Bus operation for DP-3 MODUs is well established and supported by mature, robust, and proven Closed Bus / Closed Bus Tested (CB/CBT) requirements developed by maritime Classification Societies, most notably the American Bureau of Shipping (ABS) and Det Norske Veritas (DNV) for the offshore drilling industry. These requirements address the risk of fault propagation and Total Blackout through defined redundancy, protection, testing, verification, and Failure Mode and Effects Analysis (FMEA) requirements, ensuring that electrical faults remain within the vessel's Worst Case Failure Design Intent (WCFDI), typically the loss of a single DP redundancy compartment or 11 kV switchboard. When these requirements are satisfied, Closed Bus operation can provide substantial operational and economic benefits while preserving DP-3 redundancy.

Table 1: Open Bus with Three Connected MDGs vs. Closed Bus with Two Connected MDGs

Open Bus	Closed Bus
Requires a minimum of three connected generators	Allows operation with a minimum of two connected generators
Higher total vessel fuel consumption due to more engines running	Lower total vessel fuel consumption due to fewer engines running
Higher specific fuel-oil consumption due to lower engine loading (lower fuel efficiency)	Lower specific fuel-oil consumption due to higher engine loading (higher fuel efficiency)
Partial blackouts due to single engine failures	Increased engine availability – single engine failure does not cause Partial Blackouts
Greater exposure to generator unavailability during engine overhaul.	Reduced engine operating hours and maintenance burden
No exposure to 11kV fault propagation – perceived a safer configuration	Potential exposure to 11kV fault propagation – Total Blackout exposure

Figure 1: DP-3 MODUs Open and Closed Bus configurations



While Class-compliant Closed Bus operation satisfies DP-3 redundancy requirements, its business case is best understood

when evaluated against actual MODU operating profiles. DP drilling operations rarely require the vessel's maximum installed generation capacity for extended periods. Most operating hours are characterized by moderate electrical demand, while severe weather, elevated environmental loading, and other high-risk operating conditions can generally be anticipated and managed through established procedures, including temporary reconfiguration to Open Bus when required.

Analysis of actual operating data from Transocean's ship-shaped DP-3 MODU fleet confirms this observation. Figure 2 presents representative 2025 operating data for one MODU that operated exclusively in Open Bus throughout the year. The analysis shows that total vessel electrical demand remained below the two-generator operating threshold for approximately **89% of recorded operating hours**, indicating that the vessel could have operated with only two connected Main Diesel Generators (MDGs) during the majority of the year. Similar studies across multiple ship-shaped DP-3 MODUs produced comparable results, showing that two connected MDGs could satisfy total vessel demand for **more than 80% of annual operating time** regardless of operating region or vessel design.

Using the installed generator specific fuel-oil-consumption curves, the analysis predicts that operating in Closed Bus would reduce annual fuel consumption by approximately **11% to 13%** while reducing engine maintenance burden by approximately **36% to 38%**, depending on the vessel analyzed. These savings are achieved by operating fewer generators at higher and more efficient engine loading, reducing running hours, maintenance requirements, and associated emissions. For MODUs operating continuously in DP, the resulting fuel and maintenance savings create a strong economic incentive to adopt Closed Bus operation whenever operationally and technically feasible.

Accordingly, the question for today's DP-3 MODU fleet is no longer whether Closed Bus operation can be performed safely, but how it can be implemented in a Class-compliant manner while minimizing retrofit cost, installation complexity, commissioning effort, and operational disruption. The remainder of this paper presents the HaloBus-ZBØSM design, a DP-3 CBT protection architecture developed specifically to achieve that objective.

Figure 2: 2025 RIG Actual Open Bus Operation and Estimated Closed Bus Fuel and Maintenance Savings

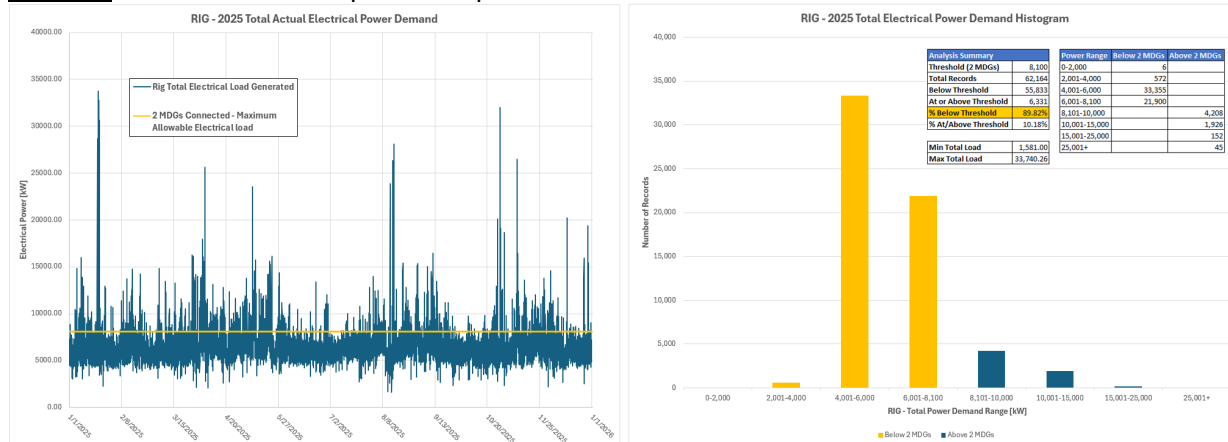


Figure 2 illustrates the key outcome of the operating-data analysis. For the representative MODU shown, total vessel electrical demand remained below the two-generator operating threshold for approximately 89.82% of annual operating hours. Using the installed Main Diesel Generator Specific Fuel Oil Consumption (SFOC) curves and the recorded annual operating profile, operation in Closed Bus configuration would have reduced annual fuel consumption by approximately **11.64%** and reduced annual Main Diesel Generator operating hours by approximately **38.39%**, resulting in a comparable reduction in routine engine-maintenance burden and overhaul-related costs.

These values represent estimated annual savings derived from the recorded operating profile and should not be interpreted as exact operational outcomes. Certain operating conditions may require additional generators to be connected irrespective of electrical demand, such as severe-weather preparations, squall-line or frontal-passage operations, well-control critical activities, or other situations where increased spinning reserve is required as a risk-mitigation measure. These conditions were not specifically excluded from the analysis. However, the results provide a realistic indication of the magnitude of fuel-efficiency and maintenance benefits achievable when Closed Bus operation is available and can be safely utilized.

DP-3 MODU Electrical Fault Characteristics

The DP-3 CBT requirements discussed previously are largely independent of vessel type because they are derived from the same Class objective: maintaining the vessel's Worst Case Failure Design Intent (WCFDI) following an electrical failure. As a result, most DP-3 MODUs share a very similar electrical architecture consisting of three segregated 11 kV switchboards, redundant bus-tie arrangements, segregated generator groups, and High Resistance Grounded (HRG) distribution systems. Although equipment manufacturers and vessel layouts differ, the electrical-fault behavior of these systems is remarkably consistent across the offshore drilling fleet.

Understanding these fault characteristics is essential because they form the technical basis of the HaloBus-ZBØSM protection philosophy. In particular, the manner in which earth faults develop and escalate into phase faults directly influences the protection functions and selectivity criteria discussed throughout the remainder of this paper.

In general terms, electrical faults are unintended conductive paths in the 11 kV power-distribution system. When the conductive path forms between an energized phase and normally non-energized equipment, vessel structure, or the hull, the fault is referred to in this paper as an Earth Fault (Ground Fault) because current returns through the grounding system and hull. When the conductive path forms between energized phases, the fault is referred to as a Phase Fault or Short-Circuit, because fault current flows directly between energized conductors.

Phase faults generally release substantially more energy than earth faults and therefore present the greater immediate threat to personnel safety and equipment integrity. The magnitude of this energy is primarily determined by the connected generation, motor contribution, and associated system impedance. Power-system equipment is designed to withstand this energy dissipation, and, in the offshore industry, short-circuit withstand ratings are typically conservatively selected so that the effects of a phase fault remain contained within the affected equipment or compartment.

Earth faults typically release less energy than phase faults, particularly in High Resistance Grounded (HRG) systems. However, an HRG earth fault raises the phase-to-ground voltage on the two healthy phases to approximately line-to-line voltage, increasing insulation stress throughout the affected 11 kV system. In aging MODU power plants, this sustained stress can accelerate insulation deterioration and increase the likelihood of fault escalation. Consequently, earth faults should not be treated as benign low-energy events; they are often precursors to insulation failure, phase faults, and severe arc-flash incidents and should therefore be detected and isolated without intentional delay.

In addition to Earth Faults and Phase Faults, electrical faults can be further classified as series faults or shunt faults. Series faults occur when one or more phases remain unintentionally open or closed, such as a three-phase contactor or circuit breaker with one or two contacts latched or welded closed while the remaining phases are open. Shunt faults occur when insulation failure creates an arcing or conductive path between phases or from phase to ground. Both fault types can produce voltage and current unbalance in the main distribution system. Although series faults are often less obvious than shunt faults, they can generate high negative-sequence currents capable of damaging generators and rotating equipment. Accordingly, Negative Sequence Current protection (46) is required for both generator and bus-tie relays. Because this protection is already established by Class Rules, it is not discussed further in this paper.

The consequences of a series fault depend primarily on its location within the 11 kV distribution system. For example, a single-pole failure in a feeder breaker may produce only limited unbalance, whereas a single-pole failure of a generator incomer can produce severe voltage unbalance, particularly if the generator remains energized and out of synchronism with the main bus. In extreme cases, the resulting voltage unbalance may exceed normal earth-fault protection pickup levels.

Except for specific failure modes that can produce high negative-sequence current, series faults are generally addressed through adequate earth-fault and negative-sequence overcurrent protection. Therefore, the remainder of this discussion focuses on shunt faults, specifically Earth Faults/Ground Faults and Phase Faults/Short-Circuits. This approach is consistent with established power-industry practice, where adequate phase-to-ground, phase-to-phase, and negative-sequence protection is expected to provide effective protection against the credible series-fault conditions relevant to this analysis.

Transocean operating experience supports this focus. Recorded 11 kV phase faults on DP-3 MODUs have predominantly

originated as earth faults that subsequently escalated because of insulation deterioration or delayed fault isolation. This behavior is largely driven by the construction of MODU power-distribution equipment, where generators, cables, switchboards, and transformers employ insulated conductors and phase-segregated compartments. As a result, insulation failures typically manifest first as earth faults before escalating into phase faults. Consequently, earth-fault detection and isolation constitute the primary and most important protection objective of the HaloBus-ZBØSM design.

Earth-Fault Protection Considerations

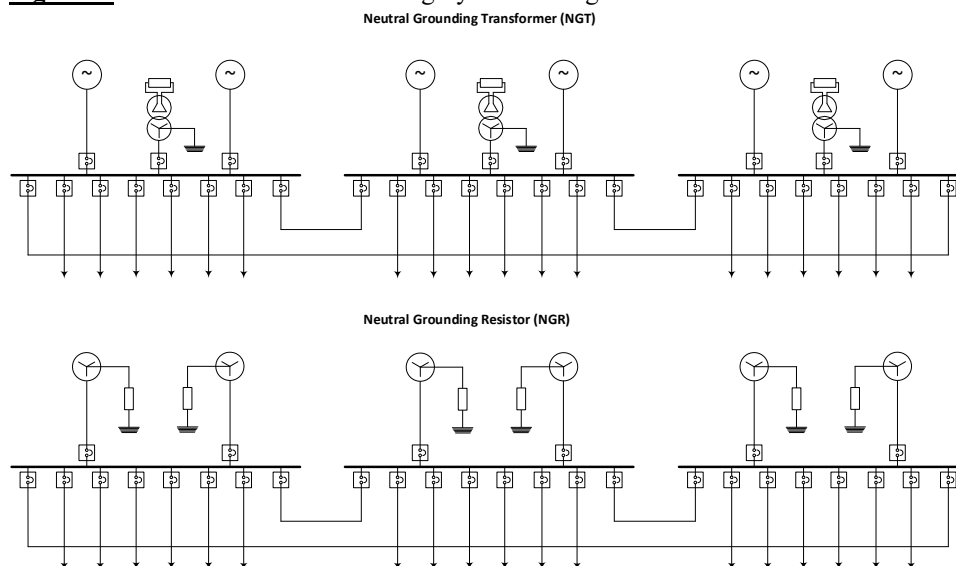
The previous section established that Earth Faults are the most common initiating electrical failure in DP-3 MODU power systems and that many recorded phase faults originate from the escalation of an Earth Fault. Consequently, Earth-Fault protection forms the foundation of HaloBus-ZBØSM protection philosophy and is the primary mechanism used to prevent more severe electrical failures.

The standard grounding arrangement for DP-3 MODU main power-distribution systems is High Resistance Grounding (HRG). Figure 3 shows the two HRG configurations commonly used within the offshore drilling industry:

- Neutral Grounding Transformer (NGT) systems, where a grounding transformer is connected to each 11 kV switchboard bus.
- Neutral Grounding Resistor (NGR) systems, where a grounding resistor is connected between each generator neutral and ground.

Both grounding philosophies are widely accepted by ABS and DNV and are commonly found across the existing DP-3 MODU fleet. While the advantages and disadvantages of each arrangement are well documented and beyond the scope of this paper, both share the same protection objective of limiting Earth-Fault current while maintaining reliable fault detection. Accordingly, HaloBus-ZBØSM is intentionally developed to be largely agnostic to the existing MODU grounding philosophy and can be applied to both NGT and NGR systems, with only limited implementation differences identified later in this paper.

Figure 3: Main Power Plant Grounding Systems Designs: NGT vs NGR



A commonly cited advantage of HRG systems is their ability to remain energized following a single Earth Fault because fault current is intentionally limited to a relatively low magnitude. This characteristic has influenced many conventional offshore protection philosophies, which often incorporate intentional Earth-Fault trip delays of one second or longer before initiating fault isolation. While this approach may be appropriate for certain industrial applications, several characteristics specific to DP-3 MODU power systems support a different protection philosophy. HaloBus-ZBØSM therefore challenges the practice of delayed Earth-Fault tripping for the following reasons:

- Class-compliant HRG 11 kV equipment is built with phase-to-ground insulation rated for operating voltage. A detectable 11 kV Earth Fault therefore indicates insulation failure, not a tolerable operating condition, and should be isolated immediately, with no intentional delay, before it escalates into a more severe fault or arc flash.
- MODUs' 11 kV feeders typically supply Low Voltage (LV) consumers through distribution transformers with delta-connected 11 kV windings. Therefore, LV-side ground faults do not require selective coordination with 11 kV earth-fault protection. When an 11 kV feeder relay detects an earth fault, the affected feeder breaker should Trip & Latch immediately, with no intentional time delay.
- Because MODU 11 kV equipment uses insulated or segregated conductors, insulation failure produces a predictable fault signature. Unlike exposed utility conductors, these systems are unlikely to introduce enough additional fault impedance to reduce earth-fault current or voltage unbalance below relay pickup levels. Therefore, even momentary insulation breakdown can be reliably detected by the protection relays.
- Continuous operation with a phase-to-ground fault imposes additional insulation stress on all equipment because the healthy phases are exposed to line-to-line voltage. This increases the risk of fast fault escalation.
- Because MODU power-distribution systems are predominantly inductive, earth faults may be intermittent or restriking rather than sustained metallic faults. These restrikes can last less than 50 ms, particularly at instrumentation-transformer cable connection points, as shown by the actual PT failure recorded in Figure 4. Long trip delays can allow repeated restrikes and voltage surges to stress healthy equipment; therefore, intermittent earth faults must be detected and isolated without intentional delay.
- The availability argument for continued operation with a single earth fault has limited practical value. Operating experience shows that unaddressed 11 kV Earth Faults can quickly escalate into higher-consequence phase faults. Immediate isolation of the initial earth fault therefore reduces the risk of catastrophic equipment damage and greater operational disruption.

Figure 4 – 11kV Voltage Sensing Transformer Insulation Failure: Actual Earth-Fault Data

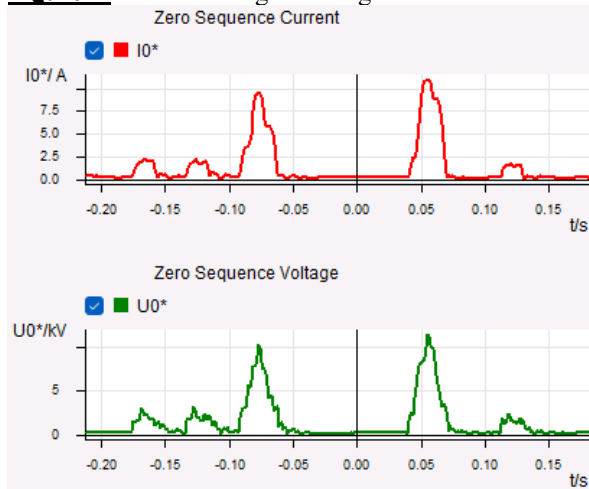


Figure 4 shows a recorded intermittent earth fault associated with insulation failure of an 11 kV voltage sensing transformer. The brief zero-sequence current and residual voltage peaks illustrate restriking earth faults lasting less than 50 ms. Although the fault duration is short, repeated restrikes subject healthy insulation to cumulative electrical stress and demonstrate why intentional earth-fault delays can permit fault escalation.

These considerations demonstrate that a detectable Earth Fault on a DP-3 MODU should not be regarded as a permissible operating condition, but rather as evidence of an active insulation failure with the potential to escalate into a Phase Fault or arc-flash event. Accordingly, Earth-Fault detection and isolation with no intentional time delay is adopted as a fundamental design requirement of HaloBus-ZBØSM. This requirement minimizes exposure to insulation deterioration, reduces the likelihood of fault escalation, and serves as the primary layer of protection for maintaining the vessel's WCFDI following an electrical failure.

Phase Fault (Short-Circuit) Protection Considerations

While Earth Faults represent the most common initiating electrical failure in DP-3 MODU power systems, Phase Faults or Short-Circuits remain the highest-energy electrical faults that can occur within the 11 kV distribution system. Consequently, effective Earth-Fault protection is intended to prevent fault escalation, while dedicated Phase-Fault protection is required to rapidly isolate higher-energy faults that occur directly or develop from an existing Earth Fault.

Traditional DP-3 CBT protection philosophies frequently prioritize downstream selectivity, often resulting in intentional time delays being applied to the 11 kV feeder Phase Overcurrent protection functions. By contrast, HaloBus-ZBØSM treats rapid fault-energy removal as the primary protection objective. Accordingly, instantaneous Phase Overcurrent protection of 11 kV distribution feeders is maintained wherever practical, with selectivity verified through short-circuit and protection-coordination studies rather than achieved through intentional tripping delays. This philosophy minimizes fault energy released into equipment, reduces equipment damage and arc-flash exposure, and improves fault containment within the vessel's WCFDI.

Implementing instantaneous 11 kV Short-Circuit protection requires consideration of three principal coordination challenges:

- Protection of generator power sections – faults within the generator protection zone, including the generator windings and associated cabling to the 11 kV incomer breaker, are primarily cleared by the generator Phase-Differential Overcurrent element (87). This function may require a short intentional delay, typically three to four cycles (50-67 ms at 60 Hz), to verify that the fault is internal and not caused by system transients or CT saturation. This inherent delay must be considered when coordinating generator protection with the bus-tie Directional Phase-Overcurrent (67) functions discussed later in this paper.
- Transformer energization and inrush currents – another challenge is distinguishing true phase faults from transformer inrush during 11 kV feeder energization. If the instantaneous 50 element operates without inrush-restraint, the transformer magnetization current can far exceed the feeder relay non-directional overcurrent element (50/51) pickup setting and can cause an undesired feeder trip. Standard DP-3 CBT designs address this on thruster feeders through transformer pre-magnetization, which supports fast blackout recovery and eliminates high inrush during normal energization. The same approach may be applied to other distribution transformers. Feeders without pre-magnetization shall use inrush-restraint, blocking, or equivalent logic during energization, with the associated status made available to the bus-tie relays where required for protection coordination. These functions are well established and are not discussed further in this paper. The transformer inrush current is therefore not, by itself, sufficient justification for disabling instantaneous 11 kV feeder protection.
- Selectivity between 11 kV feeder protection and downstream LV protection – The principal technical challenge associated with instantaneous 11 kV feeder Short-Circuit protection is maintaining selectivity with downstream LV protection. LV faults should clear at the affected LV feeder before the LV incomer or upstream 11 kV feeder breaker trips. The HaloBus-ZBØSM design, implemented on nine Transocean MODUs, shows that distribution-transformer impedance can sufficiently limit the 11 kV contribution to LV faults, allowing selective LV tripping while keeping instantaneous 11 kV feeder protection enabled. This is achieved by setting the 11 kV feeder pickup high enough to operate for faults on the 11 kV feeder, transformer primary, or transformer secondary, but not for expected LV feeder-fault currents. For other MODUs, differences in generator ratings, transformer impedance, LV motor contribution, breaker clearing times, and relay characteristics may make instantaneous 11 kV feeder tripping more difficult to coordinate selectively with downstream LV protection. This must be evaluated during the short-circuit and protection-coordination study. Where the affected LV consumers are not required for DP station keeping, loss of selectivity with the upstream 11 kV feeder may be acceptable on a case-by-case basis. Realistic LV motor-load contribution should also be reviewed so the protection objective of instantaneous 11 kV feeder breaker tripping is preserved wherever practical.

These considerations support the HaloBus-ZBØSM philosophy that Phase Faults within the 11 kV distribution system should be isolated with the minimum practical delay. While limited coordination delays may be necessary for generator differential protection, fault-direction determination, or specific selectivity requirements, instantaneous feeder Short-Circuit protection remains the preferred approach wherever practical. Consistent with the Earth-Fault philosophy discussed previously, the objective is to minimize fault energy release, limit equipment damage, and maintain the vessel's WCFDI following an electrical failure.

Closed Bus Design – Hidden Failure Analysis Framework

DP-3 CBT Class requirements recognize that demonstrating compliance requires more than showing that a protection system responds correctly to a fault under normal conditions. The protection system must also maintain the vessel's Worst

Case Failure Design Intent (WCFDI) when an electrical fault occurs in combination with a credible Hidden Failure. Accordingly, the Class definition of a Single Failure is particularly relevant to Closed Bus power systems because a Single Failure may consist of an Active Failure combined with a credible Hidden Failure that prevents the intended protective response. As a result, protection functions cannot be evaluated solely on their ability to detect and isolate a fault; they must also be evaluated for their ability to tolerate degraded sensing, protection, communication, or isolation functions while continuing to maintain the vessel's WCFDI.

This consideration is especially important for Closed Bus operation. As discussed in the preceding sections, HaloBus-ZBØSM relies on rapid isolation of Earth Faults and Phase Faults to prevent fault escalation and contain failures within a single DP segregation zone. However, a protection function that is not available when demanded provides no protection regardless of its intended operating speed or selectivity. Therefore, the effectiveness of HaloBus-ZBØSM depends not only on protection performance during an Active Failure, but also on its ability to identify, alarm, bypass, or mitigate Hidden Failures before an electrical fault occurs.

The preferred approach is to reduce the number of credible Hidden Failures carried into the Electrical Fault Analysis by providing continuous monitoring, periodic verification, automatic diagnostics, alarms, and defined failure responses wherever practical. When a protection-system deficiency is reliably detected and managed before the electrical fault used as the Active Failure, the deficiency is treated as a known failure condition rather than as an undetected concurrent failure for that specific Single Failure evaluation. This treatment does not imply that monitoring eliminates the possibility of Hidden Failures; rather, it reduces their likelihood of remaining undetected and allows the affected operating condition to be identified, alarmed, and appropriately managed before an Active Failure occurs.

To apply the Class Single Failure definition consistently, this paper groups protection-system Hidden Failures into four categories that follow the functional sequence required to detect, process, communicate, and isolate an electrical fault. These categories provide the framework used throughout the remainder of this paper to evaluate whether an Active Failure, when combined with a credible Hidden Failure, could prevent the intended protection response and cause the vessel's WCFDI to be exceeded.

- **Sensing-system or sensing-equipment Hidden Failures** – This category includes failure modes that prevent the protection relay from receiving accurate or complete fault inputs and therefore prevent the intended protection function from operating during an Active Failure. Examples include sensor malfunction, inadequate or defective Current Transformers (CTs) that saturate during high-current faults, incorrect CT polarity for ground-directional protection, or wiring errors in the sensing circuits. For traditional CBT protection designs, some relay elements may also depend on hardwired inputs from other devices, such as blocking signals or breaker-failure detection signals. Wiring faults, failed contacts, or other failures that prevent these signals from reaching the protection relay are also treated as sensing-system Hidden Failures because they can prevent the relay from receiving the information required to act on the fault.
- **Protection-equipment Hidden Failures** – This category includes failures within the protection relay or its configured logic that prevent the relay from issuing the intended protective action after the required fault inputs have been received. Software-related examples include missing or incorrect protection settings, disabled protection functions, or custom logic that was not implemented or maintained correctly. Hardware-related examples include internal relay failures, output failures, or damage caused by overcurrent, overvoltage, or other electrical stresses associated with the Active Failure.
- **Communication-system Hidden Failures** – This category includes failures in the communication paths or communication settings required for protection functions that depend on information exchanged between devices. For example, a bus-directional overcurrent scheme may require two bus-tie relays to exchange overcurrent pickup and current-direction status before the protection function can activate. If one relay fails to transmit its directional status, or if incorrect communication settings prevent the signal from being received, the dependent protection function may not operate as intended during an Active Failure.
- **Isolating-equipment Hidden Failures** – This category includes failures of the equipment required to physically isolate the fault after the protection relay has issued the intended trip command. Examples include a failed trip coil, defective trip wiring, failed auxiliary contacts, or mechanical failures within the circuit breaker operating mechanism or contact linkage. These failures can prevent the circuit breaker from opening and clearing the fault even when the upstream sensing, protection, and communication functions have operated correctly.

The objective of this framework is not merely to identify Hidden Failures, but to determine which failure modes can be detected, alarmed, bypassed, or independently mitigated by the HaloBus-ZBØSM design before an electrical fault occurs. The preferred outcome is therefore to minimize the number of undetected failure conditions carried into the Electrical Fault Analysis while retaining independent backup protection for on-demand functions that may nevertheless fail to operate. In this respect, the preferred outcome is not redundancy alone, but the systematic detection and management of failure conditions before they can remain hidden and combine with an electrical fault.

A Novel Power Plant Protection Scheme – HaloBus-ZBØSM Design Specifications

The preceding sections established the HaloBus-ZBØSM design protection philosophy for Earth Faults and Phase Faults. Specifically, Earth Faults shall be isolated with no intentional time delay, and Phase Faults shall be isolated with the minimum practical delay necessary to achieve the required selectivity and fault discrimination. The following specifications define the minimum hardware, sensing, communication, redundancy, and protection requirements necessary to implement this philosophy. These requirements supplement, but do not replace, the applicable DP-3 CB/CBT Class requirements.

Traditional DP-3 CB/CBT Closed Bus protection designs typically incorporate the required redundancy within each individual 11 kV switchboard. This approach commonly begins with downstream LV protection and then seeks to maintain selectivity with upstream 11 kV protection devices. Additional bus-differential and/or bus-directional protection schemes are subsequently added to isolate faulted switchboards. To achieve selectivity, these schemes often rely on blocking signals exchanged between feeder, generator, and bus protection relays, reducing overall protection-system autonomy. Transocean challenged this conventional approach and, together with Siemens Energy, reformulated the DP-3 Closed Bus protection philosophy by evaluating the power plant as an integrated system rather than as three independent switchboards. The resulting approach prioritizes rapid restoration of the Safe-Case Open Bus configuration through the fastest practical fault isolation at the bus level, with selective tripping applied only where required to preserve the vessel's WCFDI.

The key innovation of HaloBus-ZBØSM is not the use of new protection technology, but the implementation of two fully independent bus-directional protection zones. The primary protection zone utilizes an IEC 61850 GOOSE communication network between the two bus-tie relays installed within the affected switchboard, while the secondary protection zone utilizes dedicated Fiber Optic point-to-point communications between relays located outside the affected switchboard and within separate DP segregation zones. Each protection zone possesses independent sensing, communication, activation, and fault-isolation mechanisms and is capable of independently maintaining the vessel's WCFDI following an electrical fault. This architectural independence forms the basis for the enhanced autonomy, redundancy, and Hidden Failure tolerance demonstrated throughout the remainder of this paper.

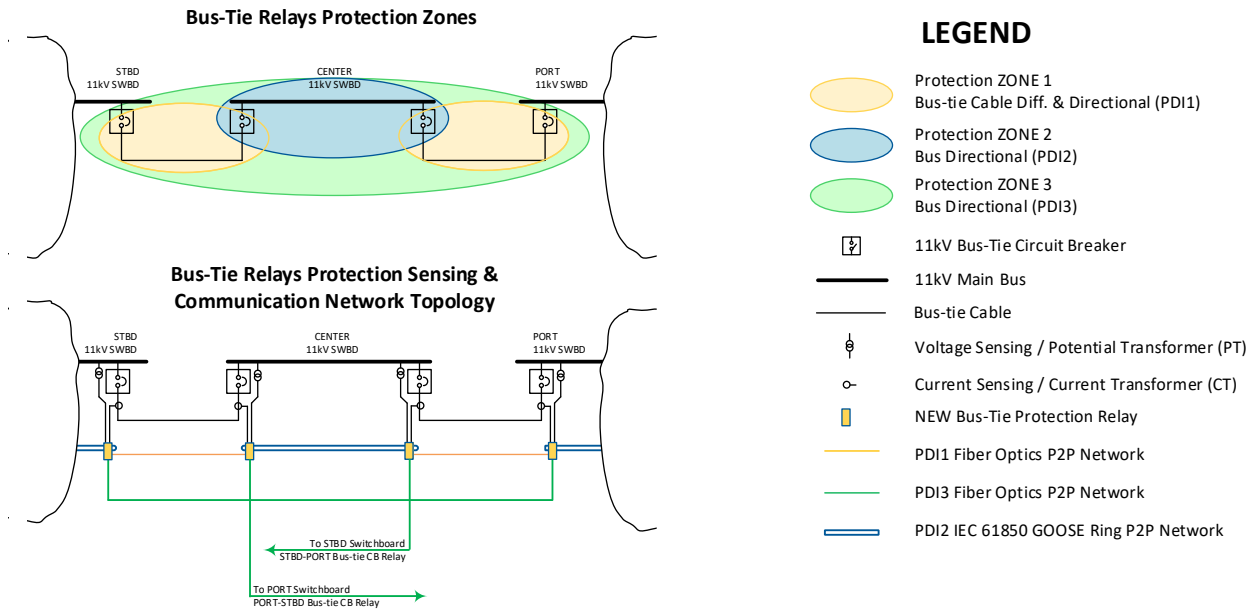
This philosophy is founded on two key observations. First, for any electrical fault within an 11 kV switchboard, including connected generators and distribution feeders, the bus-tie relays installed at both ends of each adjacent bus-tie cable observe the same fault-current magnitude and direction. This characteristic leverages the double-breaker bus-tie arrangement commonly used on DP-3 MODUs and forms the basis of the redundant bus-directional protection architecture used throughout the HaloBus-ZBØSM design. Second, when at least one MDG is connected to each 11 kV switchboard and the plant operates in Closed Bus configuration, any electrical fault within the 11 kV distribution system is detected by all bus-tie relays. Under these conditions, selective bus-tie tripping is unnecessary. Simultaneous tripping of all bus-ties restores the Safe-Case Open Bus configuration in less than 100 ms, contains the fault within a single DP segregation zone, and maintains the two unfaulted switchboards energized. Consequently, fault-location discrimination can be achieved without relying on intentional delays in the bus-tie protection functions. Selectivity delays remain necessary only where required to coordinate primary and backup protection functions.

The specifications that follow are derived directly from these observations and establish the additional hardware, sensing, communication, protection, redundancy, selectivity, and failure-response requirements specific to HaloBus-ZBØSM. For legacy DP-3 MODUs, compliance can generally be achieved through replacement of the six bus-tie protection relays and configuration of the associated protection functions as shown in Figure 5. Consistent with the protection philosophy established above, instantaneous fault isolation is the preferred protection response, with intentional time delays applied only where required to coordinate primary and backup protection functions. Accordingly, the following Selectivity Criteria defines the timing and coordination basis used throughout the HaloBus-ZBØSM design specifications.

Transocean DP-3 MODUs utilize a five-cycle protection-clearing interval at 60 Hz, consisting of approximately two cycles for protection-element operation and three cycles for circuit-breaker opening and fault interruption. This corresponds to approximately 83 ms from protection-element activation to fault clearance. To account for breaker operating tolerances, relay timing accuracy, sensing uncertainty, and equipment variation, HaloBus-ZBØSM adopts a baseline **Selectivity Criteria of 100 ms**. Where a protection function requires additional operating time, such as directional fault determination or differential-element security checks, that operating time shall be added to the 100 ms coordination interval.

When coordination between protection functions is required, backup protection shall operate after the primary protection operating time plus the 100 ms Selectivity Criteria. For example, if a generator directional earth-fault element requires 100 ms to determine fault direction, the corresponding bus-directional protection function shall operate after 200 ms. This criterion forms the timing basis for all protection functions defined in the specifications that follow.

Figure 5 – Novel HaloBus-ZBØSM dual-autonomous bus-directional protection with independent sensing and communications.



HaloBus-ZBØSM – Bus-Tie Protection Relay Hardware and Network Topology Requirements

The preceding sections established that HaloBus-ZBØSM relies on two independent bus-directional protection zones to provide autonomous fault detection and isolation. The following hardware and network topology requirements define the minimum architecture necessary to implement these protection zones.

1. Each bus-tie protection relay shall be classified as an Intelligent Electronic Device (IED) capable of providing integrated protection, control, and customizable logic functions.
2. Each bus-tie protection relay shall support three independent and fully segregated communication networks. No single network fault, including a failure of communication hardware internal to one protection relay, shall affect the relay's protection or communication functions on the other two networks.
3. The three communication networks, referred to herein as Protection Data Interfaces (PDIs), shall be provided as follows:

- 3.1. **PDI2** – one IEC 61850 GOOSE communication network configured as a point-to-point (P2P) redundant (loop) network between the two bus-tie relays installed within the same 11 kV switchboard, as shown for Protection Zone 2 in Figure 5. The network shall use redundant High-availability Seamless Redundancy (HSR) protocol in accordance with IEC 62439-3.

- 3.2. **PDI1** – one P2P Fiber-Optic (FO) network providing Protection Data Interface communication between the two bus-tie cable relays installed in adjacent switchboards, as shown for Protection Zone 1 in Figure 5.
- 3.3. **PDI3** – one P2P Fiber-Optic (FO) network providing Protection Data Interface communication between the redundant bus-directional protection functions configured in bus-tie relays installed in different switchboards, as shown for Protection Zone 3 in Figure 5.
4. The bus-tie protection relays shall not share common current or voltage sensing transformers. Each bus-tie relay shall have dedicated phase CTs and core-balance ground CTs, and shall take bus-voltage measurements from different PTs. Most MODUs built to DP-3 rules use 11 kV switchboards fitted with two sets of bus PTs, with each PT having two secondary windings: one winding set for phase-voltage measurement and one winding set for voltage-unbalance measurement. The two bus-tie relays installed in the same switchboard, shown as Zone 2 in Figure 7, shall each take bus-voltage measurements from different PTs within that switchboard.

HaloBus-ZBØSM – Bus-Tie Protection Relay Settings Group Configuration

The preceding sections also established that differing operating conditions require different protection responses. The following Settings Group requirements for each bus-tie relay define how HaloBus-ZBØSM adapts protection behavior based on MDG connection status and power-plant configuration.

5. **Settings Group 1** – activated when at least one 11 kV switchboard does not have an MDG connected. If an electrical fault occurs within the 11 kV power system while Settings Group 1 is active, the bus-tie circuit breakers shall trip to isolate the fault within a single DP segregation zone after a short intentional time delay. This delay allows the feeder breakers or generator incomers to trip first when the fault is located on a distribution feeder or generator, respectively.
6. **Settings Group 2** – activated when each of the three 11 kV switchboards has at least one MDG connected. In this mode, all bus-tie protection relays shall use their most sensitive settings and shall not rely on communication networks to trip the bus-ties for an electrical fault. If any electrical fault occurs within the 11 kV power system while Settings Group 2 is active, the bus-ties shall instantaneously trip, i.e. with no intentional time delay. This action reconfigures the power plant to the Safe-Case Open Bus configuration in less than 100 ms, based on five-cycle operation of the 11 kV circuit breakers, without requiring selective tripping for feeder or connected-generator faults.

In summary, Settings Group 1 prioritizes selective fault isolation when one switchboard lacks local generation, whereas Settings Group 2 prioritizes immediate separation to the Safe-Case Open Bus configuration when each switchboard has local generation available.

HaloBus-ZBØSM – Bus-Tie Protection Relay Interface Requirements

The HaloBus-ZBØSM design relies on coordinated actions between the protection system, Vessel Management System (VMS), and connected MDGs to restore the Safe-Case Open Bus configuration and isolate faults. The following interface requirements define these interactions.

7. **Interface to Vessel Management System (VMS)** – each bus-tie relay shall be configured to raise a **Start All Engines** request to the VMS through a hardwired connection between the bus-tie relay and the VMS Remote Input/Output (RIO) cards fitted within the Field Station (FS) installed in the same DP Segregation Zone as the interfaced relay. The Start All Engines request to the VMS is a well-established function on Transocean DP-3 CBT vessels. It was initially introduced as part of the Advanced Generator Protection (AGP) design and, in broad terms, is a request sent by the AGP system to the supervisory VMS, which in turn, sends an emergency start and connected command to all available MDGs. For DP-3 CBT vessels, and as part of the HaloBus-ZBØSM design, the VMS Start-All logic shall be configured as follows:
 - 7.1. **VMS Start All Logic requirement** – the Start All Engines function shall open the bus-ties after each 11 kV bus has at least one MDG connected. If the condition that triggers the Start All Engines request causes a sustained voltage fluctuation on the bus and the oncoming MDGs cannot synchronize, the VMS logic shall open all bus-ties before the MDG synchronization timers expire. The Start All Engines function shall also account for operating conditions in which a switchboard without a connected engine must not be isolated, such as during engine-room critical-system maintenance or when Start All Engines is triggered by an engine shutdown condition. The detailed Start All Engines logic is beyond the scope of this paper; however, the intended outcome

is that the power plant is reconfigured to Open Bus, the Safe-Case configuration, with all available MDGs connected.

8. **Interface to MDG incomers within the same switchboard** – each bus-tie relay shall have the following hardwired signals interfaced to the MDG incomer LV control sections within the same switchboard:
 - 8.1. **MDG incomer status configured as an input to the bus-tie relay** – each MDG incomer status signal shall be hardwired to the bus-tie protection relays within the same 11 kV switchboard. MDG connection status shall be broadcast to all bus-tie relays through the PDI1, PDI2, and PDI3 networks and used as the required input for Settings Group 1 or Settings Group 2 activation, as defined later in this paper.
 - 8.2. **MDG E-Stop activation configured as an output from the bus-tie relay** – each bus-tie relay shall be hardwired into the Emergency Stop (E-Stop) circuits of both MDG incomer sections within the same 11 kV switchboard. The wiring required for this interface shall be routed through the same 11 kV switchboard LV control compartment. In standard DP-3 designs, each MDG E-Stop circuit is routed through the generator incomer control section within the 11 kV switchboard; activation of this function simultaneously shuts down the main engine, shuts down the generator excitation system by shutting down the Automatic Voltage Regulator (AVR), and Trips & Latches the generator incomer. Each bus-tie relay shall be hardwired into this circuit for both MDGs connected to its 11 kV switchboard so that, if a wiring or other hidden failure prevents one relay from activating the E-Stop for both engines, the other relay within the same switchboard will activate the E-Stop and isolate the switchboard as intended by the bus-directional overcurrent protection defined later in this paper. Throughout this paper, whenever a protection element specifies **MDG E-Stop**, it shall mean that the action will **E-Stop the main diesel engine, shut down the AVR, and Trip & Latch the affected MDG incomer**, with all actions performed simultaneously and with no intentional time delay, i.e., 0 ms activation.

The following HaloBus-ZBØSM design requirements define the minimum communication-network configuration for PDI1, PDI2, and PDI3

HaloBus-ZBØSM – Bus-Tie Relays Communication Settings Requirements

Because HaloBus-ZBØSM utilizes multiple independent protection zones, communication failures must not prevent fault isolation or cause the vessel's WCFDI to be exceeded. The following requirements define the response to communication-system failures.

9. Any **communication network failure** shall be detected by the affected relay, and the relay shall simultaneously initiate the three actions defined below:
 - 9.1. Raise an alarm.
 - 9.2. Initiate a Start All Engines request to the Vessel Management System (VMS).
 - 9.3. Activate Settings Group 2, i.e., the most sensitive protection settings group as defined above.
10. The PDI2 IEC 61850 GOOSE network shall be **tested for network storm** conditions, including jabber, unicast, and multicast events to ensure that such events are not exceeding the vessel's WCFDI.

HaloBus-ZBØSM – Redundancy Requirements

The Hidden Failure framework introduced previously is used as the basis for the following redundancy requirements. These requirements are intended to reveal, alarm, bypass, or independently mitigate credible Hidden Failures before they combine with an Active Failure.

11. **All 11 kV Protection Relays Redundancy Requirements** – the following requirements apply to all 11 kV feeder, generator, and bus-tie protection relays:
 - 11.1. All relays shall be fitted with a **Trip Coil Monitoring (74)** function. Upon detection of a trip-coil failure, the relay shall initiate the actions defined below:
 - 11.1.1. Raise an alarm.

- 11.1.2. Bus-tie and generator protection relays shall also initiate a Start All Engines request to the Vessel Management System (VMS). Feeder relays are not required to initiate a Start All Engines request to the VMS; an alarm is sufficient for feeder relay trip-coil monitoring failures.
12. All bus-tie relays shall be fitted with **Breaker Failure (50BF)** protection. Upon detection of a bus-tie breaker failure to open or trip, the relay shall initiate the actions defined below:
- 12.1. Raise an alarm.
- 12.2. Initiate a Start All Engines request to the Vessel Management System (VMS).
- 12.3. Custom logic shall be defined so that, if breaker failure is detected following activation of any bus-tie cable earth- or phase-directional or differential over-current protection function defined further below, the bus-tie relay shall isolate the 11 kV switchboard containing the failed breaker. The custom logic shall issue a Trip & Latch command through the PDI2 network (GOOSE) to both bus-tie breakers and shall activate the MDG E-Stop for both MDGs on the affected switchboard, regardless of MDG connection status. The custom logic shall operate with a 100 ms time delay for all conditions listed below:
- **(50BF) + (87-PDI1)** – breaker failure following tie-cable phase-differential over-current activation.
 - **(50BF) + (87N-PDI1)** – breaker failure following tie-cable earth-differential over-current activation.
 - **(50BF) + (67-PDI1)** – breaker failure following tie-cable phase-directional over-current activation.
 - **(50BF) + (67N-PDI1)** – breaker failure following tie-cable earth-directional over-current activation.
13. All bus-tie relays shall include custom logic that Trips & Latches the corresponding bus-tie circuit breaker after a 50 ms time delay when either of the following conditions are satisfied:
- **(67) FWD + PDI3(87-PDI1)** – phase overcurrent is above the pickup setting, with current direction into the bus-tie cable, and confirmation is received through PDI3 that the paired relay has activated its bus-tie cable phase-differential overcurrent function **(87-PDI1)**.
 - **(67N) FWD + PDI3(87N-PDI1)** – earth overcurrent is above the pickup setting, with current direction into the bus-tie cable, and confirmation is received through PDI3 that the paired relay has activated its bus-tie cable earth-differential overcurrent function **(87N-PDI1)**.
14. All bus-tie relays shall include an **Inter-Trip** function so that the trip of one bus-tie breaker also trips the corresponding bus-tie breaker at the opposite end of the bus-tie cable. This requirement leverages the double-breaker bus-tie arrangement, which is intended to maintain bus-tie isolation if one breaker experiences a mechanical failure, such as a linkage or contact-operating mechanism failure.
15. For each 11 kV protection relay, all available protection elements that can provide protection against earth faults or phase faults shall be evaluated for implementation. For example, bus-tie relays shall have non-directional over-current, directional over-current, and voltage-based protection elements enabled and included in the protection scheme. Feeder relays, which typically derive voltage measurements from the bus PTs, may rely on current-based protection elements only; in such cases, non-directional over-current elements are sufficient.
16. Protection against an electrical fault shall include redundancy in protection elements, relays, and circuit breakers. For example, for an electrical fault within a generator power section multiple current- and voltage-based protection elements shall be configured in the generator protection relay. Compliance with this requirement also requires at least one independent protection relay and one independent circuit breaker capable of isolating the fault if a Hidden Failure within the generator relay or incomer prevents the affected MDG from being isolated.
17. Protection functions that rely on communication between two relays shall have at least one redundant protection element that does not rely on signals received through communication networks. For example, because the bus-directional protection schemes rely on the PDI2 or PDI3 networks, each bus-tie relay shall also have non-directional over-current protection enabled to ensure bus isolation even if both communication networks fail. Loss of two networks exceeds WCFDI, but the redundant non-directional protection provides additional defense-in-depth.
18. Each bus-tie relay and generator protection relay shall have **Switch On To Fault (SOTF) / (50HS) or Accidental Energization (50/27)** protection enabled to ensure that breaker trips if a close attempt is made onto a fault. Alternative

methods, such as bus sniffing before breaker closure, may be considered acceptable but are not preferred because they increase complexity and introduce additional failure modes.

HaloBus-ZBØSM – Earth-Fault Protection Design Specifications.

Considering the MODU earth-fault and short-circuit characteristics discussed in the previous subsections, the following HaloBus-ZBØSM specifications define the minimum required protection functions for the 11 kV protection relays. The American National Standards Institute (ANSI) device numbers for the required protection elements are included where applicable. These specifications provide a generic description of the minimum functions required by HaloBus-ZBØSM. Depending on the protection-relay manufacturer and relay type, function nomenclature may differ, and additional functions may be available to provide equivalent or supplementary protection. Where available, such functions may be enabled to further increase protection-system redundancy. Additional protection functions that are explicitly required by Class Rules shall also be included even if they are not listed here; the purpose of this section is to define the functions specific to HaloBus-ZBØSM.

19. **NGT Feeder Protection Relay** (applicable to NGT systems only) – protection against earth faults or phase faults within the grounding transformer, including the cabling to the 11 kV feeder breaker, shall not trip the NGT feeder breaker. The 11 kV earth-fault protection scheme relies on the grounding transformers remaining connected to the main 11 kV system; therefore, they shall always remain connected. From this perspective, the grounding transformer, including its power cabling, is considered part of the main 11 kV bus. Accordingly, a fault within the grounding transformer or its associated cabling shall be treated by HaloBus-ZBØSM protection system as a main-bus fault and shall be isolated by the two independent bus-directional protection schemes.
20. **Distribution Feeder Breaker Protection Relays** – protection against earth faults on 11 kV distribution feeders, including the distribution transformers' 11 kV windings, shall be provided by the **Non-Directional Earth Over-Current element (50N)**. The 50N element shall be set to Trip & Latch the affected distribution feeder circuit breaker instantaneously, i.e., with 0 ms time delay.
21. **Bus-Tie Protection Relays** – protection against earth faults within a single DP segregation zone shall be provided as follows:
 - 21.1. The bus-tie relays shall have **Bus-Tie Cable Earth-Fault Differential Over-Current (87N-PDI1) AND Bus-Tie Cable Earth-Fault Directional Over-Current (67N-PDI1)** functions set to Trip & Latch both bus-tie cable breakers instantaneously, i.e., with 0 ms time delay, as soon as the earth-fault current magnitude exceeds the pickup setting. The same settings shall apply to both Settings Group 1 and Settings Group 2. These functions isolate an earth fault on a bus-tie cable without reducing DP capability because only the affected bus-tie is opened.
 - 21.2. Two **Bus Earth-Fault Directional Over-Current** protection functions, **(67N-PDI2) AND (67N-PDI3)**, shall be configured to activate simultaneously and independently of each other. Both protection schemes shall use the same activation settings in Settings Group 1 and Settings Group 2 and shall be coordinated with the first protection layer for feeder and generator earth faults, as shown in the examples below. These functions shall activate as follows:
 - 21.2.1. **(67N-PDI2)** shall E-Stop the MDGs on the affected bus, regardless of whether the MDGs are connected to the bus and shall Trip & Latch the two bus-tie breakers controlled by the PDI2 relays.
 - 21.2.2. **(67N-PDI3)** shall Trip & Latch the two bus-tie breakers controlled by the PDI3 relays.
 - 21.3. The **Residual Over-Voltage (59N)** element shall include a second trip level, **(59N Trip 2)**, configured to activate MDG E-Stop for all generators on the affected bus, regardless of their connection status. This function shall operate after a time delay coordinated with the Generator Relay **(50N)** and **(59N)** trip functions. This action provides the final level of redundancy for earth-fault protection and is intended to back up all earth-fault protection functions configured in the generator relays, including the worst-case condition in which one MDG relay has no protection enabled because of Blind Relay Hidden Failure.
The 59N element shall also have settings-group-specific activations, as defined below.

For Settings Group 1 ONLY – when one 11 kV switchboard has no MDG connected, the following requirements apply:

21.3.1. Each bus-tie relay shall include an **Intermittent Earth-Fault Over-Current** detection function validated by the **Residual Over-Voltage** element, **(50N-INT+59N)**. If this function is not available as a built-in protection element, custom logic shall be configured to detect intermittent earth faults lasting less than 100 ms. This function shall simultaneously initiate the three actions defined below with no intentional time delay:

- Raise an alarm.
- Initiate a Start All Engines request to the Vessel Management System (VMS).
- Activate Settings Group 2, i.e., the most sensitive protection settings group as defined above.

NOTE: Certain normal operating actions, such as starting large consumers, sudden load increases, 11 kV switching, feeder or bus-tie breaker opening or closing, and generator connection or disconnection, can cause transient current unbalance. Traditionally, these conditions are addressed by adding a time delay to allow normal transients to clear. However, this approach conflicts with HaloBus-ZBØSM protection philosophy. To address this, the Non-Directional Earth-Fault Over-Current element (50N) shall be validated by the Residual Over-Voltage element (59N). In other words, earth-fault protection shall not activate when current unbalance exceeds its pickup value unless voltage unbalance also exceeds its pickup value. The (59N) validation of the (50N) activation is required for bus-tie relay protection and, as discussed further below, for generator incomer protection.

21.3.2. Both the **Residual Over-Voltage (59N)** and **Non-Directional Earth-Fault Over-Current (50N)** elements shall be set to Trip & Latch all bus-tie circuit breakers with the same time delay. This time delay shall be coordinated with the earth-fault bus-directional elements **(67N-PDI2)** and **(67N-PDI3)**.

21.3.3. The **Residual Over-Voltage (59N)** element shall include an additional activation level, **(59N Trip 3)**, set to Trip & Latch the bus-tie breakers instantaneously, i.e., with 0 ms time delay, if voltage unbalance reaches 20 kV on the 11 kV side. This protection is intended to address potential voltage surges on the 11 kV power system caused by simultaneous double failures, such as an intermittent high-inductance earth fault within the main power plant combined with a generator incomer single-contactor failure while the generator is running at rated speed and voltage out of synchronism with the main bus. As discussed further below, multiple protection functions are configured to trip the generator incomer and E-Stop the main engine and AVR of an MDG that may experience such a single-pole breaker failure. The additional protection configured in the bus-tie relay provides further assurance that such simultaneous failures will not produce excessive over-voltage surges that could affect the main power-plant equipment.

For Settings Group 2 ONLY – when each 11 kV switchboard has at least one MDG connected, the following requirements apply:

21.3.4. The **Residual Over-Voltage (59N)** element shall be set to Trip & Latch all bus-tie circuit breakers instantaneously, i.e., with 0 ms time delay, when the unbalanced voltage exceeds the pickup value. For an 11 kV HRG system, this value is typically 1,100 V on the primary side of the PT.

21.3.5. The **Non-Directional Earth-Fault Over-Current (50N)** element, validated by the **Residual Over-Voltage (59N)** element, **(50N)+(59N)**, shall be set to Trip & Latch all bus-tie breakers instantaneously, i.e., with 0 ms time delay.

22. Generator Protection Relays – protection against earth faults within the 11 kV generator power section, including the cabling to the incomer, shall be provided as follows:

22.1.Offline generator protection shall apply when the generator is not connected to the bus. At least one, and preferably both, of the protection functions listed below shall be configured to Trip & Latch the generator incomer and E-Stop the main engine and AVR instantaneously, i.e., with 0 ms time delay. For these protection elements, generator incomer status shall be included in the logic and, depending on the generator relay make and model, custom logic may be required to achieve the intended function. These functions apply to both NGT and NGR grounding systems and provide the required protection against incomer-contactor failures, generator cabling failures, and internal generator electrical failures that may occur while the MDG is running disconnected from the bus, including immediately after Unload & Disconnect during idle running or during an attempt to synchronize and connect to the bus.

22.1.1. (59N) + (Offline) – incomer open and Residual Over-Voltage exceeding the pickup setting.

- 22.1.2. **(50) + (Offline)** – incomer open and phase current above the earth-fault current pickup setting. This protection uses the generator phase CTs with settings applied for earth-fault protection.
- 22.2. The **Residual Over-Voltage (59N)** element shall be configured with two activation stages, Alarm and Trip, both using the same pickup value.
- 22.2.1. **(59N) Alarm** – the generator relay shall raise an alarm and initiate a Start All Engines request to the VMS with 0 ms time delay as soon as the residual over-voltage pickup setting is reached.
- 22.2.2. **(59N) Trip** – the generator relay shall E-Stop the MDG after a time delay coordinated with the **(50N)** and **(59N)** elements configured in the bus-tie relays for Settings Group 1.
- 22.3. The **Earth-Fault Non-Directional Over-Current (50N)** element shall be configured with two activation stages, Alarm and Trip, both using the same pickup value.
- 22.3.1. **(50N) Alarm** – the generator relay shall raise an alarm and initiate a Start All Engines request to the VMS with 0 ms time delay as soon as the earth-overcurrent or residual over-voltage pickup setting is reached.
- 22.3.2. **(50N) Trip** – depending on the MODU grounding system, this function shall be configured as follows:
- **NGR grounding systems** – the **(50N) Trip** function shall E-Stop the MDG after a time delay coordinated with the **(50N)** and **(59N)** elements configured in the bus-tie relays for Settings Group 1.
 - **NGT grounding systems** – the following requirements apply:

22.3.2..1. **(50N+59N)** – if the generator relay supports custom logic, logic shall be configured to Trip & Latch the generator incomer and E-Stop the main engine and AVR with 0 ms time delay when both the **Earth-Fault Non-Directional Over-Current (50N)** and **Residual Over-Voltage (59N)** elements have picked up, i.e., measured values are above their pickup settings. The **(59N)** validation is required to prevent nuisance tripping caused by operating transients.

22.3.2..2. In addition to the **(50N+59N)** protection logic described above, the generator relay shall also have the **(50N) Trip** function configured to E-Stop the MDG with the minimum time delay required to confirm that the current unbalance is not caused by a normal operating transient. A 100 ms time delay is typically sufficient.

NOTE: For NGT grounding systems, the generator contribution to a fault outside the generator 11 kV power section, i.e., outside the generator windings and the cable connecting the generator to the 11 kV switchboard, is insignificant. Therefore, detection of current unbalance validated by voltage unbalance, with both measured values above their pickup settings, is sufficient to confirm that the fault is located on the generator side.

- 22.4. The **Earth-Fault Directional Over-Current (67N)** element typically requires a short time delay to reliably determine earth-fault direction. This time delay, together with relay timing and sensing accuracies, shall be considered for selectivity with the bus-tie relays when Settings Group 1 is active, i.e., when one 11 kV switchboard does not have an MDG connected. Under this condition, the bus-tie relay shall allow sufficient time for the generator incomer relay to clear a fault within the generator power section before activating bus-directional protection. The **(67N)** function shall be set to Trip & Latch the generator incomer and shut down the main engine and AVR with the minimum time delay required to reliably detect earth-fault direction.
- 22.5. For **NGR grounding systems**, if the generator relay supports custom logic, **(87N+59N)** logic shall be configured to Trip & Latch the generator incomer and E-Stop the main engine and AVR with 0 ms time delay when both the **Earth-Fault Differential Over-Current (87N)** and **Residual Over-Voltage (59N)** elements have picked up, i.e., measured values are above their pickup settings. The **(59N)** validation is required to prevent nuisance tripping caused by operating transients. If the generator relay cannot support this custom logic, the **(67N)** element may be accepted as the main generator insulation-failure protection, provided the secondary protections in place ensure that no single protection failure can cause a catastrophic generator failure.

HaloBus-ZBØSM – Short-Circuit Protection Design Specifications.

Consistent with the protection philosophy established previously, Phase Faults shall be isolated with the minimum practical delay necessary to limit fault energy while preserving required selectivity.

23. **Distribution Feeder Breaker Protection Relays** – protection against short-circuits, or phase faults, on 11 kV distribution feeders, including the distribution transformers' 11 kV windings, shall be provided by the **Non-Directional Phase Over-Current element (50)**. The 50 element shall be set to Trip & Latch the affected distribution feeder circuit breaker instantaneously, i.e., with 0 ms time delay.

- 24. Bus-Tie Protection Relays** – protection against short-circuits, or phase faults, within a single DP segregation zone shall be provided as follows:
- 24.1.** The bus-tie relays shall have **Bus-Tie Cable Differential Phase Over-Current (87-PDI1) AND Bus-Tie Cable Directional Phase Over-Current (67-PDI1)** functions set to Trip & Latch both bus-tie cable breakers instantaneously, i.e., with 0 ms time delay, as soon as the current magnitude in any one of the three phases exceeds the pickup setting. The same settings shall apply to both Settings Group 1 and Settings Group 2. These functions isolate a phase fault on a bus-tie cable without reducing DP capability because only the affected bus-tie is opened.
 - 24.2.** The bus-tie relays shall have **CT Saturation Detection** enabled and properly configured to ensure that, if one of the phase CTs used by the bus-tie cable differential over-current element enters saturation during a short-circuit event, the **(87-PDI1)** element will not falsely activate.
 - 24.3.** Two **Bus Directional Phase Over-Current** protection functions, **(67-PDI2) AND (67-PDI3)**, shall be configured to activate simultaneously and independently of each other. Both Bus Directional Phase Over-Current protection schemes shall use the same activation settings in Settings Group 1 and Settings Group 2 and shall be coordinated with the first protection layer for feeder and generator phase faults, as shown in the examples below. These functions shall activate as follows:
 - 24.3.1.** **(67-PDI2)** shall E-Stop the MDGs on the affected bus, regardless of whether the MDGs are connected to the bus, and shall Trip & Latch the two bus-tie breakers controlled by the PDI2 relays.
 - 24.3.2.** **(67-PDI3)** shall Trip & Latch the two bus-tie breakers controlled by the PDI3 relays.
 - 24.4.** The **Non-Directional Phase Over-Current** element validated by the **Under-Voltage element (50)+(27)** shall be set to Trip & Latch all bus-tie breakers as defined below:
 - 24.4.1.** **For Settings Group 1** – when one 11 kV switchboard has no MDG connected, the **(50)+(27)** function shall activate with a time delay coordinated with the phase-over-current bus-directional elements **(67-PDI2)** and **(67-PDI3)**.
 - 24.4.2.** **For Settings Group 2** – when each 11 kV switchboard has at least one MDG connected, the **(50)+(27)** function shall be set to activate instantaneously, i.e., with 0 ms time delay.
- 25. Generator Protection Relays** – protection against short-circuits, or phase faults, within the 11 kV generator power section, including the cabling to the incomer, shall be provided as follows:
- 25.1.** The **Phase Differential Over-Current element (87)** shall be set to Trip & Latch the generator incomer and E-Stop the MDG with the minimum required time delay. Depending on the generator relay make and model, a short time delay may be required to confirm that the phase fault is located within the generator power section; this delay is typically 50 ms, i.e., three cycles at 60 Hz.
 - 25.2.** The generator relay shall have **CT Saturation Detection** enabled and properly configured to ensure that, if one of the phase CTs used by the generator differential over-current element enters saturation during a short-circuit event, the **(87)** element will not falsely activate.
 - 25.3.** The **Phase Directional Over-Current (67)** element typically requires a short time delay to reliably determine phase-fault current direction. This time delay, together with relay timing and sensing accuracies, shall be considered for selectivity with the bus-tie relays when Settings Group 1 is active, i.e., when one 11 kV switchboard does not have an MDG connected. Under this condition, the bus-tie relay shall allow sufficient time for the generator incomer relay to clear a fault within the generator power section before activating bus-directional protection. The **(67)** function shall be set to Trip & Latch the generator incomer and shut down the main engine and AVR with the minimum time delay required to reliably detect phase-fault current direction. This protection is a backup to the generator differential protection and, depending on the generator relay make and model, may not be available or may require a detection time that is too long to coordinate effectively with the bus-tie directional protection when Settings Group 1 is active; for this reason, this element is considered optional.
 - 25.4.** The **Phase Non-Directional Over-Current (50)** element shall be configured with two activation stages, Alarm and Trip, both using the same pickup value.
 - 25.4.1.** **(50 Alarm)** – the generator relay shall raise an alarm and initiate a Start All Engines request to the VMS with 0 ms time delay as soon as the non-directional over-current pickup setting is reached.

25.4.2. (50 Trip) – the generator relay shall E-Stop the MDG after a time delay coordinated with the **(50)** element configured in the bus-tie relays for Settings Group 1.

The above requirements are summarized in Table 2. This table identifies the phase-fault protection functions and the redundancy incorporated into HaloBus-ZBØSM design. Table 2 is not intended to list every protection function required by Class; rather, it defines the HaloBus-ZBØSM design-specific protection elements.

Depending on the protection-relay make and model, additional protection functions may be available with different sensing methods, timing characteristics, and design accuracies. These functions must all be evaluated during the Selectivity Study review and may be included where they improve overall protection-system redundancy. The protection functions shown in Table 2 represent the minimum functions required for HaloBus-ZBØSM.

Table 2: HaloBus-ZBØSM protection elements

	Feeder Breaker Relays	Time Delay (ms)	Fault on Feeder		Fault on Bus Tie Cables		Fault on Generator			Fault on Bus		Protection Elements Actions												
			Settings Group 1 Active		Settings Group 2 Active		Settings Group 1 Active		Settings Group 2 Active		Settings Group 1 Active		Settings Group 2 Active		Start All Engines	Feeder Breaker Trip & Latch	Bus-Tie Cable Both Breakers	Trip & Latch	Swbd. Both Bus-Tie Breakers	Trip & Latch	MDG E-Stop	Both Swbd MDGs E-Stop		
			NGR	NGT	NGR	NGT	NGR	NGT	NGR	NGT	NGR	NGT	NGR	NGT										
Bus-Tie Protection Relays	Phase OC - 50	50	1													X								
	Earth OC - 50N	50N														X								
	Switch On-to Fault (SOTF)																							
	Breaker Failure (SOFB)																							
	Tripping (T4TC)	100																						
	The Cable Phase Differential OC (87) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
	The Cable Phase Directional OC (67B) (Zone 1)	0																						
Generator Relays	Phase OC 50 (V<1100V)	50																						
	Earth OC 50N	50N																						
	Non-Directional Interim Fault (3V0<1100V)	0																						
	Zone 3 Pair (87N-PD11) Trip & FWD Earth OC	50																						
	Residual Overvoltage (3V0>1100V)	0																						
	Residual Overvoltage (3V0) >20kV	0																						
	Phase OC 50 (V<1100V)	0																						
	Earth OC and Residual Overvoltage (3V0)	0																						
	Residual Overvoltage (3V0>1100V)	0																						
	Switch On-to Fault / Accidental Energization (SOTF) / (50/27)	0																						
	Generator Offline OC	0																						
	Generator Offline VO	0																						
	Generator Phase Differential OC (87)	10																						
	Generator Phase Directional OC (67)	10																						
	Generator Phase OC (50) - Alarm	0																						
Generator Phase OC (50) - Trip	10 ⁰ + 300																							
Generator Residual OV Alarm (59N)	0																							
Generator Residual OV Trip (59N)	0																							
Generator Earth OC Alarm (50N)	0																							
Generator Earth Directional OC (67N)	0																							
Generator Earth Differential OC (87N)	0																							
Generator Earth OC Trip (50N)	0																							
Generator Earth Trip (3V0>1100V)	0																							
NGR																								
NGT																								

HaloBus-ZBØSM – Hidden Failure Screening for Electrical Fault Analysis

The preceding sections established the Hidden Failure framework and defined the HaloBus-ZBØSM protection architecture, including the protection functions, communication interfaces, redundancy provisions, and failure-response requirements intended to detect, alarm, bypass, or mitigate Hidden Failures. Prior to evaluating the response of HaloBus-ZBØSM design to representative Earth Fault and Phase Fault scenarios, it is necessary to determine which failures remain credible Hidden Failures and which are revealed or otherwise addressed by the design.

Accordingly, this section applies the Hidden Failure framework to the HaloBus-ZBØSM design specifications and screens each Hidden Failure category against the implemented protection architecture. Where the design detects, alarms, automatically mitigates, or otherwise manages a failure condition before an electrical fault occurs, that condition is not treated as a Hidden Failure for the Electrical Fault Analysis. The remaining failure modes identified below constitute the credible Hidden Failures carried forward into the HaloBus-ZBØSM Electrical Fault Analysis.

The screening results for each Hidden Failure category are summarized below.

Sensing-system or sensing-equipment Hidden Failures – consistent with the framework above, sensing failures are evaluated by considering whether the affected relay would lose, or detect incorrect values for the current- or voltage-based inputs required to detect an 11 kV fault. Each bus-tie relay and generator relay uses both current- and voltage-based protection elements, while feeder relays rely only on current-based protection. Therefore, the sensing-related Hidden Failures considered in this analysis are assessed as follows.

- For generator relays, a phase-voltage or phase-current sensing failure would affect the MDG's normal operating measurements, including kW and kVAr, and would be detected by load-sharing protection before an electrical fault occurs. Therefore, in this Single Failure analysis, where the electrical fault is the Active Failure, these sensing failures are not treated as Hidden Failures. They are, however, considered when evaluating Hidden Failures within the load-sharing protection function itself.
- For bus-tie relays, a phase-voltage or phase-current sensing failure would affect normal power-flow measurements across the bus-ties. Because load-sharing protection also monitors tie power flow, these failures would be detected and alarmed during normal operation. As with generator-relay sensing failures, they are therefore excluded from this electrical-fault Single Failure analysis, where the electrical fault is the Active Failure, but remain relevant when evaluating Hidden Failures within the load-sharing protection design.
- Residual voltage is derived from the same PT sets used for phase-voltage measurement, typically through dual secondary windings and an open-delta residual-voltage circuit. As with the phase-voltage and phase-current sensing failures discussed above, a residual-voltage sensing failure would be detected during normal operation. In the HaloBus-ZBØSM design, high-sensitivity voltage-unbalance protection would alarm the condition and initiate a Start All Engines request to VMS, reconfiguring the power plant to Open Bus, the Safe-Case configuration. Because this response occurs before the electrical fault used as the Active Failure in this analysis, the sensing failure is not treated as hidden.
- CT saturation is a potential sensing-related Hidden Failure when the electrical fault is the Active Failure because high short-circuit current can prevent a degraded phase CT from accurately reproducing the primary fault current. This could affect phase-differential overcurrent (87) protection. The HaloBus-ZBØSM design requires generator and bus-tie relays to incorporate CT Saturation Detection or equivalent restraint functions within the (87) protection element to prevent undesired operation resulting from saturation of a single phase CT. Directional and non-directional phase-overcurrent elements are not affected by single-phase CT saturation because a phase fault produces overcurrent in at least two phases and these elements operate on single-phase pickup. Earth-fault protection is also not affected because HRG systems limit earth-fault current below ground-CT saturation levels. In addition, Transocean mitigates this risk through CT-saturation verification during PM activities. On this basis, CT saturation is not treated as a Hidden Failure in this Single Failure analysis.
- Earth-fault CT polarity is another potential sensing-related Hidden Failure because incorrect polarity may not be evident during normal balanced-load operation. Transocean verifies earth-CT polarity during the five-year PM

interval by primary injection through the core-balance CTs on all 11 kV feeders, bus-ties, and generator relays. Polarity is also verified for all bus-tie relays and two generator relays during live earth-fault testing required for DP-3 CBT Class compliance. However, polarity could still be affected between test intervals by loose wiring or maintenance/troubleshooting errors. In that case, incorrect earth-CT polarity could affect directional overcurrent elements, but not earth-differential overcurrent elements, which use phasor summation of two CT measurements similar to phase-differential protection. The affected protection elements are:

- Bus-tie relays: **(67N-PDI1)**, **(67N-PDI2)**, and **(67N-PDI3)**.
- Generator relays: **(67N)**.

Protection-equipment Hidden Failures – 11 kV protection relays installed on DP-3 MODUs are purpose-built for power-system protection and are designed to withstand the electromagnetic stresses associated with major electrical faults. They include internal self-monitoring, diagnostics, and separation between protection elements so that an internal relay failure is detected and alarmed or remains limited to the affected function. For this reason, internal relay failures are generally not treated as Hidden Failures in this analysis.

Blind Relay Hidden Failure – For the purpose of this paper, a Blind Relay Hidden Failure is defined as any condition that prevents a protection relay from performing its intended protection function when demanded by an Active Failure. The term is intentionally independent of the specific failure mechanism. Representative causes may include incorrect settings, disabled protection functions, configuration errors, maintenance-related errors, wiring deficiencies affecting the relay's required inputs or outputs, or other unforeseen conditions that render the relay effectively unresponsive to the Active Failure. For analytical purposes, the affected relay is assumed to provide no effective contribution to fault detection, classification, or isolation.

The Blind Relay Hidden Failure is carried forward in this analysis as the representative worst-case protection-layer Hidden Failure. Human Error resulting in missing, incorrect, disabled, or improperly implemented protection settings is used as the most readily understood example; however, the methodology is intentionally independent of the specific cause. The condition is considered particularly significant because many internal relay failures, trip-circuit deficiencies, communication failures, and circuit-breaker failures can generally be identified and alarmed when detected, allowing defined corrective actions or secondary protection responses. By contrast, a Blind Relay Hidden Failure directly challenges the ability of the protection architecture to maintain the vessel's WCFDI when the protection relay expected to act on the fault is completely unresponsive.

The Electrical Fault Analysis does not assume that multiple protection relays are simultaneously blind at the initiation of an Active Failure. Instead, each protection layer is independently challenged with its own worst-case Blind Relay Hidden Failure while carrying forward the Hidden Failures already established at preceding protection layers. This methodology evaluates whether each successive protection layer can continue to maintain the vessel's WCFDI and complete fault isolation despite progressively degraded protection-system capability.

Communication-system Hidden Failures – Consistent with the communication-network requirements defined previously, the HaloBus-ZBØSM design requires all bus-tie relays to detect communication failures, raise an alarm, initiate a Start All Engines request to the VMS, and activate Settings Group 2. Because these failures are detected, alarmed, and acted on by the network-failure logic during normal operation, they are not treated as Hidden Failures in this Single Failure analysis, where the electrical fault is the Active Failure. The remaining communication-related Hidden Failure considered is Blind Relay Hidden Failure, where one bus-tie relay does not have the required protection functions enabled or has incorrect settings. This condition does not affect the differential overcurrent elements (87-PDI1) or (87N-PDI1) because these functions are configured in both relays connected to each PDI1 network and operate from current measurements exchanged by the paired relays. The communication-based protection elements affected by Blind Relay Hidden Failure are:

- Bus-tie relays: **(67N-PDI1)**, **(67N-PDI2)**, and **(67N-PDI3)**.

Isolating-equipment Hidden Failures – this category includes failures that prevent an 11 kV circuit breaker from opening after a protection relay issues a trip command. Trip-coil circuit failures, including wiring or solenoid failures, are detected by the Trip Coil Monitoring (74) function in the bus-tie and generator relays and are therefore not treated as hidden in this analysis. The remaining isolating-equipment Hidden Failure considered is a circuit-breaker mechanical failure, such as a failure of the contact mechanism or operating linkage, that prevents the breaker from opening when

commanded. Accordingly, circuit-breaker mechanical failure is the isolating-equipment Hidden Failure carried forward into the Electrical Fault Analysis.

HaloBus-ZBØSM – Electrical Fault Analysis

The following analysis applies the screened Hidden Failures identified in the previous section to representative 11 kV Earth-Fault and Phase-Fault scenarios. For each fault location, the analysis first verifies that the vessel's WCFDI is maintained following the Active Failure combined with a credible Hidden Failure, thereby satisfying the minimum DP-3 CB/CBT Class requirement. However, unlike a conventional Single Failure demonstration, the analysis continues beyond demonstration of WCFDI compliance and follows the protection sequence through complete fault isolation. At each successive protection layer, the worst-case credible Hidden Failure applicable to that protection layer is evaluated cumulatively with the Hidden Failures already introduced at preceding protection layers. Accordingly, the analysis does not assume that multiple protection relays are simultaneously unresponsive at the beginning of the fault sequence. Instead, each protection layer is independently challenged with its own worst-case Hidden Failure while maintaining the cumulative Hidden Failures already established during evaluation of the preceding protection layers. This methodology allows the analysis to assess whether each successive protection layer can continue to maintain the vessel's WCFDI and complete fault isolation despite progressively degraded protection-system capability. Consequently, the analysis evaluates multiple simultaneous Hidden Failure combinations during the fault-isolation sequence, providing an assessment that extends substantially beyond the minimum Class requirement.

Before considering individual fault locations, it is necessary to establish the protection responses that apply to all electrical faults on the 11 kV distribution system. These common responses are summarized below and form the basis for the fault-specific analyses that follow.

Start All Engines Request to VMS – Regardless of fault location, any Earth Fault or Phase Fault within the 11 kV distribution system will be detected by the protection relays of all connected MDGs. Depending on the fault type, the generator-relay **(59N) Alarm**, **(50N) Alarm**, or **(50) Alarm** functions will initiate a Start All Engines request to the VMS. Because at least two MDGs are always connected to the main power plant, no single Hidden Failure can prevent this request from being generated, even if one MDG relay has incorrect or missing protection settings because of Blind Relay Hidden Failure.

Bus-Tie Relays Additional Response with Settings Group 1 Active – When Settings Group 1 is active, one 11 kV switchboard does not have a connected MDG. Under these conditions, a degrading phase-to-ground insulation fault within the 11 kV distribution system is detected by the bus-tie relays through the **(50N-INT)+(59N)** function. This provides an additional independent path for initiating a Start All Engines request to the VMS. In accordance with the HaloBus-ZBØSM specifications, the resulting VMS response will automatically connect the available MDGs and reconfigure the power plant to the Safe-Case Open Bus configuration. Consequently, if the insulation failure develops sufficiently slowly, the power plant may be reconfigured to Open Bus, containing the developing failure within the vessel's WCFDI before it escalates into a sustained Earth Fault. Because all six bus-tie relays initiate the Start All Engines request independently, no single Hidden Failure can prevent this response from being generated.

Bus-Tie Relays Common Response with Settings Group 2 Active – When at least one MDG is connected to each 11 kV switchboard, any detected electrical fault will cause all six bus-tie relays to issue an instantaneous Trip & Latch command to their corresponding bus-tie breakers through the applicable **(50N)+(59N)**, **(59N)**, or **(50)+(27)** functions, with 0 ms intentional time delay. For Earth-Fault conditions, the high-sensitivity **(50N)+(59N)** and **(59N)** functions can respond to detectable insulation degradation before it develops into a sustained Earth Fault. For Phase-Fault conditions, the **(50)+(27)** function provides the corresponding instantaneous bus-tie response. In either case, tripping all bus-ties restores the Safe-Case Open Bus configuration, contains the failure within a single DP segregation zone, and maintains the vessel's WCFDI in less than 100 ms. Because this response is initiated independently by all six bus-tie relays using dedicated voltage and current sensing and the double-breaker bus-tie Inter-Trip arrangement, no single Hidden Failure can prevent the power plant from reconfiguring to Open Bus and containing the Active Failure within the vessel's WCFDI.

Having established the common protection responses applicable to any electrical fault on the vessel's 11 kV distribution system, the following analysis examines faults within each major section of the power plant: feeder sections, generator power sections, bus-tie cable sections, and main bus sections. For each fault location, the analysis applies the methodology

defined above to evaluate the primary protection response, each successive backup protection layer, and complete fault isolation.

Fault on an 11 kV Feeder (Active Fault) – See Figure 6 for the analysis of an Earth Fault or Phase Fault occurring on an 11 kV feeder or on the HV side of the associated distribution transformer. The following protection sequence applies.

Primary Protection – The feeder relay provides primary protection and shall Trip & Latch the affected feeder breaker instantaneously, with 0 ms intentional time delay, using (50N) for an Earth Fault or (50) for a Phase Fault. This action isolates the Active Failure without power-plant disruption other than loss of the affected feeder loads. If Settings Group 2 is active, the general response defined previously will also cause all bus-tie relays to issue instantaneous Trip & Latch commands, reconfiguring the power plant to the Safe-Case Open Bus configuration and maintaining the vessel's WCFDI in less than 100 ms.

Primary Protection Worst-Case Hidden Failure (1st Hidden Failure) – The first Hidden Failure is conservatively represented by either Blind Relay Hidden Failure that prevents the feeder relay from issuing the required trip command, such as missing or disabled protection settings, or a mechanical failure that prevents the feeder breaker from opening after receiving the command. In either case, the feeder remains connected to the Active Failure and backup protection is required.

Settings Group 1 Active – one 11 kV switchboard does not have a connected MDG.

Secondary Protection – Depending on the fault type, the two independent bus-directional overcurrent schemes, (67N-PDI2) and (67N-PDI3) for an Earth Fault or (67-PDI2) and (67-PDI3) for a Phase Fault, will activate and Trip & Latch the applicable bus-tie breakers. The PDI2 protection function will also E-Stop both MDGs associated with the affected bus, regardless of their connection status, thereby removing all potential local energy sources. This action isolates the affected DP segregation zone, maintains the vessel's WCFDI, and provides Secondary Protection in (T0 + 100) ms, as summarized in Table 2. Because the two bus-directional schemes are fully independent and use the double-breaker bus-tie Inter-Trip arrangement, no additional single Hidden Failure can cause the vessel's WCFDI to be exceeded.

Secondary Protection Worst-Case Hidden Failure (2nd Hidden Failure) – If the Active Failure occurs on a feeder supplied from the bus section without a connected MDG, Secondary Protection isolates the faulted DP segregation zone, and no local energy source remains connected to the fault. If the fault occurs on a bus section with one connected MDG, a second Hidden Failure, represented by Blind Relay Hidden Failure that leaves one PDI2 bus-tie relay with incorrect or missing settings, may prevent the applicable (67N-PDI2) or (67-PDI2) function from operating. The independent PDI3 bus-directional protection will nevertheless isolate the affected bus from the remainder of the power plant and maintain the vessel's WCFDI. However, because PDI3 does not initiate MDG E-Stop, the connected MDG may remain exposed to the feeder fault and must be removed by the next protection layer.

Tertiary Protection – Any MDG that remains connected to the affected bus will be isolated by the applicable protection elements within its generator relay. For an Earth Fault, the applicable protection is (50N) AND (59N) for NGR grounding systems or (59N) for NGT grounding systems. For a Phase Fault, the applicable protection is (50). These elements will operate after a (T0 + 300) ms time delay and E-Stop the affected MDG, removing the remaining energy source and completing fault isolation. If only one MDG was connected to the affected bus when the Active Failure occurred, one of the following outcomes will result:

1. If the feeder breaker opens on undervoltage after the connected MDG is E-Stopped, the Start All Engines function will start and connect another MDG to the de-energized bus, restoring power in less than 20 seconds.
2. If the feeder breaker remains closed and the fault remains connected to the de-energized bus, the oncoming MDG will be blocked from connecting or tripped by SOTF or (50/27) protection, which will E-Stop the oncoming MDG.

Tertiary Protection Worst-Case Hidden Failure (3rd Hidden Failure) – At this stage, the PDI3 bus-directional protection has already isolated the affected bus from the remainder of the power plant and maintained the vessel's WCFDI, while the connected-MDG generator relay provides an independent protection layer for removing the remaining energy source. This level of redundancy already exceeds the minimum Class

requirement. Nevertheless, the analysis conservatively introduces a third Hidden Failure consisting of Blind Relay Hidden Failure that leaves the connected-MDG generator relay with no effective protection functions enabled. In that case, the Quaternary Protection described below completes fault isolation. This cumulative third-Hidden-Failure condition is shown in Figure 6.

Quaternary Protection – If the connected-MDG generator relay does not isolate the fault because of Blind Relay Hidden Failure, the remaining correctly configured bus-tie relay or independent AVR protection provides the final protection layer. For an Earth Fault, the bus-tie relay **(59N) Trip 2** function will E-Stop the affected MDG after the applicable **(T0 + 400) ms** time delay. For a Phase Fault, the affected MDG's AVR **Loss of Sensing (LOS)** protection will activate and E-Stop the MDG. These independent actions remove the remaining energy source and complete fault isolation.

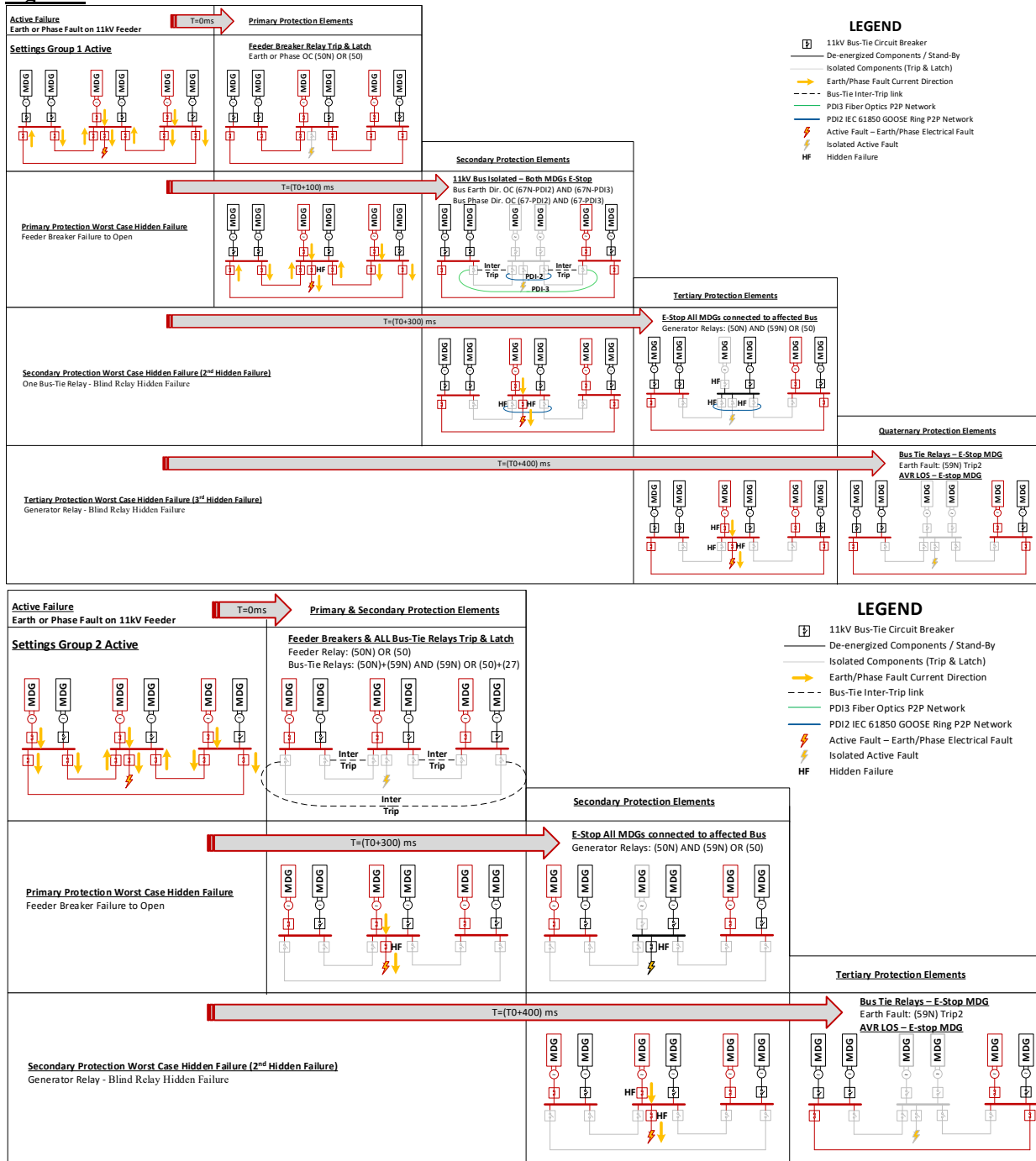
Settings Group 2 Active – If each 11 kV switchboard has at least one connected MDG when the Active Failure occurs, the bus-tie relays will already have reconfigured the power plant to the Safe-Case Open Bus configuration through the common Settings Group 2 response defined previously. With the bus-ties open, the vessel's WCFDI is maintained and no Earth-Fault or Phase-Fault current flows between DP segregation zones. Consequently, the bus-directional protection functions **(67N-PDI2)** and **(67N-PDI3)**, or **(67-PDI2)** and **(67-PDI3)**, will not activate. The remaining protection sequence therefore addresses complete isolation of the feeder fault within the affected bus section.

Secondary Protection – With the bus-ties already open, the remaining task is to remove the MDGs supplying the feeder fault within the affected bus section. Depending on the fault type, the generator relays of the connected MDGs will activate **(50N) AND (59N)** for an Earth Fault in an NGR system, **(59N)** for an Earth Fault in an NGT system, or **(50)** for a Phase Fault. These elements will operate after a **(T0 + 300) ms** time delay and E-Stop the affected MDGs, removing the remaining energy sources and completing fault isolation. If only one MDG was connected to the affected bus when the Active Failure occurred, one of the following outcomes will result:

1. If the feeder breaker opens on undervoltage after the MDG is E-Stopped, the Start All Engines function will start and connect another MDG to the de-energized bus, restoring power in less than 20 seconds.
2. If the feeder breaker remains closed and the fault remains connected to the de-energized bus, the oncoming MDG will be blocked from connecting or tripped by **SOTF** or **(50/27)** protection, which will E-Stop the oncoming MDG.

Secondary Protection Worst-Case Hidden Failure (2nd Hidden Failure) – Because Secondary Protection relies on the generator relays of the MDGs connected to the affected bus, the worst-case additional Hidden Failure is Blind Relay Hidden Failure that leaves one generator relay with no effective protection functions enabled. If two MDGs are connected to the affected switchboard, the correctly configured generator relay will isolate its MDG. Generator-relay functions that initiate MDG E-Stop are not defeated by an incomer mechanical failure because the E-Stop simultaneously shuts down the main engine and excitation system in addition to issuing the incomer Trip & Latch command. Therefore, Blind Relay in the remaining MDG relay is the only screened Hidden Failure that could leave an MDG energizing the fault.

Tertiary Protection – For an Earth Fault, both bus-tie relays associated with the affected switchboard will detect residual overvoltage and activate **(59N) Trip 2** after **(T0 + 400) ms**, E-Stopping the remaining MDG and removing the final energy source. Because two independent bus-tie relays perform this action using separate bus-voltage sensing PTs, no additional single Hidden Failure can prevent complete Earth-Fault isolation. For a Phase Fault, the affected MDG's AVR **Loss of Sensing (LOS)** protection will E-Stop the MDG, Trip & Latch the incomer, and shut down the AVR after the applicable delay coordinated with reactive-power-sharing protection. This independent AVR response completes fault isolation after the vessel's WCFDI has already been maintained by the Settings Group 2 Open Bus response.

Figure 6 Active Fault on 11kV Feeder


Fault on an 11 kV Bus-Tie Cable (Active Fault) – See **Figure 7** for the analysis of an Earth Fault or Phase Fault occurring on one of the main bus-tie cables. The following protection sequence applies.

Primary Protection – The two bus-tie relays controlling the breakers at opposite ends of the affected bus-tie cable provide primary protection. For an Earth Fault, the applicable protection elements are **(87N-PDI1)** and **(67N-PDI1)**; for a Phase Fault, the applicable protection elements are **(87-PDI1)** and **(67-PDI1)**. These differential and directional protection elements operate independently and shall Trip & Latch both breakers at the ends of the affected bus-tie cable with 0 ms intentional time delay. This action isolates the Active Failure, reconfigures the power plant to Linear Closed Bus, and maintains all electrical consumers energized. When either **(87N-PDI1)** or **(87-PDI1)** activates, each of the two bus-tie relays participating in that PDI1 differential function sends an activation confirmation over the PDI3 network to its separate paired relay in the redundant bus-directional protection scheme.

Primary Protection Worst-Case Hidden Failure (1st Hidden Failure) – The worst-case credible Hidden Failure for this scenario is a mechanical failure that prevents one of the two bus-tie breakers from opening after receiving a trip command from the applicable PDI1 earth-fault or phase-fault protection function. Under this condition, one breaker opens as intended, but the failed breaker leaves the faulted cable connected to the adjacent 11 kV switchboard. Blind Relay Hidden Failure that leaves one bus-tie relay with missing, disabled, or incorrect protection settings is not carried forward as the first Worst Case Hidden Failure because it does not prevent operation of the **(87N-PDI1)** or **(87-PDI1)** differential protection. Each differential function is implemented through the paired relays connected by the PDI1 network, allowing the correctly configured relay to detect the differential condition and initiate the required trip commands. Accordingly, the circuit-breaker mechanical failure is the first Worst Case Hidden Failure carried forward into the Secondary Protection analysis.

Secondary Protection – If one bus-tie breaker fails to open following activation of a PDI1 bus-tie cable protection function, there are two independent protection functions that act as defined below.

1. The applicable breaker-failure logic will operate through **(50BF)+(87-PDI1)**, **(50BF)+(67-PDI1)**, **(50BF)+(87N-PDI1)**, or **(50BF)+(67N-PDI1)**. After the 100 ms breaker-failure coordination delay, this logic will isolate the 11 kV switchboard containing the failed breaker by Trip & Latch of both adjacent bus-ties and E-Stop of both MDGs associated with that switchboard, regardless of their connection status. This action removes all remaining energy sources that could feed the bus-tie cable fault and completes fault isolation. The breaker-failure response is independently implemented by both bus-tie relays associated with the affected switchboard. The relays issue the required Trip & Latch commands through the redundant PDI2 GOOSE network, and each relay is independently hardwired to E-Stop both MDGs associated with the switchboard.
2. If only one bus-tie breaker opens, the power plant is effectively reconfigured to Linear Closed Bus, causing fault current to redistribute through the remaining closed bus-tie path. Under this condition, the bus-tie relay paired through PDI3 with the relay that controls the successfully opened breaker detects fault-current contribution in the forward direction, i.e., out of its bus and into the bus-tie cable. When this forward-current condition is present and PDI3 conformation is received that its paired relay has activated **(87N-PDI1)** or **(87-PDI1)**, the relay activates **(67N) FWD + PDI3(87N-PDI1)** or **(67) FWD + PDI3(87-PDI1)**, respectively. After the 50 ms coordination delay, plus approximately 50ms time required for fault current direction stabilization and detection, it Trips & Latches its circuit breaker and, through the bus-tie Inter-Trip function, trips the breaker at the opposite end of that bus-tie, isolating the fault to a single 11 kV bus.

The two protection functions defined above operate independently and either function is sufficient to contain the fault within the vessel's WCFDI; therefore, no additional single failure can prevent this Secondary Protection response from maintaining the WCFDI. This Secondary Protection sequence applies with either Settings Group 1 or Settings Group 2 active. When Settings Group 2 is active, the bus-tie non-directional **(50N)+(59N)** or **(50)+(27)** protection functions also operate with 0 ms intentional time delay. These functions provide an additional simultaneous and communication-independent protection response by tripping the bus-ties and restoring the Safe-Case Open Bus configuration before completion of the delayed breaker-failure sequence.

Secondary Protection Worst-Case Hidden Failure (2nd Hidden Failure) – As discussed above, the two independent Secondary Protection functions are sufficient to contain the fault within the vessel's WCFDI. For complete fault isolation, however, the worst-case additional Hidden Failure is Blind Relay Hidden Failure that

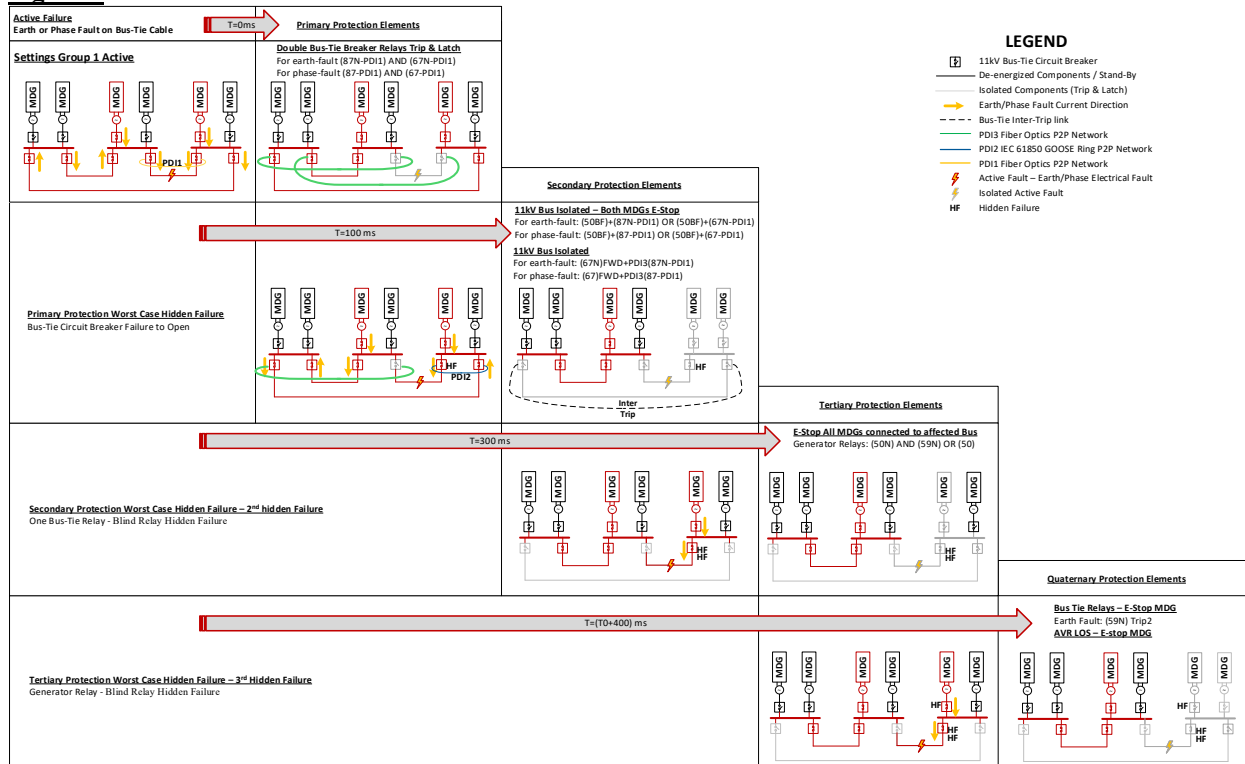
prevents the applicable breaker-failure logic, **(50BF)+(87-PDI1)**, **(50BF)+(67-PDI1)**, **(50BF)+(87N-PDI1)**, or **(50BF)+(67N-PDI1)**, from operating in the bus-tie relay associated with the breaker that failed to open. This may occur if the relay has the 50BF logic disabled or has no effective protection elements enabled. Under this condition, the other bus-tie relay will still activate **(87N-PDI1)** or **(87-PDI1)** and the independent PDI3-confirmed forward-overcurrent logic can still maintain the vessel's WCFDI. However, if the failed bus-tie breaker remains connected to a switchboard with one MDG online, that MDG may remain exposed to the bus-tie cable fault. The next protection layer is therefore required to remove the remaining energy source and complete fault isolation.

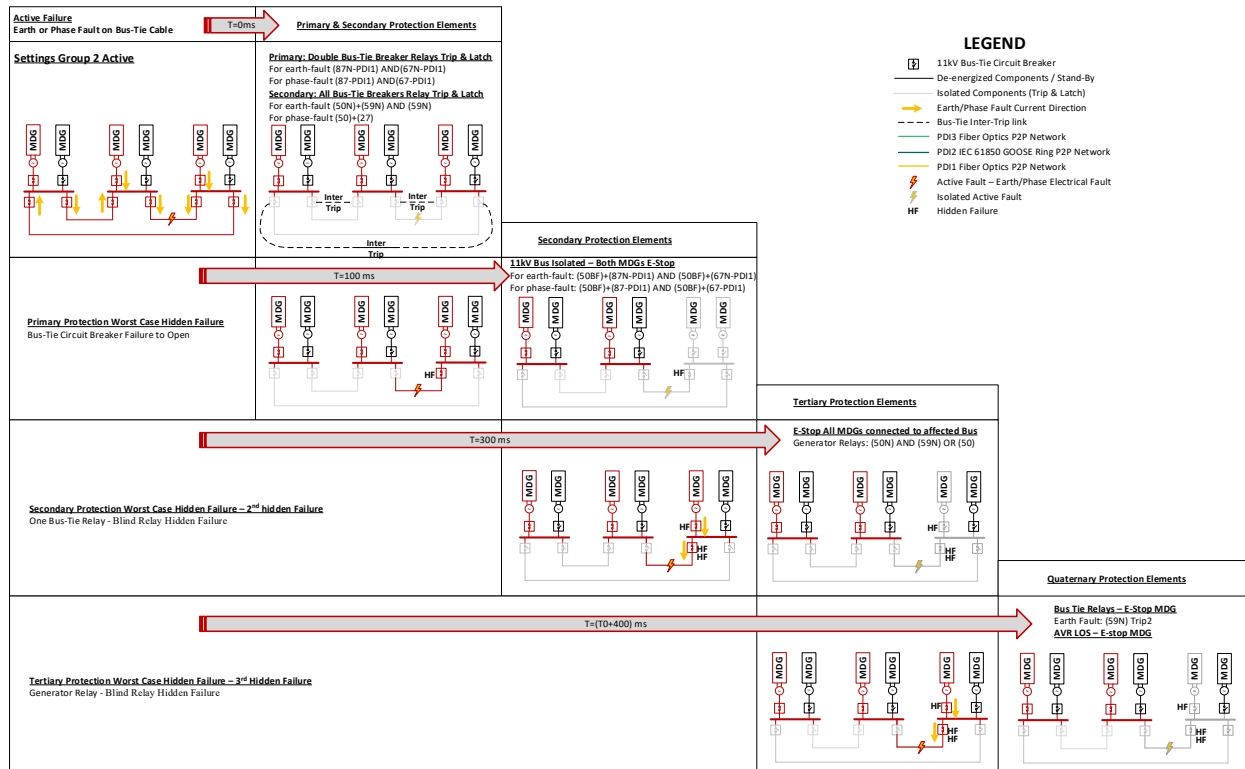
Tertiary Protection – the MDG that remains connected to the affected bus will be isolated by the applicable protection elements within its generator relay. For an Earth Fault, the applicable protection is **(50N) AND (59N)** for NGR grounding systems or **(59N)** for NGT grounding systems. For a Phase Fault, the applicable protection is **(50)**. These elements will operate after a **(T0 + 300) ms** time delay and E-Stop the affected MDG, removing the remaining energy source and completing fault isolation.

Tertiary Protection Worst-Case Hidden Failure (3rd Hidden Failure) – This level of redundancy far exceeds the minimum Class requirement. Nevertheless, the analysis conservatively introduces a third Hidden Failure consisting of Blind Relay Hidden Failure that leaves the connected-MDG generator relay with no effective protection functions enabled. In that case, the Quaternary Protection described below completes fault isolation. This cumulative third-Hidden-Failure condition is shown in Figure 7.

Quaternary Protection – If the connected-MDG generator relay does not isolate the fault because of Blind Relay Hidden Failure, the remaining correctly configured bus-tie relay or independent AVR protection provides the final protection layer. For an Earth Fault, the bus-tie relay **(59N) Trip 2** function will E-Stop the affected MDG after the applicable **(T0 + 400) ms** time delay. For a Phase Fault, the affected MDG's AVR **Loss of Sensing (LOS)** protection will activate and E-Stop the MDG. These independent actions remove the remaining energy source and complete fault isolation.

Figure 7 Active Fault on Bus-Tie Cable





Fault on an MDG (Active Fault) – See Figure 8 for the analysis of an Earth Fault or Phase Fault occurring within the power section of a connected MDG, including the generator windings and the power cabling between the generator and its 11 kV incomer breaker. The following protection sequence applies.

Primary Protection – The generator protection relay provides primary protection for faults within the MDG power section. For an Earth Fault, the applicable protection elements operate with either 0 ms intentional time delay or the minimum time required for reliable fault-direction determination, depending on the MODU grounding-system design:

- **NGR grounding system:** (87N)+(59N) and (67N).
- **NGT grounding system:** (50N)+(59N), (67N), and (50N).

For a Phase Fault, the generator-relay (87) and, where available, (67) elements operate with the minimum time required to confirm that the fault is within the generator protection zone. For the analysis that follows, **T₀** represents the longest operating time among the applicable primary generator protection functions for the fault being evaluated. Upon activation, these functions Trip & Latch the generator incomer and E-Stop the affected MDG, thereby shutting down the main engine and AVR and isolating the Active Failure without affecting the remaining 11 kV consumers.

Primary Protection Worst-Case Hidden Failure (1st Hidden Failure) – The redundancy of the protection elements configured within the generator relay would normally ensure isolation of an electrical fault within the MDG power section. The first and worst-case credible Hidden Failure is conservatively represented by Blind Relay Hidden Failure that leaves the generator relay with no effective protection functions enabled. Under this condition, the faulted MDG may remain connected to the 11 kV bus, exposing the power plant to the Active Failure and requiring the next protection layer.

Settings Group 1 Active – one 11 kV switchboard does not have a connected MDG.

Secondary Protection – Depending on the fault type, the two independent bus-directional overcurrent schemes will activate through (67N-PD12) and (67N-PD13) for an Earth Fault or (67-PD12) and (67-PD13) for a Phase Fault. Both schemes will Trip & Latch the applicable bus-tie breakers. The PD12 protection function will additionally E-Stop both MDGs associated with the affected switchboard, regardless of their connection status. As defined previously, MDG E-Stop simultaneously shuts down the main engine and AVR and Trips & Latches the generator incomer.

Because the Secondary Protection response is initiated by the bus-tie relays rather than by the generator relay affected

by the first Hidden Failure, the faulted MDG is disconnected and shut down even though its generator relay does not operate. This action isolates the affected DP segregation zone, maintains the vessel's WCFDI, and completes fault isolation in **(T0 + 100) ms**, as summarized in Table 2. The two bus-directional schemes are fully independent and are supported by the double-breaker bus-tie Inter-Trip arrangement. Therefore, no additional single Hidden Failure can cause the vessel's WCFDI to be exceeded.

Secondary Protection Worst-Case Hidden Failure (2nd Hidden Failure) – A second Hidden Failure, represented by Blind Relay Hidden Failure that leaves one PDI2 bus-tie relay with incorrect or missing settings, may prevent the applicable **(67N-PDI2)** or **(67-PDI2)** function from operating. The independent PDI3 bus-directional protection will nevertheless Trip & Latch the applicable bus-tie breakers, isolate the affected bus from the remainder of the power plant, and maintain the vessel's WCFDI. However, because PDI3 does not initiate MDG E-Stop, the faulted MDG may remain connected to the isolated bus and continue energizing the fault within its own power section. Although the vessel's WCFDI has already been maintained, an additional independent protection layer is required to achieve complete fault isolation.

Tertiary Protection – If the faulted MDG remains connected after the second Hidden Failure, protection independent of the affected generator relay provides the final isolation response:

- For an Earth Fault, the remaining correctly configured bus-tie relay will detect the residual overvoltage and activate **(59N) Trip 2** after **(T0 + 400) ms**, E-Stopping the affected MDG.
- For a Phase Fault, the affected MDG's AVR **Loss of Sensing (LOS)** protection will activate after the applicable delay coordinated with reactive-power-sharing protection and E-Stop the affected MDG.

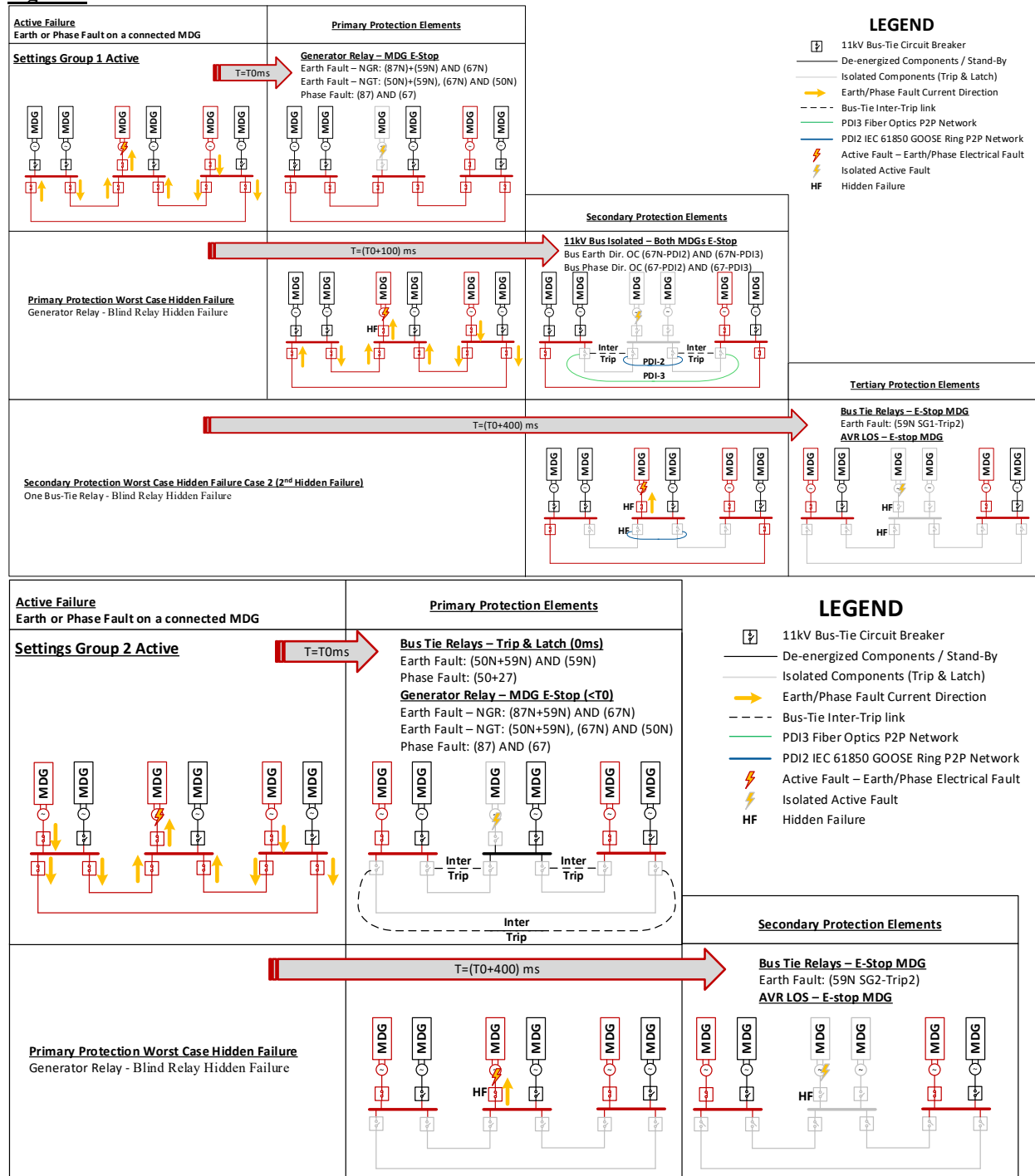
These independent actions remove the remaining energy source and complete fault isolation. Accordingly, the Settings Group 1 analysis demonstrates maintenance of the vessel's WCFDI despite the Active Failure and two cumulative Hidden Failures, followed by complete isolation of the fault through a third independent protection layer.

Settings Group 2 Active – When each 11 kV switchboard has at least one connected MDG at the time of the Active Failure, the bus-tie relays will already have reconfigured the power plant to the Safe-Case Open Bus configuration through the common Settings Group 2 response defined previously. This response contains the Active Failure within a single DP segregation zone and maintains the vessel's WCFDI in less than 100 ms. With the bus-ties open, no Earth-Fault or Phase-Fault current flows between DP segregation zones. Consequently, the bus-directional protection functions **(67N-PDI2)** and **(67N-PDI3)** for an Earth Fault, or **(67-PDI2)** and **(67-PDI3)** for a Phase Fault, will no longer detect the directional conditions required for operation. The remaining protection sequence therefore addresses complete isolation of the MDG power-section fault within the affected bus section.

Secondary Protection – If two MDGs are connected to the affected switchboard, the correctly configured generator relay of the MDG not affected by the first Hidden Failure will detect the bus fault and activate the applicable delayed backup protection function:

- **(59N) Trip** or **(50N) Trip** for an Earth Fault.
- **(50) Trip** for a Phase Fault.

This response E-Stops and disconnects the correctly protected MDG. The faulted MDG whose generator relay has no effective protection functions enabled because of the first Hidden Failure may remain connected to the bus and continue energizing its own power-section fault. The final isolation response therefore depends on the fault type. For an Earth Fault, both bus-tie relays associated with the affected switchboard will independently detect residual overvoltage through separate bus-voltage sensing PTs and activate **(59N) Trip 2** after **(T0 + 400) ms**. Each relay is capable of E-Stopping the remaining MDG, removing the final energy source and completing Earth-Fault isolation. Because this action is performed through two independent relays and separate voltage-sensing paths, no additional single Hidden Failure can prevent complete Earth-Fault isolation. For a Phase Fault, the affected MDG's AVR **Loss of Sensing (LOS)** protection will E-Stop the MDG after the applicable delay coordinated with reactive-power-sharing protection. This action shuts down the main engine and excitation system and Trips & Latches the generator incomer, thereby removing the remaining energy source and completing Phase-Fault isolation. In both cases, the vessel's WCFDI is maintained first through the instantaneous Settings Group 2 Open Bus response, while complete fault isolation is subsequently achieved through protection functions independent of the generator relay affected by the first Hidden Failure.

Figure 8 Active Fault on Connected MDG


Fault on an 11 kV Bus (Active Fault) – See Figure 9 for the analysis of an Earth Fault or Phase Fault occurring on one of the main 11 kV buses. Because a main-bus fault cannot be isolated by a feeder or generator incomer breaker alone, complete fault isolation requires opening the adjacent bus-ties and removing all MDGs capable of energizing the affected bus. The following protection sequence applies.

Settings Group 1 Active – at the time of the Active Fault, one 11 kV switchboard has no MDG connected.

Primary Protection – Depending on the fault type, the two independent bus-directional overcurrent schemes will activate

through **(67N-PDI2)** and **(67N-PDI3)** for an Earth Fault or **(67-PDI2)** and **(67-PDI3)** for a Phase Fault. Both schemes will Trip & Latch the applicable bus-tie breakers. The **PDI2** protection function will additionally E-Stop both MDGs associated with the affected switchboard, regardless of their connection status. As defined previously, MDG E-Stop simultaneously shuts down the main engine and AVR and Trips & Latches the generator incomer. This response isolates the affected DP segregation zone, maintains the vessel's WCFDI, and, when PDI2 operates as intended, removes all local energy sources capable of energizing the bus fault. Primary Protection is completed in **(T₀ + 100) ms**, as summarized in Table 2. Because the PDI2 and PDI3 bus-directional schemes are fully independent and supported by the double-breaker bus-tie Inter-Trip arrangement, no additional single Hidden Failure can cause the vessel's WCFDI to be exceeded.

Primary Protection Worst-Case Hidden Failure (1st Hidden Failure) – The first and worst-case credible Hidden Failure is represented by Blind Relay Hidden Failure that leaves one PDI2 bus-tie relay with incorrect, missing, or disabled protection settings. This condition may prevent the applicable **(67N-PDI2)** or **(67-PDI2)** function from operating. The independent PDI3 bus-directional protection will nevertheless Trip & Latch the applicable bus-tie breakers, isolate the affected bus from the remainder of the power plant, and maintain the vessel's WCFDI. However, because PDI3 does not initiate MDG E-Stop, any MDG connected to the affected bus may remain connected and continue energizing the bus fault. Although the Active Failure has been contained within one DP segregation zone, the next protection layer is required to achieve complete fault isolation.

Secondary Protection – Any MDG remaining connected to the affected 11 kV bus will be isolated by the applicable backup protection elements within its generator relay. For an Earth Fault, the applicable protection is **(50N) AND (59N)** for NGR grounding systems or **(59N)** for NGT grounding systems. For a Phase Fault, the applicable protection is **(50)**. These elements will operate after a **(T₀ + 300) ms** time delay and E-Stop the affected MDG, thereby shutting down the main engine and AVR and Trips & Latches the generator incomer. This action removes the remaining energy source and completes fault isolation. If the Start All Engines function subsequently attempts to connect another MDG to the faulted bus, the oncoming MDG will be blocked from connecting or tripped by **SOTF** or **(50/27)** protection. This response will E-Stop the oncoming MDG and prevent the bus fault from being re-energized.

Secondary Protection Worst-Case Hidden Failure (2nd Hidden Failure) – A second Hidden Failure is conservatively represented by Blind Relay Hidden Failure that leaves the connected-MDG generator relay with no effective protection functions enabled. Under this cumulative condition, the PDI2 bus-directional protection has failed because of the first Hidden Failure, and the generator relay does not remove the remaining MDG because of the second Hidden Failure. The PDI3 protection has already isolated the affected bus from the remainder of the power plant and maintained the vessel's WCFDI, but the connected MDG may continue energizing the bus fault. A third independent protection layer is therefore required to complete fault isolation.

Tertiary Protection – Protection independent of both the affected PDI2 function and the connected-MDG generator relay provides the final isolation response:

- For an Earth Fault, the remaining correctly configured bus-tie relay will detect residual overvoltage and activate **(59N) Trip 2** after **(T₀ + 400) ms**, E-Stopping the connected MDG.
- For a Phase Fault, the connected MDG's AVR **Loss of Sensing (LOS)** protection will activate after the applicable delay coordinated with reactive-power-sharing protection and E-Stop the MDG.

These independent actions remove the final energy source and complete fault isolation. Accordingly, under Settings Group 1, the PDI3 bus-directional protection first maintains the vessel's WCFDI despite the Active Failure and the first Hidden Failure, while the Tertiary Protection subsequently completes fault isolation despite the addition of a second simultaneous Hidden Failure.

Settings Group 2 Active – When each 11 kV switchboard has at least one connected MDG at the time of the Active Failure, the common Settings Group 2 response defined previously will cause all six bus-tie relays to issue instantaneous Trip & Latch commands, with 0 ms intentional time delay. This response restores the Safe-Case Open Bus configuration, contains the Active Failure within a single DP segregation zone, and maintains the vessel's WCFDI in less than 100 ms. With the bus-ties open, no Earth-Fault or Phase-Fault current flows between DP segregation zones. The remaining protection task is therefore to remove all MDGs connected to the faulted bus and achieve complete fault isolation.

Primary Protection – The generator relays of the MDGs connected to the affected bus will activate the applicable backup protection functions:

- **(50N) AND (59N)** for an Earth Fault in an NGR grounding system.

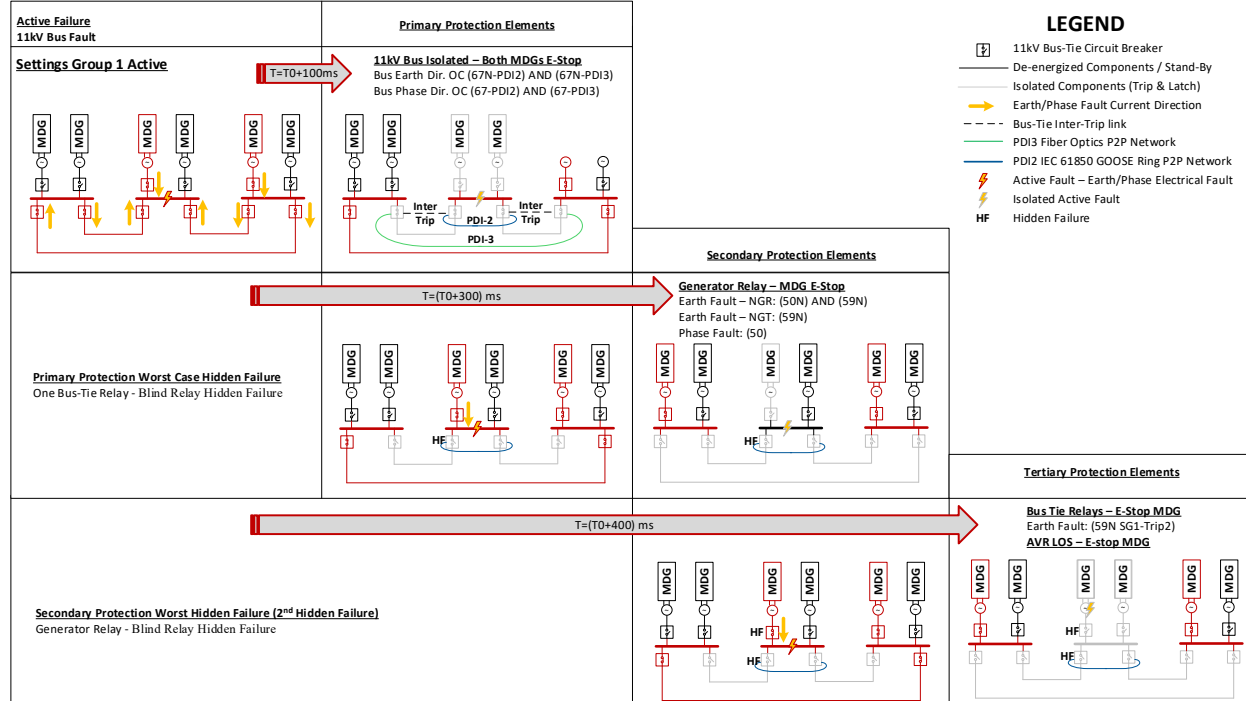
- (59N) for an Earth Fault in an NGT grounding system.
- (50) for a Phase Fault.

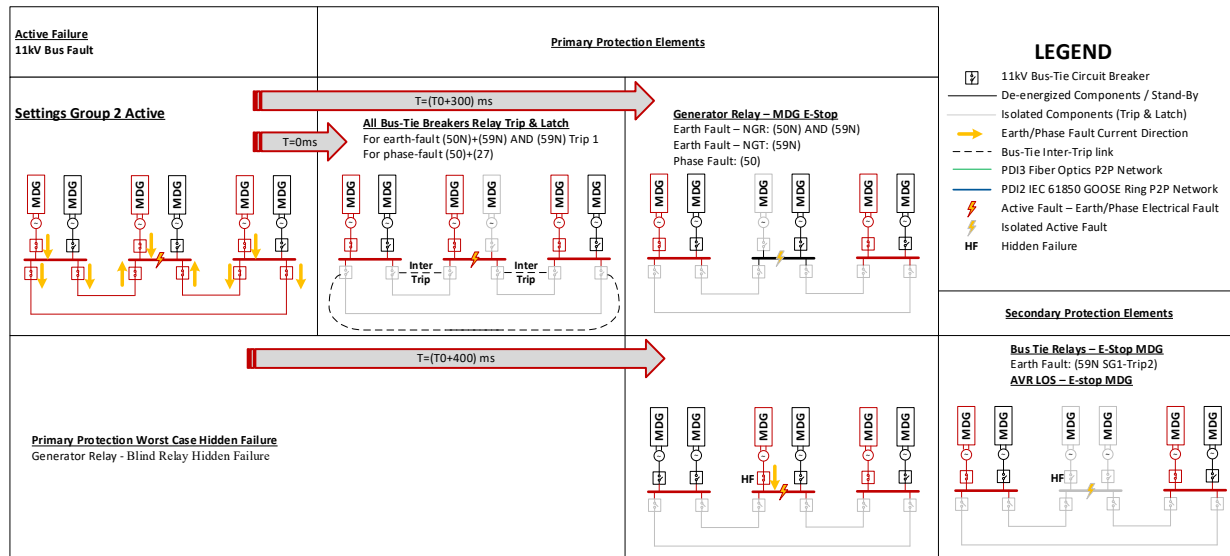
These elements will operate after a **(T₀ + 300) ms** time delay and E-Stop the connected MDGs, thereby shutting down the main engines and AVR and Trips & Latches the generator incomers. This action removes all remaining energy sources and completes fault isolation within the affected DP segregation zone.

Primary Protection Worst-Case Hidden Failure (1st Hidden Failure) – The worst-case credible Hidden Failure is represented by Blind Relay Hidden Failure that leaves one connected-MDG generator relay with no effective protection functions enabled. If two MDGs are connected to the affected switchboard, the correctly configured generator relay will activate the applicable **(59N) Trip**, **(50N) Trip**, or **(50) Trip** function and isolate its MDG. However, the MDG whose generator relay is affected by the Hidden Failure may remain connected and continue energizing the bus fault. The vessel's WCFDI has already been maintained through the instantaneous Settings Group 2 Open Bus response, but an additional independent protection layer is required to remove the remaining energy source and complete fault isolation.

Secondary Protection – The final isolation response depends on the fault type. For an Earth Fault, both bus-tie relays associated with the affected switchboard will independently detect residual overvoltage through separate bus-voltage sensing PTs and activate **(59N) Trip 2** after **(T₀ + 400) ms**. Each relay is independently capable of E-Stopping the remaining MDG and removing the final energy source. For a Phase Fault, the remaining MDG's AVR **Loss of Sensing (LOS)** protection will activate the MDG E-Stop circuit after the applicable delay coordinated with reactive-power-sharing protection. This action will Trip & Latch the generator incomer and shut down the main engine and AVR. These independent backup responses complete fault isolation after the vessel's WCFDI has already been maintained by the Settings Group 2 Open Bus response.

Figure 9 Active Fault on an 11kV bus





HaloBus-ZBØSM Live Earth-Fault & Short-Circuit Test Results

The preceding sections established the HaloBus-ZBØSM design protection philosophy through detailed evaluation of DP-3 MODU electrical-fault characteristics, protection selectivity, Hidden Failure screening, and Electrical Fault Analysis. The expected protection responses for representative Earth-Fault and Phase-Fault scenarios were derived analytically and verified through selectivity, short-circuit, and earth-fault studies. To confirm that these analytical predictions accurately represent actual system performance, the HaloBus-ZBØSM design was subjected to full-scale live fault testing following implementation on nine DP-3 MODUs.

As part of CB/CBT Class verification testing, each upgraded vessel underwent live Earth-Fault and Short-Circuit tests in which actual faults were intentionally applied to the 11 kV power-distribution system under controlled conditions. Unlike analytical studies, simulations, or secondary-injection testing, these tests expose the complete power plant to an actual electrical fault and validate the coordinated response of protection relays, communication networks, circuit breakers, generators, the Vessel Management System (VMS), and connected consumers. Consequently, the results presented in this section provide direct confirmation that HaloBus-ZBØSM performs as intended during actual fault conditions and not solely under modeled scenarios.

The objective of the live testing was to validate the core HaloBus-ZBØSM design principles established throughout this paper:

- Rapid fault detection and isolation.
- Maintenance of the vessel's Worst Case Failure Design Intent (WCEDI).
- Proper operation of the redundant bus-directional protection architecture.
- Tolerance of representative Hidden Failure conditions.
- Automatic restoration of the power plant to the Safe-Case Open Bus configuration.

To illustrate the observed system behavior, this section presents recorded data from one representative upgraded MODU, hereafter referred to as **RIG**. On this vessel, both the live Earth-Fault test and the three-phase-to-earth Short-Circuit test were applied at the same location within the 11 kV distribution system and under the same power-plant operating configuration. The remaining eight upgraded MODUs were tested under alternate approved operating configurations, providing broader validation of the HaloBus-ZBØSM design across the fleet.

The applied faults correspond directly to the **11 kV feeder-fault scenarios** evaluated in the preceding Electrical Fault Analysis. To validate HaloBus-ZBØSM response to an Active Failure combined with a credible Hidden Failure, the feeder relay associated with the faulted feeder was intentionally prevented from performing its normal protection function. Accordingly, the live tests provide direct validation of the fault-isolation sequence developed in the preceding analytical sections.

Importantly, the live testing validated not only the protection settings, but also the fundamental operating principles of the dual autonomous bus-directional architecture described throughout this paper.

Representative Test Configuration

Before performing the live fault tests, all applicable feeder, bus-tie, and generator protection functions were verified through secondary-injection testing to confirm proper relay operation and protection coordination. The following RIG-specific implementation details are relevant to interpretation of the recorded test results:

- Because of the vessel's pre-upgrade protection architecture, generator-relay(**50N**) **Alarm**, (**59N**) **Alarm**, and (**50**) **Alarm** functions were additionally configured to Trip & Latch the left-side bus-tie breakers to improve overall protection selectivity.
- The installed generator relays record relay activation events but do not record pickup values. Consequently, the generator-relay data presented in this section contain activation events only.
- The applied fault location was outside the generator protection zones; therefore, generator differential (**87**) and generator directional earth-fault(**67N**) elements were not expected to operate.
- Generator non-directional protection elements were coordinated to remain inactive while the bus-directional protection functions performed the intended fault-isolation sequence.
- The installed generator relays require approximately **100 ms** for reliable(**67N**) directional-earth-fault determination. Consistent with the Selectivity Criteria established previously, the associated bus-directional protection functions(**67N-PDI2**) and(**67N-PDI3**) were therefore configured with a **200 ms** operating delay.
- The installed generator differential protection (**87**) requires approximately **50 ms** before operation. Consequently, the corresponding bus-directional phase-fault protection functions(**67-PDI2**) and(**67-PDI3**) were configured with a **150 ms** operating delay.

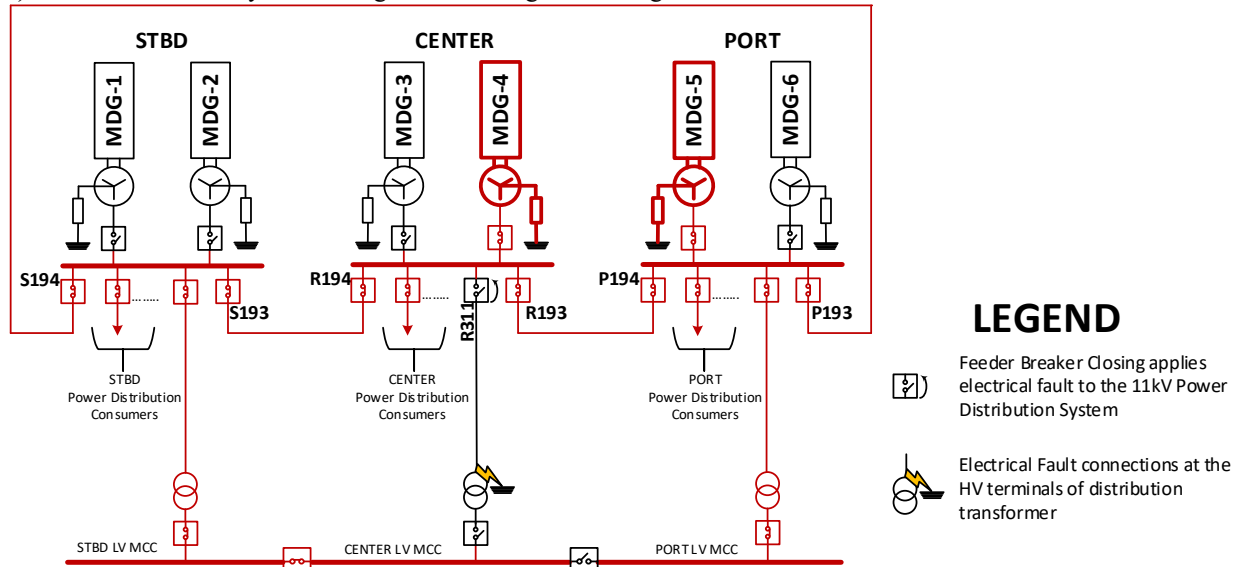
For both the live Earth-Fault and live Short-Circuit tests, the power plant was configured as follows:

- The vessel operated in **Closed Bus** configuration, with all bus-tie breakers closed.
- One MDG was connected to the Center switchboard and one MDG was connected to the Port switchboard; therefore, **Settings Group 1** was active.
- All thrusters remained operating in DP throughout the testing.
- Distribution transformers and connected vessel loads remained energized to provide operating conditions representative of normal vessel operations.
- The applied fault was introduced at the high-voltage terminals of the distribution transformer supplied from feeder breaker **R311**, as shown in Figure 10. This location allowed the fault to be applied at the main-switchboard distribution level while all DP-relevant thrusters and supporting systems remained energized and operating in automatic DP mode.
- The feeder-relay trip settings for R311 were intentionally modified so that the feeder breaker would not immediately isolate the fault, thereby simulating the Blind Relay Hidden Failure defined in the Electrical Fault Analysis.
- The associated feeder interlocks were temporarily bypassed to permit controlled application of the test fault to the energized distribution system.

Figure 10 illustrates the live-test arrangement used to validate the HaloBus-ZBØSM design fault-isolation sequence. Figure 10(a) identifies the power-plant configuration and the applied fault location, while Figures 10(b) and 10(c) show the physical connections used for the live Earth-Fault and live Short-Circuit tests, respectively.

Figure 10 Live Earth-Fault and Short-Circuit testing

a) Power distribution system configuration during live testing



b) Live Earth-Fault test connection

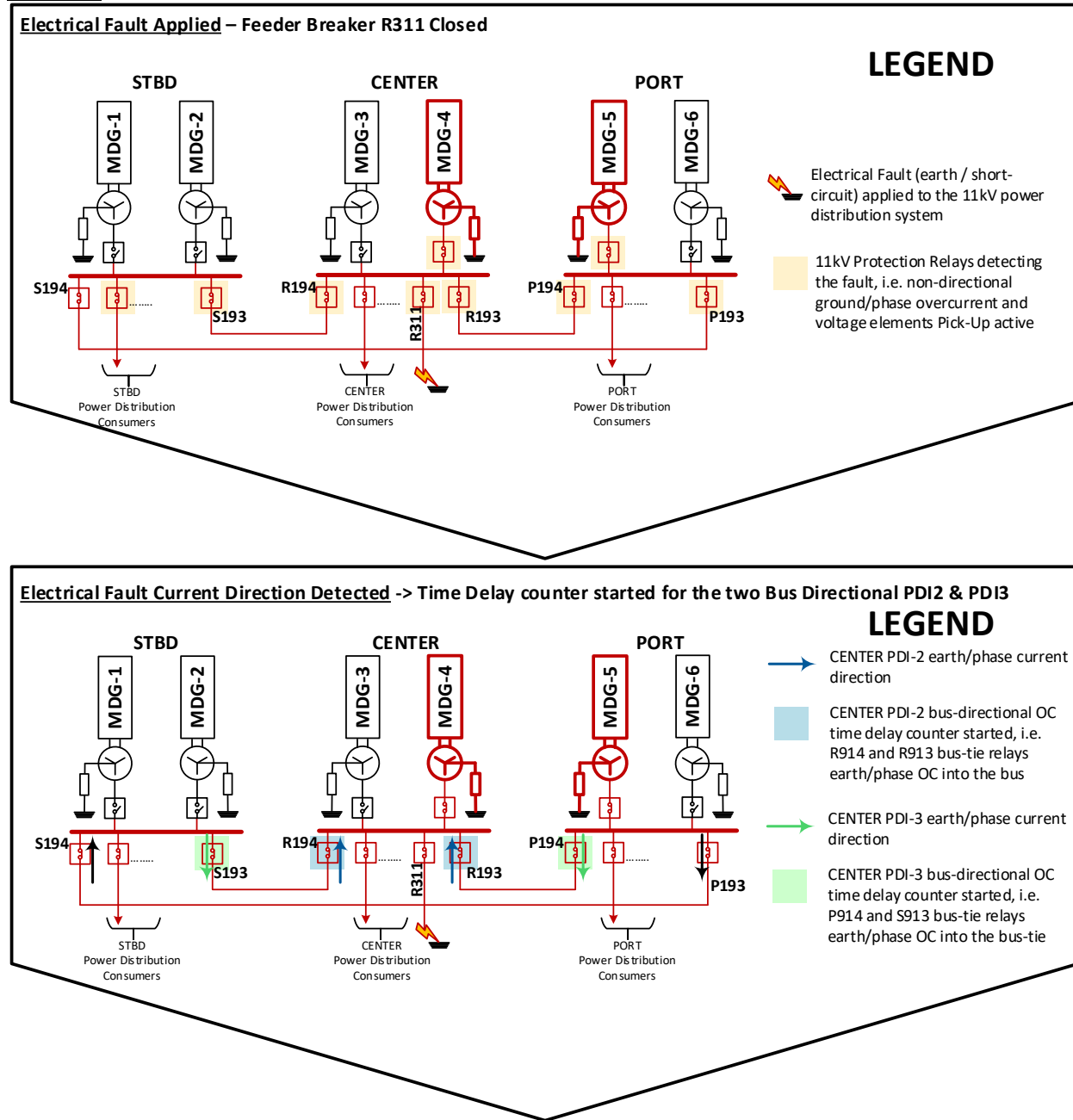


c) Live Short-Circuit test connection



Figure 11 summarizes the overall protection sequence observed during both tests, from initial fault detection through fault isolation and subsequent VMS-initiated restoration to the Safe-Case Open Bus configuration. Although different protection elements initiated the response for the Earth-Fault and Short-Circuit scenarios, the overall protection philosophy and power-plant recovery sequence remained consistent with the behavior predicted by the preceding Electrical Fault Analysis.

Figure 11 Live Earth-Fault and Live Short-Circuit tests HaloBus-ZBØSM actions



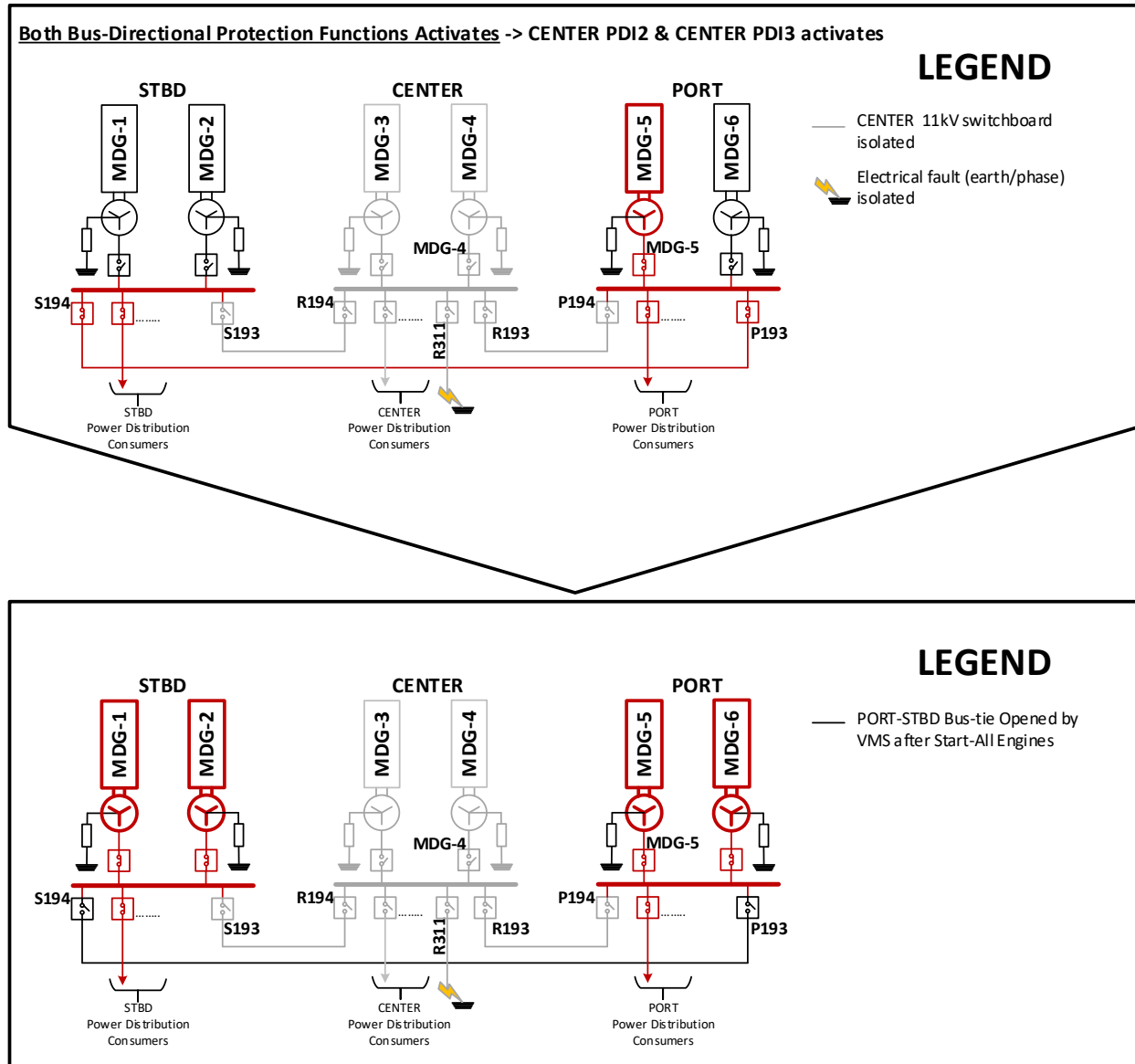


Table 3 summarizes the event data recorded by the 11 kV protection relays during the live earth-fault test. Time zero corresponds to the first recorded detection of the applied fault by each 11 kV relay.

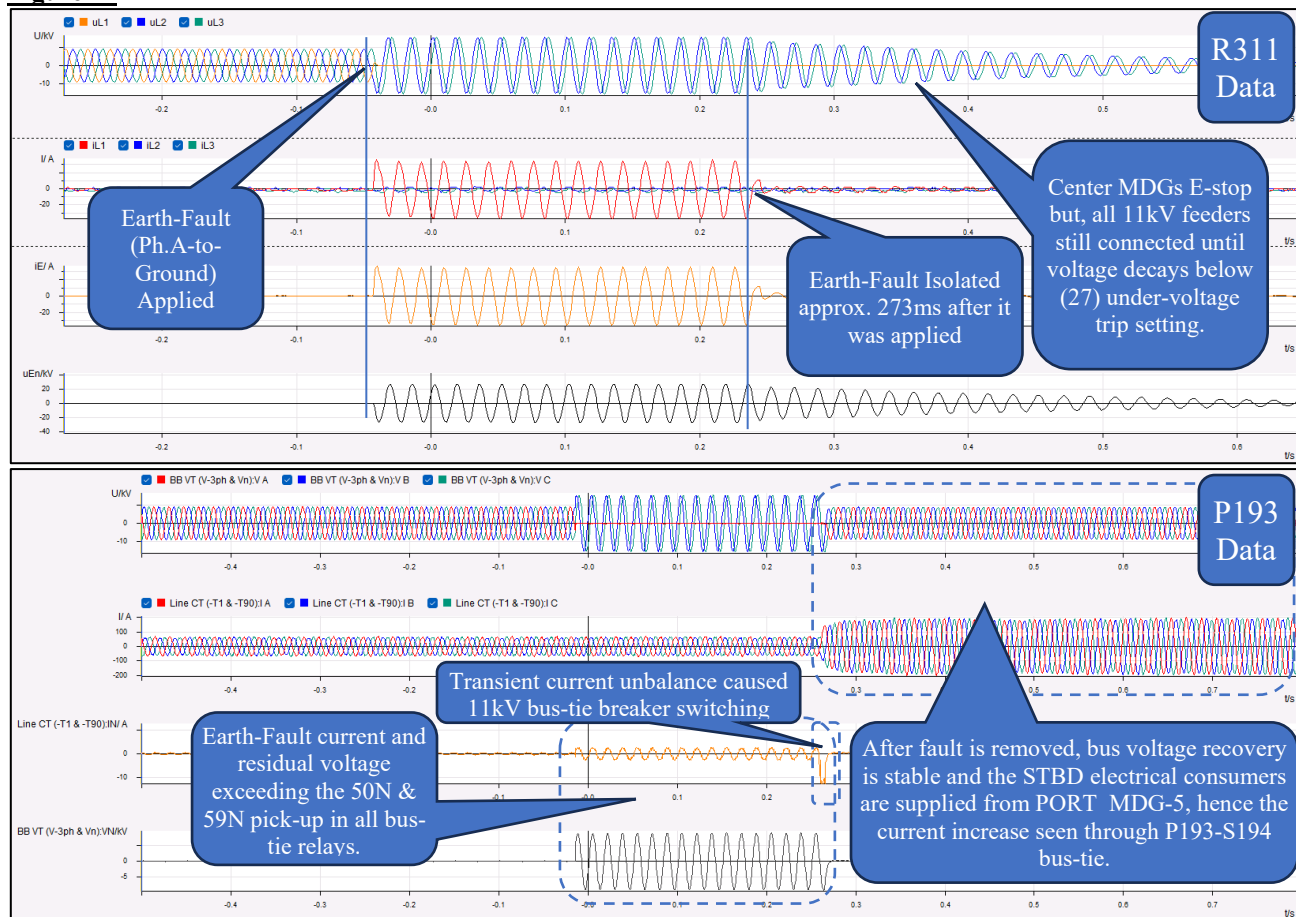
Table 3: Live Earth Fault testing, HaloBus-ZBØSM fault isolation actions

Protection System Action	Protection Relay (Breaker Number)	Time from Fault (ms)	Relay Recorded Event Description	Action / Comments
Fault Applied	Feeder R311	0	(50N) Pick-Up ON	Feeder relay detects fault but, due to modified settings (Blind Relay Hidden Failure) does not take action to isolate, i.e. (50N) time delay changed from 0ms to 600ms for the purpose of the test.
	bus-tie P193	0 1	(50N) Pick-Up ON (59N) Pick-Up ON	All bus-tie relays (50N) and (59N) picked-up – timer for Settings Group 1 started. Note: if Settings Group 2 was active, the bus-tie Trip & Latch would have been initiated by each bus-tie relay.
	bus-tie P194	0 11	(50N) Pick-Up ON (59N) Pick-Up ON	
	bus-tie R193	0 11	(50N) Pick-Up ON (59N) Pick-Up ON	
	bus-tie R194	0 7	(50N) Pick-Up ON (59N) Pick-Up ON	
	bus-tie S193	0 7	(50N) Pick-Up ON (59N) Pick-Up ON	
	bus-tie S194	0 1	(50N) Pick-Up ON (59N) Pick-Up ON	
Earth-Fault Current Direction detection (<=26ms)	bus-tie P193	25	(67N-PDI1) Pick-Up ON Forward (67N-PDI2) Forward (67N-PDI3) Pick-Up Forward	P193 Bus-tie relay detects the fault current in forward direction, that is: out of the bus and into the tie cable. Sends: (67N) active to S194 across PDI-1 and (67N) active to R194 across PDI3.
	bus-tie P194	19	(67N-PDI1) Pick-Up ON Forward (67N-PDI2) Forward (67N-PDI3) Pick-Up Forward	P194 Bus-tie relay detects the fault current in forward direction, that is: out of the bus and into the tie cable. Sends: (67N) active to R193 across PDI-1 and (67N) active to S193 across PDI3.
	bus-tie R193	10	(67N-PDI1) Backward (67N-PDI2) Pick-Up Backward (67N-PDI3) Backward	R193 Bus-tie relay detects the fault current in backward direction, that is: into the bus and out of the tie cable. Sends: (67N) active to R194 across PDI-2.
	bus-tie R194	18	(67N-PDI1) Backward (67N-PDI2) Pick-Up Backward (67N-PDI3) Backward	R194 Bus-tie relay detects the fault current in backward direction, that is: into the bus and out of the tie cable. Sends: (67N) active to R193 across PDI-2.
	bus-tie S193	17	(67N-PDI1) Pick-Up ON Forward (67N-PDI2) Forward (67N-PDI3) Pick-Up Forward	S193 Bus-tie relay detects the fault current in forward direction, that is: out of the bus and into the tie cable. Sends: (67N) active to R194 across PDI-1 and (67N) active to P194 across PDI3.
	bus-tie S194	26	(67N-PDI1) Backward (67N-PDI2) Pick-Up Backward (67N-PDI3) Backward	S194 Bus-tie relay detects the fault current in backward direction, that is: into the bus and out of the tie cable. Sends: (67N) active to S193 across PDI-2.
Bus-Tie 67N-PDI2 & 67N-PDI3 Active Time Counters	bus-tie P193	29 31	(67N-PDI1) disabled (67N-PDI3) disabled	(67N-PDI1) disabled due to S194 backward direction detected (67N-PDI3) disabled due to R194 backward direction detected
	bus-tie P194	18 20	(67N-PDI1) disabled (67N-PDI3) Active Counter	(67N-PDI1) disabled due to R193 backward direction detected (67N-PDI3) start timer due to S193 forward direction detected
	bus-tie R193	18	(67N-PDI2) Active Counter	(67N-PDI2) start timer after R194 backward direction detected
	bus-tie R194	10	(67N-PDI2) Active Counter	(67N-PDI2) starts timer due to R193 backward direction detected
	bus-tie S193	16 19	(67N-PDI1) disabled (67N-PDI3) Active Counter	(67N-PDI1) disabled due to R194 backward direction detected (67N-PDI3) starts timer due to P194 forward direction detected
	bus-tie S194	35	67N-PDI2 disabled	(67N-PDI1) disabled due to S193 backward direction detected
Bus-Tie 67N-PDI2 & 67N-PDI3 Activation	bus-tie P194	223	(67N-PDI3) Activates	Trip & Latch after the 200ms time delay expires
	bus-tie R193	220	(67N-PDI2) Activates	E-Stop both MDGs after the 200ms time delay expires
	bus-tie R194	216	(67N-PDI2) Activates	Trip & Latch & E-Stop both MDGs after the 200ms time delay expires
	bus-tie S193	220	(67N-PDI3) Activates	Trip & Latch after the 200ms time delay expires
Fault Isolated Confirmation	bus-tie P194	270	P194 Breaker Open	Breaker Open feedback received, confirms Trip & Latch
	bus-tie R193	268 273	R193 Breaker Open MDGs Incomer Open	Breaker Open feedback received, confirms Trip & Latch MDGs incomers status received, confirms MDGs E-Stop
	bus-tie R194	265 273	R194 Breaker Open MDGs Incomer Open	Breaker Open feedback received, confirms Trip & Latch MDGs incomers status received, confirms MDGs E-Stop
	bus-tie S193	266	S193 Breaker Open	Breaker Open feedback received, confirms Trip & Latch
VMS Start All Engines Actions	CENTER	---	MDG-3 & MDG-4	Due to E-Stop active, MDGs on Center are not started by VMS
	STBD MDG-2	8000	MDG-2 Connects	8sec after fault MDG-2 connects to STBD bus
	P194 & S193 PORT-STBD bus-tie	15000	Port-Stbd Bus-tie Open	15sec after fault applied, 5sec after first STBD MDG connects to the bus, VMS Start All Engine logic opens Port-Stbd bus-tie. Due to inter-trip, both bus-tie breakers P193 and S194 are simultaneously opened.
	STBD MDG-1	20000	MDG-1 Connects	20sec after fault MDG-1 connects to STBD bus and starts load sharing. Note: by this time, the Port-Stbd bus-tie was opened by

Protection System Action	Protection Relay (Breaker Number)	Time from Fault (ms)	Relay Recorded Event Description	Action / Comments
	PORT MDG-6	20000	MDG-6 Connects	VMS Start All Engines logic. 20sec after fault MDG-6 connects to PORT bus and starts load sharing. Note: by this time, the Port-Stbd bus-tie was opened by VMS Start All Engines logic.

Figure 12 shows the three-phase voltages and currents recorded by the R311 feeder relay and the P193 and R194 bus-tie relays during the live earth-fault test. The figure also includes annotations to clarify the recorded waveforms and relay responses.

Figure 12 Live Earth-Fault Test recorded data



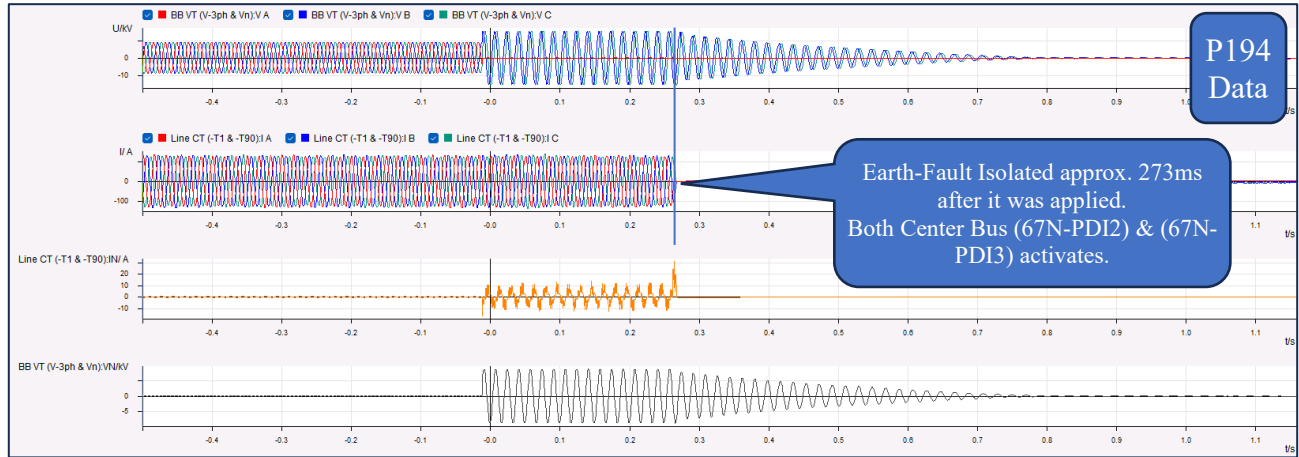


Table 4 summarizes the event data recorded by the 11 kV protection relays during the live short-circuit test. Time zero corresponds to the first recorded detection of the applied fault by each 11 kV relay.

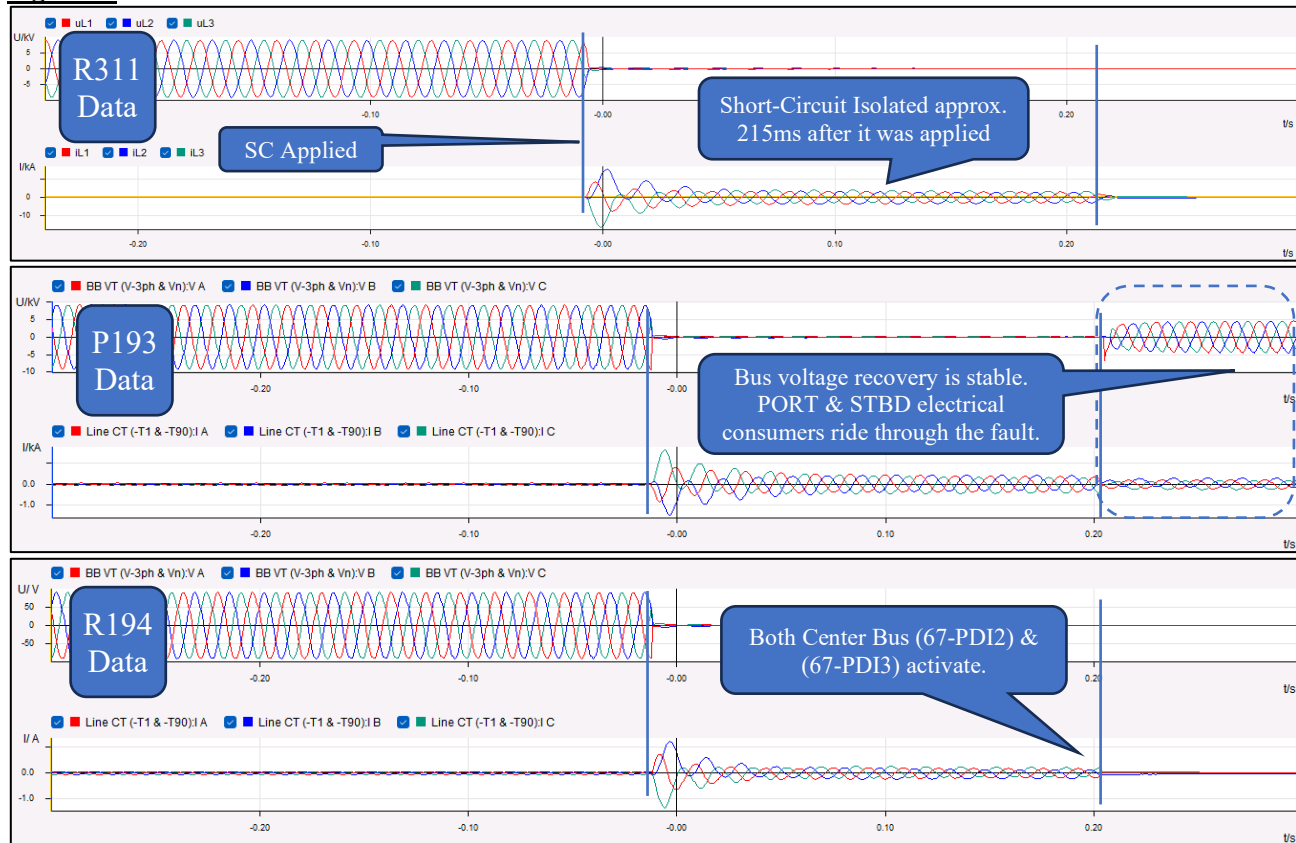
Table 4: Live Short-Circuit testing, HaloBus-ZBØSM fault isolation actions

Protection System Action	Protection Relay (Breaker Number)	Time from Fault (ms)	Relay Recorded Event Description	Action / Comments
Fault Applied	Feeder R311	0	(50) Pick-Up ON	Feeder relay detects fault but, due to modified settings does not take action to isolate, i.e. (50) time delay changed from 0ms to 600ms for the purpose of the test (to simulate Hidden Failure)
	bus-tie P193	1	(50+27) Pick-Up ON	All bus-tie relays (50+27) picked-up – timer for Settings Group 1 started.
	bus-tie P194	1	(50+27) Pick-Up ON	
	bus-tie R193	1	(50+27) Pick-Up ON	Note: if Settings Group 2 was active, the bus-tie Trip & Latch would have been initiated by each bus-tie relay.
	bus-tie R194	1	(50+27) Pick-Up ON	
	bus-tie S193	1	(50+27) Pick-Up ON	
Phase-Fault Current Direction detection (<=26ms)	bus-tie P193	7	(67-PDI1) Pick-Up ON Forward (67-PDI2) Forward (67-PDI3) Pick-Up Forward	P193 Bus-tie relay detects the fault current in forward direction, that is: out of the bus and into the tie cable. Sends: (67) active to S194 across PDI-1 and (67) active to R194 across PDI3.
	bus-tie P194	7	(67-PDI1) Pick-Up ON Forward (67-PDI2) Forward (67-PDI3) Pick-Up Forward	P194 Bus-tie relay detects the fault current in forward direction, that is: out of the bus and into the tie cable. Sends: (67) active to R193 across PDI-1 and (67) active to S193 across PDI3.
	bus-tie R193	7	(67-PDI1) Backward (67-PDI2) Pick-Up Backward (67-PDI3) Backward	R193 Bus-tie relay detects the fault current in backward direction, that is: into the bus and out of the tie cable. Sends: (67) active to R194 across PDI-2.
	bus-tie R194	7	(67-PDI1) Backward (67-PDI2) Pick-Up Backward (67-PDI3) Backward	R194 Bus-tie relay detects the fault current in backward direction, that is: into the bus and out of the tie cable. Sends: (67) active to R193 across PDI-2.
	bus-tie S193	10	(67-PDI1) Pick-Up ON Forward (67-PDI2) Forward (67-PDI3) Pick-Up Forward	S193 Bus-tie relay detects the fault current in forward direction, that is: out of the bus and into the tie cable. Sends: (67) active to R194 across PDI-1 and (67) active to P194 across PDI3.
	bus-tie S194	8	(67-PDI1) Backward (67-PDI2) Pick-Up Backward (67-PDI3) Backward	S194 Bus-tie relay detects the fault current in backward direction, that is: into the bus and out of the tie cable. Sends: (67) active to S193 across PDI-2.
Bus-Tie 67-PDI2 & 67-PDI3 Active Time Counters	bus-tie P193	8	(67-PDI1) disabled (67-PDI3) disabled	(67-PDI1) disabled due to S194 backward direction detected (67-PDI3) disabled due to R194 backward direction detected
	bus-tie P194	7	(67-PDI1) disabled	(67-PDI1) disabled due to R193 backward direction detected
	bus-tie R193	10	(67-PDI3) Active Counter	(67-PDI3) start timer due to S193 forward direction detected
	bus-tie R194	7	(67-PDI2) Active Counter	(67-PDI2) start timer due to R194 backward direction detected
	bus-tie S193	7	(67-PDI2) Active Counter	(67-PDI2) start timer due to R193 backward direction detected
	bus-tie S194	10	(67-PDI1) disabled (67-PDI3) Active Counter	(67-PDI1) disabled due to R194 backward direction detected (67-PDI3) start timer due to P194 forward direction detected
Bus-Tie 67-PDI2 & 67-PDI3	bus-tie P194	160	(67-PDI3) Activates	Trip & Latch after the 150ms time delay expires
	bus-tie R193	157	(67-PDI2) Activates	Trip & Latch & E-Stop both MDGs after the 150ms time delay expires

Protection System Action	Protection Relay (Breaker Number)	Time from Fault (ms)	Relay Recorded Event Description	Action / Comments
Activation	bus-tie R194	157	(67-PDI2) Activates	Trip & Latch & E-Stop both MDGs after the 150ms time delay expires
	bus-tie S193	160	(67-PDI3) Activates	Trip & Latch after the 150ms time delay expires
Fault Isolated Confirmation	bus-tie P194	213	P194 Breaker Open	Breaker Open feedback received, confirms Trip & Latch
	bus-tie R193	215 207	R193 Breaker Open MDGs Incomer Open	Breaker Open feedback received, confirms Trip & Latch MDGs incomers status received, confirms MDGs E-Stop
	bus-tie R194	216 207	R194 Breaker Open MDGs Incomer Open	Breaker Open feedback received, confirms Trip & Latch MDGs incomers status received, confirms MDGs E-Stop
	bus-tie S193	214	S193 Breaker Open	Breaker Open feedback received, confirms Trip & Latch
VMS Start All Engines Actions	CENTER	---	MDG-3 & MDG-4	Due to E-Stop active, the two MDGs on Center are not started by VMS
	STBD MDG-2	29000	MDG-2 Connects	29sec after fault MDG-2 connects to STBD bus and starts load sharing
	STBD MDG-1	30000	MDG-1 Connects	30sec after fault MDG-1 connects to STBD bus and starts load sharing.
	PORT MDG-6	24000	MDG-6 Connects	24sec after fault MDG-6 connects to PORT bus and starts load sharing.
	P194 & S193 PORT-STBD bus-tie	34000	Port-Stbd Bus-tie Open	34sec after fault applied, 5sec after first STBD MDG connects to the bus, VMS Start All Engine logic opens Port-Stbd bus-tie. Due to inter-trip, both bus-tie breakers P193 and S194 are simultaneously opened.

Figure 13 shows the three-phase voltages and currents recorded by the R311 feeder relay and the P193 and R194 bus-tie relays during the live short-circuit test. The figure also includes annotations to clarify the recorded waveforms and relay responses.

Figure 13 Live Short-Circuit Test recorded data



The live Earth-Fault and Short-Circuit test data presented in Tables 3 and 4, supported by Figures 12 and 13, provide direct validation of the analytical conclusions developed throughout this paper. In both test scenarios, the HaloBus-ZBØSM protection system responded as predicted by the Electrical Fault Analysis, successfully detecting, isolating, and containing the applied fault within a single DP segregation zone while maintaining the vessel's WCFDI. The observed protection sequence also validated the HaloBus-ZBØSM design capability to tolerate representative Hidden Failure conditions, including the simulated feeder-protection failure introduced during testing. Collectively, these results confirm that the protection architecture, selectivity philosophy, and fault-isolation strategy perform as intended under actual fault conditions, support compliance with the applicable DP-3 CB/CBT Class requirements, and validate the additional cumulative Hidden Failure evaluation presented in this paper.

A detailed analysis of the recorded waveforms and relay-event sequences is beyond the scope of this paper. However, testing performed on the nine MODUs upgraded with HaloBus-ZBØSM consistently confirmed the following:

- The effects of an Earth Fault or Phase Fault applied anywhere within the 11 kV power-distribution system do not exceed the vessel's WCFDI; fault consequences remain limited to a single 11 kV switchboard or DP segregation zone.
- The HaloBus-ZBØSM protection functions, communication interfaces, and associated circuit breakers operate as predicted by the vessel's Selectivity Study.
- The generator short-circuit contributions are consistent with the decrement curves and fault-current values used in the vessel's Short-Circuit Study.
- Main-bus voltage recovers successfully following fault isolation, with no propulsion-critical consumers or generators tripping on over-voltage.
- Loads supplied through Variable Frequency Drives (VFDs), including thrusters and major drilling consumers, remain in service and are not tripped by DC-link over-voltage conditions.
- Thrusters connected to the energized 11 kV buses remain available for DP operation throughout the disturbance.
- Generators and critical consumers are automatically restored to service with no manual operator intervention.
- Measured Earth-Fault currents are consistent with the predictions of the vessel's Earth-Fault Study.

HaloBus-ZBØSM vs Traditional designs

The preceding sections defined the HaloBus-ZBØSM design requirements, evaluated the protection philosophy against representative electrical-fault scenarios, and demonstrated performance through both analytical evaluation and full-scale live testing. These results confirm that the HaloBus-ZBØSM satisfies the same fundamental DP-3 CB/CBT objective as established traditional protection-system architectures: maintaining the vessel's WCFDI following electrical faults, including faults occurring in combination with credible Hidden Failures.

Traditional DP-3 CB/CBT protection systems have been successfully implemented across the offshore industry and are supported by mature and robust Classification Society requirements. The intent of this section is therefore not to assess adequacy or compliance, but rather to compare how the HaloBus-ZBØSM design and traditional solutions achieve the same protection objective through different architectural approaches. Particular focus is placed on fault-isolation philosophy, protection autonomy, redundancy, communication dependency, implementation complexity, and retrofit scope. These differences demonstrate how HaloBus-ZBØSM can provide increased protection-system autonomy, enhanced redundancy, simplified implementation, and reduced lifecycle cost while maintaining full alignment with established DP-3 CB/CBT requirements.

Beyond implementation benefits, the architectural differences also influence protection-system behavior during fault conditions. HaloBus-ZBØSM uses multiple independently operating protection layers that do not require primary-protection devices to communicate fault-identification or blocking signals before backup protection can act. This approach increases protection autonomy and reduces dependency on specific devices, communication paths, or sensing elements for successful fault isolation. The result is a protection architecture that maintains compliance with established DP-3 CB/CBT requirements while providing additional defense-in-depth against Hidden Failures.

These architectural simplifications also reduce engineering effort, installation scope, commissioning complexity, and lifecycle cost. Fleet implementation demonstrated that upgrades could be completed without vessel out-of-service time and at approximately one-tenth of the cost of traditional retrofit solutions.

In summary, both traditional DP-3 CB/CBT protection systems and HaloBus-ZBØSM can achieve compliance with current Classification Society requirements and maintain the vessel's WCFDI following electrical faults. The principal distinction is not the compliance objective itself, but the method used to achieve it. HaloBus-ZBØSM emphasizes protection autonomy, independent fault-isolation paths, reduced communication dependency, and rapid restoration of the Safe-Case Open Bus configuration. As demonstrated through the Electrical Fault Analysis and fleet live-testing results presented in this paper, these attributes provide an additional level of redundancy and operational resilience while significantly reducing retrofit complexity and implementation cost.

Figure 14 – Closed Bus protection-system upgrades: HaloBus-ZBØSM vs. traditional designs

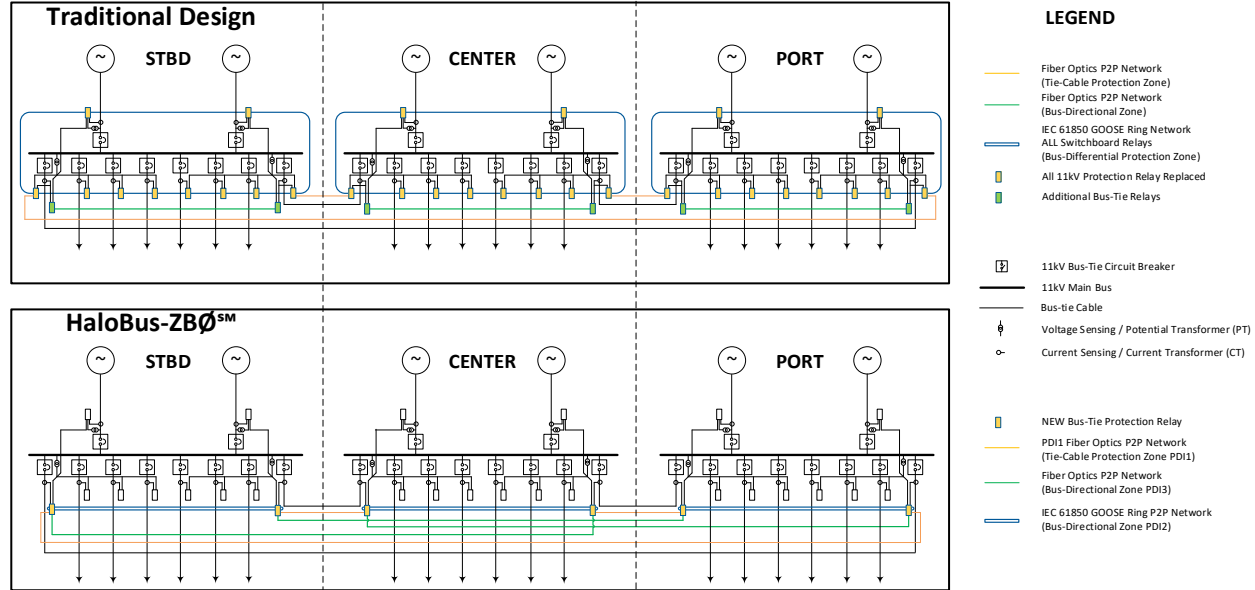


Table 5: High-Level Comparison of HaloBus-ZBØSM and Traditional DP-3 CBT Closed Bus Protection Designs

DP-3 CB/CBT Bus Protection Compliance	HaloBus-ZBØ SM	Traditional Designs
Protection-function autonomy and redundancy	Two fully independent bus-directional protection zones.	One bus-directional scheme and one bus-differential scheme
Protection-relay hardware redundancy	Uses existing double-breaker bus-tie relay locations, with one relay per bus-tie breaker	Requires additional bus-tie relays, typically two relays per bus-tie breaker
Fault sensing redundancy	Two fully independent bus-directional zones rely on independent voltage and current transformers. One protection zone includes all required sensing equipment installed outside the protected switchboard and in different DP segregation zones.	Relies on common voltage and/or current sensing transformers installed within the same protected switchboard ¹ .
Hidden-Failure tolerance and autonomous backup protection	Primary and secondary protection functions operate independently. Selectivity is achieved through defined protection timing where required, while redundant bus-directional protection provides simultaneous isolation paths that do not depend on blocking signals from primary protection relays.	Selective tripping for key earth- and phase-fault protection functions relies on primary protection relays sending blocking signals to upstream protection relays. If the primary relay fails to detect the fault, the blocking signal is not sent; secondary protection will then isolate the failure within the vessel WCFDI, but may cause unnecessary loss of electrical consumers.
Circuit-breaker redundancy	Two fully independent bus-directional zones use two separate sets of circuit breakers to isolate bus faults. One protection zone uses two breakers installed outside the protected switchboard and in different DP segregation zones.	Relies on the same two circuit breakers installed within the protected switchboard
Relay communication-network redundancy	One bus-directional protection zone uses a GOOSE loop connection between only the two bus-tie relays within the same switchboard, creating a simple point-to-point connection with lower network traffic and reduced setup complexity. The other bus-directional protection zone uses a fiber-optic (FO) network with cabling routed outside the protected switchboard room.	Bus-differential protection requires a looped GOOSE communication network with all 11 kV relays within the same switchboard communicating across the network. This requires complex network setup and creates high network-traffic utilization. The additional relays used for bus-directional protection use a dedicated network routed through the same switchboard ¹ .

Note 1: For catastrophic compartment-failure scenarios, most Failure Mode and Effects Analyses (FMEAs) must consider the simultaneous loss of all components located within the affected compartment. Although a compartment fire or flood may not cause every component in that space to fail at exactly the same time, the FMEA evaluates the commonality as a simultaneous failure. From this perspective, traditional designs may be exposed to simultaneous loss of both bus-directional and bus-differential protection schemes because the current and voltage sensing circuits, as well as the associated communication networks, are commonly located within or

routed through the protected switchboard compartment. For this failure mode, HaloBus-ZBØSM provides a stronger redundancy basis because one bus-directional protection zone includes the required current sensing, voltage sensing, and dedicated FO communication installed outside the protected switchboard and in a different DP segregation zone. As a result, even for the catastrophic switchboard-failure scenario discussed here, HaloBus-ZBØSM maintains main power-plant protection through a redundant protection scheme whose required components are installed outside the affected DP segregation zone.

Conclusions

HaloBus-ZBØSM introduces a novel DP-3 Closed Bus protection architecture based on two fully independent bus-directional protection zones. Unlike traditional CBT implementations that combine bus-differential and bus-directional protection within the protected switchboard, HaloBus-ZBØSM establishes two autonomous protection paths with independent sensing, communication, activation, and fault-isolation mechanisms. The resulting architecture achieves protection redundancy through physical and functional independence rather than through duplication of similar protection functions. Established protection-relay hardware, conventional sensing methods, and mature communication technologies are used throughout. The innovation lies in the protection philosophy and system architecture, not in any individual device or technology.

The technical foundation of HaloBus-ZBØSM is the independence of its two bus-directional protection zones. Each zone is capable of detecting, classifying, and isolating electrical faults without relying on the protection inputs, sensing transformers, communication interfaces, or activation paths used by the other zone. This independence provides the protection autonomy that enables the redundancy, Hidden Failure tolerance, and rapid fault-isolation characteristics demonstrated throughout this paper.

The Electrical Fault Analysis intentionally adopted an exceptionally conservative Hidden Failure assumption. It did not attempt to identify or justify a specific internal failure mechanism capable of making a modern protection relay completely blind to an electrical fault. State-of-the-art protection relays incorporate internal diagnostics, functional separation, multiple sensing methods, and independent protection elements specifically designed to remain dependable during the high-energy electrical events against which they protect. Instead, the analysis simply accepted that a protection relay could have no effective protection functions enabled because its settings were missing, incorrect, disabled, or not implemented in accordance with the approved engineering studies. The affected relay was therefore treated as completely unresponsive to the Active Failure, without considering the probability or cause of that condition.

Under normal industry practice, a relay with no effective protection settings would indicate a severe breakdown of established procedural controls or deliberate interference. Such conditions are ordinarily prevented through formal settings-management procedures, independent engineering reviews, Software Management of Change controls, secondary-injection testing, commissioning verification, Class-approved test programs, and periodic maintenance testing. Nevertheless, the analysis did not rely on these controls to dismiss the failure. It accepted the affected relay as entirely blind to the fault and evaluated whether the remaining protection architecture could independently maintain the vessel's WCFDI and complete fault isolation.

The analysis progressed substantially beyond the minimum DP-3 CB/CBT Class requirement. Rather than stopping after demonstrating that the vessel's WCFDI is maintained following an Active Failure combined with one credible Hidden Failure, the analysis continued through complete fault isolation while cumulatively introducing additional simultaneous Hidden Failures at successive protection layers. It therefore evaluated not only whether the fault could be contained within one DP segregation zone, but also whether all remaining sources of fault energy could be removed after preceding protection layers had been conservatively assumed to fail.

The dual autonomous bus-directional architecture was subsequently validated through full-scale live Earth-Fault and Short-Circuit testing following implementation on nine DP-3 MODUs. The analytical results demonstrate that HaloBus-ZBØSM can first contain an Earth Fault or Phase Fault within a single DP segregation zone and subsequently complete fault isolation despite the cumulative Blind Relay Hidden Failure assumptions progressively applied at successive protection layers. The live tests included intentional delay of the primary feeder-protection response to simulate the Blind Relay Hidden Failure used throughout the Electrical Fault Analysis. In all tested scenarios, the recorded relay events, circuit-breaker operations, MDG isolation, bus-voltage recovery, and automatic power-plant reconfiguration followed the

predicted protection sequence and maintained the vessel's WCFDI.

To the author's knowledge, this cumulative treatment of multiple simultaneous protection-setting failures, carried beyond WCFDI compliance through complete electrical-fault isolation and subsequently validated through full-scale live-fault testing, represents one of the most comprehensive publicly documented evaluations of a DP-3 MODU Closed Bus protection system. Furthermore, the implementation of two fully independent bus-directional protection zones introduces a novel protection architecture that achieves redundancy through autonomous fault-isolation paths rather than through duplication of similar protection functions.

The principal contributions of this work are:

1. **A novel dual autonomous bus-directional protection architecture** that provides two physically and functionally independent fault-isolation paths.
2. **A cumulative Hidden Failure evaluation methodology** that extends beyond conventional WCFDI demonstrations and follows the protection response through complete fault isolation.
3. **Full-scale live-fault validation** of the architecture and analytical methodology through Earth-Fault and Short-Circuit testing on nine DP-3 MODUs.
4. **Practical fleet implementation** at approximately one-tenth of the cost of traditional retrofit approaches and without dedicated vessel out-of-service time.

Unlike traditional Single Failure demonstrations, the analysis intentionally continued beyond maintenance of the vessel's WCFDI and examined whether complete fault isolation could still be achieved as additional Hidden Failures were progressively introduced. Within the fault scenarios, operating configurations, and failure combinations evaluated in this paper, the results support a bold conclusion:

With the HaloBus-ZBØSM dual autonomous bus-directional protection architecture, electrical-fault-induced Total Blackout should no longer be regarded as an unavoidable consequence of Closed Bus operation, but as a preventable event.

The designation ZBØ stands for Zero Black-Out. It is intentionally framed as a bold mission statement, not as a claim that residual risk has been eliminated or that any single design is infallible. Its purpose is to establish a clear industry objective: through disciplined engineering, independent protection layers, rigorous testing, operational learning, and continued scrutiny, electrical-fault-induced Total Blackout on rigs operating in Closed Bus should be treated as an outcome to be designed out, not an event to be accepted as inevitable.

The author recognizes that this conclusion is intentionally bold. It is, however, founded on detailed Electrical Fault Analysis, cumulative Hidden Failure evaluation, and full-scale live Earth-Fault and Short-Circuit testing on nine DP-3 MODUs. The analysis intentionally adopted assumptions extending significantly beyond normal industry practice, including the conservative assumption that the protection relay associated with the active protection layer may be affected by a Blind Relay Hidden Failure and therefore be completely unresponsive to the Active Failure. At each successive protection layer, the analysis introduces the worst-case Blind Relay Hidden Failure applicable to that layer while carrying forward the Hidden Failures already introduced at preceding protection layers. Consequently, the analysis does not assume that multiple protection relays are simultaneously blind at the beginning of the fault sequence. Rather, it evaluates whether each successive protection layer can maintain the vessel's WCFDI and continue fault isolation despite the cumulative Hidden Failures already established during evaluation of the preceding protection layers. These results provide confidence that the architecture remains robust under conditions extending substantially beyond current DP-3 CB/CBT requirements.

The offshore industry was built on a pioneering spirit that challenged accepted limitations through engineering, testing, and operational experience. That same spirit should guide the industry's approach to DP-3 Closed Bus protection. Classification requirements must appropriately recognize that residual risk can never be reduced to zero; however, this necessary conservatism should not prevent the industry from pursuing protection architectures designed to make electrical-fault-induced Total Blackout preventable. The HaloBus-ZBØSM design is presented in that spirit. Its dual

autonomous bus-directional architecture has been subjected to detailed Electrical Fault Analysis, progressively challenged through cumulative Hidden Failure assumptions, validated by full-scale live Earth-Fault and Short-Circuit testing, and successfully implemented on nine DP-3 MODUs. The author therefore invite the industry to challenge the design, identify credible failure mechanisms not considered herein, and use that collective scrutiny to further strengthen the architecture. Until the design has gained wider industry review and operational experience, elevated-risk activities may continue to be managed by temporarily reverting to the vessel's defined Safe-Case Open Bus configuration during well-control critical activities, severe-weather preparations, or other operations requiring the highest available segregation. Because such conditions represent only a limited portion of annual operations, this mitigation does not materially diminish the substantial fuel, maintenance, and emissions benefits available from Closed Bus operation during the remainder of the vessel's operating profile. The industry should therefore not allow historical concern regarding Total Blackout to prevent wider adoption of Closed Bus operation, but should instead apply the same pioneering engineering discipline that has advanced every previous generation of DP technology. In this context, the Zero Black-Out mission is not an expression of hubris; it is an invitation for the industry to align around a demanding, testable objective and to strengthen the design wherever credible vulnerabilities are identified.

The technical basis supporting the conclusion is summarized as follows:

- **Immediate fault containment:** Earth Faults are isolated with no intentional delay wherever practical, while Phase Faults are isolated with the minimum delay required for fault discrimination and protection coordination. When each 11 kV switchboard has at least one connected MDG, the bus-tie relays restore the Safe-Case Open Bus configuration in less than 100 ms. When the power plant operates efficiently with two connected MDGs, the redundant bus-directional protection functions isolate the affected DP segregation zone after the applicable directional-detection and selectivity intervals.
- **Redundancy beyond the minimum Class requirement:** The protection architecture maintains the vessel's WCFDI following an Active Failure combined with a credible Hidden Failure and then continues through complete fault isolation while considering additional cumulative Hidden Failures. This includes the severe assumed condition in which the protection relay associated with the active protection layer is affected by a Blind Relay Hidden Failure and therefore has no effective protection functions enabled.
- **Independent and autonomous protection zones:** Two bus-directional protection zones provide independent fault-sensing, communication, activation, and isolation paths. Each zone uses dedicated current and voltage inputs, separate communication interfaces, and independent protection logic. One protection zone includes the required sensing, communication, and circuit-breaker isolation components outside the compartment containing the protected switchboard and within separate DP segregation zones. This reduces the commonality that may exist in traditional arrangements where bus-directional and bus-differential protection schemes share PTs, CTs, communication-routing locations, or circuit breakers.
- **Autonomous backup protection:** Secondary and subsequent protection layers do not require the affected primary protection relay to identify the fault, issue a blocking signal, or transmit an activation request before backup protection can act. If the primary relay remains completely unresponsive, independently sensing protection functions can still maintain the vessel's WCFDI and complete fault isolation.
- **Communication-independent defense-in-depth:** Although point-to-point communications support the directional and differential protection functions, non-directional current- and voltage-based protection elements provide additional fault-isolation capability without depending on relay-to-relay communication. Detected communication failures also initiate alarms, activate the most sensitive protection settings group, and request automatic restoration of the Safe-Case operating configuration.
- **Protection of critical equipment after WCFDI has been maintained:** The analysis does not end when the faulted DP segregation zone has been separated from the healthy power plant. Additional generator-relay, bus-tie-relay, breaker-failure, MDG E-Stop, Switch On To Fault, and AVR protection layers remove any MDG that could continue energizing the isolated fault. These subsequent protection layers limit equipment exposure and complete fault isolation after the vessel's WCFDI has already been secured.

Importantly, these technical advantages were achieved through **architectural simplification rather than increased system complexity**. Unlike traditional approaches that obtain additional protection redundancy through more relays, expanded bus-protection systems, and additional communication interfaces, the HaloBus-ZBØSM design achieves increased autonomy and fault tolerance through the independent arrangement of two bus-directional protection zones. This distinction is fundamental because it improves both protection-system performance and practical implementability.

For a typical three-switchboard DP-3 MODU retrofit, HaloBus-ZBØSM generally limits equipment replacement to the six bus-tie protection relays, retains suitable existing feeder and generator protection, and uses simplified point-to-point Fiber-Optic and GOOSE communication interfaces. Traditional retrofit solutions may require replacement of more than forty 11 kV protection relays, installation of additional bus-protection hardware, and implementation of system-wide relay communication networks. The reduced device count, communication scope, engineering interfaces, and commissioning boundaries of the HaloBus-ZBØSM design also simplify testing, troubleshooting, failure investigation, lifecycle support, and future settings management.

Fleet implementation confirms that this architectural simplification produces substantial execution and commercial benefits. Nine DP-3 MODUs were upgraded using the HaloBus-ZBØSM design at approximately one-tenth of the total cost of a traditional retrofit solution. This cost included engineering, procurement, installation, commissioning, validation testing, and Class approvals. All nine upgrades were completed without dedicated vessel out-of-service time and required less than four days of scheduled preventive-maintenance time per vessel.

These advantages directly address the principal barriers that have historically limited wider adoption of Closed Bus operation on existing DP-3 MODUs: perceived Total Blackout exposure, protection-system complexity, extensive retrofit scope, commissioning risk, vessel downtime, and implementation cost. By addressing these barriers simultaneously, HaloBus-ZBØSM makes the operational and economic benefits of Closed Bus operation practically achievable. Fleet operating-data analysis indicates that Closed Bus operation can reduce annual fuel consumption by approximately **11% to 13%** and annual engine-maintenance burden by approximately **36% to 38%**, depending on vessel configuration and operating profile.

Closed Bus capability also provides the electrical-system foundation required for further power-plant efficiency improvements. Hybrid energy-storage systems, dynamic spinning-reserve optimization, rate-of-change-based load management, and other advanced fuel-efficiency strategies depend on the ability to share generation and stored energy across an interconnected power plant. HaloBus-ZBØSM should therefore be viewed not only as a Closed Bus protection upgrade, but also as an enabling step toward broader power-system optimization and future decarbonization initiatives.

Taken together, the analytical results, cumulative Hidden Failure evaluation, full-scale live-fault testing, and successful fleet implementation demonstrate that HaloBus-ZBØSM provides a highly autonomous, exceptionally redundant, and commercially practical DP-3 Closed Bus protection architecture. Most importantly, these outcomes were achieved through architectural simplification rather than increased complexity. By combining proven protection technologies within two fully independent bus-directional protection zones, HaloBus-ZBØSM provides a practical and economically viable path toward treating electrical-fault-induced Total Blackout as a preventable design outcome rather than an unavoidable consequence of DP-3 Closed Bus operation. In doing so, the design not only unlocks the operational and economic benefits of Closed Bus operation, but also provides the resilient electrical-system foundation required for the next generation of offshore power-system optimization and decarbonization technologies.

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